MICROELECTRO MECHANICAL SYSTEM NOTES

AKSHANSH CHAUDHARY

Micro Electro Mechanical Systems (MEMS) Notes, First Edition

Presented by: Akshansh Chaudhary
Graduate of BITS Pilani, Dubai Campus
Batch of 2011

Course content by: Dr. Anand Kumar
Then Faculty, BITS Pilani, Dubai Campus

Layout design by: AC Creations © 2013

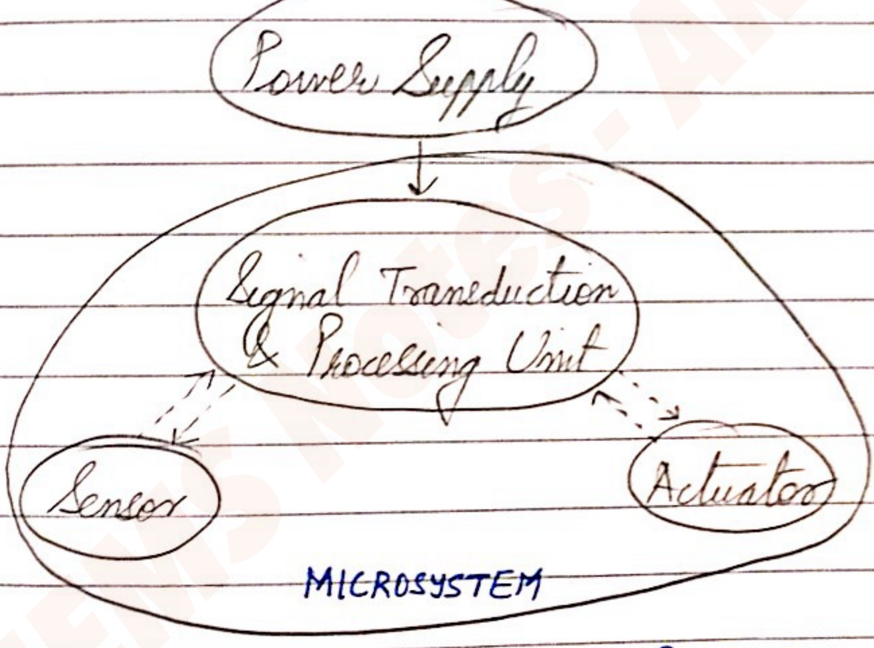
The course content was prepared during Spring, 2014.
More content available at: www.Akshansh.weebly.com

MEMS

↳ micro electro mechanical systems
↳ also called MICROSYSTEMS

- Microsystems tech. (MST)
- Nano tech (NT)
- 1 μm ≈ 1/10th of human hair
- 1 nm ≈ span of 10 H_2 atoms

* Components of Microsystems.



* Commercial MEMS & Microsys. Products

* Micro Sensors
  - ↳ Acoustic wave sensors
  - ↳ Biomedical & biosensors
  - ↳ Chemical
  - ↳ Optical
  - ↳ Pressure
  - ↳ Stress
  - ↳ Thermal

* Micro Actuators
  - ↳ Grippers
  - ↳ Motors
  - ↳ Relays & switches
  - ↳ Valves & pumps
  - ↳ Optical Equipment

Date
Page

* Microsystems = sensors + actuators + signal transduction

* Microelectronics | Micro systems (Si based)

Microelectronics	Micro systems (Si based)
• Mainly 2D	• Complex 3D structure
• Stationary structure	• Has moving component
• Mainly electrical signals	• Bio, chem, optical, electrical ... signals.
• Mass production	• Batch production.
• Std. fabricn technique	• No std. procedure for microfabricn

* Microsystems includes all science and engineering
- automotive, biomedical, aerospace, consumer products industry

* Note: See the applicns in all industries

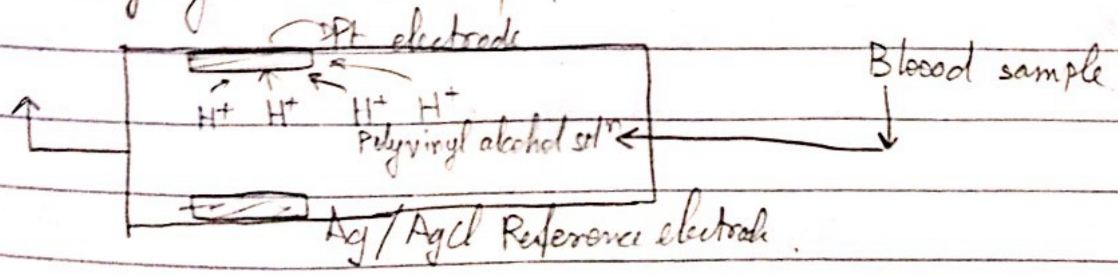
Chapter - 2

- Acoustic wave sensors.
  - use of Piezoelectric material
  - applicⁿ : acts like "band filters" in mobile phones & base stations.

- Bio MEMS
  - Biosensors for identificⁿ & measurement of biological subs.
  - Bioinstruments and surgical tools
  - Bio analytical sys. for testing and diagnosis
  - Issues
    - adaptive to existing instrument
    - compatibility with biological sys. of patients
    - Approval by FDA

* I/p signal
* Microsensing elemt
* Transduction unit
* O/p signal

eg Measuring glucose conc. of patient : Bio medical sensor.



→ eg :- SnO_2

★ Types of Chemical sensors :
(1) Chemiresistor ~~ser~~ sensors (metals change shape when chemicals apply on it. Change of shape is measured)
(2) Chemicapacitor sensors.

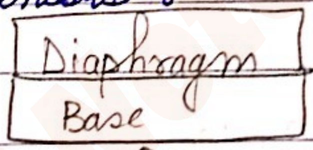
Diff from metal oxide sensors where metal oxides are used instead of metals.

★ Optical sensors
↳ detects intensity of light.
eg: photo diode, photo transistor

★ Common sensing materials : Si, GaAs, Li, Na, K, Rb.

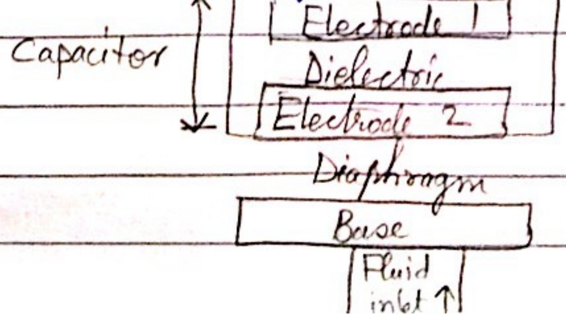
light (photons) ≡ light energy
↓ ↓ ↓
PN junction diode
↓
Current
↓
Sensing ✓

★ Pressure sensors :
↳



⇑
detector by fluid causing change in shape of diaphragm } ⇒ detection (converts to electrical voltage)

★ Piezoresistors : resistors, defined such that their values change on change in size, shape, ...



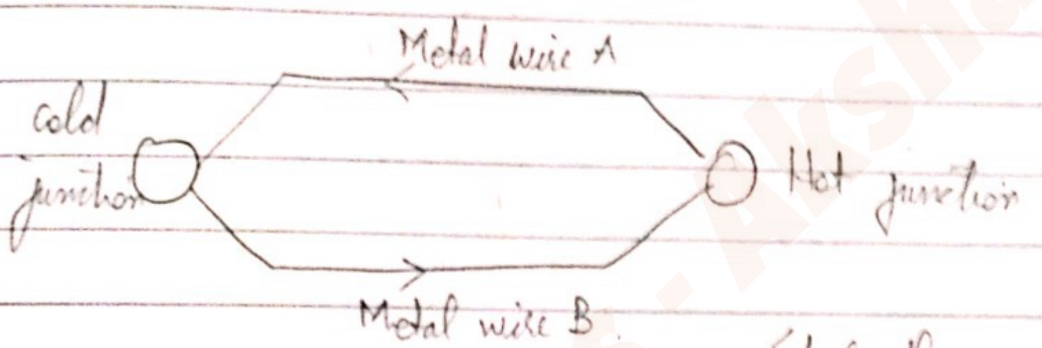
Fluid inlet ⇒ Diaphragm compress
↓
capacitance changes ⇐ Dielectric distance ↓

- Common types of micro pressure sensors
  - ✓ Piezoresistor sensors
    - small size, linear i/o rel^n, temp. sensitive
  - ✓ Capacitance sensors
    - bulky, lower cost, non linear i/p rel^n

☆ Main issue of pressure sensors : Packaging

☆ Thermal sensors:

↳ thermal sensors involve thermocouple & thermopiles.



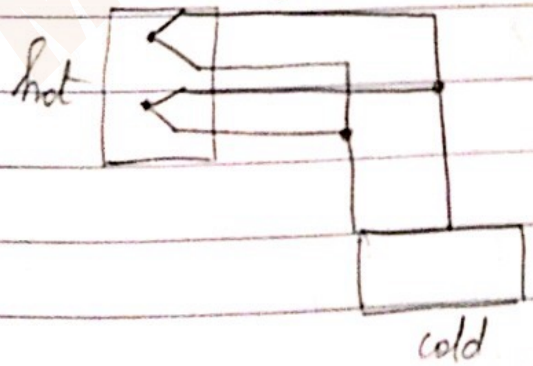
(dual thermocouple junction)

* Sensing happens due to diff in temp b/w 2 sides.
* Metal wires are chosen on the basis of temp. we need to measure

$\Delta V = \beta \Delta T$

ΔV → Induced voltage; β → seebeck coeff

☆ Another way :

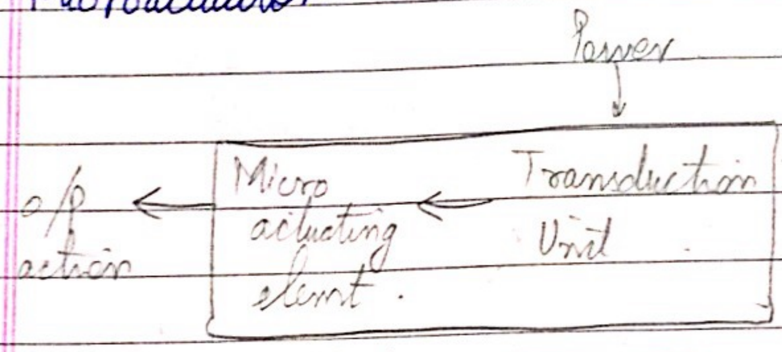


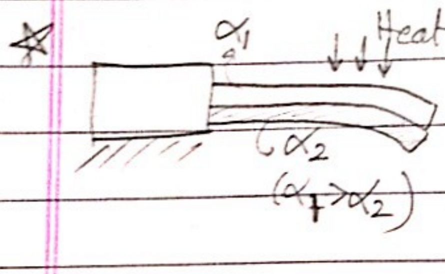
$\Delta V = N\beta\Delta T$

N → no. of thermocouples

SMA : Shape Memory Alloys.

- Microactuator



★ 

The amount of change in shape on temp. change can also be used for detection

★ SMA : Apply Heat : Shape changes.
Remove heat : Original shape restored.
So, such things can be used multiple times.

★ Piezoelectric crystals :
Actuation happens when mechanical force induces electrical voltage & vice versa.

★ Actuation using Electrostatic forces.
→ Use of attractive/repulsive forces b/w charges. (Coulomb's Law)
→ Using parallel plate's capacitance,

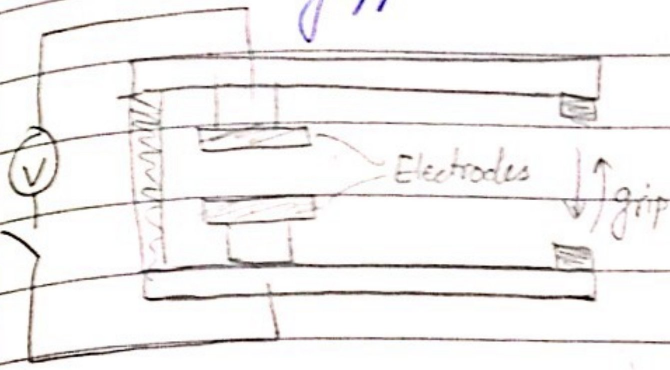
$$F_d = \frac{\frac{1}{2}CV^2}{d} = \frac{\frac{1}{2}\frac{A\epsilon_0\epsilon_r}{d}V^2}{d} = \frac{1}{2}\frac{WL\epsilon_0\epsilon_r V^2}{d^2}$$

(F_d : ⊥ force)

→ If ∥ plates are not perfectly aligned, apart from ⊥ components, ∃ other components (along W, L) also.

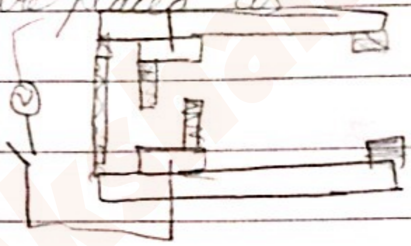
* Applicⁿˢ of Microactuators

✓ Microgrippers.



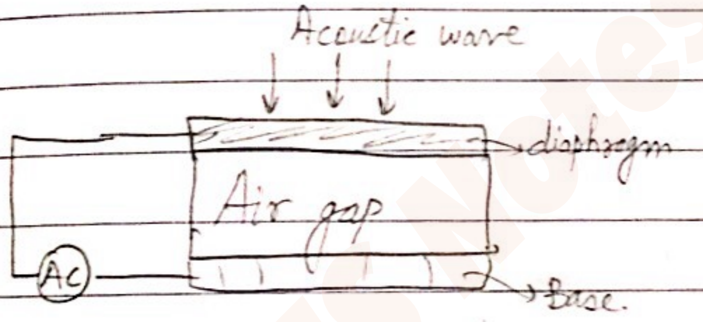
Idea, when the electrodes are aligned, force (F_d) due to that grips. (releases when mis-aligned)

↳ Opposite of this happens when electrodes are placed as



✓ Miniature microphones.

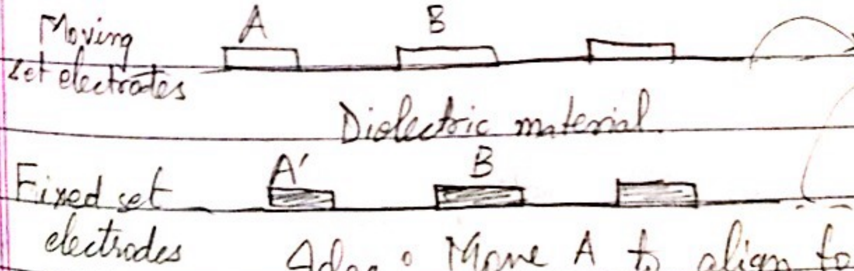
↳ Applicⁿ of acoustic wave on a diaphragm.



(fig: Just to give idea)

⇓
Air gap reduces
⇓
Capacitance changes
⇓
Electrical signal ✓

✓ Micromotors



→ Misaligned electrodes

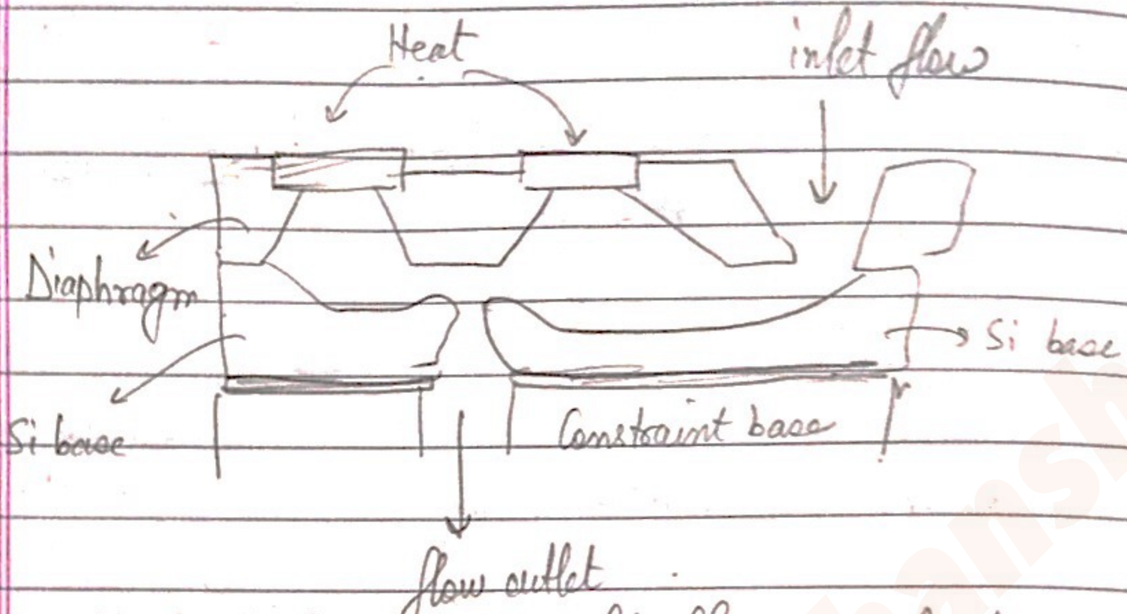
→ C changes.

Idea: Move A to align to A'. ⇒ Voltage got

Then match B & B', C & C' ....

✓ Same thing for rotary stepping motors.

- Microvalves

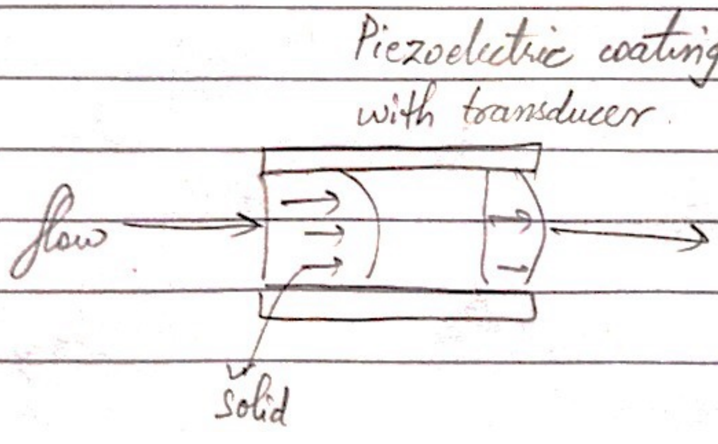


Heat diaphragm ⇒ outlet flow is restricted ⇒ pressure builds up ⇒ actuation happens.

- Micropumps

Apply voltage
⇓
Diaphragm moves ⇒ Pressure becomes high/low
⇓
i/p valve opens. Now, Remove voltage ⇒ fluid comes in.
⇓
On reverse action of voltage, fluid goes out.

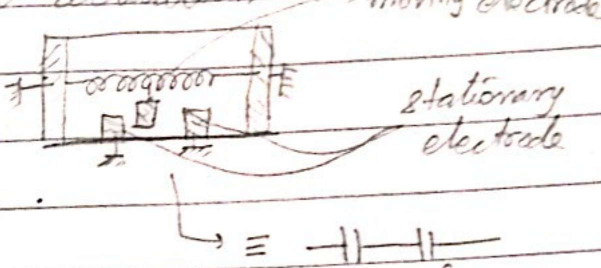
* **Piezoelectrically actuated pump.**



Idea: flow causes deform^n of solid ⇒ inside volume ↓ ⇒ transducer converts to electrical ⇒ flow out.

* ## Micro accelerometers

Use of spring force for actuation



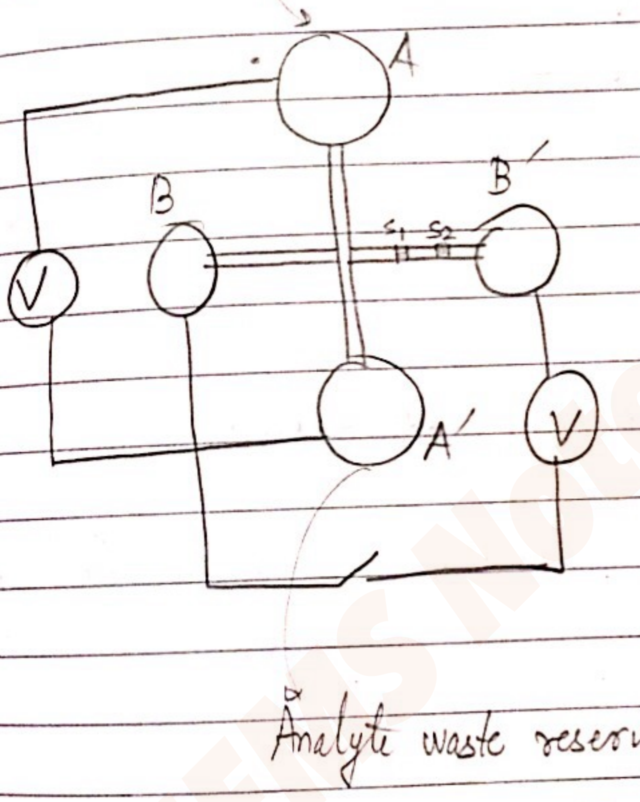
(capacitance changes as electrodes move. That gives dirⁿ & magnitude of accⁿ)

* ## Micro gyroscopes

An accelerometer that measures angular rotⁿ rates.

Change of rotⁿᵃˡ speed (ω) of solid can be related to coriolis force.

* eg Analyte Injected Reservoir, A
  (Sample with species S_1, S_2.



B : Buffer solvent injection reservoir

B' - Buffer solvent waste reservoir.

Idea : A has species
It goes through channel (capillary)
A solvent is there in B
leads to separⁿ of species

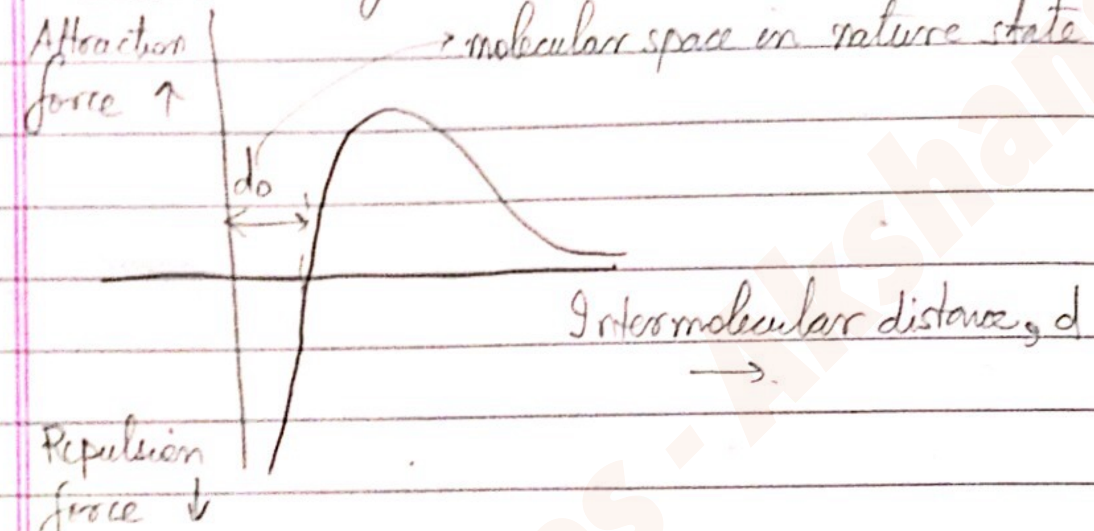
* ## Atomic Structure

- Diameter of outer orbit of atom : $2-3 \times 10^{-8}$ cm or 0.2 to 0.3 nm.
- Mass of proton $\simeq 1.67 \times 10^{-24}$ g.
- Mass of electron $\simeq 9.11 \times 10^{-28}$ g

He ↗ 2
Ne ↗ 2, 8
Ar ↗ 2, 8, 8
Kr ↗ 2, 8, 18, 8
Xe ↗ 2, 8, 18, 18, 8
Rn ↗ 2, 8, 18, 32, 18, 8

✱ Ioniz^n of gas requires 50 – 100 eV of i/p energy.
〃
1.6022×10^{-19} J

Intermolecular force



Idea : force b/w ions   ion = ion

$Na^+ Cl^-$: Force varies as $1/d$ → distance b/w ions
ion – ion

Na^+ H_2O : $1/d^2$
ion-dipole

HCl - HCl : $1/d^6$
dipole - dipole

Date: 16/2/14

* Diffusion :
  Applicⁿˢ :- - production of p-n junction, piezoresistors,
  - oxidⁿ of semiconducting material.
  - Chemical vapor deposⁿ processes
  - solid - solid diffusion
    eg: Si with B or As or P
  * Diffusivity of materials : Al > As.

* Diffusivity ∝ Temperature
  (or solubility) — upto a certain temp. range

---

* Plasma :
  - a gas containing high energy ions that carries electronic charges.
  - used to knock out substrate materials at desired localities in a dry etching process
  - used to carry out chemical vapor deposⁿ process

* Electrochemistry :
  - Electrolysis → electroplating polymers
  - Electrohydrodynamics → pumping fluids in microfluidics
    - Principle of moving fluids in micro channels or passages is similar to electrolysis i.e by ionizing the fluid first using electric potential. The ionized fluid will move in dirⁿ of preferred electrodes - achieving pumping process.

Pumping technique : Electro-osmotic pumping
↳ moving entire fluid in micro passages
- Electrophoretic pumping.

~ end of Ch-3 ~

Chapter -6

↳ SCALING LAWS IN MINIATURIZATION
- ↳ Scaling in geometry
- ↳ Scaling in size & material of object.

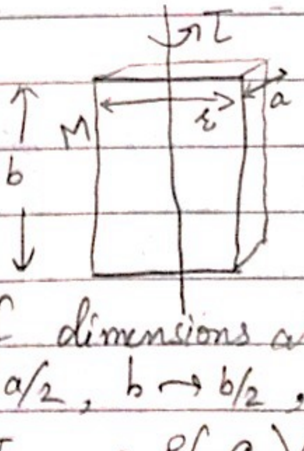
Scaling in geometry : main effect on Volume (V) & Surface (S)
↓ affects
inertia, buoyancy, forces.

$V \propto l^3$

$S \propto l^2$

↳ $S/V = l^{-1}$ ⇒ ∃ 10 times reduction in length.

eg :-



$I = Mr^2$

$= (\rho V) r^2$

$= \rho (abr) r^2$

$I = \rho a b r^3$

Now, if dimensions are halved,

$a \to a/2, \; b \to b/2, \; r \to r/2$

$\Rightarrow I_{new} = \rho \left(\frac{a}{2}\right)\left(\frac{b}{2}\right)\left(\frac{r}{2}\right)^3 = \frac{1}{32}\left(\rho a b r^3\right) \Rightarrow \frac{1}{32}$ times reduction

* For a rigid body, we look into its inertia.
  - Force (generated by power supply) reqd to move a part.
  - seeing how fast, the desired movements be achieved.
  - analysing how to stop that part.

Force = Ma ; $s = ut + \frac{1}{2}at^2$

$\hookrightarrow u = 0$

$\Rightarrow F = M\left(\frac{2s}{t^2}\right)$; $\Rightarrow a = \frac{2s}{t^2}$

$\Rightarrow F = \rho(V)\left(\frac{2s}{t^2}\right) \propto [L^3 \, L^1 \, T^{-2}] = [L^4 \, T^{-2}]$

($L^3 \to V$, $L^1 \to s$, $T^{-2} \to 1/t^2$) (dimensions)

* Power density = $\left(\frac{P}{V_0}\right)$

Dimensions = $\frac{P}{V_0} = \left(\frac{F \cdot s}{t}\right) \times \frac{1}{V_0} = \frac{(L^4 T^{-2})(L)}{[T][L^3]}$

$= [L^2 \, T^{-3}]$

Now, idea :-

let dimensions of F = $L^F = \begin{bmatrix} L^1 \\ L^2 \\ L^3 \\ L^4 \end{bmatrix}$ ☆

So, $L^F \propto L^4 T^{-2}$

$\Rightarrow T^{-2} \propto \frac{L^F}{L^4} \Rightarrow T \propto \sqrt{\frac{L^4}{L^F}}$

$\Rightarrow T \propto [L^2 \, L^{-F/2}]$

So, $\frac{P}{V_0} \propto L^2 \, T^{-3} = L^2 \left[L^2 L^{-F/2}\right]^{-3}$

$= L^2 \left[\frac{L^{F/2}}{L^2}\right]^3 = L^{-4}\left[L^{3F/2}\right]$

$\Rightarrow \frac{P}{V_0} \propto L^{-4} \begin{bmatrix} L \\ L^2 \\ L^3 \\ L^4 \end{bmatrix}^{3/2}$

Q. Estimate associated changes in accl^n (a) & time (t) and power supply (P) to actuate MEMS device if weight is reduced by 10.

$W \propto V \equiv [L^3]$.

So, order = 3.

$\Rightarrow$ no red^n in accl^n.

$L^{1/2} = 10^{1/2} = 3.16$: in time

$L^{0.5} = 3.16$ times red^n in power density.

★ Scaling in Electrostatic forces :

For a parallel plate capacitor, $U = -\frac{1}{2} C V^2$

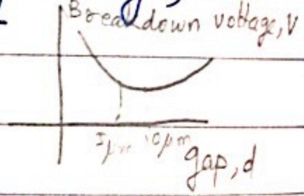
$\hookrightarrow C = \frac{(A) \epsilon_0 \epsilon_r}{d} = \frac{(WL) \epsilon_0 \epsilon_r}{d}$

Now,

ϵ_0, ϵ_r : $[L^0]$

W, L, d : $[L^1]$

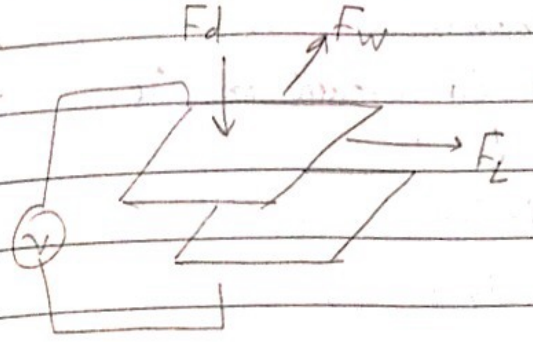
Voltage, V : $[L^1]$. By Paschen's effect, considering linear region for voltage, $V \propto L^1$



So,
$$U \propto \frac{[L^2][L^0][L^2]}{[L]}$$

$\Rightarrow U \propto [L^3]$ $\Rightarrow$ 10 times ~~red~~ reduction in linear size of electrodes $\Rightarrow$ 1000 times reduction in potential energy.

(VERY Important) ★ RB1 : Tai-Ran Hsu : MCQ's from textbook back questions — will come in tests, quizzes, compre - directly



★ Finding electrostatic forces in misaligned electrodes. Seeing in all 3 dir^{ns}:
F_d, F_w & F_L $\propto l^2$.

* So, 10 times red^n in electrode linear dimensions
  ⇒ 100 times ~~req~~ req reduction in electrostatic forces.

★ We are trying to accomplish movement of object (actuation). We find that on reduction in size, force reduces considerably. This is not desired. So, electromechanical forces are not directly used for MEMS practically.

* electrical resistance, $R = \frac{\rho l}{a} \propto l^{-1}$

* resistive power loss, $P = \frac{V^2}{R} \propto l^1$

* Electric field energy, $U = \frac{1}{2} \epsilon E^2 \propto l^{-2}$

* Ratio of power loss to available power,

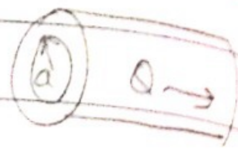
$$\frac{P}{E_{av}} = \frac{l^1}{l^3} = l^{-2}$$

↳ ⇒ decreasing dimension ⇒ power loss increases

* Current, $i \propto l^2$
* Voltage, $V \propto l$
* Resistance, $R \propto l^{-1}$
# * Inductance, $L \propto l$
# * Power, $P \propto l^2$
* Capacitance, $C \propto l$

* Scaling in fluid mechanics

✓ Reduction of 10 in conduit radius



⇓

flow ($Q \propto a^4$) 10^4 times reduction in volumetric flow.

✓ $\frac{\Delta P}{L}$ = Pressure drop per length $\propto a^{-3}$. (a → radius)

* Scaling in Heat Conduction

✓ thermal conductivity (k) $\propto l^1$

✓ time taken to heat solid $\propto l^2$.

end of Ch-6

Puffin
Date 23.2.14
Page

Chapter -4

ENGINEERING MECHANICS FOR MICROSYSTEMS DESIGN.

↳ look into stress, strain & deformation.

* Mechanical design of microstructures
  ↳ Theories needed to know:
  - linear theory of elasticity for stress analysis
  - Newton's Law for dynamic & vibration analysis
  - Fourier law for heat conduction analysis
  - Fick's law for diffusion analysis.
  - Navier-Stokes eq^{ns}

* Common geometry of MEMS Components
  - Beams
    Microrelays, gripping arms, beam spring.
  - Plates
    Diaphragms
  - Tubes
    Capillary tubes.
  - Channels

* Conversion formulas

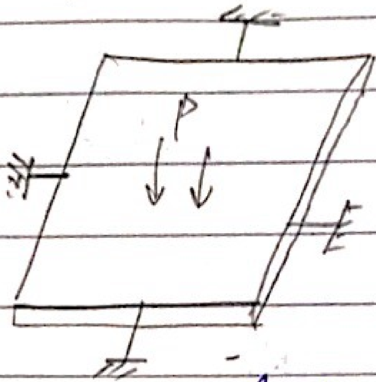
1 g = 9.81 m/s^2
1 kgf = 9.81 N
1 μm = 10^{-6} m
1 Pa = 1 N/m^2
1 MPa = 10^6 Pa = 10^6 N/m^2

1 m = 39.37 in = 3.28 ft
1 N = 0.2252 lb_f (force)
1 kg_f = 2.2 lb_f (weight)
1 MPa = 145.05 psi

SI unit: Mass density = g/cm^3

* Static bending of thin plates

Considering a plate fixed from all 4 sides.



If some pressure (P) is applied, the plate's bending moment tends to change (M_x, M_y → bending moment)

MPa

Induced deflection of plate : $W(x,y)$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right) = \frac{P}{D}$$

→ D = flexural rigidity

$$= \frac{E h^3}{12(1+\nu^2)}$$

E → Young's modulus (MPa)

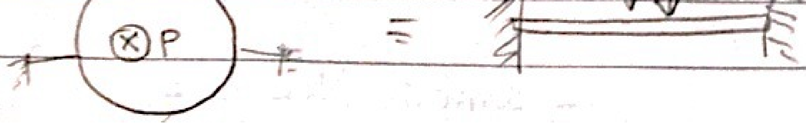
ν → Poisson's ratio

* Bending moments (M_x, M_y, M_{xy}) & bending stresses $(\sigma_{xx})_{max}$, $(\sigma_{yy})_{max}$, $(\sigma_{xy})_{max}$ can be found.

→ Max. bending stress ∝ Max. bending moment.

→ $(\sigma_{xx})_{max} = \frac{6 (M_x)_{max}}{h^2}$

* Similar can be seen for a circular plate, fixed from all sides & pressure applied at centre.



→ here, we'll have bending stresses $(\sigma_{rr})_{max}$ & $(\sigma_{\theta\theta})_{max}$

* Max. stress will be along the edges.

$$(\sigma_{rr}, \sigma_{\theta\theta})_{center} = \frac{1}{2}(\sigma_{rr}, \sigma_{\theta\theta})_{edges}$$

* Max. deflection of plate occurs at its center.

$$(\sigma_{rr})_{max} = \frac{3W}{4\pi h^2}, \quad (\sigma_{\theta\theta})_{max} = \frac{3\nu W}{4\pi h^2}.$$

eg Determine min. thickness of circular diaphragm of a microsensor made of Si, as shown.

Condns: diameter, $d = 600\,\mu m$

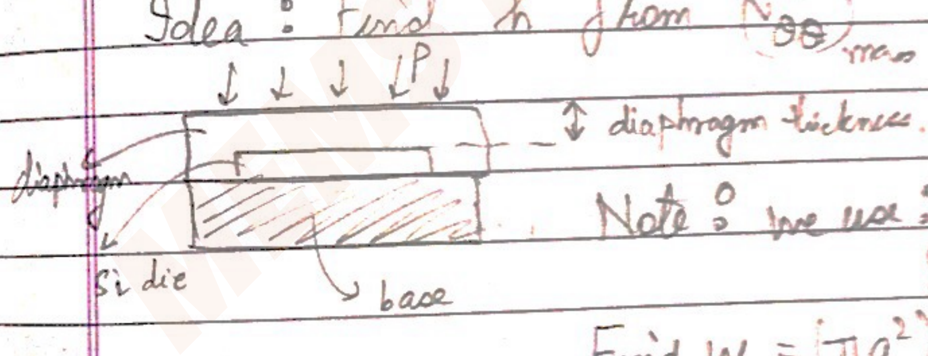
Applied pressure $= p = 20\,MPa$

Yield strength of Si $= \sigma_y = 7000\,MPa$

$E = 190{,}000\,MPa$

$\nu = 0.25$.

Idea: Find h from $(\sigma_{\theta\theta})_{max}$ $\left(\to \frac{3\nu W}{4\pi h^2}\right)$ & $(\sigma_{rr})_{max}$ $\left(\to \frac{3W}{4\pi h^2}\right)$.



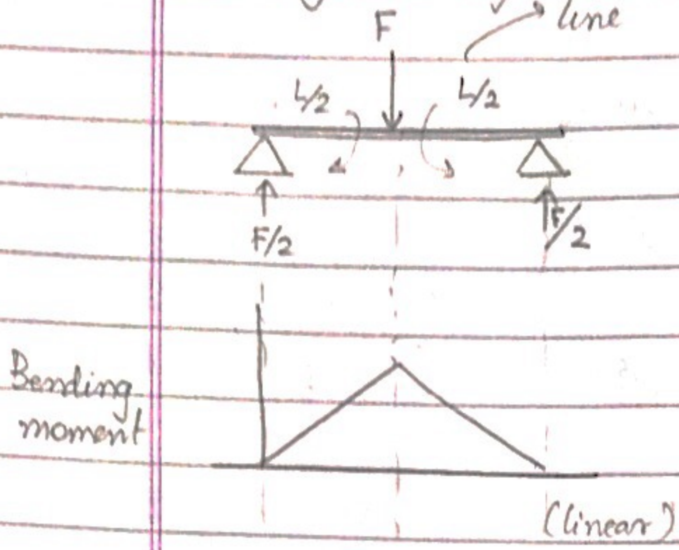
Note: we use: $\sigma_{rr} < \sigma_y = 7000\,MPa$

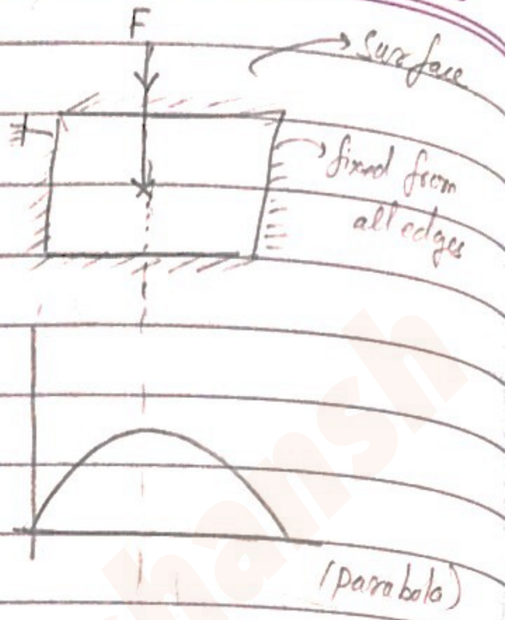
& $\sigma_{\theta\theta} < \sigma_y = 7000\,MPa$

Find $W = (\pi a^2)p$, a = radius

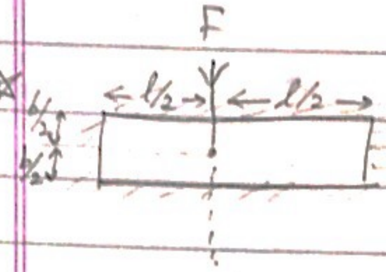
Then, use the larger value of h

★ Seeing Bending Moment :





★



For a point force applied, Bending moment (= Force × distance) will be more along the length (l) as compared to breadth (b)
Inverse is true for Stress

* Max. stress should be along the longer edge.

★ For a square plate (side = a)

$$\sigma_{max} = \text{Max. stress} = \frac{\beta p a^2}{h^2} \quad (Pa)$$

$$\omega_{max} = \text{max. deflection} = -\frac{\beta p a^4}{E h^3} \quad (\mu m)$$

(for rectangle, replace "a" with the larger length)

★ Pressure sensors : mainly used in fluid flows

* Underdamped = 
* Overdamped = 

* General comparison

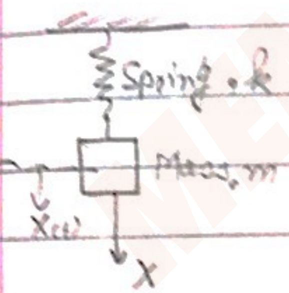
Geometry	Max stress (MPa)	Max. Deflection (µm)
	7000	55.97
	7293	21.76
	9040	43

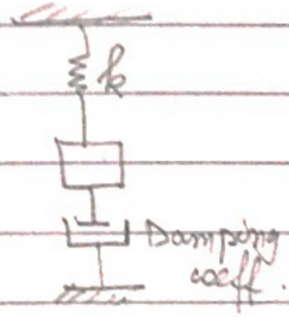
→ assuming same area & thickness
→ applying same pressure

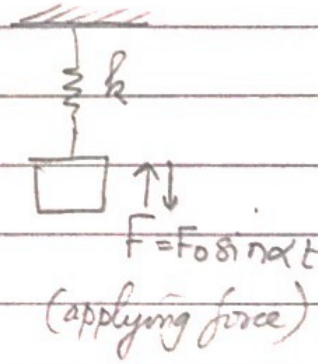
* Mechanical Vibration Analysis

• Simple mechanical vibration systems :

Free vibration | Damped vibration | Forced vibration







• Circular frequency $(\omega) = \sqrt{\frac{k}{m}}$ = Angular frequency

• Natural frequency $(f) = \frac{\omega}{2\pi}$

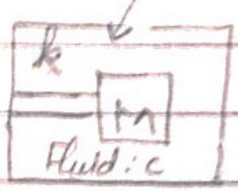
• Self 8 eq 4.6 (Pg - 121)

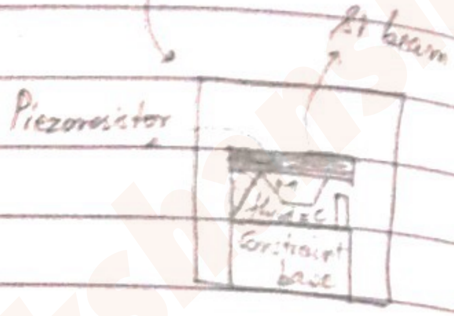
Puffin
Date
Page

* MICRO ACCELEROMETERS

↳ used to measure accl^n (or deceler^n).

Conventional accelerometers : spring mass, spring mass dashpot
Microaccelerometers : Beam mass, beam attached mass





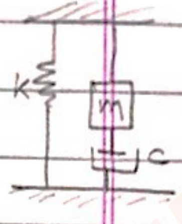
• Design theory of accelerometers :

$$\text{amplitude, } Z_{max} = \frac{\omega^2 X}{\sqrt{\left(\frac{k}{m}-\omega^2\right) - \left(\frac{\omega c}{m}\right)^2}} = f(X, k, m, c)$$

Z_{max} → $= -(a_{base\ max})/\omega_n^2$

X → magnitude of change in spring length (amplitude of vibration), $X(t) = X \sin \omega t$

c → friction coeff



$Z(t) = y(t) - X(t)$ → $= Z \sin(\omega t - \phi)$

(Difference : to consider phase)

$$\text{phase, } \phi = \tan^{-1}\left(\frac{\frac{\omega c}{m}}{\frac{k}{m} - \omega^2}\right)$$

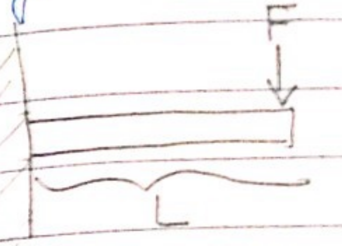
$$* \ h = \frac{c}{2 m \omega_n} = \frac{c}{c_c}$$ (c → damping coeff)

$$* \ \omega_n = \sqrt{\frac{k}{m}}$$

- Spring constant of simple beams:-

Spring constant, $k = \dfrac{\text{Applied force, } F}{\text{Induced deflection, } \delta} = \dfrac{3EI}{L^3}$

(E → Youngs modulus; I → moment of inertia)



* Damping coefficients:
(1) Squeeze film damping
(2) Micro damping in shear

eg Assume $X(t)\Big|_{t=0} = 0$.

i.e. max amplitude for base = 0 initially

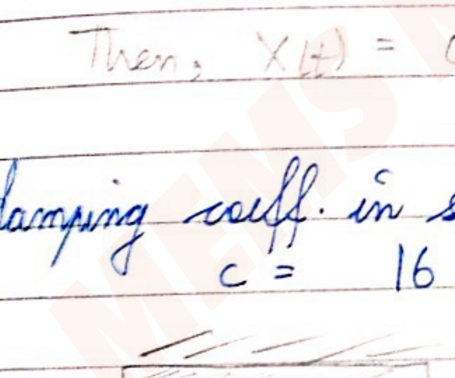
& $\dfrac{dX(t)}{dt} = 50$ km/hr

Then, $X(t) = 0.0282 \sin(1083.2t)$

- damping coeff. in shear film,

$$c = 16 f\left(\frac{W}{L}\right) W^3 L H_0^3$$

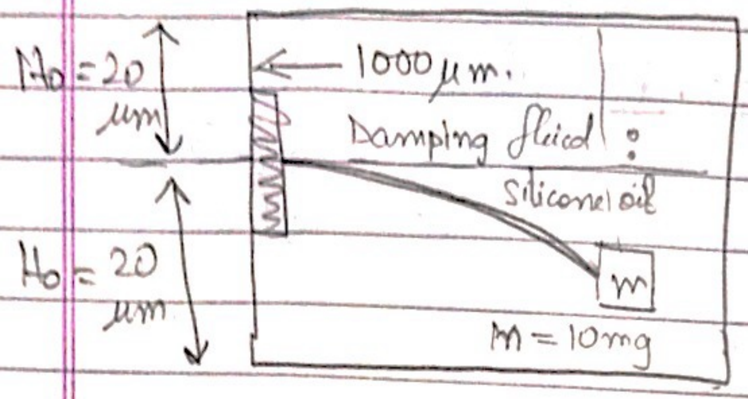
(H_0 → nominal thickness of thin film.)



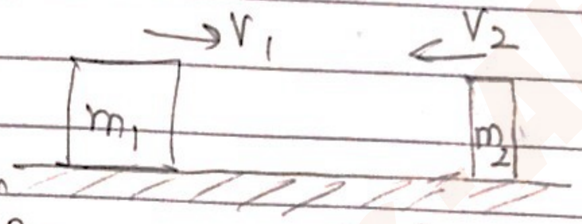
* damping coeff, $c = \dfrac{2\mu L b}{H}$

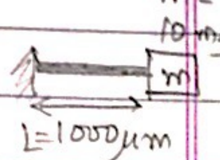
(L → length, b → breadth, H → gap)

eg estimate damping coeff

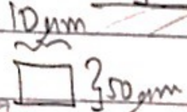


pg-142 eg Design inertia sensor for airbag deployment sys in automobiles.





(using property of beam spring)



Crossection of beam

Given :- m_1, m_2 (m_1 → 12K, m_2 → 8K), $V_1 = V_2 = 50$ Km/hr

Idea :- Find MOI (Moment of Inertia), k

$k \rightarrow \frac{3 \times 190000 \times 10^6 \times I}{(1000\,\mu m)^3}$, $I \rightarrow \frac{10\,\mu m \times (50\,\mu m)^3}{12}$

Then, $\omega_n = \sqrt{\frac{k}{m}}$.

$k = \frac{3EI}{L^3}$

Now, by conservation of momentum,

$(m_1 + m_2)V = m_1 V_1 + m_2 V_2$

$\Rightarrow V = 10$ Kmph.

Assume $\Delta t = 0.5$ sec

$\Rightarrow \ddot{X}_{m_1} = \frac{V - V_1}{\Delta t} = -22.2$ m/s.

Also., Z (Deflection) $= -\frac{a_{base}}{\omega_n^2} = 3.74$ μm.

Now, $F = kx = kZ = 2.2213 \times 10^{-4}$ N

$M_{max} = F \cdot L = 2.2213 \times 10^{-4} \times 10^{-3}$ N-m.

$\sigma_{max} = \text{Stress} = \frac{M_{max} \times C}{I}$ (C → 25 μm) $= 532.95 \times 10^5$ N/m² or Pa.

So, σ_{max} ≡ change of resistance of Piezoresistor

Strain, $\epsilon_{max} = \frac{\sigma_{max}}{E}$ $= 2.81 \times 10^{-4}$ $= 0.0281\ \%$

E → Young's modulus

ϵ_{max} ≡ change of voltage of piezoelectric crystal.

THERMOMECHANICS

↳ Includes mechanical effects induced by thermal forces.

* $E \propto 1/T$ (E → Young's modulus, T → Temperature)

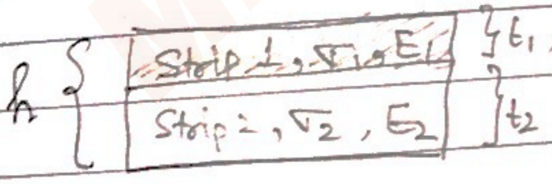
$\sigma_y, \sigma_u \propto 1/T$ (→ stress)

$k, \alpha, c \propto T$

- k → Spring constant
- α → Thermal expansion coeff
- c → damping coeff.

* Creep resistance : Resistance not varying much with time.

eg Consider 2 strips connected laterally (α_1, E_1 & α_2, E_2)



let's change temp. :
$\Delta T = T - T_0$.

Assume :- $t_2 > t_1$ & $\alpha_2 > \alpha_1$

So, bending happens :

→ strip 2 expands more.

let radius of curvature = ρ

$m = t_1/t_2$, $n = E_1/E_2$

$$I_1 = \frac{t_1^3}{12}, \quad I_2 = \frac{t_2^3}{12}.$$

$$\frac{1}{\rho} = \frac{6(1+m)^2(\alpha_1-\alpha_2)\Delta T}{h\left[3(1+m)^2 + (1+mn)\left(m^2+\frac{1}{mn}\right)\right]}$$

→ If $t_1 = t_2 \Rightarrow m = 1$

$$\Rightarrow \frac{1}{\rho} = \frac{24(\alpha_1-\alpha_2)\Delta T}{h\left[12 + (1+n)\left(1+\frac{1}{n}\right)\right]}$$

→ If $E_1 \simeq E_2 \Rightarrow n = 1$

$$\Rightarrow \frac{1}{\rho} = \frac{24(\alpha_1-\alpha_2)\Delta T}{h[12+2(2)]}$$

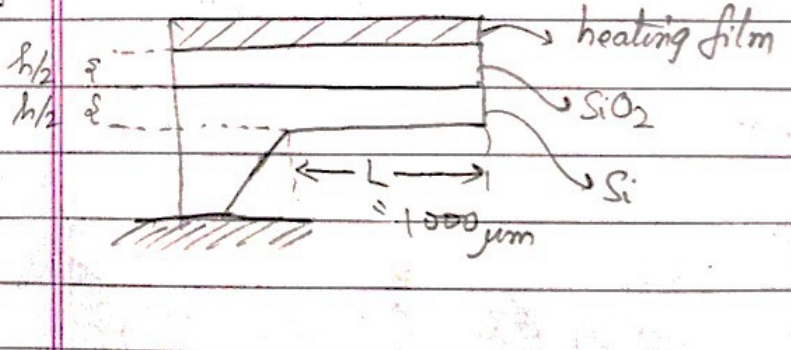
$$\Rightarrow \rho = \frac{2h}{3(\alpha_2-\alpha_1)\Delta T}$$

Now, $F = \frac{(\alpha_2-\alpha_1)\Delta T}{8} \frac{hb}{\left(\frac{1}{E_1}+\frac{1}{E_2}\right)}$

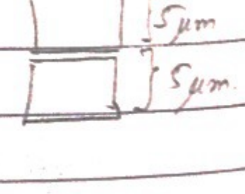
(can be calculated)

★ Now, seeing deflection for different materials

eg Consider a heating film.



Also given cross section:



Given : $\alpha_{SiO_2} = \alpha_1 = 0.5 \times 10^{-6} /°C$

$\alpha_{Si} = \alpha_2 = 2.33 \times 10^{-6} /°C$

$E_{SiO_2} = E_1 = 385000$ MPa

$E_{Si} = E_2 = 190000$ MPa

$\Delta T = 10°$ change.

Now, using formula,

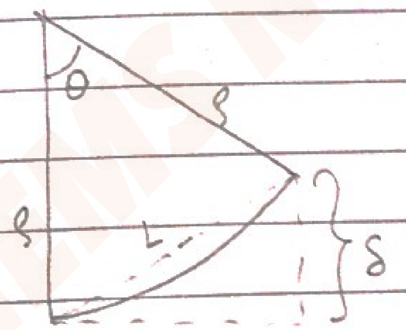
$$F = \frac{(\alpha_2 - \alpha_1)\,\Delta T \; h\, b}{8 \left(\frac{1}{E_1} + \frac{1}{E_2}\right)} = 14.55 \times 10^{-6}\, N$$

($h \to 10\mu m$, $b \to 5\mu m$)

& $\rho = 0.3643$ m (from original formula)

Now, see it in a pendulum.

We have to find θ, δ



$2\pi\rho \longrightarrow 360°$

$L \longrightarrow \theta$

$\Rightarrow \theta = 0.1574°$

& $\delta = \rho - \rho\cos\theta$

$= 1.373\, \mu m$

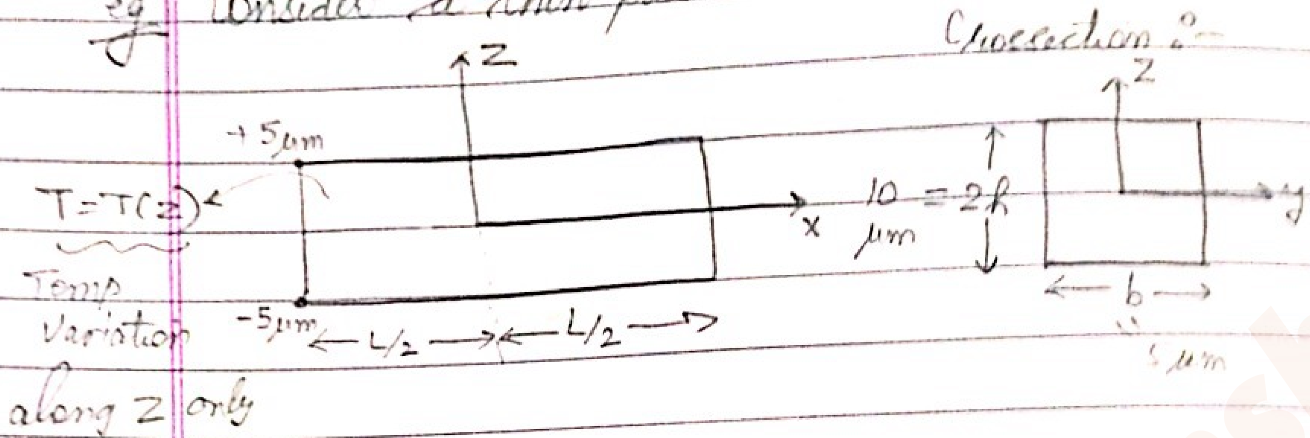
= Deflection

Note : If thickness ($t_1, t_2 \rightarrow$ same before) is now changed, we can get a different type of bending

↳ eg. If $t_1 = 2\mu m$, $t_2 = 8\mu m \rightarrow$

What will come: Not a numeral directly. But, numerical analysis. Like, if length increases, what happens?

eg. Consider a thin plate



Find: Bending stress, deflection.

Assume: Shearing stress (τ_{zx}, τ_{xz}) = 0.

$$A = \text{Area} = 2bh$$

$$I = MOI = \frac{2h^3 b}{3}$$

Bending stress :- (α: coeff. of thermal expansion; E: Young's modulus; N_T: Thermal force; M_T: thermal moment)

$$\tau_{xx}(x,z) = -\alpha E\, T(z) + \frac{b N_T}{A} + \frac{z (b M_T)}{I}$$

Given: α = coeff. of thermal expansion = 2.33×10^{-6} /°C

E = young's modulus = 190000×10^{6} N/m²

$\nu = 0.25$ = Poisson's Ratio

$T(z) = 2.1 \times 10^{6} z + 28.8$ °C

→ $t = 1\,\mu s$

i.e., $T(z,t) = T(z, 1\mu s)$

We know everything except N_T, M_T (in τ_{xx})

So, $N_T = \alpha E \int_{-h}^{h} T(z)\,dz = 127.5$

$M_T = \alpha E \int_{-h}^{h} T(z).z\,dz = 77.4725 \times 10^{-6}$ N-m.

Using all these values, we get

$\tau_{xx}(z, 1\mu s) = f^n(z)$

* Piezoresistor : measure stress
* Piezoelectric crystal : measure strain

So, we have σ_{xx} as a fn of z. Differentiating & putting equal to zero, we get σ_{max}

So,

$$\sigma_{max} = -500\,Pa \text{ at } z = 5\,\mu m$$

(seen by varying z from $-5\,\mu m$ to $5\,\mu m$).

Strain :

$$\epsilon_{xx}(x,z) = \frac{1}{E}\left[\frac{bN_T}{A} + \frac{z}{I}(bM_T)\right]$$

(So, we can find strain for diff^{nt} pos^{ns} by varying z)

Illy,
$$\epsilon_{zz}(x,z) = -\frac{\gamma}{E}\left[\frac{bN_T}{A} + \frac{z}{I}(bM_T)\right] + \left(\frac{1+\gamma}{E}\right)\alpha T(z)$$

$$\Rightarrow \epsilon_{zz}(x,z) = -\gamma\,\epsilon_{xx}(x,z) + \left(\frac{1+\gamma}{E}\right)\alpha T(z)$$

So, $\epsilon_{xx}(z) = f_1(z) \Rightarrow \epsilon_{xx,max} = 0.0092\%$

$\epsilon_{zz}(z) = f_2(z) = \epsilon_{zz,max} = 0.0023\%$

Note : We assumed shearing stress = 0. If we ↑ h from 10 μm, it sort of doesn't remain 2D. So, ∃ some shearing stress.

Now, Deflections : $u(x,z) = \frac{x}{E}\left(\frac{bN_T}{A} + \frac{z}{I}(bM_T)\right)$

$\Rightarrow u(x,z) = 0.046\,\mu m \rightarrow x$ dir^n

& $w(x,z) = -0.612\,\mu m \rightarrow z$ dir^n.

Lastly, radius of curvature, $1/\rho = -bM_T/EI = -4.892\,m^{-1}$

some breakage.

Puffin
Date
Page

✲ Application of Fracture Mechanics in MEMS & Microsystem Design.

✲ MEMS components are made of layers of thin films so fractures possible.

✲ Now, a crack can keep extending, once it happens

✲ Linear elastic fracture mechanics (LEFM)

✲ Cracks (fracture) is more probable in layered structure

✲ Stress Intensity Factors:

- Consider an elastic solid having crack.
- Its subjected to thermal loading
- Stress field induced due to loading
- We can see the stress components near the crack's tip

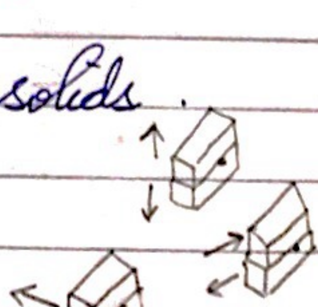
→ shearing & bending stress on all dirⁿ

✲ ∃ 3 modes of fracture of solids.

Mode I Opening mode :

Mode II Shearing mode :

Mode III Tearing mode :



✲ Stress intensity factor (K)

K_I : stress intensity factor for mode I fracture

K_{II} : " " " II

K_{III} : " " " III

Near tip stress $(\sigma_{ij}) \propto K_I / K_{II} / K_{III}, 1/\sqrt{r}$

Near tip displacement $(u_i) \propto K_I / K_{II} / K_{III}, \sqrt{r}$

Date
Page

* Fracture toughness (K_c)

↳ K_{IC}, K_{IIC}, K_{IIIC}

If, $K_I > K_{IC}$: Unstable crack in mode I fracture

$K_{II} > K_{IIC}$: " " " II "

$K_{III} > K_{IIIC}$: " " " III "

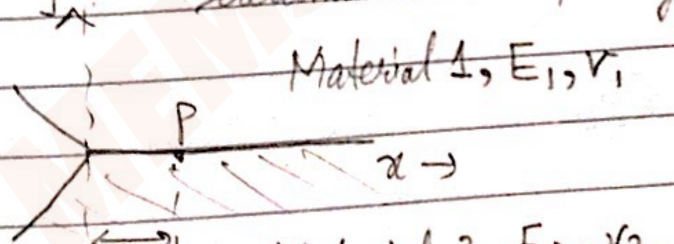
* Critical load (P_{cr})

$$K_{IC} = \sigma_c \sqrt{\pi C}\, F(C/b)$$

- $F(C/b)$ → a constt
- σ_c → $\frac{P_{cr}}{A}$, where A ↳ entire object area
- C ↳ Crack length

* Interfacial Fracture

↳ delamination of layers



$$\sigma_{ij} = \frac{K_I \text{ or } K_{II}}{r^{\lambda}}$$

λ → Singularity parameter

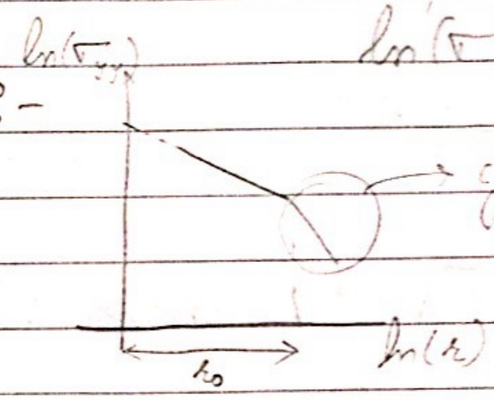
→ when $r \to 0$, L_{ij} is small.

$$\sigma_{ij} = \frac{K_I \text{ or } K_{II}}{r^{\lambda}} + L_{ij} \ln(r) + \text{other terms}$$

So, $\sigma_{yy} = \frac{K_I}{r^{?_I}}$, $\sigma_{xy} = \frac{K_{II}}{r^{?_{II}}}$.

→ can be plotted on log scale $\ln(\sigma)$ vs $\ln(r)$

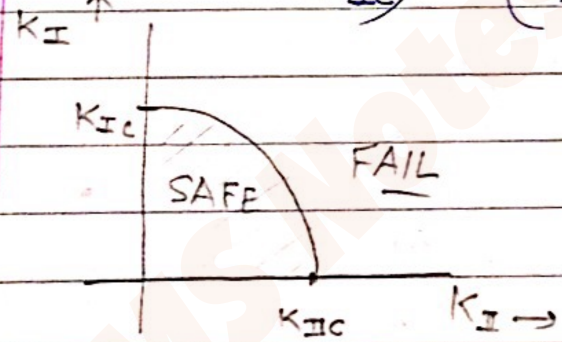
Note :-



→ fracture inside the surface is likely NOT to collapse

* Failure (fracture) criteria

$$\left(\frac{K_I}{K_{IC}}\right)^2 + \left(\frac{K_{II}}{K_{IIc}}\right)^2 = 1$$



* Note : The films are thin. So, molecular forces cannot be ignored.

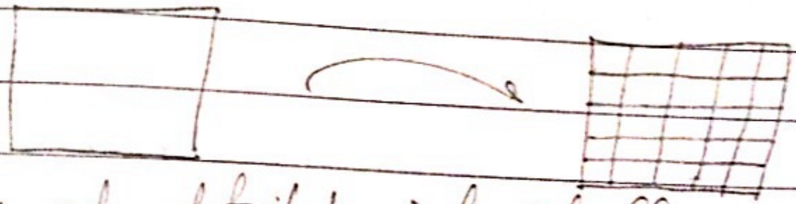
$$\sigma = \sigma_{thermal} + \sigma_{mechanical} + \sigma_{intrinsic}$$

($\sigma_{intrinsic}$ →) due to molecular forces & residual stresses

Puffin
Date
Page

✱ FEM : Finite element method

↳ divide object into finite no. of pieces & each connected via nodes.
- Then we see stress for each interface individually.



- We get detailed info, if the size of element is small
- Assume : nodes are interconnected
- It was seen in COMSOL : MESH tool → density of nodes (or size of elements) can be changed.
- For this analysis, we can give material property i/p (young's modulus ...) & look at boundary & loading condⁿˢ - for stress analysis and heat conduction ~~of~~ analysis.

✱ von-Mises stress : → a representative stress in multi axial stress situation.
defined as :-

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{xx} - \sigma_{zz})^2 + (\sigma_{yy} - \sigma_{zz})^2 + 6(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{xz}^2)}$$

✱ Note : FEM takes time to implement.
So, its done mainly in those areas where fracture is likely to occur.

Puffin
Date 10.9.14
Page

CHAPTER - 7

MATERIALS FOR MEMS & MICROSYSTEMS

↳ mainly Silicon will be studied.

- Other Si compounds : SiO_2, SiC, Si_3N_4, poly silicon.

Silicon (Si)

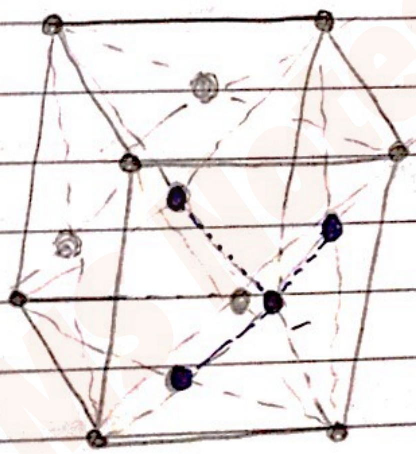
- most abundant material on earth.
- most widely used substrate material for MEMS.
- Properties:
  - Mechanically stable → used in electronic substrate.
  - for p- or n-type piezoresistive → for signal transduction
  - Ideal structure material
    - ↳ ✓ Youngs modulus → that of steel.
    - ↳ ✓ As light as Al.
  - Melting pt. : 1400°C (twice as of Al)
  - Thermal expansion coeff : 8 times smaller than that of steel. & 10 times smaller than Al. (i.e, it doesn't expand much)
  - Shows no mechanical hysteresis. (i.e, T ↑, L ↑ & T ↓, L ↓ by same ratio)
  - Flat wafers (——, instead of ~~~) So, chances of fracture are low; Distrib^n of heat will be uniform in Si; finite element analysis is easier.
  - Great flexibility in design & manufacture (∵ it has been used to manufacture since ages)

Puffin
Date
Page

* Single Crystal Si :

Method to produce : CZOCHRALSKI (CZ) method.
Equipment : crucible & puller
Idea : ✓ Melt Si in a crucible
✓ Take a rod having Si initially on it (Si seed)
✓ Puller is used to pull out the rod, forming Si boule.
✓ Slicing is done of the boules to get wafers
* ∃ some std. sizes of wafers.

* Single-Si crystal
↳ follows FCC structure (face-cubic center)



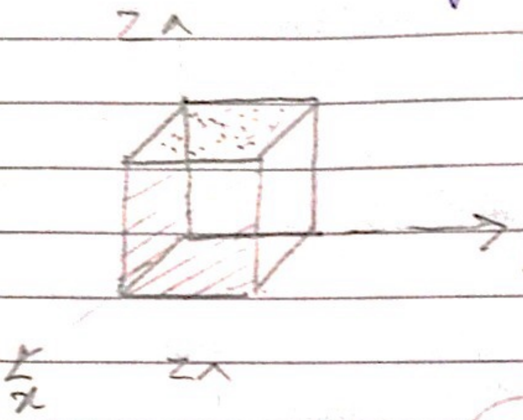
Si has 4 e^- in valence shell. So, usually we merge 2 Si FCC

Total no. of atoms :
8 corners + 6 face centres
= 14

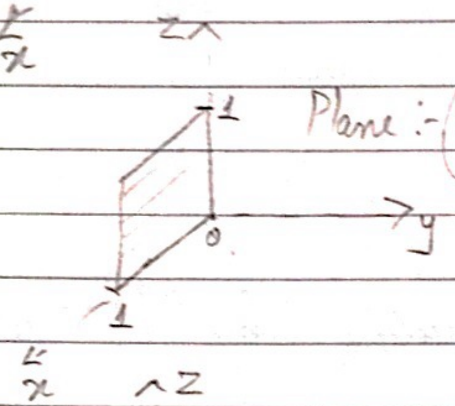
* Miller Indices : describes faces of crystalline materials.

Consider a plane, intersecting x, y, z axis at a, b, c resp.
So, eq^n of plane, P = $\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1$
↳ If $1/a = h$, $1/b = k$, $1/c = m$
$\Rightarrow hx + ky + mz = 1$.

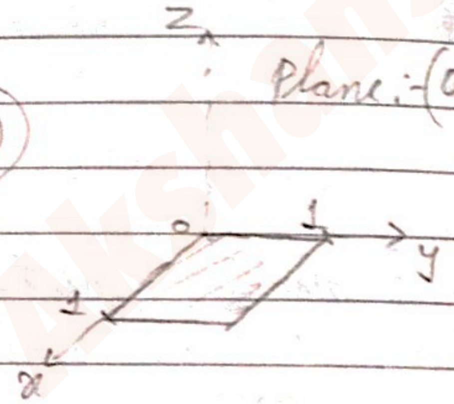
(h k m) : Designation of face, of plane.
<h k m> : Designation of direction.



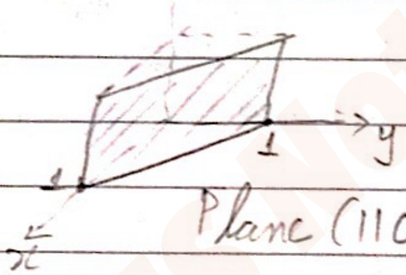
Front face plane : (1 0 0)
Top face plane : (0 0 1)



Plane :- (0 1 0)



Plane :- (0 0 1)



Plane (110)

→ we take the direction ratios of the line ⊥ to the plane while writing or designating a plane using Miller Indices.

~

self ☆ SiO_2

☆ Polycrystalline Silicon.
↳ called Polysilicon.

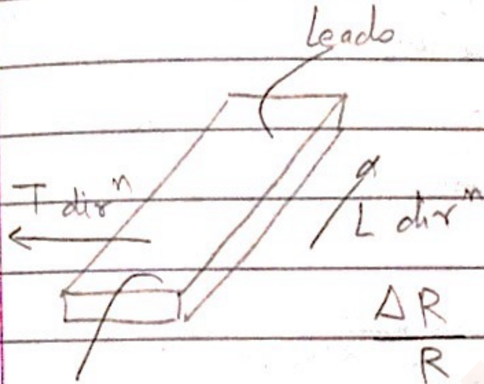
✓ mainly used to make resistor, transistor
✓ stronger than single Si. film.

★ Mechanical properties :
Poisson's ratio should be less ($\simeq 0.2$)

★ Si - Piezoresistors :
Piezoresistance: Apply stress ⇒ electric resistance of solids change.
Relⁿ b/w change in resistance (ΔR) & σ

$$\Delta R = [\pi]\,\sigma$$

→ Piezoresistive coeff matrix
↳ Mainly, we need $\pi_{11}, \pi_{12}, \pi_{44}$
→ the coeff. of matrix on 1st row, 1st column.



$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$$

↳ π_L, π_T : always have value of π_{44}.

Q Given :- $\sigma_{max} = 186.81\,MPa$, Applied pressure = 70 MPa

Estimate change in resistance in Si piezoresistors attached to diaphragm of a pressure sensor.

$\sigma_L = \sigma_T = \sigma_{max} = 186.81\,MPa$.

$\pi_L = \pi_T = 0.2\,\pi_{44}$.

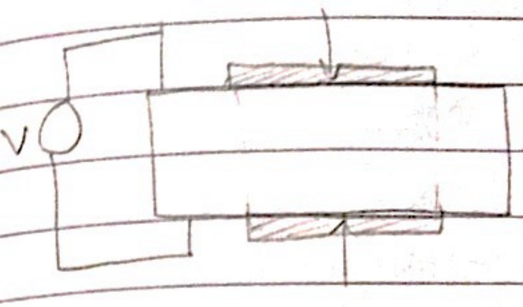
Then, $\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$ ✓

* TCR: Temp. coeff. of resistance
  TCP: Temp. coeff. of piezoresistivity.

~~~

✩ GaAs

- ✓ difficult to process (∵ a compound)
- ✓ high e^- mobility (7 times more mobile than Si)
- ✓ good thermal insulator.
- low yield strength.

* Property

Property	GaAs	Si
1) Optoelectronics	✓	✗
2) Piezoelectric effect	✓	✗
3) Cost	High	low.
4) Bonding to substrates	Tough	Easy

✩ Quartz

- a compound of SiO_2
- single unit - shape of tetrahedron.
- has dimensional stability.
- Thermal conductivity ↓ with temperature.
- offers electrical insulation in microsystems

~~~

Puffin
Date
Page

* Piezoelectric Crystals



Force generates potential & vice versa

$K = \frac{\text{o/p of electrical Energy}}{\text{i/p of mechanical energy}}$ $\sigma = \frac{\text{o/p of mechanical en.}}{\text{i/p of electrical energy}}$

• Piezoelectric crystal film (PZT)

eg

$$MOI, \; I = \frac{T w^3}{12}$$

$$M_{max} = P_{eq} \cdot L$$

$$\sigma_{max} = \frac{M_{max} \cdot C}{I} \quad Pa$$

$$\epsilon_{max} = \frac{\sigma_{max}}{E}$$

Q Determine req^d electric voltage for ejecting droplet of ink for inkjet printed head using PZT piezoelectric crystal as pumping mechanism

Soln: D : diameter of dot film on paper

$$\frac{4}{3} \pi \delta^3 = \pi \left(\frac{d}{2}\right)^2$$

W : vertical expansion of PZT cover induced by applied voltage, V

Δ : diameter of PZT cover

$$\left(\frac{4}{3}\pi r^3 = V_{dot} \right)$$

$$\& \; V_{dot} = \frac{\pi}{4}\Delta^2 w$$

POLYMERS

- ✓ used in biomedical applicⁿˢ.
- ✓ used as substrates with electrical conductivity made possible by doping.
- ✓ has long chains of hydrocarbons.
- ✓ low melting pt, poor electrical conductivity.
- ✓ light weight
- ✓ easy to process.
- ✓ low cost of raw material
- ✓ high electrical resistance & corrosion resistance.
- ✓ high flexibility & dimensional stability.

• Use in MEMS

In/As :- Photolithography, LIGA process, Organic substrates (Conductive polymers), piezoelectric crystals (Ferroelectric polymers), coating substance, Langmuir-Blodgett (LB) film, electric insulators, facilitate electroosmotic flow, EMI, RFI, encapsulation.

Puffin
Date
Page

Conductivity :

Conductors	Cu	:	$10^6 - 10^8$
	C	:	10^4
Semiconductor	Ge	:	10
	Si	:	$10^{-4} - 10^{-2}$
Insulator	Glass	:	$10^{-10} - 10^{-3}$
	Nylon (Polymer)	:	$10^{-14} - 10^{-12}$

* Making polymers electrically conducting :

M1) Pyrolysis

Pyro polymer - base Phthalonitrile resin + (600°C) Amine = Conductive polymer
$\simeq 2.7 \times 10^4$ S/m conductivity

M2) Doping
Introducing metal atoms in polymer = conductive polymers.

M3) Insertion of Conductive fibres
fibres of Ag, Au.

* LB films
↳ spreading volatile solvent over the surface active substrate material.
↳ Applications :
(1) Ferroelectric (magnetic) polymer thin films.
↳ like : PVDF

- Applicⁿˢ include : Sound transducers in air & water, tactile sensors, biomedical applicⁿˢ

(2) Coating material with conductive properties

(3) Microsensors eg : gas sensor

☆ SU-8 Photoresists :

- ✓ negative epoxy based polymer sensitive to UV light.
- ✓ Used for thin film production
- ✓ in liquid form (commercially)
- ✓ high Young's modulus (4400 MPa) than Si
- ✓ Impact of temp. change is lower as compared to Si (coeff. of thermal expansion : SU-8 < Si)

Process :

Substrate treatment → Spin coating SU-8 photoresist → Soft bake → Expose to UV light → Post expose bake → Develop SU-8 photoresist → Rinse & dry → Hard bake → SU-8 film removal

☆ Packaging of MEMS Material :

Involves various materials like plastics, polymers, stainless stell, ...

Chapter - 8

MICROSYSTEMS FABRICATION PROCESS

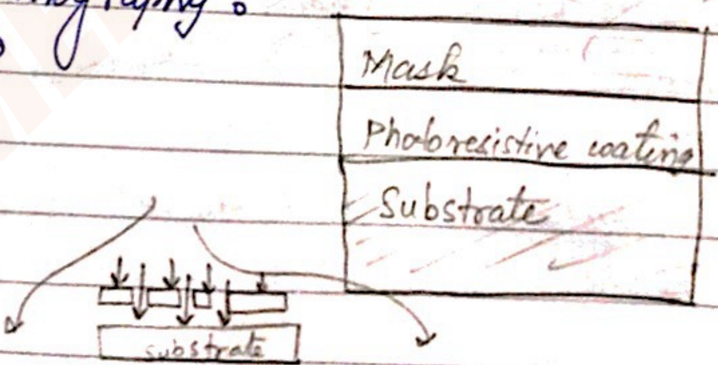
✓ use of non-machine tool techniques (∵ size is very small)

✓ Si is used for ~~pro~~ MEMS & microsystem compounds ∵ its used to produce IC's.

* Microfabrication Processes.

(1) ✓ Photolithography
✓ Ion Implantation
✓ Diffusion
✓ Oxidⁿ
✓ CVD (Chemical vapor deposⁿ)
✓ PVD (Physical vapor deposⁿ)
✓ Deposⁿ by epitaxy
✓ Etching

(1) Photolithography :
↳



> mask changes depending on the basis of our choice of e⁻ beam, X-ray or UV ray.

+ve Photoresist
wherever UV rays fall, that is soft, rest hard

-ve Photoresist
UV light falls → that region hard, rest soft.

Puffin Date____ Page____

- Positive resist
  - PMMA
  - Two component DQN resist.
    - Sensitive to UV light. Max. sensitivity at (220 nm
    - can be developed in alkaline solvents like KOH, TMAH)

- Negative resist
  - Two component bis (aryl) azide rubber resists
  - Kodak KTFR (azide-sensitized Polyisotroprene rubber)
    - less sensitive to optical & X-Rays; more sensitive to e^- beams

- Details on Photoresist development, removal and post baking.
  - removal → by O_2 plasma followed by etching

☆ The material for -ve & +ve photoresist differs. Hence, solvent req^d for them differs.

§ ION IMPLANTATION

- used to dope Si substrates
- involves "forcing" free charge carrying ionized atoms of B, P or As into Si crystals.
- Ions with high kinetic energy get penetrated in Si substrate

* What determines shape of zone in ion implantation

Physical process :

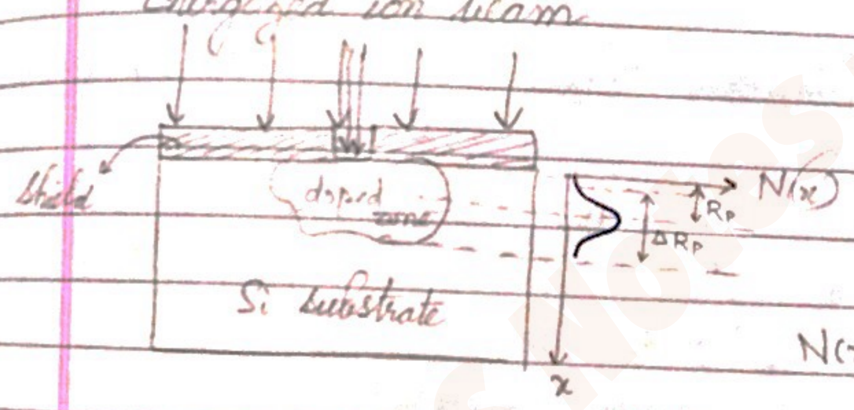
Beam Controller → Accelerator —High Energy beam→ Beam Controller
↑ Ion beam — Ion Source
↓ High energy ion beam — Si Substrate

• Req^d energy for ion implantation (ioniz^n energy, eV)

n type P > As > Sb (0.044, 0.049, 0.039)

p type B > Al > Ga < In (0.045, 0.160)

Energized ion beam



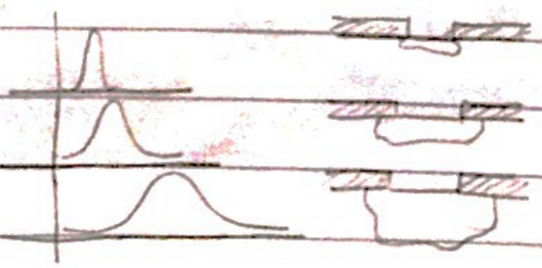
dose of ion beams (atoms/cm²); projected range/μm

$$N(x) = \frac{Q}{\sqrt{2\pi}\,\Delta R_p} \exp\left[\frac{-(x-R_p)^2}{2\Delta R_p^2}\right]$$

ΔR_p: straggle or scatter length (μm)

* For elements B, P and As :
Increasing the energy level increases the penetration (R_p) and standard deviation (ΔR_p)
Value of R_p & ΔR_p : B > P > As

↳ Use As
Use P
Use B



N(x) → conc. : As > P > B

Q. A Si substrate is doped with boron ions at 100 keV. Assume max. conc. after doping $(N(x)) = 30 \times 10^{18}/cm^3$. Find (a) Q
(b) dopant conc. at depth 0.15 μm
(c) depth at which dopant conc. is at 0.1% of max. value

(a) $N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p)} \exp\left[\frac{-(x-R_p)^2}{2(\Delta R_p)^2}\right]$

$N(x) \to 30 \times 10^{18}$, $R_p \to 307$ nm, $\Delta R_p \to 69$ nm

max. conc. = at $x = R_p$

$\Rightarrow N(x)\Big|_{max} = \frac{Q}{\sqrt{2\pi}(\Delta R_p)}$ Q ✓

(b)

$Q = (2\pi)^{0.5}(\Delta R_p) N_{max} = (6.28)^{0.5} (69\,nm)(30 \times 10^{18} cm^{-3})$

(c) $N(x=?) = \frac{0.1}{100} \times N_{max}$

$\to N(x_0) = \frac{5.2 \times 10^{14}}{\sqrt{2\pi} \times 69\,nm} e^{-\left[\frac{-(x-R_p)^2}{2(\Delta R_p)^2}\right]}$

DIFFUSION

- operates at high temp.
- spread of dopant on substrate is more than ion implantation

* Fick's Law: $F = -D \frac{\partial N(x)}{\partial x}$

$N(x)$ → dopant conc p.u volume

F → Dopant flux p.u time

D → Diffusion coeff of substrate to dopant

Solⁿ of eqⁿ: $N(x,t) = N_s \, erfc\left[\frac{x}{2\sqrt{Dt}}\right]$

$\hookrightarrow erfc = 1 - erf(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$

Puffin Date Page

- diffusion eqⁿ :- $\frac{\partial N(x,t)}{\partial t} = D \frac{\partial^2 N(x,t)}{\partial x^2}$

  ↳ Solution of eqⁿ:

  ✓ Initial condⁿ: $t = 0$

  $N(x,0) = 0$

  ✓ Boundary condⁿ ($x = 0, \infty$)

  $N(0,t) = N$

  $N(\infty,t) = 0$

* Diffusivity (D)

emperical formula, $\ln(\sqrt{D}) = aT' + b$.

↳ a, b : constants

$T' \rightarrow \frac{1000}{T}$, T ↳ Diffusion temp (K)

(8.2)

eg :- Si substrate is subjected to diffusion of boron dopant at 1000°c with dose of $10^{11}/cm^2$

Find :- expression for estimating conc of dopant in substrate.

Idea : Find D for a, b, (T') $\rightarrow \frac{1000}{1000+273}$

↳ from table

Initially $N(x,0) = 0$, $N(0,t) = N_s = 10^{11}$ atoms/cm³

$$N(x,t) = N_s \, erfc\left[\frac{x}{2\sqrt{Dt}}\right]$$

☆ Oxidation

↳ SiO_2 : imp. element for MEMS.

- used as thermal insulation media.
- used as dielectric layers for electrical insulation
- diff^t thickness of SiO_2 shows diff^t colors
- Produced : over surface of Si substrates
  (One of the methods : CVD)

- Thermal oxidation : a combined continuous physical diffusion & chemical reactions.

☆ Thickness of SiO_2 layer (x) :

For small time : $x = \frac{B}{A}(t+\tau)$

large time : $x = \sqrt{B(t+\tau)}$

$\tau = \frac{d_0^2 + Ad_0}{B}$, $B = \frac{2DN_0}{N_1}$, $\tau = \frac{d_0^2 + Ad_0}{B}$

$A = 2D\left(\frac{1}{K_s} + \frac{1}{h}\right) \simeq \frac{2D}{K_s}$ $\Rightarrow \tau = \left(\frac{d_0^2 + \frac{2Dd_0}{K_s}}{2DN_0}\right) \times N_1$

cm^2/sec ← ☆ D : Diffusivity of oxide of Si
N_0 : conc. of oxygen molecules in carrier gas
N_1 : no. of oxidizing species in oxide
cm/sec ← K_s : surface reaction rate constt.
cm ← d_0

Rate of thermal oxidⁿ :-

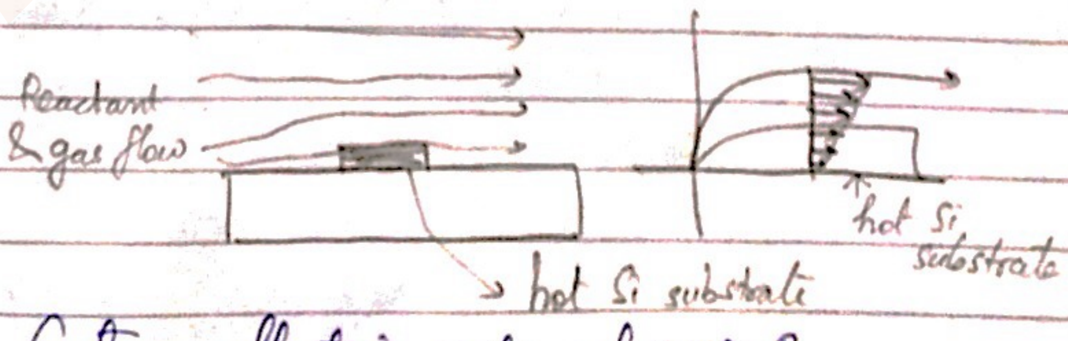
Small time, t : $\log\left(\frac{B}{A}\right) = aT' + b$.

Large time, t : $\ln(B) = aT' + b$.

* Chemical Vapour Deposition → Seen in horizontal reactor

- used for producing thin films
- Materials used for CVD :
  Metals, Organic materials.
- 3 major CVD processes
  1) APCVD (Atmosphere)
  2) LPCVD (Low Pressure)
  3) PECVD (Plasma enhanced)
- Chemical reaction :

use of Silane (SiH_4)
- → CVD of SiO_2 on Si substrates
- → CVD of Si_3N_4 on Si substrates
- → CVD of polysilicon on Si substrates



- Major factors affecting rate of CVD :
  → Reynold's No. (Re), boundary layer thickness (δ), Diffusion flux (N) of reactant

Doing Numericals

Puffin Date ____ Page ____

Numerical Analysis

★ $PV = nRT$: Ideal Gas Law

for a constt 'n' → amount of material

$\Rightarrow \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$; $T_1 = 20°C = 293\,k$
$T_2 = 490°C = 763\,k$

for $P_1 = P_2$

$\Rightarrow \frac{V_1}{T_1} = \frac{V_2}{T_2}$; $V_1 = 22.4 \times 10^{-3}\ m^3/mole$

★ Note : Molar density $(d) = \frac{1}{V}$ moles/m^3,

↳ $d_2 = 17.1433$ moles/m^3

Also,

★ $\delta(x)$ = boundary layer thickness.

$\Rightarrow \delta(x) = \frac{x}{\sqrt{Re(x)}}$

↳ $Re(x) = \frac{\rho L V(x)}{\mu}$

ρ → mass density gas; L → char. length of flow; $V(x)$ → Velocity; μ → dynamic viscosity

Diffusion flux of reactant ★ $\vec{N} = \frac{D}{\delta}(N_G - N_S)$ atoms or molecules/m^2-s

D → diffusivity of reactant in gas cm^2/s

$(N_G - N_S)$ → conc. of reactant (gas & solid part)

★ Diffusivity (D) $\propto \frac{1}{\text{Dilection factor } (\eta)}$

→ $N_G = N_A \times d_2 = 103.24$ moles/m^3

N_A → Avogadro's no.

ρ_{O_2} = (Molecular weight of O_2) $\times d_2$
$= 32$ g/mole $\times 17.1433$ moles/m^3

$\rho_{O_2} = 548.586\ g/m^3$

Char. length of flow, L = Diameter of pipe (D)

$$R_e = \frac{\rho D V}{\mu}$$

($\rho \rightarrow \rho_{O_2}$; $V \rightarrow$ yet to be known to get Re)

$\mu \rightarrow \mu_{O_2}$ = table

→ If V is given, we can find Re. After putting all values, we get $R_e = 137.147$

Now,

$$\delta = \frac{L}{\sqrt{Re}}$$ → length of substrate (150mm, given say)

$\Rightarrow \delta = 0.01281\ m$

Assume : $N_S = 0$

$$\Rightarrow \vec{N} = \frac{D}{\delta} N_G$$

D → Varies with temp. Fixed for const T.

→ If $N = 10^{24}$ mole/m²-sec

$D = 0.062\ m^2/s$.

Finding Surface reaction rate : $k_s = \frac{D\vec{N}}{DN_G - \delta\vec{N}}$

$= 0.09884$ m/sec

Rate of growth, r = (of Si)

$$r = \begin{cases} \frac{DN_G}{\gamma\delta} ; & \gamma k_s \gg D \\ \frac{N_G k_s}{\gamma} ; & \gamma k_s \ll D \end{cases}$$

$$\rightarrow \gamma = \frac{1}{\frac{4}{3}\pi a^3}$$

a → radius of SiO_2 = 0.117 nm.

Using formula, we get $\gamma k_s \ll D$. So, find r = 0.47 μm/s

Puffin
Date
Page

★ Note :-

Rates of CVD (r) $\propto T^{3/2}$ (Temp)
$\propto P^{-1}$ (Pressure)
$\propto V^{-1}$ (velocity of gass)
$\propto x^{1/2}$ (dir^n of gas flow)

★ Low Pressure CVD :-

$$r \propto \frac{(T^{3/2})(x^{0.5})(D)}{(P)(V)(\delta)}$$

★ Enhance rate of CVD :-

1. Increase T. ⇒ D ↑ but harms substrate
2. Decrease V ⇒ Re ↓ & δ ↑ So, no effect.
3. Decrease P. ✓ better than above 2

- Both APCVD & LPCVD operate at high temp. (damages substrate).
  ↳ Alternate : use Plasma generated from RF (radio-freq) sources.

Comparison of 3 CVD processes

	APCVD		LPCVD		PECVD
P:		>		>	
T		<		>>	
Depos^n Rate:		>>		<	

✮ SPUTTERING :

A form of Physical ~~Layer~~ Vapor Deposition

✓ carried out with plasma
low P
high vacuum
Room temp.

✓ used to deposit metal films on substrate
✓ No chem. reaction is involved.

✓ Process : Metal vapor created by plasma (with high energy RF sources) + Ar gas made to fall on substrate.

• Deposition by ~~Ep~~ Epitaxy:

✓ Mainly meant for depos^n of same material on same material. eg: GaAs on GaAs substrate
✓ Both CVD & PVD are used for this depos^n
✓ Methods : Horizontal & Vertical reactors.

Puffin
Date ____
Page ____

* Etching
  - removing substrate material at desired loc^{ns}.
  - Ways :-
    - Wet etching
    - Dry etching
  - To protect other parts of substrate from etching, masks made of strong resistance materials are used.

Ch-9

MICRO MANUFACTURING

Type 1 * BULK Micoomanufacturing

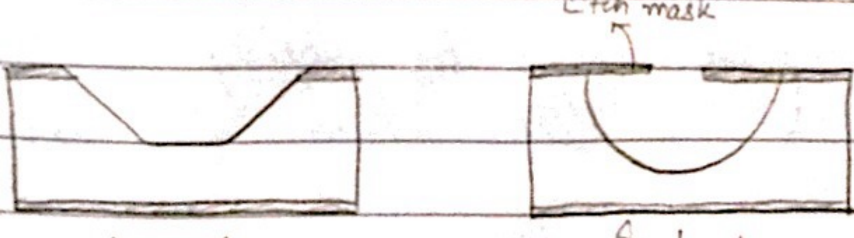
↳ Create 3D components by removing materials from thick substrates using primarily etching methods.

Etching can be wet or dry.

- wet → use of chemical solvents (called etchants)
- dry → use of plasma

- Isotropic and Anisotropic etching.
  ↳ Pure Si crystals are anisotoopic.
  For a crystal, the planes of etching have difference in ease : ⟨100⟩ plane easier than ⟨111⟩ plane

- Anisotropic etching : easier to control.
  ↳ Disadvantages :
  - slower etching
  - temp sensitive
  - best performance at high temp, so, temp resistive masks are required



Anisotoopic   Isotoopic

★HNA : HF + Nitric + Acetic Acid.

Puffin Date Page

- Wet etchants
  - ↳ HNA for isotropic etching at RT.
  - ↳ Alkaline chemicals with pH > 12 for anisotropic etching

★ Popular etchants : (anisotropic)
KOH, EDP, TMAH, Hydrazine.

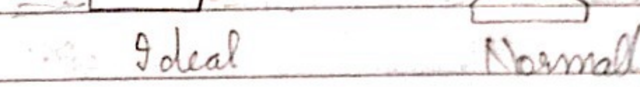
Selectivity Ratio of Etchants

$$\text{Selectivity ratio} = \frac{\text{Etching rate of Si}}{\text{Etching rate of material}}$$

(using same etching)

★ Si compounds are more sensitive to etching as compared to Si → can be used as masks
★ Higher selectivity ratio, better mask material

★ Etching will be affected by :
- timing and flow patterns (in geometry) of substrates
- Endurance of masks



Ideal Normally etched.

★ Stopping Etching :

- ✓ Controlling by doping
- ✓ By electrochemical etch stop.

* Self : Deep Reactive Ion etching

* Self : Diff b/w dry and wet etching

Dry	Wet
good for most materials	Only with simple crystal materials
production automation good	poor
low environmental impact	high (due to acids)
expensive	less expensive
control of etch rate good	difficult

☒ Surface Micromachining

↳ No material is removed from substrates. Rather material is added

- Same or different materials
- deposition process is costly
- requires multiple masks.

Create Cantilever :

Method :

(Si constraint base) + (Depos^n of sacrificial layer of PSG) + (Make mask of Si_3N_4 for etching of PSG area) + (Deposite poly-Si) + (Remove PSG) = Cantilever beam

* Common sacrificial layer materials :

I. PSG (Phosphosilicate glass)

II. SiO_2

III. BPSG (Boronphosphosilicate)

↳ Etching rate : III > I > II

- Mechanical Problems
  (1) Quality of adhesion of layers.
  (2) Interfacial stresses due to mismatch of CTE.
  (3) Stiction (collapse of unsupported beam)

✱ LIGA Process

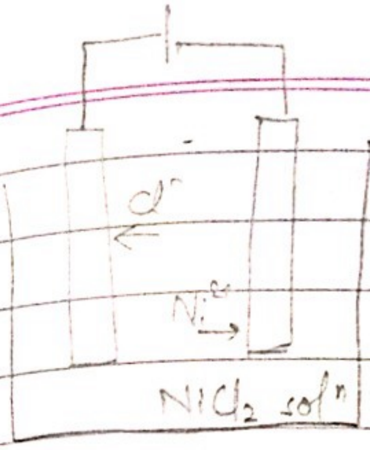
↳ LIthography, Electroforming, Molding
(Galvanoforming) (Aboforming)

✓ requires X-ray facility for etching

✓ Gold plated region: for blocking X-ray.
✓ Mask Si_3N_4: (transparent to x-ray)
✓ Metal tube: Made of Ni

✱ Self: Major steps in LIGA process
✱ Materials: Should be conductive to enhance electroplating → metals like steel, Ti, Cu, Ni
↳ Substrate
↳ Photoresist: should be sensitive to X-rays

✱ Polymers used in LIGA process: PMMA, POM, PAS, PMI, PLG.
↳ can be compared on sensitivity, resolution, sidewall smoothness, stress corrosion, adhesion on substrate.
↳ PLG, the best (when compared)



: Electroplating

- **Comparison**
  - → Bulk micromanufacturing :
    - lot of material loss.
    - good for simple geometry.
    - ---
  - → Surface micromachining :
    - Complex masking reqᵈ.
    - tedious process.
    - good for complex geometry.
    - ----
  - → LIGA process
    - Most expensive initial setup.
    - used for mass productions.
    - requires synchrotron radiation facility
    - ---

Modelling in MEMS.

* MEMS is done by :

Device / system design .
↕
Sys. analysis
↕
Process design
↕
Fabrication
↕
Testing .

* We use some methodologies for MEMS design. These methodologies depends on :
  - Fabrication techniques limitation .
  - Cost .
  - Technology limitation .

* High Level Design Issues :

1 * Device category
  - Technology demonstration .
    having a device only to demonstrate tech.
  - Research tools .
    The tools used for research should work well through time .

Commercial Product

A commercial product has issues of getting high yield and giving consistency in manufacturing

2 * Market
Study the market, the needs, the size, the devt speed

3 * Impact
We have to see what'll be the impact of my product

4 * Competition
∃ competition from equivalent product / organizⁿ

5 * Technology

6 * Cost

* Necessary ingredients for MEMS design:

- ✓ Design Constraints
- ✓ Selection of material.
- ✓ Selection of manufacturing process.
- ✓ Transduction of signals.
- ✓ EM, Structural, design
- ✓ Packaging.

* MEMS CAD

- → complexity reduced.
- → doing simulations before fabrications

(CAD tools packages – Conventorware, Intellisuite, Sugar...)

* Main parts of MEMS design :-
  - Electromechanical design.
  - Process flow
  - Design verification

* Study of Designer input at different levels
  What to do at process level, - - -

* MEMS Design Issues:
  - Size
  - Material selection
  - Environment Sensitivity.
  - Internal heat build-up.
  - Withstanding variety of loads (Strains) & vibrations
  - Packaging.

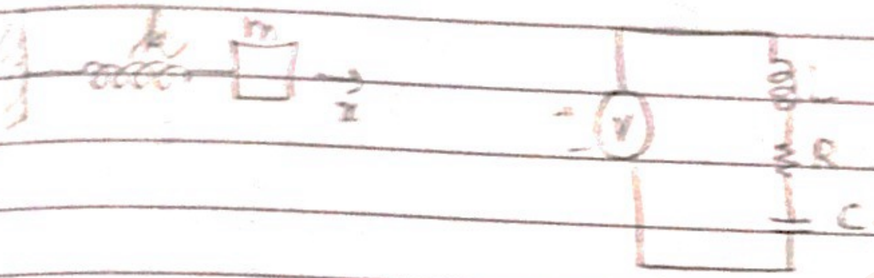
* Modeling Approaches :
  - Physical simulation.
  - Behavioral simulation.

• Physical modelling :-
  - uses finite element modeling & boundary element modeling

• System modeling :
  Simple component models → like 2 nodes & 6 degrees of freedom to describe beam.

* IC world uses combined approach
  - → System function for design feedback
  - → Physical simulation for check parasitics

* Physical world ≡ Electrical world



$k \equiv L$

$m \equiv 1/C$

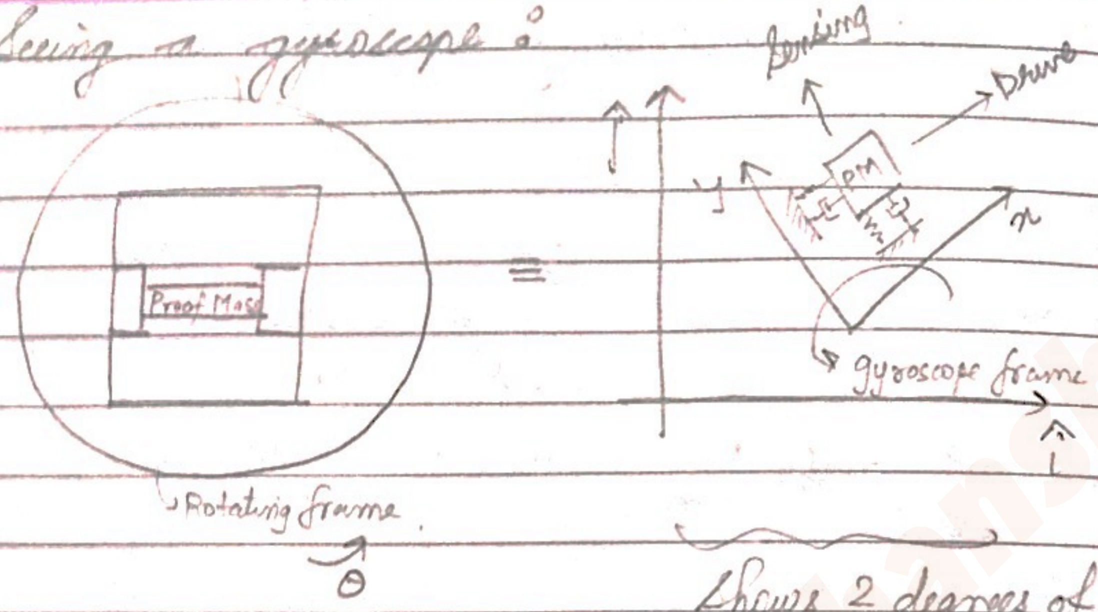
* Physical domain	Flow qty. (through)	Diff. qty (across)
Electrical	Current	Voltage
Mechanical - transl^n	Force	Vel/disp.
Mechanical - rot^n	Torque	Angular vel.
Pneumatic	Volume flow	Pressure
Thermal	Heat flow	temp.

→ Sum of ACROSS Quantities in a loop = 0
→ Sum of THROUGH Quantities at a node = 0.

(for electrical, its called KVL, KCL)

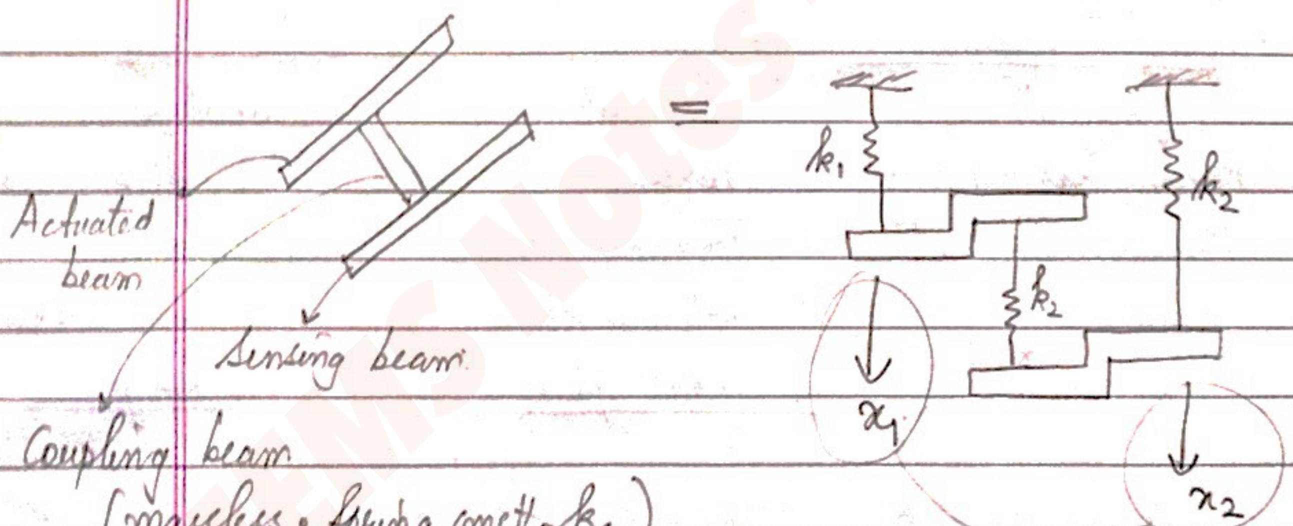
PM: Proof Mass

* Seeing a gyroscope:



Shows 2 degrees of freedom

* Seeing a Micromechanical filter



Coupling beam
(massless, spring constt, k_c)

Shows 2 degrees of freedom

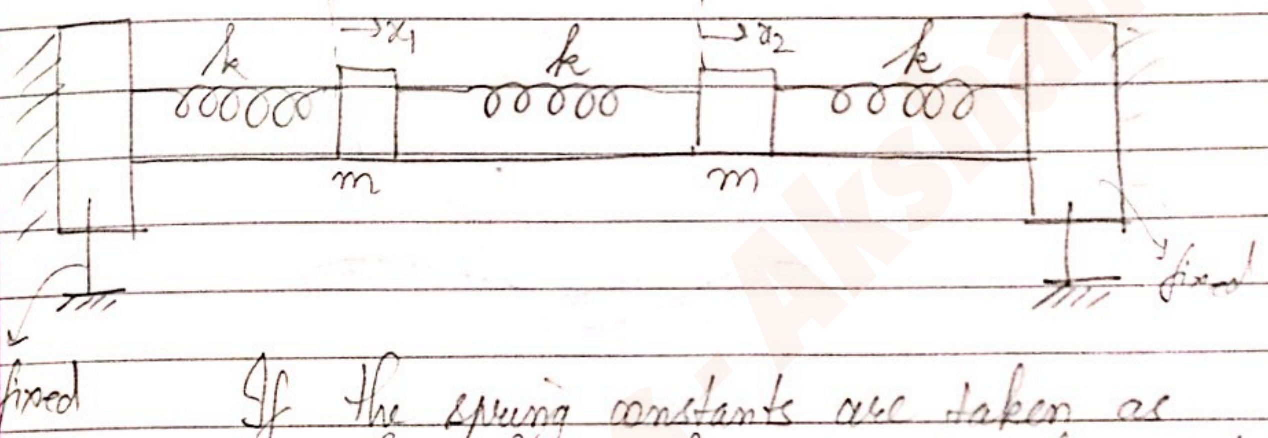
→ For this sys, we can write:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} k_1+k_c & -k_c \\ -k_c & k_2+k_c \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

* Seeing a spring mass sys & analysing degrees of freedom :-

$$m\ddot{x}_1 = -kx_1 + k(x_2 - x_1)$$
$$m\ddot{x}_2 = -k(x_2 - x_1) + k(-x_2)$$

$$\Rightarrow \begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} = \begin{bmatrix} -2k & k \\ k & -2k \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$



If the spring constants are taken as k_1, k_2, k_3 (in order from L to R) & masses m_1, m_2

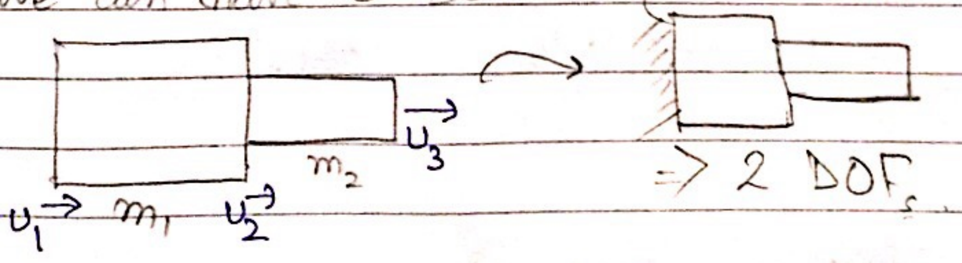
$$\Rightarrow m_1\ddot{x}_1 = -k_1x_1 + k_2(x_2 - x_1)$$
$$m_2\ddot{x}_2 = -k_2(x_2 - x_1) + k_3(-x_2)$$

$$\Rightarrow \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} = \begin{bmatrix} -k_1-k_2 & k_2 \\ k_2 & -k_2-k_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

↳ $= m\ddot{x} + kx = 0$ → eigen value can be used → $|k_{ij} - \omega^2 m_{ij}|$

* x_1, x_2 are independent of each other ; So, ∃ 2 DOF (degrees of freedom).

* Note: We can have 3 DOF.



(PRB)

☆ PSEUDO RIGID BODY MODELLING

✓ Approximating an elastic structure as a group of rigid bodies connected by springs

✓ Orthoplanar concept

☆ COMPLIANT ORTHO-PLANAR Devices / instruments:

↳ Making the device with one piece, without any joint or losses

eg: in macro scale, in binding clips, nail cutter, stapler etc.

☆ Electro-Thermally Actuated MEMS Devices:

☆ Electro Thermal Compliant MEMS

- Electro → electrical actuation by applying voltage
- Thermal → Joule heating causes thermal loads
- Compliant → structure is flexible
- MEMS ⇒ small

↳ Basically, we do Electrical, Thermal & Elastic ANALYSIS of my device.

☆ MUMP: Multi-User-MEMS Processes

* 3 analysis.

Electrical → Voltage & Current.

(leads to coming of Joule heating term giving rise to)

Thermal → Temperature

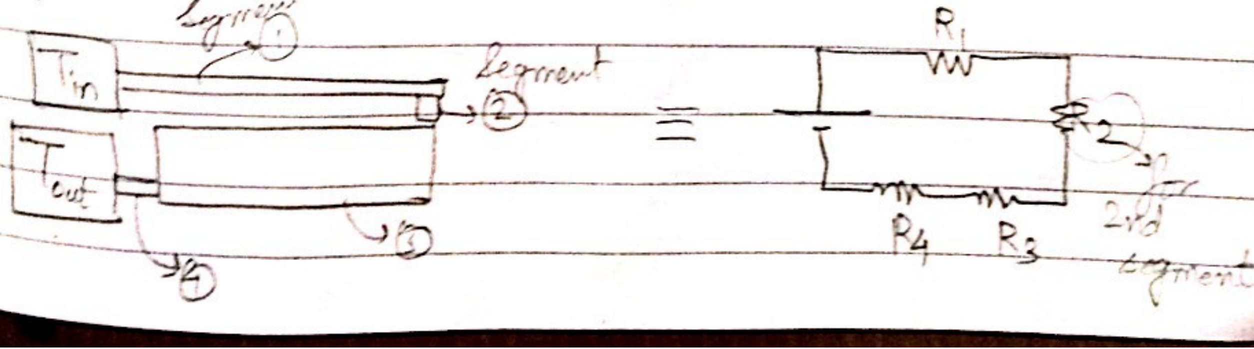
(Temp. change leads to)

Elastic

* Issues in Thermal modeling
  - Issues in convection, radiation, boundary cond^ns, conduction through trapped air volume, temp. dependence of thermo-physical properties.
    - → Essential vs Natural Boundary Cond^ns.
      - Thermally grounded (i.e., maintains a const^t temp., lets out the heat)
      - Not thermally grounded

  * For same temp, meso scale (in cm) device provide more deflection than micro scale.

Physical / Thermal Model Electrical Model



- Electro thermal compliant design :

Problems Types :

1. ✓ Uniform temp rise.
2. ✓ Non-uniform temp with external heating
3. ✓ Non uniform heating with voltage (Joule heating)

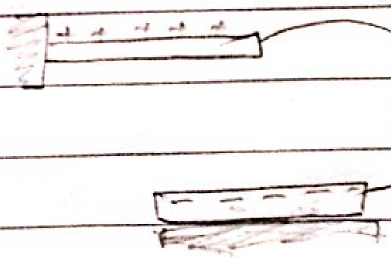
- Design parameters

Thermal diffusivity (α), viscocity (μ), Young's modulus (E), Thermal conductivity (k).....

☆ Electrostatic Actuation :

- ease of fabric^n
- ease of actuation
- energy efficient.
- easy sensing mechanism
- scalability.

- Electrostatic Actuator.



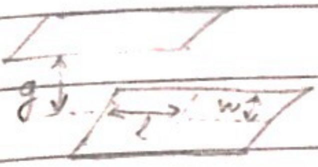
☆ No current consumption during actuation

⇓

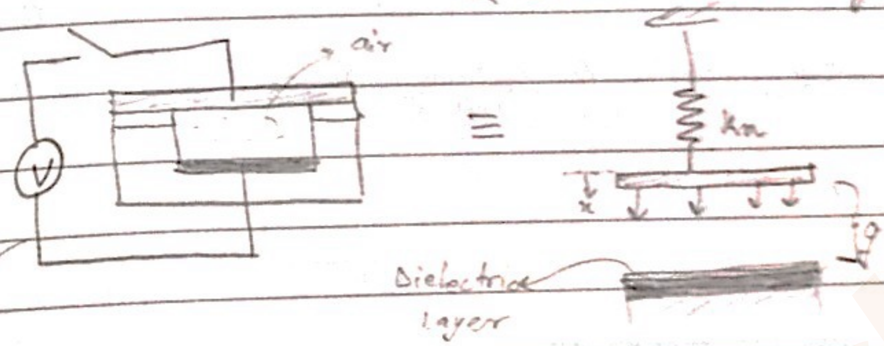
Consumes no power

#

* Computing electrostatic force in parallel plate capacitor

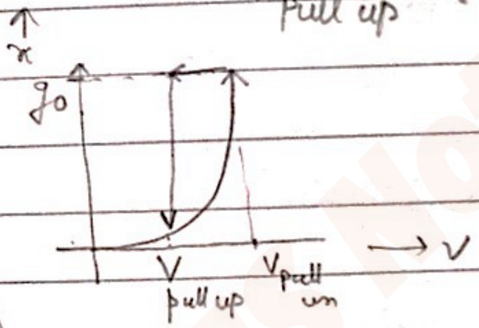


* We can see forces along l, w & g & potential energy see other electro & elasto static systems



Lumped (1 DOF) Modeling

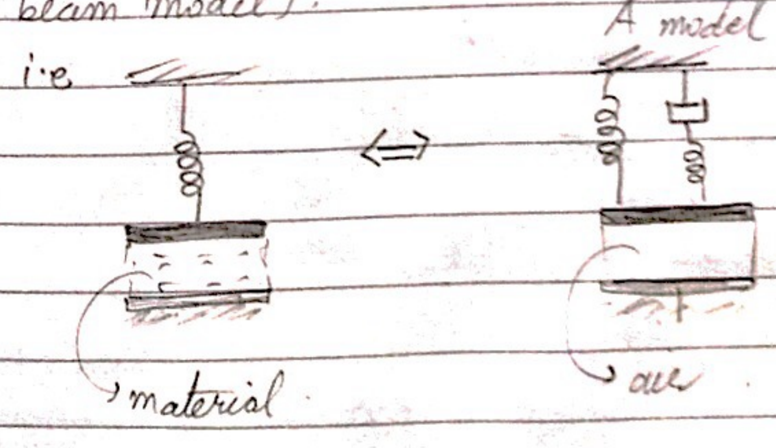
* Stability test of sys can be done by using or doing 2nd derivative of PE
* Pull in voltage expression tells critical stability
* $V_{pull\ up} < V_{pull\ in}$



* FEM (finite element method) & FDM (finite difference method) are used to solve non-linear equation.

If we have some material instead of AIR, we can find eq^ns for lumped 1 dof model & beam model).

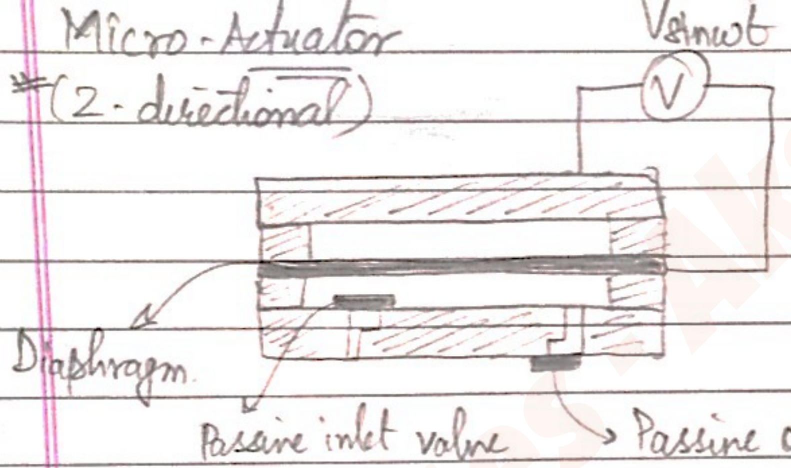
i.e



eg: If we have an electrostatic comb drive, then, the shape of the drive & size determines if the force on it will be linear, analog.....

* In actual designing, we get a lot of errors. Linearity isn't achieved

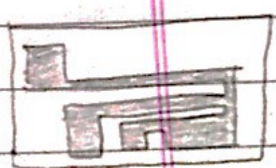
* Micro-Actuator
*(2-directional)



Energies involved:
- Electrical
- Mechanical
- Fluid

Apply voltage → diaphragm moves up → inlet valve opens → water comes in → Change voltage → diaphragm moves down → inlet valve closes & outlet valve opens & water goes out.

* Thermal Actuator
* SMA: Shape memory alloy.
↳ Thermal actuators are like that they retain the memory of their shape. Remove heat & they get back to actual shape.



* That is accomplished by using the SAME material, with different geometries (bending & reverse bending)

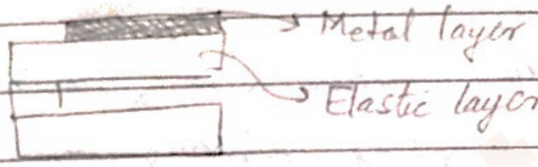
Two Arm Model

☆ Principles of Oper^n of Electrothermal Microactuator

Read

☆ Thermal Bimorph MicroActuation

✓ CTE : Coeff. of thermal expansion



* Tensile and compressive stress leads to bending (on temp. change)

Applic^ns : projection imaging, optical switching

Puffin
Date 20.4.14
Page

Ch. RF. Mems

- Radio freq. MEMS : μm – mm wave.
- transporting 9 kHz to 300 GHz signals.
- Electro mechanical.
- Devices : switches, conductors, varactors.
- Circuit : Phase shifter, filter, Oscillator.

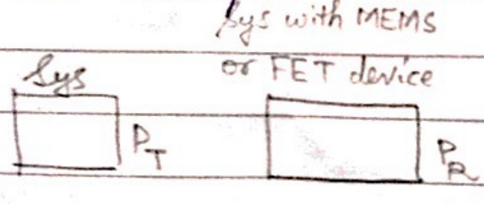
* Main Advantage :
  1. Reduction in size, weight, power consumption & component counts.
  2.

* RF MEMS Switch - Need

Self

Type	GaAs FET	MEMS
Insertion loss	High (> 1 dB)	low (< 0.2 dB)
Switching time	Fast (~10 ns)	Slow (μs)
Reliability	Excellent	V. High
DC bias	low (~3.3 V)	high (10 to 30 V)

* Insertion Loss :-
If any external element is introduced in sys, what is the power loss.



$$\text{Insertion loss} = 10 \log\left(\frac{P_T}{P_R}\right)$$

✶ Series & Shunt Switches

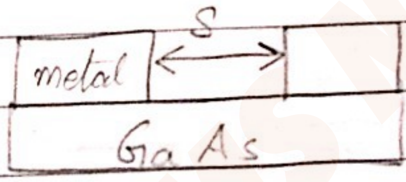
✓ Contactless switches ≡ Shunt switches
✓ Contact switches ≡ Series switches

✶ RF Switch design types :
① ✓ Cantilever
② ✓ Fixed-fixed beam

- Rockwell's Resistive type MEMS switch (for series)
- HRL's Cantilever Switch
- Beam type MEMS Switch (for shunt)
- Resistive (Series) Mems switch
- Capacitive RF switch (Shunt)

(for high freq. applicⁿ)

✶ RF_{in} should not be affected by RF_{out}. So, less distance should have problems (comparitively).



✶ RF MEMS ~~Device~~ Applicⁿˢ

- RF mems devices
- MEMS variable capacitor
- MEMS tunable inductor

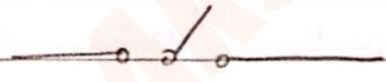
✶ Advantages

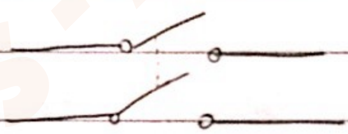
- Very good isolation and insertion loss.

- Study shows that RF MEMS will be around a billion dollar market.
- Applicⁿ as seen in communicⁿ systems : RF tuning (Tunes the i/p radio frequency to 455 kHz : Helps to detect FM).

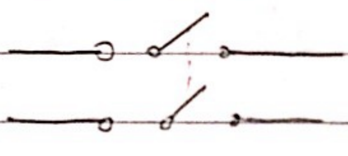
★ Switch

(SPST) Single Pole Single Throw 

(SPDT) Single Pole Double Throw 

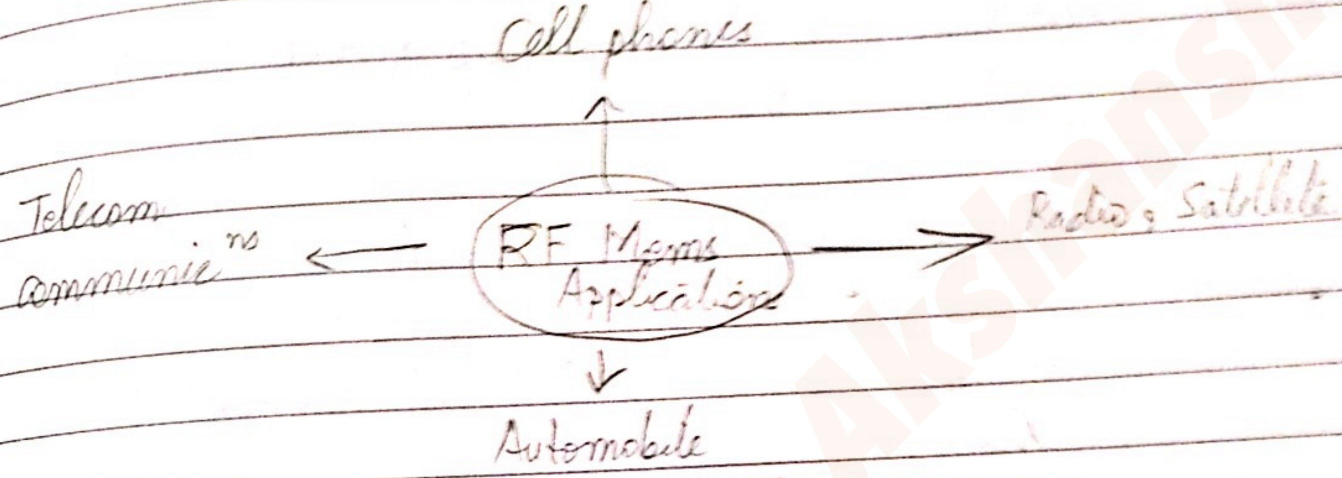
(DPST) Double pole single Throw 

(DPDT) Double pole double throw



★ MEMS Variable Capacitor :

1. Using springs to change the capacitance b/w plates
2. Laterally more plates to get misaligned plates & change capacitance
3. Use of something like comb drive 



* Mainly do the applications of RF MEMS.

Date 22/4/14

Chapter-5

THERMOFLUID ENGINEERING AND MICROSYSTEMS DESIGN.

- microscaled devices involving heat and/or fluid flows.
- Fluids cannot withstand normal stresses, other than hydrostatic pressures.
- Shear stress (≡ viscosity) is responsible for fluid flow.
- Reynold's number: $Re = \frac{\rho L V}{\mu}$ (ρ → mass density, L → length, V → velocity)
- Equation of Continuity:

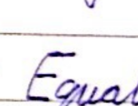
$$A_1 v_1 = A_2 v_2$$

(A → Area, v → velocity)

- Computing volumetric flow (Q) → $[L^3 T^{-1}]$
- Momentum Equation.

$$\sum F = \frac{dP}{dt} = \frac{d}{dt}(mv) = \left(\frac{dm}{dt}\right)(\vec{V}_2 - \vec{V}_1)$$

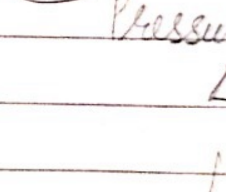
- for fluid flowing along a pipe, say.
- Hagen-Poiseuille Eqn
  - → Laminar flow in circular conduits.



Pressure drop in fluid over tube length, L is

$$\Delta P = \frac{8\mu L Q}{\pi a^4}, \quad \Delta P \propto \frac{1}{a^4}$$

→ For non circular - cross-section



$$d_h = \frac{4A}{P}$$

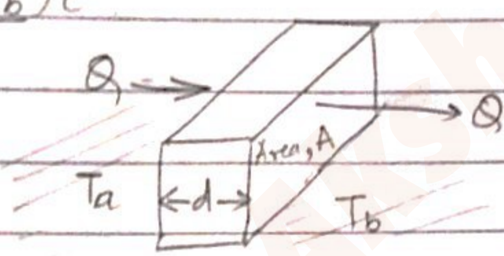
(A → Area of crossection, P → wet perimeter)

* Incompressible Fluid Flow in Microconduits :-
  - Surface tension is an important factor.
  - Surface tension gives shape to droplets. So, larger pressure is reqd to give pumping. This happens in cappilary action.

* ✓ Amount of heat flow, given by Q.
  - Fourier Law of Heat Conduction.

$$Q = k \times \frac{A(T_a - T_b)t}{d}$$

k → Thermal conductivity of solid



✓ Heat flux, q

$$q = \frac{Q}{At} = \text{intensity of heat flow}$$

* Thermal diffusivity, $\alpha = \frac{k}{\rho C}$

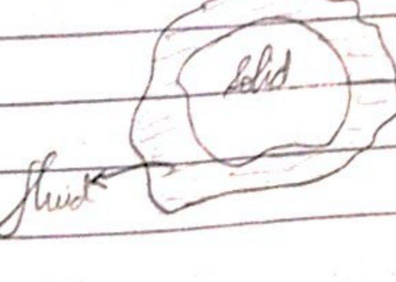
k → Thermal conductivity
C → specific heat of solid
ρ → mass density

* Newton's Cooling Law.

heat flux, $q = h(T_a - T_b)$

h → heat transfer coeff.

* Study of heat flux and movement of heat flow for solid-fluid interface.



* Conditions that will influence heat flow : value of h, Temperature

h → $W/m^2\text{-}°C$

Puffin
Date
Page

☆ Heat conduction in multilayered thin films

↳ requires specific formul^{ns}

↳ Boundary cond^{ns} ∃ at interface of every 2 layers.

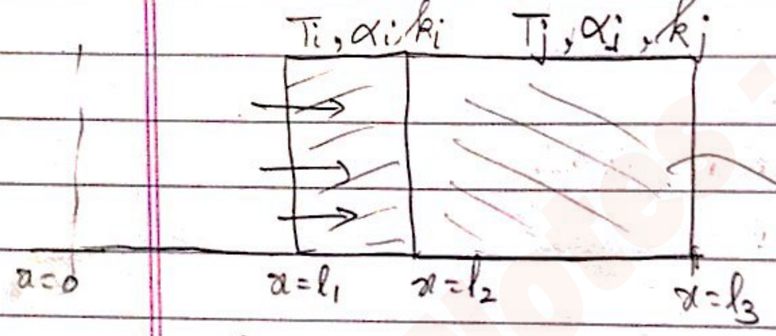
$$k_1 \frac{\partial T_1}{\partial x} = k_2 \frac{\partial T_2}{\partial x} \ldots$$

(derivative at interface / boundaries remain same)

Numerical Idea ☆ To see heat flow, see

$$\frac{\partial^2 T_i(x,t)}{\partial x^2} = \frac{1}{\alpha_i} \frac{\partial T_i(x,t)}{\partial t}$$

↳ $x \in [l_1, l_2]$



→ materials like Si, SiO_2 . . .

So,

$$\frac{\partial^2 T_j(x,t)}{\partial x^2} = \frac{1}{\alpha_j} \frac{\partial T_j(x,t)}{\partial t} \quad ; x \in [l_2, l_3]$$

$$\& \quad k_i \frac{\partial T_i(x,t)}{\partial x}\bigg|_{x=l_2} = k_j \frac{\partial T_j(x,t)}{\partial x}\bigg|_{x=l_2}$$

$$\& \quad T_i(x,t)\Big|_{x=l_2} = T_j(x,t)\Big|_{x=l_2}$$

} same at boundary

Heat Conduction Eq^n ☆

$$\nabla^2 T(r,t) + \frac{Q}{K} = \frac{1}{\alpha} \frac{\partial T(r,t)}{\partial t}$$

Chapter-10.

MEMS & Microsystems Design & Manufacture.

✯ Overview of Microsystems design :

Product Defin^n.
↓
① Initial Design Consider^{ns}
✓ Packaging
✓ Select Manufacturing process
- - - - -
↓
② Conceptual Design Analysis
↓
③ Design Verific^n
↓
④ Product

① In Initial design consider^{ns}, we see :
what customers want
- environment cond^{ns}, cost, availability of material, loc^n of manufacture, - - -
- Select material to be used for doping, masking, packaging, - - -
- Which manufacturing technique or process has to be used (ion implant^n / diffusion / sputtering - -) That depends on the applic^n.
- Signal transduction : how signals will be measured (with what) → loc^{ns}, transduction methods, Interconnects - - -

Puffin
Date
Page

- Packaging : materials, process design assembly strategy & methods ; testing

Mechanical Design

Stress analysis : Linear thory
Heat Conduction Analysis : Fourier law
Diffusion analysis : Fick's law
: Napier's Law

See : ✓ Common geometry of MEMS Components
(1) ✓ Thermomechanical loading
- Forces common to Mechanical design.
- Forces unique in MEMS & microsystems design

(2) ✓ Thermomechanical stress analysis
M1 ↳ Closed form sol^n
M2 ↳ Finite Element Analysis (FEA)

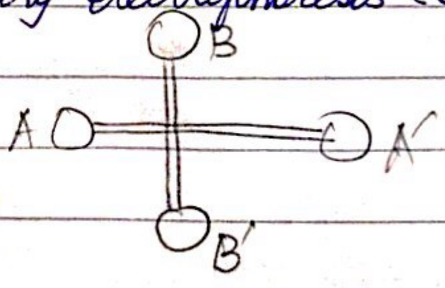
(3) ✓ Dynamic Analysis :
↳ measured under forced $cond^n$

(4) ✓ Interfacial fracture mechanical analysis.

☆ Birth & Death elements are included in the structure of microcomponent

Design of Microfluidic Network Systems.

↳ Capillary electrophoresis (CE) network systems.



Puffin
Date
Page

Idea: Apply voltage across A & A'. Then, across B & B'. On the basis of diff^t electroosmotic behaviour of diff^t parts of species, separ^n happens.

Mathematical model: 3 physio-chemical activities:

* Advection, Diffusion, Electromigration

* Flux vector (J) ∝ Conc. of species (C)
∝ Velocity of species (V)
∝ Electroosmotic mobility (ω) ∝ charge of ion (Z)
∝ $\frac{1}{\text{radius of ion } (r)}$
∝ $\frac{1}{\text{Viscosity of ion } (\mu)}$
∝ Applied electric potential ($\nabla\phi$)
∝ Diffusion coefficient of species (D)

* These methods are quick & accurate. So, biological testing time reduces.

Computer Aided Design for Microsystems

↳ tools used: IntelliSuite, MEMCAD, ...

* General structure of CAD Microsystems: Material, Design & Fabric^n Database

* Selection of CAD package:
  - ✓ Completeness of material database in package.
  - ✓

* Substrate

Major steps in design:

S1) Choose a substrate (Si wafer, generally) → Czoralski method.

S2) Substrate cleaning → eg. using Parahna

S3) Create SiO_2 layer by dry oxidn

S4) LPCVD deposn of poly-Si structure layer

S5) Aluminium sputtering

S6) +ve photoresist is applied to Al. layer.

S7) Photolithography by UV exposure

S8) Wet etching to remove photoresist.

S9) Wet etching on Al

S10) Wet etching to remove Photoresist from Al

S11) Photoresist deposn & photolithography of complete structure (Go to

S12) Remove photoresist by wet etch

S13) Etch poly-Si by reactive ion etching.

S14) Remove SiO_2 sacrificial layer.

S15) Separn of gripper from photoresist

S16) Electromechanical analysis

Chapter - 11

ASSEMBLY, PACKAGING & TESTING (APT)

- Packaging also includes performance & reliability testing of finished products.

§ MICRO ASSEMBLY (dimensions :- 1μm to 1 mm)

✓ MEMS microdevices composed of multiple devices, one over the other. So, assembly is costly.
Plus, the number of items produced aren't very much. So, cost is higher per item

✓ Cannot be seen by naked eye. So, equipment req^d to see.

✱ FLOW CHART

Wafers → Micrfabric^n on wafers → Sub group assemblies
Product Packaging ← Sys. assembly ← packaged sub-groups ←

✱ Reasons for lack of automated microassembly technology

✓ Lack of Std. procedure & rules
✓ Lack of effective tools →
✓ Requirement of reliable visual & alignment equipment
✓ Have to deal with physical - chemical process
✓ Lack of established methodologies in setting tolerances in insertion & assemblies
✓ lack of established methodology in setting proper tolerances.

§ MICROASSEMBLY PROCESSES
- Parts feeding
- Part grasping by microgrippers, manipulators & robots
- Part mating by specially designed tools
- Part bonding & fastening
- Encapsulⁿ & passivation.
- Sensing & verificⁿ.

* Read : Major Technical problems in Microassembly

- Tolerances : Geometric, Alignment, Other.

- Adhesive forces in Micrograsping :
  - Van der Walls force (F_v)
  - Electrostatic force (F_e)
  - Surface Tension. (F_s)

* Essential Elements
- Integrated micropositioner
- Microscope optics & imaging unit.
- Micro-controlled cards + Operⁿ software

* Mechanical Packaging of Microelectronics
∃ 4 levels of microelectronics packaging !
1) Si chip into a module
2) Card level
3) Cards to boards
4) Boards to system.

Date
Page

* Level 1 & 2 packaging
  Reliability issues & failure mechanisms exist

* Factors in packaging
  - Cost
  - Environmental effects
  - Choice of materials

* 3 levels of microsystems packaging
  Level 1 : Die level
  Level 2 : Device level
  Level 3 : System level

- 1) Die level packaging :
  Objectives : ✓ protect die from deform^n
  ✓ protect active circuitry for signal transduction of sys.
  ✓ provide necessary mechanical isol^n of elements.

- 2) Device level packaging
- 3) System level packaging :
  Putting everything into the system directly

* Surface Bonding:
    (1) Adhesives
    (2) Eutectic soldering
    (3) Anodic bonding
    (4) Silicon fusion Bonding.

* Wirebonding
    (1) Thermo compression
    (2) Wedge-wedge ultrasonic
    (3) Wire-wire bonding

* ~~St~~ Sealing
    * Different methods to seal
        → RTP: Rapid Thermal Processing.

* Concept of 3D packaging

* Selecting the Package Material.

---

* Signal Mapping
    Develop & establish strategies in selecting both the type & posn of microsystems

* Signal Transduction.

Puffin
Date
Page

§ Reliability & Testing of Microsystems

- Thermal Shock Test → -60°C → then suddenly 100°C (≡ shock)
- Thermal Cycling Test → -60°C to gradual 100°C to gradual -60°C to gradual 100°C.....
- Burn-in test → test under harsh condns of temp, pressure & humidity ≡ endurance test
- Self Testing

✱ Failure mechanisms in MEMS & Microsystems

↳ mainly due to over stressing & over heating

end of course