UNIT - IV

1

Microaccelerometer (Micromachined accelerometer):-

Difference between micromachine & Conventional accelerometers:-

From past 50 years we have accelerometers which are bulky accelerometers and are made of heavy metals.

Different small parts are integrated and to make an accelerometer basically made from electromechanical Principles.

Mechanical parts ~~are~~ and electronics parts are Present which weigh some kilos which needs a higher Voltage and current to operate.

It needs careful maintenance and Calibration from time to time.

These are highly expensive because it is not throw away type.

These are very sensitive and gives large output Compared to micromachine accelerometers.

MEMS Accelerometers:-

Micro machine accelerometers are micro size and light weight.

It uses just small amount of silicon to make the Complete structure.

It is batch fabricated by using advanced microfabrication technology.

It is of low cost and it is throw away type.

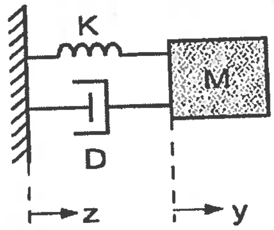
∵ MEMS accelerometers are of small size it operates in a low voltage and low current.

So the power consumption is extremely small.

MEMS accelerometers has certain advantages on chip integration, smart, intelligent and reliable.

Because of on chip on the devices side you can integrate it's signal processing circuits replacing majority of the conventional system by the MEMS accelerometer.

Working Principle:- An accelerometer generally consists of proof mass suspended by compliant beams anchored to a fixed frame. Proof mass has a mass (M)

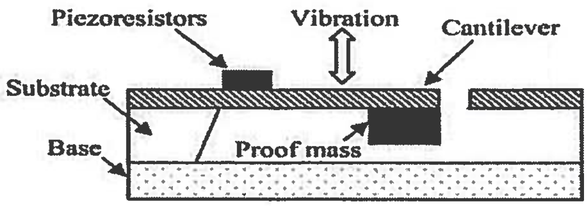


suspension beams have an effective spring constant k and a damping factor (D). Which affects the dynamic movement of mass.

External acceleration displaces the support frame relative to proof mass which changes the internal stress in the relative suspension spring.

Device Types:-

Piezoresistive Devices:-



The accelerometers incorporate silicon piezoresistors in their suspension beam.

As supportive frame moves relative proof mass the suspension beams will elongate or shorten which leads to change in resistance. The resistors are placed at the edge of support beam and proof mass.

Half or full bridge can be formed by employing two or four piezoresistors.

Advantages:-

→ Simplicity in structure.

→ Simple fabrication process including their read out circuitry.

→ less susceptible to parasitic capacitance and electromagnetic Interference.

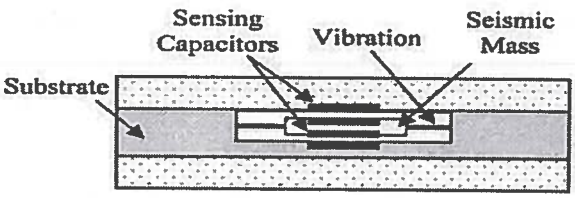
Disadvantages:-

→ large temperature Sensitivity.

→ Small over all sensitivity than capacitive devices and hence a large proof mass is preferred for them.

→ Temperature Compensation Circuitry is desirable.

Capacitive Microaccelerometer :-



In the presence of external acceleration the support frame of an accelerometer moves from its rest position thus change in Capacitance occurs between Proof mass and a fixed Conductive electrode seperated with a narrow gap. This change in Capacitance can be measured using electronic circuitry.

Technology:- (fabrication):-

1.) Use of bulk micromachining and wafer bonding.

→ A silicon middle wafer is anodically bonded to two glass wafers on top and bottom of accelerometer.

→ The surface structure will have two differential sense capacitors with the proof-mass forming the middle electrode and metal on the glass wafers forming the top/bottom fixed electrodes.

→ Air gap is formed by recessing the silicon on glass wafers.

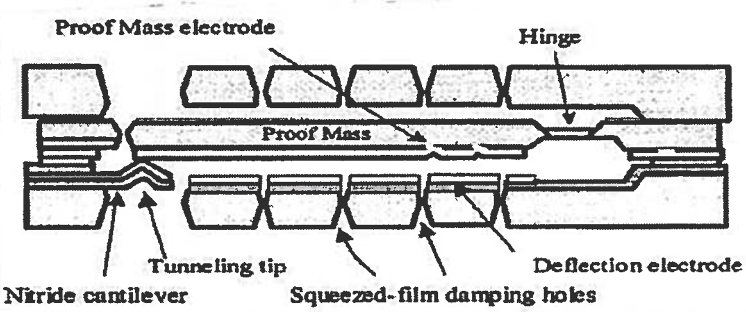
Advantages:-

→ low temperature sensitivity
→ Good dc response and noise performance.
→ High sensitivity.
→ low-power dissipation.

Disadvantages:-

→ Very difficult to eliminate parasitic components
→ Susceptible to electromagnetic interference (EMI) which can be addressed by proper Packaging.

Tunneling MicroAccelerometer:-



High resolution physical sensors including accelerometers use a constant tunneling current between tunneling tip and it's counter electrode to sense displacement. When tip is brought sufficiently close to it's counter electrode using electrostatic force generated by bottom deflection electrode. A tunneling current is established (I_{tun}) and remain constant if the tunneling voltage (V_{tun}) and distance between the tip and counter electrode are unchanged.

$$I_{tun} \propto V_{tun}\, e^{-\alpha x \sqrt{\phi}}$$

I_{tun}: tunneling current
V_{tun}: " voltage
α: " constant
ϕ: tunneling barrier
x: seperation.

Technology :- (fabrication):-

The tunneling accelerometer is fabricated in two

Parts:- 1.) The Cantilever with it's integrated tip.

2.) The base of the accelerometer.

Bottom is base wafer and we have another is Cantilever wafer.

two wafers are N type 100 silicon wafer.

Then it is oxidized by thermal oxidation. (top and bottom).

Tunneling electrode.

a.) e-beam evaporation

b.) SiO_2 deposition and etching

c.) p++ silicon layer.

d.) Removal of back Si, tip mold etched.

e.) e-beam evaporation

f.) mask and ion milling

g.) Cantilever release.

(Counter-electrode Cantilever)

a.) e-beam evaporation.

b.) lithography and ion milling.

c.) Sacrificial layer

d.) masking and metal evaporation.

e.) Cantilever release (removal of Sacrificial layer).

Advantages:-

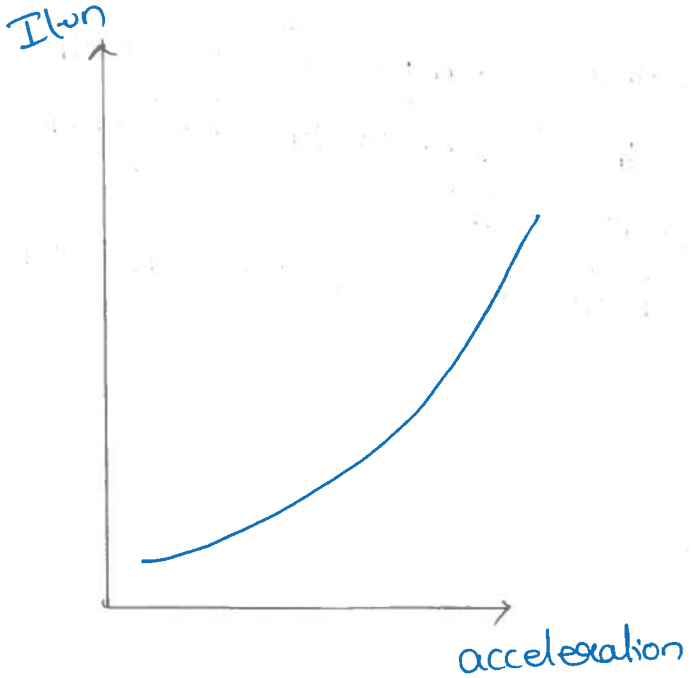
→ High sensitivity

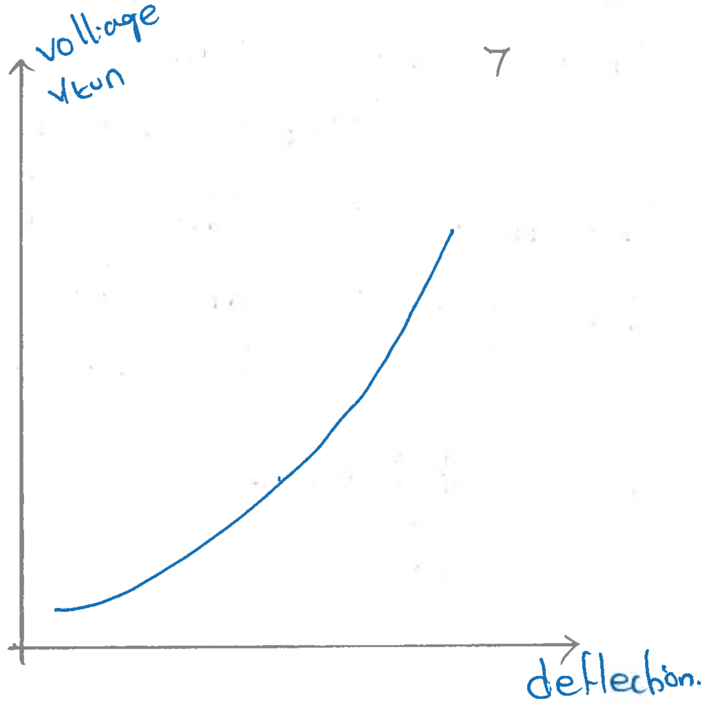
→ High Bandwidth

→ Great Range.

→ less noise effect

→





Resonant Micro Accelerometer:- (Quartz Micromachining).

The main Advantage of resonant sensor is their direct digital output.

The devices can be of RL, LC & RLC. if we consider LC i.e a reactive parameter either L or C chang. The resonance frequency also changes.

let the variation of capacitance which may be connected with accelerometer structure, which makes an oscillator whose frequency oscillation changes with respect to movement of the proof mass.

Thermal Devices (Micro accelerometer):-

Accelerometer based on Thermal transduction.

Principle:- Temperature flux from a heater to heat sink plate is inversely proportional to their seperation.

Hence by measuring temperature using thermopiles, the change in seperation between the plates can be measured.

It uses both Bulk and surface micromachining for fabrication.

MEMS Accelerometer for Avionics:-

Objective:-

Design and fabrication of a microaccelerometer for aircraft motion sensing to satisfy the need of flight Control System (FCS). in Normal mode:-

This mechanism is based on piezoresistor Sensing which is used in aircraft.

Device specifications:-

Range:-	±13g
Resolution :-	2mg
Natural frequency:-	>100HZ
Full scale output:-	±6.5VDC
temperature :-	-40°c to 65°C
linearity :-	1% Full scale (FS)
Damping Ratio :-	0.7±0.2

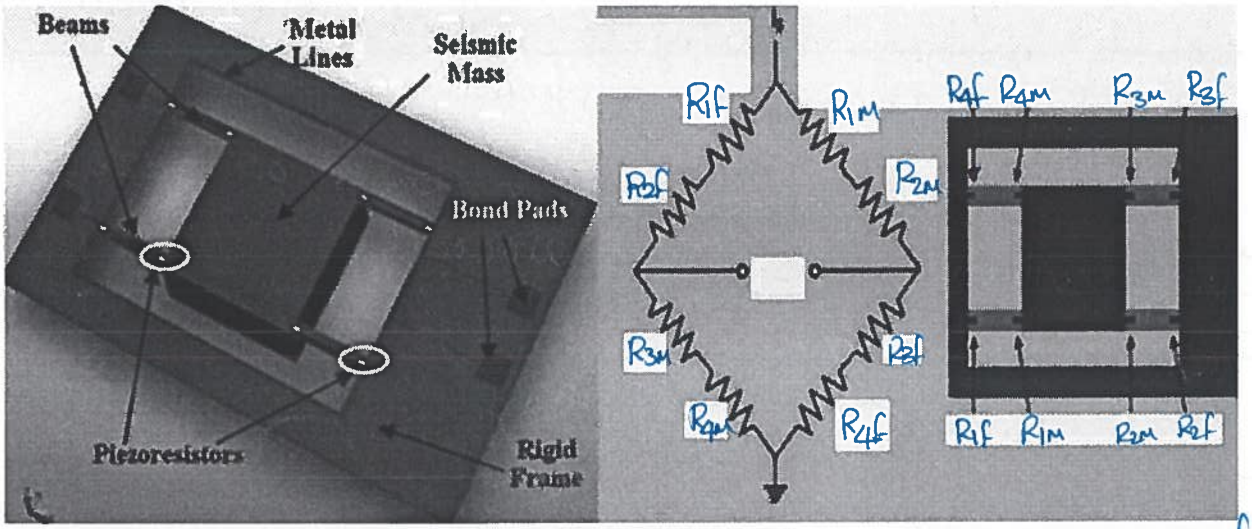
Design of silicon Micromachined piezoresistive Accelerometer With low off Axis Sensitivity:-

off axis sensitivity is the device should be sensitive to acceleration in one direction but insensitive to acceleration in other directions.

If Sensitivity in desired direction is 1% then the Sensitivity in other 2 axis is 001%.

In Case of aircraft motion sensing or avionics if it is in 1-axis accelerometer. So off axis sensitivity should be extremely low.

Bulk micromachined piezoresistive accelerometer consists of four flexures supporting proof mass. Four pairs of boron diffused piezoresistors are located at maximum



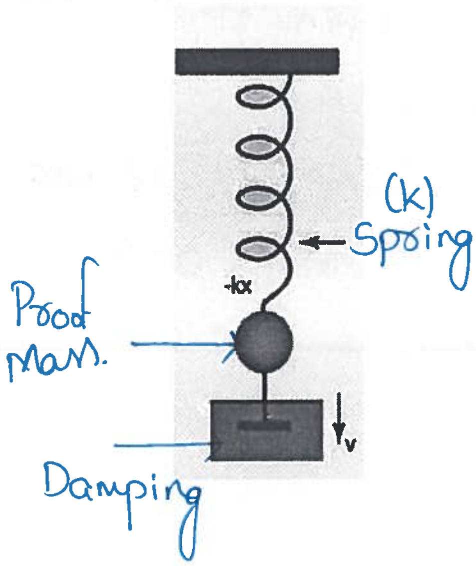
stress points on the flexures near the proof mass and frame ends.

These piezo resistors can be connected to form a wheat stone bridge.

This accelerometer can independently detect three components of linear acceleration along 3 directions.

The detecting principle is based on piezoresistive effects in single crystal silicon.

The equivalent model of accelerometer is shown in fig.

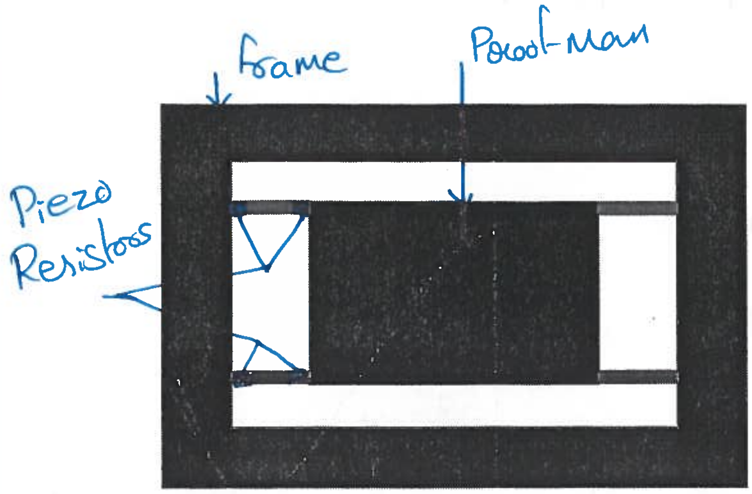


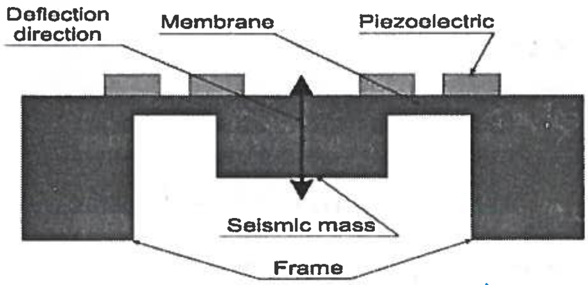
Proof mass m
Spring factor k

If you give acceleration where acceleration is force equal to mass * acceleration which is equal to k.x. i.e $F = kx$

k = spring constant
x = displacement.

Fabrication Process:-





Piezoresistive accelerometer was fabricated by Bulk micromachining technology.

So keeping the technology limitation and the maximum stress region as limitation you have to decide the value of resistances.

If Resistance has change in large over small stress large value of R should be taken.

Resistors are fabricated over small area where sheet Resistance depends on the doping concentration.

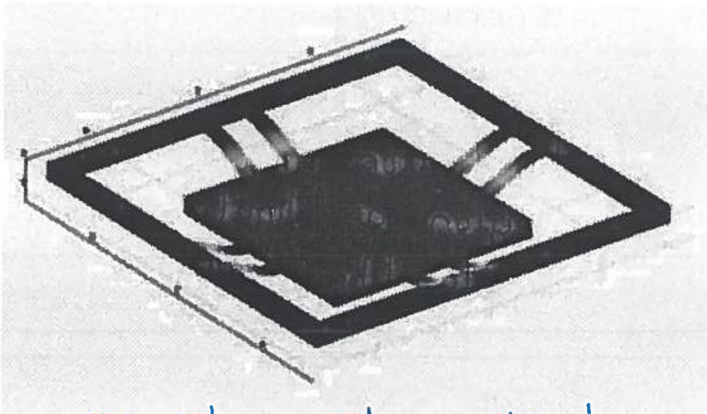
Resistance is normally fabricated using boron doping & P-type silicon since p-type silicon has got the high Piezoresistive coefficient in which helps in better resolution compare to N-type which has less piezoresistive coefficient compared to p-type silicon.

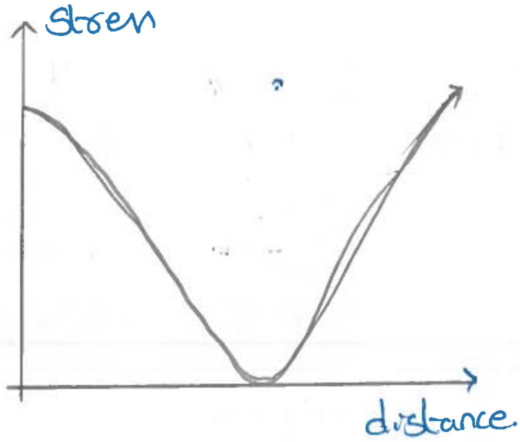
Stress Analysis:-

If acceleration is facing in Z direction where Z direction is vertically upward or downward. If acceleration is applied at 13 g force the proofmass will go downwards. Now for 13 g force the proofmass will go downwords because of its inertia.

Now the stress on supportive beams changes. The stress at the frame end will be high known as tensile strain. The stress at the mass end will be low known as compressive strain.

Maximum change in current or ΔR occurs at approximately the Same points at which the maximum stress on the beams were obtained.





MEMS Accelerometer structure:-

Dimensions of accelerometer:-

Sensior dimension:- 8000µm x 8000µm x 280µm

Proof mass :- 3500µm x 3500µm x 280µm

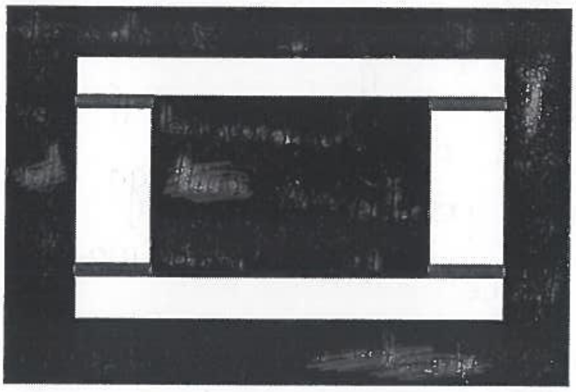
Mass of the proof mass:- 7.50mg.

Flexure dimension = 1200µm x 250µm x 20µm.

Resistor specifications:-

Resistor dimensions:- 120µm x 20µm

Contact pad :- 40µm x 40µm.



Resistor material properties:-

Junction depth:- 2.5µm.

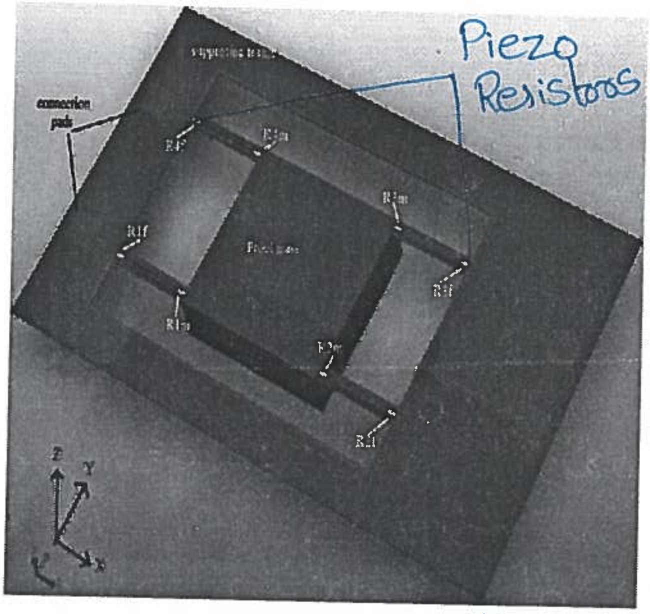
Boron doped Resistor sheet resistance = 250Ω/sq.

Sensing Mechanism:-

→ Each flexure Contains two diffused piezo-resistors

→ Placement of resistors at maximum stress region one near frame end and other near Proof mass end.

Resistance value changes due to piezoresistive effect in silicon

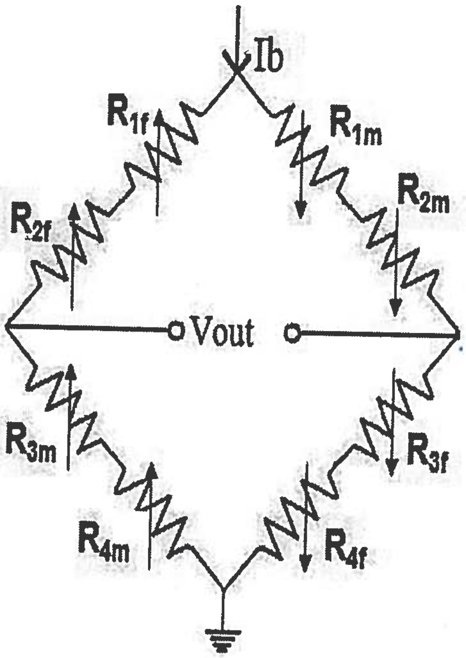


→ We have totally 4 flexures each flexure is having 2 resistances.
So total resistances will be 8
in one of two resistances at each flexure one resistance is at the maximum stress region. (So the resistance value will change due to piezoresistance effects).

→ Resistances value of four resistors will increase and other four will decrease due to Positive/negative stress (tensile/compressive stress).

→ Eight resistors are connected in wheatstone bridge configuration.

→ Changes of voltage at wheatstone bridge output is proportional to the acceleration ($V_o \propto \Delta R$).



Piezoresistors	ΔR Mode-1 (x Desired Axis)	ΔR Mode-2 Y	ΔR Mode-3 Z
R1f	⇩	⇧	⇧
R1m	⇧	⇩	⇩
R2f	⇩	⇩	⇧
R2m	⇧	⇧	⇩
R3f	⇩	⇩	⇩
R3m	⇧	⇧	⇧
R4f	⇩	⇧	⇩
R4m	⇧	⇩	⇧

Now from above diagram you can see the off axis sensitivity? In the above table Resistances are named as Rxf $ Rxm where x varies from (1 to 4). f stands for frame end and m stands for mass end.

For Example Z-axis acceleration Vo should have Some value in Z-axis but in X and y axis it should be zero.

	ΔR X-axis	ΔR Y	ΔR Z
R1f	↓	↑	↑
R4m	↑	↓	↑
Vo	0	0	↑

So at R1f & R4m X-axis ΔR is decreasing at R1f and ΔR axis at R4m is increasing So Vo becomes zero similarly at ΔR of Y-axis.

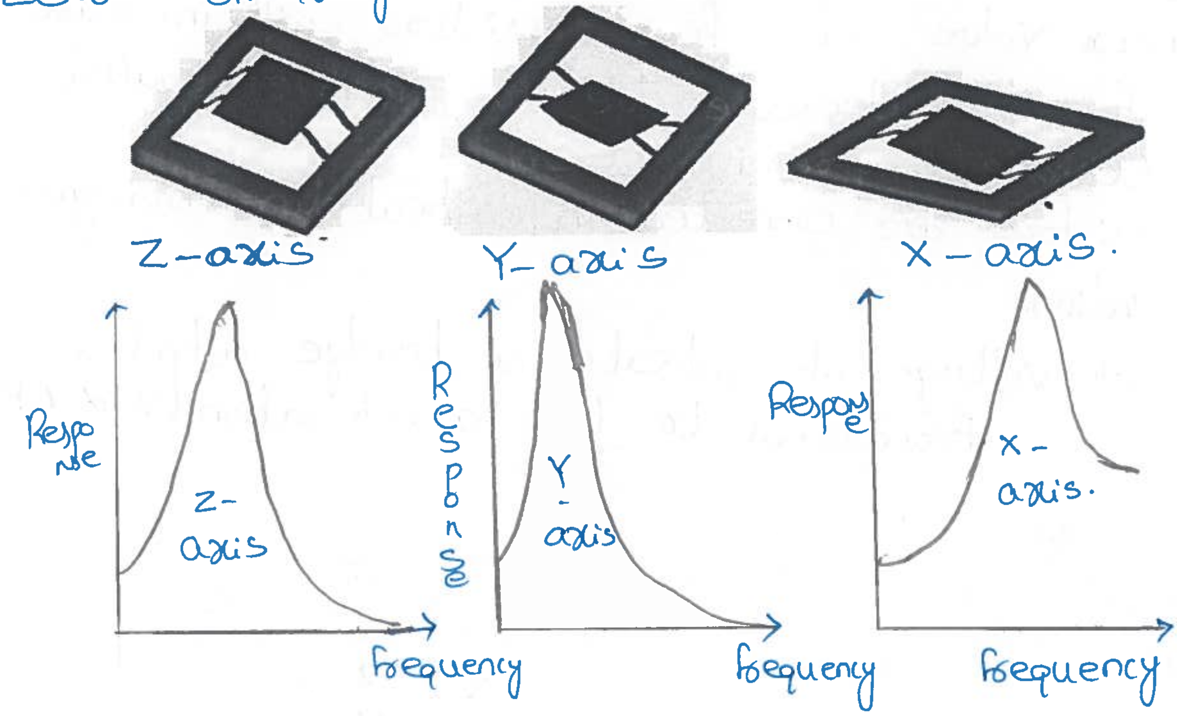


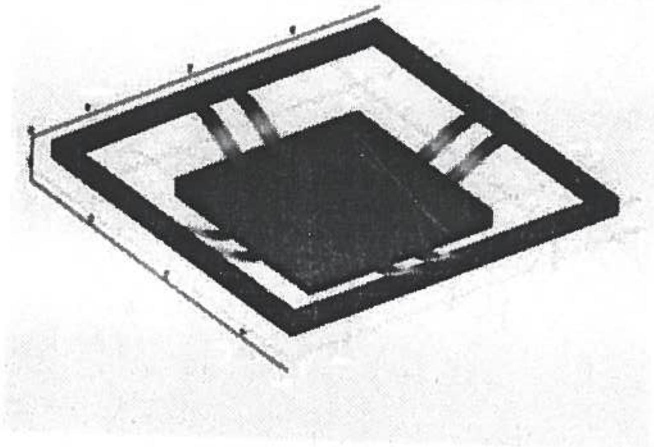
fig:- frequency Vs Response (Signal output) using Convertor wave frequencies above 100Hz.

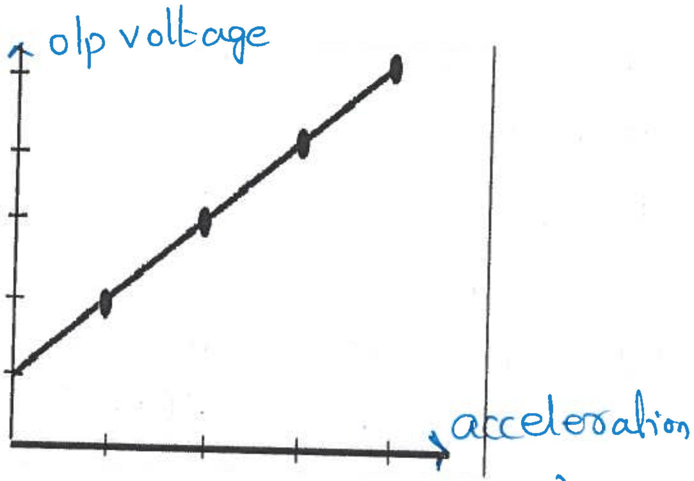
Example from table if it is Y-axis acceleration Vo Should have Some value in Y-axis.

	ΔR X-axis	ΔR Y-axis	ΔR Z-axis
R1f	↓	↑	↑
R2m	↑	↑	↓
Vo	0	↑	0

If Z-axis acceleration (13 g) :-

No. load Resistance = 1357.19 Ω





Resistance	R(ohms)	ΔR(Ω)	$\frac{\Delta R}{R}$ ($\times e^{-3}$)
R_{1f}	1362.87	+5.682	4.186
R_{1m}	1351.69	-5.5021	4.054
R_{2f}	1362.87	+5.682	4.186
R_{2m}	1351.69	-5.5021	4.054
R_{3f}	1362.87	+5.682	4.186
R_{3m}	1351.69	-5.5021	4.054
R_{4f}	1362.87	+5.682	4.186
R_{4m}	1351.69	-5.5021	4.054

All frame end resistors will increase, while all mass end resistors will decrease. this is at proof mass displacement of 1.18 um.

the o/p voltage (vo) of wheatstone bridge is 19.15 mV.

From above as the acceleration increases output voltage increases.

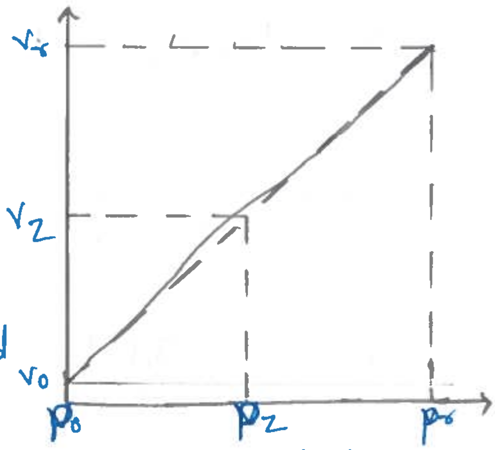
off-axis Accelerations:-

13 g Acceleration	Z-axis	X-axis	Y-axis.
o/p voltage	19.15 mV 1.47 mV/g	1.22 uV 0.0938 uV/g	0.615 uV. 0.047 uV/g.
Proof mass displacement	1.18 um	0.047 um	0.092 um

Non linearity:-

The nonlinearity by end point fit method is given by

$I_o = (V_z - V_0)(V_r - V_0) - (P_z - P_0)(P_r - P_0)$



the linearity as Calculated by end point from the specifications is 0.16% Fs (full scale) which is lesser than the Desired value of linearity which is 1% Full scale). The designed linearity is less than the desired linearity which is satisfied with the specifications of off axis sensitivity.

Temperature Drift and Damping Analysis:-

Temperature Drift and Damping are two important parameters for a piezoresistive accelerometer.

Temperature coefficient is the specification that defines how a voltage references output voltage will drift over a given temperature.

In response to a differential change of acceleration (Δg). the differential output voltage (ΔV) of an ideally balanced bridged with assumed identical resistance change (ΔR) is

$$\Delta V = \frac{\Delta R}{R} V_s.$$

R = Zero stress Resistance.

V_s = supply voltage.

The sensitivity of the bridge (S) is defined as relative change of output voltage per unit applied differential acceleration.

$$S = \frac{\Delta V}{\Delta g} \cdot \frac{1}{I_s} = \frac{\Delta R}{R} \cdot \frac{1}{\Delta g}.$$

Temperature drift is contributed by three factors:-

- Temperature Coefficient of Resistance (TCR).
- Variation of Coefficient of piezoresistivity (TCP) with temperature.
- Variation of elastic Constant (stress) with temperature.

* Temperature Coefficient of Resistance (TCR) is not going to change the Voltage that much.
* Variation of Coefficient of piezoresistivity (TCP) with temperature. Temperature Coefficients of Piezoresistances change because of stress. due to the development of stress the resistance is going to change. Coefficient is given as $(\pi_{11}, \pi_{44}, \pi_{12})$ So the π value changes with temperature.
* Variation of elastic Constant with temperature. elastic Constant means Young's modulus.

~~Temperature Drift in Piezoresistive Accelerom.~~

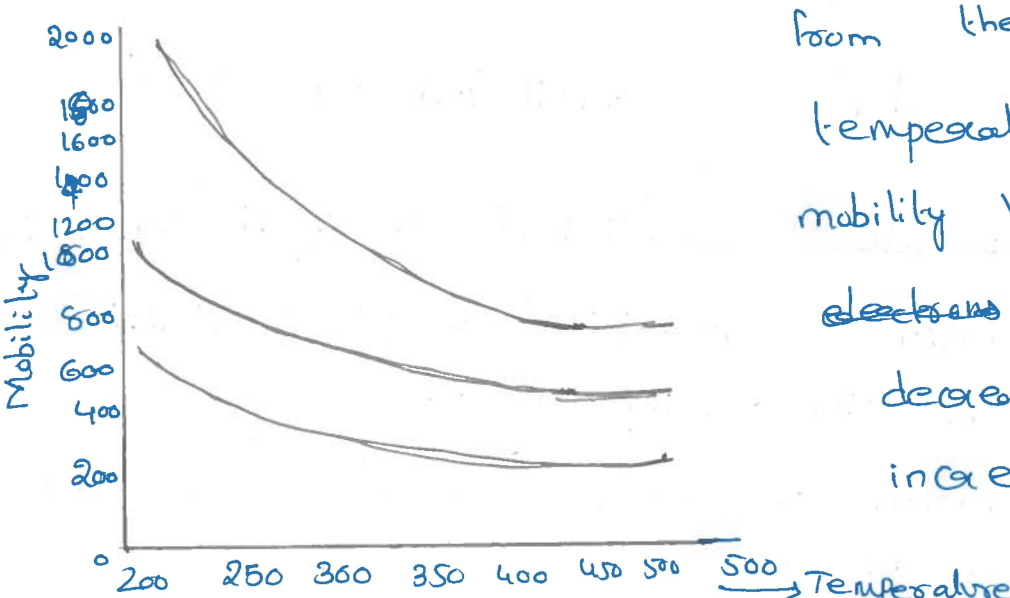
Electron and hole mobility in Silicon:-

Empirical relations for the temperature as well as doping dependence of the Carrier mobilities in silicon is

$$\mu_p(N,T) = 54.3\left(\frac{T}{300}\right)^{0.57} + \frac{1.35\times10^{8}\,T^{2.23}}{1+\frac{N}{2.35\times10^{17}\left(\frac{T}{300}\right)^{24}}\,0.88\left(\frac{T}{300}\right)^{0.146}} \ \text{cm}^2/\text{V.s.}$$

N doping Concentration

T temperature.



From the graph as the temperature increases the mobility value decreases i.e ~~electrons~~ Electrons and holes decreases as temperature increases.

Temperature Coefficients of piezoresistor:- (two major effects):-

* Temperature Coefficient of offset (TCO):-

Temperature change is a common mode effect on resistors and so in ideal balanced bridge the offset remains zero with temperature change.

* Temperature Coefficient of sensitivity (TCS):-

great influence because of the temperature dependence of the piezoresistive coefficients.

Bridge Excitation (Constant V vs Constant I):-

Constant bridge voltage TCS_V:-

TCS_V (temperature Coefficient of Sensitivity):-

$$TCS_V = \frac{1}{S} \cdot \frac{\Delta S}{\Delta T} = \frac{1}{\pi_{44}} \cdot \frac{\Delta \pi_{44}}{\Delta T} + \frac{1}{(\sigma_l - \sigma_t)} \cdot \frac{\Delta(\sigma_l - \sigma_t)}{\Delta T} \rightarrow a$$

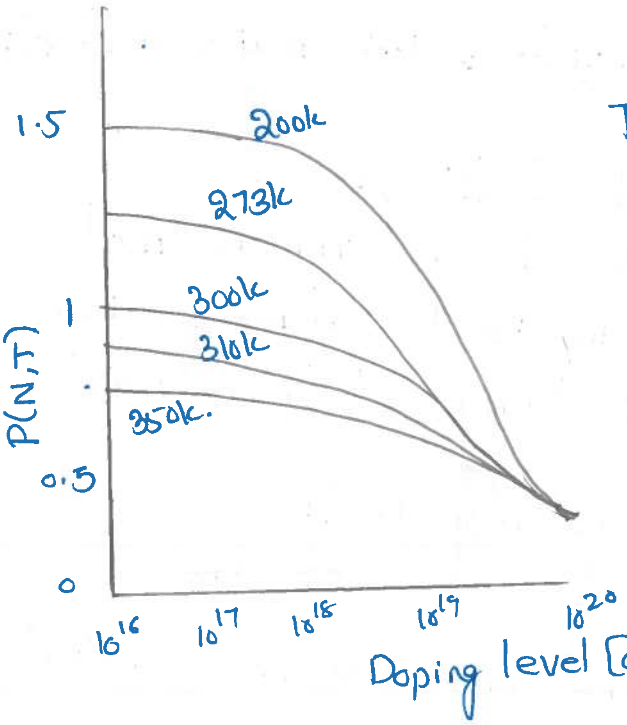
$$S = \frac{\pi_{44}(\sigma_l - \sigma_t)}{2\Delta g}$$

$$TCS_I = \frac{1}{S} \cdot \frac{\Delta S}{\Delta T} = \frac{1}{\pi_{44}} \cdot \frac{\Delta \pi_{44}}{\Delta T} + \frac{1}{R} \cdot \frac{\Delta R}{\Delta T} + \frac{1}{(\sigma_l - \sigma_t)} \frac{\Delta(\sigma_l - \sigma_t)}{\Delta T} \rightarrow b$$

In Expression (a) both first and second terms of expression are negative.

In Expression (b) first and third term are negative but second term is positive for high doping concentrations.

So that bridge excitation by constant voltage and constant current will not be the same. we need to choose one case where sensitivity is more.



The piezoresistant factor P(N,T) and piezoresistance Constant $\pi(N,T)$.

The piezoresistances decrease with increase in doping Concentration Variation plot shows that lower Concentration Varies much with temperature but at higher Concentration the variation is less.

$$\frac{\Delta R}{R} = \pi_{44}(\sigma_l - \sigma_t).$$

* Bridge Excitation of Constant current Source is preferred than Constant Voltage Source*

temperature (kelvin)	P(N,T)	$\pi_{11} \times e^{-5}$	$\pi_{44} \times e^{-5}$
225	1.2025	7.93	166.06
250	1.135	7.49	156.74
300	1	6.6	138.1
350	0.865	5.709	119.45

P(N,T) taken from Kanda (IEEE, 1982)

$TCP = -2.7 \times 10^{-3} k^{-1}$

Dopant:- Boron

$Conc = 5 \times 10^{18}/cm^3$

sensitivity = 0.914 27 mV/mA/g

$TCS: -2.6 \times 10^{-3}/k$

Temperature Dependence of Elastic Constants:-

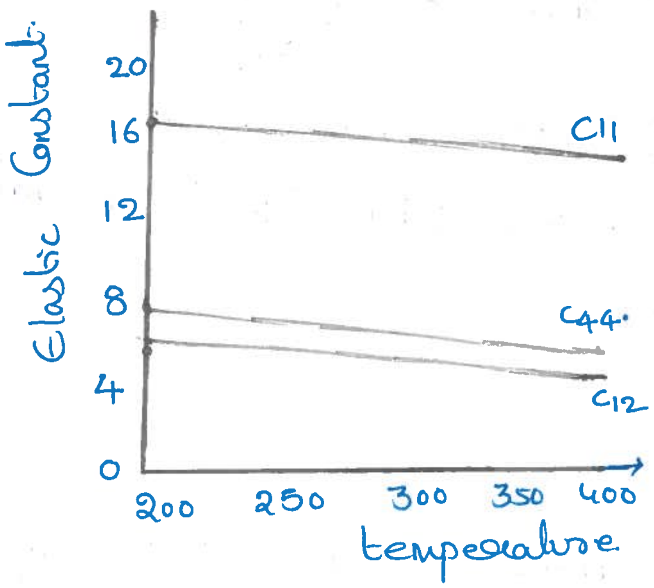
Elastic coefficients or Elastic stiffness Constants are the Constants proportionality between Components of stress and strain.

They are designated by term C_{hk} (h and k are integers from 1 to 6) and for Cubic Crystals the values are :-

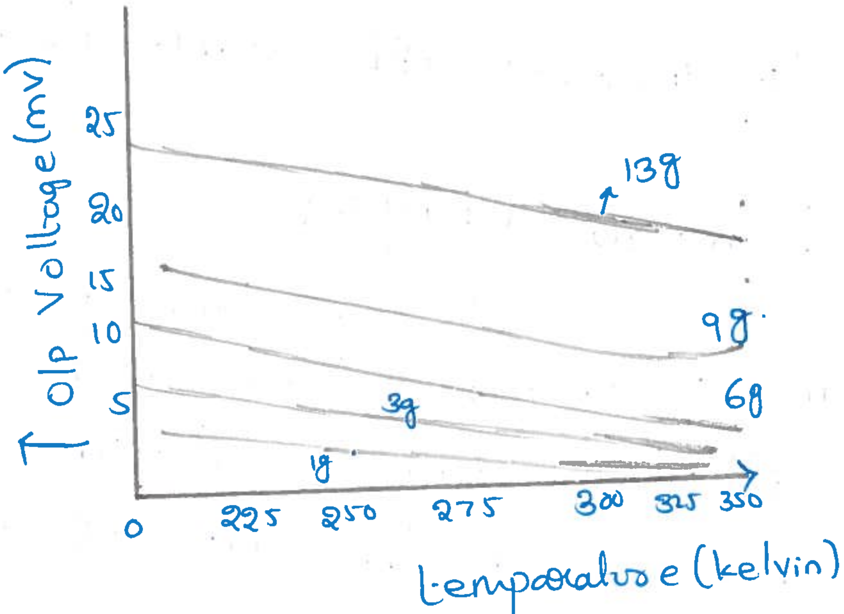
$C_{11} = 16.38 - 1.28 \times 10^{-3} T$
$C_{12} = 5.98 - 0.48 \times 10^{-3} T$
$C_{44} = 8.17 - 0.59 \times 10^{-3} T$

Temperature dependance of Elastic Constants (Si):-

Temp (K)	C_{11}	C_{12}	C_{44}	Young's Modulus (MPa)	CR Modulus MPa
200	16.6	6.4	7.96	130.191×10^3	7.962×10^4
225	16.6	6.4	7.96	"	"
250	16.6	6.4	7.96	"	"
300	16.6	6.4	7.96	"	"
350	16.536	6.376	7.93	129.873×10^3	7.93×10^4
400	16.472	6.352	7.90	129.36×10^3	7.90×10^4



Plot with temperature elastic constant variation by Nika Nikanorov in 1971.



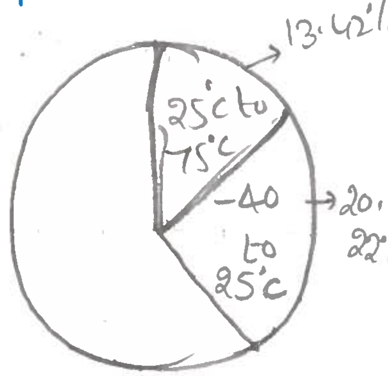
Variation of bridge o/p with temperature (for z-axis).

Temperature Drift of Si Accelerometer:-

For operating range of the device i.e from -45° to 75°c the deviation from the values is as follows

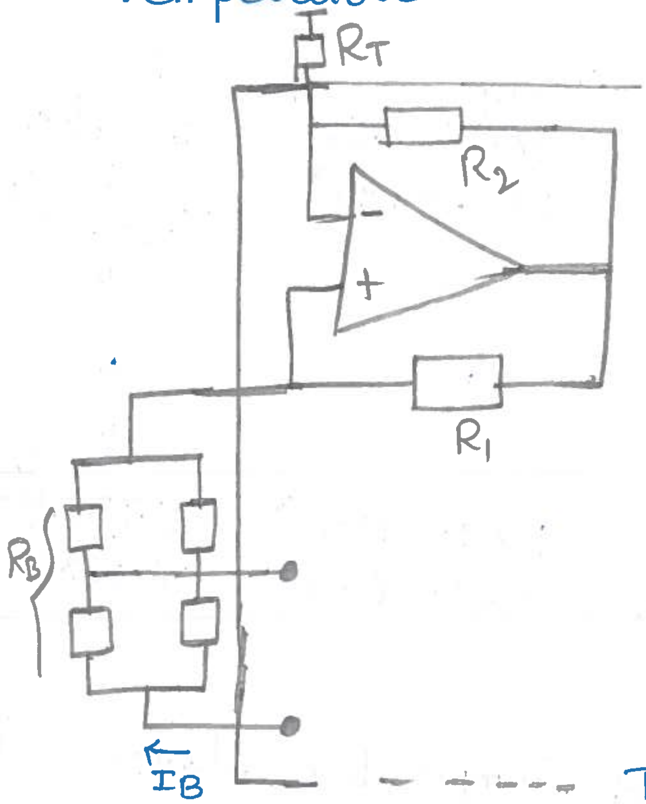
25°c to 75°c 13.42%

-40°c to 25°c 20.22%



temperature drift at lower temperature is more than at higher

Temperature Drift Compensation Circuit:-



if temperature increases bridge Resistance will decrease and Sensitivity will reduce.

if I_B (Bias Current) made to depend inversely on bridge Resistance R_B, the o/p voltage becomes temperature insensitive.

Total Resistance $R = \frac{R_T R_1}{R_2}$

A Negative Impedence Converter (NIC) implements a negative resistance $(-R_N)$ in series with R_B such that I_B increases with temperature.

Damping Analysis:-

Whenever the proof mass of the accelerometer moves perpendicularly to it's surface near the wall with a signal oscillation of some frequency f, the gas in the gap will exert a back force on the proof mass.

The force have: In phase Velocity / out phase Velocity

In phase Component is the gas damping force

Out phase Component is the spring force.

Damping force is the Component of the fluid force that is in-phase with the velocity oscillation.

Computed by integrating over the damping area of pressure times with Cosine of phase angle.

Damping coefficient is ratio of damping force to the amplitude of velocity of mass.

Spring force is the Component of fluid force that is out-phase with the velocity of oscillation.

Spring Coefficient is the ratio of spring force to the amplitude of displacement of mass.

Damping Analysis:- (MEM).

MEM Damping module of Conventorware 2003 was used to extract damping and spring coefficients for operating environment as well as phase angle.

The damping coefficient will be used to Calculate the damping factor of the device.

let x be the displacement
m is relative mass.

$$F = m\ddot{x} + c\dot{x} + kx.$$

k and c are damping and spring coefficients.

acceleration Can be determined by measuring x.

2nd order equation of motion $F(s) = s^2 mx + scx + kx.$

$$\frac{F(s)}{m} = s^2 x + s\frac{C}{m}x + \frac{k}{m}x.$$

$$a = s^2 + 2\xi\omega_n + \omega_n^2$$

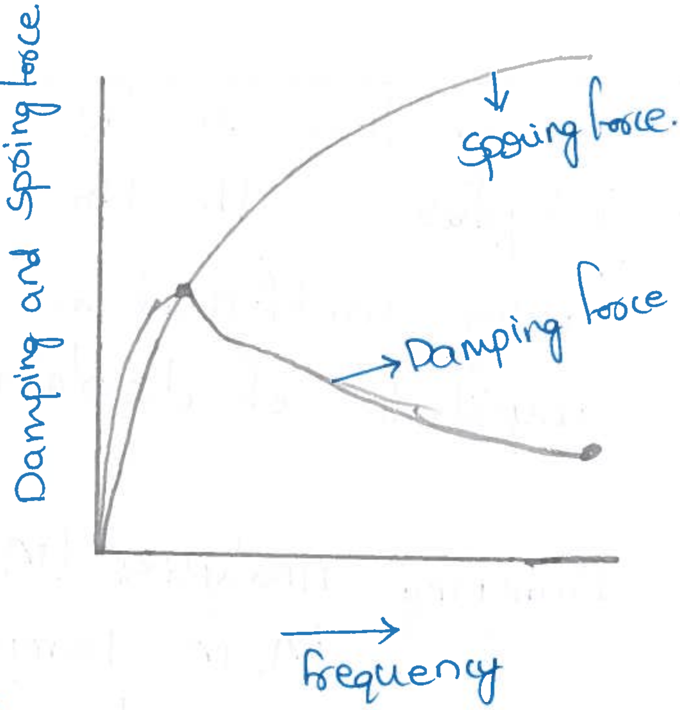
$$\omega_n = \sqrt{k/m} \quad \text{and} \quad \xi = \frac{C}{2m\omega_n} = \frac{C}{C_c}$$

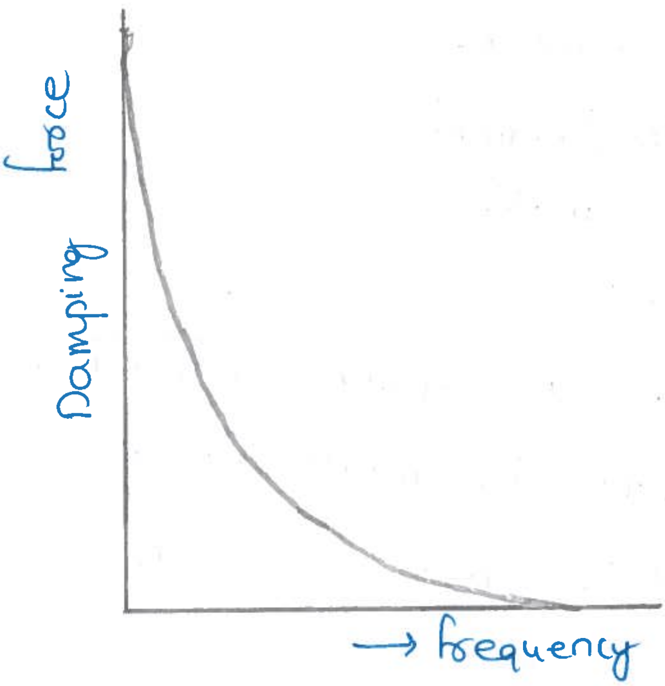
C is damping Coefficient

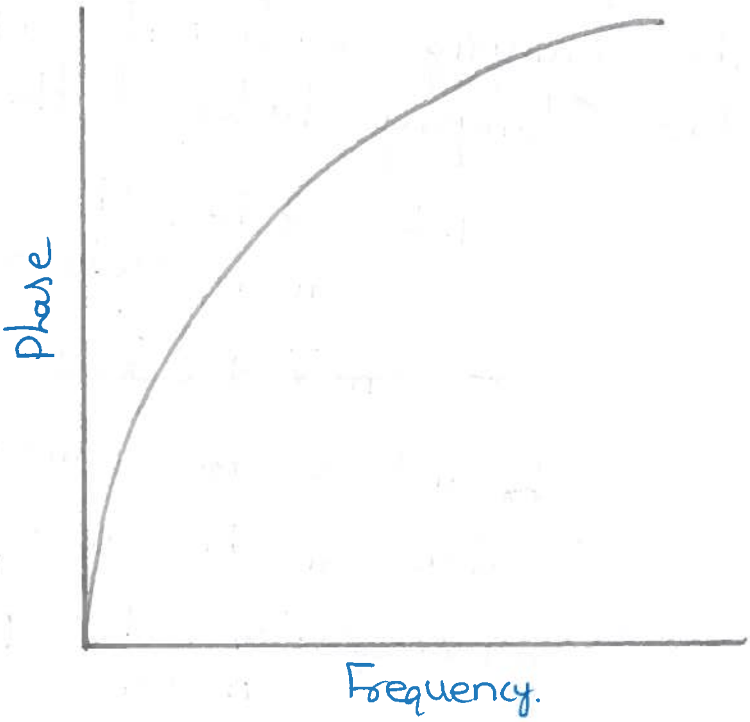
C_c is Critical damping

Results:-

The spring force rises rapidly. The air captured in the cavity is squeezed since there is no real cavity at low frequency the air can escape and force is small at high frequency. So damping force have a peak value and the goes to reduce where as spring force increases linearly.

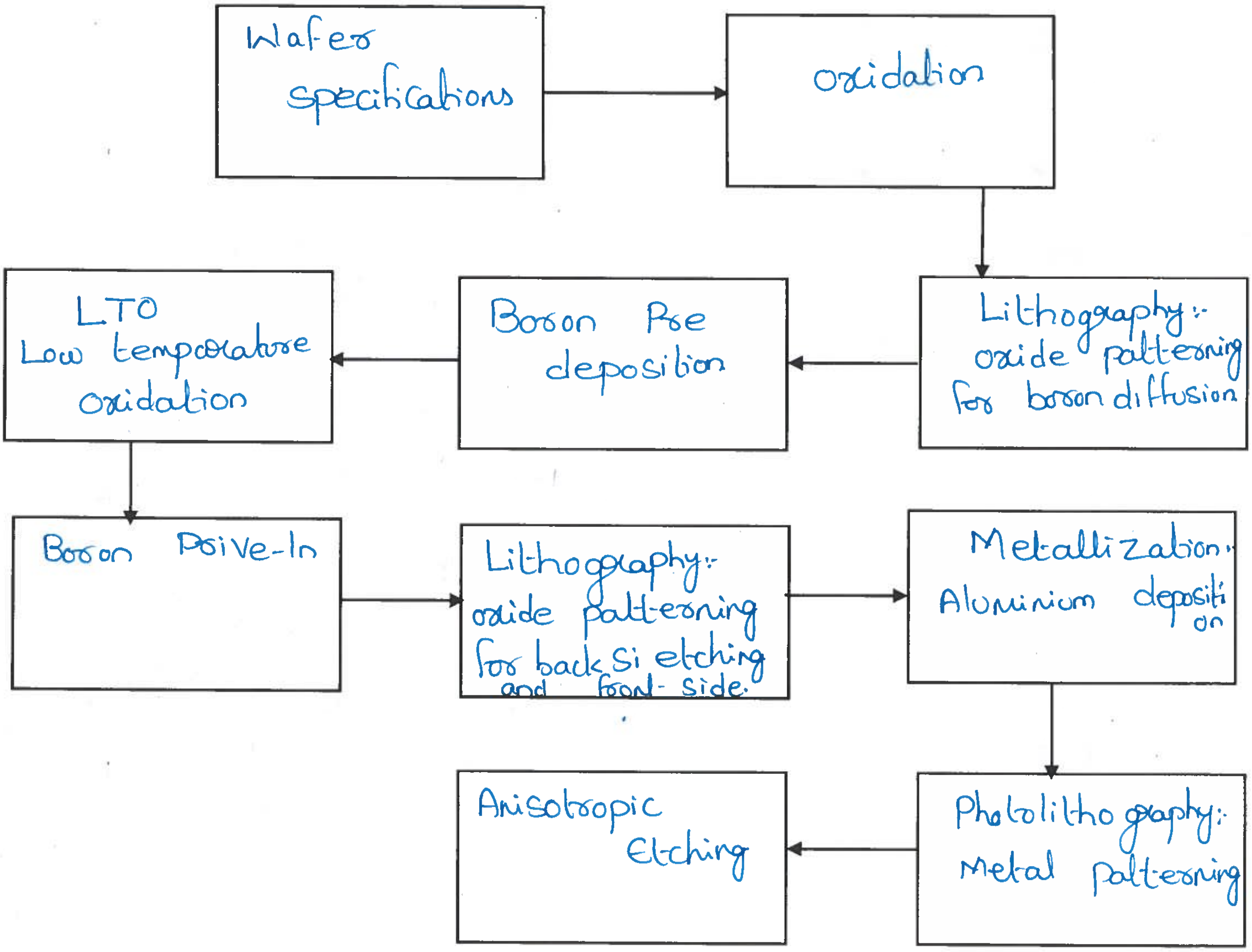




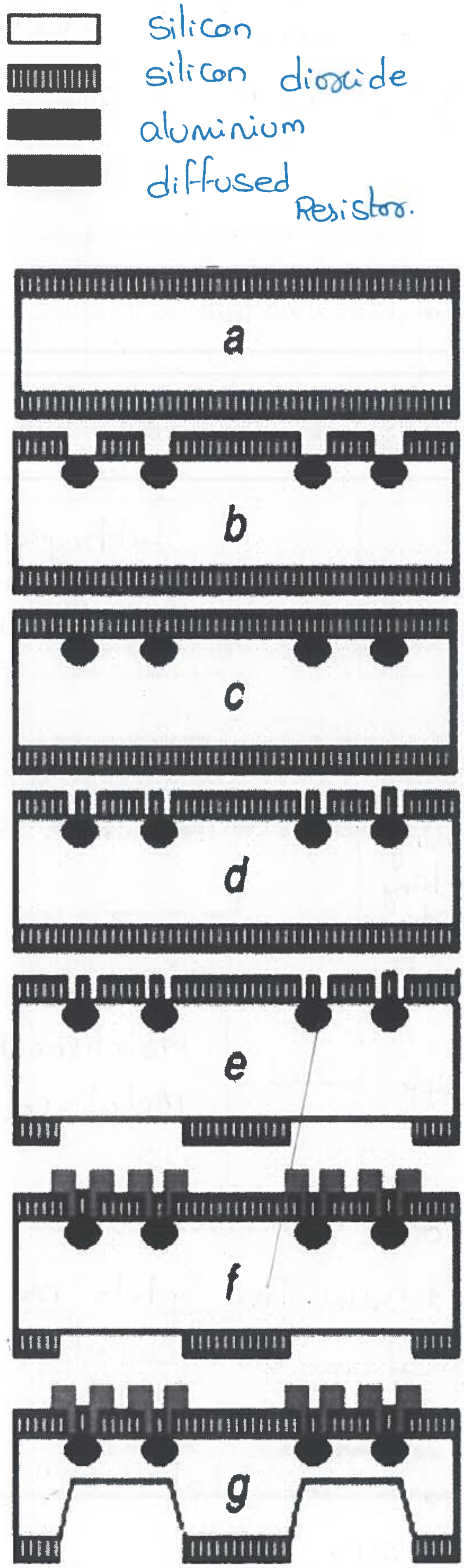


Piezoresistive Accelerometer Technology:-

Fabrication process of piezoresistive accelerometer first the type of wafer is double-side Polished <100> oriented n-type silicon wafers with a resistivity 3 to 6 Ω-cm.



The size of the wafer is 2-inch diameter with thickness 270µm ± 5µm. Five photo masks are required for complete fabrication of accelerometer. Four masks are required for complete fabrication of sensing element and one mask for fabrication of glass on top and bottom of the device.



a.) Initially wafers were thermally oxidised by a cyclic oxidation at 1092°c at Pressure 1 Pa for 30 hours.

b.) After opening a window in front side by BOE (Buffered oxide etch).
Boron impurity atoms were diffused into the front surface of the wafers in a two step process using ion implantation
Pre deposition for 15 min at high temperature 950°c with 3.2×10^{16} atom/cm³ and at low temperature 750°c with 3.2×10^{14} atom/cm³ at kinetic energy of 80kev.

c & d:- Patterned lithography using Photo resist and etching.
E.) The back side oxide was Patterned to open windows for back side anisotropic etching of silicon to define proof mass and supporting frame.

F.) Aluminium layer with thickness of 900A sputtered on top of surface and etching at 65°c using H_3PO_4 acid.

G.) Etching is done on back side of silicon to define Proof mass and supporting frame using KOH solution (to create cavity between top and bottom).

Surface and total device was finally fused with 7740 glass by anodic bonding at temperature 470°c.

Silicon- Glass Anodic Bonding:-

→ It is necessary to seal the small MEMS devices within a cavity to protect it from outside and to operate in Hazardous environment.

→ Field assisted Si - glass bonding are done at relatively low temperature (350-450°c) and at high voltages (500- 1500V)

→ Sodium Rich glass should have the equivalent thermal coefficient of expansion as silicon

→ Surface roughness of the two samples must be less than 0.1μm.

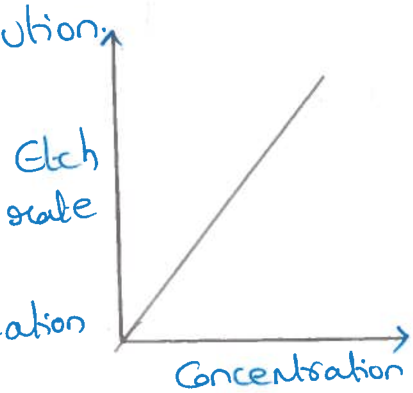
→ Si substrate are to be kept on heating plate.

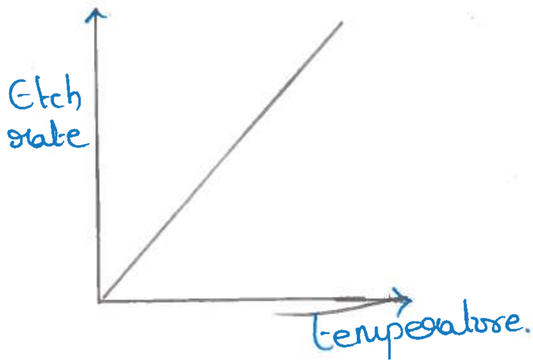
Glass Etching:-

→ Since the glass is composed of SiO_2, the glass etchants should be HF based solution.

→ Photo resist mask will not withstand for long time in HF based solution.

→

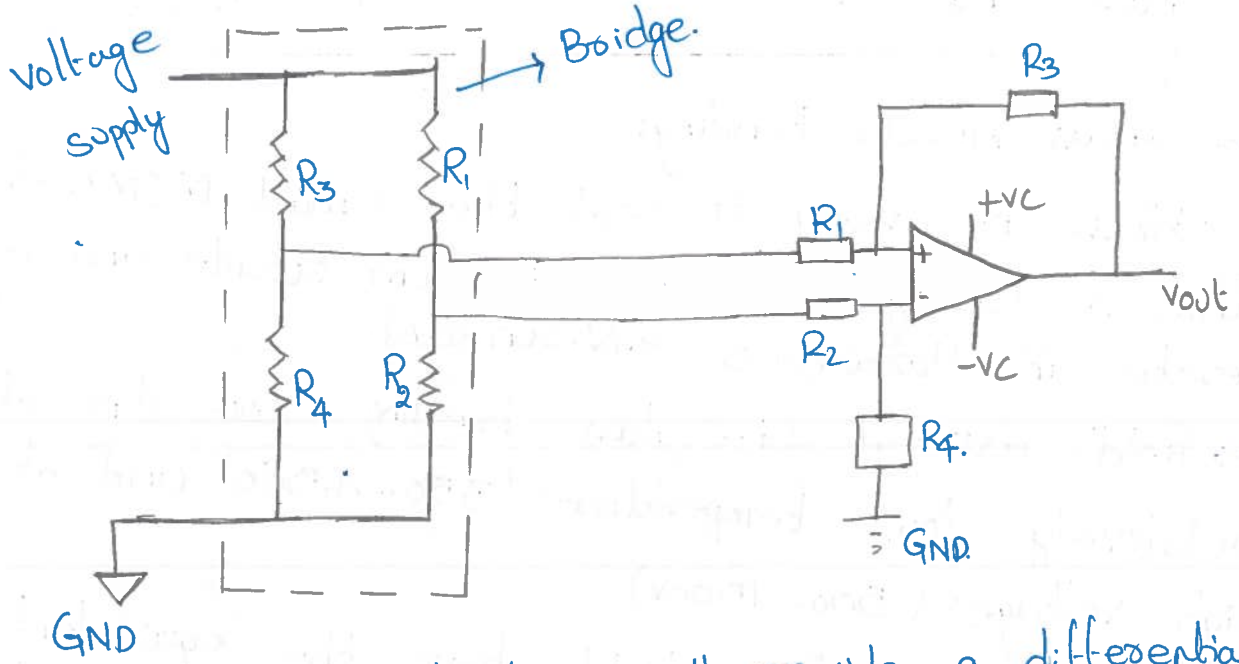




The etch rate variation for different concentration of HF solution and at different temperature has to be made befor glass machining.

∵ as Concentration and temperature increases etch rate increases.

Test setup with interface Circuit:-

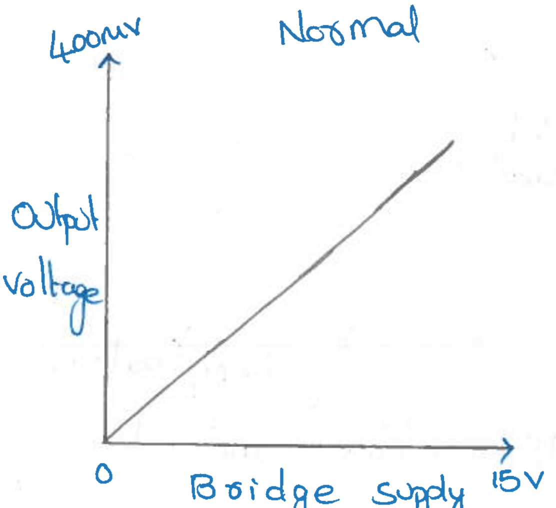


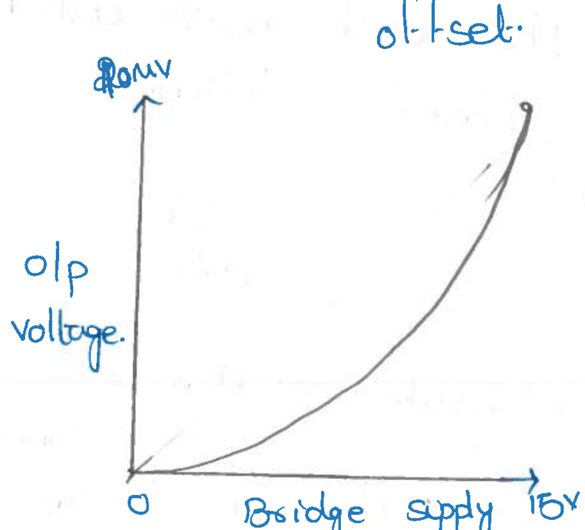
→ The sensor bridge will provide a differential low frequency (< 100Hz), low amplitude(< 20 mV p-p) signal.

→ Above designed amplifier configuration provides stable output up to 200Hz. The calibration is linear providing a gain 306.67 HZ.

→ The resistance values used to achieve ±6.5V p-p are $r_1 = r_2 = 1k\Omega$ and $r_3 = r_4 = 500k\Omega$.

Bridge supply Versus output voltage:-





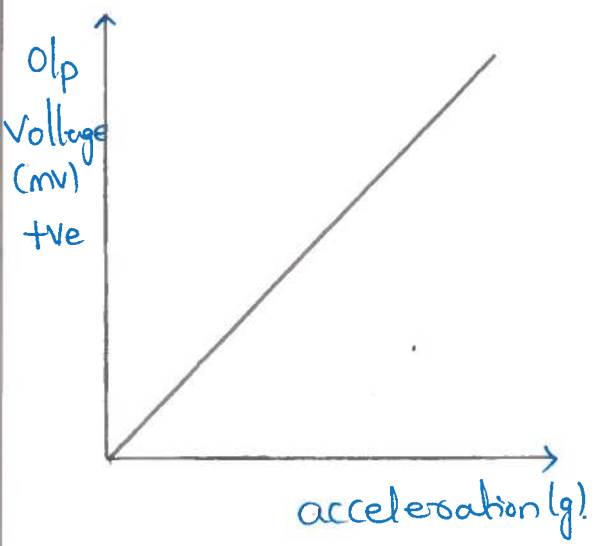
→ Bridge offset not used in first graph where with Power supply 0 to 15V we got the bridge voltage nearly

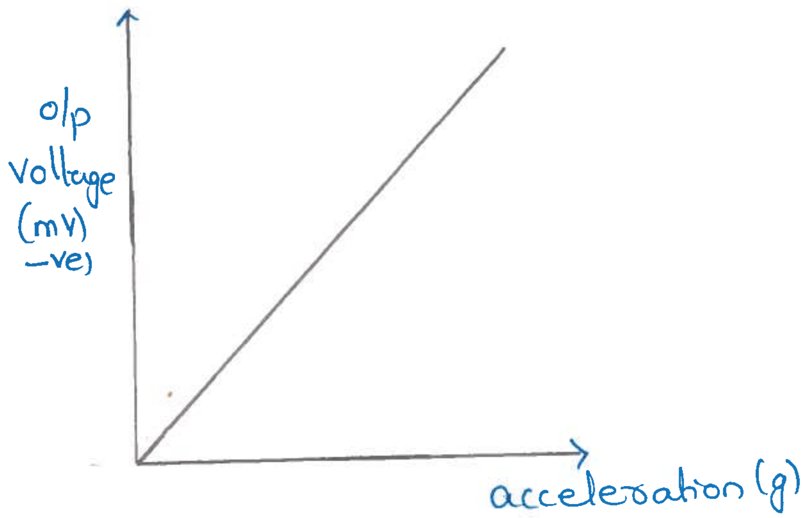
400mV.

Where 400mV is Very high So you Cannot use for Sensing.

∴ Bridge voltage has been balanced using shunt resistance and the off-set voltage was reduced from 450mV - 10mV for voltage variation 0 - 15V.

Z- axis acceleration Measurements:-





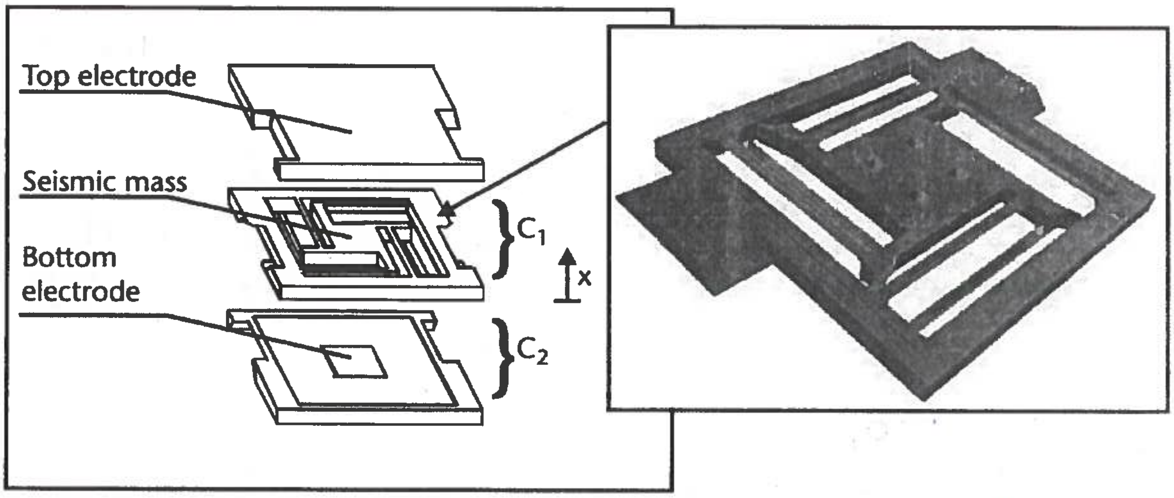
as the acceleration increases output voltage (mV) increases

∴ acceleration(g) ∝ o/p voltage.

MEMS Capacitive Accelerometer:-

Design specifications:-

Range	±10g
Over Range	30g
Damping Ratio	0.7 to 1.2
Natural frequency	100Hz (min)
Non linearity	+1% Full scale
operating temperature Range	-85 to 40°c
Resolution	0.02g (max)



In bulk micromachined Capacitive accelerometers the sensing element typically comprises of proof mass which can move freely between two fixed electrodes.

The fixed electrode forms a capacitor with the seismic mass which acts as a Common centre electrode. The fixed electrodes are one is top and other is bottom electrode.

The Seismic or proof mass will move either up or down and accordingly the capacitance between the Seismic mass and top electrode and bottom electrode will change. change in Capacitance will be the measure of your acceleration.

Differential change in capacitance between the Capacitors is proportional to the deflection of the Proof mass from the centre position.

Advantages

→ low temperature sensitivity

→ Higher output levels

→ High sensitivity.

→ Can be readily used in force-balancing; closed loop operation.

dis advantages

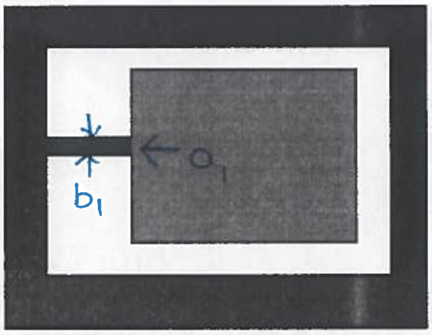
→ Sensitive to parasitic capacitances and electro magnetic interference.

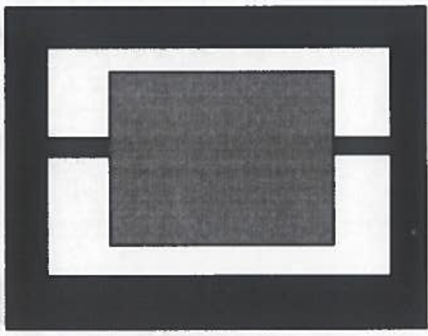
→ Electronics for the signal processing are more complex.

Types of structures:- 1) Cantilever structure:- The proof mass is held with cantilever; single cantilever.

2.) Bridge structure:- Seismic mass is held with a frame two cantilevers supported in the opposite side.

Cantilever (1)





Bridge (2)

Deflection of Mass End in single beam Cantilever structure:-

acceleration of seismic mass in z direction:-

$$\text{displacement } (z) = \left[\frac{2ma}{Eb_1h_1^3}\right]\left\{(15La_1) - (5a_1^2) - (12L^2)\right\}a_1$$

m = mass of proof mass

a = acceleration

E = Modulus of Elasticity

b_1 = width of beam

h_1 = thickness of beam.

a_1 = length of beam.

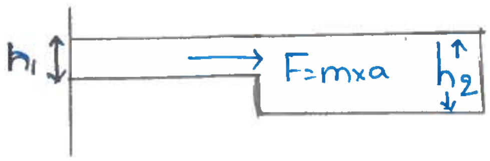
L = Centre of mass from the clamped end of beam

Deflection of Mass end in two beam Cantilever Structure:-

$$Z = \left[\frac{ma}{Eb_1h_1^3}\right]\left\{(15La_1) - (5a_1^2) - (12L^2)\right\}a_1$$

The difference between single beam and two beam is ma where in single beam it is twice when compared to two beam structure.

The two beam Cantilever structure (Bridge) is advantageous due to cross axis sensitivity.



If you use single beam motion of mass due to acceleration in x direction cannot be distinguished.

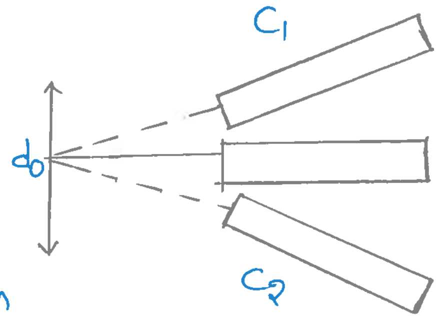
The deflection of mass in z direction due to acceleration in x direction can be expressed mathematically.

$$Z = \left(\frac{1}{2E}\right) ma(h_2 - h_1)\, a_1 \left(a_2 - \frac{a_1}{2}\right)$$

h_1 = thickness of beam
h_2 = " of proof mass
m = mass
a = acceleration
a_1 = length of beam
a_2 = length of proof mass.
E = Modulus of Elasticity.

Capacitance Variation:-

→ C_1 is the capacitance formed between the upper electrode and mass.
C_2 is the capacitance between the lower electrode and the mass.



→ $C_1 = C_2 = C_0$ when the mass is at rest

→ With acceleration movement of the mass is changed from it's rest position the capacitance between fixed electrode and movable electrode can be found by integration.

$$C_1 = \int_{a_1}^{a_2} \frac{\varepsilon b_2}{d_0 - A - B(x - a_1)}\, dx \qquad C_2 = \int_{a_1}^{a_2} \frac{\varepsilon b_2}{d_0 + A + B(x - a_1)}\, dx$$

d_0 = average of deviation.

The net change in Capacitance is $\Delta C = C_1 - C_2$

$$\Delta C = C_1 - C_2 = C_0 \left(\frac{2A + (a_2 - a_1)B}{d_0} \right) \left[1 + \frac{A^2}{d_0^2} \right]$$

$$\text{Sensitivity } S = \frac{\Delta C}{C_0 a} = \frac{2 m a_1}{E b_1 h_1^3 d_0} \left[2(3L - a_1) a_1 + 3(2L - a_1)(a_2 - a_1) \right]$$

$$\text{Non linearity } NL = \left[\frac{2 a^2 m}{3\sqrt{3}\, d_0^2} \right] \left\{ \frac{2 m a_1^2 (3L - a_1)}{E b_1 h_1^3} \right\}^2$$

Cantilever beam mass structure is a continuous system. The free vibration frequency is found using Rayleigh Ritz method.

$$\omega_0 = \frac{1}{4} \sqrt{\frac{E b_1 h_1^3}{m L^2 a_1} \left(1 + 1.25 \frac{a_1}{L} + 1.08 \frac{a_1^2}{L^2} \right)}$$

$$\text{Spring Constant } k_{eff} = \frac{E b_1 h_1^3}{12 L^2 a_1 \left(1 - \frac{a_1}{L} + \frac{a_1^2}{3L^2} \right)}$$

Deflection of Proof mass in Bridge Structure:- There are different kinds of bridge structures availabe:- 1.) Held by 2 flexures
2.) Held by 4 flexures (Piezoresistive accelerometer).

1.) 2 flexures:- $Z = \left[\frac{m a}{2 E_1 b_1 h_1^3} \right] a_1^3$

2.) 4 flexures:- $Z = \left[\frac{m a}{4 E b_1 h_1^3} \right] a_1^3$

→ The moment of mass is parallel to the fixed electrode

$$\Delta C = C_1 - C_2 = 2C_0\left[1 + \frac{x^2}{d_0^2}\right]$$

Sensitivity $S = \dfrac{\Delta C}{C_0 \times a} = \left[\dfrac{m \times a_1^3}{d_0 E b_1 h_1^3}\right]$

Non linearity $NL = \left[\dfrac{2a^2 m}{3\sqrt{3}\, d_0^2}\right]\left\{\dfrac{m a_1^3}{2E b_1 h_1^3}\right\}^2$

Natural frequency $f = \dfrac{1}{2\pi}\sqrt{\dfrac{K}{M}}$ $\quad k = \dfrac{2E b_1 h_1^3}{a_1^3}$

Damping Analysis:-

The basic mechanism for micromechanical structures is squeez-film air damping.

Between seismic mass top electrode and bottom electrode is filled with air if their is any acceleration air will flow in any direction. The air pressure and damping will obstruct the movement will be exerted in the structure.

Damping coefficient for a square mass can be expressed as

Damping Coefficient $(c) = 2\left[\dfrac{0.42\,\mu a_2^4}{d_0^3}\right]$

Damping Ration $\psi = \dfrac{c}{2m\omega_0}$

Design optimization:-

→ The mathematical models shown earlier were used for optimization purpose.

→ Three structures were optimized for the given structures.

a.) two beam cantilever without Perforation

b.) two beam cantilever with Perforation

c) Multi beam bridge type structure.

Perforation:- Put holes at different location of the proofmass.

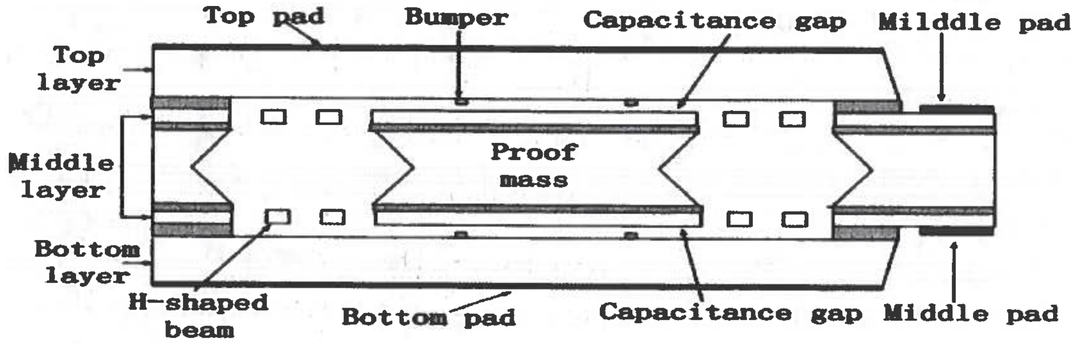
Design optimization:-

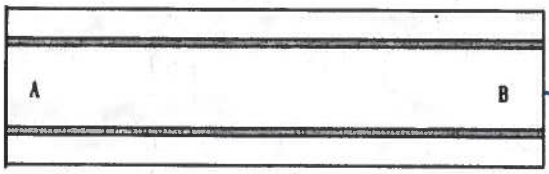
	two beam without Perforation	Cantilever with Perforation	Eight beam Cross bridge structure.
a_1	660 µm	900 µm	1400 µm
b_1	225 µm	200 µm	250 µm
h_1	44 µm	120 µm	40 µm
b_2	2440 µm	4000 µm	5300 µm
h_2	575 µm	575 µm	575 µm
d_0	19 µm	10 µm	3 µm
Max length	2440 µm	4000 µm	5300 µm
Sensitivity	0.00125	0.00120	0.00158
Non linearity	0.927%	0.89%	0.934%
Natural frequency	933 HZ	1.31 kHZ	2.31 kHZ
Damping ration	0.835	0.8**	4
Δz at 1g	4.12 µm	2.12 µm	0.466 µm.

The above mentioned tabled is for displacement along z direction.

The displacement along z direction without Perforation is more compact compare to with perforation. Since displacement is more with without perforation if displacement is more change in capacitance is also more.

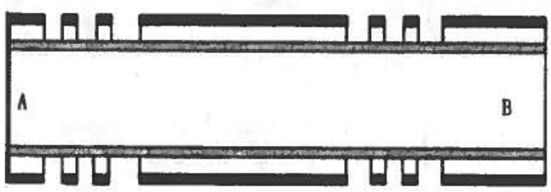
Fabrication Process:- N-type <100> oriented silicon wafer for double device & Middle layer is used.





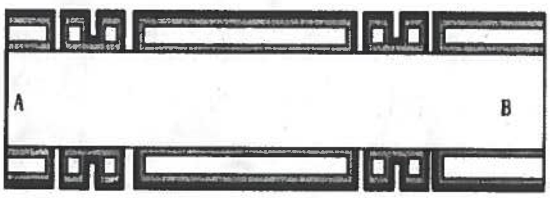
(a)

→ The fabrication process is started with double device layers of Silicon.



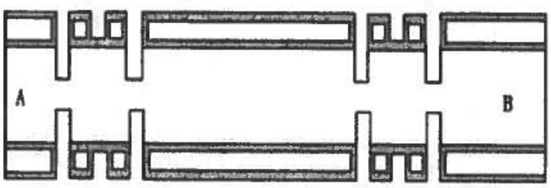
(b)

→ First step is to define the H-shaped beam mass structure in device layer by DRIE using photoresists as masks.



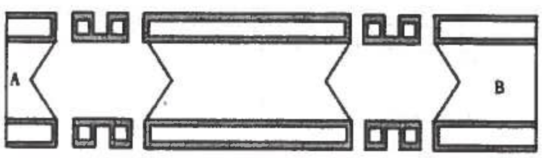
(c)

→ After removing photoresists mask the wafer is oxidized to obtain a Protection layer. Etching is done by Ammonium Fluoride H-shaped structure is protected by SiO_2.



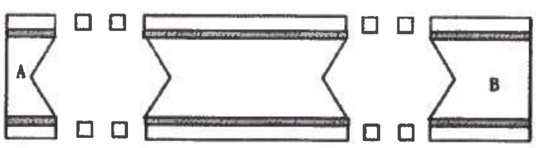
(d)

→ Remaining photoresist as the mask for both sides are removed by DRIE.



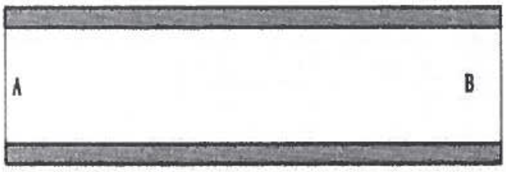
(e)

→ Etching in KOH Solution the H-shaped beam mass are released.



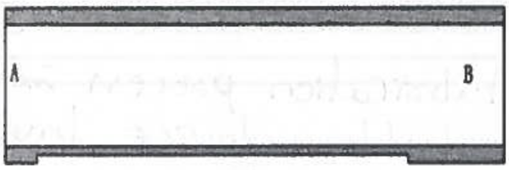
(f)

→ After etching SiO_2 mask in Ammonium Fluoride etchants Middle layer is obtained.



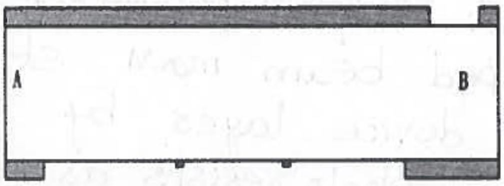
(g)

→ The first Process step of top and bottom layers is to define capacitive gap on one side of wafer. The Process starts with thermal oxidization with 1.8um SiO_2



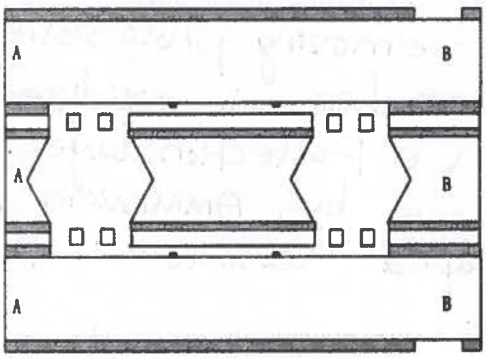
(h)

→ SiO_2 layers are patterned to form shallow gap over a large area to form Capacitance gaps.



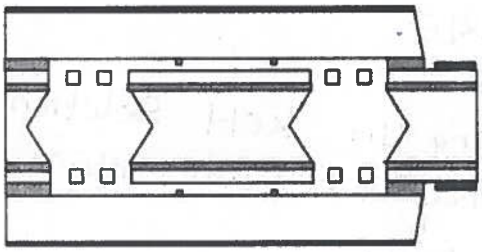
(i)

→ Then bumpers are formed by KOH etching on top and bottom layer. (4 bumpers).



(j)

→ After three layers the middle layer i.e beam-mass structures is bonded with top and bottom Cap wafers in vaccum chamber. bonding temperature is 480'c. Bonded wafer is annealed at 1100'c.



(k)

Wire bonding Cavity etching on
→ both sides of bonded wafers and metallization on both sides of bonded wafer.

Cantilever Vs Bridge structure:-

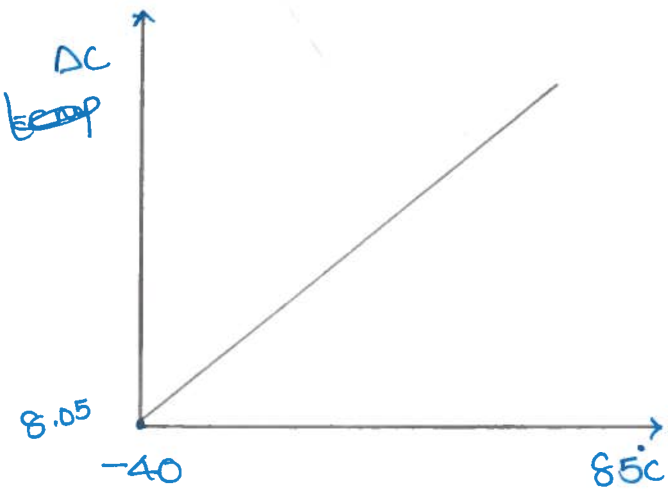
→ In Cantilever structure the damping is within limits and can be tailored to meet the specification by perforation. Hence it can be used in open loop configuration.

→ In bridge type structure air damping is very high and hence force feedback configuration is a must Besides, measures such as sealing is required to control air pressure inside the device.

→ Sensitivity of a bridge type structure is more as compared to the cantilever structures.

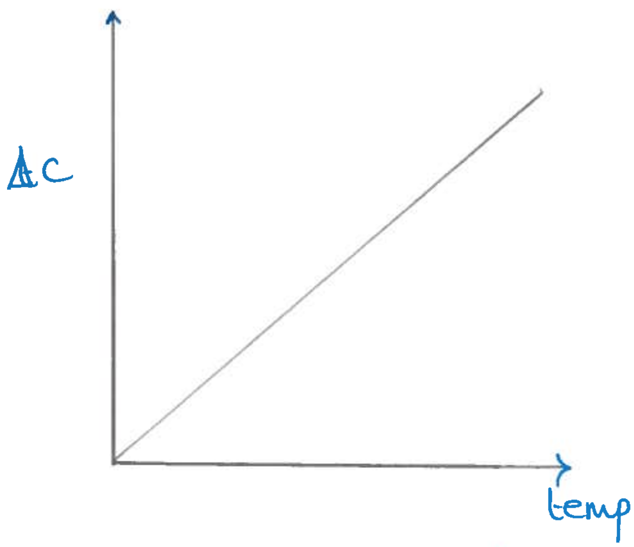
Variation of ΔC on g and temperature

ΔC ~~Volatile~~ variation at 1g



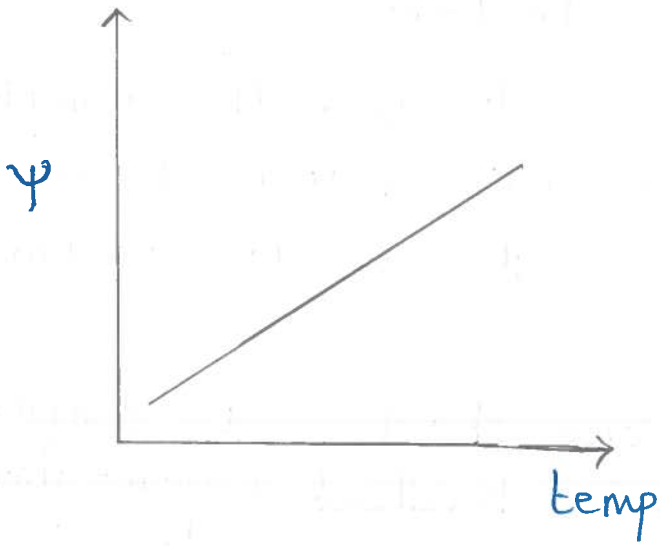
temp	ΔC
-40°C	8.0526×10^{-14} F
+20°C	8.0576×10^{-14} F
+85°C	8.0631×10^{-14} F

ΔC Variation at 10g.



temp	ΔC
-40°C	8.2420×10^{-13} F
+20°C	8.2473×10^{-13} F
+85°C	8.2530×10^{-3} F.

ψ Variation with temperature



temp	φ(ξ)
−40°c	0.729
+20°c	0.898
+85°c	1.03

MEMS GYRO SENSOR:-

Applications:-

→ Automotive applications for ride stabilization and rollover detection.

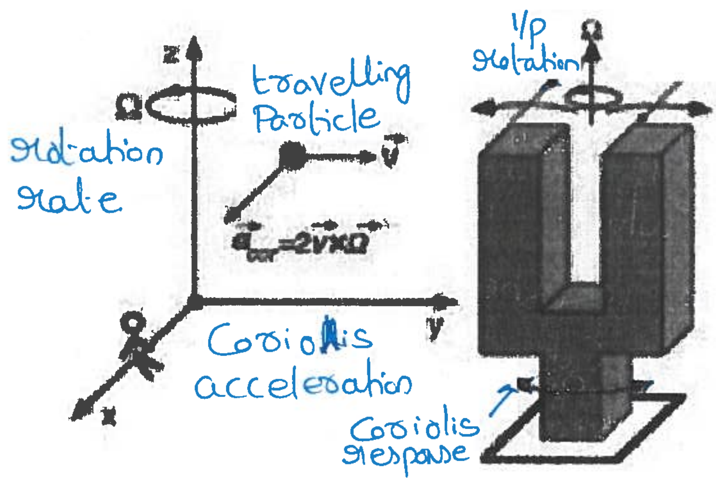
→ Consumer electronic applications such as video-Camera stabilization, inertial mouse for Computers

→ Military applications: Wide range of guided missiles

→ Robotic application

→ low cost Miniature Companion with micromachined accelerometers to provide heading information for inertial navigation purposes.

This sensor has been used from 18^{th} century when MEMS is not available. People used mechanical Gyro which was bulky and too expensive each gyroscope Cost is nearly 10,000 USD to 1,00,000 USD in Some Cases. After the Existence of MEMS micromachined Gyro Scope Cost is 1000 USD. In China they produced cheap gyroscope at cost of 100USD.



Basic principle:-
Transfer of energy between two vibrating resonators Caused by Coriolis acceleration.

Gyroscope measures the change in orientation of an object. silicon micromachined gyros are fabricated on the basis of coupled resonators and they use vibrating mechanical element to sense rotation.

Coriolis Acceleration is an apparent acceleration that arises in a rotation reference frame and is proportional to the rate of rotation.

Force ∝ rotation rate.

This is the basic operation underlying in all vibratory structure gyroscopes.

Performance parameters:-

→ Resolution:- It is expressed in terms of standard deviation of equivalent rotation rate per square root of bandwidth of detection [rotation rate/ $\sqrt{B.W}$]

→ Scale factor:- It is defined as the amount of change in the output signal per unit change of rotation rate. Expressed in Voltage or [degree/ second].

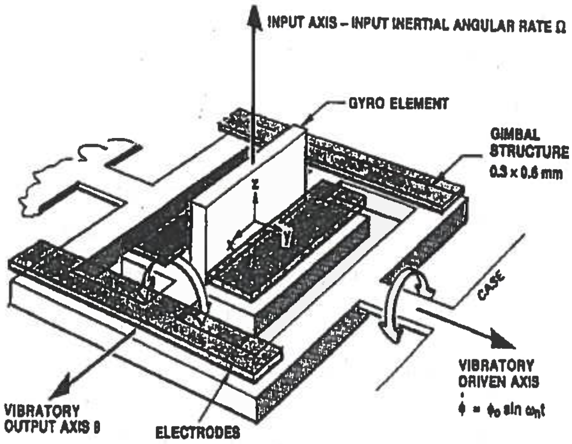
→ Zero Rate output:- Represents output of the device in the absence of a rotation rate.

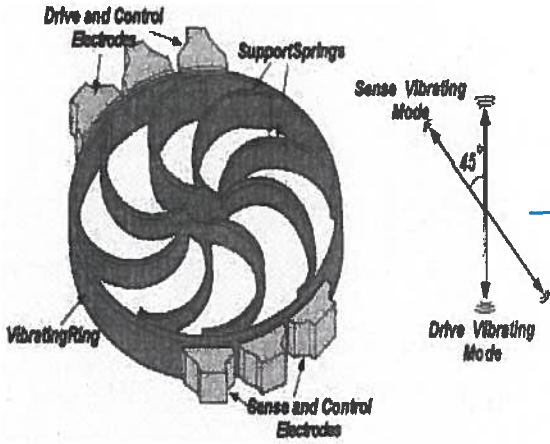
→ Short or Long term Drift:-

It is a peak to peak value of a slowly varying function which influences the output signal of a gyroscope in the absence of rotation.

The short or long term drift means the performance changes with time.

fig a →





→ fig b

In fig a The two gimbals are supported by the torsional flexures.

During the operation inner gimbal is driven at Constant amplitude and frequency by the electrostatic drive electrodes. In presence of an angular rotational rate normal to the device plane, the Coriolis force will Cause outer gimbal to oscillate around it's output axis with frequency equal to the driving frequency and amplitude proportional to the inertial rate.

This structure is highly complicated. As different elements have to be fabricated and it has to be Coupled and fixed in a proper manner.

Fig b Represents the Ring GyroScope. It is very popular gyro in the beginning of 19 century which is not based on MEMS known as ring laser gyro. It is also high Precision and not that much bulky as the Mechanical gyros. laser beam will interfere each other and if you rotate the system the interference pattern will change from the interference pattern defines the rotation of total system.

Vibrating Gyro:-

It is based on concept of tuning fork.

→ Tines are differentially resonated to a fixed amplitude and when rotated, Coriolis force causes a differential sinusoidal force to develop on the individual tines. orthogonal to the main vibration.

→ Tines senses the resonance by electrostatic, electromagnetic or piezoelectric mechanism.

→ By differential bending of the tuning fork stem the force can be detected.

Coriolis Force $\vec{F_c} = k \vec{V} \times \vec{\Omega}$

k = Constant Ω = angular velocity.
V = Velocity

Technologies used for Vibrating Gyro:-

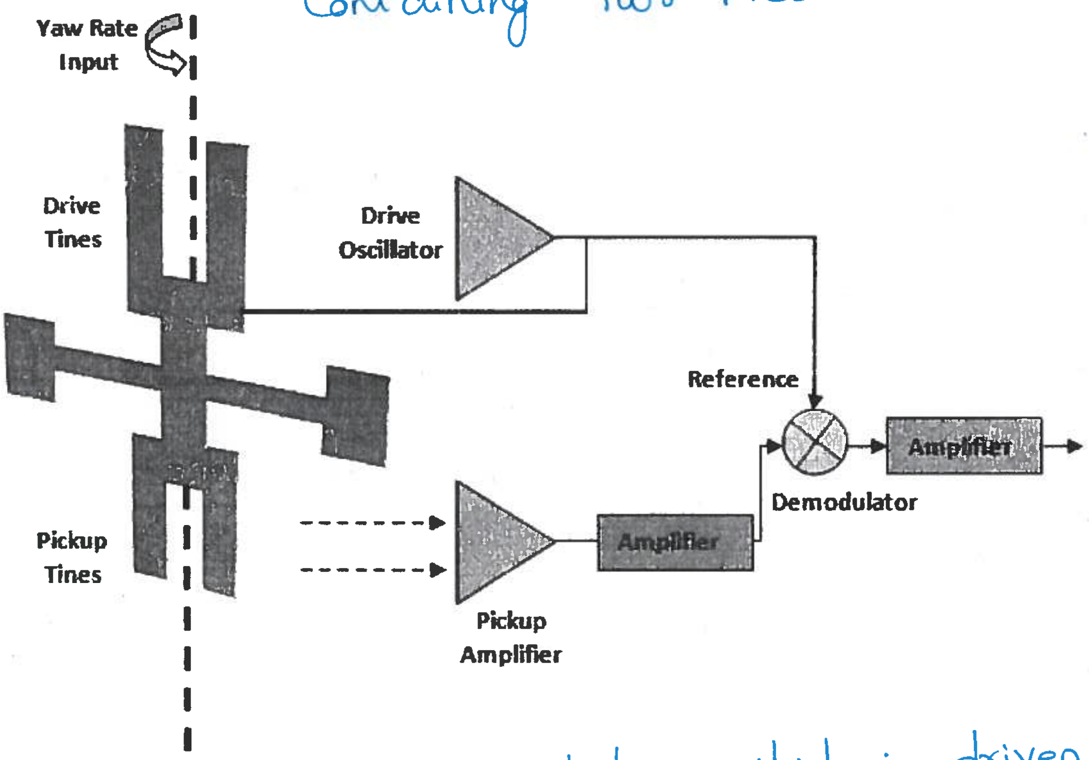
1.) Silicon bulk Micromachining and wafer bonding.
2.) Polysilicon Surface Micromachining
3.) Metal electroforming and LIGA.
4.) Combined bulk - Surface micromachining.

Combined bulk - surface micromachining is used now a days ~~wafer~~ designing of typical type of high precision gyros.

Dual Tuning Fork Gyro chip:-

These instruments use vibrating structures gyroscopes. The main motive of this sensor is to determine the Yaw angle of the vehicle (Vehicle rotation about it's vertical axis). These sensors play a key role in electronic stability Control systems.

The below mentioned fig is a Piezo electric type of sensor Consists of a tuning fork shaped structure. Containing four Piezo elements.



two on top and two below, which is driven at a set of frequency by the drive oscillator. While driving on a straight path the upper piezo elements do not generate a disruption in the frequency because there is no existing Coriolis force. When Cornering the orientation movement Causes the upper part of the tuning fork to leave the oscillatory plane Causing deviation in frequency. The pickup signal is amplified and demodulated to determine the difference between the oscillation frequency and drive frequency.

An additional stage of amplication and processing allows the sensor to generate a voltage proportional to the Yaw rate.

Micromachined Quartz Gyro chips:-

→ Uses Z-cut Quartz Crystal planes with 500µm thick.

→ The miniature dual tuning fork formed by micromachining uses photolithography anisotropic etching of Quartz

→ Natural resonance frequency of tuning fork is 40kHz and dimensions of structure is 11mm x 12mm x 0.5mm length, width and thickness.

→ Upper tines are used for piezoelectric driving for in plane vibrations.

→ lower tines for sensing out of plane vibrations due to Coriolis force.

→ It senses the rotation speed.

Development:- (fabrication)

5 masks required for fabrication:-

Mask-1:- Electrode Patterning (Electrodes are chromium & gold).

Mask-2:- Controlled etching for Microbridges (If the chip thickness is of 500µm the microbridge thickness is 20 to 30µm). The vibration travel through microbridge. transfer of vibration depends on how thin you can make the microbridges.

Mask 3:- Deep Micromachining (Releasing the tuning fork structure). Quartz micromachining.

Mask 4:- Silicon tub formation (Separating each of the Sensors).

Mask 5:- Silicon stencil mask for electrodes over microbridges.

Etching Solutions:-

→ Anisotropic etching for quartz is different from silicon we use hydrofluoric acid, ammonium fluoride and water for etching quartz.

$$HF + NH_4HF_2 + H_2O$$

etch rate at 22°c — 6µm/hr

80°c — 16µm/hr.

→ For chromium etchant:-

Ceric ammonium nitrate + Perchloric acid + water

etch rate at 22°c - 100A /min.

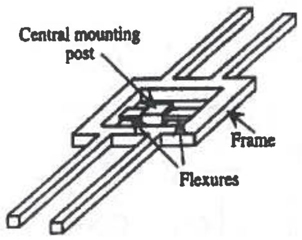
→ For Gold etchant:-

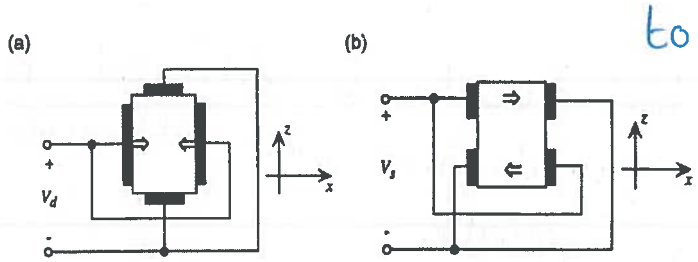
Standard iodine based gold etchant from M/s Transene, USA

etch rate at 22°c - 0.1µm /min

→ Removal of kinks to get Vertical sidewall.

The vibrating microgyroscope has a double tuning fork Quartz structure, the drive lines and sense lines Both are supported by a frame Connected by two flexures to a Central mounting post.





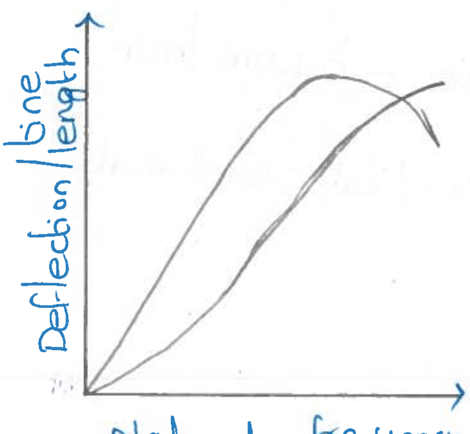
The electrode configuration for the drive mode (a) and for the sense mode (b).

Both the actuation and the sensing mechanisms of the device utilise the piezoelectric effect.

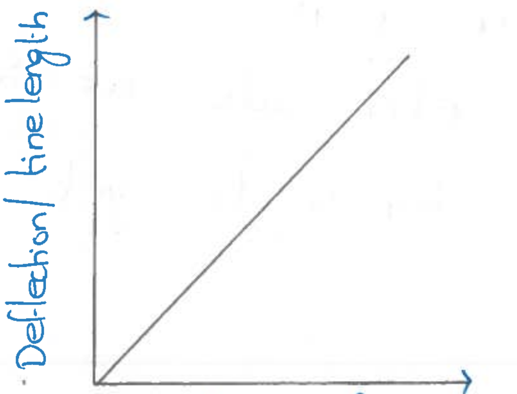
The Configuration of the electrodes on the surface of the Quartz lines is different for the two modes.

The piezoelectrically actuated bending of drive lines is obtained in a plane parallel to the substrate.

The bending of sense lines which produces the electric field to be detected occurs perpendicular to the substrate.



(a)



(b)

a → linearity plot of the lower line responses with rigid stem

b → linearity Plot of the lower line responses with flexible stem.