UNIT-3

INTRODUCTION

- Various kinds of micro sensors which are fabricated using MEMS technologies and which are integrated with microstructures that are fabricated using either bulk micromachining or surface micromachining or LIGA or Stereolithography.
- In this chapter, we are concerned with miniature sensors, so-called *micro sensors,* which are fabricated using predominantly the bulk- and surface-micromachining technologies
- There have been rapid developments in the field of microsensors during the past 10 years, and a sharp increase has taken place in the size of the world market, which has become some billions of Euros today.
- Here, we focus upon the main types of microsensors, which have powered this sensing revolution, together with some of the emerging new designs.

MEMS THERMAL SENSOR

- Thermal sensors are sensors that measure a primary thermal quantity, such as temperature, heat flow, or thermal conductivity.
- Other sensors may be based on a thermal measurement; for example, a thermal anemometer measures air flow.
- However, according to our classification of measurand energy domain, this would be regarded as a mechanical sensor.
- Consequently, the most important thermal sensor is the temperature sensor.

THERMAL DETECTORS:

- So thermal sensors are basically thermal detectors.
- It can detect thermal energy. So thermal detection process consist of two stages.

1. Radiation which is absorbed by the material and after absorption of the material it generates phonons causing the lattice heat up.

2. Because of the heating after absorption of the radiation local temperature will increase and this increase of temperature causes variations in the material properties.

THERMAL EFFECTS:

- So thermal effects are three-fold:
    1. Thermo electric
    2. Bolometric
    3. Pyroelectric
- These are the three basic thermal effects which are utilized in making thermal sensor.

THERMOELECTRIC EFFECT/ SEEBECK EFFECT:

- When two different materials are connected to form junctions and if those junctions are kept at different temperature then a thermo EMF will be generated in across the junctions and this thermo EMF is directly proportional to the temperature difference between the hot and cold junctions.

BOLOMETRIC EFFECT:

- Basically there are certain materials whose temperature, after absorption of temperature the resistance changes.
- All the material will have the temperature coefficient of resistance.
- After absorption of thermal radiation the temperature coefficient resistance will change.
- As a result of which the total resistance of the structure will change.
- That is known as the bolometric effect and the bolometric materials may be of different kinds.

PYROELECTRIC EFFECT:

- There are certain materials which will have the charge accumulation at the surface.
- Now after absorption of thermal energy the dipole movement also changes and because of the change of the dipole movement, the surface charge are going to be changed and that effect is known as pyroelectric effect.
- So these three effects are used in thermal sensors and when those sensors are made on membrane or on some flexures or on some cantilevers then these are called MEMS thermal sensor

THERMAL DETECTORS COMPARISON:

THERMOPILE	BOLOMETER	PYROELECTRICS
• Self generating effect • No need any external supply • No need of chopper • Preferred due to performance cost and reliability	• Need an external bias. • If you need an external bias supply which introduces 1/f noise and this noise makes the sensor less sensitive at low frequency because of that noise.	• Responsibility is very high and faster. • Because it is not two-step process, thermal thermopile sensors are two-step process, this is a single step process. • Needs modulated radiation

DIFFERENCES BETWEEN PHOTON AND THERMAL DETECTORS:

PHOTON DETECTOR	THERMAL DETECTOR
Sensitive and faster	Slower
Single step transduction process	Two step transduction process
Characterized by long wavelength cut off (photons with energy less than Eg produce no signal	Continuous response over a broadband spectral range
Must be cooled for higher sensitivity	Operate well at room temperature

DETECTOR CHARACTERIZATION:

- There are certain parameter based on which we characterize the particular detector.

1. Time constant
2. Responsivity
3. Noise equivalent power
4. Relative detectivity

Time constant:

- Time constant has an important parameter because we always look for a sensor which works very fast whose time constant is low is the faster sensor.

$$\tau = Rth \cdot H$$

- It is a product of heat resistance and heat capacitance

  Where Rth = Detector thermal/ heat resistance

  H = Heat capacitance

Reponsivity:

- The Reponsivity is characterized by the ratio of the detector output and the input power.
- How much input power you are consuming to achieve certain detector output. That is known as the Reponsivity. That is R.

Noise equivalent power:

- Noise equivalent power or NEP, it is basically the minimum detectable power of the detector and is given by the ratio of the noise signal and the Reponsivity.
- That means noise equivalent power if your response, due to the thermal detection and is comparable with the noise.
- So you cannot make out your actual signal due to the thermal effect.
- So even in the presence of noise your request signal will be picked up.

Relative directivity:

$$D^* = [\sqrt{(AD.B)} / NEP]$$

- AD is absorbing area of the detector because you are just making the detector over certain area in your putting some absorber
- B is the bandwidth

THERMOPILE DETECTOR:

- Several thermocouples connected in a series to make a thermopile.
- Why do we connect it?
- Because a particular thermocouple the thermo EMF will be very small, that is maybe say a few microvolts.
- Now if we add the thermo EMF of number of thermocouples in series, then total thermo EMF will be added.
- So we can have a considerable amount of the thermo EMF.
- So that you can sense the minimum change of temperature, if you add like that.
- So that is why that is known as a thermopile
- The thermo EMF generated due to the Seebeck effect.
- Based on the Seebeck effect

$$[\Delta V = (\alpha s.1 - \alpha s.2)\ \Delta T]$$

Where ΔV = Seebeck effect

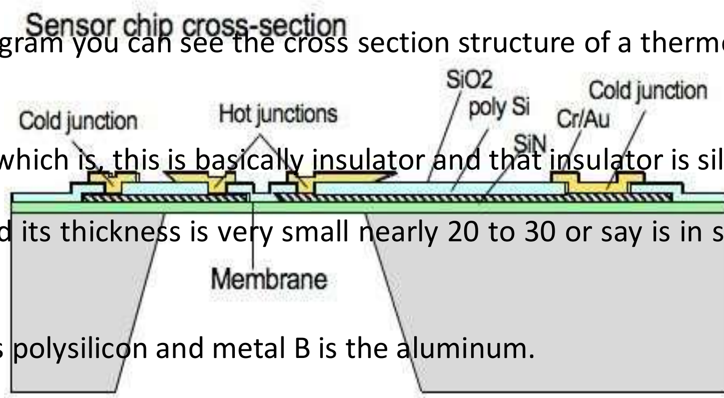
Alpha s are basically the Seebeck coefficient of metal one and metal two or material one and material two

ΔT is the temperature change.

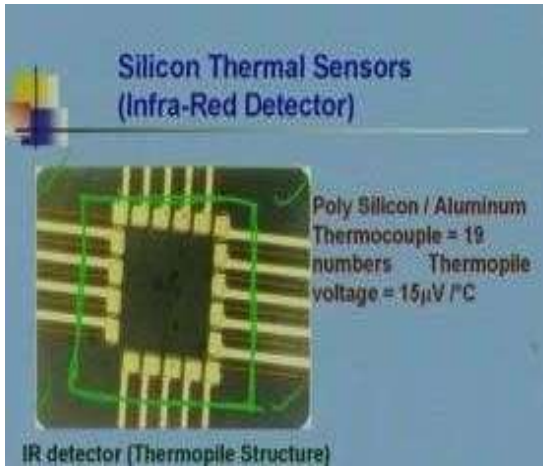
- The hot junctions are supported on thin insulating membrane to reduce the thermal conductivity of the device and are located in proximity to a radiation absorber.
- In some cases black wax is used. A thin layer of black wax is put on the sensing element where the thermal energy is incident so that immediately the thermal energy will be absorbed and that will be transferred on to the hot junction of the thermocouple.

- The cold junctions are on a thick frame which acts as a heat sink. So the temperature difference more, means you will get more thermo EMF.
- Both the hot and cold junction should not be maintained at the same temperature.
- Hot junction should be placed membrane and cold junction should be kept away from the membrane and that is on thick rim which has large thermal mask and which we call it as heat sink.
- A thick layer of absorbing material is necessary to absorb the incident radiation efficiently over a broad spectral range.
- Materials having high Seebeck coefficient and easy to handle are usually chosen to absorb the incident radiation.

SILICON THERMAL SENSOR:



- Here in the diagram you can see the cross section structure of a thermopile on membrane.
- The top layer which is, this is basically insulator and that insulator is silicon dioxide.
- Membrane and its thickness is very small nearly 20 to 30 or say is in some cases 50 micrometers.
- One metal A is polysilicon and metal B is the aluminum.
- Aluminum and polysilicon the thermocouples are fabricated and that are connected in series to get the complete thermopile structure and at the same time you can see here the hot ends, the hot junction, are placed on the membrane.



BOLOMETER DETECTOR:

- Bolometer detectors are based on the change of resistivity of the material in response to the heating effect of the incident radiation.
- Temperature coefficient $\alpha = dR/ RdT$

  R= Resistance with no radiation

  dR= change in resistance

  dT= change in Temperature
- So now bolometer consists of a resistive element constructed from material with a large value of alpha.

Principle:

- A constant current I is driven to the bolometer from a regulated current supply.
- Now the incident radiation produces a change in ΔR of the resistor, after absorption of the radiation.
- The power supply needed to keep the current I constant will adjust the voltage by a small amount ΔV which is given by

$$\Delta V = I\ R\ \alpha\ \Delta T$$

TYPES OF BOLOMETER DETECTOR:

- There are two kind of bolometer;

  1. Metal bolometer,
  2. Thermistor.

Metal bolometer:

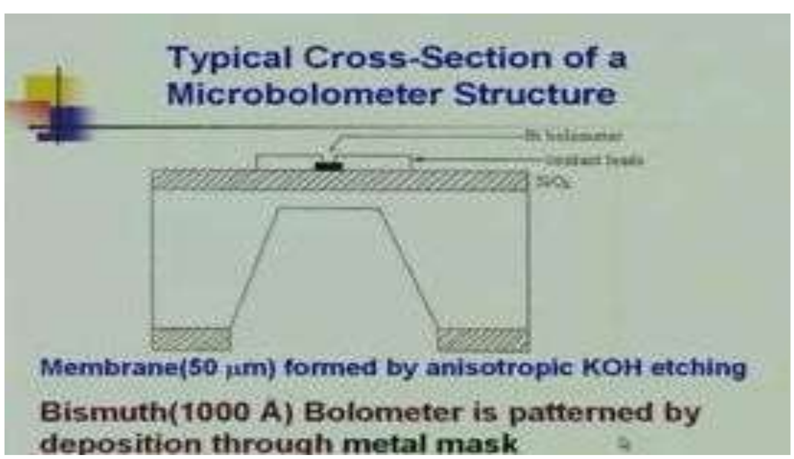
- Metal bolometer material is a metal having positive alpha temperature coefficient of resistance alpha is a positive and examples are platinum, gold, nickel, bismuth.
- These are the four material which have lot of application is metal bolometer.

Thermistor:

- There the material is a semiconductor having negative alpha.
- Oxide mixtures of manganese, nickel, cobalt, that also will have negative temperature coefficient and mixture oxides from manganese, nickel or cobalt are sometimes used for as a Thermistor material also other than the semiconductor.
- Single crystal semiconductors are obviously in many cases used as a Thermistor.

Characteristics of bolometer:

- Reponsivity in this case of bolometer is much higher than the thermopile detectors.
- Bolometer detectors are easy to fabricate than pyroelectric detectors.
- In our study the sensing element (bismuth) has been suspended on silicon membrane to make bolometer detector.



PYROELECTRIC DETECTOR:

- Pyroelectric effect is exhibited in temperature sensitive pyroelectric crystals.
- Temperature sensitive pyroelectric crystal examples are PZT, TGS, and SBN.
- Out of that PZT is a well known material, lead, zirconium, zirconate titanate.
- So it is PZT and these materials will have internal electric dipole moment.
- Change of temperature produces changes in the internal dipole moment and we get a measurable change in the surface charge. So that is the principle..
- Pyroelectric detectors are irradiated with modulated radiation and alternating temperature change delta T will rises and alternating charge delta Q. So by change of delta T by the chopper, you can alternating charge delta Q will get on the external electrodes which is given by

$$\Delta Q = p\ A\ \Delta T$$

p is the pyroelectric coefficient of the material vary from 0.4 to 4 into 10 to power 8 coulomb per centimeters square Kelvin and

A is the area over which the incident radiation is absorbed

MECHANICAL MICROMACHINED MICROSENSOR

- How the mechanical energy is translated into the electrical energy and how that electrical energy is picked up. That is the basis of the mechanical Micro machined Microsensor.

MECHANICAL MICROSENSOR:

- Its physical principle is transformation of mechanical signal into electrical signal for display or further electronic treatment.
- Four important types of mechanical Microsensors:

1. Pressure
2. Flow
3. Acceleration
4. Gyro

APPLICATIONS OF MECHANICAL MICROSENSOR:

- Primary application areas are

  1. Process industry,
  2. Automotive electronics,
  3. Medical devices and equipment,
  4. Household appliance.

- With the increase of safety and comfort requirements, the automotive industry is probably the fastest growing sensor market for applications such as air bags, active suspension control, antilock brake systems, gas injection and combustion control, tire pressure monitoring and others

READ OUT TECHNIQUES IN MECHANICAL SENSORS:

- There are three read out techniques in mechanical sensor:

  1. Piezoresistive read out technique,
  2. Piezo-hall read out technique,
  3. Piezo-junction read out techniques
  4. Deformation and displacement
  5. Resonant structure

PIEZORESISTIVE READ OUT TECHNIQUE:

- Piezoresistive elements are sensitive to the stresses that are induced by deformation in the microstructure.
- Because of the deformation the stresses will be there and because of that stress, if you apply a stress sensitive element which is the piezoresistance, then automatically the change of resistance can be converted into the change of voltage or current.
- So easily you can pick up the signal that is one readout technique.

PIEZO -HALL READ OUT TECHNIQUE:

- Piezo-hall is the observation that an electric filed is developed perpendicular to the current flow is subjected to a shear stress.
- Current is flowing through a sensor element.
- Now if we apply stress an electric field normally to the direction of current to will change and that is basically the hall-effect.
- So when that hall-effect is basically there one magnetic field is hall measurement.
- Piezo-hall means voltage and current perpendicular direction is changing with the application of non-magnetic field, with the application of the pressure that means stress.

PIEZO -JUNCTION EFFECT:

- Here current gain and VBE depends on the applied stress.
- VBE is basically base emitter voltage of the junction or transistor base emitter junction or PN junction.
- The cutting voltage which we call it is that voltage as well as the beta current gain of the transistor changes with the application of the stress inside the silicon material.

DEFORMATION AND DISPLACEMENT:

- Deformation and displacement detection one is the capacity, another is the optical inference.
- Optical inference is the promising for high temperature application and capacity is used even in low frequency application and normal mechanical sensor use the capacitive change that is deformation and displacement.
- If something is deformed, the capacitance changes.

RESONANT STRUCTURE:

- A frequency signal is interesting from the point of view of data acquisition.
- In some case of mechanical sensors, we can sense the mechanical signal with the change of frequency. Frequency change is also electrical.

- A resonance structure you have to make either the tuning fork kind of thing or you may simply the vibrator or resonator you can make out of the material by micromachining and those things we will also frequency will change by deformation.

- If you apply stress inside the material so because of stress change the resonance frequency be also change and if you pick-up that resonance change and there is a relation between stress change versus resonance frequency and that kind of thing you can use for making this mechanical sensor.

MEASURANDS OF MECHANICAL MICROSENSORS:

- The main measurands of mechanical micro sensor are

    1. Acceleration/ Deceleration
    2. Force/Torque
    3. Pressure/Stress
    4. Flow rate
    5. Position/ Angle
    6. Displacement

- Flow rate, flow of fluid may be air may be liquid.

- Position and angle detection by change of the structure deformation position of the some sensory element may change that position or angle, displacement.

- When we sense the acceleration deceleration that is known as accelerometer force.

- Position detector when the angle or rotation change is that is known as gyro sensor.

- Sometimes force or torque also pressure or stress change is also pressure sensor, flow rate change in which sense that is known as a flow sensor.

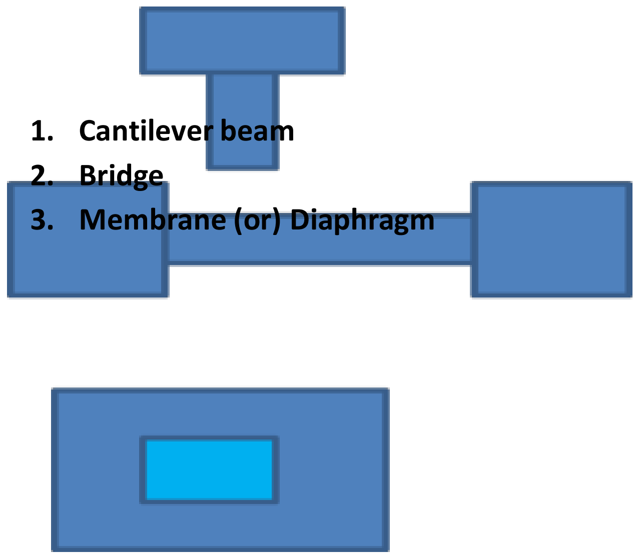
MECHANICAL STRUCTURES IN MECHANICAL SENSOR:

- Micro mechanical structures used in mechanical sensors are:

1. Cantilever Beam
2. Bridge
3. Diaphragm

4. Membrane

1. **Cantilever beam**
2. **Bridge**
3. **Membrane (or) Diaphragm**



- Cantilever is shown here and the cantilever structure has got many applications in case of mechanical structures.
- Then there is a bridge, this is a bridge or it is sometimes called flexure. That means the two support beam is there and in between there is a thin membrane, then it is known as bridge.
- Third structure is diaphragm on membrane. Diaphragm and membranes are similar, but not exactly same.
- A membrane is formed by tension and a diaphragm is formed by stiffness, if a structure exhibits elasticity, it is a diaphragm.

DIFFERENT WAYS OF DETECTION OF MECHANICAL MOVEMENT:

- There are three ways:

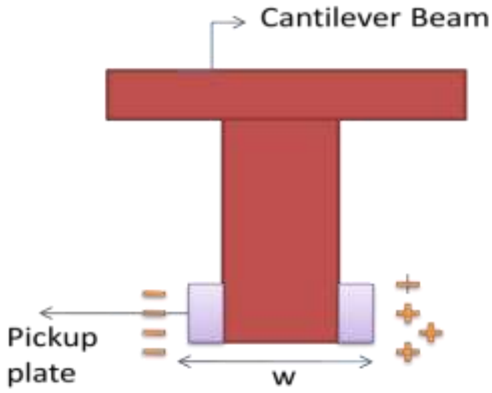
1. Capacitive (electrostatic) pick up

2. Resistive (conductive) pick up

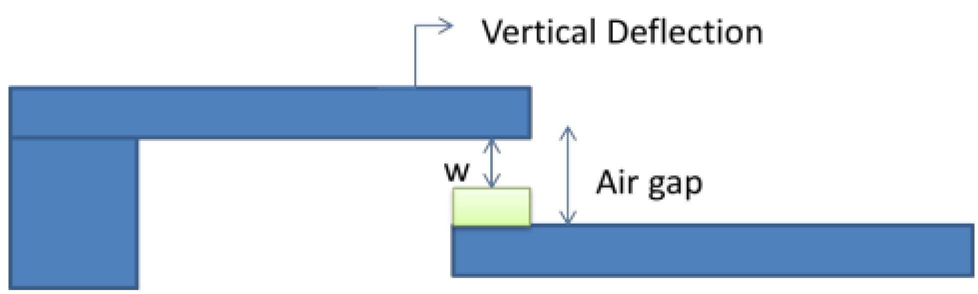
3. Inductive (amperometric) pick up

CAPACITIVE MEASUREMENT OF THE DEFLECTION OF THE SIMPLE CANTILEVER BEAM:

- **Below figure shows the simple cantilever beam**



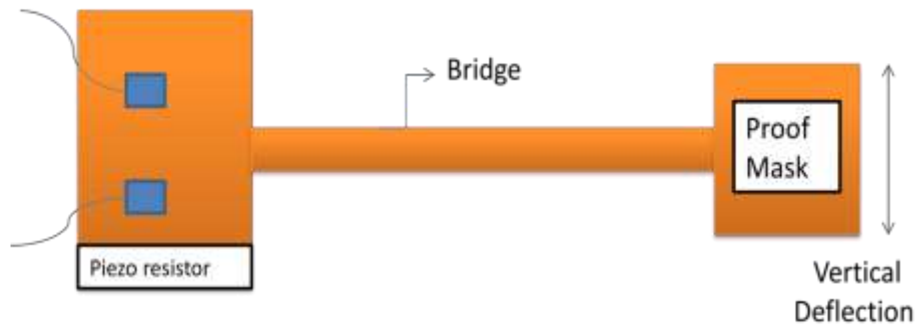
- The Factors that changes the capacitance are- plate separation w, area of overlap A, and dielectric permittivity ϵ.
- If the cantilever beam is fixed, now the pickup plate if it is moves in lateral direction, the overlap area between the electrodes will change and hence capacitance will change.
- In figure 2, if the beam is made to deflect in vertical direction then the gap between the two electrodes will change as a result capacitance changes.



PIEZO RESISTIVE MEASUREMENT OF THE DEFLECTION OF A SIMPLE CANTILEVER BEAM:

- Piezoresistive pickup is explained here.
- You can see here a structure which is having a prove mask and a bridge kind of thing.
- This bridge has got two supports; one is this and another is a one right hand side, another left hand side, two support beams are there and in between that, there is a bridge which is a thin kind of cantilever.

- But cantilever the open end there is proof mask attached to the cantilever and now depending on the vertical moment or motion or pressure on the proof mask the bend the flexure will bend.



- It will deform and if you can make a piezoresistor in this particular location which is highly sensitive location and here this particular region is highly sensitive region.
- If you make a piezoresistor in this region and then automatically the moment of the proof mask top and if vertically you move top and bottom then here, there will be a bend and there maximum stress region the piezoresistance will change and here you can just measure the resistance values.
- if you want to convert the resistance value into a voltage change. So accordingly you can use certain circuit like Wheatstone bridge, similar kind of things so you can get the resistance change convert into voltage change.
- Doped silicon resistance are fabricated which is very common in normal integrated circuit technology and this technology is well established.
- So the cost will be less and doped silicon will have a strain gage factor which is known as K^{gf} and this much higher than that of metal.
- Doped silicon resistor if gage factor is very high, that is being used in strain gage for strain measurement of the heavy structure when it is deformed.
- So that is the K^{gf} and utilizing that strain gage of factor we can make sensors which may have lot of application in mechanical and civil engineering devices.

SINGLE CRYSTAL SILICON AS A PIEZORESISTIVE MATERIAL:

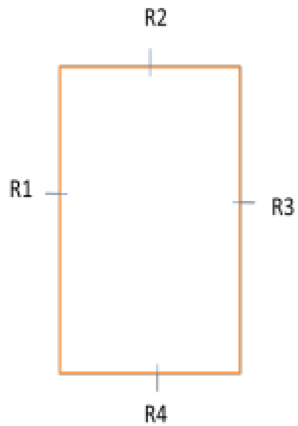
- Single crystal silicon is a very good Piezoresistive material and it is highly suited for the conversion of mechanical deformation to an electrical signal and is used as the basic material for Piezoresistive sensors, for mechanical signals such as pressure, flow, force, acceleration.

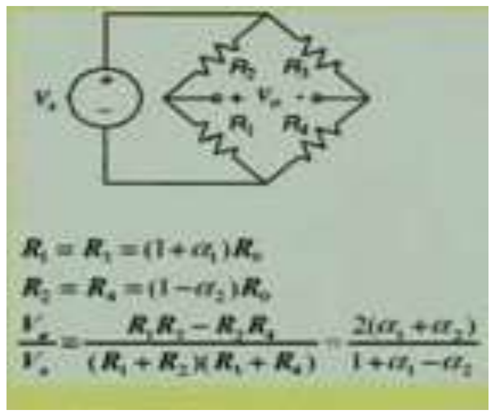
- Silicon Piezoresistive sensors show better performance compared with the classical metal strain gage
- Silicon is a very robust material
- The signal crystal Piezo resistive material for mechanical sensor application is good matching of resistors can be achieved which is particularly useful if Wheatstone bridges are used. Because Wheatstone bridge has to be balanced.

POSITION OF FOUR PIEZORESISTOR ON A MEMBRANE:

- If you want to use a Wheatstone bridge for sensing, the resistance changes in terms of voltage.
- So you have to make a bridge and that Wheatstone bridge you know there are 4 resistances.
- Then those 4 resistances we will give you the non-condition of the bridge if there is no force applied on the sensor.
- That means when sensor is not sensing the measurement, normally the bridge should be balanced.
- So that means the 4 resistances should be exactly matched. But by small change of the mechanical energy, so you have to have a large amount of the output, Wheatstone bridge output
- In order to achieve that, location of the piezoresistance are very important point, important aspect where we will place the resistances.
- 2piezoresistors are oriented so that they can sense stresses in the direction of their current axes and 2 are placed to sense stress perpendicular to the current flow. One will be direction of the current access; other two will be the perpendicular to the direction of the current flow.
- And you can see here the $R^1$and $R^3$are parallel to the opposite edges. But $R^2$and $R^4$are perpendicular to the opposite edges
- So that if there is a deformation on the beam, so that change of since one is parallel, one is a perpendicular, though change will be more.

- So that your pickup signal will be more. The resistance change in the first two piezoresistor will always be opposite to that of the other two, because we have placed in opposite fashion.
- Two are parallel to these; another two is perpendicular to opposite edges so the resistance changes will be opposite.
- In membrane two piezo-resistors can be placed parallel to the opposite edges of the membrane and the other two perpendiculars to the other two edges





MICROMACHNED PRESSURE SENSOR

- So micromachine pressure sensor is a mechanical sensor which occupies the major chunk of the mechanical microsensor, marker the pressure sensor and what are the various ranges of pressure sensor use for various applications it is shown in this table.

Pressure Ranges for Various Applications

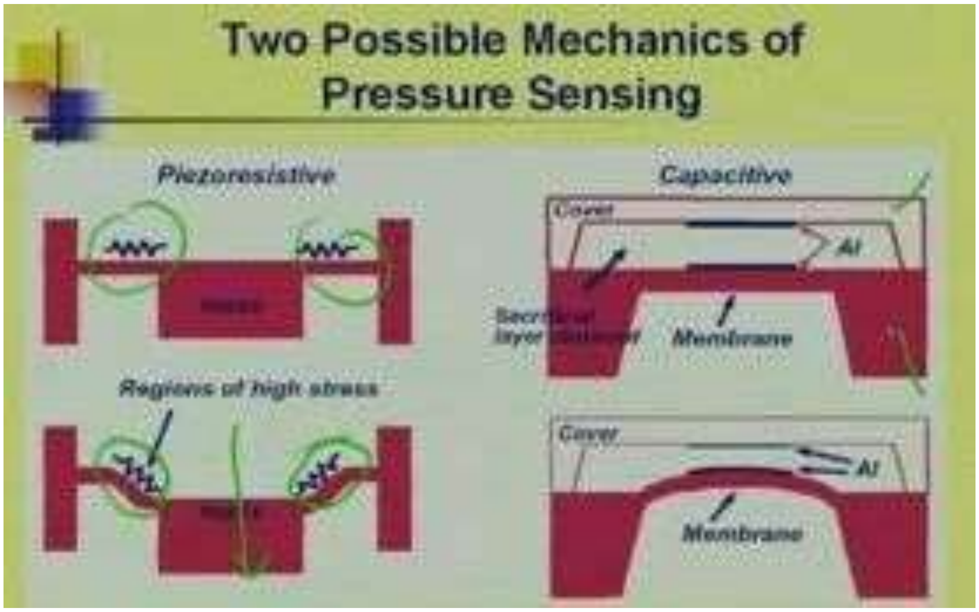
Application	Pressure range (kPa)
Manifold pressure	0 – 105
Barometric pressure	50 – 105
Exhaust gas re-circulation	0 – 105
Fuel pressure	0 – 105
Tire pressure	500
Active suspension hydraulics	20 000
Climate control	50 – 105

APPLICATIONS:

- Applications related to biomedical pressure sensor
- Here is basically the muscle contraction and then it will create a pressure if you pump inside your body.
- So you see here a pressure, you can see here this particular portion a pressure sensor is fixed on that muscle.
- So that during the expansion and contraction of that muscle in how much pressure is created on the muscle that you can monitor and it is basically connected to a catheter.
- So it is a biological sensor, two things we have to remember always.
- One the sense in material are the catheter through which you are guiding the pressure sensor must be biocompatible.
- So you will not harm the biological fluids. You should not react with the biological fluid inside the body. That is known as the biocompatibility
- Intraocular pressure measurement that is also an important application area
- That means in your eye there are fluids flowing inside the eye and the flow of the fluid in the eye, how much pressure is applied on the retina that is very important for perfect view.
- That means if the pressure changes your vision capacity is also going to change. So the eye specialist many times they measure the pressure of the fluid in your eye.

MICROMACHINED PRESSURE SENSOR:

- It is a first type and most matured silicon micromachined sensor with the widespread commercial availability.
- Largest market is in automotive sector with nearly 20 percent growth.
- Piezoresistive and capacitive are the two basic types of micromachine pressure sensor people are now concentrating and also marketing.
- Two common methods to fabricate pressure sensors are bulk micromachining of silicon and surface micromachining of polysilicon.
- Silicon diaphragms are the commonly used microstructure in such sensor. In most cases either silicon diaphragm or the cantilever at the tip or at the bend of the cantilever.



- There are two types of pressure sensor:
  1. Piezo resistive Pressure sensor
  2. Capacitive pressure sensor

PIEZO RESISTIVE PRESSURE SENSOR- WORKING PRINCIPLE:

- Deflection in the diaphragm can be measured using the piezoresistive strain gages located in the region of the maximum strength.
- Strain gages are made from doped silicon and design in pairs with a readout circuit such as Wheatstone bridge.
- Change in strain can be related to the applied pressure(P – Po)
- The relationship between the pressure change and output voltage-

$$V_{out}\ \alpha\ \Delta R\ \alpha_{\pi}\ (P - Po)$$

π Is the piezoresistive coefficient

P is the constant pressure in the waveform in the chamber and

P is the external pressure.

ΔR is the change in the Resistance

V_{out} is the output voltage

- Single crystal silicon is an excellent material for diaphragm because neither creep nor hysteresis occurs.

- Silicon does not have any hysteresis effect. It neither has creep effect, so this is an ideal material for the diaphragm.
- Straightforward measurement of pressure in the range of 0 to 1 megapascal. It is possible with help of the piezoresistive pressure sensor.

CAPACITIVE PRESSURE SENSOR- WORKING PRINCIPLE:

- A capacitive bridge can be formed with two reference capacitors and the two and the output voltage is related to the defection of the membrane delta X

$$\mathbf{V_{out}}\ \alpha\ \mathbf{\Delta C}\ \alpha\ \mathbf{\Delta X}\ \alpha\ \mathbf{(P - Po)}$$

$P_0$is the constant pressure in the waveform in the chamber and

P is the external pressure.

ΔC is the change in the capacitance

ΔC is the change in the Deflection

V_{out} is the output voltage

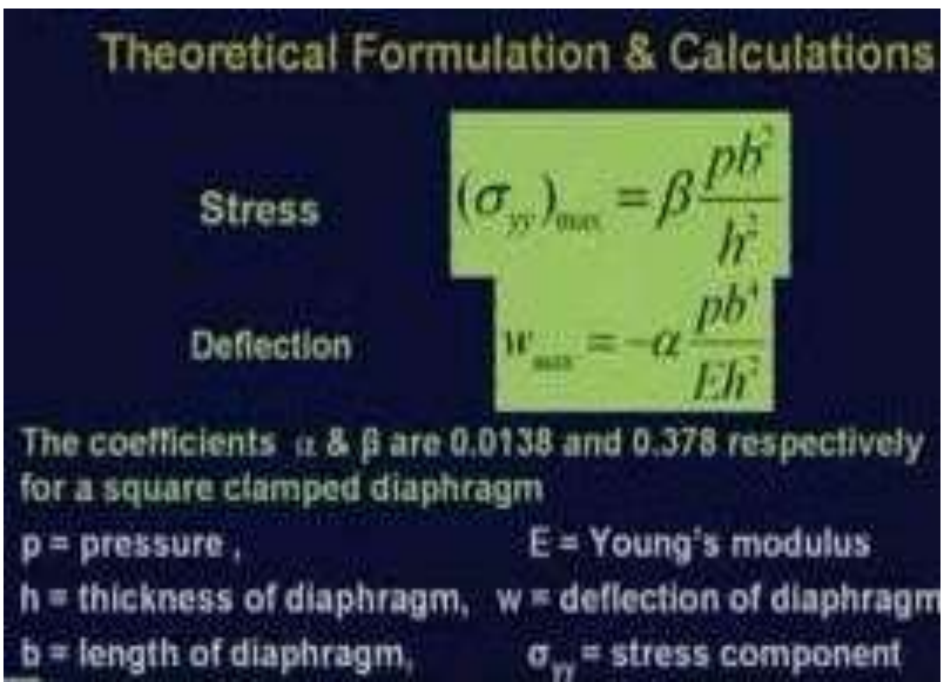
- Accurate positioning of the pickup electrode is a crucial

THREE BASIC PRESSURE SENSORS:

1. One is the absolute pressure sensor where the P_0equal to 0. That means inside the cavity, cavity has to be kept in vacuum.
2. Second one is gage type pressure sensor that is reference to atmospheric pressure and atmospheric pressure is P_0equal to 1 atmosphere. That means inside the cavity where the capacitance is the parallel plate capacitance are fabricated there, the atmospheric pressure is to be maintained.
3. Differential or relative type. There P_0inside the cavity is constant but that value may change, may not be atmospheric pressure. But many other pressure, there you can have a differential or relative pressure.

Table 8.10 Relative merits of capacitive and piezoresistive static deflection pressure sensors

	Advantages	Disadvantages
Capacitive	More sensitive (polysilicon)	Large piece of silicon for bulk micromachining
	Less temperature-sensitive	Electronically more complicated
	More robust	Needs integrated electronics
Piezoresistive	Smaller structure than bulk capacitance	Strong temperature-dependence
	Simple transducer circuit	Piezocoefficient depends on the doping level
	No need for integration	



MICRO MACHINED FLOW SENSOR:

Introduction:

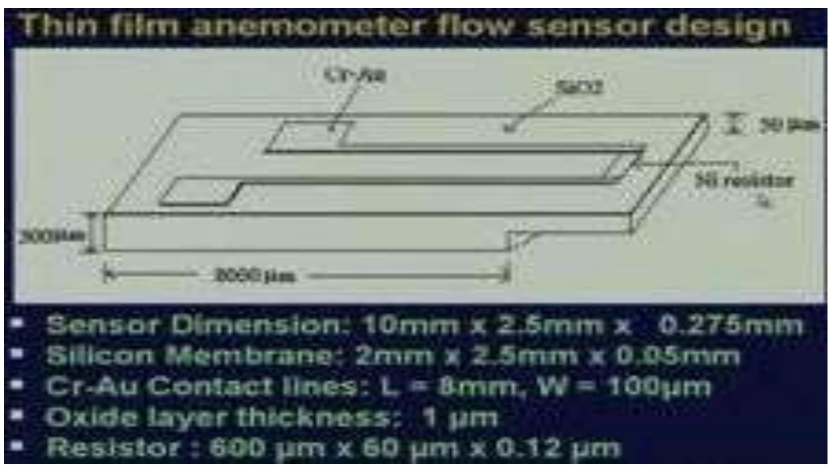
- The measurement of the flow rate of a gas (or liquid).
- So micromachined flow sensors, there are two principle used for realization of micromachined flow sensor.
    1. Micromachined thermal flow sensors based on thin film Anemometer principle.
    2. Micromachined thermal flow sensors based on differential temperature technique
- There are various applications, namely industry automotive domestic and medical.
- Flow measurement that flow measurement of fluid. That fluid may be the air, that fluid may be gas, any kind of gas and that fluid may be the liquid also.
- The bio fluid flow or blood circulation of what the artery or vein is an important aspect.
- So there flow measurement in a big pipe, the water flow measurement is also important and also gas flow about different instrument different system.
- The micromachined flow sensor and the advantages of micromachined flow sensors are many fold namely it will achieve a high sensitivity quick response, small size and low power consumption.
- These are the four basic advantages of micromachined flow sensor.
- Thermal flow sensors are characterized by high sensitivity for low flows and small size.
- If the flow is turbulent or the flow is large, there this kind of thermal flow sensors is not used some other structure may be used.

THIN FILM ANEMOMETER PRINCIPLE:

- So that thin film metal will have temperature coefficient of resistance
- As a result of which the resistance will also change and heating means if you heat a particular metallic film, resistor film, then with flow the temperature of that particular sensor resistive element will change with flow the heat will dissipate from the resistance.

HOT FILM ANEMOMETER TECHNIQUE:

- Single resistor is used as heater and sensing element.
- Fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium.
- First a thin dielectric layer of silicon dioxide of 1 micron is thermally grown on the silicon cantilever.
- Silicon dioxide provides the electrical isolation between the sensing element and bilk silicon.
- A very thin membrane is created and the free hanging end of the cantilever on which the sensing element is placed. That reduces the mass of active area.



ANALYTICAL ANALYSIS:

- A metal thin film resistor and this resistor is powered by constant current source is introduced in the fluid medium.
- That means a thin film resistance which is put into the fluid medium, either it is a gas or it is a liquid.
- So a constant current is sent through that thin film resistance.
- If the sensing element is in thermal equilibrium with its ambient then the input electrical power is equal to the power loss due to the convective heat transfer.

$$I^2 R_w = h.\, A_w (T_w - T_f)$$

h stands for the heat transfer coefficient of the film.

T_w is the temperature of the film and

T_f is the temperature of the fluid.

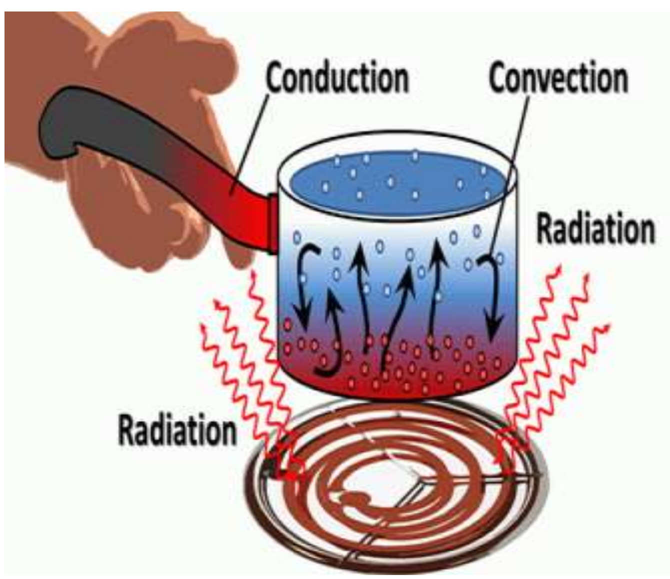
R_w is the resistance of the nickel resistor which is the sensing element

A_w is the heat transfer area

I is the input current

THERMAL FLOW SENSOR: HEAT TRANSFER MECHANISM:

- Heat transfer mechanism can be grouped into three broad categories.
  1. Conduction
  2. Convection
  3. Radiation
- Then 150 degree centigrade then radiation loss is very small and can be neglect because the heat loss due to radiation is governed by the Stephen's Law.
- If the temperature is very small, under that condition you can have this radiation loss is negligible. So only loss is due to conduction and convection
- Difference between Conduction, Convection and Radiation. While conduction is the transfer of heat energy by direct contact, convection is the movement of heat by actual motion of matter; radiation is the transfer of energy with the help of electromagnetic waves
-



Methods of Heat Energy Transfer

- Conduction is the transfer of heat energy by
  - Between particles of objects in direct contact
- Convection is the transfer of heat energy by
  - the movement of fluids(gas or liquid)
  - convection currents due to hot fluid rising and cold fluid sinking
- Radiation is the transfer of heat energy by
  - electromagnetic waves
  - does not involve the movement of matter

	Definition	Example on the Sun	Example on the Earth
Convection	Currents are created when there are differences in temperature and density within a fluid	Convective currents swirl around until they pass through the photosphere	Cooling yourself by using a fan
Conduction	The transfer of heat by direct contact between two materials with different temperatures	NA **(Remember that the Sun has no solid surfaces — it is a "ball of gas.")**	Heat loss through an exterior house wall
Radiation	The movement of heat waves	The way energy from the Sun's core moves to the Sun's surface	Cooking food in a solar oven

Thermal Flow Sensor

Initially laminar flow is ensured using Reynold's Number Re for air as a fluid material

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

= 637.84 (which is < 2300, critical point for a flow transition from laminar to turbulent)

ρ = density of fluid = 1.18 Kg/m3

V = velocity of fluid = 1 m/s

D = diameter of the flow channel = 0.01m

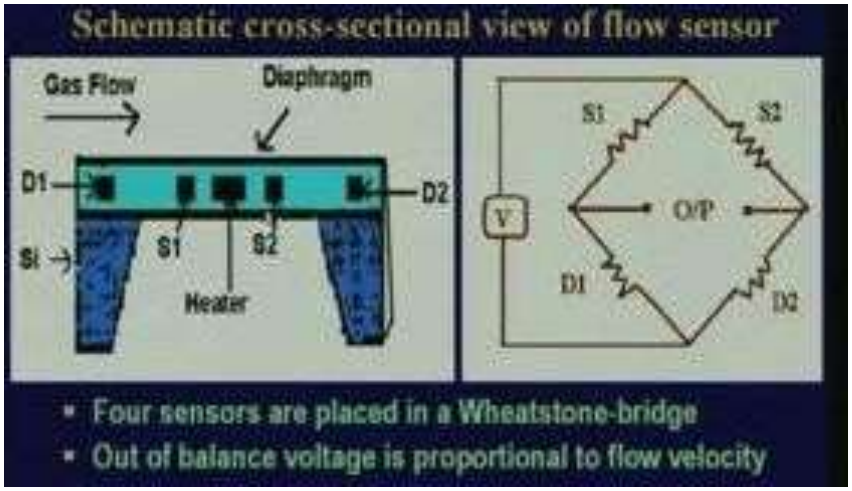
μ = dynamic viscosity of the fluid= 1.85e5 kg/m-s

DIFERENTIAL TEMPARATURE TECHNIQUE:

- In thin film anemometer principle we have used single resistance which is used for heating as well as for sensing.
- But in differential temperature technique there are used three resistors.
- One central resistor that is used as heater.
- That is for heating two resistors symmetrically positioned on either side of the heater for temperature sensing.
- Because, central heater is used for heating purpose and the both side there are two other resistors.
- One will sense both resistors placed on either side will sense the temperature of the fluid.
- Now heat the fluid flows in this direction, so left side heater will be at the cooling condition and during the flow from here the heat will be disappear transmitted to the next heater.
- The temperature difference will depend on the flow of the fluid.
- So that is the differential temperature technique and that will give much more accurate flow measurement compare to the single resistor technique which is thin film anemometer technique.
- So here as the fluid flows over the sensor surface it cools the upstream resistor.
- This is up left side is the upstream resistor and right side is the downstream resistor. It cools the upstream resistor and heats the downstream resistor downstream is this one.
- If the flow direction is that so the upstream resistors will be cooled down and downstream resistor will be heated up.
- The difference of the downstream and upstream temperature depends on the flow velocity and can be detected by a Wheatstone bridge.

DESIGN:

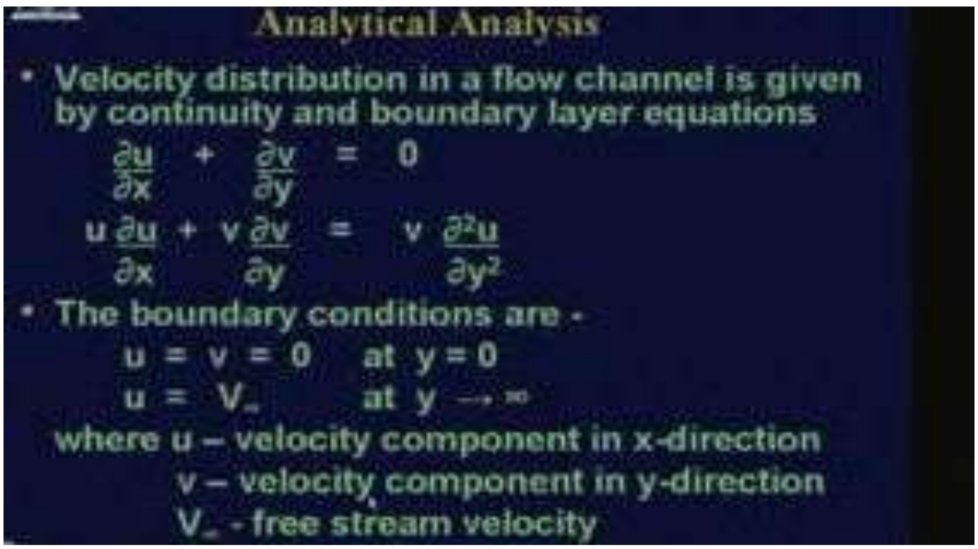
- This is the membrane structure basically here you are going to measure going make 4 resistances D1, D2, S1 and S2.
- Similarly almost resistances you have made and in the central portion is a heater



- In this particular technique the heater and sensing elements are different heater is placed at the middle and the D1 and D2 is a far array from this sensor part far away.
- So that it can measure these two resistance will basically the ambient resistant, it will measure and that since we are not going it is far away from the heater, these two will not are not going to change.
- Now this is the D1 and D2 we can call it is a reference resistance and now the S1 and S2 are kept here and here. So when there is steady state and no heater is there. So then all the resistance is D1, S1, S2 and D2 will be the same.
- At the steady state under the ambient condition. No heating will be there, if you are not heating is all kept at room temperature
- Both flow resistance will be equal and in under that condition the bridge will be perfectly balanced; bridge will be perfectly balanced output will be 0.
- Now what is done here the whole, the 4 resistance along with the heater, heater is nothing but is also resistant is put on the silicon nitride is a black region
- If we power the heater, so during the flow from the heater, the fluid will absorb the heat and it will flow in this direction.
- This S1 will be in the cool region and S2 will be in the hot region because the flow is gas flow is in this direction.
- So now when the gas flow will be here, this will be from here the gas is flowing heater from the heater some of the temperature will be transferred into the gas and the gas will be hot and because of the gas this S2 will be at the hot region and this will be the

cold region. Temperature difference will be there and because of that you will have the unbalancing the bridge.

- So one will be the in the cold region other will be in the hot region.
- If the flow is more and more, so then more heat will be transferred into the S2.
- So that the S2 change will be more compared to the S1 chain. So there is a gas flow velocity.
- Depending on that if it is a more so difference of the resistance change S1 and S2 will be more and more.
- So accordingly bridge will be more and more unbalanced if you estimate.



FABRICATION STEPS:

Stating material: Two inch diameter double side polished silicon wafer, n-type resistivity 4-6 Ω-cm, and thickness 2.5μm.

1. First you have to grow the thermal oxide (dry-wet-dry) 20-120-20min @1100^{0}C and thickness nearly 1 μm.
2. Photolithography of the front side oxide, while protecting backside with photoresist layer.
3. Photolithography for patterning of the backside oxide, while protecting Front side with photoresist layer. This step requires both top and bottom alignments.
4. Thermal evaporation of chromium nickel film to form resistors. The Cr film thickness is 150 Armstrong's and Ni film thickness is nearly 2000 Armstrong's.

5. Photolithography for Cr-Ni Patterning
6. Thermal evaporation of chromium Aurum (gold) l film to form contact. The Cr film thickness is 150 Armstrong's and Au film thickness is nearly 3000 Armstrong's.
7. Photolithography for Cr-Au Patterning
8. Backside etching of the silicon substrate from the diaphragm structure

INERTIAL SENSOR:

Introduction:

- Inertial sensor is a most important type of mechanical sensors belongs to the mechanical sensor group and basically there are two sensors.
- One is acceleration sensors and another is rotation sensors.
- So the inertial sensor basically used for measurement of linear acceleration and angular velocity linear acceleration is measured by accelerometer and angular velocity is measured by gyro sensor.
- Now Micromachined inertial sensors accordingly are classified in two groups.

    1. Micro accelerometer,

    2. Microgyrometer

- Inertial sensors are the second largest sales volume after pressure sensor.
- The major volume of MEMS sensors is a pressure sensor and accelerometers are the second largest sales volume.
- Accelerometer market has been estimated to 609 million in 2005 with a 13 percent CAGR. That is cumulative annual growth rate is 13 percent.
- Every year market is growing and in 2005, it is estimated to be 600 million US dollar market nearly
- On the other hand micro machined gyroscopes the measure rate of angle of rotation.
- There should not be mass produced although at the moment the market of gyroscope is not that much like micro accelerometer.

- Today the automotive application of the inertial sensors is 90 percent of the overall market.
- The 609 million in 2005 estimated target, out of that 90 percent is used by automobile sector particularly airbag deployment and active suspension.
- These are two major application areas in automobile where the lot of MEMS sensors is being used because of its miniature form and high reliability and electronics is established for controller part as well.

Basic inertial sensor:

- Basic inertial sensors are accelerometer and gyro sensor.
- Accelerometer measures acceleration, velocity, displacement.
- On the other hand in case of gyro it measures rotation rate and that is axis and angle of, here in the accelerometer displacement similarly here it can locate the angle of a particular device or system in which angle it is located it can easily measure by the gyro

Application areas of inertial sensor:

- So the 4 major application areas of the inertial sensors are
    1. Automobile
    2. Aerospace
    3. Missile
    4. Robotics

OTHER APPLICATIONS:

- **Consumer applications:**

  1. Active stabilization of picture in camcorder

  2. Head mounted displays and inertial reality.

  3. Three dimensional mouse which is used in many of the computer application and

  4. Sports equipment.

  5. Also the house hold consumer applications are electronic toys, washing machines etc

- **Biomedical applications** are also there for inertial sensors, particularly for activity monitoring.

- **Industrial applications** are in robotics machine and vibration monitoring.

- **Tracking and monitoring mechanical shock** and vibration during transport and handling of a variety of equipment and goods.

- There is certain high sensitive equipment when you are transporting from one place to other place.

- So you have to avoid the shock or large vibrations that may damage the equipment as well as the balancing part may be damaged.

- So for that you have to use certain some kind of acceleration sensor.

- So that you can properly monitor and track the vibration of the table on which you are transporting the machine from one place to other place.

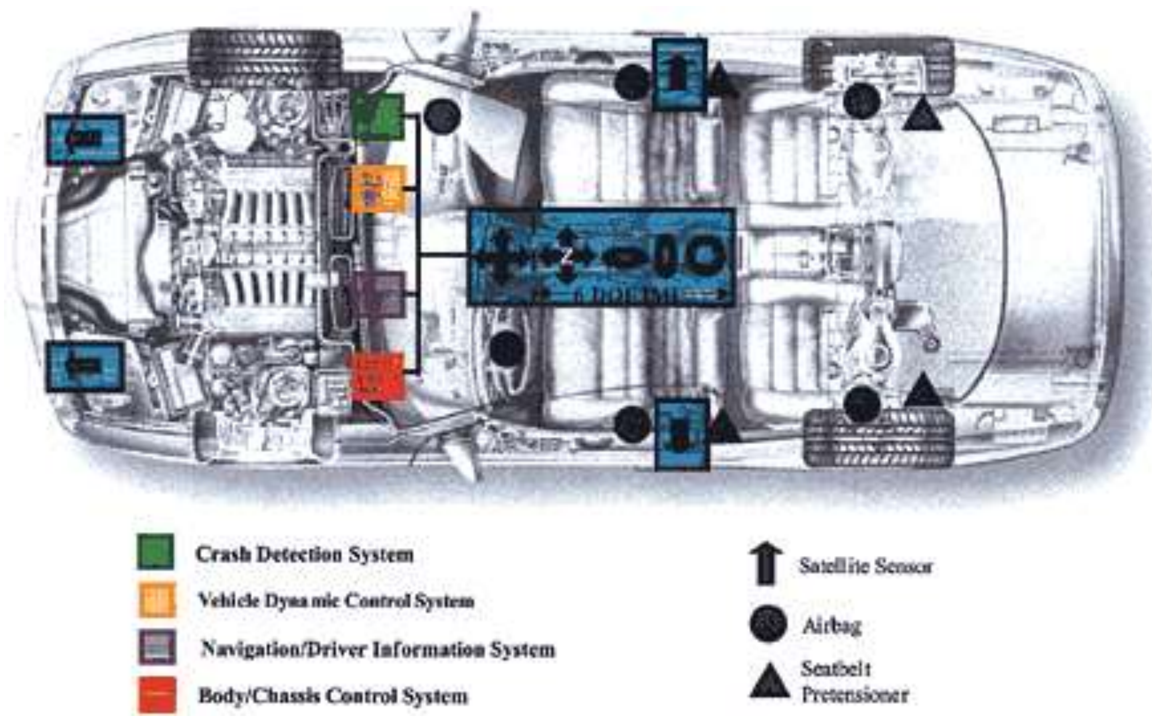
- **Automobile applications:**

  1. Antilock breaking system ABS,

  2. Tracks and control system TCS,

3. Virtual reality VR
4. Airbag deployment wheel motion
5. Active suspension

Inertial sensors in vehicles



Inertial accelerometer sensor: Status and trends:

- Pricing and trends of plus minus 3g accelerometer for active suspension which is one of the major areas of application in automobile active suspension.
- Its average price at in 2002 is a 5 Dollar
- The market will multiply is going to multiply 3 times every year in terms of number of devices with a price reduction of nearly 50 percent per unit.
- Strong need due to extended use of security systems for car stabilization.
- Today although 90 percent application is automobile, overall market for airbag deployment sensing and active suspension.

- Yearly car production of 40 million units estimated accelerometer requirement in 2005 is 180 million with a low cost chip in the range of 3 to 5 Dollar per unit.
- The yearly production of the comb-drive accelerometers is 45 million units. Comb drive is another kind of accelerometers and which are highly sensitive and which can withstand temperature range also.
- 40 percent of the total production is a comb-drive and the production agencies are Bosch, Motorola, Analog devices, Denso, Delphi, and etcetera.
- Pricing trends of the precise low g accelerometer for seismic applications.
- Average price is 8 Dollar in 2002.
- 50 percent growth expected between 2002 and 2005 in terms of number of devices.
- The price decrease will be low due to lack of competition and agreements between the existing players namely Tronics and Microsystems and Sercel.

MAJOR PLAYERS WORLDWIDE:

- **Accelerometers:**
  1. VTI technologies leader with 35 percent market share.
  2. Denso, Delphi-Delco, Analog Devices Bosch are the other challengers.
  3. Possible new comers in the accelerometers are Infineon, Sensonor, STM, Tronics Microsystems, Colibrys, X- Fab are there.
- **Gyroscope:**
  1. BAE, Bosch, Delphi-Delco, Murata and Samsung.
  2. These are the contenders in case of the gyroscope or the rotation sensors manufacturer.

What does an accelerometer do?

- Measurements of static gravitational force. E.g.: tilt and inclination
- Measurement of dynamic acceleration.

  E.g. vibration and shock.

- Inertial measurement of velocity and position

  E.g. 1. Position and velocity, acceleration single integrated for velocity and

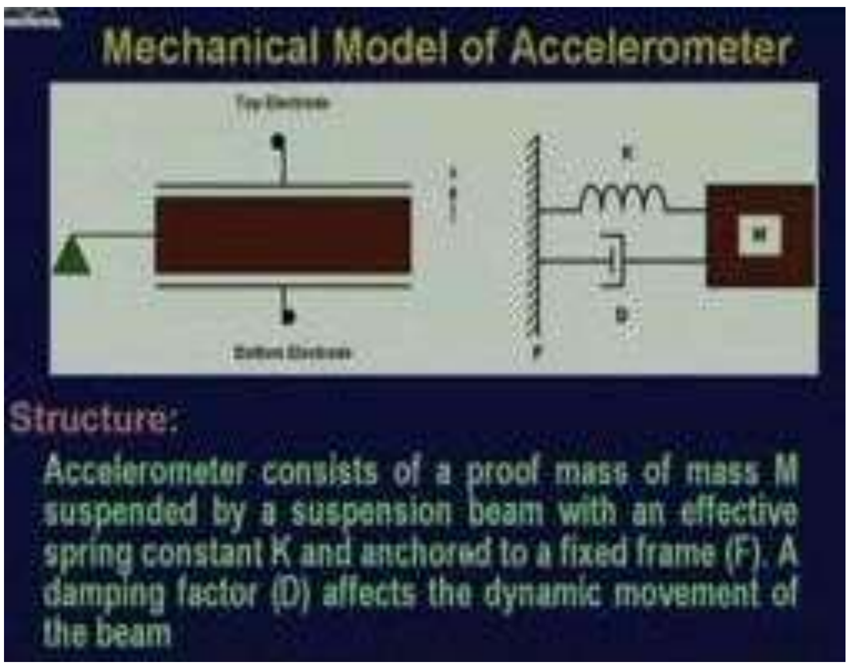
  2. Acceleration double integrated for position

BASIC WORKING PRINCIPLE OF INERTIAL SENSOR:

- They normally need a seismic mass which is also called a proof mass.
- They need an elastic spring a dashpot and a method to measure the displacement of the seismic mass.
- Basically a seismic mass or the proof mass will be there and that proof mass must be connected with an elastic spring and a dashpot is required to protect the system.
- Because if the proof mass moves faster and moves beyond its limit, so dashpot will resist it and it will protect the proof mass before it breaks from the elastic spring.
- So that is the job of the dashpot.
- Proof mass is used to generate an inertial force due to an acceleration or deceleration event and the elastic spring to mechanically support the proof mass and to restore the mass to its neutral position after the acceleration is removed. That is why it is known as the elastic spring.
- The acceleration is measured, at the same time negative acceleration means when very high velocity moving it will come to a rest so that deceleration so both are possible.
- So that the spring which is used to connect the proof mass has to be elastic in nature; should not be plastic in nature.
- That means if the acceleration becomes deceleration it will come to its normal position.
- The deformation which is being taken place due to the acceleration should not be permanent.
- When is in opposite direction its moves, it will come back to its original shape and position.
- That is the elastic spring is essential to hold this proof mass with the body.

MECHANICAL MODEL OF ACCELEROMETER:

- External acceleration displaces the support frame relative to the proof mass which in turn changes the inertial stress in the suspension spring.
- Both these relative displacement and suspension beam stress can be used as a measure of external acceleration.
- General model or mechanical model of the accelerometer. So now the stress developed at a spring will depend on how much the mass is moving which in turn depends on the how much acceleration you are applying.



VARIOUS PARAMETERS OF ACCELEROMETERS:

- Sensitivity
- Maximum operation range
- Frequency response
- Resolution
- Full scale non linearity
- Offset

- Shock survival and
- Off-axis sensitivity
- **Sensitivity** mainly the flexure dimension is one important parameter. If the flexures are very thin so you can have much more sensitivity.
- **Maximum operation range** accordingly you have to design the proof mass and other dimension of the accelerometers.
- **Frequency response** is mainly determined by the dashpot configuration and the proof mass dimension.
- **Resolution** is also the minimum amount of the measurements which can be detected
- **Full scale non linearity** is also because everybody wants in any kind of sensor the linearity so that output change will be exactly near with respect to the input.
- **Shock survival** is another parameter so that although you design an accelerometer

TECHNOLOGIES OF INERTIAL SENSOR:

- Surface Micromachining
- LIGA
- Mixed process
- Bulk Micromachining

TRANSDUCTION MECHANISMS OF MICROACCELEROMETER:

- Piezoresistive pickup
- Capacitive pick up of seismic mass movement
- Tunneling current Pickup
- Resonant frequency pickup
- Thermal pickup
- Optical piezoelectric and electromagnetic principles

GYRO SENSOR

INTRODUCTION:

- Gyroscope is a well-known device which is widely used in navigational purpose.
- And this particular sensor is used from 18th century even from there but that time MEMS technology was not available and people used the mechanical gyro and which was bulky and these sensors that time were expensive also.
- Each mechanical gyroscope cost is nearly starting from 10000 US Dollar to 100000 US Dollar even in some cases.

APPLICATIONS:

- The major application there, those expensive and high precision mechanical gyros are in case of inertial navigation systems.
- They collect the heading information of the aeroplanes that is in avionics, missiles and satellites.
- So those where the major areas we need such kind of sensors for getting the heading information and guided properly in proper direction.
- In the area of automotive applications for ride stabilization and rollover detection.
- Consumer electronics applications are also there. One important application Japanese people are using, that is in their video-camera for video-camera stabilizer in camcorder that using the gyros and those gyros cost nearly 100 US dollar per chip.
- Nowadays in many of the optical mouse for computer they use also gyros; miniature gyros.
- Lot of applications is there in robotics. Because in robotics there are lots of moments, rotations are there. Different parts of a robot and we have to give the control moment of the parts with particular rotation.

- Now days there are a great demand of gyros for missile technology which is basically the military applications.

- Because in a guided missile how much in what acceleration it will move and not only that, if you want to hit a target, then how much rotation, how much inclination you have to apply, so that it will take a definite path to hit an object. So that monitoring is necessary then you need gyros also.

BASIC PRINCIPLES OF MICROGYROMETER:

- It 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.

- There will be two systems; one for driving, another is for sensing.

- So in that two systems we have to have separate arrangement for resonating.

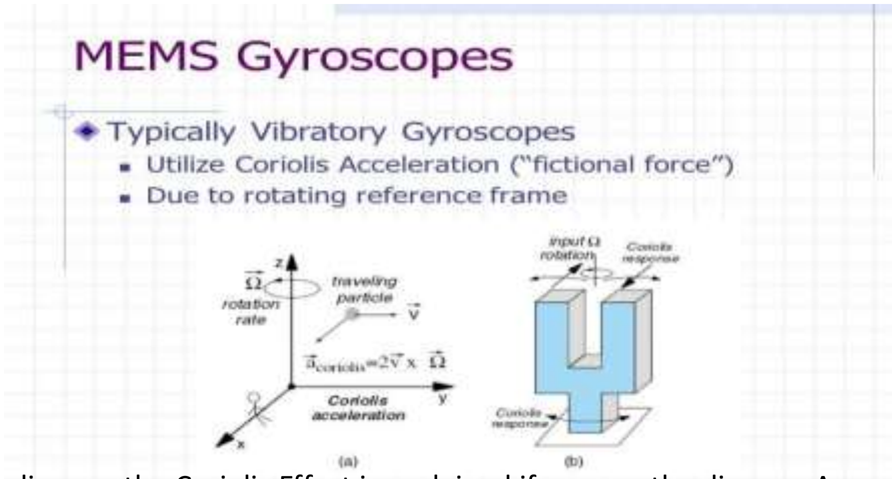
- Some vibration will be given to particular parts or particular the electrodes and then due to the rotation, another force will be generated.

- That also will vibrate and that is again you have to arrange for pickup of that vibration which the resultant vibration is dependent on the rotation or angular velocity and angular moment of the system.

- The basic principal behind the gyros is transfer of energy between two vibrating resonators caused by Coriolis acceleration. The Coriolis acceleration is an important aspect in case of gyro action and gyro designed or gyro simulation.

- This is basically an apparent acceleration that arises in a rotation reference frame and is proportional to the rate of rotation. That is the Coriolis acceleration.

BASIC PRINCIPLES OF VIBRATORY GYROSCOPES:



- In this diagram the Coriolis Effect is explained if you see the diagram A.

- So there in X Y Z system a particle which is moving along Y direction with velocity V. Now if it moves with acceleration or there is motion along V, there is a linear motion.

- Now if you apply a rotation of the particle along Z direction, these are rotation rate you have seen here. You can see here these are rotation along Z is omega, that angular velocity in which it is rotates along Z axis.

- Then due to the interaction of linear velocity V, a Coriolis acceleration will be developed and that Coriolis acceleration is along the X direction which is perpendicular two both Y and the Z direction and that acceleration alpha Coriolis acceleration is equal to twice V cross omega.

- So that is the basic idea of coriolis acceleration and this kind of acceleration can be very easily generated in tuning fork structure. So in the B diagram a tuning fork, vibrating tuning fork is shown. Now here if you excite the two times of tuning fork, then these two tuning forks will vibrate in plane.

- That is normal tuning fork vibration if you hit one time, so then it will be some natural vibration along the plane Now if you rotate these tuning forks along the vertical axis, so this is shown by the circle.

- As a result of which Coriolis acceleration will be developed and because of that there is a force which will be generated which is perpendicular to both the driving or in plane vibration and the rotation axis.

- So in plane one of these direction and that is in the direction that you are driving, you are applying force. So now you are rotating the tuning fork. So because of that another vibration will start, that is in this direction.

- As a result of which the vibration will be generated this out of plane vibration. Now that vibration if you can pick up by certain mean and that vibration is dependent on the rotation.

- Now how much angle the tuning fork is rotating, so that can be measured with help of this out of plane vibration. If you can pick up that vibration by some electronics, so that will give you the idea of the gyro or rotation, so this is the basic mechanism of the vibratory gyroscope.

PERFORMANCE PARAMETERS OF GYROSCOPE:

- Now there are certain parameters of gyroscope
- When you pick up a particular device for certain application. Those are
    1. Resolution
    2. Angle random walk
    3. Scale factor
    4. Zero rate Output(ZRO)
    5. Short or Long term Drift

RESOLUTION:

- Resolution of the gyro is expressed in terms of the standard deviation of equivalent rotation rate per square root of bandwidth of detection.

- Degree per hour per root hertz, so that is its unit.

ANGLE RANDOM WALK:

- Gyro one terminology used that is angle random walk. That is a basically it is another terminology instead of the resolution and its unit normally define the degree parts root hertz.

SCALE FACTOR:

- Scale factor of the gyro is defined as the amount of change in the output signal per unit change of rotation rate expressed in volt degree per second. That is the scale factor.

ZERO RATE OUTPUT (ZRO):

- It represents the output of the device in the absence of a rotation rate.
- That is basically normal sensor we call something is offset.
- No input has given, but you get some output
- So here in gyro it is called ZRO or zero rate output. That means you are not giving any rotation and even then if you get some output, so that is a ZRO or zero rate output.

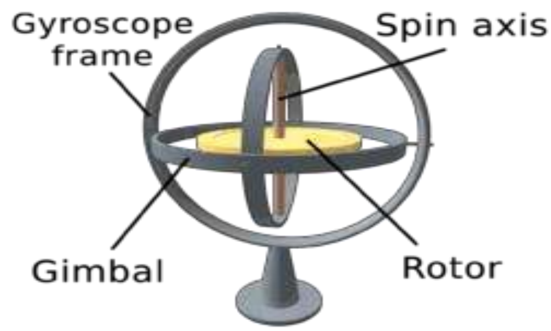
SHORT OR LONG TERM DRIFT:

- This is the 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.

CLAASIFICATION OF GYRO SCOPES:

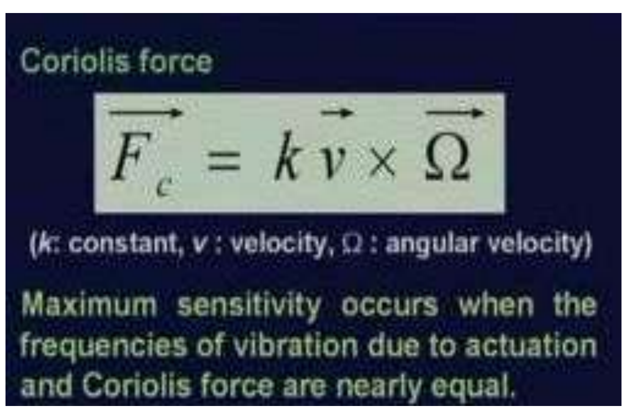
- Gyroscopes are classified into three categories.

  1. Inertial grade,
  2. Tactical grade and
  3. Rate grade.



VIBRATING GYRO TUNING FORK TYPE:

- The vibrating gyro tuning fork type which is developed in our laboratory also using quartz micromachining technology.
- In tuning fork the tines are differentially resonated to fixed amplitude.
- When rotate it the Coriolis force causes a differential sinusoidal force to develop on the individual tines orthogonal to the main vibration.
- This force is detected as differential bending of the tuning fork
- So the tines are drives sensed into resonance by electrostatic, electromagnetic or piezoelectric mechanism



TECHNOLOGIES OF INERTIAL SENSOR:

- Combined Bulk - Surface Micromachining
- Silicon Bulk Micromachining and Wafer Bonding
- Polysilicon Surface Micromachining
- Metal electroforming and LIGA