UNIT-4

INTRODUCTION:

- ☐ As an extension for inertial sensors, today we concentrate on a particular inertial sensor which has got lot of importance and application also, that is accelerometer.
- ☐ So micromachined accelerometer for MEMS and a detail discussion on design aspects, development, packaging and fabrication of MEMS accelerometer for various applications.

MICROMACHINED MICROACCELEROMETERS

CONVENTIONAL ACCELEROMETER SENSOR:

- ☐ Made of bulky and heavy metal parts.
- ☐ Manufactured based on electromechanical principle.
- ☐ Mechanical parts are there as well as electronics is there and each weighs several kilos like requires a higher operating voltage and also current.
- ☐ It also needs careful maintenance and calibration time for heavy mechanical structures.
- ☐ Those are highly expensive because it is not throw-away type.
- ☐ Highly sensitive and it always gives large output

MEMS ACCELEROMETERS:

- ☐ Micro size and light weight.
- ☐ Batch fabricated by advanced Micro fabrication technology.
- ☐ low cost and it is thrown away type.
- ☐ It operates in a low voltage and low current and so the power consumption is extremely small.
- ☐ On chip that is on the device side you can integrate its signal processing circuits replacing majority of the conventional system by the MEMS accelerometer nowadays.

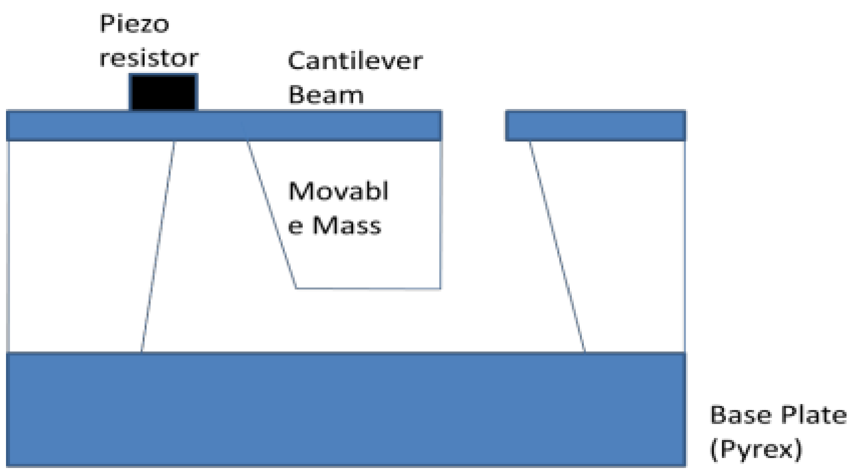
MICROMACHINED MICROACCELEROMETERS:

- There are three broad kinds of micro accelerometers:

1. Piezoresistive micro accelerometer
2. Capacitive micro accelerometer
3. Tunneling current micro accelerometer

PIEZORESISTIVE MICROACCELEROMETER:

- In the below figure, this is substrate and this is the moveable mass and here is the cantilever beam and other is the piezoresistor and in the bottom Pyrex plate is there.
- The substrate is bonded with the Pyrex plate, Pyrex glass.
- So in this structure if you fix the whole thing, this Pyrex glass is fitted rigidly on the body whose acceleration you are going to measure.



- So then on moment of that particular body or system, then moveable mass because of inertia will move either upward or downward.
- As a result of which sense it is fixed on this cantilever beam.
- So its resistance value will change and that will be the measure of the acceleration of this kind of accelerometers.
- So this is a very simple kind of Piezoresistive accelerometer.

PRINCIPLE:

- ☐ The support frame moves relative to the proof mass, the suspension beam will elongate or shorten which changes their stress profile and hence the resistivity of their embedded piezoresistor.
- ☐ These piezoresistor are generally placed at the edge of support rim and proof mass where stress variation is maximum.

ADVANTAGES:

- ☐ Simple in structure
- ☐ Simple fabrication process including their readout circuitry
- ☐ It is less acceptable to parasitic capacitance and electromagnetic interference.

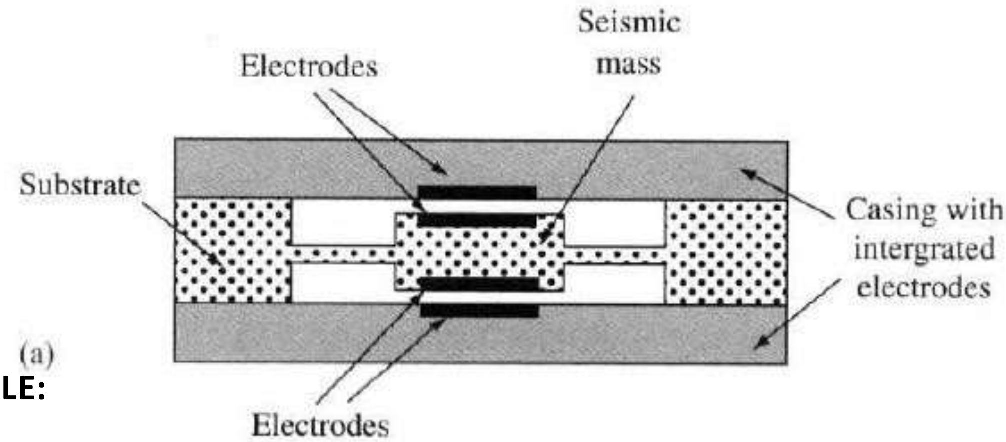
DISADVANTAGES:

- ☐ Large temperature sensitivity.
- ☐ Small over all sensitivity, then capacitive devices A and hence a large proof mass is prepared for them.
- ☐ So temperature compensation circuitry is desirable in this kind of sensor

CAPACITIVE MICROACCELEROMETERS:

- ☐ So now capacitive micro accelerometer, simple structure is here in the diagram you can see.
- ☐ This seismic mass is held with to these structures and capacitance are made from the top surface of the seismic mass and upper cover upper case and another capacitance in the bottom surface of the of the cover plate and the bottom surface of the seismic mass.
- ☐ That means at the top there is a capacitance, and bottom also there is another capacitance.
- ☐ So if you bond the middle structure also with the top and bottom cover plates then two capacitance C^1 and C^2 in one capacitance will increase another one decrease.

- ☐ So because of the proof mass moment the gap if it goes upward to gap of the bottom parallel plate capacitance will reduce and the gap of the top parallel plate capacitance, gap between the electrodes of the top parallel capacitance will increase.
- ☐ So that means there is difference will increase delta C if we take the difference between one another.



PRINCIPLE:

- ☐ The principle is in presence of the external acceleration, the support frame of accelerometer moves from its rest position.
- ☐ As a result the narrow gap between the proof mass and the fixed conductive electrode changes which in turn changes the capacitance form between them.
- ☐ This change of capacitance can be measured using electronic circuit.

ADVANTAGES:

- ☐ Low temperature sensitivity
- ☐ Good DC response and noise performance
- ☐ Low drift
- ☐ High sensitivity
- ☐ Low power dissipation

DISADVANTAGES:

- ☐ Very difficult to eliminate parasitic components

- ☐ Susceptible to (EMI)electromagnetic inference problem which can be address by proper package

TECHNOLOGY OF CAPACITIVE ACCELEROMETER:

- ☐ **Use of bulk silicon micromachining and wafer bonding.**

1. A silicon middle wafer is anodically bonded to 2 glass wafers on top and bottom to form a z-axis accelerometer.
2. The structure will have two different differential sense capacitors with the proof mass forming the middle electrode and metal on the glass wafers forming the top/bottom fixed electrode.
3. Air gap is formed by recessing the silicon on glass wafer.

- ☐ **Same scheme one but using all three pieces made of silicon**

1. This will reduce its temperature sensitivity long term drift, incorporation of damping holes in the proof mass to control damping.
2. So by just damping is also an important phenomenon if you go for designing an accelerometer
3. If damping is not there, so it will take long times to stabilize the thing.
4. Use of second silicon wafer bonded on top to provide over range protection.

- ☐ **Surface micromachining accelerometer offers the opportunity to integrate the sensor and interface circuitry on a single chip.**

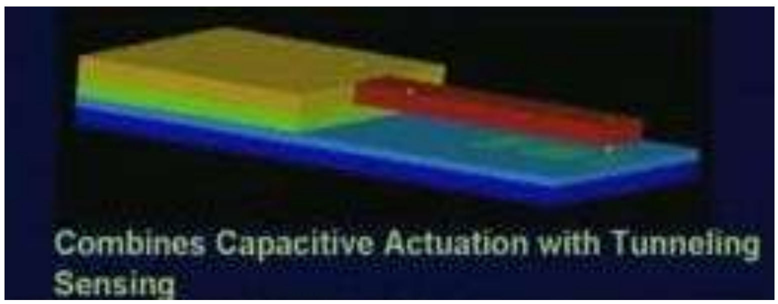
1. It enables detection of very small capacitance variation less than 1femtofarads
2. Sensor and interference electronics can be implemented in a small area.

- ☐ **High precision accelerometer uses a combine surface and bulk micromachining process to obtain large proof mass, controllable and small damping and small air gap for large capacitance variation.**

MICROMACHINED TUNNELING ACCELEROMETER:

- ☐ It has some capability of measuring very low G and its basic principle is like that.
- ☐ It uses a constant tunneling current between one tunneling tip attached a moveable microstructure and its counter electrode sense displacement.

- This kind of accelerometer combines capacitive actuation with tunneling sensing.
- Here, this kind of accelerometer combines capacitive actuation with tunneling sensing.
- There are two pieces; one is the bottom piece which is blue in color and a top red along with this the green color thing.
- In the top layer, there is a micro cantilever and at the end of the cantilever there is a tip. This is known as a tunneling tip indicated by small yellow color
- Now in the bottom plate there are two patches, those are for capacitive actuation.

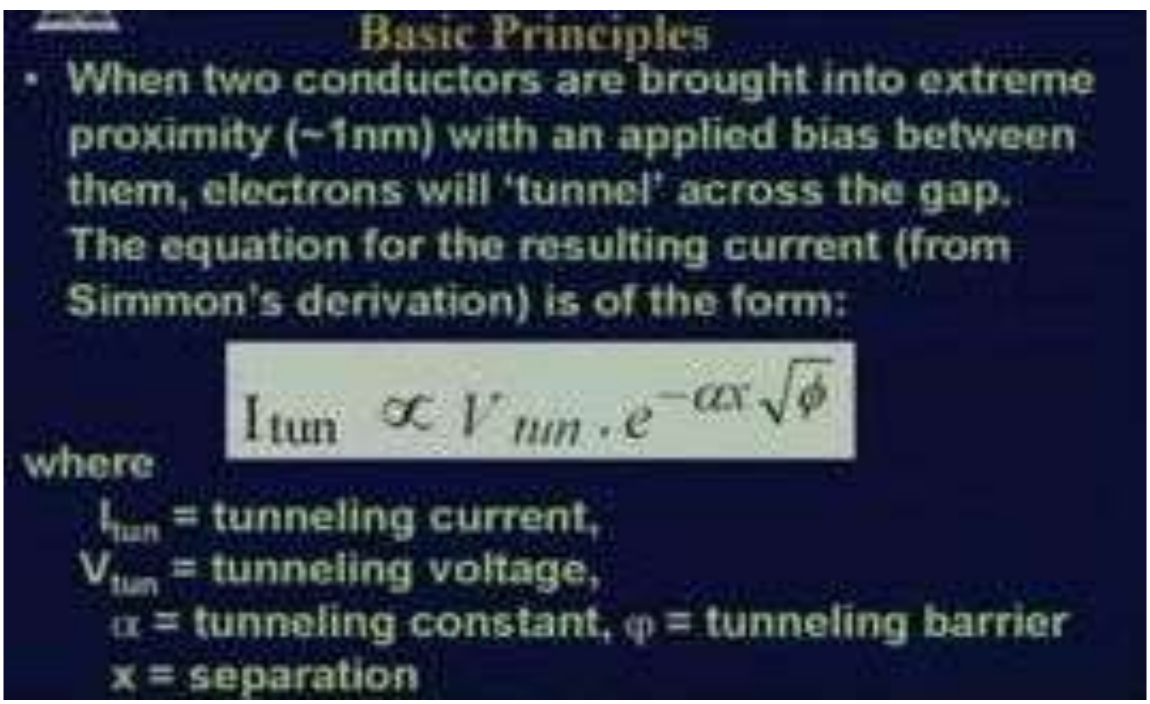


- So by applying certain potential in the top patch and top electrode and the bottom patch, the gap for this particular tip with the bottom piece can be controlled.
- The tunneling is only when the two electrodes, gap between the two electrodes are extremely small.
- Then with application of certain voltage the tunneling current will flow.
- Basically the gap between two electrodes means here the small gap that is a dielectric.
- A dielectric withdrawn current through that you will get the current and this small gap between the top, with a top tip in the bottom the conducting patch should be of the order of few angstrom.
- After that if you move this whole thing or it vibrates the whole structure, then because of the mass of that inertial, of that top cantilever beam, that tip gap between the bottom and top will change and that change is because of the inertia of the top cantilever and then the tunneling current also will change.

TUNNELING MICROACCELEROMETERS:

- As the tip is brought sufficiently close to the counter electrode. Counter electrode is at the bottom few angstroms using electrostatic force generated by bottom deflection electrode. A tunneling current is established and remains constant. If the tunneling voltage and distance between the tip and counter electrode are unchanged is clear.

- Once the proof mass is displaced due to acceleration, the readout circuits responds to the change of current and adjust the bottom deflection voltage to move the proof mass back to its original position. Thus maintaining constant tunneling current.
- Acceleration can be measured by reading the bottom deflection voltage in this closed loop system.
- Now as the tunneling current changes by a factor of two, for each angstrom displacement accelerometer using this principle achieves very high sensitivity and capable of measuring micro g acceleration. This is the basic sensor advantage for this current of accelerometer.
- These devices have large low frequency noise level of the order of 4 milli g per hertz at 0.5 hertz and 0.1 milli g for hertz at 2.5 kilo hertz.
- Requirement of high supply voltage 10 to 100 volt limits.



ADVANTAGES:

- Reduces cross axis sensitivity
- Modeling simplicity

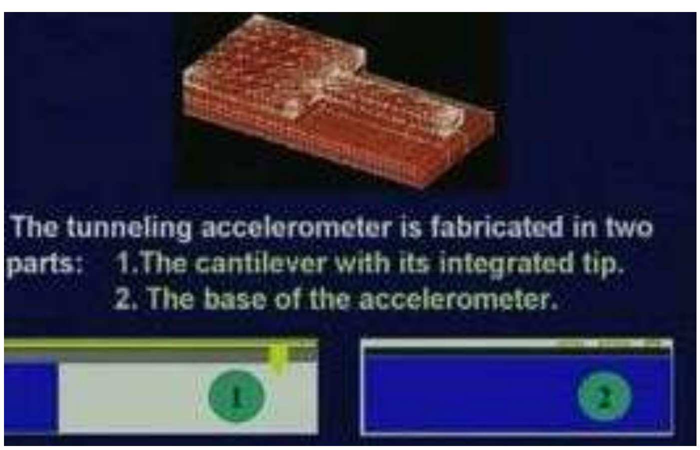
- High natural frequency
- Well-damped bending mode for faster transient response and small settling time
- Low electrostatic voltage requirement for DC reflection and self-test
- High band width
- Less noise effect

APPLICATION AREAS:

- Space
- Defense
- Seismic
- Science and Upper atmospheric studies

STEPS FOR ANALYZING:

- Layout
- Process definition
- 3D model building
- Meshing
- MemMech (mechanical analysis)
- Cosolve (Electromechanical analysis)



ACCELEROMETER PACKAGING:

- ☐ Protection of sensor structure without inducing significant stress or drift.
- ☐ Because package should not produce the additional stress or drift.
- ☐ Proper mounting without misalignment otherwise it may affect the sense direction and overall performance of the device should not affect.
- ☐ Adversely the sensor frequency response or temperature sensitivity.

TEMPATRURE DRIFT AND DAMPING ANALYSIS

INTRODUCTION:

- ☐ Most important point is the temperature drift because the sensing element is made based on piezoresistive sensing and the piezoresistance is a temperature sensitive element
- ☐ By the change in the temperature what parameter is going to change and because of that your output is drifting from the desired value.
- ☐ The second aspect is the damping analyzation.
- ☐ How do you design the accelerometer particularly the upper glass upper cover plate and bottom cover plate as well as the gap between the cover plate.
- ☐ So that the proper damping is given to the vibrating structure (or) vibrating sensing element which is the middle layer.

SENSITIVITY:

- ☐ In a response to differential change of acceleration (Δg), the differential output (ΔV) of an ideally balanced bridge with assumed identical resistance change (ΔR) is given by

$$\Delta V = \Delta R/R\ .V_s$$

- ☐ Sensitivity of the bridge is defined as a relative change of the output voltage per unit applied differential acceleration.

$$S = \Delta V/\ \Delta g.\ 1/\ I_b = \Delta R/R.\ 1/\ \Delta g$$

- For a balanced current bridge temperature variation changes the resistances of all piezoresistor equally, so that output of the bridge remains 0.
- So that means here with temperature the bridge resistance is going to change.
- But if all the resistances change equally, equally means either positive or negative direction whatever it is equally all positive direction then output voltage of the bridge should not change.
- Because it is basically the ratio of the resistances R1 by R2 equal to R3 R4.
- So all the resistances are change equally so ratio remains same, in that case you may not get the change of the output.

Temperature drift is contributed by three factors:

1. Temperature coefficient of resistance TCR: That is because of the change of the mobility of the carrier by with temperature and with doping concentration.
2. Variation of coefficient of piezoresistivity with temperature which is TCP temperature coefficient of piezoresistivity: You are applying pressure or even if you apply acceleration, then stress is developed and because of that the resistance is going to change
3. Variation of elastic constant with temperature: elastic constants means the CR modulus or Young's modulus those values those constant.

TEMPERATURE COEFFICENTS OF PIEZORESISTORS:

- Two Major effects:

    1. Temperature coefficient of offset and

    2. Temperature coefficient of sensitivity

Temperature coefficient of offset:

- This is a temperature change is a common mode effect on resistors and so in an ideal balanced bridge the offset remains 0 with temperature change.

- So now the offset is coming from for what reason, so that means the all the 4 bridges we found that there are total 8 resistances.

- And we assume the when under no stress condition all the resistance of the 4 bridges will be the same to show output voltage will be 0.
- Normally if some offset is there they should not vary with temperature.
- But some variation you are getting because of the change of the contact resistance and the conducting line conductivity with temperature.
- So little bit variation will be there, because of that you will get the temperature coefficient of offset.

Temperature coefficient of sensitivity:

- Great influence because of the temperature dependence of the piezoresistive coefficient.

Temperature dependence of elastic constants:

- These basically are proportionality between components of stress and strain ration of stress and strain is this stiffness constant.
- They are designated by the term C_{hk} where h and k are integers between one and six like the pie 1 1, 1 2, 1 3, 1 4, 1 5, 1 6, similarly here also.

DAMPING:

- So first we have to know what is the damping and what kind of damping we are going to use in this particular sensor
- We are going to use a squeeze film damping.

Squeeze film damping:

- Squeeze film damping means a film means a gap between your sensing element and the fixed plate at the bottom will be maintain and because of the moment of proof mass the gap is going to change and the film is air or whatever thing you give you allow in between the sensing the element and the bottom or top plate that is going to squeeze and that will creative pressure in opposite direction to the proof mass; proof mass of going to go downward.

- Whenever the proof mass for the accelerometer moves perpendicular to its surface near the wall with a small signal oscillation some frequency F the gas in the gap will exert a back force on the mass.
- That is a damping in opposite back force on the mass. The forces have component both in phase and outer phase with the velocity of mass.
- The velocity in phase component is the gas damping force and out of phase component is the spring force.
- Because there are two forces; one is the damping force, another is a spring force.
- So velocity in first component is known as the damping force and velocity {com} the outer phase component is the spring force.

DAMPING COEFFICIENT (N/(m/s)) AND DAMPING FORCE (N/M):

- The damping force is component on the fluid force that is in phase with the velocity oscillation.
- It is computed by integrating over the damping area of the pressure times, the cosine of the phase angle
- The damping coefficient is ratio of this damping force to the amplitude of velocity of mass. The coefficient is measure of dissipative forces of fluid
- Fluid means what either gas or if you use liquid, then liquid or gas normally gasses are used with certain pressure.
- So that is how much dissipative force you are going apply on the film, that is going to be decided by the damping factor.

SPRING COEFFICIENT & SPRING FORCE:

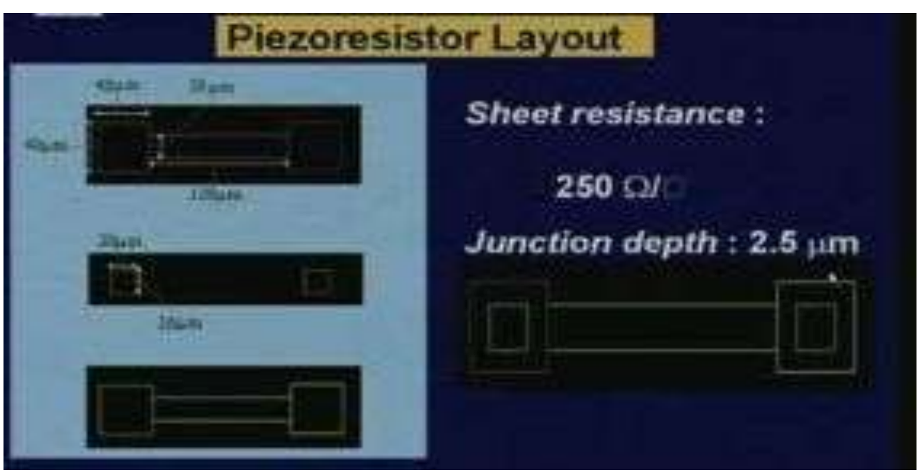
- ☐ Spring force is the component of the fluid force that is the outer phase with the velocity of oscillation.
- ☐ The spring coefficient again is the ratio of this spring force to the amplitude of displacement of mass.
- ☐ This spring force divide by the amplitude displacement of mass is known as the spring constant.

DAMPING ANALYSIS:

- ☐ The Coventorware 2003, one main damping module is there; microelectric mechanic system the damping module.
- ☐ That module we has been employed to find the value of the damping and spring coefficient for the operating environment as well as phase angle between the force exerted by the gas on the device and the device velocity.
- ☐ The damping coefficient will be used to calculate the damping factor of the device.

PIEZORESISTIVE MICROACCELEROMETER TECHNOLOGY

INTRODUCTION:



- Now for the layout of the mask; here first you have to design the resistance, piezoresistance

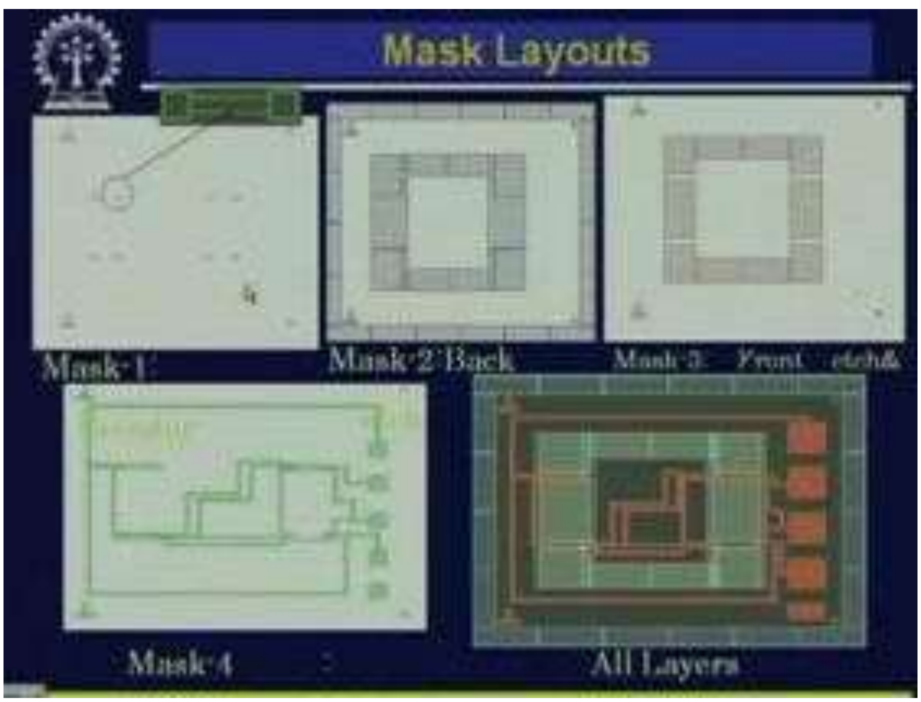
- The sheet resistance value we have assumed is a 250 ohm per square and junction depth is 2.5 micrometer.

- So there you can see the diagram in the left side. So there the width of the resistor we assume it is a 20 micron.

- So now this is the contact area in the second diagram, it is 20 micron by 20 micron.

- It depends on your technology, but here we have taken the robust values of 20 micron by 20 micron so that in future we will not have any problem.

- So the contact is the second diagram is the contact pads and the overall the structure looks like that.



MASK LAYOUT:

- Now after the piezoresistance layout, then we will go for other layouts that mean etching.

- ☐ We are going to etch and metallization so here basically it will be nearly in masks are nearly 4 but another 2 mask are required.
- ☐ So that is for the glass etching mask is required as well as some passivation mask is also required
- ☐ There are for masks:

  1. Resistor mask,
  2. Backside etching mask,
  3. Front etch and contact window,
  4. Metal line

- ❑ These are the four masks and if all the fours masks are overlapped, then it looks like that all the layers together

FABRICATION PROCESS:

WAFER SPECIFICATION:

- ☐ First step you have to specify the wafer and we are going to use silicon 1 0 0 n-type.
- ☐ Because we are going to make resistance p-type diffusion and resistivity of the wafer is 4 to 6 ohm per square, thickness of the wafer 270 micrometer, plus minus 5 or 10 percent variation is there and this is a double side polished and this is 2 inch diameter wafer.
- ☐ In 2 inch diameter wafer the thickness is roughly 280 micrometer plus minus 5 micrometer already tolerance is there.

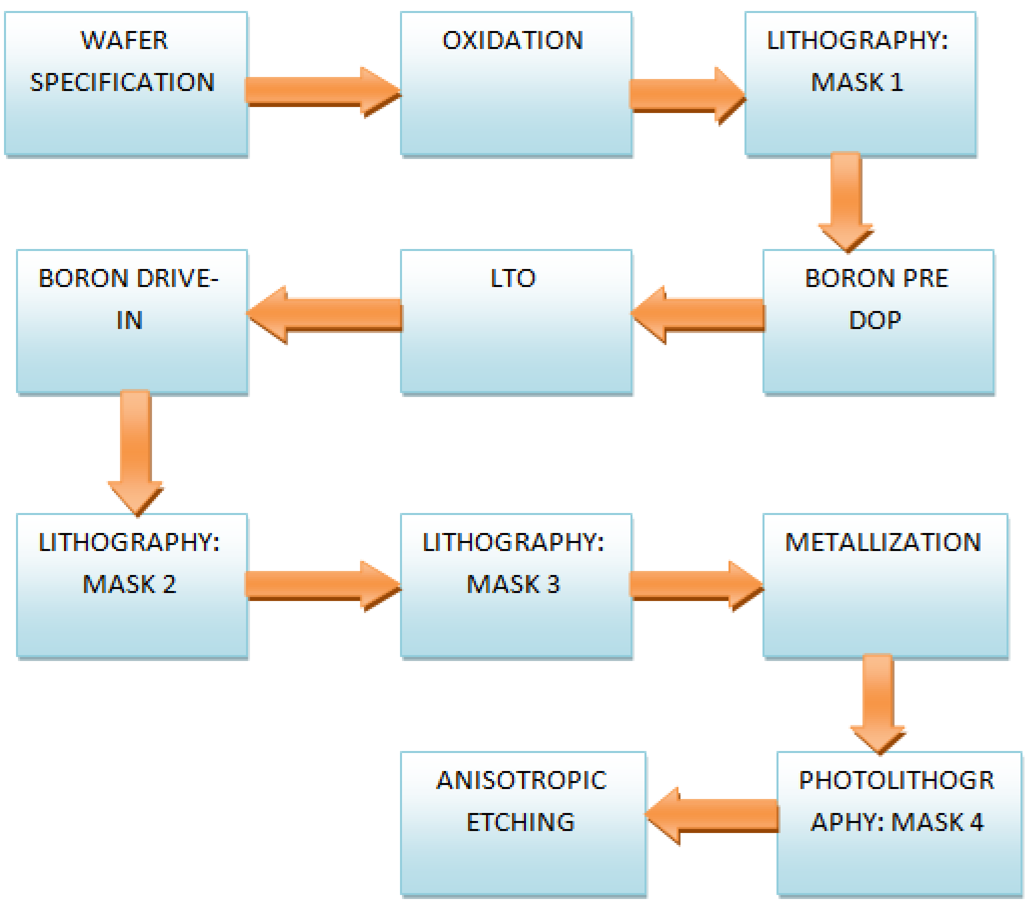
OXIDATION:

- ☐ After taking that wafer we go for oxidation and that is called initial masking oxidation.

- That is 20 minute to dry oxidation; 120 minute wet oxidation, another 20 minutes is again dry oxidation.
- So that quality of the oxide is good as well as it will not take much time and it has been done at 1100 degree centigrade and if you follow this sequence the thickness is expected to be 1 micrometer.

LITHOGRAPHY MASK 1:

- Now after masking oxidation you we are going to use mask number 1. Mask number one is oxides patterning for boron diffusion.
- So oxide patterning for boron diffusion for resistance, source is boron nitrite cake and from there has 2 step we will follow.



- First is pre deposition and then is drive in and boron pre deposition diffusion we follow 15 minute 950 degree centigrade and there the sheet resistance is approximately 90 ohm per square.

LTO (Low Temperature Oxidation):

- So with that step next is LTO. LTO is low temperature oxidation; in particular boron diffusion normally in between pre deposition diffusion and drive in diffusion we follow a step which is known as a LTO low temperature oxidation.
- During the pre deposition diffusion using the boron source, boron nitrate cake, a boron stain that is borosilicate glass a very thin layer of borosilicate glass will be deposited along with pre deposition diffusion. This thin layer of borosilicate glass is very difficult to remove afterwards.
- Boron stain is formed, that has to be removed and that can only be removed if that borosilicate glass is completely oxidized.
- That means we have to go for a very low temperature weight oxidation. 30 minutes, 75 degree C, so with that whatever the borosilicate stain layer is formed on the surface of the silicon, that will be converted into silicon dioxide and after that you give in buffer hydrofluoric acid a dip.
- That mean etch that these boron stain by buffer hydrofluoric acid, then clean it will be the surface boron source from the stain will completely be removed.

BORON DRIVE IN:

- After that you go for boron drive-in and that boron drive-in we follow here 100 minute of drive-in and 1125 degree C.
- That is basically the oxidation and annealing together and because of that you know the impurity which has been inserted by boron pre deposition will reduce to and it will

further go along the depth of the silicon and junction depth will be decided by the boron drive in process mainly.

- And after drive-in is completed, the expected sheet resistance is 250 ohm per square.

LITHOGRAPHY MASK 2 & 3:

- We pattern the oxide for backside silicon etching. That is the mask number 2 is for backside silicon etching.
- So after that, again we go for lithography with mask number 3.
- Mask number 3 is oxide patterning from front and CW is contact window and front side silicon etching.
- So backside lithography we did it but after that in mask number 2, in the previous slide after that we did not go for the complete etching.
- Then subsequently go for because it has double side polished wafer, we go for the mask number3 and lithography there and after lithography then front side silicon is etched little bit.
- Oxide is removed in the lithography then the silicon is etched.

METALLIZATION:

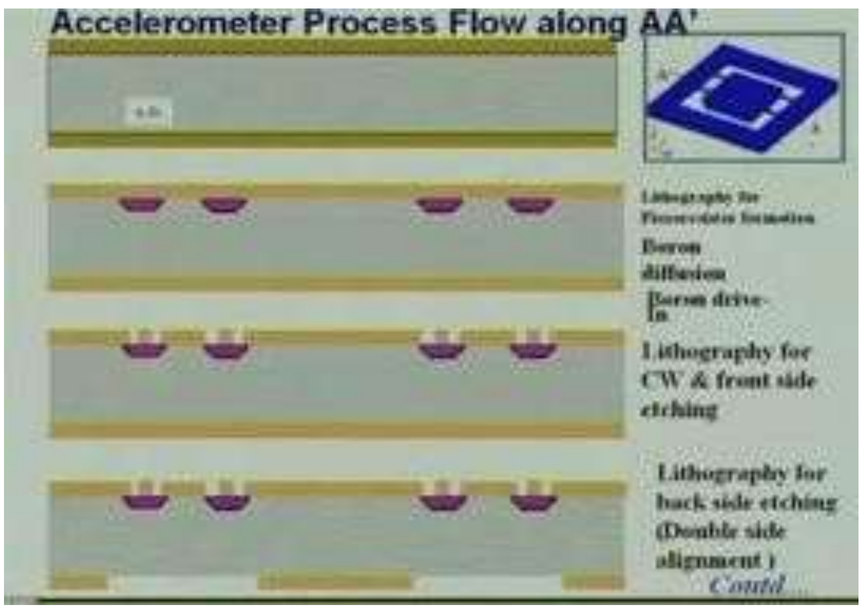
- So few 100 angstrom or say at the most 1 micron or 2 micron you etch it, after that you go for metallization and there aluminum is deposited and patterned and aluminum thickness is 1 micron.
- Then this aluminum will remain on the top and in the top and bottom both places we have defined the regions where silicon is to be etched by using lithography mask number 2 and mask number 3.

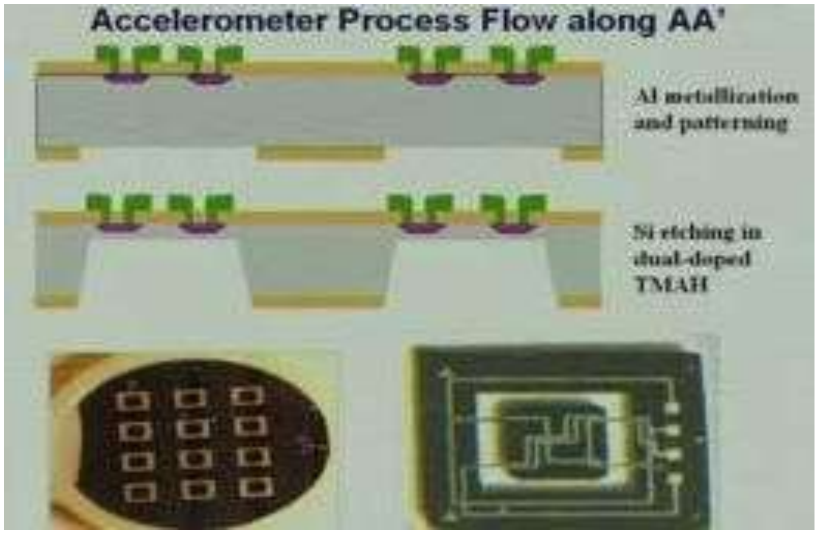
ANISOTROPIC ETCHING:

- Then after metal pattern is over that is the mask number 4 then you go for anisotropic etching. This etching in 5 weight percent dual doped TMAH at 70 degree centigrade, dual doped TMAH etching

- So with that thickness you have to recalculate or re-estimate again how much will be the output voltage of the bridge and it so obviously whatever the stress values we have defined earlier during the design, it will not be the same the flexure thickness is different.

- And exact flexure thickness you cannot get until or unless you go for this doping selective etching or electrochemical etching. Here we what we follow here is a time etch.

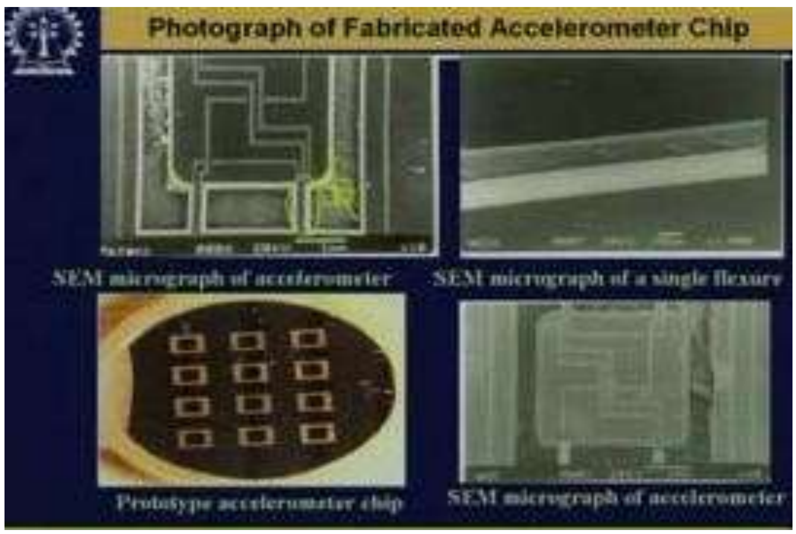




PROCESS:

- ☐ Now initially the end silicon wafer.
- ☐ Now what is done? If the oxide is grown, when you grow the oxide it will be from top and bottom both sides oxide is there, that oxide is grown.
- ☐ In the next step we just lithography for piezoresistive formation. That means front side lithography you have made so that you have open the windows from the top side oxide where the boron is to be doped.
- ☐ Then the boron diffusion pre deposition and drive in deposition we made. So you can the pink color regions are the boron atoms which has already inserted into the silicon wafer.
- ☐ Then we go for the boron drive-in. Initially the pre deposition and drive-in. During the drive in process whatever the groups followed and that will again cover.
- ☐ So that means oxide both front and backside will cover this silicon bear silicon. So that is after boron drive-in it looks like that.
- ☐ Next step is the lithography for contact and front side etching that you can see here the contact as will open and the oxide was etched and it is the front side is defined.

- Next we go for the lithography for backside etching using double side alignment.
- Then in the next step you can go for the aluminum metallization and patterning.
- So aluminum metallization the green levels are aluminum the along the cross section diagram it is again.
- So now you can go for the silicon etching in dual doped TMAH.



SILICON – GLASS ANOIDIC BONDING:

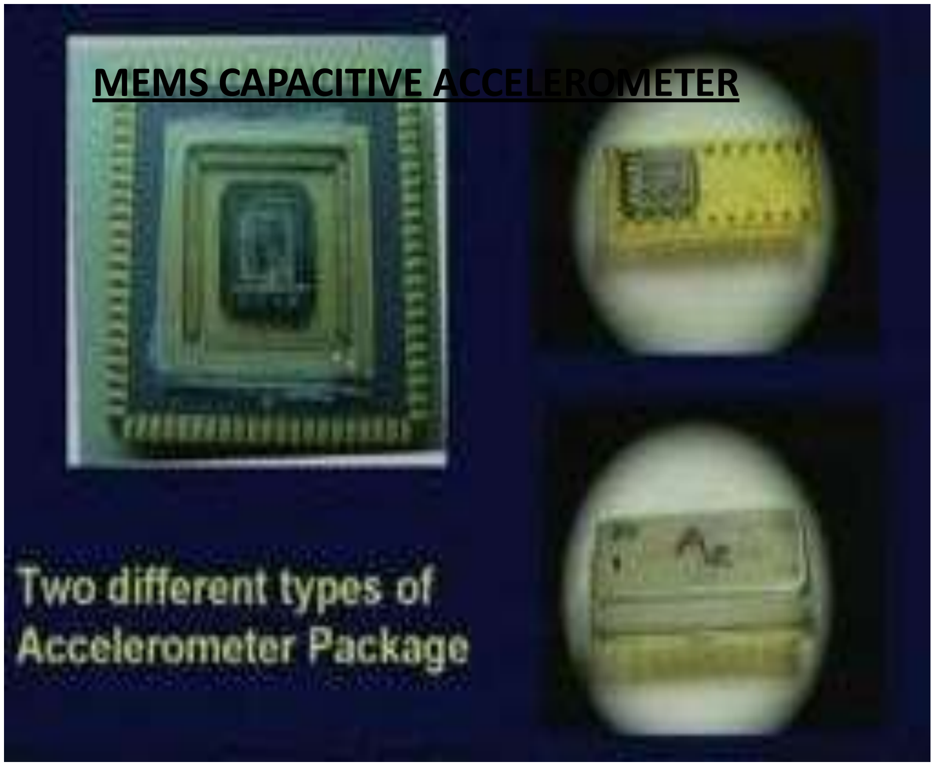
- So here the glass and silicon bonding has been done using the anodic bonding technique and that basically if you apply a voltage of the order of say 500 to 1000 volt and increase the temperature of the glass and substrate to 350 to 450 degree C, then the silicon and glass will be bonded together which we cannot separate. That is known as the field assisted bonding or anodic bonding.
- And this is very sensitive technology in the respect that when you bond the silicon and glass so surface of the silicon and glass is to be extremely clean.

- ☐ If it is not clean, contamination is there or not smooth enough so bonding will not be proper and it cannot be shield.
- ☐ Sodium rich glass should have the equivalent thermal coefficient of expansion as silicon which is 3.253 10 minus 6 per K at 400 Kelvin.
- ☐ So if you go for 400 Kelvin temperature, during the bonding so there the matching of the expansion coefficient is also important because after that when you cool it will crack.
- ☐ The bonding regions will be crack and sealing will not be the proper.
- ☐ So these are the 2 points; one is matching of the expansion coefficient and other is the cleanliness of the surface of both glass and silicon where you are making the anodic bonding.
- ☐ Whole thing is to be done in a vacuum chamber at low pressure.
- ☐ So that the environment hazardous will not be there.
- ☐ In vacuum chamber there are two electrodes where you can apply voltage and at the same time you have to heat the substrate in the range of 3 to 400 degree Kelvin and then if you allow certain time it will be automatically bond it, anodic bonding will be there.

GLASS ETCHING FOR CAPPING LAYER:

- ☐ Since the glass is composed of silicon dioxide, the glass etchants should be HF based solution.
- ☐ Photo resist layer may not withstand long time in the hydrofluoric acid solution
- ☐ Chromium gold metal mask, gold is a metal. So is better solution as the hydrofluoric base solution will not allow you to use the photo resist as a masking material.
- ☐ So the etch rate variation of different concentration of HF solution at different temperature has to be made before glass machining.

MEMS CAPACITIVE ACCELEROMETER



INTRODUCTION:

- Case study for MEMS capacitive accelerometer. That is for generalized application for defense and many other automobile sector also you required such accelerometer.

Design specification:

Design Specifications

Range	±10g
Over Range	30g
Damping Ratio	0.7 to 1.2
Natural Freq.	100 Hz (min)
Non linearity	±1% of FS
Resolution	0.02g (max)
Threshold	0.01g(max)
Operating Temp Range	- 85°C to + 40°C

CAPACITIVE MICROACCELEROMETER:

- ☐ The structure of the capacitive accelerometer is shown in the figure here you can see and this figure has 3 modules.
- ☐ Middle piece is basically the sensing element and it comprises of a proof mass which is also known as seismic mass which can move freely between 2 fixed electrodes i.e. one is held at the top and another is held at the bottom.
- ☐ The bottom piece which is a fixed and a parallel plate electrode is configured; Similarly at the top fixed electrode also there is a metalized plane which acts as electrode.
- ☐ So then the fixed electrode top and fixed electrode bottom will form capacitances with the middle sensing element.
- ☐ Now middle sensing element you can see here a movable seismic mass because of the movement of the object whose acceleration we want to measure.
- ☐ So this proof mass or the seismic mass will move either up or down and accordingly the capacitance between the seismic mass and top electrode and bottom electrode will change.
- ☐ So that change of capacitance will be the measure of your acceleration. That is the capacitive accelerometer principle
- ☐ Now the differential change in capacitance between the capacitors is proportional to the deflection of the seismic mass from the center position.
- ☐ So obviously if the seismic mass which is at the central position, if it moves upward then the gap between the top electrode and seismic mass will be less and the gap between the middle seismic mass and bottom electrode will be more.
- ☐ So that means in one case capacitance will increase, in other case will decrease.
- ☐ So this differential change we are interested so that we can eliminate some of the parasitic things.
- ☐ So the differential change obviously is proportional to the movement or to the g value of the object on which this accelerometer is fixed.
- ☐ So that is the basic idea and basic principle.

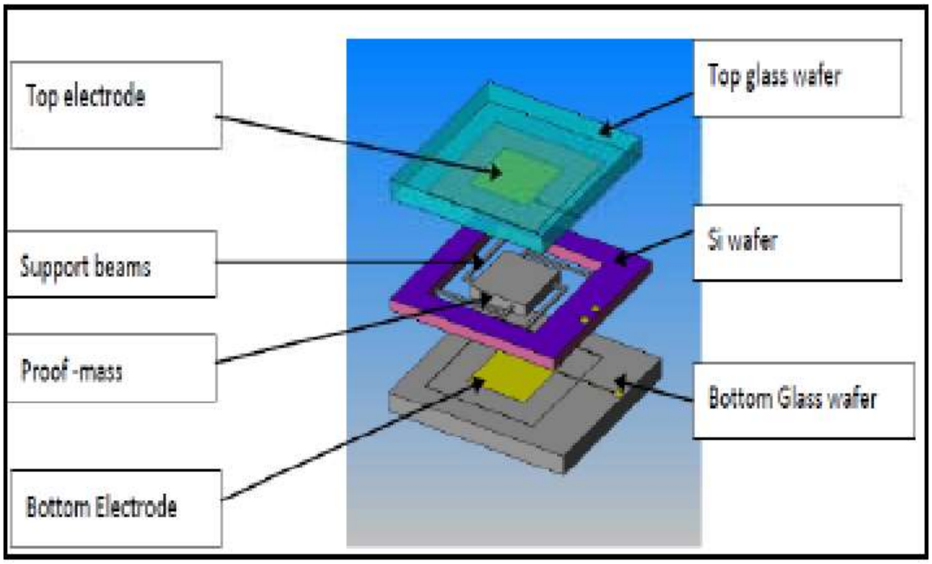


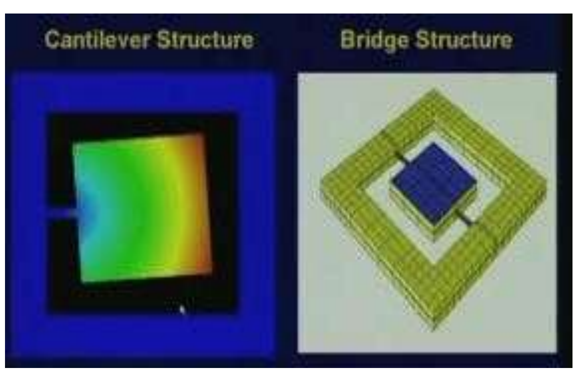
Fig. 2: Capacitive Accelerometer Configuration

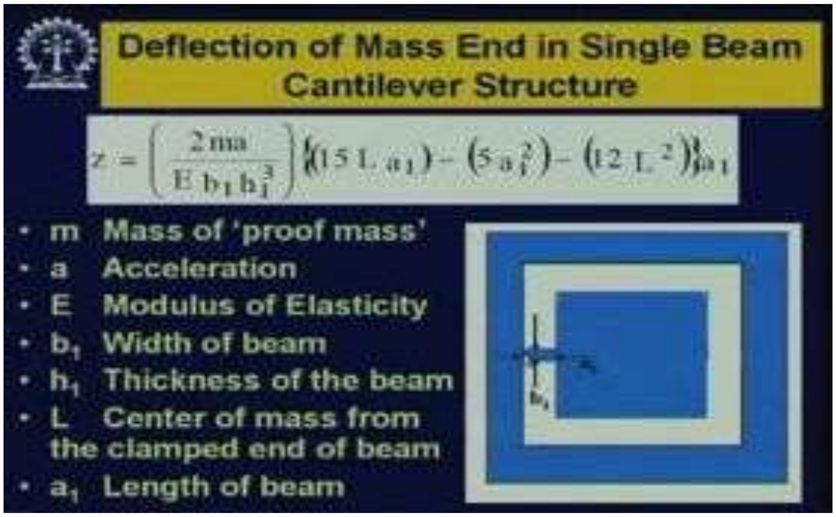
ADVANTAGES:

- ☐ Low temperature sensitivity
- ☐ Good DC response and noise performance
- ☐ Low drift
- ☐ High sensitivity
- ☐ Low power dissipation

CHALLENGES:

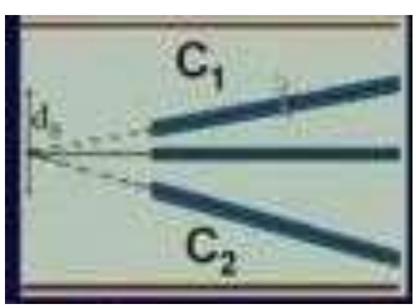
- ☐ Very difficult to eliminate parasitic components
- ☐ Susceptible to (EMI)electromagnetic inference problem which can be address by proper package





CAPACITANCE VARIATION:

- ☐ Now C_1 is the capacitance with the top electrode and seismic mass and C_2 is capacitance with the bottom electrode and seismic mass.
- ☐ So now the C_1 is equal to C_2 is C_0 when the mass is at rest that is obvious.
- ☐ So when this is there is no movement of the structure which is a rest position the C_1 will be equal to C_1.
- ☐ So if you move or you under g only the C_1, C_{12} will vary. So this is the capacitance variation how it varies you can see from this diagram.
- ☐ Average displacement of that means gap change between the fixed and the bottom. Because this how much moves in up and down that average value is d_0 basically.
- ☐ Now with acceleration movement of the mass, that is basically like a fan, this will move up and down and between the fixed electrode and moveable electrode can be found out by integration along the length.



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

CANTILEVER Vs BRIDGE STRUCTURE:

- In cantilever structure the damping is within limits and can be tailored to meet the specifications by perforation. Hence it can be used in open loop configuration.
- On the other hand in bridge type structure air damping is very high and hence force feedback configuration is must. You have to go for force feedback configuration in order to settle the open bridge structure.
- Sensitivity of a bridge type structure is more as compared to the cantilever structure.
- Now due to the anisotropic etching, the silicon anisotropic etching of the silicon the structure of the beam is not exactly rectangular. But it will take the form of the hexagonal shape like the figure it was shown here.

b_1

b_{12}

CAPACITIVE MICROACCELEROMETER PROCESS

TWO BEAM CANTILEVER:

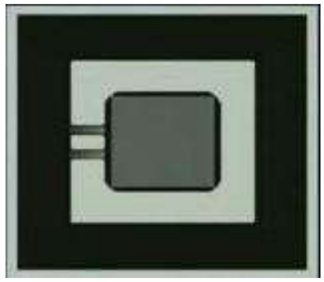
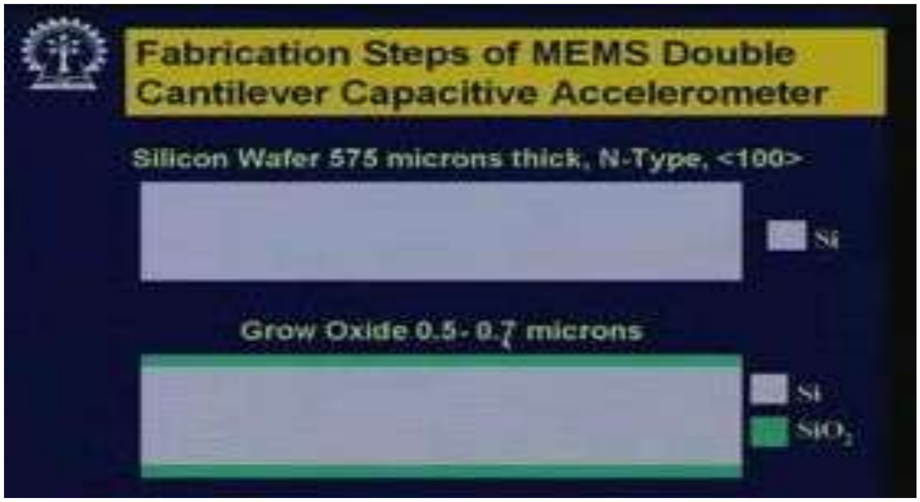
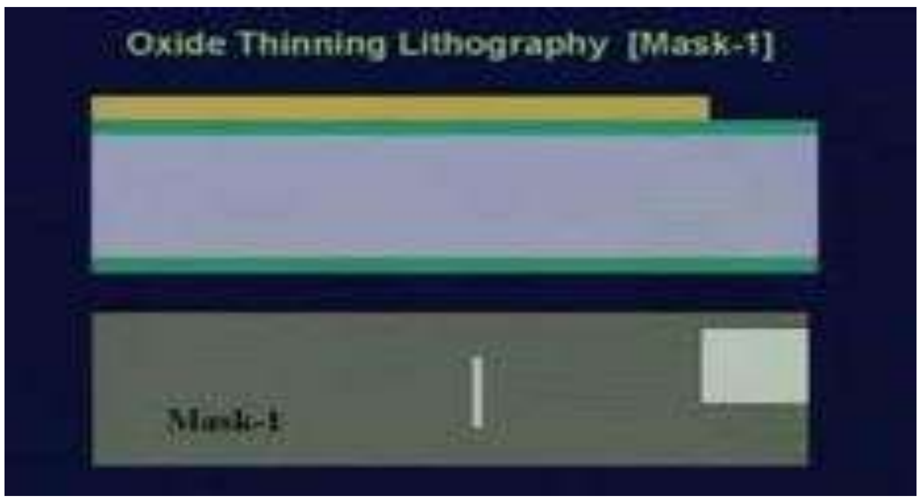


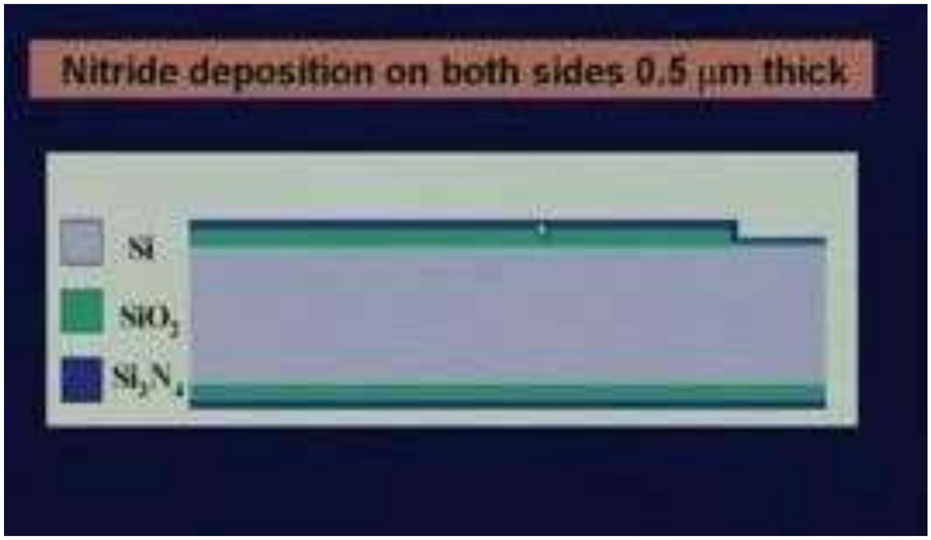
Fig: Two beam cantilever as fabricated in Intellisuite Software

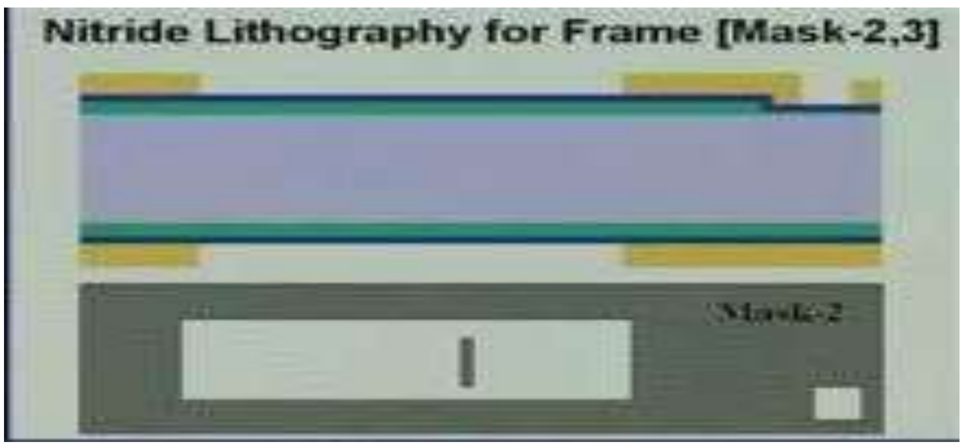
- That is two cantilever beam structure, this middle one is proof mass and this structure is to be fabricated using micromachining technology and before that within using some standard, the process simulator which is intellisuite software
- But in this particular case we are not going to fabricate the piezoresistances. Rather here sensing mechanism is capacitance variation.
- So the flexure you have design such that the displacement of the plate will be maximum.
- Plate means here the proof mass. Proof mass has got certain area and that proof mass displacement with acceleration from the top of and bottom fixed electrode should be as maximum as possible.
- Since there is no passive element we are not going to fabricate on the structure
- So here our main objective is the displacement.
- Initial etching with oxide mask over beam is carried out and subsequent etching is done without any oxide mask.
- Width of beam in the mask is kept more due to recession during mask less etching recession means it side all also little bit it will attack.
- So that is why the mask level, the size or width of the basically flexure beam is kept little bit more compared to the actual weight.
- So now let us see how the process will follow.

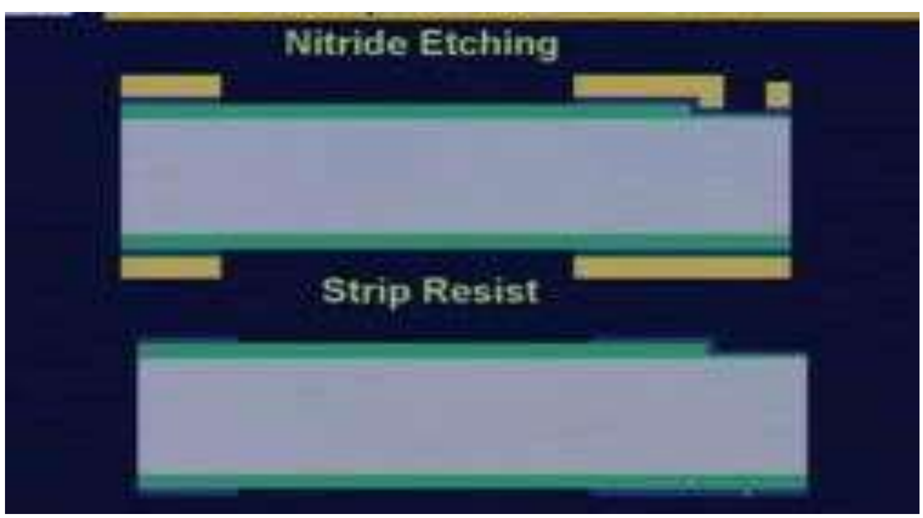

Fabrication Steps of MEMS Double Cantilever Capacitive Accelerometer
Silicon Wafer 575 microns thick, N-Type, <100>
Si
Grow Oxide 0.5- 0.7 microns
Si
SiO_2


Oxide Thinning Lithography [Mask-1]
Mask-1

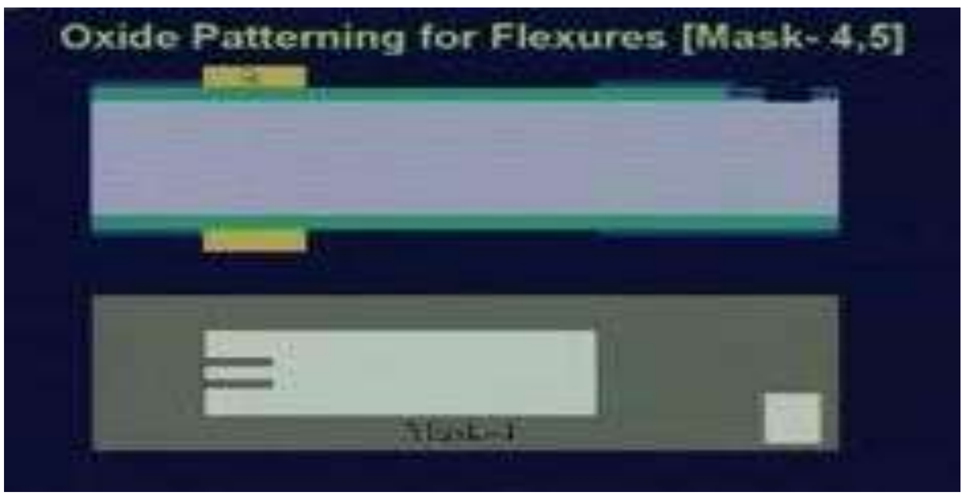

Oxide Etching in RIE
Etch to leave 1000 A
Strip Resist

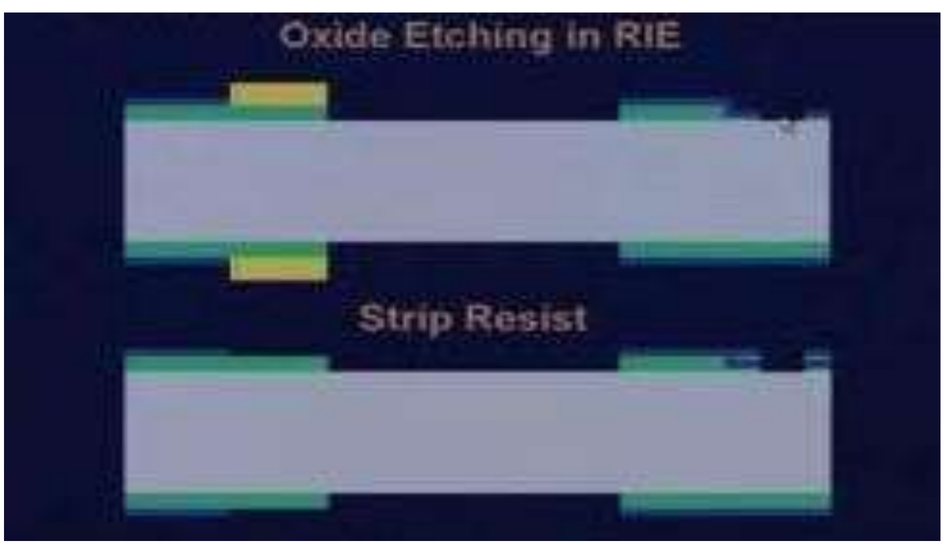

Nitride deposition on both sides 0.5 μm thick
Si
SiO2
Si3N4

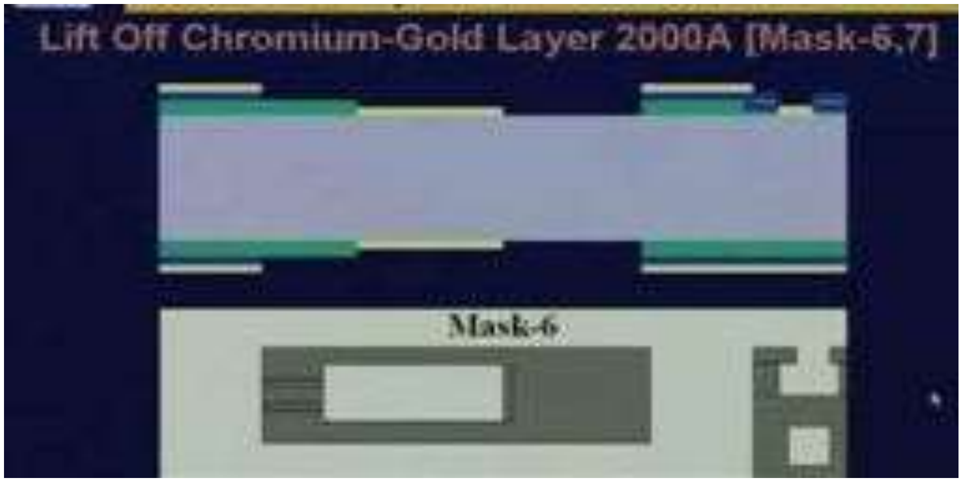

Nitride Lithography for Frame [Mask-2,3]
Mask-2

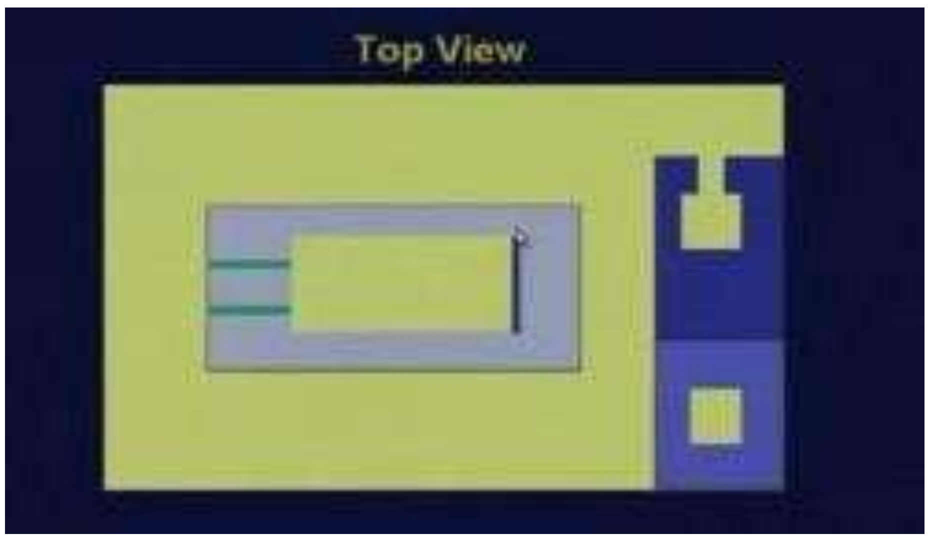

Nitride Etching
Strip Resist

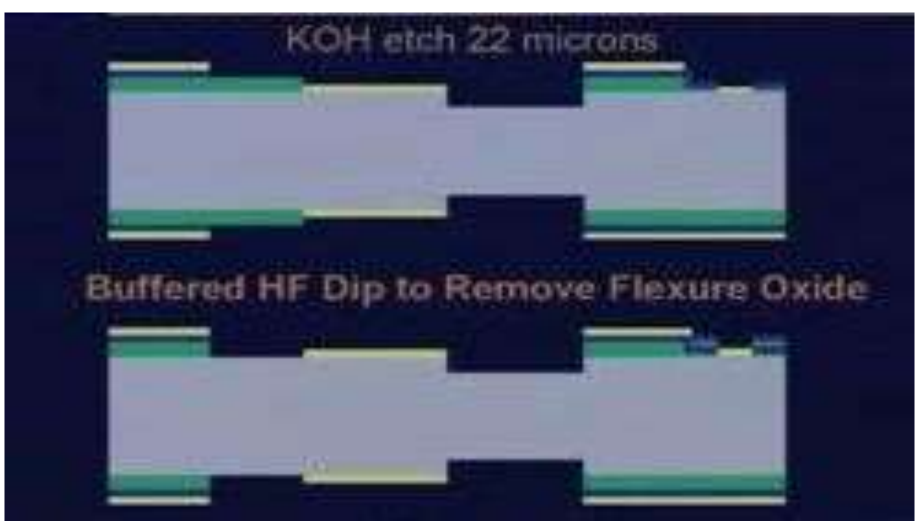

Top View


Oxide Patterning for Flexures [Mask- 4,5]


Oxide Etching in RIE
Strip Resist

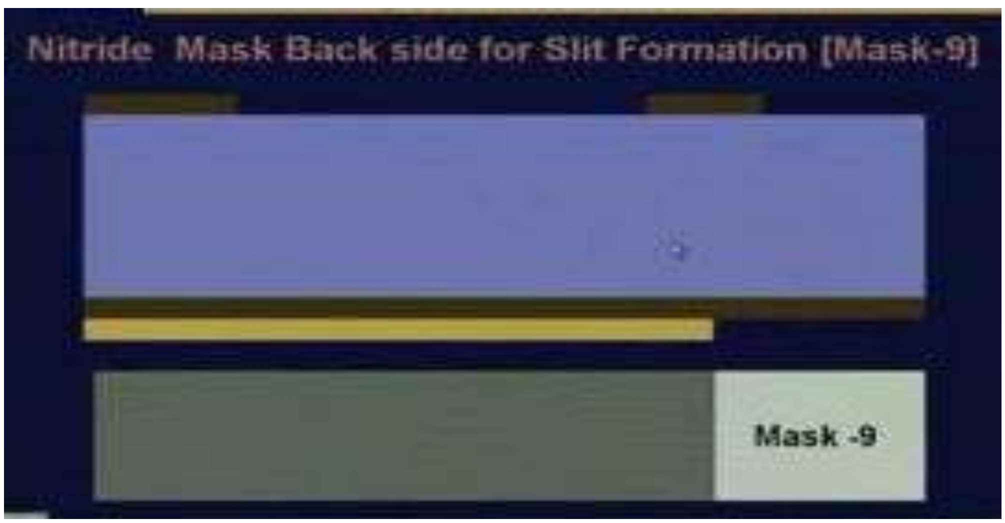

Lift Off Chromium-Gold Layer 2000A [Mask-6,7]
Mask-6


Top View


KOH etch 22 microns
Buffered HF Dip to Remove Flexure Oxide

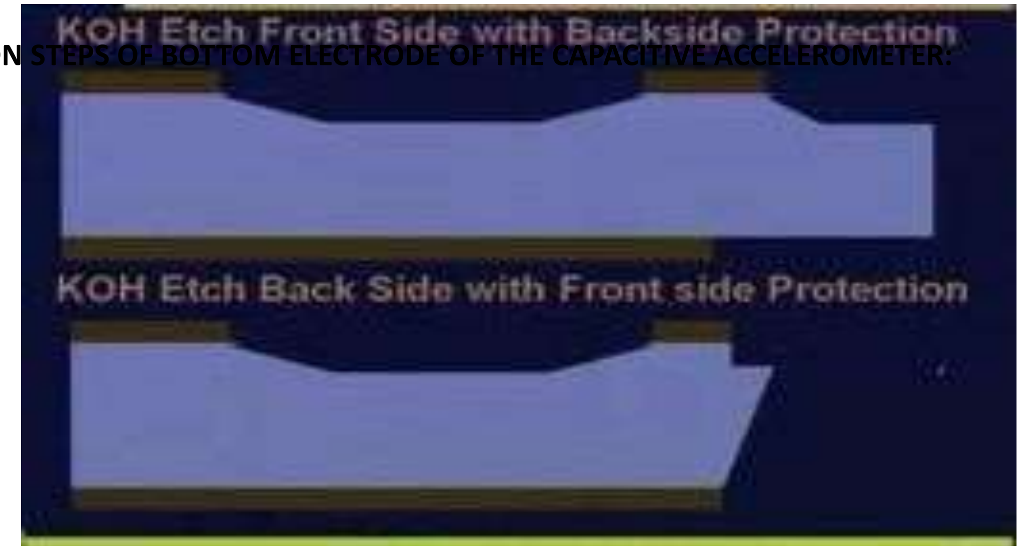
FABRICATION STEPS OF TOP ELECTRODE OF THE CAPACITIVE ACCELEROMETER:

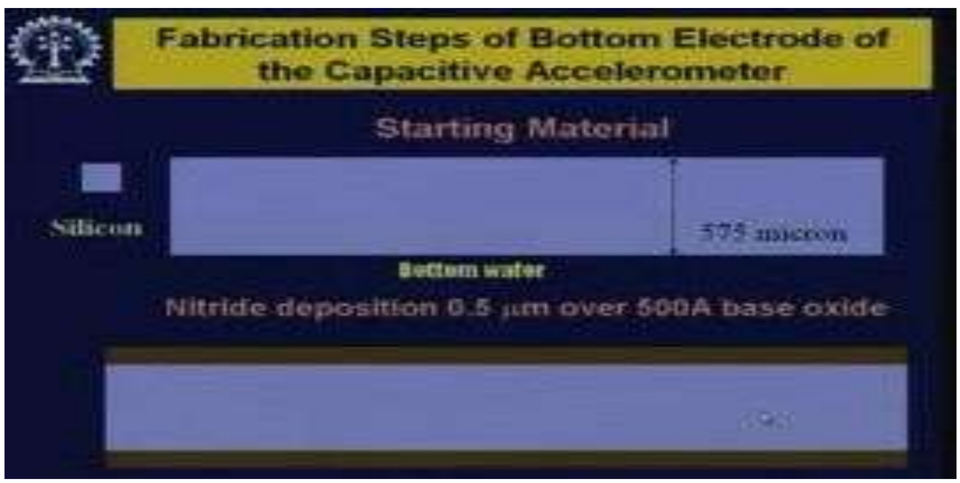

Nitride Etch
Strip Resist

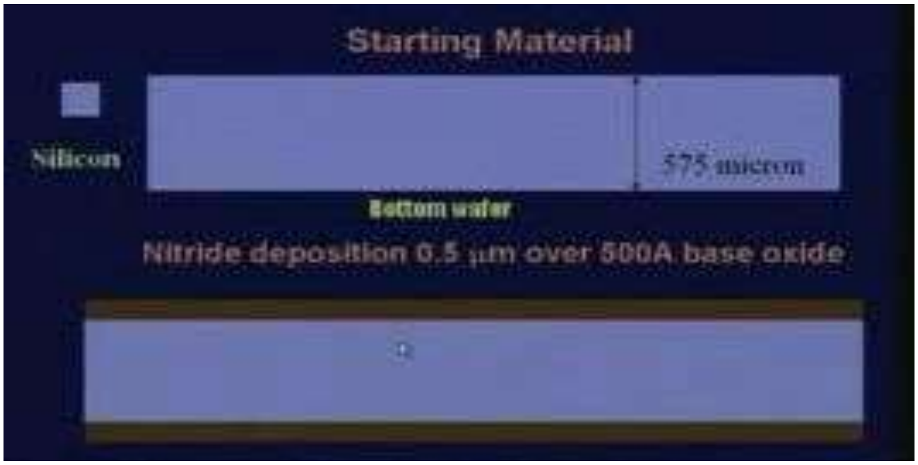

Nitride Mask Back side for Slit Formation [Mask-9]
Mask -9

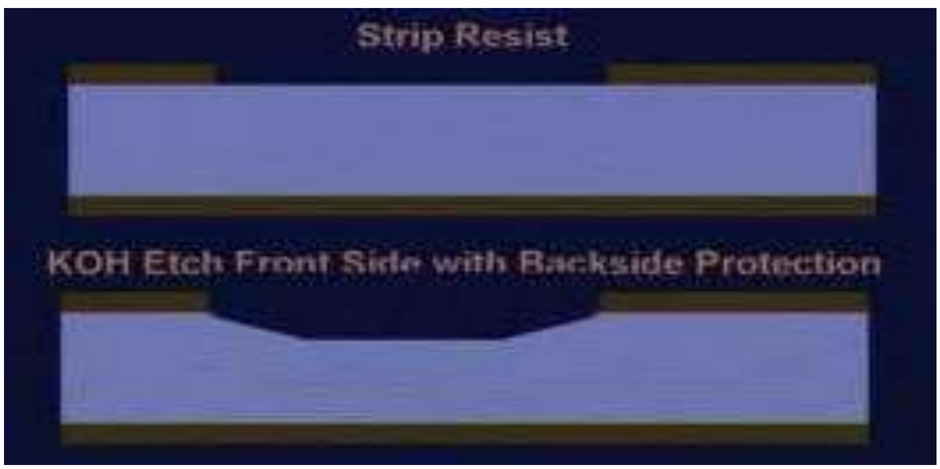

Nitride Etch
Strip Resist

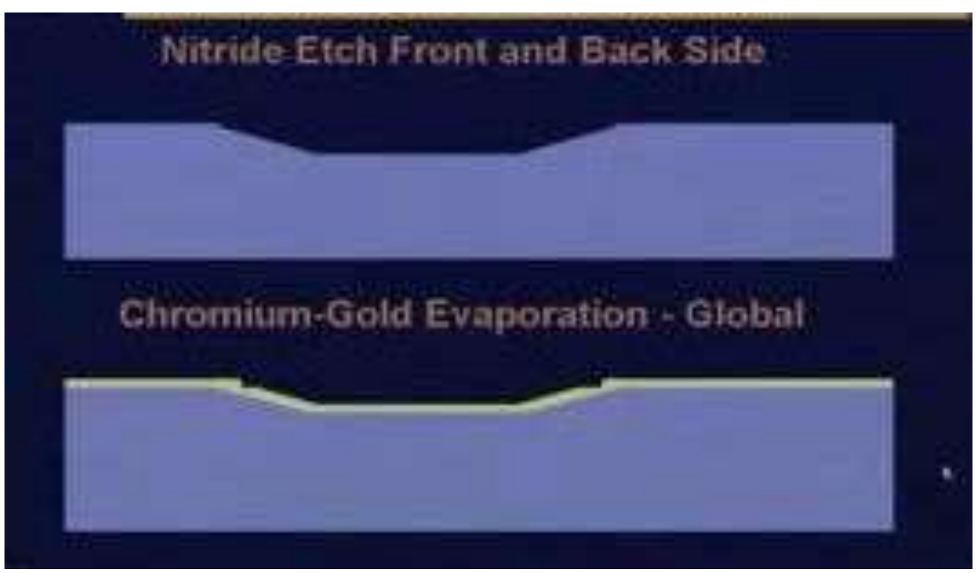
FABRICATION STEPS OF BOTTOM ELECTRODE OF THE CAPACITIVE ACCELEROMETER:

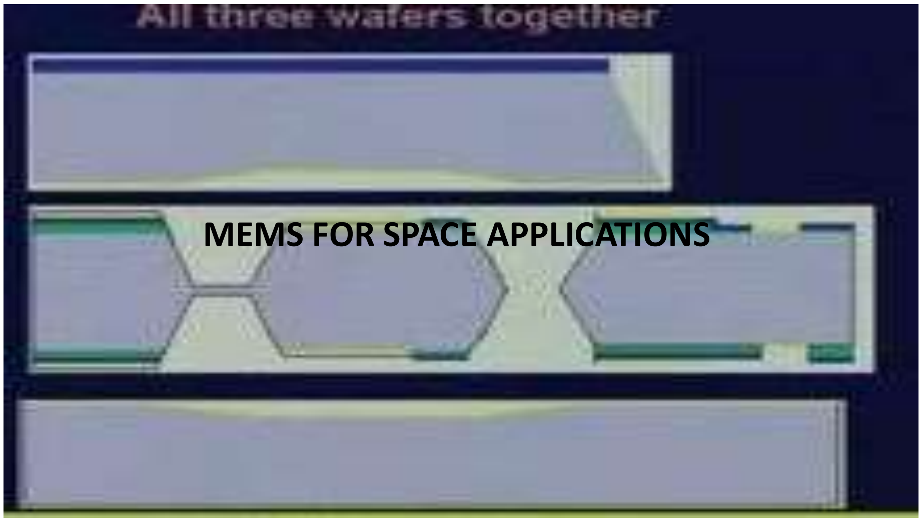





Starting Material
Silicon
575 micron
Bottom wafer
Nitride deposition 0.5 µm over 500A base oxide


Strip Resist
KOH Etch Front Side with Backside Protection

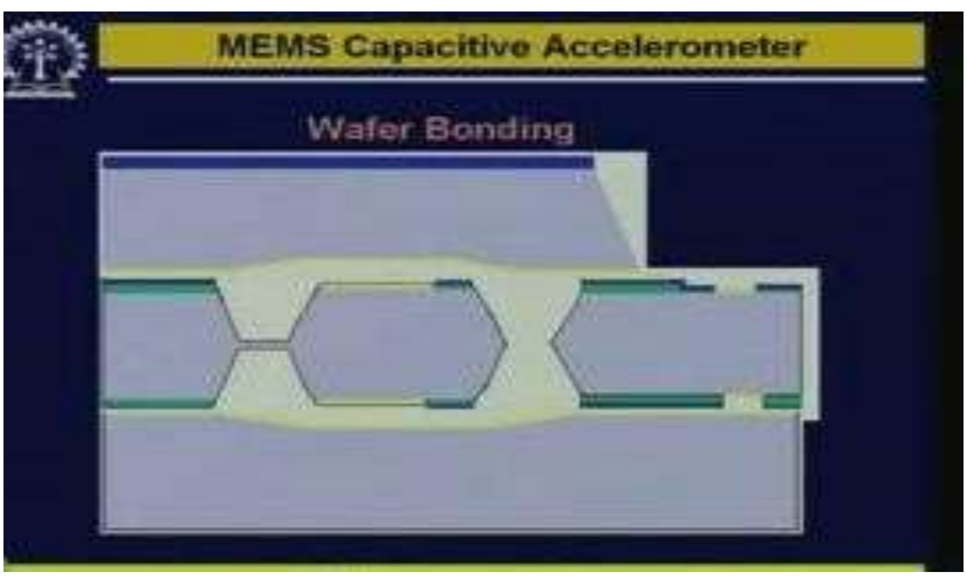

Nitride Etch Front and Back Side
Chromium-Gold Evaporation - Global



MEMS FOR SPACE APPLICATIONS

INTRODUCTION:

- ☐ Positioning a satellite in a particular orbit is an important issue.
- ☐ So how the MEMS device is playing an important role for satellite positioning that is the topic.



- Whatever the either airplane or satellite or the missile whatever you are going to send in space, one of the major concerns is the weight.
- So miniaturization one of the important issue miniaturization of the devices and different components is one of the major issue when you are going to integrate them either in a space craft or airplane or missile wherever it is.
- So the weight and small size the MEMS will give you a process or a technology where you can miniaturize devices as much as possible with lot of micromechanical action also.
- So today we will discuss on micro thrusters which are basically used for Pico satellite program micro satellite and pico satellite is a topic of research today in many of the advance level institutions around the globe.
- So Indian Space Research Organization, ISRO is also thinking in near future for micro satellite or pico satellite program.
- So they had initiated and R&D effort to miniaturize different components and to get highly reliable space qualified low small mass and small size devices which may be helpful for reducing the weight of the space vehicle.

LIQUID PROPELLANT MICROTHUSTER FOR AEROSPACE APPLICATIONS:

INTRODUCTION:

- So one interesting area in space market today is to reduce cost and increase reliability.
- So micro propulsion and in one example of the application of the MEMS to the space environment.
- The main application of the micro thruster is the micro propagation for microsatellite whose weight is within 2 to 20 to 100 kilo and Nano satellites whose complete weight is less than 20 kg.
- So that is for those satellites, how those satellites will be position accurately in a particular orbital system by using a small size micro thruster.

PROPULSION:

- ☐ Propulsion is the act of changing motion of the body.
- ☐ So when you are sending a space craft in space so many times you have to change the motion of the space craft.
- ☐ So that you can accurately position the space vehicle in a particular orbit location.
- ☐ So to changing its motion that is done remotely and by using certain devices which is known the thruster.
- ☐ You have to put some pressure so that the whole satellite could be changed from one location to another location.
- ☐ So propulsion mechanism provides a force that moves bodies that are initially at rest, then of velocity will take place. That is the propulsion.

ROCKET PROPELLANT:

- ☐ Rocket propulsion provides thrust by ejecting stored matter called propellant.
- ☐ So that is the material which is known as propellant there are various kinds of propellant lot of research is going on in the propellant, high efficiency propellant.

CLASSIFICATIONS OF THE PROPULSION SYSTEM:

- ☐ They can be classified according to different categories

1. Type of energy source that mean energy resource is chemical, nuclear or solar
2. Basic function whether function of the propulsion is attitude control or orbit station keeping
3. Type of vehicle which kind of vehicle you are using it may be aircrafts; it may be missile
4. Size
5. Type of propellant,

6. Type of construction and
7. Method of producing thrust

PARAMETERS OF PROPULSION SYSTEM:

- ☐ Thrust
- ☐ Total impulse
- ☐ Specific Impulse
- ☐ Mass Ratio
- ☐ Impulse to Weight Ratio
- ☐ Thrust to Weight ratio
- ☐ Effective exhaust velocity

THRUST:

- ☐ It is the force produced by rocket propulsion systems acting upon a vehicle or reaction experienced by its structure due to the ejection of the matter at high velocity.

TOTAL IMPULSE:

- ☐ Total impulse which is known as I_t for constant thrust the I_t is given by

$$I_t = F \cdot t$$

Where F is a thrust force and t is the burning time.

- ☐ That is known as the total impulse; time multiplied by thrust force is called impulse.
- ☐ It is the total energy released by the propellant in a propulsion system that is known as impulse which is designated as I_t.

SPECIFIC IMPULSE:

- ☐ I_s is defined as total impulse per unit weight of propellant.

MASS RATIO:

- Mass ratio is defined as ratio of mass, final mass m_f and m_0 that is mf is final mass m_0 is before rocket operation and parameter for analyzing flight information, that m mass ratio is one the job is for analyze flight performance.

IMPULSE TO WEIGHT RATIO:

- Impulse to weight ratio that is total impulse I_t divided by propellant loaded vehicle weight W_0. I_t by W_0 is an impulse to weight ratio its high value means efficient design. Impulse to weight ratio should be very high for an efficient propellant system

THRUST TO WEIGHT RATIO:

- It expresses the acceleration F that the engine is capable of given to it over loaded propulsion system mass, thrust to weight ratio.

EFFECTIVE EXHAUST VELOCITY:

- Effective exhaust velocity, this is another parameter define as average equivalent velocity at which is propellant is ejected from the vehicle.

THRUST OF PROPULSION SYSTEM:

- Thrust of a rocket unit is independent of the flight velocity.
- Change in ambient pressure affect the pressure thrust that is there is variation of the rocket thrust with altitude.
- Atmospheric pressure decreases with increase of altitude so the thrust and specific impulse will increase as the vehicle is propel to higher altitudes.
- This change in pressure thrust due to altitude change can be 10 to 30 percent of the overall thrust. Variation may be 10 to 30 percent of the overall thrust.

PROPELLANT:

- ☐ There are two kinds propellant used: one is solid propellant, another is liquid propellant.
- ☐ Basically it has to burn; it has to produce some gases which will eject to the nozzle as a result of which your device push forward.
- ☐ A thrust is applied to the space craft or satellite whatever it is. That is the basic objective.

PROPELLANT CHARACTERISTICS:

- ☐ High specific impulse or high performance. This means high gas temperature and or low molecular mass.
- ☐ Low absorption of the moisture which often causes chemical deterioration.
- ☐ Safe, Simple, Low cost and reproducible.
- ☐ Low technical risk, such as favorable history of prior applications
- ☐ Non-toxic exhaust gases

SOLID PROPELLANT:

EXAMPLES:

- ☐ One is double base mixture of some compounds are sometime use.
- ☐ Sometimes simply some chemicals are also used DB, AP, AL is basically aluminum, AP is ammonium perchlorate.
- ☐ Sometimes mixture of aluminum and HMX which is cyclotetramethylene tetranitramine.
- ☐ So these are the a few chemicals and apart from those for preliminary testing you can use simple water also has propellant for testing purpose.

ADVANTAGES:

- ☐ Simple design,
- ☐ Few or no moving part
- ☐ Will not leak or spill if it is a liquid, there is a chance of leaking or spilling over
- ☐ Can be stopped and restored few times if programmed

- ☐ Can be stored for 5 to 25 years without any deterioration of the material.

DISADVANTAGES:

- ☐ Explosion and fire potential is larger compare to liquid propellant.
- ☐ Requires an ignition system because since it is an explosion, it has to be fired.
- ☐ Each restart requires a separate ignition system. Once you start it then second chamber you have to stop then again. If you have to fire the second chamber, you have to again put an ignition system. So each time you want to fire it.
- ☐ Some propellant can deteriorate in storage which is known as self-decompose.
- ☐ Cannot be tested prior to use because testing is highly risky.
- ☐ Need very much safety precautions because of the total system is explosive system and it involves lot of fire hazards.

LIQUID PROPELLANT:

- ☐ Liquid propellants are water, ammonia and hydrazine. These are the three liquid propellants which are commonly used.
- ☐ Liquid propellant embraces all the various liquids used and may be one of the following

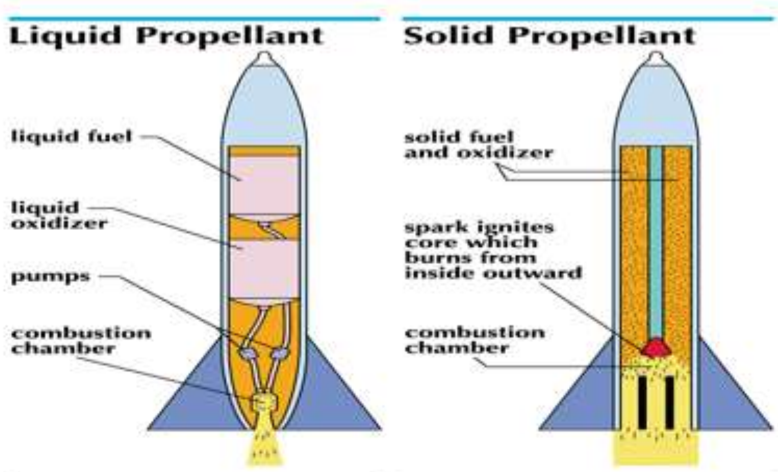
1. Oxidizer that is liquid oxygen, nitric acid etcetera.
2. Fuel that is alcohol, liquid hydrogen, gasoline etcetera.
3. Chemical compound or mixture of oxidizer and fuel ingredients capable of self-decomposition.
4. Any of the above but with gelling agency behaves as thick paint. If you put some gel, that it will not spill but can flow under pressure.
5. So one of the advantages in case of the solid propellant we told that it since it is solid, it is spilling over problem will not be there.
6. But in case of liquid with very low density, there is a leakage kind of thing and some spillover kind of things always that problem is there. So people try to mix some gelling agent. So that its density will be higher and problem of spilling over will be reduced.

ADVANTAGES:

- ☐ It should be it usually highest specific impulse
- ☐ Can be randomly stopped and restarted which cannot be done. In case solid can be largely checked out just prior to operation.
- ☐ Can be tested at ground or launch pad prior to flight,
- ☐ Most propellant has nontoxic exhaust which is environmentally acceptable. These are the plus point in case of liquid propellant.

DISADVANTAGES:

- ☐ A relatively complex design
- ☐ More parts are component leads to more things to go wrong.
- ☐ Cryogenic propellant cannot be stored for long period except when tanks are well insulated.
- ☐ Gases basically these are the Cryogenic propellant, leaks or spills of several propellants can be hazardous toxic. But this can be minimized with gel propellants which has mentioned in earlier slide also.
- ☐ Tanks need to be pressurized by separate pressurization system.
- ☐ If want to eject the propellant efficiently, few propellant gives toxic vapors red fuming nitric acid in some of the propellant like hydrogen, that is not user friendly at all

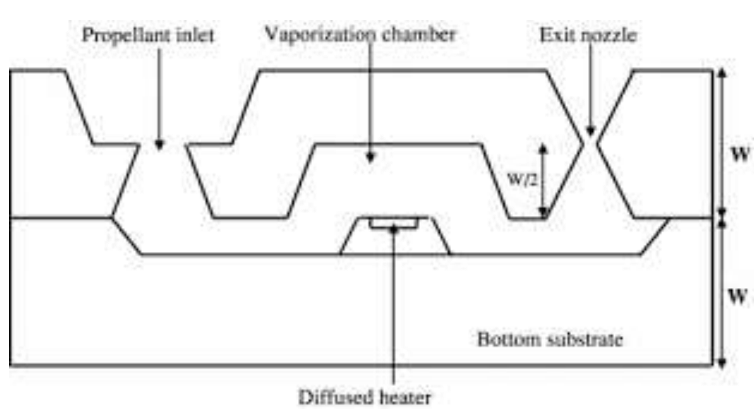


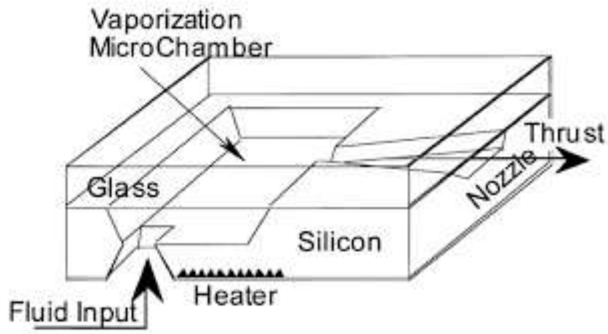
OVERVIEW OF MICRO PROPULSION DEVOLOPMENTS:

- ☐ Cold gas system
- ☐ Bi propellant thruster
- ☐ Monopropellant thrusters
- ☐ Colloid thrusters
- ☐ Field emission electric propellants
- ☐ Plasma pulsed thrusters PPT
- ☐ Microion thruster MUIT
- ☐ Hall-effect thrusters
- ☐ Laser plasma thrusters
- ☐ Micro solid propellant thrusters and lastly
- ☐ Vaporizing liquid thruster VLT

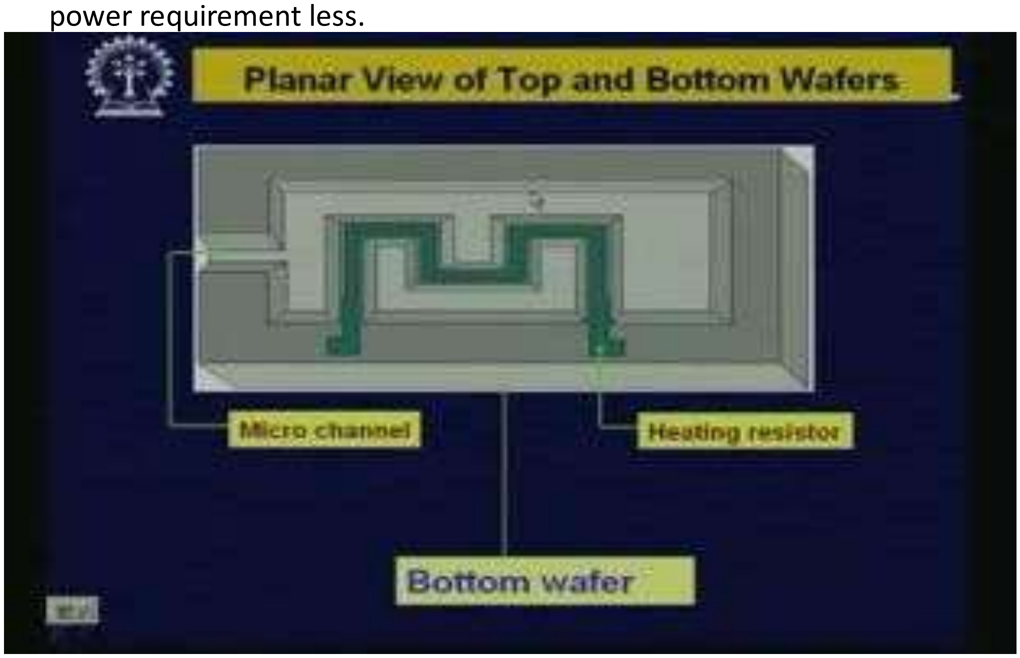
VAPOURIZNG LIQUID MICROTHRUSTER (VLT):

- ☐ VLT is a typical example of MEMS based micro propulsion device.
- ☐ It can be easily fabricated using MEMS technology, micromachining technology.
- ☐ The change of phase, what phase liquid to gas is exploited to produce a thrust.
- ☐ Liquid will use initially in the leak chamber propulsion chamber then convert into gas and will force the gas to eject from narrow nozzles which will produce thrust.
- ☐ That is basic principle it request a heating resistor, a vaporizing chamber, a nozzle, a propellant inlet, and a micro channel. So these are the components of the micro thruster. All those things can be integrated together to have the micro thruster.





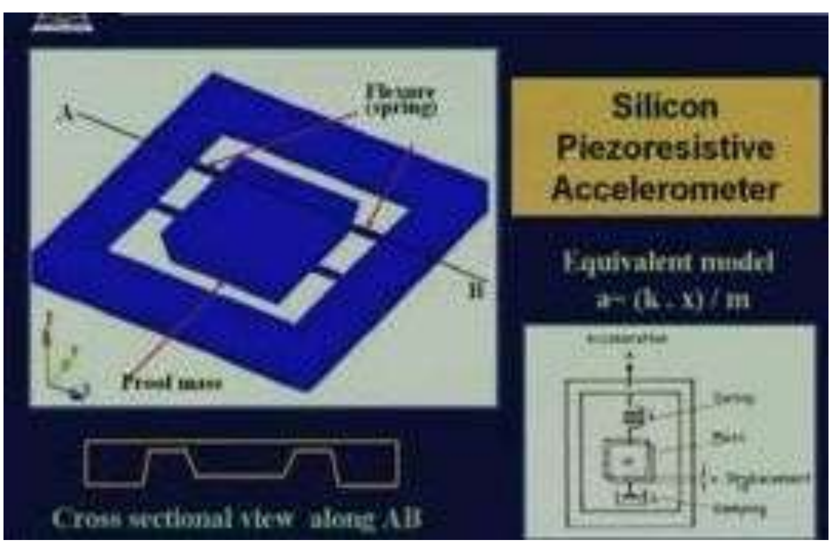
- Vaporization of the fuel in the micro chamber has a longer pre-vaporizing warm of time because heat is being delivered only to one side.
- Even with the glass cover the silicon containing diffused heaters provided sufficient thermal contact and conductivity to effectively heat the micro chamber.
- This design issues more power efficient and allows thermal input from heaters on both side of the micro chamber and utilizes the high thermal conductivity of silicon.
- Because you are fitting if you want resistor in one side asymmetric so your power requirement less.

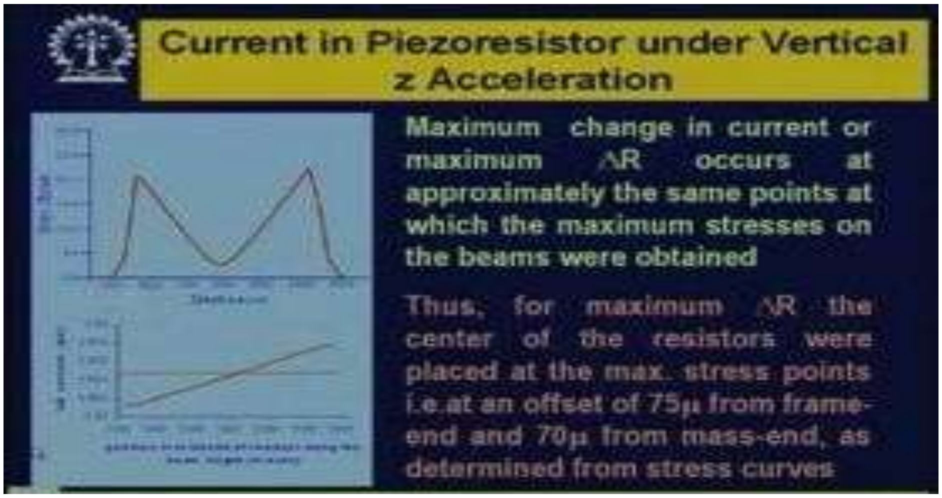


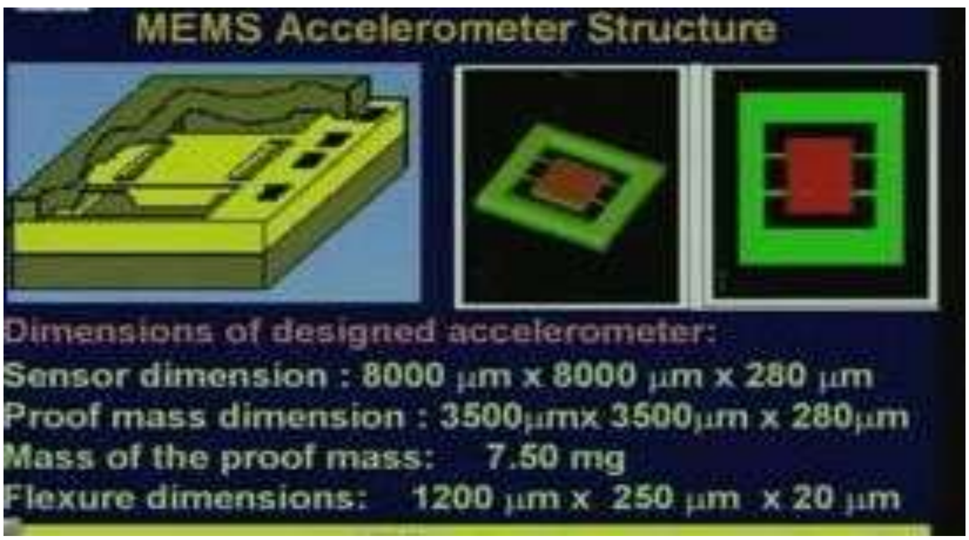
MEMS ACCELEROMETER FOR AVIONICS:

- ☐ Design and fabrication of a microaccelerometer for aircraft motion sensing to satisfy the need for FCS normal mode.
- ☐ The accelerometer we which we are going to develop, that is based on piezoresistor mechanism, piezoresistor sensing mechanism and it is used in aircraft.
- ☐ Accelerometers are in greatly useful for specific applications ranging from guidance and stabilization of space-crafts, measure tilt motion, vibration and high shock application.

DESIGN OF SILICON MICROMACHINED PIEZORESISTIVE ACCELEROMETER WITH LOW OFF AXIS SENSITIVITY:







Resistor specifications:

Resistor dimensions : 120 μm x 20 μm

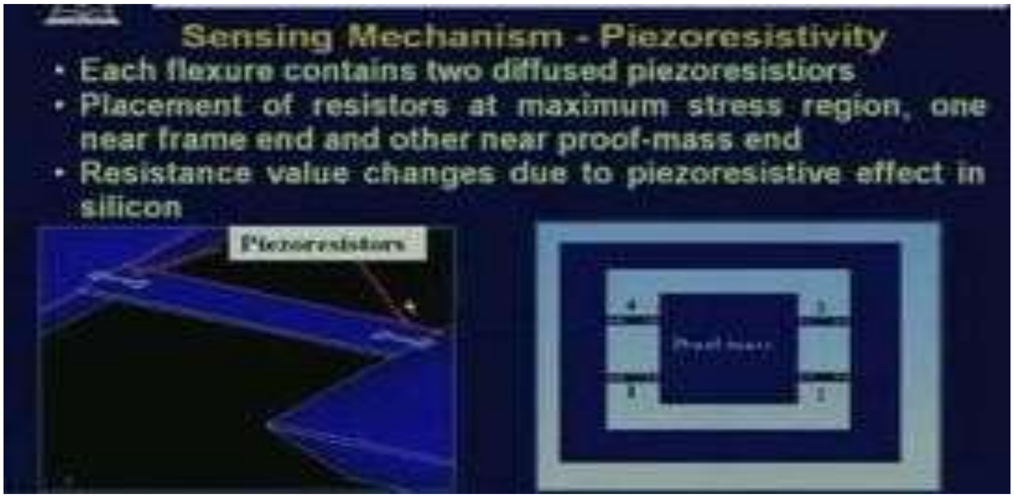
Contact pad dimensions: 40 μm x 40 μm

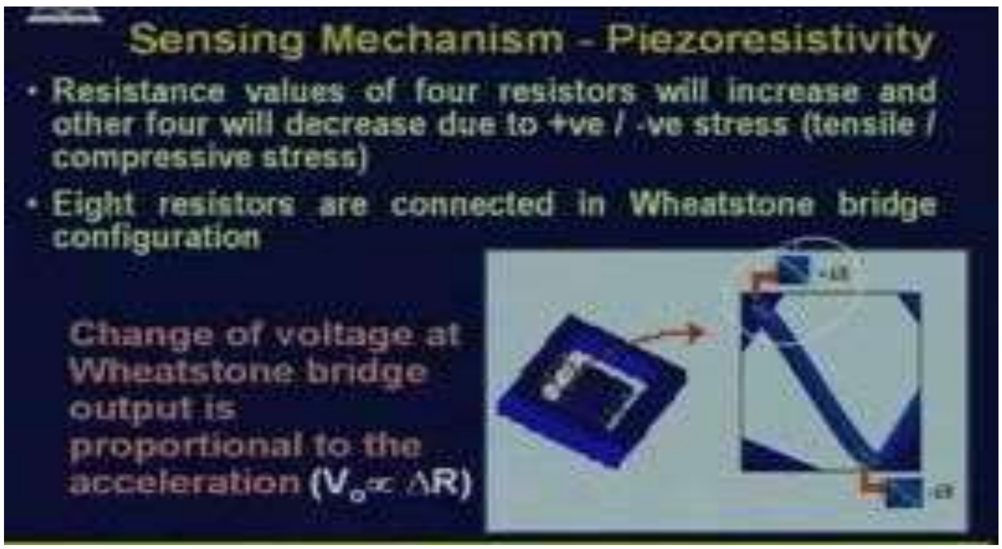
Resistor material properties:

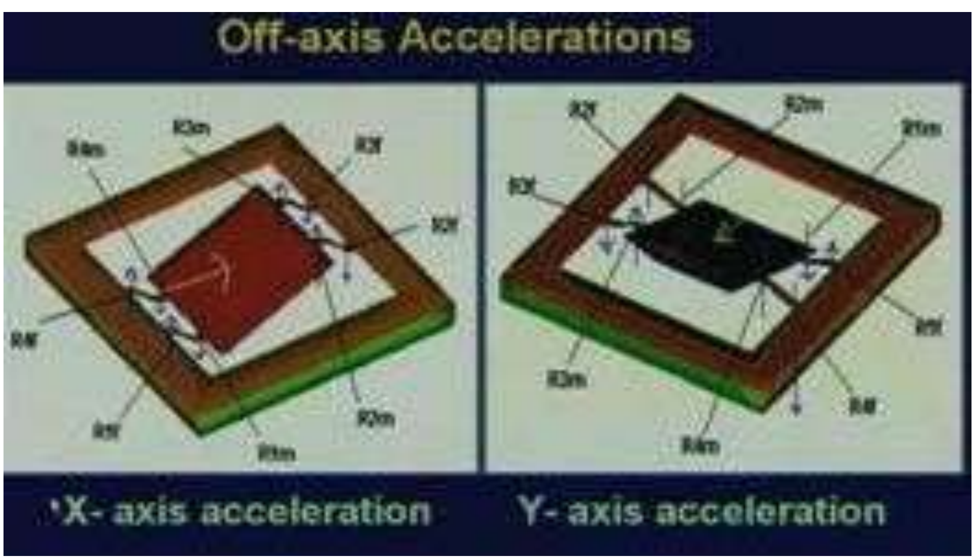
Boron doped resistor

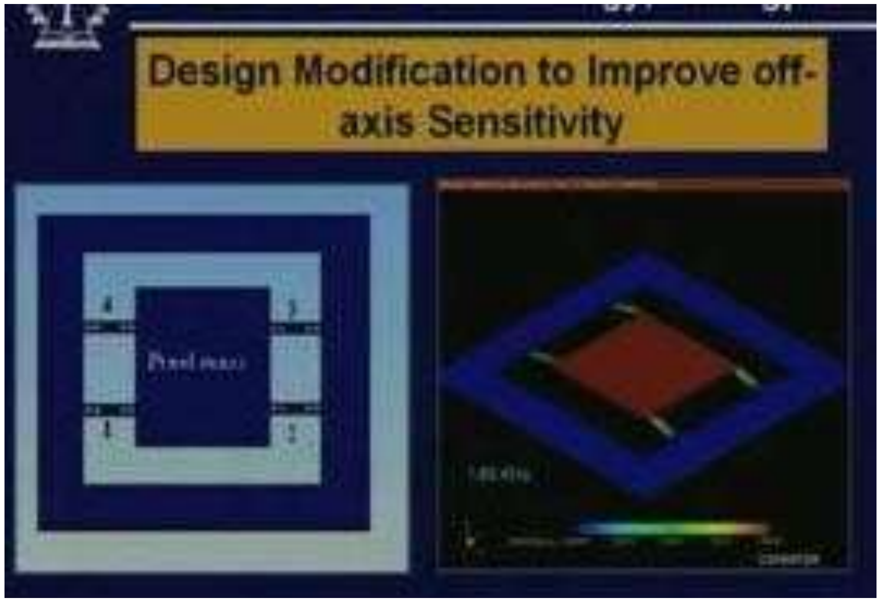
Sheet resistance =250 Ω /□

Junction depth = 2.5 μm


Sensing Mechanism - Piezoresistivity
• Each flexure contains two diffused piezoresistiors
• 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
Piezoresistors


Sensing Mechanism - Piezoresistivity
• Resistance values of four resistors will increase and other four will decrease due to +ve / -ve stress (tensile / compressive stress)
• Eight resistors are connected in Wheatstone bridge configuration
Change of voltage at Wheatstone bridge output is proportional to the acceleration ($V_o \propto \Delta R$)


Off-axis Accelerations
•X- axis acceleration
Y- axis acceleration


Design Modification to Improve off-axis Sensitivity
Proof mass