Micro and Smart Systems
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Lecture - 39
Pressure Sensor Design Concepts, Processing, and Packaging: Part -3 Capacitive Micro-accelerometer: Part -1

Today, we will spend few minutes on the last few slides on the Pressure sensor, which we discussed in the previous lecture number 38 and then we will continue on another sensor that is the Silicon accelerometer, okay.

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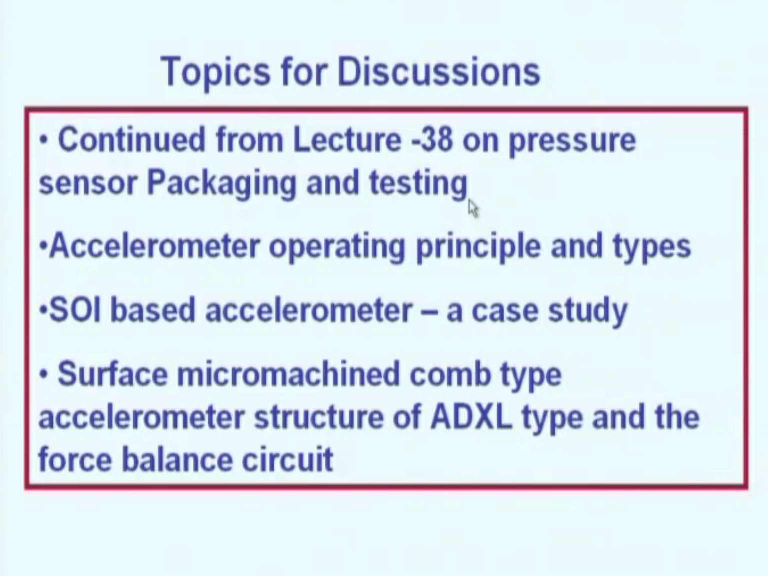

Topics for Discussions

- Continued from Lecture -38 on pressure sensor Packaging and testing
- Accelerometer operating principle and types
- SOI based accelerometer – a case study
- Surface micromachined comb type accelerometer structure of ADXL type and the force balance circuit

So we will go back to the slide that we have shown yesterday, and the topics that we are going to do will be continued from lecture-38 on pressure sensor packaging and testing few slides just a glance through them. Accelerometer operating principles and types of accelerometers. Then Silicon on Insulator based accelerometer a case study, we already discussed the silicon on insulator approach for pressure sensor.

Then we will also discuss Surface Micromachined comb type accelerometer structure, ADXL type which is the proprietary of the analog devices along with the force balance circuit that is the sensor and electronics, okay.

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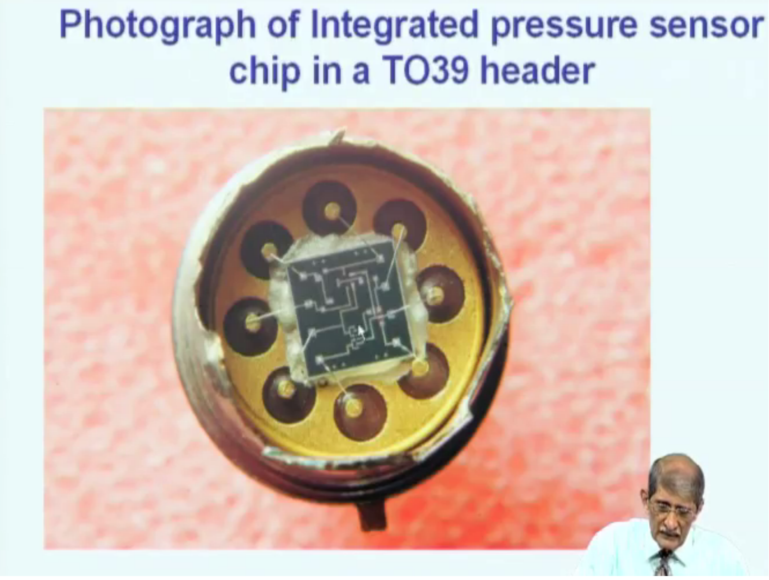

Photograph of Integrated pressure sensor chip in a TO39 header

So these are just to go back to the previous lecture we had shown that integrated pressure sensor die or the chip moulted on to the header which is gold plated, and we can see that is the grue on these edges so this is the portion where the pressure sensor is present, that is below this portion there is a cavity and this is the portion where electronics is present.

And as I pointed out already in my previous lecture there are all these are the bond pairs and the bond pairs are connected to the post this is also gold plated by means of aluminium wire, if you bond one end here take the other end and bond it onto the other side cut the wire. So now you can see this is coming out from other end of this header at as a (()) (02:20), so there are number of these pins are there to which connection are taken okay, now this is actually the cutter view of the complete the device.

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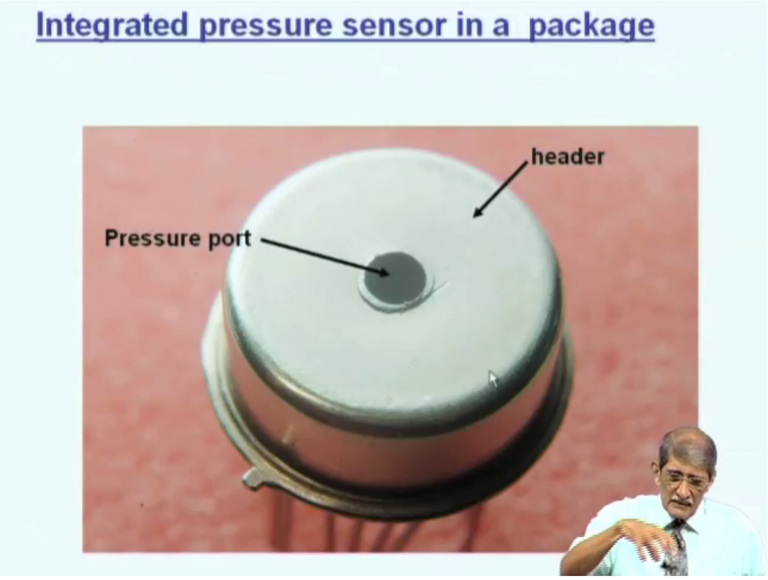

Integrated pressure sensor in a package

So actually the completed devices like this, so what you saw in the previous slide is cut here, so that you can see the inside okay. Now you see the pressure port so you have to make either you can connect tube straight away into this outside like that and connect it to the place where you want to measure the pressure, while testing we will connect it to a gas cylinder or because it is done like this for quick fabrication thing, what we have to do is use a jig which will just hold on to this tube is in the jig in this fashion

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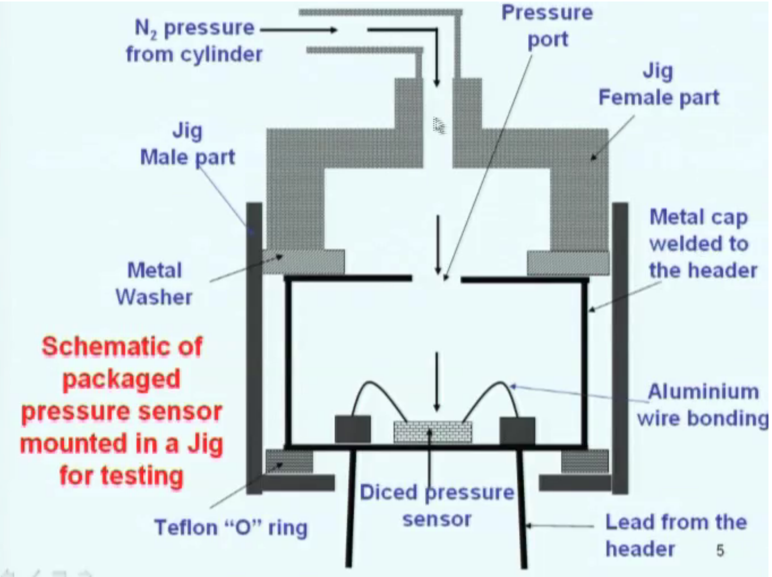

Schematic of packaged pressure sensor mounted in a Jig for testing

So this is that the metal cap is here with a hole, the metal cap is here the hole is here, and inside the metal cap the die is there to go back and see inside the die is here and okay the leads are connected from here to here that is the aluminium wire and the leads are coming out here, the wires are bonded aluminium wire bonding done.

And then whole thing is put inside jig which can be held in position by means of some arrangement, and that jig tube is connected to that if you already have a tube connected to this then you can straight away connect the pressure cylinder straight into that, but we have to make this arrangement because this as what we got it done to package okay.

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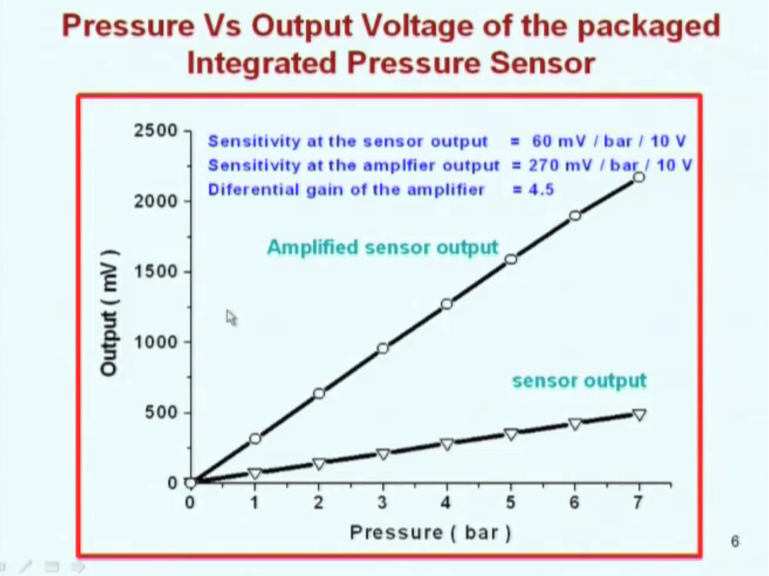

Pressure Vs Output Voltage of the packaged Integrated Pressure Sensor

Sensitivity at the sensor output = 60 mV / bar / 10 V
Sensitivity at the amplfier output = 270 mV / bar / 10 V
Diferential gain of the amplifier = 4.5

So while testing you apply the pressure here to monitor the pressure by means of a digital gauge that is the pressure, and you see the output voltage from the bridge for a some 10 volts input supply, so you got about 60 millivolts per bar output from the sensor and it is quietly there in the 7 bar pressure and the output from the entire sensor + electronics after amplification of by factor 4.5 you have 270 millivolts per bar per 10 volts, you can see at 7 bar it is more than 2 volts of the output, okay so that is the thing.

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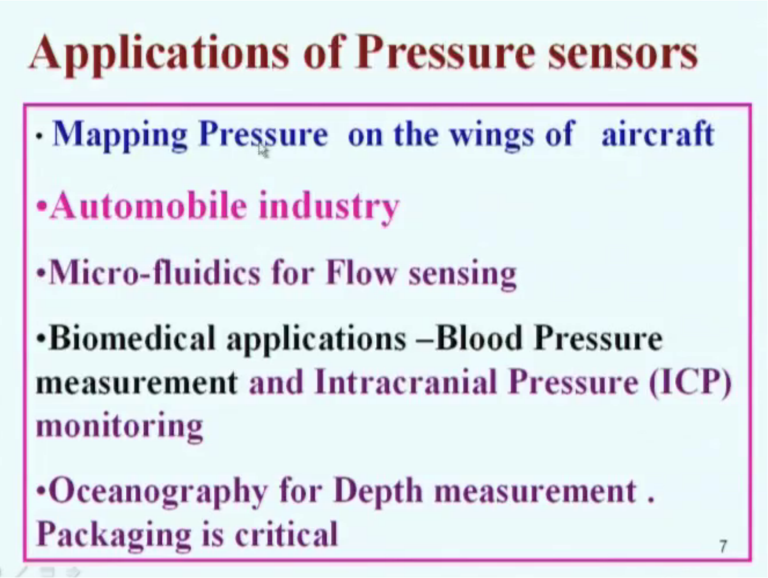

Applications of Pressure sensors

- Mapping Pressure on the wings of aircraft
- Automobile industry
- Micro-fluidics for Flow sensing
- Biomedical applications –Blood Pressure measurement and Intracranial Pressure (ICP) monitoring
- Oceanography for Depth measurement . Packaging is critical

Then applications, I just wanted to quickly run through this. One of the very important application that is being used is the mapping the pressure on the wing of an aircraft which is under research, so under research you may like to modify the shape of the wing etc. to adjust the pressure distribution across the wing okay, then you want to have the pressure mapped all over the wing and for that you need microsensor.

And the packaging of this will not be like this, it will be a flat type of package, so that it can be kept straight on the surface of the wing and you can take leads horizontally, this is one of the applications. Automobile industry varieties of applications the air pressure, tyre pressure, then you can also measure the level of fuel in the fuel tank, because after all if the sensor is put under the bottom of the tank you know how much fuel is present.

And the fuel level comes down the pressure experienced by the pressure sensor will go down, the pleasure of the fluid is rho density*g, rho g h where h is the height, so as height keeps on falling the pressure will fall, so we can just monitor the fuel level also. Micro-fluids for flow sensing you can measure the sense of flow by means of flow sensor I will show how is it done, you require when the flow is of the order of microliters per minute is very difficult to measure.

You need special arrangement for measuring those flow especially for biomedical applications where you want to monitor the fluid flow in microliters per minute, you have a flow sensing device I will in the next slide how it is done. Biomedical applications I pointed this out right at the beginning of my first lecture, you can use the pressure sensor to monitor the Intracranial pressure, to monitor the pressure of the brain.

When a person meets with an accident and undergoes head injury there is swelling in the head and the pressure of the brain goes up and there will be severe headache sensed by the patient, apart from this accident it can also be a tumor which is present in the brain that also can give to rise in pressure that pressure you want to monitor and that you drill a hole put a pressure sensor inside which is biocompatible you cannot use metal can.

So biocompatible packaging has to be done put it inside the intracranial region, pressure you can monitor it through the okay, so the fluid can be removed out to release the pressure that is what is done in the for monitoring the pressure and controlling the pressure. Other applications is blood pressure, when you have to monitor the blood pressure you know you can monitor it as in the useful way using a cuff but you sites systolic and diastolic.

But when you want to monitor very close to the heart when the operation is being done surgery, then you have to do insert this into that location and also the pressure near the heart will be high compared to the usual 80/120 it may be at least 2 to 3 times higher there, so you want to monitor there that has to be with a microprocessor sensor, biocompatible again when you use polymer packaging.

Then an Oceanography where you want to measure the conductivity temperature and death, you can use for the depth measurement the pressure sensor but the packaging is critical here also, because the water at the ocean is very highly corrosive you must have proper package which you will not get corroded, particularly you can use gold quoted materials there for that purpose, okay.

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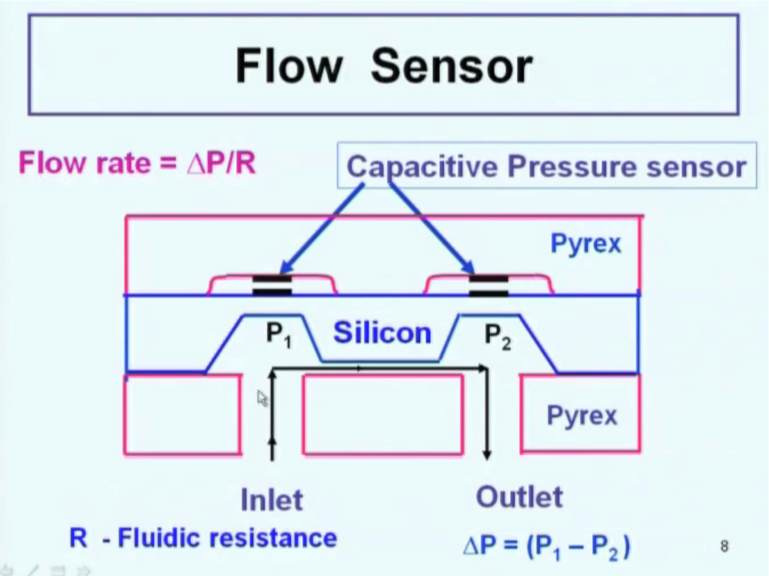

Flow Sensor

Flow rate = $\Delta P/R$

Capacitive Pressure sensor

R - Fluidic resistance

$\Delta P = (P_1 - P_2)$

Now the flow sensor I will give a schematic diagram here, this works in a principal same as you measure the current when you have a resistor you apply voltage across that the current flows voltage by resistance is the current. So here P1 is the pressure at this port I can measure it by means of the capacitive pressure sensor or pressure resistive on the beam, P2 is the pressure at the other end of this channel this is the channel.

The fluidic resistance is coming through this, the flow is due to the pressure difference okay, so because the flow is laminar you can use the relation P1-P2=delta P that divided by the resistance of the channel is gives you the flow rate like V/R is the current, so this is when laminar flow, turbulent flow this may not hold good. So usually these are all very slow moments, so flow is laminar.

Now P1 and P2 can be measured and you have to celebrate it, the R in the design you can do it by proper design of the channel dimensions. In a resistance you know that R=rho L/A, rho is resistivity, L is the length, A is area of cross-section of the resistor. Here, L is the length of the channel, A is area of cross-section of the channel, and rho is the viscosity of the fluid, so that you can measure the flow using this concept, so R is designed to get the particular values.

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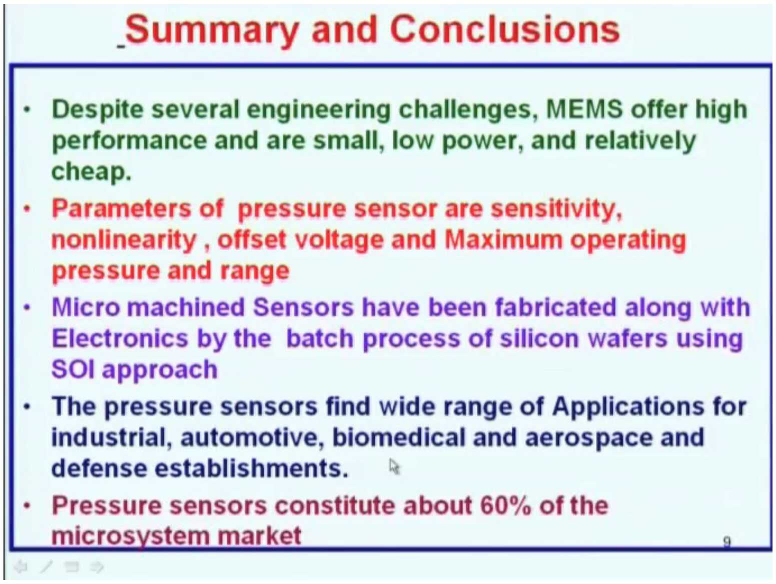

Summary and Conclusions

- Despite several engineering challenges, MEMS offer high performance and are small, low power, and relatively cheap.
- Parameters of pressure sensor are sensitivity, nonlinearity , offset voltage and Maximum operating pressure and range
- Micro machined Sensors have been fabricated along with Electronics by the batch process of silicon wafers using SOI approach
- The pressure sensors find wide range of Applications for industrial, automotive, biomedical and aerospace and defense establishments.
- Pressure sensors constitute about 60% of the microsystem market

So in summary, despite of several engineering challenges MEMS offer high performance, small, low power, and relatively cheap because it can do batch processing. Parameters important for pressure sensors are sensitivity, nonlinearity, offset voltage and maximum operating pressure and the range of the pressure, these are the specifications all that we have discussed.

And we also discussed a case study where micro machined sensors have been fabricated along with the Electronics by batch process of silicon wafers using SOI approach. The pressure sensors find wide range of applications for industrial, automotive, biomedical, and aerospace and defense establishments. In fact pressure sensors among all the microsystem’s sensors and actuators pressure sensor constitutes about 60 % of the microsystem market, because it is used in all walks of life, wherever there is pressure you need to monitor it, you need to measure it.

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References

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V.Vinoth Kumar, Amitava DasGupta and K.N.Bhat, "Processoptimization for monolithic integration of piezoresistive pressure sensor and MOSFET amplifier with SOI approach" Journal of Physics, Institute of ics Publishing, Vol.34, pp210-215, 2006

So that I close we can now see look through these references on review article which I wrote in 2007 on Silicon Micromachined pressure sensors contains most of this what I have discussed. Then for the modelling of the resistor there is a paper that is written by some of my students and colleagues and myself in the Transaction on Electron devices.

Then the integration of the Electronics that is given in this paper first paper and also this one, which has appeared in the journal of Physics in 2006, we had we also have published in the international conference in Singapore, okay.

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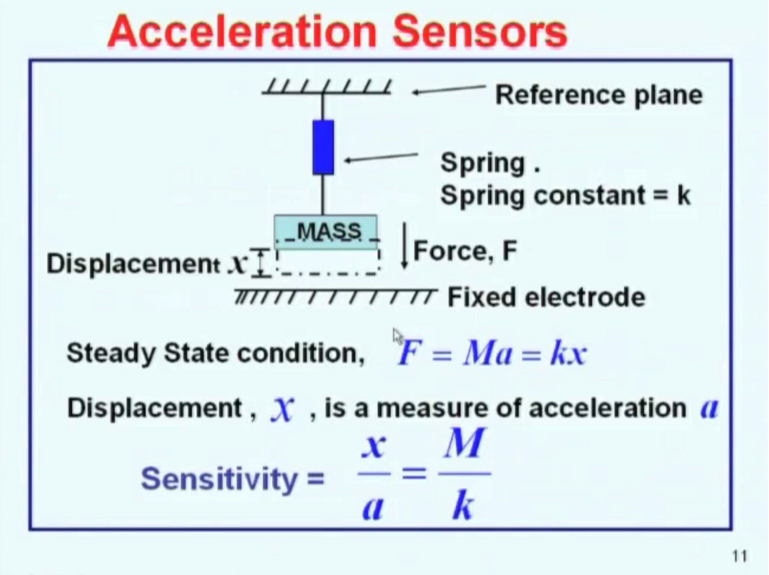

Acceleration Sensors

Steady State condition, $F = Ma = kx$

Displacement , x , is a measure of acceleration a

$$\text{Sensitivity} = \frac{x}{a} = \frac{M}{k}$$

Now (()) (12:54) we discuss another sensor that is acceleration sensor and we go through how it is processed and how it is designed okay, so the principle I am sure scenario of during the course of this series of lectures you have heard about this, the principle is the accelerometer works on the principle of spring and a mass concept, spring is anchored onto a reference plane which is rigid and other end of the spring you attached a mass so okay.

The mass will supposing this entire frame this and this are the frame, the mass can move with respect to the frame, the mass is attached only to the spring, so this mass moves in the upward direction okay, then due to the inertial force the mass moves backward frame moves up carrying the mass it moves in upside direction.

The good example of that is if you are sitting on the car suddenly if the car accelerates in the forward direction you are actually the mass attached to the frame of the car where you are sitting that is attached you move immediately to the back, so car moves forward accelerates you move backward, because you are the mass attached onto the seat. So if the frame moves up the frame carries a spring mass system, the spring move the mass moves in the upside direction.

It will move to such an extent that at steady state the acceleration is constant at steady state the displacement takes place okay, the force is experienced by the mass is force=mass*acceleration Newton's Law okay. Now what prevents it from keeping on moving, what prevents it from keeping on moving is the spring restoring force provided by the spring, how much is a restoring force depends upon, how much it is stretched, how much it is stretched it depends upon how much is the displacement.

So the restoring force is a k spring constant okay, restoring force is proportional to the displacement, proportionality constant k the spring constant so the restoring force=k*x and force experienced by the mass is mass*acceleration under steady state condition, and the force is constant you will have under steady state conditions for a given force mass*acceleration is k*x.

Which would imply I measure x that is if I measure the displacement by some means, k is a known quantity it depends upon the dimensions of the spring, and mass is a known quantity depends upon the size of the mass, a is the one acceleration is the one that you want to know. Since, the mass is known if acceleration is known force is known, so this can be either acceleration sensor or force sensor okay.

So acceleration=k*x/mass, so if you measure x you can measure the acceleration and the force, so that is the principle of the acceleration sensor or the force sensor. Now for a given acceleration you will get if you get more displacement you say that this sensitivity is more, so x divided by displacement by the acceleration is called the sensitivity of the accelerometer, so you can see that depends upon M/k ratio.

So mass is heavier for a given spring, if the mass is heavier if I have a spring like this if a mass attached to that okay if the mass is heavier it will move for a given force okay for a given force M a is constant therefore if the mass is heavier for a given system x will be more okay, so heavier the mass more will be the sensitivity. On the other hand for a given force and for a given mass M a is constant okay, so if k is smaller x will be more.

So if more flexible spring is there displacement will be more, to sum up actually sensitivity will be higher if the mass is higher or if k is smaller, more flexible spring sensitivity will be more higher the mass sensitivity will be more okay, these are the concepts in over here. Now how do you measure this x, one of the ways of doing that is put another plate here estimate the capacitance between the mass plate and the frame.

So the displacement the distance between the mass and the plate changes by distance x, if original distance is D, the new distance is D-x, so if x increases the distance between the mass and this reference plane decreases capacitance increases, so you can monitor the capacitor and say how much is that you can calibrate the sensor capacitance as a function of acceleration, so you will be able to measure unknown acceleration or force by measuring the capacitance.

Other way of doing that is piezoresistive, piezoresistance works wherever there is stress, when this spring is stretched there is stress on the spring so locate your piezoresistor on the spring, so if you located on that if the spring is stretched like that the resistance will go up, you monitor the change in the resistance you can use a Wheatstone bridge or a Half bridge as I am going to show to monitor this change in the resistance and change in the acceleration by that means okay.

The change in resistance will be related to the stress and the stress will be related to how much the spring is stretched which actually depends upon the displacement.

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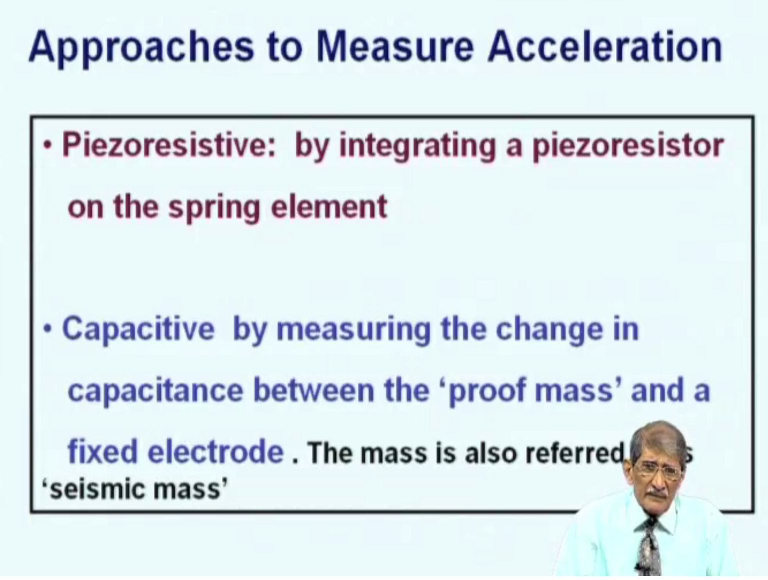

Approaches to Measure Acceleration

- Piezoresistive: by integrating a piezoresistor on the spring element
- Capacitive by measuring the change in capacitance between the 'proof mass' and a fixed electrode . The mass is also referred s 'seismic mass'

So as I pointed out approaches to measure acceleration are piezoresistive by integrating the piezoresistor on the spring element. Other one is capacitive by measuring the change in the capacitance between the mass is sometime referred to as the proof mass and the fixed electrode, this is the proof mass that is called sometimes proof mass and the fixed electrode. And the proof mass or other this mass is also called sometimes as the seismic mass.

Seismic, all of you may know may be aware it is related to the earthquake, the frequency during the earthquake is very very small, you can measure the earthquake that frequency and the force by using the accelerometer vibration of the spring mass system, that is you can measure very small frequencies see it is not just a constant force or acceleration that you are measuring.

A continuously you will be monitoring that, if there is a continuous vibration like earthquake you can monitor that by means of that accelerometer which can be used right at very very low frequencies couple of hertz that range also you can use okay.

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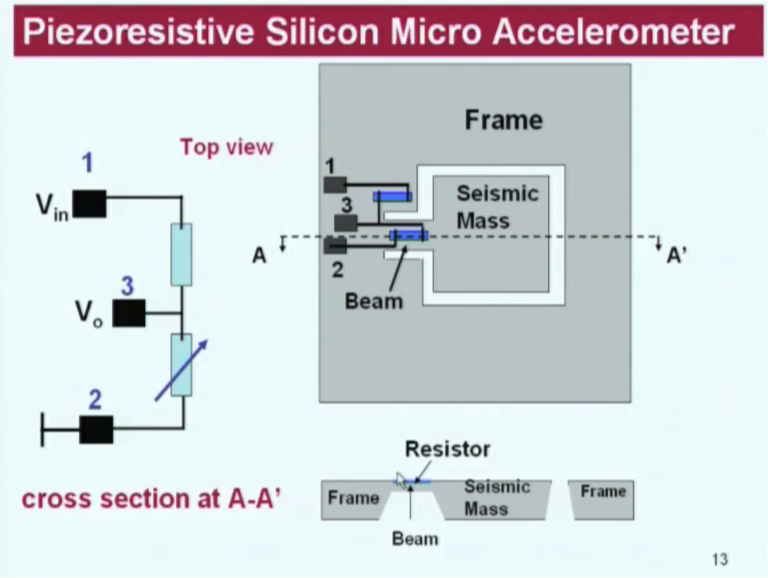

Piezoresistive Silicon Micro Accelerometer

So now let us take a look at some of these things structures, piezoresistive see this is the top view of that device, I am showing only the wafer level not package, this is the top view in which there is a grue all around white thing is the grue, this is the mass which is supported onto this frame by means of this beam, this is the fixed beam this is the mass which can actually like this.

This is mass which has a trench all round and it is held by means of a beam like this which is anchored onto the frame. So this mass can move like that and when it moves this is the beam which is holding it that will experiences the stress, you monitor the stress experience by this beam by putting a resistor there, this is the mass so around that there is a trench you can see that here the white region.

In cross-section if we take the cross-section here and as you can see this is the frame that is the depth of the frame, this is a thin beam 10 microns, 20 microns depending upon the sensitivity that is required, thicker the beam stronger are the it becomes rigid, thicker the beam more rigidities, so the sensitivity will be less, in fact the spring constant will be proportional to the thickness cubed, so if I doubled the thickness it will be 8 times more rigid

So this thickness is very important the length of the beam also will control the rigidity or the spring constant, the spring constant is the inversely proportional to the L cube okay, so if I doubled the length the spring constant will fall by a factor of 8 2 to the power of 3, so that is the idea so that is the design criterion for here, depending upon how much is stretching the resistance will change, this is seismic mass you can see this is big one the mass.

And this is attached to this but for this I am taking cross section looks as a little bit different part, if you go around it is attached. So now the principle is there are 2 resistors one on the beam, one on the outside, the resistance outside on the frame will not change its value, the resistance outside on the beam will change its value depending upon the acceleration or the force.

If the force is downwards okay from top to towards this plane of the mass the spring will get stretched and this this resistor will get stretched, as a result the resistance will change it increases its P type if its stretched, what you do is the fixed resistor which is on the anchor and this resistor are connected like together and if we apply voltage between the 2 measure the voltage across this variable resistance which is on this spring that is a beam okay, this is called the half bridge.

Full view it has a 4 resistors this has got 2resistors, when you apply the voltage Vin between the 1 and 2 terminal, between the terminal 1 and 2 and monitor the voltage monitor the voltage between the terminal 2 and 3, between 2 and 3 you will get a V0 that is the voltage across the resistor that is the calibration okay that is piezoresistive.

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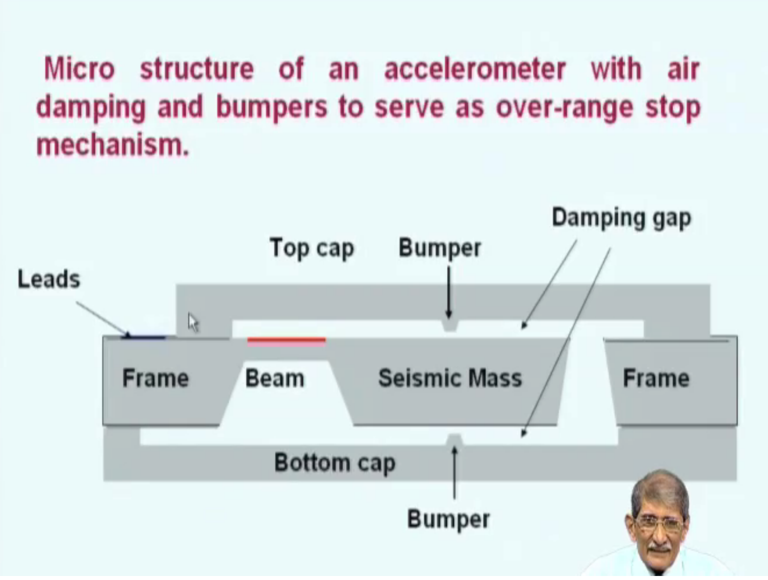

Micro structure of an accelerometer with air damping and bumpers to serve as over-range stop mechanism.

You can have sophistication on this by putting some you know top cap and bottom cab, so that you have got some air or pressure adjusted within this experienced by this mass, and the mass moves up and down, there will be some damping, that damping can be controlled by controlling the air pressure here, and also we can provide bumper here.

So that it serves as a over-range stop mechanism, so if it is subjected to more stress it will not deflect more beyond certain value, to ensure that this beam does not break by subjected to a stress, so that is piezoresistive.

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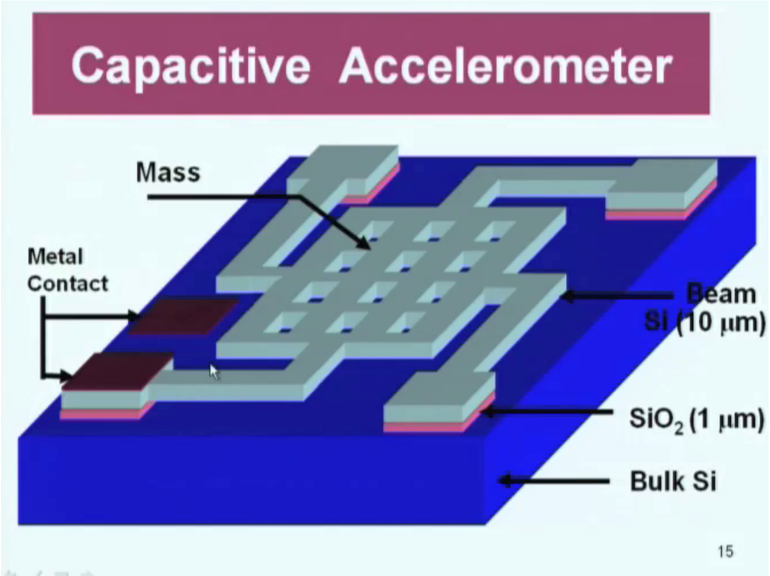

Capacitive Accelerometer

Now capacitive accelerometer okay, this is the very good example of capacitive accelerometer, this is the one case study we will study go through the process and also go through how to design that, so ultimately what you have here is a spring mass structure. Where is a mass? This square plate is a mass, the size of that in this example what we show is about 1 millimeter/1 millimeter it is a very small mass it will be micrograms mass.

So this is the square mass okay with some holes, I will discuss why those holes are provided, you can make actually the entire plate as without holes but it has some purposes okay, so that is the mass. And where is the spring? Spring in all this microstructures is the beam, so here you have got this mass okay is held by this beam and this mass is separated by this blue line by means of a gap which is about 1 micron.

You can see between this pad and this blue there is a 1 micron thick oxide insulating layer, but that oxide has been removed from this mass and this blue color, so there is air gap of 1 micron between this mass and this blue okay. So this is the beam which serves as the spring and this spring is anchored onto this frame which is rigid through this oxide, you provide this oxide to serve as an electrical isolation between the mass and the substrate which is also silicon.

This is silicon, this is silicon, this is silicon oxide and this is the metal okay, so the idea is you have this silicon mass which is about 10 or 15 micron thickness and size 1 millimeter/1 millimeter separated from the blue colored region that is silicon by a 1 micron gap that gap is your design 1 micron or 2 microns okay with air gap, and this mass is supported by means of a spring which is the beam.

The beam is anchored by means of the oxide onto this frame, the oxide provides electrical isolation between the mass and the anchor on the substrate okay. Now you can have a metal contact made onto this surface the silicon bottom plate and this top plate by putting metal on this, this is actually to sense the capacitance, so with this mass okay.

I will just again take this example where this is the mass okay, and this is the beam I sure will 2 beams, actually there are 2 beams here 2 beams here, these are the 2 beams and anchor is here, you can see that is held like this, the anchor is held here it is okay, in this case that gap is between this and this so much, but in the example that we are doing it is very very small, the gap is very very smart.

So I have anchored it there, so now what happens is if there are 4 springs 4 beams how strong it is depends upon the size of that beam and the mass you know from the dimensions of that area and the thickness and the density of silicon density 2.33 grams per centimeter cube you know the mass. So if the mass experiences a force in this direction the mass will get deflected, the spring will also move a bit like this but it is anchored at the bottom.

So the spring will move like that and the gap between the mass and the bottom plate decreases, so if the gap decreases the capacitance increases, because capacitance is epsilon 0 because there permittivity into area of cross-section of the mass okay divided by the distance, so if the force is in the direction the gap decreases and capacitance increases, d decreases capacitance increases okay.

If the force is in the other direction it will move up okay, actually as I mentioned if the entire frame is experiences down acceleration down the mass will move up, the frame experiences the moment upwards the mass will move down, the inertial forces is opposite to the direction of force okay, so what we are telling is the mass will move down if the inertial forces is down okay. Now this is you we will go through the technology how this done and how this sign is done.

Now the question is why these holes are present there? It has one technological issue that we will discuss when you go through the technology. The other issue is when this mass is moving down like that, if the mass is fully rigid this is important particularly in microsystems where the gaps are just 1 micron, so if the gap is very small okay.

If that is rigid and this is 1 micron gap it moves in the direction down in between the 2 plates there is air or even when the whole systems moving up like that there will be air and because of this air and it moves down the air filled between them will get squeezed and when it gets squeezed it tries to push it back, in the sense there is a force which prevents it from moving down okay that is called damping.

So it damps the moment in this direction, in steady state of course that damping will not come because once it has moved that will depend upon force is equal to mass and acceleration*k*x, but during dynamical conditions when the force changes that moment experiences the damping force the squeezing force between the 2 plates, this has to be taken care. Now how to reduce the damping?

Now if the plate is like this air from between the 2 had to come up only sideways through the between the 2, if there a holes between the 2 we will go back to the slide now, so if there is no hole here when it moves down, the air has to come only through the edges okay, to let the mass move. Now if the holes are present the air can not only come through this, it can come through this holes also.

You can precisely adjust the damping coefficient by adjusting the size of the hole and number of holes, this is the another design criterion which is used for designing the accelerometers. So did not may lean of if you are designed the size of the mass and size of the spring and the number of springs, more the number of springs more the rigidities, and notice is also in addition to this it is important to these number of holes and size of holes incorporated in the design okay.

Now here one more point that would like to notice is you can use this support this entire mass by means of 1 spring or by means of 2 strings, but what you have provided for what happens is if the spring constant is k1 due to 1 which depends upon the length of this beam inversely proportional to the length cube the spring constant, and the thickness of the beam directly proportional to thickness cube and the width B of the Beam okay derived before.

So B*t cube, t thickness divided by L cube divided by 4 that is the spring constant, if I put 4 of them it will be 4 times that, so that is 4 goes off beam B width*thickness cube divided by L cube is the total spring constant, it will be 4 times the spring constant of the 1, you made it rigid. But more importantly this particular sensor is used for monitoring or measuring the acceleration only in the Z direction like that.

So you need to hold it, for example if I have it like this you do not want to that if I have only 1 okay, it can experiences the acceleration that direction and move, it can experiences acceleration other direction also like that or like this. So in order to ensure that the acceleration is experiences in only that direction you hold it rigidly from all the 4 directions, so that it does not waffle like that or like that it will move only in that direction.

So to ensure that you have put this flanges or springs or beans in all the 4 directions, so now with using one of the sensors you can measure the acceleration in that direction. If you want to measure the acceleration in that direction in a navigation applications then you must put a sensor in that direction which can move in that direction okay, and the other direction you would put. So

3 different sensors mount in different directions oriented in different directions attached onto the frame of the navigation system, okay.

Now otherwise there are also sensors 3 axes accelerometers with one design you can ensure that the acceleration is measured in all the 3 directions, best thing is to mount it on a single page have it all in 3 directions measured okay, that is the basic idea of the accelerometer dealing with everything.

Now this structure so when it deflects upper down the capacitance between this plate and this bottom plate changes and that is monitored by measuring the capacitance between this metal contact and this metal contact, and you notice it is a capacitance changes that is coming out to measure that you must convert that change in capacitance to voltage, you definitely need electronics for converting this capacitance into voltage.

So in the capacitive sensors you definitely need electronics okay, we will come back to this later after discussing the sensor part okay. Now we will go back to this and also the electrical isolation provided by this, there will be the capacitance now will be the capacitance between the plate and this bottom plate allow in parallel to that, the stray capacitance which is the capacitance of this pad with respect to the bottom plate, that does not change that it is a oxide.

So you do not want to make this pad very large at the same time you cannot afford to make it very small due to technological constraints, so we will see we will go through technology quickly using Silicon on Insulator approach, we will see why this holes are required for technological purpose okay. We have discussed why from the design consideration is required to control the damping.

And from technological considerations you cannot make it very small though you prefer this to a very small to reduce the capacitance stray capacitance, because stray capacitance will depend upon the area of this pad, and this pad will be used for the mounting wire from to that okay, and this anchor region also should be sufficiently strong enough if it is too weak it will come out from there also. We will see what are the reasons for that? Okay.

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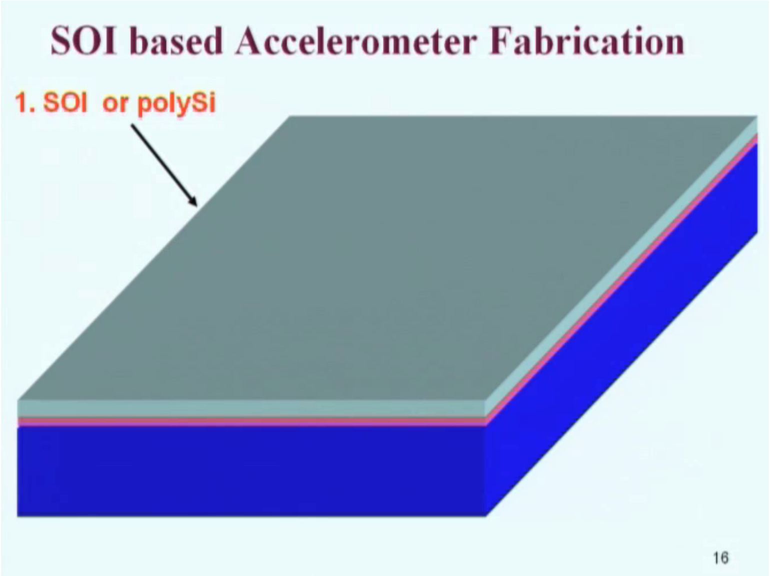

SOI based Accelerometer Fabrication

1. SOI or polySi

So what we will do quickly is go through that process steps, how is the process step is done, start with the Silicon on Insulator wafer. I discussed this portion in my previous lecture on piezoresistive pressure sensor, I discussed how to realize the silicon on the oxide insulator SOI wafer or you can buy commercially also. Commercial wafers are available okay, smart cut wafers they are called Sai Tech is the company which sales this okay.

You can actually ask for what is the thickness of this silicon layer on the top, what is the oxide thickness because after all the thickness of this top layer will decide how much is the thickness of this mass okay, you are realizing this mass using the SOI layer and this oxide between the anchor and this bottom plane is the buried oxide. So what you do if you check this wafer I am showing it as a square it will be easily a circular wafer.

I am showing one cut piece of that wafer, so that you can go through the process of one device simultaneously number of devices are being process okay.

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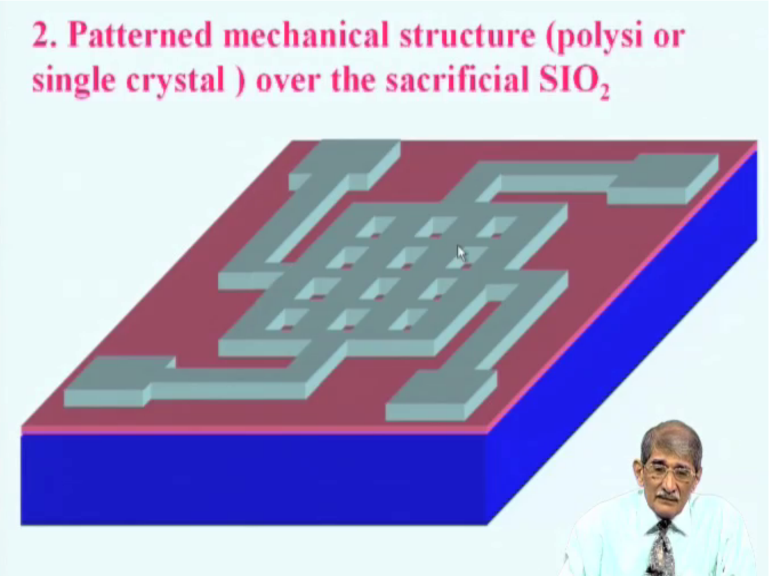

2. Patterned mechanical structure (polysi or single crystal) over the sacrificial SIO_2

So what you do is do a lithography on this and etch this top wafer the green color like that, by a lithography you can etch this whatever was this color throughout has become like this, now you can see you made holes in that silicon layer by means of this etching and you have define the beam you define the mass, but this red color oxide is not etched on, there is a very good selectivity between the silicon and this oxide.

We use the KOH etching the oxide does not really get etched much it is a very slow rate at which it is etched or you can use other etchings like TMAH it will not attack liquid oxides at all okay. This is you can do that anisotropic etching or die etching reactive ion etching you can do, you can get the entire pattern transferred from the photomask onto this layer like this. Now what you have to do is you can see now why these holes are required.

You have to remove these oxides from everywhere, so that this entire mass, spring everything is released that is the surface micromachining approach is released that is it is released from the bottom wafer, you remove this oxide that is etched oxide from everywhere except under these pads that is these 4 anchor agents you retained that oxide below that.

Now if I do not have these holes which I require holes for adjusting the damping but from technological constraints if you do not have these holes say this is 1 millimeter/1 millimeter, I will kept this let us say 0.2 millimeter/0.2 millimeter by the time if I do not have the hole, you can see if I have these mass like that if I have the mass when I etched from the top the etching fluid has to enter from here go underneath that and etched rate of that oxide is very very small maybe about 0.1 micron per minute.

So 1 millimeter will take several hours to go through that, it was just go from here from that side and this side, now if I have a number of holes everywhere the fluid can not only enter here it can enter through other portions also there, and it can start etching both. You can see in the diagram more clearly here if you see the fluid can enter onto the edges get start etching sideways underneath this plate.

If you do not have the holes it will take the long time it has to go half a millimeter from this side and half a millimeter this from side, but by the time it has gone through some distance you can see this is only 0.2 millimeter, so by the time you etched 0.1 millimeter the oxide underneath has etched completely, so that means this anchor will not remain by the time you etched this oxide underneath the mass okay, and it will take enormously long time.

So if you put this holes the liquid is etched is hydrochloric acid dilute or buffered that can enter here and also it can enter through these hole, so the gap between these can be kept says about 100 microns. So by the time 50 microns from this side, 50 microns from this side it has gone through all the way, by the time you etched 100 microns this one it also etched 100 microns here.

So by the time you etched 100 microns the entire thing will be released, that means actually when you etch this underneath this if this is about 200 microns okay, 50 microns will go this side both sides it will go order all around 50 microns, so if it were 200 microns the anchor will be 100 microns/100 microns it will still hold in position.

So that is what you see here just watch carefully, now I am subjecting it to etching so that this red color will go from everywhere that is oxide is etched, so that this mass is separated from this blue color by 1 micron except underneath this oxide there that is it.

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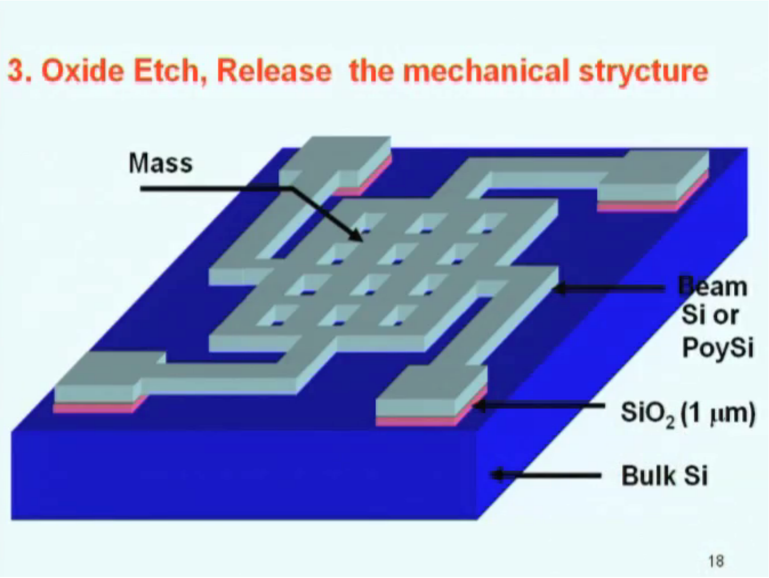

3. Oxide Etch, Release the mechanical stryucture

The oxide from everywhere is gone and this red color is there underneath, in fact this red color will not be all through this area if I could not show it, this will go slightly inside undercutting will be there by about 50 microns if his gap is 100 microns by return which 50 microns it would have released, so 50 microns will go undercut will be there. But still this is be anchored okay, that is the reason why you have the hole here plus you cannot make this too small,

If I make this 100 microns by the time this has etched 50 microns the oxide will be undercut that 50 micron from this side 50 micron from this side that is 100 microns. So the entire oxide will go, so actually what will happen will be your mass which is held here supposed to be anchored here this anchor collapse and this will go on like that. So the entire mask will fall down onto the surface, you will not have the accelerometer okay that is a thing.

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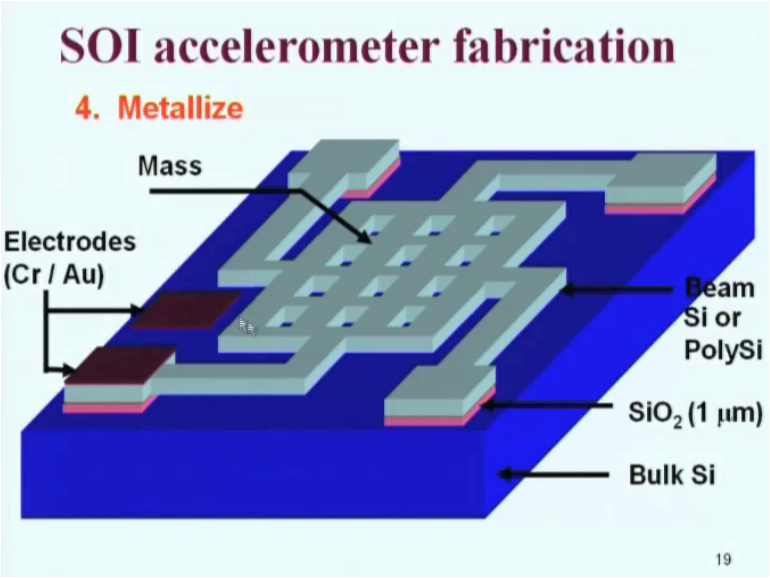

SOI accelerometer fabrication

4. Metallize

Now you can actually after releasing that you can put a metal contact on to that this structure is complete, so this is this can be used as an accelerometer or this can also be used as a variable capacitor that is it can be used as a sensor or as an actuator. Sensor senses the physical phenomena gives some output which can convert it into electrical signal. Actuator uses electrical signal converts it into mechanical signal okay.

So the actuator here will be if I apply between voltage between these 2 plates there will be electrostatic force between this mass and the substrate, if there is electrostatic force that is always a force of attraction, so the mass will move down if the mass moves down the capacitance between the top late and the bottom plate will increase, so if I apply voltage between these 2 plates okay the capacitance will increase.

So that means if I vary the voltage the capacitance will vary, you use it as a variable capacitance or a varactor, this can be used in as a filter in the filter circuit for RF applications okay. So that is the varactor that is the actuator, but what we are talking of now is the opposite of that. That is the accelerometer which is a sensor where it experiences the mechanical sensing acceleration and gives an electrical output capacitance output okay.

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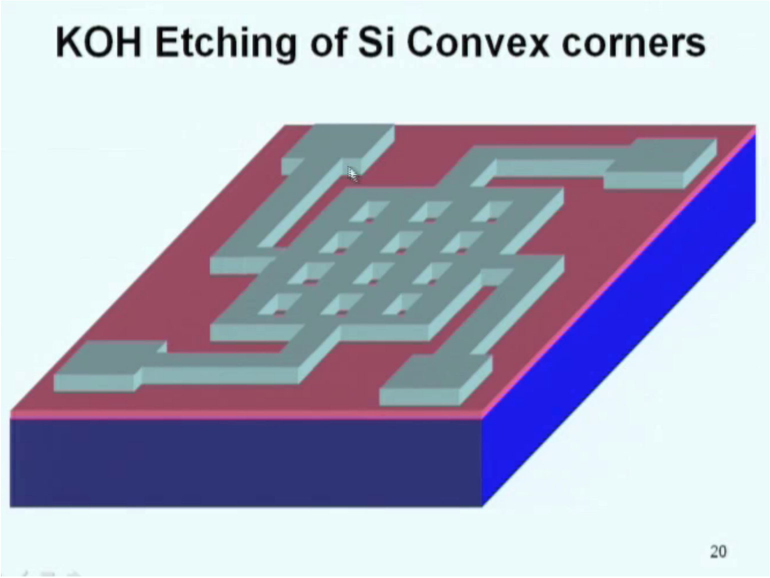
KOH Etching of Si Convex corners

Now we will go to some small things one has to remember, when we do this KOH etching see these are all particular planes 111 lines and 111 planes which are getting etched, but that will not be vertical going at an angle guided by the 111 planes, but this corner will get like that rounded off.

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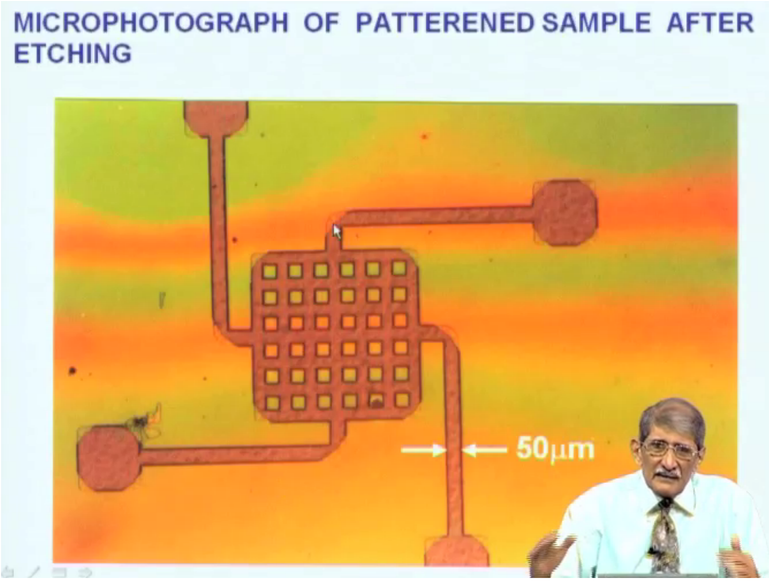
MICROPHOTOGRAPH OF PATTERENED SAMPLE AFTER ETCHING

If you use KOH etching straight away that is the problem with this etching if you have this corners plane surfaces in this it is concave the angle is <90 degrees or 90 degree, here the angle is >90 degrees okay, so that will be cornered there that will get rounded off, so if that corner get rounded off you can see the beam can get etched completely and the entire mask can collapse.

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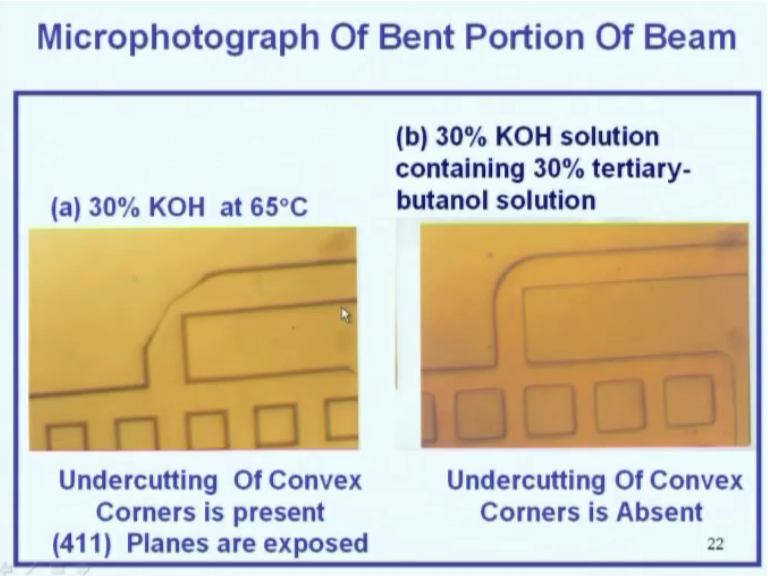

Microphotograph Of Bent Portion Of Beam

(a) 30% KOH at 65°C

(b) 30% KOH solution containing 30% tertiary-butanol solution

Undercutting Of Convex Corners is present
(411) Planes are exposed

Undercutting Of Convex Corners is Absent

So what you do is you use some tricks like this is the beam get etched rounded off there that is a chemistry involved, you can overcome that by adding 30% tertiary butanol alcohol to this KOH then I am not going to mixed over that it will not get rounded off it will get closer to this sharp corner, it will not be sharp like this but still it will be etched like that.

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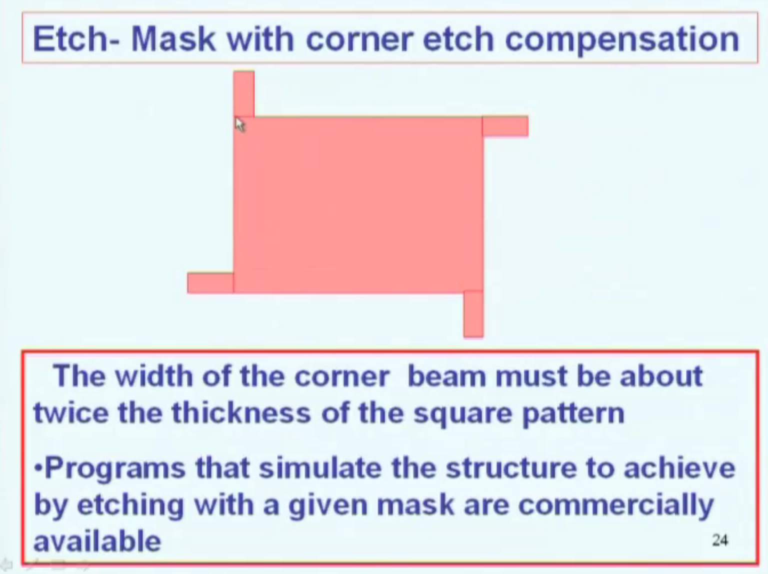

Etch- Mask with corner etch compensation

The width of the corner beam must be about twice the thickness of the square pattern

- Programs that simulate the structure to achieve by etching with a given mask are commercially available

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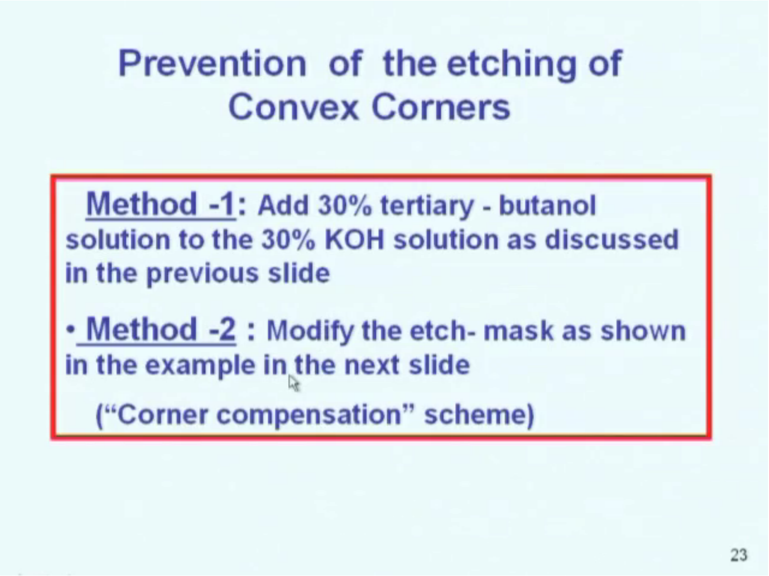

Prevention of the etching of Convex Corners

Method -1: Add 30% tertiary - butanol solution to the 30% KOH solution as discussed in the previous slide

- **Method -2** : Modify the etch- mask as shown in the example in the next slide

("Corner compensation" scheme)

Alternately, you can do a mask design like this is, these are whatever I have said is written there or modify the mask here like this, in the mask you should have providing it rounding it square like that put a projection like that, so that when it gets etched finally you will get the square pattern like that okay. That will be more involved I would prefer to use this etching solution change, so that you get this etched only partially okay.

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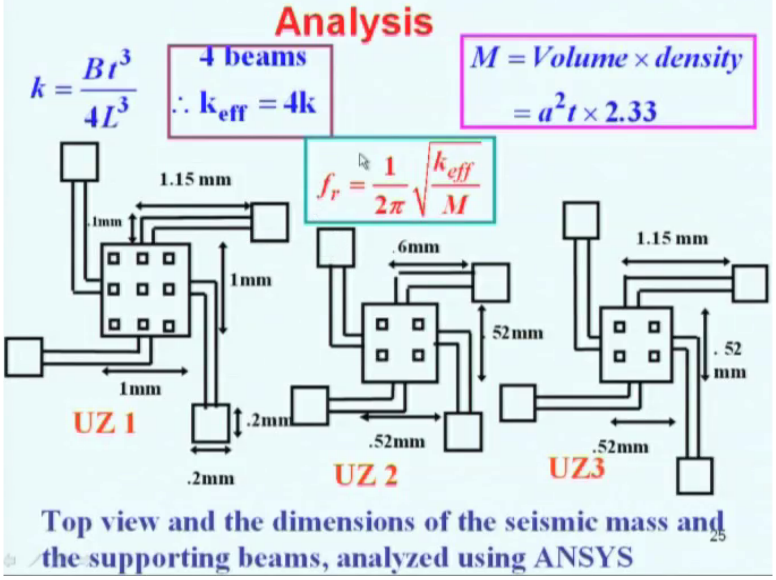

Analysis

$$k = \frac{Bt^3}{4L^3}$$

4 beams

$$\therefore k_{eff} = 4k$$

$$M = Volume \times density$$
$$= a^2 t \times 2.33$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{M}}$$

Top view and the dimensions of the seismic mass and the supporting beams, analyzed using ANSYS

Now I will go to the last phase of my lecture today that is on the design analysis. I will show the mass, the beam, mass of 1 millimeter1 millimeter, the beam which is 0.1 millimeter +1.15 millimeter and this is a pad which is just fine 0.2 millimeter/0.2 millimeter that is 200 microns that is one. Here, you can see the spring constant depends upon the width and thickness cube which you are chosen here as 10 microns and the length cube.

So 3 different designs just to see what will happen and you can see the holes also are there, in this first UZ 1 design the length is 1.15+1.1 this is 1 millimeter/1 millimeter. If you go to the UZ 3 length is the same, beam length is the same, but the mass is made by half, so in fact you will see later on when we see dynamics the resonance frequency.

The any mechanical systems will have a resonance frequency if you keep on vibrating it, it is vibrate with certain amplitude but if I keep on increasing the frequency of vibration 1 when the rate at which are vibrating it, the frequency of the force matches with the resonance frequency of this system the amplitude will become more, that is the resonance frequency okay. That resonance frequency is proportional to square root of k/M.

You saw that the sensitivity is proportional to M/k, I am used to here k effective because k of 1 spring is given by this expression, it is 4 times that k, k if it is 4 times k okay, now what we have comparing is this, same length, same length with the UZ 1 and UZ 3 only thing is the area you have reduced. The mass is proportional to volume*density volume is side length a square into the thickness.

So here if I have reduced this area of the mass, what will happen will be the mass will be reduced by a factor of 4 if I reduced it by a factor of 2, the side length is reduced by a factor of 2, so the area is reduced by a factor of 4, so the sensitivity will actually increase by a factor of 4 but the frequency of resonance will reduced by a factor of square root of 4 that is 2 okay. So this is another dimensions where both are changed that is both this, this and this are reduced.

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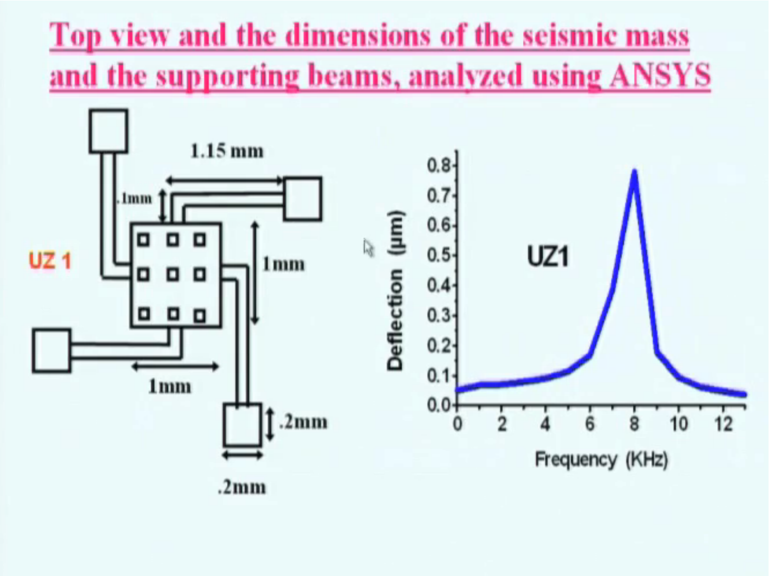

Top view and the dimensions of the seismic mass and the supporting beams, analyzed using ANSYS

Let us compare the one of them first, the first one is that this one that has got resonance frequency of about 8 kilowatts see the deflection vibration like that is almost flat in that frequency, then it goes up at resonance frequency, the resonance frequency is given by this formula. Mass is reduced by a factor of 4 okay the resonance frequency will go up by factor of way fact the corresponding to that.

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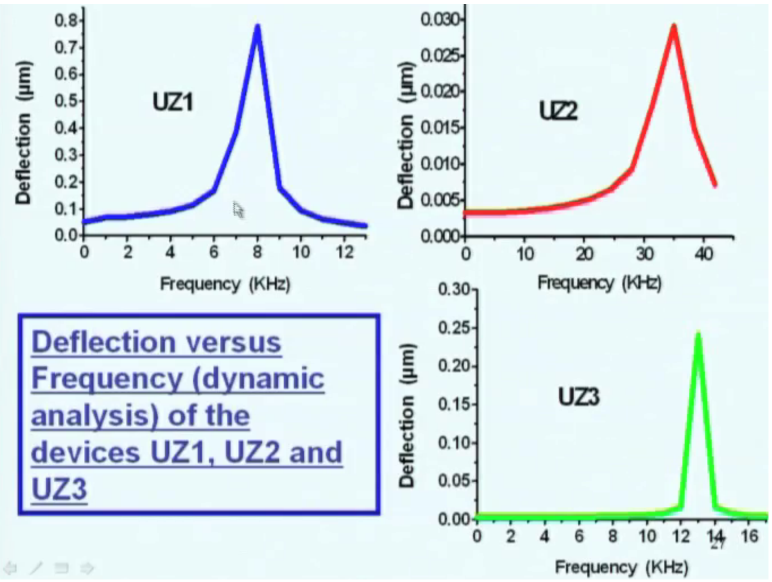

Deflection versus Frequency (dynamic analysis) of the devices UZ1, UZ2 and UZ3

So here you can see this mass okay is in this case just to take this example just let us not worry about the numbers here, the resonance frequency is 8 here, in the other case the mass is reduced okay therefore the frequency has gone up. In the other case mass is reduced I will not be dabbled with numbers at this moment, the mass is reduced frequency will go up. Spring constant is increased by reducing the length I am sorry if we increase the length spring constant is reduced okay.

So you will just see I am just not descramble on both these things we will come back to this in our next presentation, what I am trying to point out is by changing the proper design we will come back to this in our next lecture. By changing the proper design the mass you can by change, we can change the frequency, we can change the sensitivity, we can change the length, and we can change the spring constant okay.

For example, if I reduced the length spring constant will go up, so if I reduced the length spring constant will go up by this factor, if spring constant goes up the frequency of resonance will go up, so between these 2 I have reduced that length. Therefore, the resonance frequency has gone up drastically okay, so you can see from 8 it has gone to 32, so that is what we are trying to see here.

So you can use this whole thing to illustrate, we will come back to this again to start next time, so that once again we will just go through this quickly right when you are fresh in the beginning of the lecture. So I have shown the 3 designs where I can change the beam length okay, here I changed only the mass reduced the mass, so that the frequency will go up.

See here, here I have not only reduced the mass reduced the length also both increase the frequency drastically, only the mass reduced spring constant will go up by some factor, both mass is reduced and also this length is reduced that is the spring constant is increased the frequency goes up drastically, so actually I will show you okay here this is for the design.

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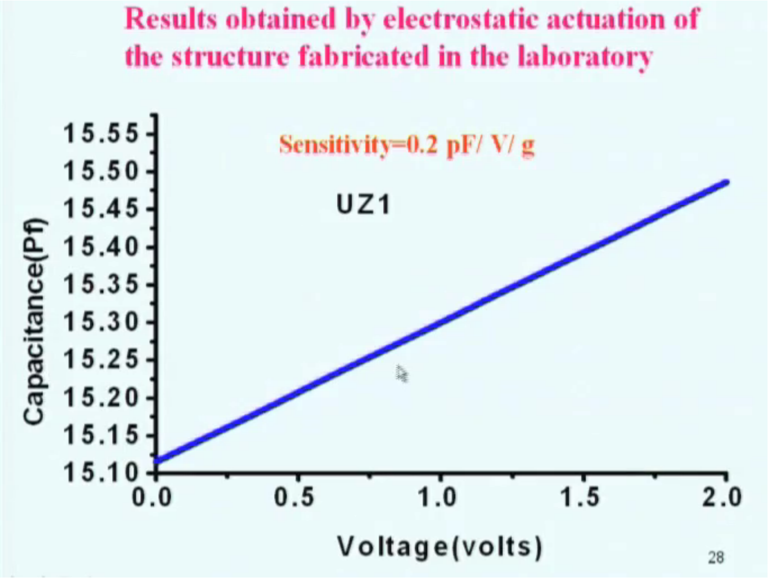

Results obtained by electrostatic actuation of the structure fabricated in the laboratory

Now you can see the capacitance you can just to test it, you can change the voltage across this sensor, apply the voltage between the 2 here you can apply the voltage between this and this and see how the capacitance will change that is what we plotted here. So you can see capacitance versus voltage take a capacitance 15.1 picofarads it can change the voltage from 0 to 2 volts the capacitance changes by 0.45 picofarads very small values changes, sensitivity the correspondingly change that to acceleration it turns out to be 0.2 picofarads per volts per gravity.

I will continue on this more about this acceleration sensor briefly about this particular sensor, and I will take on the other sensors ADXL in the next lecture, thank you very much.