MEMS & Microsystems

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Lecture No. # 21

Micromachined Micrometer for MEMS

I remember that I discussed on the inertial sensors. As an extension for inertial sensors, today I will concentrate on a particular inertial sensor which has got lot of importance and application also, that is accelerometer. So micromachine accelerometer for MEMS, so I will briefly discuss on that, after that I will go for a case study. Detail discussion on design aspects, development, packaging and fabrication of MEMS accelerometer for various applications. Detail case study I would like to make only one device in this lecture series. That is accelerometer. So it will take may be 2, 3 lectures. But today just for a background of that case study I want to discuss on the MEMS accelerometers in particular, its classifications and its basic principle and what are the various aspects of the accelerometer.

(Refer Slide Time: 02:00)

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Conventional Acceleration Sensors

- Made of bulky, heavy metal parts
- Based on electro-mechanical principle
- Requires higher operating voltage / current
- Needs careful maintenance and calibration
- Highly expensive, not throw-away type
- Very high sensitivity / large output

S. KAL Micromachined Microaccelerometer 2

Now if I go for micromachine accelerometers, obviously a thing is coming in your mind. What is the difference in micromachine and conventional accelerometer? It is not that true, that the accelerometers we are making first times and micromachine accelerometer, before that it was not there. For long time, last 25, 30, 40 years accelerometers are there. But those are bulky accelerometers conventional and these are made of heavy metals. Different small parts are integrated and to make those kind of accelerometer and these are basically made from electromechanical principles. Mechanical parts are there as well as electronics is there and each weighs several kilos like that and you request a higher operating voltage and also current. Obviously you need larger power for those kinds of accelerometer. It also needs careful maintenance and calibration time to time heavy mechanical structures are there. Obviously maintenance part will be there and with frequent use here we need calibration of those devices after certain period of time. Those are highly expensive because it is not throw-away type. If something goes bad, it repairs. Because it is very expensive and those bulk conventional accelerometer acceleration sensors are highly sensitive and it always gives large output in compression to it micromachine accelerometers.

(Refer Slide Time: 03:47)

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Micro-Electro-Mechanical System (MEMS) Accelerometers

- Micro-size, light-weight
- Batch fabricated by advanced microfabrication technology
- Low cost, throw-away type
- Low voltage / power, compatible with IC chips
- On-chip integration, smart, intelligent, reliable
- Replacing majority of conventional systems

On the other hand if you compare those conventional accelerometers with micromachine accelerometers the following points are coming in our mind. That has, those are micromachine accelerometers are micro size light weight. Obviously you are making use of silicon, small amount of silicon to make the complete the structure. It is batch fabricated by advanced microfabrication technology. Because of that, obviously it will be of low cost and it is thrown away type. It something goes bad, you throw away, you take a new one. There is not change of repairing those micromachine or MEMS accelerometers which is possible in conventional heavy bulk micro accelerometers or accelerometers, obviously sense the MEMS accelerometers are smaller in size. So it operates in a low voltage and low current and so the power consumption is extremely small. That is one biggest advantage.

When you are going to put those accelerometers, you need number of pieces for microsystem and individual piece if requires a considerable amount of power, total power requirement of the system is will be very high and many cases those accelerometers are used either in avionics or aerospace or say missile program or anywhere. So their power consumption, an important issue, so always people look for low voltage, low power circuits, low voltage, low power devices. Not only that now days the time has come, that everything operated in a remote. A remote control system and not only that you say many cases we use some hand held systems. So those cases obviously power consumption is an important criterion. In that respect the MEMS accelerometer has certain advantages on chip integration smart intelligent and reliable. That is obviously an advantage and is a great advantage. Because you can on chip on the device side you can integrate its signal processing circuits replacing majority of the conventional system by the MEMS accelerometer nowadays.

(Refer Slide Time: 06:10)

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Micromachined Microaccelerometer

1. Piezoresistive Microaccelerometer
2. Capacitive Microaccelerometer
3. Tunneling current Microaccelerometer

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Now there are three broad kinds of microaccelerometers. Obviously there are other kinds which are not that much popular, I will discuss one by one. Out of the different microaccelerometers MEMS accelerometer, three are very important which are one kind is based piezoresistive microaccelerometer. The second is capacity microaccelerometer and third is tunneling current microaccelerometers. So first two piezoresistive and capacitive accelerometers are meant for higher Gs. But the third kind tunneling microaccelerometers meant for low G. In some cases milli G or micro G level acceleration can be sense by tunneling current microaccelerometer. So the basic principle of those three, I will discuss.

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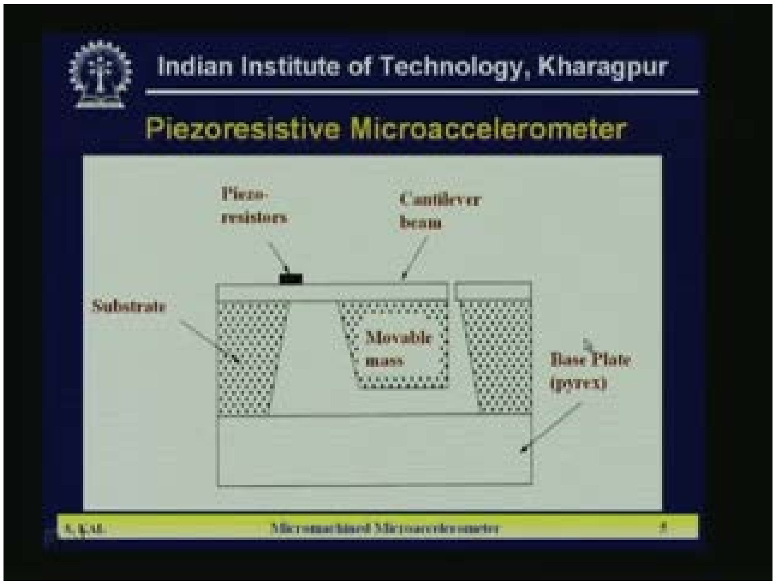

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Piezoresistive Microaccelerometer

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This is one, the piezoresistive microaccelerometer in general form I am talking. There what is there you see, this is substrate and this is the moveable mass and here is the cantilever beam and this is the piezoresistor and in the bottom page is Pyrex plate is there. So it is bonded, 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 you stress in the beam, we will change and because of if you put a piezoresistance there. 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. But there are lot of modification for different for getting certain improvement or certain specific performance of an accelerometer for specific application those I will highlight in subsequent classes. So general structure is like this.

(Refer Slide Time: 08:29)

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Piezoresistive Microaccelerometer

Principle: As 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 piezoresistors. These piezoresistors are generally placed at the edge of support rim and proof mass, where stress variation is maximum.

Next principle is mentioned, what I have just told you, as 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 piezoresistors. These piezoresistors are generally placed at the edge of support rim and proof mass where stress variation is maximum. At the edge of the support beam, that particular edge or location you have to find out and that requires a rigorous analysis of the structure. That is stress analysis of the structure that normally we do with the help of certain software.

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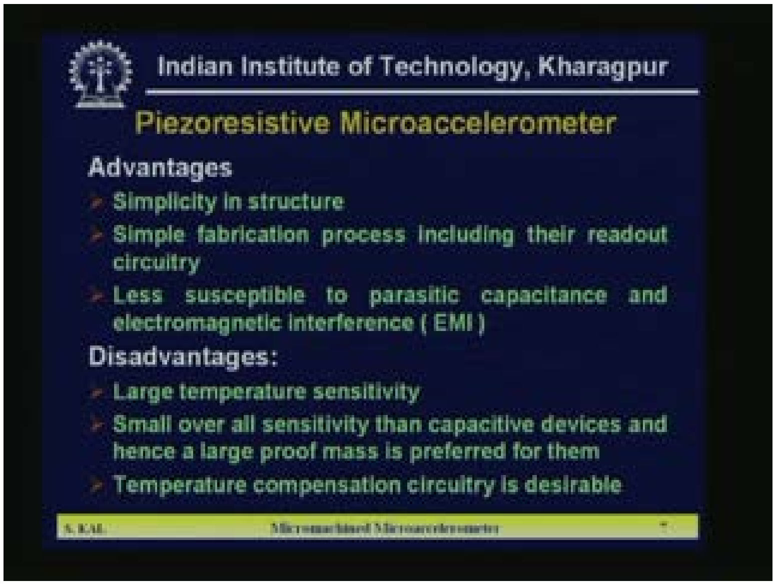

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Piezoresistive Microaccelerometer

Advantages

- Simplicity in structure
- Simple fabrication process including their readout circuitry
- Less susceptible to parasitic capacitance and electromagnetic interference (EMI)

Disadvantages:

- Large temperature sensitivity
- Small over all sensitivity than capacitive devices and hence a large proof mass is preferred for them
- Temperature compensation circuitry is desirable

Now this kind of piezoresistive accelerometers if I compare with other kind capacitive or say tunneling current microaccelerometers. So it is a simple in structure. Simple fabrication process including their readout circuitry compare to capacitive and also to some extent tunneling. Tunneling is also simple but capacitive is not that much simple. It is less acceptable to parasitic capacitance and electromagnetic interference. That is one important aspect. If you those kind of accelerometers in space then obviously the EMI EMC problem we will have to look into because of that some parasitic your stress signal you can pickup because EMI and EMC problem and sometime if you electromagnetic interference is much so that may change the performance or total readout electronics or total the output which you are getting out of the accelerometers may change little bit because of that problem. You have to take care of those and it is also less acceptable to parasitic capacitance and it is also an important phenomenon because we know the output of those kinds of MEMS accelerometers are very small.

Its signal is very much negligible in the range of the milivolt or microvolt, in case of pick current sense it is a picoampere or say microampere range. So there you have to take care. Their parasitic signals should not be comfortable with that. With that means what? The output of these accelerometers. So that is in that respect it has got advantage. Senses parasitic capacitances are not coming into the picture in case piezoresistive cases. But it has got disadvantage also. Those are large temperature sensitivity. Because we know piezoresistance, resistance because of the change mobility I will discuss in detail that temperature compensation as well as the temperature drifts in case of these piezoresistive devices. So with temperature lot of changes will take place inside the crystal. So far strain is concern, so far stress is concern, and so far mobility is concern.

So because of that the output may change and that output will 100 percent not signify the input variation or G variation, so that is one disadvantage. Small over all sensitivity, then capacitive devices small over all sensitivity then capacitive devices and hence a large proof mass is prepared for them. If you want to increase the sensitivity of this kind of structures. One aspect is you have to increase the mass of the proof mass and in that case it will be not much integral compare to others. So that you can say it is a disadvantage. If you want to increase the proof mass, obviously either thickness of the proof mass remover or the area of the proof mass will be more. That means it requires larger silicon area. So that is obviously, this is not a good point. So temperature compensation circuitry is desirable in this kind of sensor which is not desirable in capacitive cases.

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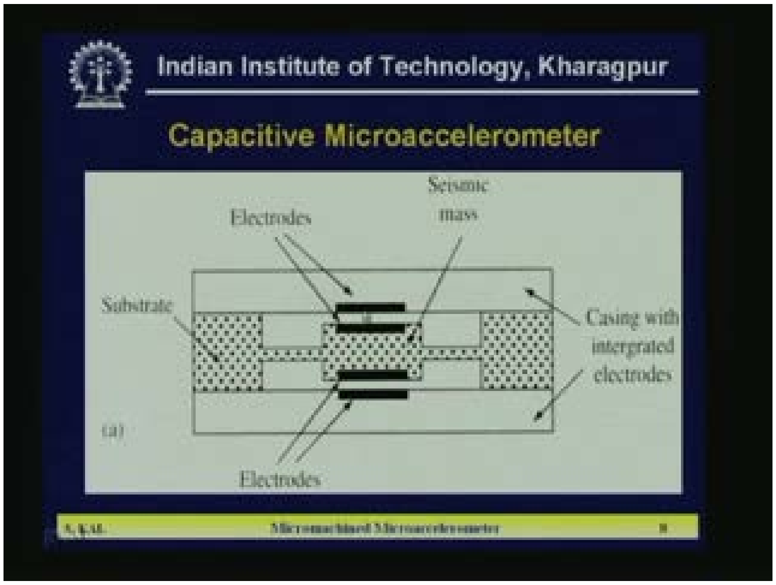

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Capacitive Microaccelerometer

So now capacitive microaccelerometer, simple structure is here in the diagram you can see. So what is there is kind of structure. 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, that is a capacitance and bottom also there is another capacitance. So if you bond the middle structure also with the top and bottom the cover plates then two capacitance C_1 and C_2 in one capacitance will increase another one decrease. So because of the moment 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 where reduce bottom one to the capacitance will increase and top electrode this capacitance will decrease. So that means there is difference will increase delta C if we take the difference between one another. So that if you consider the differential techniques in this particular case top and bottom, then you can avert some sort of the parasitic capacitance also. So this is the basic structure of that.

(Refer Slide Time: 14:37)

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Capacitive Microaccelerometer

Principle: In presence of external acceleration, the support frame of accelerometer moves from its rest position. As a result the narrow gap between the proof mass and a fixed conductive electrode changes which in turn changes the capacitance formed between them. This change of capacitance can be measured using electronic circuitry.

S. KAL Micromachined Microaccelerometer 9

And here 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. So that is the basic principle.

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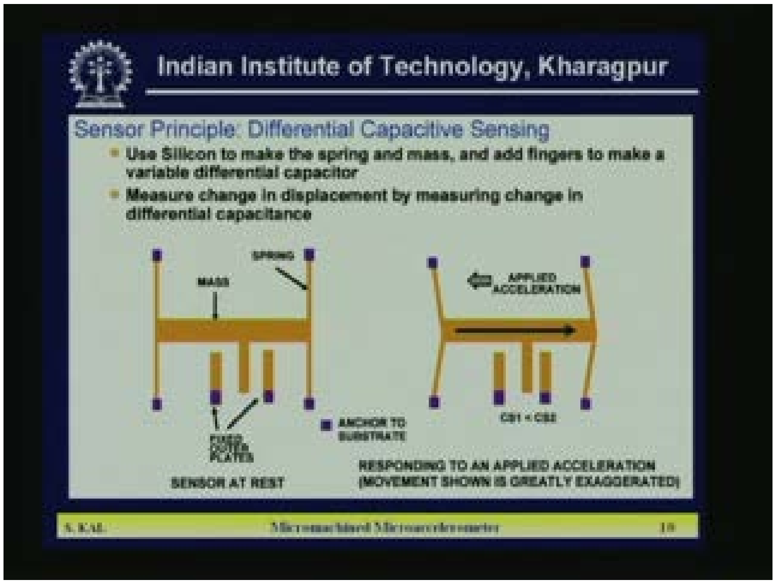

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Sensor Principle: Differential Capacitive Sensing

- Use Silicon to make the spring and mass, and add fingers to make a variable differential capacitor
- Measure change in displacement by measuring change in differential capacitance

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Now there is another kind of accelerometers are available nowadays which are basically the comb type accelerometers and those are made using surface micromachining technology and here this kind of structures are preferable when you want to integrate the readout electron circuitry and the sensing part together over a small area on that top surface of the silicon.

Here silicon is use as spring and mass section and you can use the inter-digital structure some fingers are there and the fingers will make the variable capacitance. There are two things one is this spring and the mass and these are fixed outer plates. So now you can see if these springs, as mass if it moves in this direction, so these are the fixed electrodes. So there what will happen? If this moves, some of the central electrode is fixed with that. So if you say CS1 the capacitance of this part and CS2 is a capacitance of this part. So the gap increases, so obviously CS1 will reduce and the here gap reduces the CS2 will increase, this capacitance will increase. So as a result of which you will get a differential change if this things moves there so it can be made if it is an inter-digital in the surface also and it can be made as a bulk also.

Both were possible but are a preferable. It is easy to make using surface micromachining technology at the surface itself and if you use the lot of fingers together, there will be lot of parallel capacitance. If you add together, so that total capacitance value will be more and as a result of which sensitivity, change of capacitance was will be more or that means small acceleration also you can sense with this kind of structure. So that is inter-digital kind of structure. In some case there are two kind of methodology is followed, in some cases the mass and spring is fixed so and this fingers are moving. In other case the fingers are fixed and the mass and spring will move both are possible for different application and both have got certain advantage and disadvantage. So change in displace will basically change. Change of displacement means it will change the gap between the two electrodes. So as a result of which the capacitance will change and this is also differential capacitance. You can see one capacitance will increase another will decrease. So that we need for removing or eliminating some for the parasitic things.

(Refer Slide Time: 18:02)

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Capacitive Microaccelerometer

Advantages

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

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Now here the advantages are it is low temperature sensitivity. Obviously the capacitances, the principle, what I discuss that is not depend on temperature. So low temperature sensitivity good

DC response and noise performance low drift high sensitivity and low power dissipation. So these are the some basic advantages of the capacitive microaccelerometer.

(Refer Slide Time: 18:28)

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Capacitive Microaccelerometer

Disadvantages

- ☐ Very difficult to eliminate parasitic components
- ☐ Susceptible to electromagnetic interference (EMI) which can be addressed by proper packaging

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Disadvantage obviously the parasitic components and the EMI electromagnetic inference problem which can be address by proper package. So EMI, EMC only can be eliminated by a special kind of package which will not allow changing the signal on the EMI or electromagnetic radiation which is very high in the space.

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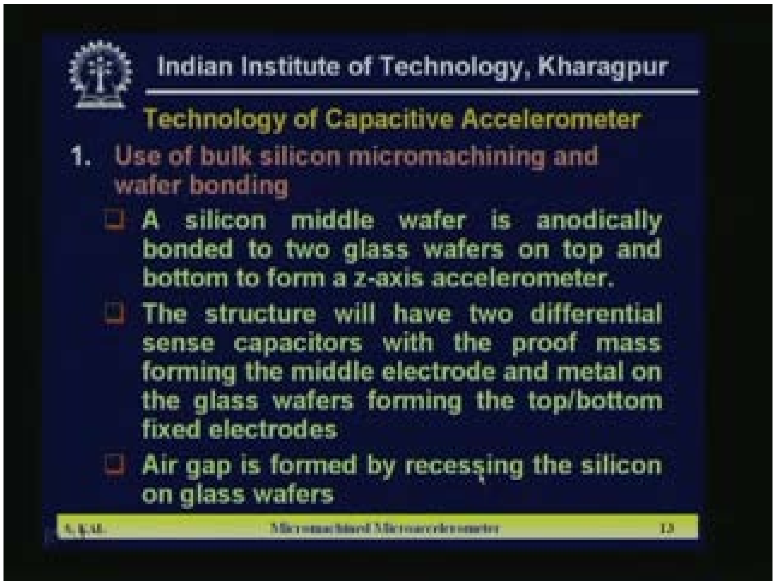

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Technology of Capacitive Accelerometer

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

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So now the capacitive accelerometer they use the bulk silicon micromachining and wafer bonding. A silicon middle wafer is anodically bonded to 2 glass wafers on top and bottom to form a z-axis accelerometer. The structure will have two different differential sense capacitors with the proof mass forming middle electrode and metal on the glass wafers forming the top bottom fixed electrode. Air gap is formed by recessing the silicon on glass wafer. So that is the wafer bond and silicon micromachining. Both are required not only that glass recessing which I which is mention is the third point. So that means you need micromachining of glass also before bonding. So silicon as well as dark glass, both micromachining techniques has to be standardized for making these kinds of accelerometer.

(Refer Slide Time: 19:56)

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Technology of Capacitive Accelerometer

2. Same as scheme 1 but using all three pieces made of silicon

This will reduce its temperature sensitivity long term drift

- Incorporation of damping holes in the proof mass to control damping
- Use of second silicon wafer bonded on top to provide over range protection.

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Now there is a second approach where we use the same scheme one but using all three pieces made of silicon. This first one are those are made the two are glass and bottom is silicon. But in this case the all you can make silicon. This will reduce its temperature sensitivity long term drift, incorporation of damping holes in the proof mass to control damping. So by just damping is also an important phenomenon if you go for designing an accelerometer. So their specific design is to be included to reduce the damping because I mentioned earlier also. If damping is not there, so it will take long times to stabilize the thing. That means its time cost, it will not be very high speed, the measurement is not possible if damping is not provided. Not only that if you do not apply proper damping, there is a chance of the resonance of the complete structure.

So as a result of which the complete thing can damage. So for that is also this is important and various kinds of damping incorporation or damping technology are considered in case of the accelerometer. In some cases only just using the top and bottom cover plate and inside some ambient and ambient pressure is change in some time it is done incomplete vacuum sometime may different gas pressure of different viscosity is used inside the encapsulation chamber. Some cases you make some perforation on the proof mass to have desire value of the damping factor.

Use of second silicon wafer bonded on top to provide over range protection. These are the second approach and third approach is surface micromachining accelerometer offers the opportunity to integrate the sensor and interface circuitry on a single chip.

(Refer Slide Time: 22:10)

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Technology of Capacitive Accelerometer

3. Surface micromachined accelerometer offers the opportunity to integrate the sensor and interface circuitry on a single chip
   - ✓ Enables detection of very small capacitance variation (<1 fF)
   - ✓ Sensor and interface electronics can be implemented in a small area
4. High precision accelerometer uses a combined surface and bulk micromachining process to obtain large proof mass, controllable/ small damping and a small air gap for large capacitance variation.

It enables detection of very small capacitance variation less than 1femtofarads which is required for, if you want to measure very low G. 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. So these are the four approaches and for many case depending on the infrastructure available in a particular laboratory depending on the advantage many out of the four. Something is selected for some application, some particular method is selected for particular fabrication, particular kind accelerometer fabrication.

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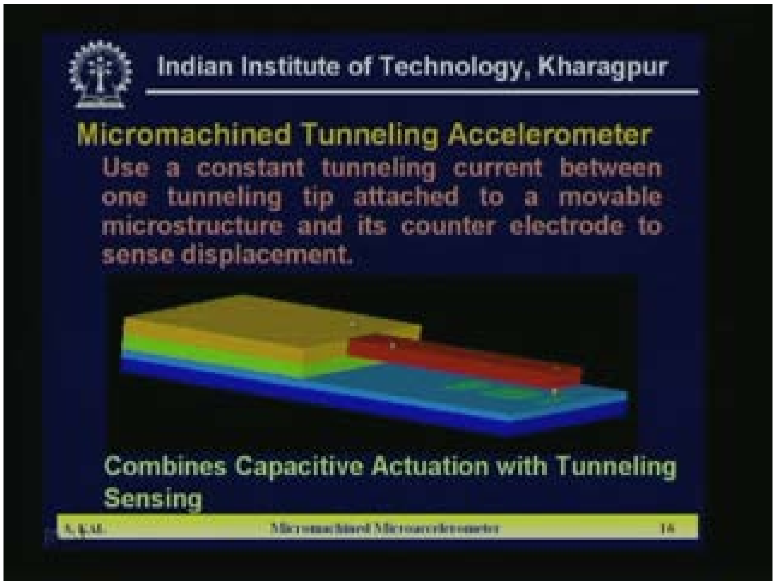

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Micromachined Tunneling Accelerometer

Use a constant tunneling current between one tunneling tip attached to a movable microstructure and its counter electrode to sense displacement.

Combines Capacitive Actuation with Tunneling Sensing

Now the micromachining tunneling accelerometer. So tunneling accelerometer is also getting importance now days. Because 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. You can see the structure here, this kind of accelerometer combines capacitive actuation with tunneling sensing. What is that capacitive actuation and with tunneling sensing you can see here, 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. Now here you can see in the top layer, there is a cantilever, microcantilever and at the end of the cantilever there is a tip. This is known as a tunneling tip small yellow color here you can see in the figure is a tip. Now in the bottom plate there are two patches are there. Those are for capacitive actuation. What it the purpose of that? So now you see by applying some voltage of this top cantilever is conductive kind of thing or if it is not conduct silicon, so at the bottom of this cantilever is gold coated. So now by applying the electrostatic energy, this cantilever at the top can be pulled down to the bottom can be pulled down to the bottom that is known as 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. Because we know 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. May be 2 angstrom, 3 angstrom, 10 angstrom like that in that range. So exactly making that gap could be very difficult and not only that if you want to have certain amounts of tunneling current, by electrostatic actuation this gap between the tip and the bottom plate can be adjusted. So that you can have considerable amount of the tunneling current. After that if you apply the fixed electrostatic actuation voltage, so you fixed of these, that means this thing will be the cantilever tip and the bottom gap is kept constant.

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. That is because of g, there will two things you remember. First you have to adjust the constant tunneling current between the top electrode in the bottom by adjusting the gap and that is normally done by electrostatic, means the actuation capacity of actuator we can say it. So after that you fix the whole thing in a body whose g or movement of vibration you want to measure. Now because of the movement of that, the small gap between the tip and the bottom plate is going to change and then tunneling current also is going to change. So this is the basic principle now.

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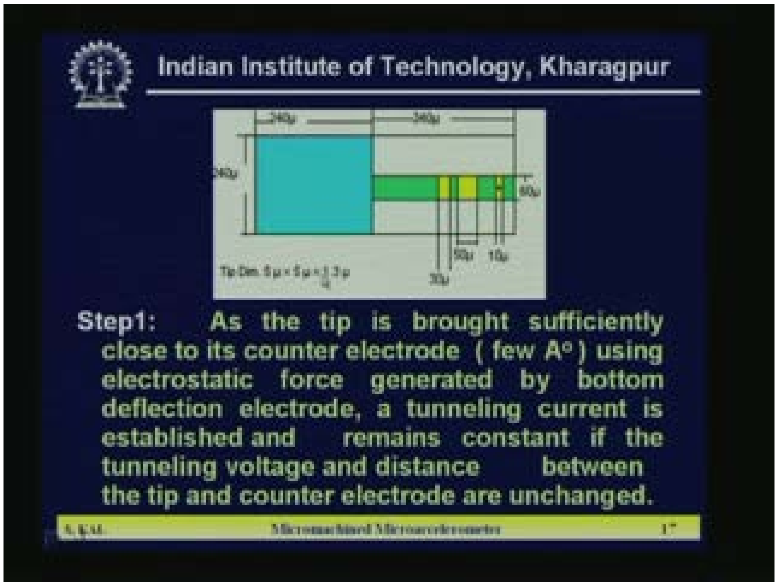

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Step1: As the tip is brought sufficiently close to its counter electrode (few A°) using electrostatic force generated by bottom deflection electrode, a tunneling current is established and remains constant if the tunneling voltage and distance between the tip and counter electrode are unchanged.

A. KAL Micromachined Microaccelerometer 17

One of the dimensions is shown here. This is the base where the tunneling tip is fixed. These are the two patches and here is basically the tip is here. This is 60 micron width is the cantilever beam and these are the horizontal and lateral dimensions of the structure is shown and now if you concentrate the working principle, so what are the steps followed. First is, 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.

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Micromachined Tunneling Accelerometer

Step2: Once the proof mass is displaced due to acceleration, the readout circuit 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.

Step3: Acceleration can be measured by reading the bottom deflection voltage in this closed loop system. Application Areas: Space, Defense, Seismic Science & upper atmospheric

S. KAL Micromachined Microaccelerometer 18

After that step two. 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. So you see this approach change of current is very difficult to measure. So what they are doing? So because of that acceleration the tip is going down and the current is going to change. Now what we can do that the electrostatic energy which is applied the patch to that is electrostatic actuation. Dry voltage is there, so that whole the cantilever is goes down or up. So that voltage you change, so that the gap also can change and maintain the same tunneling current. That mean constant tunneling current is desired and how we are maintaining the constant current, by changing the voltage between the two patches. That is electrostatic drive voltage. So that change of voltage will be the measure of the acceleration always in any of the signal condition. Your signal your portion circuit changes of voltage is very easy to handle the change of current. So that is why you can get the change of current. But that is not the final thing, you have to process that signal.

So there we know if we convert into change of voltage is easy. That is why what they are doing here, the current remains constant. Now adjust the bend, we can say that the voltage required for adjusting the gap. So that the current is maintained constant. Because of the accelerometer current change, now the gap can be adjusted, by adjusting the voltage dragging voltage between the plates, so that current again remains constant. So that is the principle used in this kind of the tunneling current microaccelerometer and the third step acceleration can be measured by reading the bottom deflection voltage in this closed loop system. That what I told you and this kind of tunneling accelerometer the application areas are space, defense, seismic science and upper atmosphere seismology. So very feeble vibration of that, so that normally is monitored with the help of this kind of tunneling accelerometer in other space, defense and upper atmosphere application. This is one of the vital applications of this seismic in case of seismic science.

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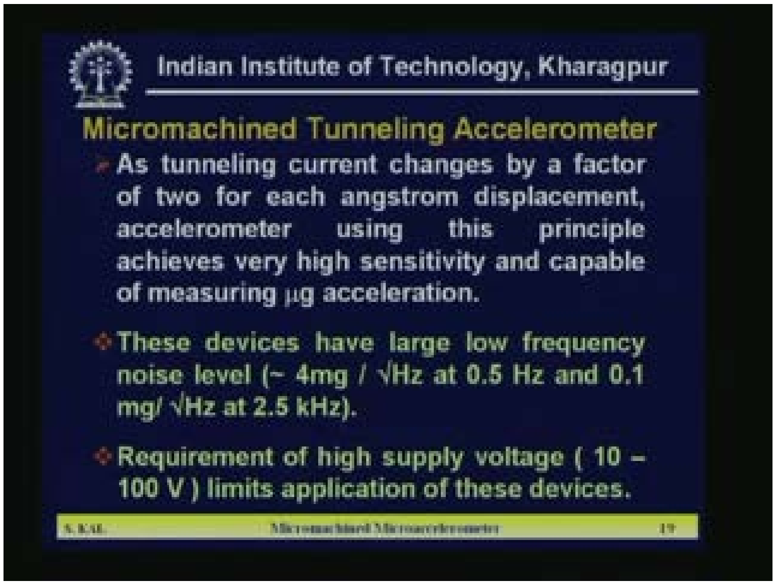

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Micromachined Tunneling Accelerometer

- As tunneling current changes by a factor of two for each angstrom displacement, accelerometer using this principle achieves very high sensitivity and capable of measuring μg acceleration.
- These devices have large low frequency noise level (~ 4mg / √Hz at 0.5 Hz and 0.1 mg/ √Hz at 2.5 kHz).
- Requirement of high supply voltage (10 – 100 V) limits application of these devices.

S. KAL Micromachined Microaccelerometer 19

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. These are some of the salient point of this kind of accelerometer that may be advantages may be disadvantaged but this is the thing we get this from this kind of accelerometers. Requirement of high supply voltage 10 to 100 volt limits. Application of these devices. Because you see the half why high supply voltage because you have whole cantilever. The actuation is done by electrostatic manner because the whole cantilever the bending of that cantilever or releasing the cantilever. So that is done by electrostatic voltage. That voltage may not be very small in the range obtained or 20 or 12 or 15. In some cases it depends on the tip dimension how fine you can make, how close gap you can make and how thin the cantilever thickness you can make. Because all this parameters will decide how much voltage you required for deflection of the cantilever beams. So that is one kind of the disadvantage you need the high supply voltage for because of the electrostatic actuation.

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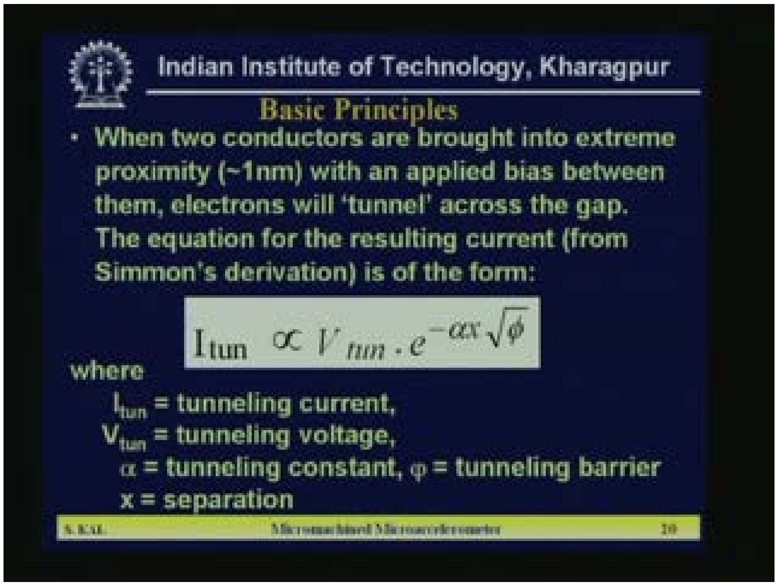

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Basic Principles

- When two conductors are brought into extreme proximity (~1nm) with an applied bias between them, electrons will 'tunnel' across the gap. The equation for the resulting current (from Simmon's derivation) is of the form:

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

where

I_{tun} = tunneling current,
V_{tun} = tunneling voltage,
α = tunneling constant, φ = tunneling barrier
x = separation

S. KAL Micromachined Microaccelerometer 20

Now the basic principles if you look, then when two conductors are brought into extreme proximity of the order of 1 nanometer with an applied bias between them, electrons will tunnel across the gap. That is the tunnel in principle the equation for the tunnel current is of the form I tunneling which is proportional to V tunneling dot e to the power minus alpha x under root phi. So this relation is known Simmon's relation and it wills derivation is given by Simmon and in this expression I_{tun} is basically tunneling current. V_{tun} is tunneling voltage, alpha is a tunneling constant and phi is a tunneling barrier, x is a separation, phi is a tunneling barrier. It depends from the gap and directly dielectric constant of the two, in between two electrodes. So this is the relation between the, I tunneling and V tunneling with two constants; one is alpha, another is a phi which one case is tunneling constant. On this tunneling barrier, tunneling constant depend on so many parameters and of the structural parameter and that is why all together we route it is alpha and is constant for a particular device.

(Refer Slide Time: 34:45)

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Why tunneling accelerometer ?

- Reduced 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 deflection and Self test.
- High bandwidth
- Less noise effect
- Application Areas: Space, Defense, Seismic Science & upper atmospheric studies(smart sphere)

Now the thing is that what are the basic advantages means why the tunneling accelerometer we go for. Although it is a very critical fabrication is not so simple like the capacity for piezoresistive accelerometer, but even then people are going for this specific reason and those are mentioned here. First is, it reduces cross axis sensitivity. Cross axis sensitivity means you know if you it is meant for one axis, the other axis sensitivity will not be there. That means it is vertical because it depends on the small gap between the tunneling point and the base plane. So that is one direction only if you can make the tip and the base point the electrode that is very small level, very small size and tip dimension may be of the order of say few angstrom, 4, 5, 16 angstrom tip. So that in other direction it will not sense. Modeling simplicity, high natural frequency, these are all its plus points, well-damped bending mode for faster transient response and small settling time. Low electrostatic voltage requirement for DC reflection and self-test. That also depends on your structure. If the structure is big at the flexure dimension you cannot make very fine thin. So you have to go for high voltage also. High band width, less noise effect. So these are some for its advantage.

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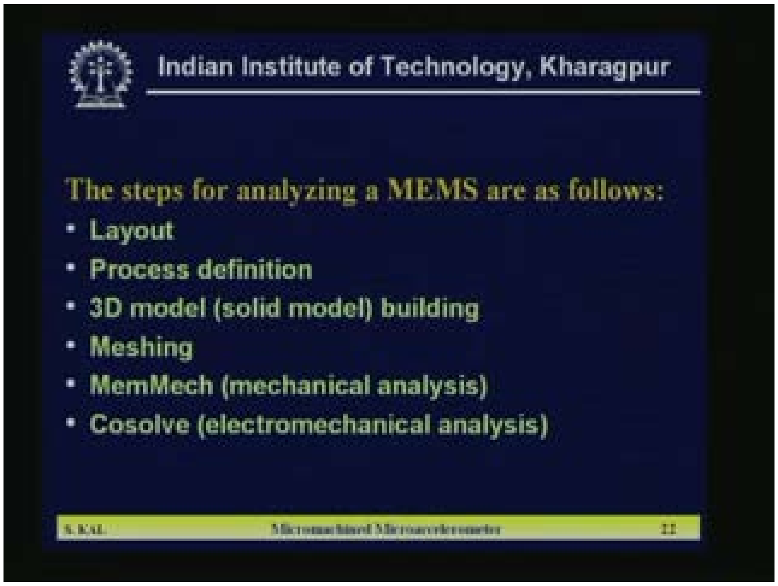

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The steps for analyzing a MEMS are as follows:

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

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Now any kind of the accelerometer you will be developing, you need certain steps for analyzing this kind of accelerometer. What are those is not only accelerometer, any kind of MEMS devices the basic steps for designing is as follows. First you have to go for a layout, tentative layout. Tentative structure you have to think from your specifications. So after finalizing the tentative layout that is not may not be final, tentative icon. So after that you have to go for process definition. That means what are the steps you will follow for making those devices, then you have to go for 3D model because the small structure you need always 3D because these are MEMS are all 3D devices. So you need 3D solid module you have to build that and for modeling that obviously it will not possible to model this kind of structure using the linear equations or some analytical solution is not possible any kind of structure. That is why you have to go for meshing. Meshing is required for what? For finite elements or numerical analysis of those structures.

Then after meshing you have to go for the mechanical analysis and mechanical analysis may make some software tools are available and since some another software tools are also available. So either using those, not only that various now days a kind of the numerical software tools are coming into the market. You can use any of them after proper meshing. Then you have to do the mechanical analysis which you call memmech. Because any kind of this kind of sensor. There is mechanical movements will be there. That is reflected into electrical signal pickup. That means electromechanical system the complete thing. So we have to go for memmech which is mechanical analysis. Then electromechanical analysis the mechanical analysis next step is electromechanical. So that you can for the electromechanical, after electromechanical analysis you may get the electrical signal or electrical output or other things. That is cosolve which is electromechanical analysis. So these are the steps normally follow in case of the MEMS analysis of any of the structure any of the devices.

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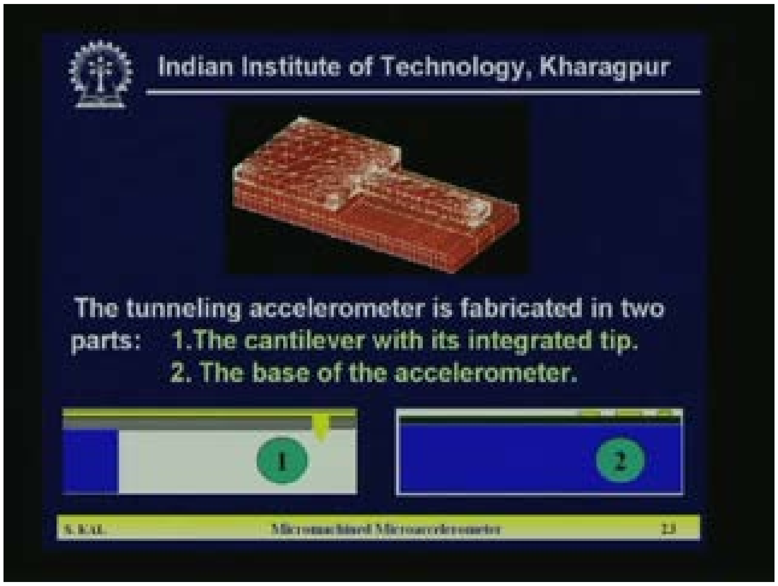

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The tunneling accelerometer is fabricated in two parts: 1.The cantilever with its integrated tip.
2. The base of the accelerometer.

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Now this is one kind of the steps or methods we follow in case of the tunneling accelerometer. You can see the mesh, how the mesh is defined in these cases. Mesh size may be different for different kind of structures that also I mentioned sometimes back. So that is where you need the much more rigor analysis. You can reduce the mesh size so that number of elements will be more. You will get much accurate analysis and after that you can go for increasing the size of the mesh. So the number of elements will be less, as a result you can get some kind of time management. Because your analysis will take more time if you go for higher number of elements. So now here the two structures are there which obviously the top structures where number one is the cantilever with its integrated tip. So here is basically you are getting this stress in this cantilever. So obviously here the structure of the mesh should be a design or fixed accordingly. So small size structure in the bottom is this one. This is the bottom; second one the base of the accelerometer. There you may go for the larger element side.

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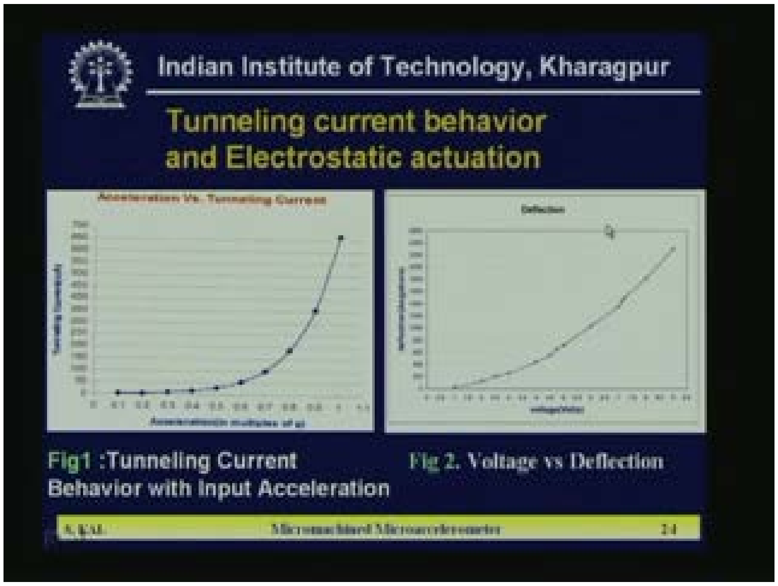

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Tunneling current behavior and Electrostatic actuation

Fig1 :Tunneling Current Behavior with Input Acceleration

Fig 2. Voltage vs Deflection

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Now so here are some results of the tunneling current behavior and the electrostatic actuation. You can see here the tunneling current versus acceleration is a plotted. You can see is a point up to point 1, point 2, and point 3g. The current is almost negligible, that means the g higher means obviously the tip e movement is more. So hence tip movement tip movement is more, so you can get after the point 4g to up to 1g you can see after g is a rapidly increasing the tunneling current. Obviously the current is in the of the graph nanoampere. So this because, that means it is sensitive after the point 4g. So to may be 1 or 2g, here this region is linear almost and if you look into the reflection voltage what is the deflection that is also plotted here using the analysis of final judgment analysis. So deflection verses voltage and the so voltage required to maintain the constant current or if you apply this voltage, so how much deflection of the tip will be there, that is the electrostatic actuation. That is plotted here, so you can see is not very high is a 4,5,6,7 or 8 volt is there. There you can have the reflection from 400 to say 2000 angstrom in that rate. So this is the deflection versus the voltage.

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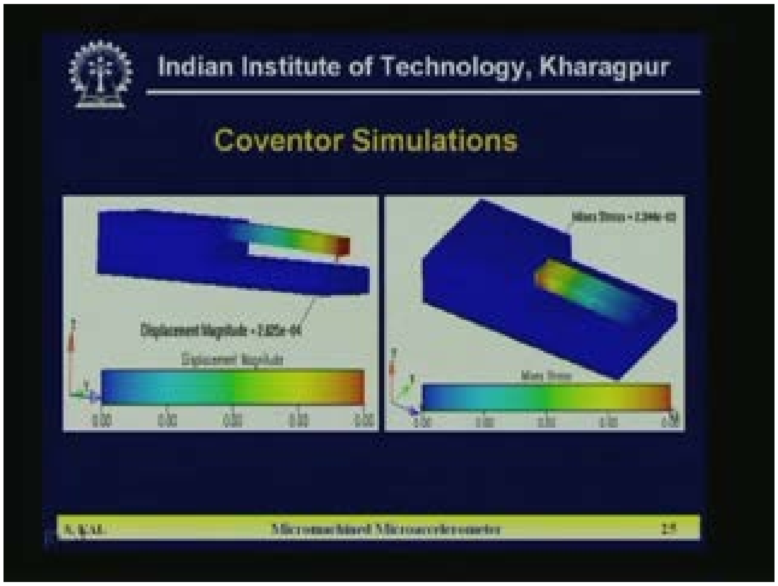

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Coventor Simulations

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Now you can see here some of the photo we have figures generated from coventor simulation. So displacement is here, you can see 2.625, 10 to the power minus 4 centimeters whether that is the displacement of the tip and here is the stress developed at the tip for different acceleration. So this kind of pictures you can generate from the coventor software.

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Figure : Silicon tunneling accelerometer process flow.

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Now these are the tunneling accelerometer process flow.
So there are two pieces I have told you, the bottom and top. The bottom is base wafer and these cantilever wafer first what you did you two k n type 1 0 0 silicon wafer and then you go for thermal oxidation. The both top and bottom is oxidized. Oxidized layers are here, you can see. Then after that you are depositing the metal, the patches in the bottom 1,2,3,4. So these are the patches base electrode fabrication. Now in the other side the top is the silicon epilayer on n type 1 0 0 silicon. That is for top tip fabrication, then you define by dry etch the epilayer is defined here. Then after that you just again form the base point where the cantilever will be fixed with the other part and the tip. The tip formation is highly crucial. So after making the two pieces, then this piece is inverted and you just put upside down on the base. So this and this are the two pieces. Now this you make upside down and place on the top of this and then you fix. This is a metal and this is a material the gold foil. That will be fixed here. So that means and these are the electrostatic actuators and this is the tip and this is gap of the tip. In this way you can fabricate this tunneling accelerometer.

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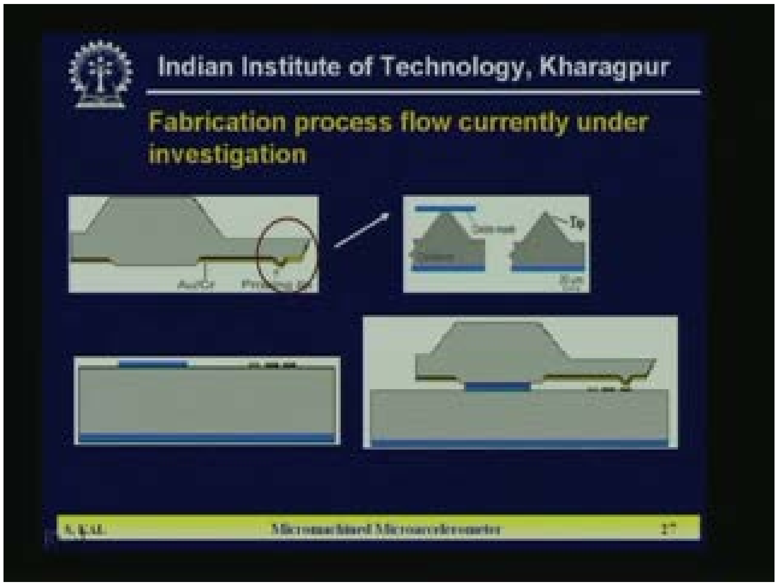

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Fabrication process flow currently under investigation

These are some of the photographs of the tip and the tip looks like that. Making the tip is highly crucial you can see here the oxide mask. Then you have to etch some kind of v group etching and then the tip of the group is something like that, pointed tip and then how it is inverted and fixed top and bottom that is also shown here.

(Refer Slide Time: 44:58)

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Micromachined Resonant Accelerometer

→ Use a resonant silicon cantilever beam

1. Silicon resonant accelerometers transfer the proof-mass inertial force to axial force on resonant beams and thus shifting their frequency.
2. A differential matched resonator configuration helps to cancel device thermal mismatches and non-linearities.
   Typical resolution ~ 700 Hz/ g with 524 kHz center freq.
   Stability ~ 2 μg in more than several days
   Small bandwidth ~ < few Hz
3. Quartz micromachined resonators

S. KAL Micromachined Microaccelerometer 28

Now there are another two kinds of accelerometers are there. Just I will take 2, 3 minutes. So that is micro machine resonant accelerometer. They use a resonant silicon cantilever beam. Silicon resonant accelerometers transfer the proof mass, inertial force to axial force on a resonant beams and shifting their frequency. So here basically the frequency change is the observation for variation of g. A differential matched resonator configuration helps to cancel device thermal mismatches and non-linearity. So this kind of sensors obviously free from any thermal problems or the parasitic capacitors problem etcetera. Because you are not directly dealing with the capacitance, but directly frequency structural vibration etcetera. That frequency is going to change and one example is quartz micromachine resonators.

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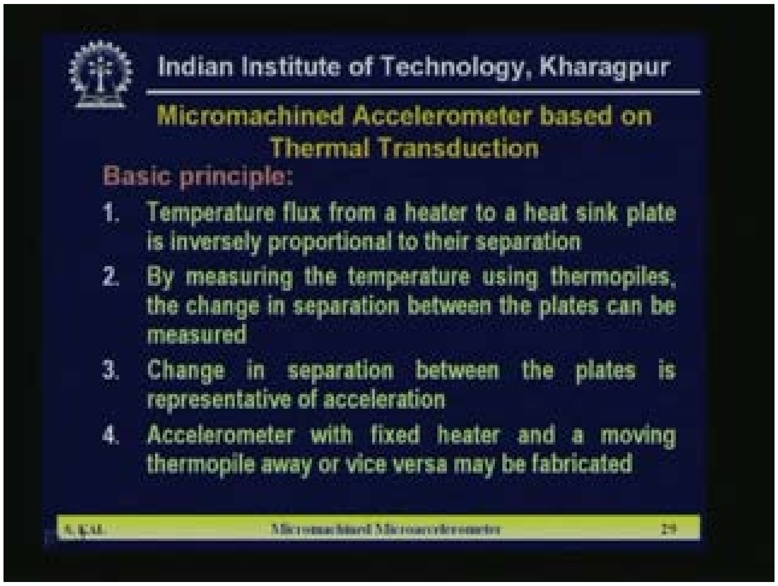

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Micromachined Accelerometer based on Thermal Transduction

Basic principle:

1. Temperature flux from a heater to a heat sink plate is inversely proportional to their separation
2. By measuring the temperature using thermopiles, the change in separation between the plates can be measured
3. Change in separation between the plates is representative of acceleration
4. Accelerometer with fixed heater and a moving thermopile away or vice versa may be fabricated

S. KAL Micromachined Microaccelerometer 29

So these are the thermal transduction mechanism that also I told you the temperature flux from heater to heat sink plate is inversely proportional to their separation. By measuring the temperature using thermopiles the change in separation between the plates can be measured. Change in separation between the plates is representative of the acceleration. Accelerometer with fixed heater and a moving thermopile away of vice versa may be fabricated. That is not very much popular, the thermal transduction mechanism and last is the packaging.

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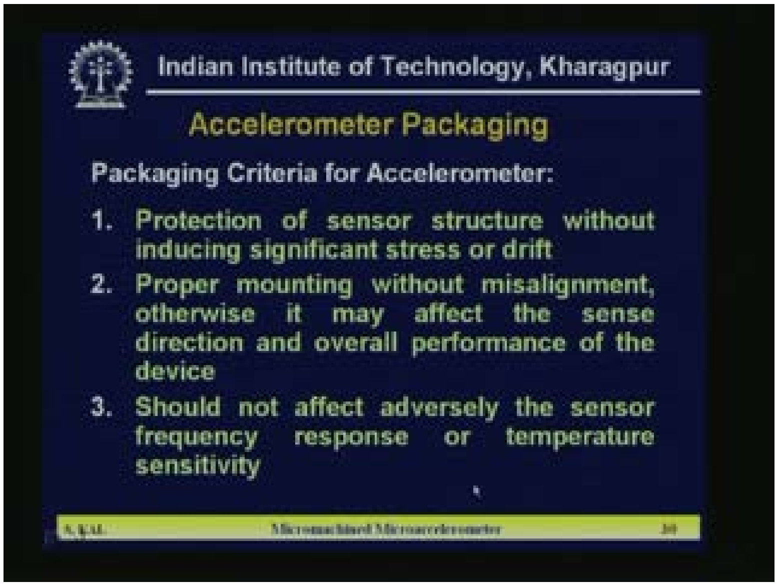

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Accelerometer Packaging

Packaging Criteria for Accelerometer:

1. Protection of sensor structure without inducing significant stress or drift
2. Proper mounting without misalignment, otherwise it may affect the sense direction and overall performance of the device
3. Should not affect adversely the sensor frequency response or temperature sensitivity

Micromachined Microaccelerometer

Package criteria of accelerometer are also very important issue. 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. These are the three points which you have to look in detail before going for packaging. So with this let me stop here today. So in next class I will just concentrate on a case study, first design, then analysis, then fabrication. Thank you very much.