MEMS & Microsystems
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Lecture No. # 18
MEMS Pressure and Flow Sensor

Lecture we had a discussion on mechanical micro sensors for MEMS application and in mechanical micro sensors, one of the most used sensor is pressure sensor. We discussed at length on pressure sensor.

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MEMS Pressure and Flow Sensors

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Today I want to discuss on the design prospective of a pressure sensor and its mechanical analysis so that you will know how the stress is distributed over the piezoresistors in membrane. Let us at the beginning discuss on pressure sensor and after that I will continue on flow sensors which measure the velocity of fluid. That fluid may be the air or that fluid may be liquid. So that is the second part of today’s lecture. First I will concentrate on MEMS pressure sensor design.

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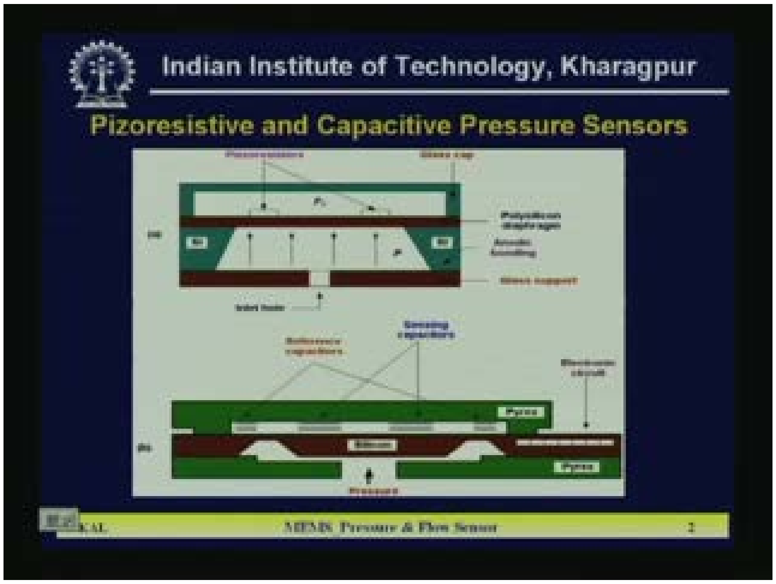

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Pizoresistive and Capacitive Pressure Sensors

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So as you know there are two techniques of measuring pressure. The one is piezoresistive technique and other is capacitive technique for measuring pressure. So the basic structures if you remember are as follows. In the figure A is a micromachined piezoresisitive pressure sensors and figure B is a micromachined capacitive pressure sensor. In pizoresistive pressure sensor there will be two resistances which are embedded into a silicon or polysilicon and that is in the form of a diaphragm. This is the diaphragm and bulk silicon is shown here. On the bulk silicon it may fabricate the resistances on polysilicon diaphragm or also you can fabricate inside single crystal bulk in silicon also. Now this kind of sensor will have three parts; one is the top glass cap, one is the bottom glass support and in the middle you can find the sensor element. So the sensor elements are just a rim and polysilicon diaphragm.

On polysilicon diaphragm, two piezoresistors are fabricated. Or you can just diffuse or implant piezoresistance in to the bulk silicon and then you edge from the bottom to have that diaphragm or the three membranes. And in my last lecture I also discussed about the positioning of different resistance. Resistances over the membrane and there you have seen that the two resistance resistors are located such that the current direction is perpendicular and to are located in such a method and a such location where it is parallel to one edge and other two are perpendicular to opposite edge. So in this way if you make then all the four resistors are connected to form Wheatstone’s bridge. Now here if you want to measure the pressure with respect to atmospheric pressure, then you may not need the top glass cap. But if you measure the pressure, absolute pressure, that means with respect to vacuum or if you want to measure pressure of an ambient or environment with respect to certain reference pressure, then the top glass cap is necessary.

Now in both the cases in the bottom is also required because there you can make a small inlet hole through which the membrane will come in contact with the ambient whose pressure you are going to measure. So that means when you are packaging the whole device, so on the package or encapsulation mold there should be some hole. So that there is direct connection between the sensing element and the ambient, which is outside the package. So now if you want to measure the pressure with respect to vacuum, then the top glass cap lid has to be evacuated. Then the P_0 pressure should be in vacuum. Then whatever the pressure, if you measure this with respect to vacuum which is absolute pressure or if you want to have some reference pressure, so when you are bonding the top glass cap with the main sensing element then inside the cap some pressure has to be maintained which is known as the reference pressure.

So this is one kind of pressure sensor which piezoresistive pressure sensor. The bottom structure is for capacity pressure sensor. Here what has been done, again here you can see there are three layers. One is top pyrex glass layer and this is a bottom pyrex glass layer and in the middle layer is the thick silicon which is micromachined to have certain structure and now here since it is based on the measurement of capacitance. The capacitance will vary with respect to the pressure. So the capacitances are basically parallel plate capacitor and in this diagram you can see how the capacitors are made. So on the top pyrex glass there is a some electrode. This is one, this one and you can see this is the third one; this is the fourth one and in the bottom the electrode is made on the surface of the silicon and this silicon is micromachined to have either a thick rim or you can have a membrane also.

Now here instead of 2 capacitors there are 4 capacitors are made. Two are known as reference capacitor and 2 are known as sensing capacitor. Now the reference capacitors are made on the thick rim this side and this side. So that will not change with respect to the pressure. It will always remain constant and this is not the correct location. It should be shift a little bit in right side so that it will locate here in the rim, thick rim and other two capacitors which are known as sensing capacitor, those two capacitors are made where the silicon microsturcture will deform with respect to the pressure. So as a result of which when the pressure in the inside cavity and outside cavity this is a first cavity. This we called a second cavity is different then there is deformation of the microstructure, silicon microstructure. As a result of which the gap between the electrodes of the sensing capacitors will change and capacitance will vary with respect to the reference capacitor. A reference capacitor is suppose to not to change with pressure.

So you will get the differential capacitors. Differential capacitor measurement is desired because it can eliminate some of the parasitic capacitance also. Only you are interested in the change in capacitor with respect to the pressure not the absolute value of the capacitor. So absolute value of the capacitor change may be of different reason. So that can be eliminated if you go for differential capacitors measurement technique. This differential capacitor k delta c is again translated in to the either some voltage change or some frequency change depending on what kind of read out electronic circuit you are adding with this capacitor pressure sensor. Now here one point I would like to emphasize that here in case of capacitive pressure sensor the electronic circuit means read out electronic circuit should be in close viscidity of the sensing element.

If it is not so, then what will happen? Then if it is a far away from the structure, so this interconnect lines to the sensing electronic circuit and the sensor part will again add some amount of capacitances and those are parasitic capacitance and more over since this electronic circuit is far away. From that it may pick up lot of noise and that is very sensitive because if the change of capacitance is very small, then addition of noise signal as well as the parasitic capacitance from sensor to the read out electronics is considerable. Then you may not be able to sense the actual change of capacitors due to the change of pressure. On the other hand the first structure piezoresistive pressure sensor there that problem is not there. The read out electronics may not be in the very close vicinity of the sensing element. It may be little bit away from the sensing elements. It will not create the problems which are sensitive with capacitive pressure sensor.

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Capacitive and Piezoresistive Pressure Sensors - A Comparison

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

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Now if you compare this advantage and disadvantage of capacitive and piezoresistive pressure sensor. Then we found that the advantage of capacitor pressure sensor is that is more sensitive particularly in case of polysilicon resistor in comparison to the bulk diffused or implanted resistors are the more sensitive. Second advantage is it is less temperature sensitive. You know capacitors does not change with temperature is a great advantage. It will not change with the environmental humidity, environmental temperature change and the third one is more robust. On the other hand the disadvantages of capacitive pressure sensors are large piece of silicon for bulk micromachining. You have seen the diagram in the last viewgraph that whole silicon is micromachining large amount of silicon pieces to be etched. Second one electronically more complicated. That is what electronically more complicated means to pick-ups electron. Pick-ups signal electron means the change of capacitance should be converted to change of either current or voltage or frequency, whatever it is.

So that electronic circuit is not as simple as Wheatstone's bridge which is used in case of the piezoresistive pressure sensor. That is electronically more complicated and the third disadvantage needs integrated electronics. Integrated electronics means just now I mention it should be in a close vicinity of the sensing element. That is it needs integrated electronics. If you go for the hybrid approach, that means the sensing element somewhere and the signal conditioning circuit far away from the sensing element, then it may create problem. That is signal conditioning circuit as well as pick up electronic circuit and the sensing element should be integrated together in monolithically in single silicon piece, then its advantage you can exploit. On the other hand if you look into the piezoresistive pressure sensor, there advantages are smaller structure than bulk capacitance sensor. Simple transducer circuit simple transducer circuit is a Wheatstone's bridge, very simple. No need for integration may not essential you may not go for its not must that if you go, if you integrate both the pickup electronic circuit and sensing is good. But it is not necessary always and disadvantage of the piezoresistive pressure sensor are strong temperature dependence is a very importantly consideration.

Here its temperature dependency is crucial and that means when you are changing the resistance with respect to pressure that will also change with respect to temperature also because I mean temperature varies, piezocoefficient depends on the doping level if you make the resistances, you are going to use certain amount of doping and that doping varies from 10 to the power 20 to 10 to the power 19 per cc of boron. So that doping level if you vary so piezoresistive coefficient will also change. So that is because before you are I we before you are going to design and you settle the complete process parameter. You have to look in to the doping concentration when you are calculating the piezoresistive coefficient and you are calculating the stress and relevant to the stress is the variation of the piezoresistances. So that thing that time you have to take care of the doping concentration also.

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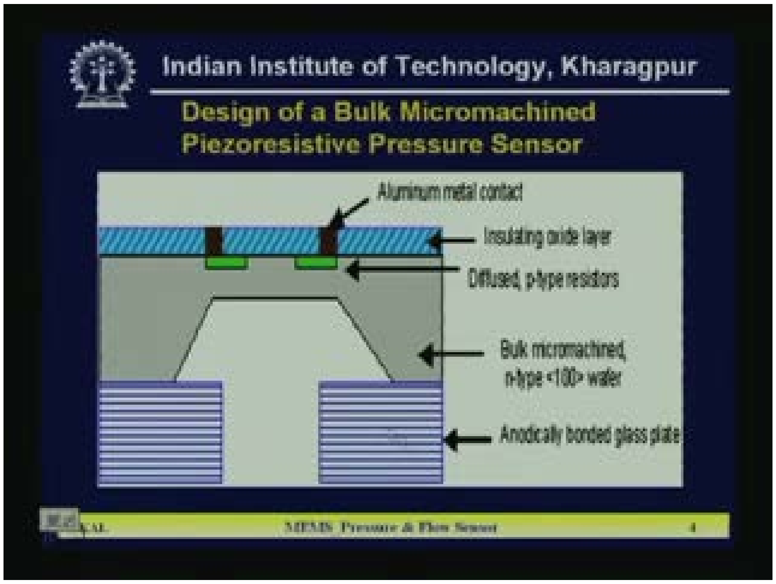

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Design of a Bulk Micromachined Piezoresistive Pressure Sensor

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Now, we are now, we discuss a design of a bulk micormachined piezoresistive pressure sensor and here as you have seen in the earlier diagram this is not polysilicon, this is basically the diffused silicon. Piezoresistance are there, you can see this is insulating oxide layer and the green colour. These are two diffused resistance and the black one from green to the top from here to here is the aluminum metal contact and this is the bulk silicon and in bulk silicon you have diffused p-type resistors here and then this is a 1 0 0 surface has raised from the bottom and this structure, the silicon structure is anodically bonded with that bottom glass plate and there is a hole in the bottom glass plate. So that you can have direct contact of the ambient with the membrane. This is that thin membrane where you have diffused the resistors. This kind of structure cannot measure the absolute pressure. Because the other side is not kept in vacuum. You have just anodically bonded the bottom one, then it will always measure pressure with respect to atmospheric pressure. A reference pressure is atmospheric pressure.

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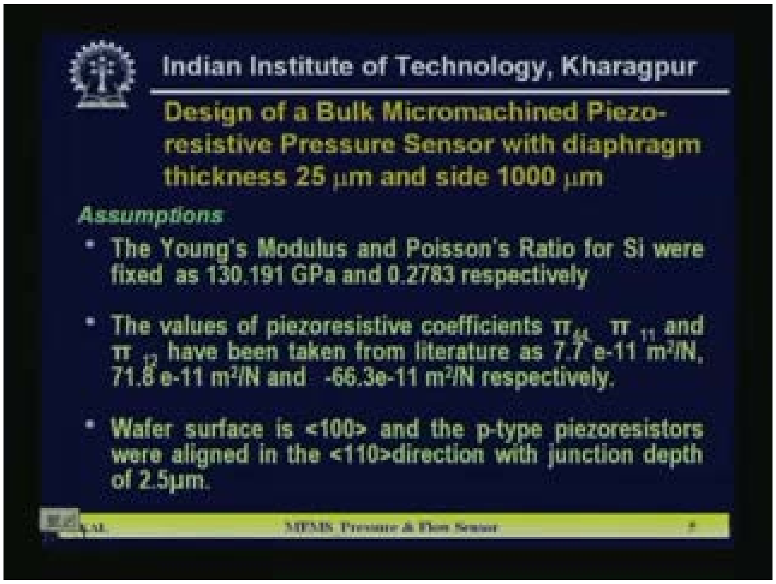

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Design of a Bulk Micromachined Piezoresistive Pressure Sensor with diaphragm thickness 25 μm and side 1000 μm

Assumptions

- The Young's Modulus and Poisson's Ratio for Si were fixed as 130.191 GPa and 0.2783 respectively
- The values of piezoresistive coefficients π_{44}, π_{11} and π_{12} have been taken from literature as 7.7 e-11 m^2/N, 71.8 e-11 m^2/N and -66.3e-11 m^2/N respectively.
- Wafer surface is <100> and the p-type piezoresistors were aligned in the <110>direction with junction depth of 2.5μm.

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Now this structure how you will analyze? If you go for design then you have to, at the beginning you have to go for some simulation and there are certain relations analytical relations available if your structure is very simple and those relation required some parameters and those parameter values we have to fix up at the beginning and we thought the pressure sensor will be made with the diaphragm of thickness 25 micron and whose side will be 1000 micron by certain micron on membrane side. Now first you have to make some assumption. What are those? You have to fix up the Young's modulus and Poisson's ratio for silicon and those values for the present design what we made in our laboratory, we have fix up it is 130.191 Giga Pascal is the Young's modulus and Poisson's ratio is 0.2783 for silicon single crystal silicon. Next step is the value of piezoresistive coefficients has to be fixed. That has to be found from the look up table which are available in literature and you have seen the piezoresistive coefficients. Out of these sensor element is you have seen the 6 by 6 elements.

Out of that the major components are pi 4 4, pi 1 1 and pi 1 2. These are very important piezoresistive coefficient which will change a lot with respect to the stress in silicon substrate and those values are found for 1 0 0 p-type single crystal silicon and that are mentioned here 7.7 e minus 11 meter squared per Newton is pi 4 4. Pi 1 1 is 71.8e minus 11 meter squared per Newton and pi 1 2 is minus 66.3 e minus eleven meter squared per Newton. So those values is to be fixed and the third stage is wafer surface is 1 0 0 and the p-type piezoresistors were aligned in 1 1 0 direction with junction depth of 2.5 micrometer. So we decided that the junction depth of piezoresistance, there were diffused resistance will be 2.5 micron and we have to align. We have to keep the resistance in such a fashion that it will on the 1 1 0 direction because 1 0 0 direction will be etched and 1 1 0 will not be etched in solution. It will remain there, so the diffused resistance will be in that locality on this single crystal silicon.

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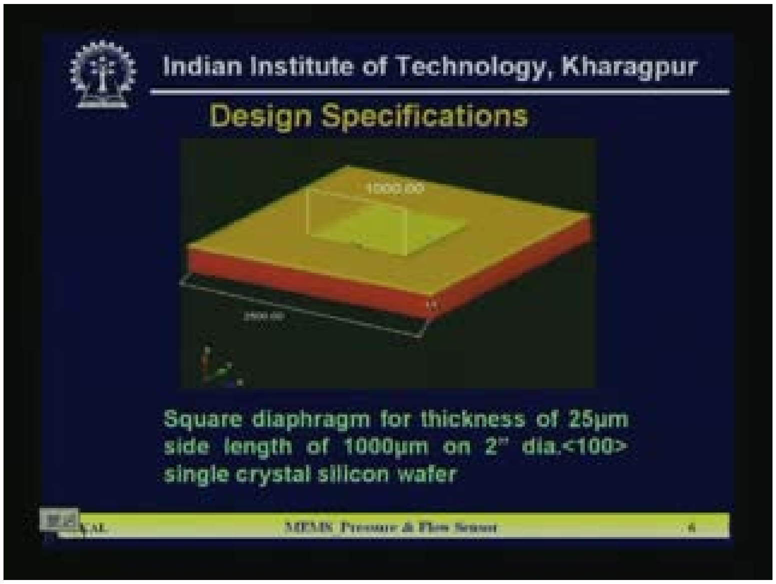

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Design Specifications

Square diaphragm for thickness of 25μm side length of 1000μm on 2" dia.<100> single crystal silicon wafer

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Next step is the structure definition. There is a software tool available for the simulation of mechanical structure which is MEMS mechanical structure and that tool is known as coventorware. Some of you are already using this software for designing the mechanical microstructure and first when you define you have to define the size of the membrane. This is the size of the membrane or diaphragm. I told it is a square diaphragm is a 1000 by 1000 and is a 2500 by 2500 micrometer is the total area of the device. That means here your rim other than the 1000 by 1000 micrometer, rest of the portion will work as a thick rim of the silicon structure, thick rim. Now this structure which is defined has to divide into number of small size meshes. You know in case of mechanical structure simulation many of the structures are irregular. You will not many cases you may not face with the regular structure means it is a square or it is cubic or it is say triangular similar kind of regular structure may not be available after micromachining.

So structure is highly irregular in nature. Those structures will have problem if you go for normal analytical solution using available equation with the boundary condition. The boundary conditions will be there, but that boundary condition may not valid properly if the structure is highly irregular. In those cases only the correct simulation you can get it using the numerical techniques. You may not have the clues from solution of an irregular structure, but if you go for numerical analysis or numerical technique then you can have solution and from there you can determine many of the structural parameters. Now the numerical solution one of the important method is finite difference method and finite element method. And finite element method the first step you have to divide the complete structure into small mesh, small elements and those elements may be of different structure. That small element may be square, that small element may be tetrahedron, and the small element may be triangular structure.

So each element you have to write an equation and those equations when are added over the complete structure depending on how may number of elements the metric size you will change and that equation you have to solve with boundary condition individually. So this numerical technique, in one way it is advantageous because you can get solution of irregular structures accurately. On the other hand disadvantage is that if you take number of elements in finite element methods means you are dividing the structure with small elements, if the element size is large so computation type time will be more and more and it will take lot of time to convert the solution. If you will not properly select the element size as well as proper boundary condition, then the equations, the metrics equation may not convert. So you cannot get a unique solution these are the problems.

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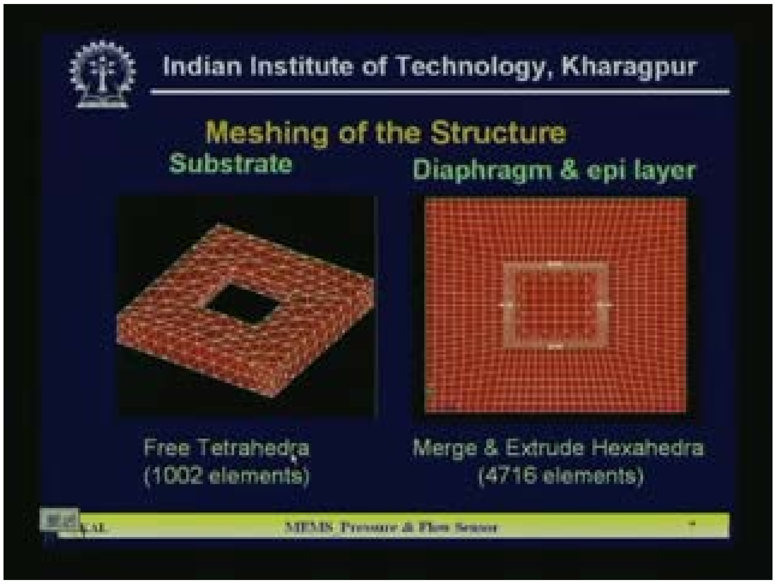

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Meshing of the Structure

Substrate

Diaphragm & epi layer

Free Tetrahedra
(1002 elements)

Merge & Extrude Hexahedra
(4716 elements)

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Now let us see here how the mesh is formed. That is meshing of the structure you see as I told you, this is substrate the rim structure in the left hand side. In the right hand side you can see in the top layer. Top layer means the membrane this size is a 1000 micron by 1000 micron membrane and along with on the periphery also the thickness of the diaphragm if it is a 25 micron the similar 25 micron is also taken in the rim structure. Normally if you go for I mentioned early, if you go for the diffusion a p-resistor diffusion and the substrate should be n-type and always in n-type substrate has certain problem. If you want to have the monolithic circuit in the same device n-type substrate is not used, you use p-type. So in that case where resistance has to be diffused in p-type, so p-type diffusion in p-type is not possible. So that is why normal substrate we take for any of the IC or VLSI fabrication for bipolar case is n on p, n epitaxial layer on p substrate. On n epitaxial layer you are going to fabricate the diffused resistance. That means your membrane will be n epitaxial layer, there you can do the etching is electrochemical etching stop since n-p junction will be there that is the advantage.

That is why most of the cases the bulk micromachined pressure sensor people prefer N on P wafer. So that you can go for electrochemical etching as well as you will have the liberty of fabricating the electronic circuit on the same silicon in same epi layer. So now this epi layer, that is why the diaphragm and epi layer is shown here and only the thick rim which is a p substrate, that is shown here and here the structure element structure is tetrahedral and the dimension what I mentioned earlier about the dimension 1002 elements have be taken and here these epi layer and diaphragm the structure is extrude hexahedra, that is the structure. This sought of structures are there available in the coventorware simulator. So you can choose different structure and accordingly number of elements may change and here one point I would like to mention for this finite element analysis that most sensitive region you can reduce the mesh size to get more accurate result.

But which is just support structure there mesh size may not be very small you can increase the mesh size. So the number of elements will be less so computation time will be less. So in that way the meshing is an important step. When you go for mechanical structure simulation whether the structure is used for the pressure or acceleration sensor or gyroscope it does not matter. In mechanical analysis you have to go for meshing and that meshing optimization important in order to save the complexity in order to save the computational time. So the most important in crucial regions you mesh very close space. So that there the analysis will be much more accurate. That is why you can see here the rim is only 1002 elements. But the epi layer and diaphragm the total number of elements is 4716. So after completely completion of the meshing of the structures, then you have to write down the equation of each mesh and then you have to apply the boundary condition and you have to have the nontrivial solution and for that you have to solve the metric's equation.

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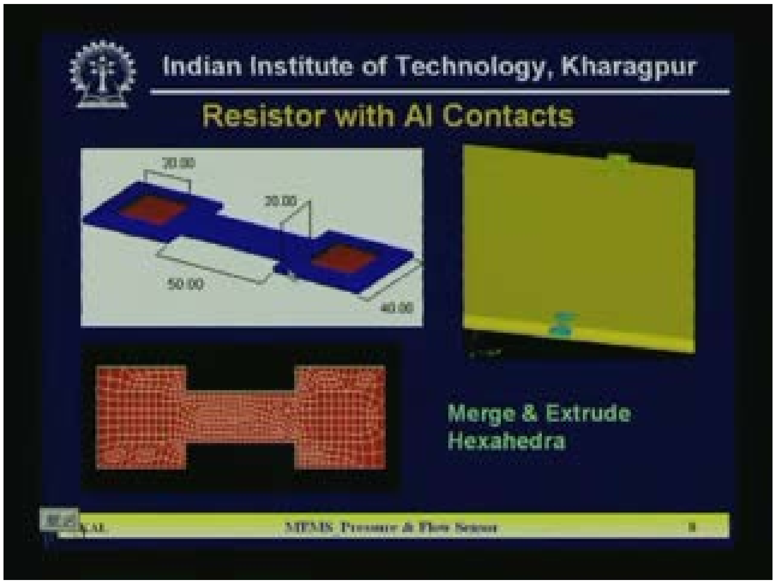

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Resistor with Al Contacts

Merge & Extrude Hexahedra

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So now those are the silicon now you are coming to the resistor structure. So this diagram shows the resistor structure and the resistance in the red region. Here is a contact for aluminum and the blue colour is the resistance and length is 50 micron and width is 20 micron and you can see the contact window open is 20 by 20. So accordingly here the size is 40 by 40 so that 10 micron in space is left surrounding the contact. So that is for alignment tolerance here. So now the total resistance you can calculate similar to the resistance values estimated in case of integrated circuit. That is if you know the sheet resistance then multiplied by the number of square and each contact will have to consider the half square. So here is a 50 and 20 so divide that you will get the total number of squares and here is half square and this contact half square, so you add another square, so total number of square you know and if you know the ohm per square sheet resistance of diffusion then you can calculate the total value of the resistor. That is the normal technique and that also you can mesh and that mesh is merging and extrudes hexahedra is the meshing size here in this resistance structure. The blue color is the resistance the red portion here is only the contact windows. If you see the cross section diffuse, you can see blue colour thing here and here these are the doped silicon and rest of the color is the basic epitaxial layer.

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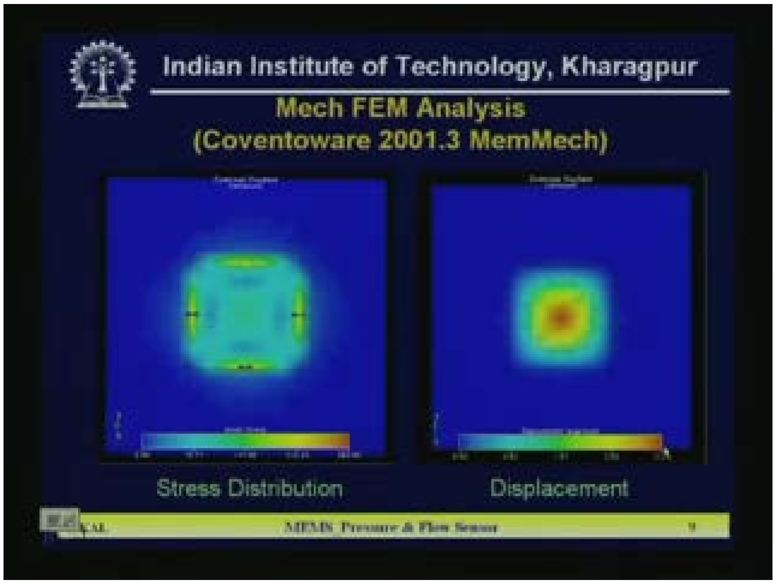

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Mech FEM Analysis
(Coventoware 2001.3 MemMech)

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So after that you have to go for mechanical FEM analysis and that is, as I mentioned they have used the 2001.3 coventorware MemMech module of the coventorware and there if you see this stress distribution and displacement it looks like that. So in that the colour diagram colour pictorial diagram you can find the maximum stress region and this is the blue colour is a minimum stress and the red is maximum stress and it varies in between there is major stress basically 00270. Here is 101, 212 and is 293. So you can see from the diagram that, at the edges where the diaphragm or membrane is connected with the rim. There the stress is maximum this yellowish color, this color is here and here. So these are the maximum stress region. Now if you look the displacement of the membrane under application of spacer it is like that. So maximum displacement is at the middle for this kind of structure. This is the red region, this is the maximum is a maximum is the middle region the red and you can see peripheral region gradually the displacement is less and surrounding the rim the displacement is minimum. Almost no displacement a blue color. So that is the displacement color diagram this is stress distribution over the membrane. Now the stress distribution over the resistor.

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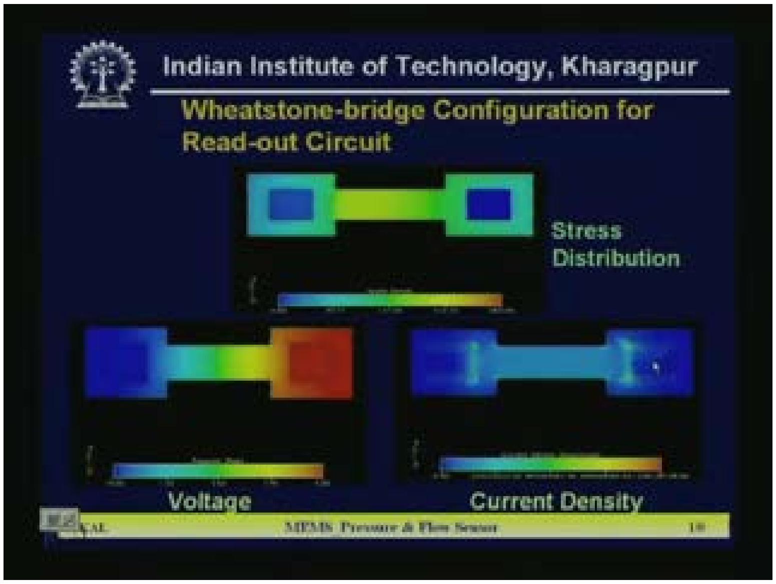

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Wheatstone-bridge Configuration for Read-out Circuit

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So resistors are kept at the periphery of the membrane. So there you can see the color diagram. Here that is the variation of the stress over the resistive element. Now this is the voltage and this is the current density distribution over the length of the resistance it is like. That means depending on the stress the location of the resistance which is in high stress. So there voltage change will be more, so that is clear here. Similarly the current distribution is a current density is not that much variation it is almost uniform over the complete structure.

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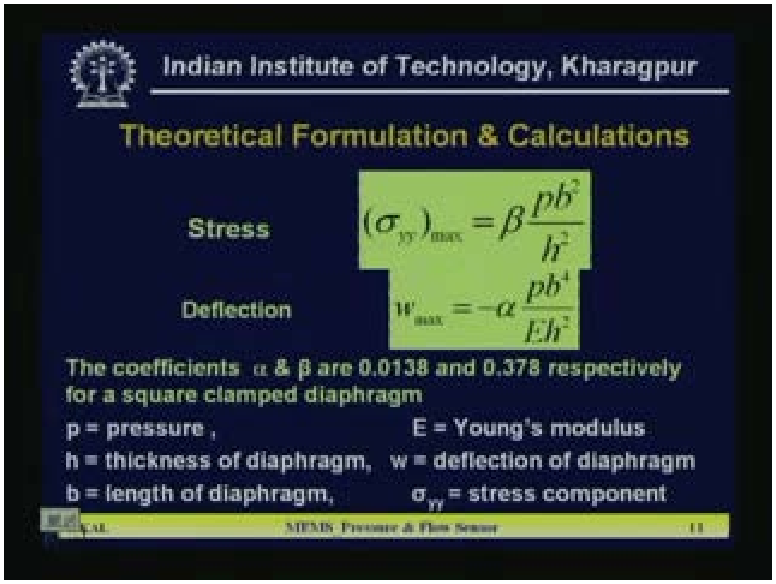

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Theoretical Formulation & Calculations

Stress $(\sigma_{yy})_{max} = \beta \frac{pb^2}{h^2}$

Deflection $w_{max} = -\alpha \frac{pb^4}{Eh^2}$

The coefficients α & β are 0.0138 and 0.378 respectively for a square clamped diaphragm

p = pressure ,

E = Young's modulus

h = thickness of diaphragm,

w = deflection of diaphragm

b = length of diaphragm,

σ_{yy} = stress component

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Now after this analysis you can go for the stress and deflection values you can calculate from the simulator. Now at the same time you can estimate those values stress and deflection from your analytical closed loop equation. The equation of stress for similar structure is given by sigma yy is maximum stress only. That is given by beta pb squared by h squared and the deflection maximum deflection is at the center is given minus alpha pb to the power 4 Eh squared. What are those values, p is the pressure, and b is the length of the diaphragm that is squared diaphragm. These relations are valid for squared diaphragm. That means b is the length 1000 micrometer by 1000 micrometer, h is the thickness of the diaphragm is h small h and the E is the Young’s modulus, this E is the Young’s modulus. Sigma yy stress component and E is the Young’s modulus. Alpha and beta these two are the coefficient and those coefficient for that kind of doping in silicon is obtained as 0.0138 and 0.378 respectively for a square clamped diaphragm.

So the square structure is taken only to compare because if you take the regular square structure close form analytical relations are available for that and constants which are to be used in the equation are those values are also available. That is why you have selected those fine regular structures; so that we can compare our simulation result along with this these hand calculation analytical results. Because the numerical result is in coventorware software. What is going on inside you do not know. Only to valid the coventorware where the simulations are right track. So that your understanding is correct, you have to ensure that. Then you can go for complicated structure using coventorware which is not possible by manual calculation using close form analytical solution. So that is the objective basically. So those equations if you solve, then you can get the maximum stress values as well as maximum deflections and those who has simulated.

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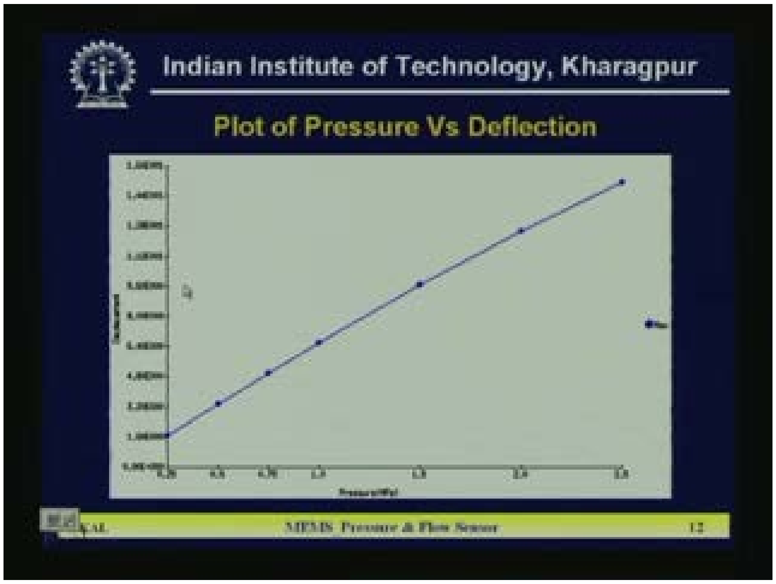

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Plot of Pressure Vs Deflection

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The plot is shown here, that is pressure versus the displacement of the central region is a maximum deflection. That is, looks like that linear if you increase the pressure. This is in megapascal and this is in the micrometer. So that plot is with application of pressure maximum deflection variation is linear.

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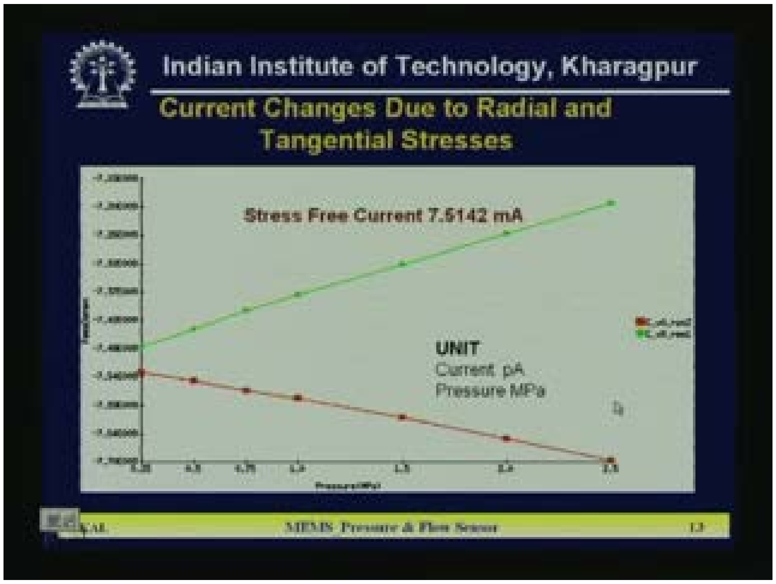

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Current Changes Due to Radial and Tangential Stresses

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Now this is simulation of the current change due to radial and tangential stress. In some case it will get the stress is radial and another is tangential. Because we place the resistance you have seen two are perpendicular to one side and other two are parallel to the opposite side. So because of that the some resistance will get the radial stress and some will get tangential stress. So that you can see one the resistance has been is increasing and other is decreasing. Because of this radial and tangential phenomenon. So now the pico ampere the current scale is in pico ampere and pressure in megapascal. So resistance one and resistance two; one is for radial and resistance two for tangential and the variation of the resistance change or variation of resistance change means current will also change and that current change with the pressure is shown in this simulation.

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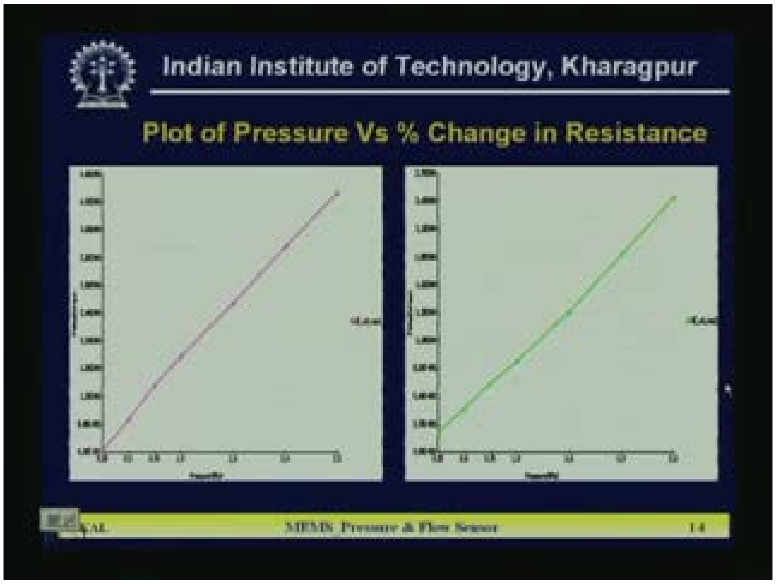

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Plot of Pressure Vs % Change in Resistance

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Now next is the plot of pressure versus percentage change in resistance. The change in resistance percent change in resistance with pressure for both the radial stress resistors and tangential stress resistance are simulated and those are plotted here. In both cases you can see the variation is highly linear. So complete structure is basically the regular structure and that is why you will get this kind of variation.

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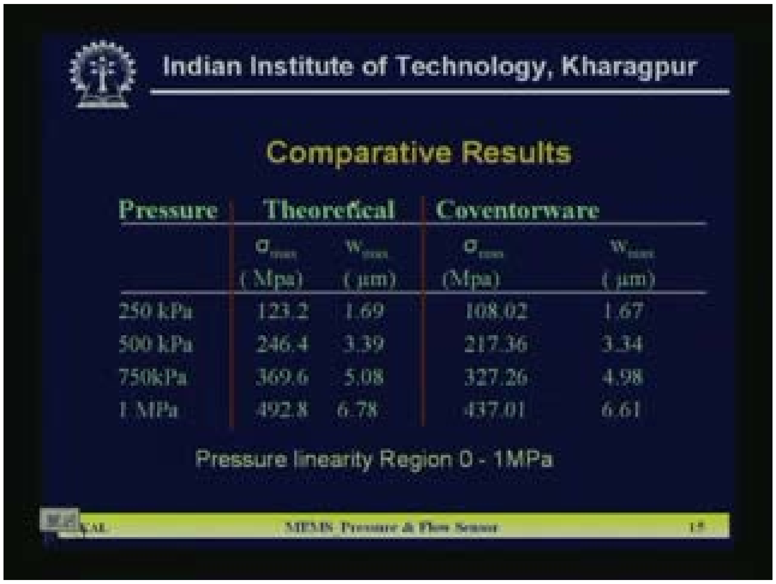

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Comparative Results

Pressure	Theoretical		Coventorware	
	σ_{max} (Mpa)	w_{max} (μm)	σ_{max} (Mpa)	w_{max} (μm)
250 kPa	123.2	1.69	108.02	1.67
500 kPa	246.4	3.39	217.36	3.34
750kPa	369.6	5.08	327.26	4.98
1 MPa	492.8	6.78	437.01	6.61

Pressure linearity Region 0 - 1MPa

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Now next is a comparison comparative result. Because one is coventorware simulation other is a theoretical simulation using those relations which I mentioned in earlier view graph. Now for the simulated for 4 pressure values, one is 1 megapascal starting from 250 kilopascal, 500 kilopascal, 750 kilopascal and 1 megapascal and the maximum sigma$_{max}$ and w $_{max}$ is a maximum stress and maximum deflection. Theoretical means using the relation which I mentioned earlier, coventor means numerical solution. So if you compare the values so you can see that deflection if you look is 1.69, 1.67 so here is 3.39 kilopascal for 500 kilopascal. The deflection maximum is 3.39 micron. Here is 3.34 micron for 750 kilopascal 5.08 micron, there is 4.98 micron.

So it is 6.78, 6.61 is very close. On the other hand the maximum stress regions say 5 to 10 percent variation is a close. That means we are just on the right direction. We should say our understanding is it tells that. So pressure linearity region is 0 to 1 megapascal. So that is the linear region, all sensors are decide to work in linear region. So that the sensing output should be accurate if it is a linear region. Though in any of the sensor one of the important aspect is linearity. So we are not going to use the region which is parabolic or exponential part. Then what is the problem there? You cannot get the faithful representation of the variable with respect to the pressure or other thing and that is why we always select the linear region of the sensor.

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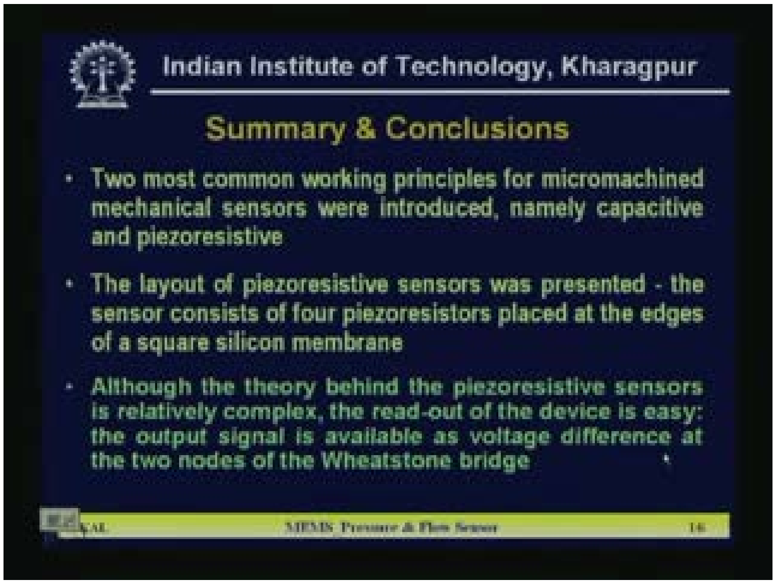

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Summary & Conclusions

- Two most common working principles for micromachined mechanical sensors were introduced, namely capacitive and piezoresistive
- The layout of piezoresistive sensors was presented - the sensor consists of four piezoresistors placed at the edges of a square silicon membrane
- Although the theory behind the piezoresistive sensors is relatively complex, the read-out of the device is easy: the output signal is available as voltage difference at the two nodes of the Wheatstone bridge

Now if we control on the pressure sensor part, so we can say that two most common working principles for micromachined mechanical sensors were introduced. One is capacitive other is piezoresistive. It is not true for pressure; it is true in acceleration sensor also. There when I discuss on microaccelerometer you will see that is also piezoresistive and capacitive accelerometers are very common, very important like the pressure sensor. Layout of piezoresistive sensors was presented. The sensor consist of four piezoresisitor placed at the edges of the square silicon membrane. Why at the edges? Because this is the maximum stress region you can get by MemMech solution. Although the theory behind the piezoresistive sensor is relatively complex. The read out of the device is easy the output signal is available as voltage difference at the two nodes of the Wheatstone bridge.

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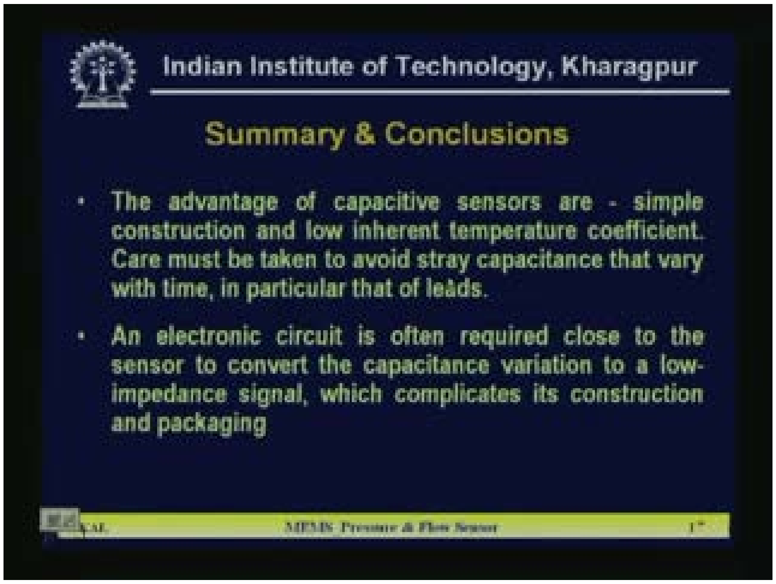

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Summary & Conclusions

- The advantage of capacitive sensors are - simple construction and low inherent temperature coefficient. Care must be taken to avoid stray capacitance that vary with time, in particular that of leads.
- An electronic circuit is often required close to the sensor to convert the capacitance variation to a low-impedance signal, which complicates its construction and packaging

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But in capacitance the advantage of capacitive sensors are simple construction and low inherent temperature coefficient. Care must be taken to avoid stray capacitances that vary with time in particular that of leads; bonding leads. So that you have to take care. An electronic circuit is often required close to the sensor, to convert the capacity variation to a low impedance signal which complicates the construction and packaging. That is in case of capacitance sensor which I mentioned earlier also. So this is about the pressure sensor and now I want to switch from capa sensor to another very important kind of sensor that is the flow sensor.

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Micromachined Thermal Flow Sensors

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So let us discuss on micromachined thermal flow sensor. We will concentrate on thermal flow sensor and in our laboratory these kind of sensors we are working on that and we have also fabricated some of the sensors. Some of the result also I will discuss along with there design prospective and basic principle of work basic working principle.

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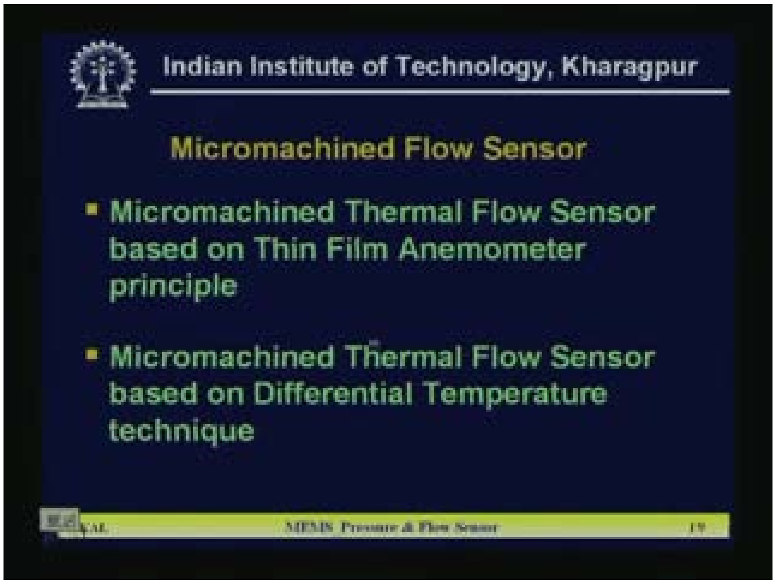

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Micromachined Flow Sensor

- Micromachined Thermal Flow Sensor based on Thin Film Anemometer principle
- Micromachined Thermal Flow Sensor based on Differential Temperature technique

SAL MEMS Pressure & Flow Sensor 19

So micromachined flow sensors, there are two principle used for realization of micromachined flow sensor. Those are namely one is thin film anemometer principle and that is known principle. But we are using some cantilever structure and some thin film metals. So that thin film metal will have temperature coefficient of resistance and with heating the TCL value will change. As a result of which the resistance will also change and heating means if you heat a particular metallic film, resistor film, then with flow the temperature of that particular sensor resistive element will change with flow the heat will dissipate from the resistance. So as a result of which the TCL will change and resistance value will change. That is the basic principle there in thin film anemometer principle and other kind of sensor flow sensor is based on the differential temperature technique. So differential temperature technique and thin film anemometer technique will be discussed in detail and we will see how the flow sensors are designed based on these two principle.

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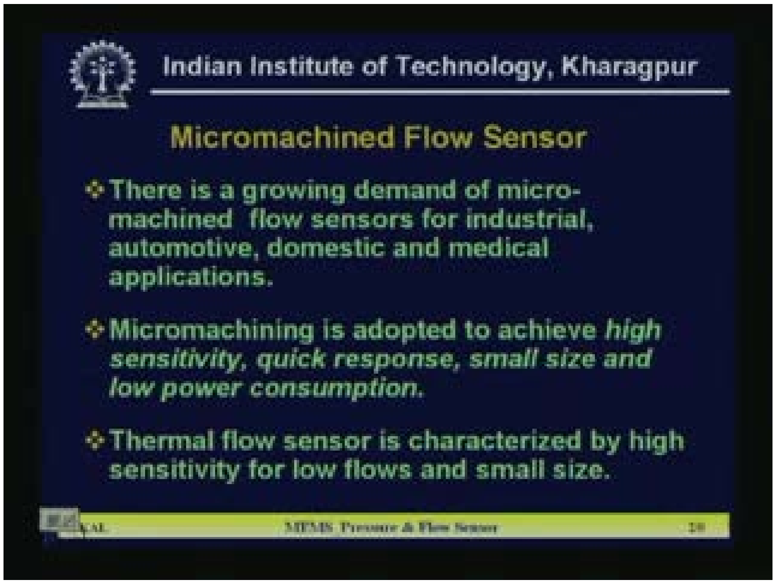

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Micromachined Flow Sensor

- There is a growing demand of micro-machined flow sensors for industrial, automotive, domestic and medical applications.
- Micromachining is adopted to achieve *high sensitivity, quick response, small size and low power consumption.*
- Thermal flow sensor is characterized by high sensitivity for low flows and small size.

MEMS Pressure & Flow Sensor

Now whether the application of the micromachined flow sensor. There are various applications, namely industry automotive domestic and medical. Flow measurement that flow measurement of fluid. That fluid may be the air, that fluid may be gas, any kind of gas and that fluid may be the liquid also. So liquid flow in biological application. The bio fluid flow or blood circulation of what the artery or vein is an important aspect. So there flow measurement in a big pipe, the water flow measurement is also important and also gas flow about different instrument different system. We need to flow gases accurately for having certain reaction or certain the mission. So that is why both industry automotive domestic and medical applications are there and then question comes. Those kind of flow sensor where available long time back why the micromachined flow sensor and the advantages of micromachined flow sensors are many fold namely it will achieve a high sensitivity quick response, small size and low power consumption. These are the four basic advantages of micromachined flow sensor.

High sensitivity quick response small size and low power consumption. Thermal flow sensors are characterized by high sensitivity for low flows and small size. High sensitivity for low flow basically the thermal flow sensors are used for low flow. That means if the flow is laminar. If the flow is turbulent or the flow is large, there this kind of thermal flow sensors is not used some other structure may be used. So you can see that if you in the tip of silicon cantilever if you make a piezoresistive piezoresistance, so if you put it into the pressure high pressure, there also the tip will bend and there you can detect the change of resistance because of the flow. That also can be used as a flow sensor pressure because variation of pressure if the flow is more pressure on the tip will be more and that can you can calibrate so that principle can be used. But this kind of sensors, thermal flow sensors is most highly sensitive and accurate value it gives and it is mostly valid for low flow. That is flow must be laminating not stream line flow not turbulent flow.

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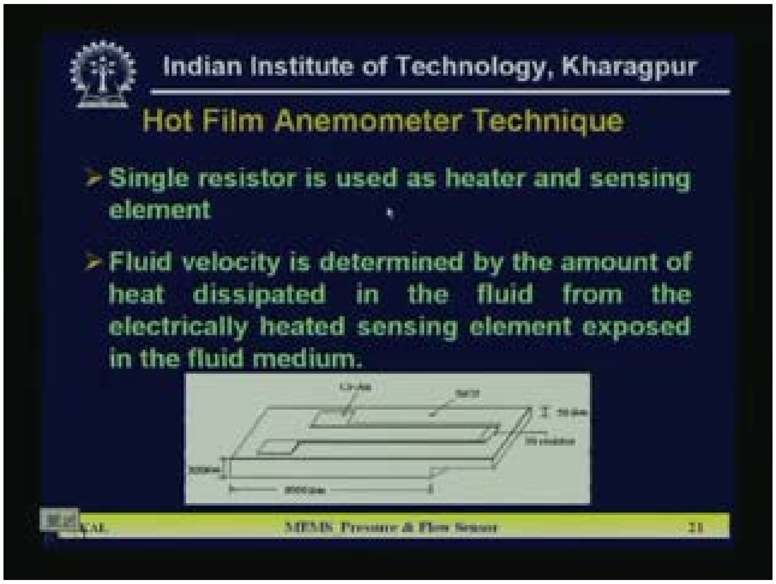

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Hot Film Anemometer Technique

- Single resistor is used as heater and sensing element
- Fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium.

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So now hot film anemometer technique is discussed here. Single resistor is used as heater and sensing element same resistor will be used as a heater as sensing element, both purpose will be served. Fluid velocity is determined by the amount of heat dissipated in the fluid from the electrically heated sensing element exposed in the fluid medium. You see this structure here. Here, this is basically, this part you can see is a nickel resistor. So this is a small nickel resistance at the end thin film nickel and there at this end and this end are connected with chromium gold line. This is a chromium gold line, this is another chromium gold line and for taking the contact from there and from here you can take contact and this is the chromium gold line on silicon dioxide. Silicon dioxide is the thermal insulator. It is insulating from the semiconducting silicon and this portion has been edged and 250 microns. So that its thermal mass is very less and total substrate thickness is 300 micron and this region 8000 micrometer. So this is a typical structure of the flow sensor based on hot film anemometer technique.

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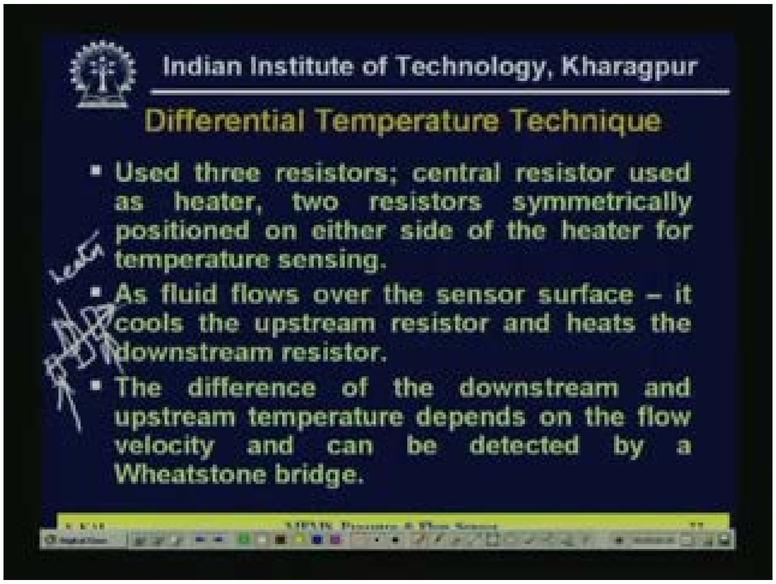

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Differential Temperature Technique

- Used three resistors; central resistor used as heater, two resistors symmetrically positioned on either side of the heater for temperature sensing.
- As fluid flows over the sensor surface – it cools the upstream resistor and heats the downstream resistor.
- The difference of the downstream and upstream temperature depends on the flow velocity and can be detected by a Wheatstone bridge.

Now if we go to the next slide, so in case of differential temperature technique what are the basic principles? There we used three resistor. In thin film anemometer principle we have used single resistance which is used for heating as well as for sensing. But in differential temperature technique there are used three resistors. One central resistor that is used as heater. That is for heating two resistors symmetrically positioned on either side of the heater for temperature sensing. Because, central heater is used for heating purpose and the both side there are two other resistors. One will sense both resistors placed on either side will sense the temperature of the fluid. That means if you at the center there is a heater and both side there are two heater. Now heat the fluid flows in this direction, so left side this is heater will be at the cooling condition and during the flow from here the heat will be disappear transmitted to the next heater. So that means next heater temperature will be more. So that means you will have a differential kind of the temperature you will be getting. So now if we see here I can just show you in this, here you can see, here this is a say heater. So this is another now you see this direction. If it is flows, so now this central is heating.

This is heater, so now fluid flows in this direction, then what will happen? So now this two are sensing left and right. So now the heat will be transmitted from the central region to this side. So that means this resistance will get more heat because of the heat transmission from the center to this direction and this is the cooler region. So you will get this heater and this heater there is a temperature difference. So the temperature difference will depend on the flow of the fluid. The temperature difference will depend on the flow of the fluid. So that is the differential temperature technique and that will give much more accurate flow measurement compare to the single resistor technique which is thin film anemometer technique. So here as the fluid flows over the sensor surface it cools the upstream resistor. This is up left side is the upstream resistor and right side is the downstream resistor. It cools the upstream resistor and heats the downstream resistor downstream is this one. If the flow direction is that so the upstream resistors will be cooled down and downstream resistor will be heated up. The difference of the downstream and upstream temperature depends on the flow velocity and can be detected by a Wheatstone bridge.

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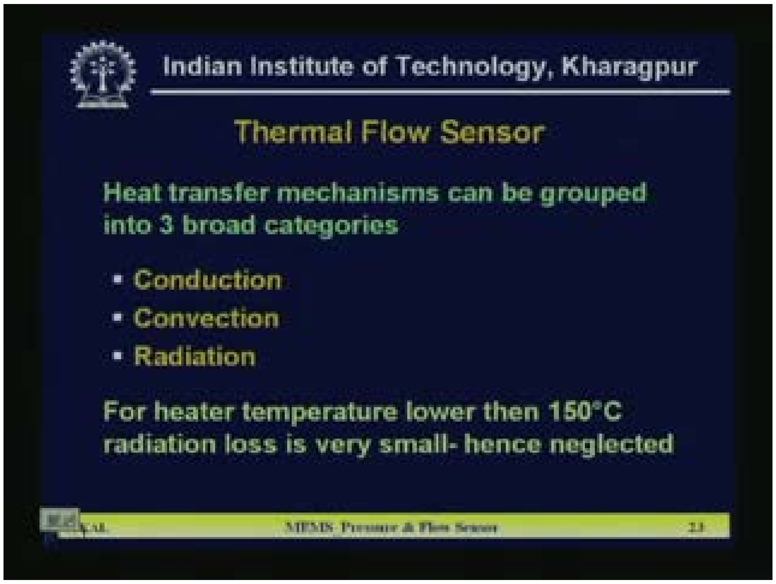

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Thermal Flow Sensor

Heat transfer mechanisms can be grouped into 3 broad categories

- Conduction
- Convection
- Radiation

For heater temperature lower then 150°C radiation loss is very small- hence neglected

Now in case of thermal flow sensor, heat transfer mechanism can be grouped into three broad categories. What are the heat transfer mechanisms? One is a conduction, convection and radiation, so out of the three mechanism for heater temperature lower. Then 150 degree centigrade then radiation loss is very small and can be neglect because the heat loss due to radiation is governed by the Stephen’s Law. That is t to the power 4 proportional t to the power 4. If the temperature is very small, under that condition you can have this radiation loss is negligible. So only loss is due to conduction and convection. Now for this kind of thermal sensor we will for laminar low flow, small flow purpose we will just take account the heat transfer only by conduction and convection mechanism because liquid is flowing. There will be convection and the conduction will be there. These two mechanism we will concentrate on that for dissipation of heat from one region to other region due to the fluid flow.

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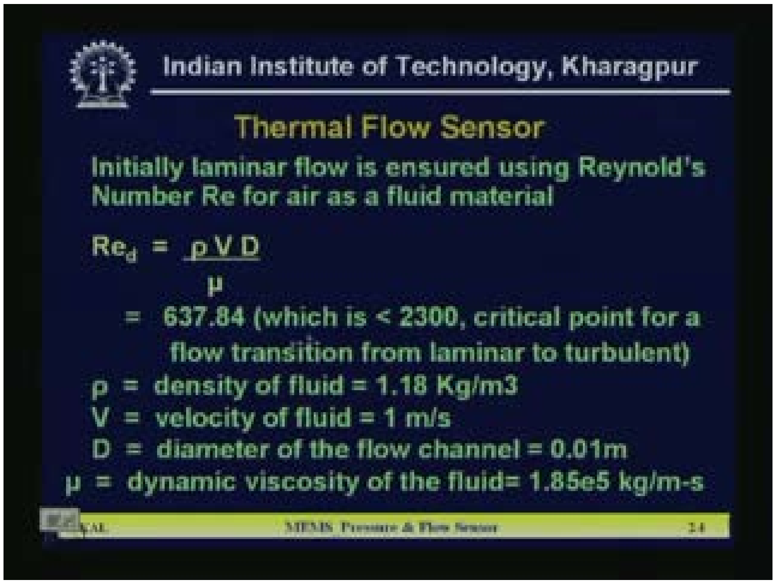

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Thermal Flow Sensor

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

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

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

ρ = density of fluid = 1.18 Kg/m3
V = velocity of fluid = 1 m/s
D = diameter of the flow channel = 0.01m
μ = dynamic viscosity of the fluid= 1.85e5 kg/m-s

Now based on this principle we will develop the sensors. But before that the flow sensor as I mentioned the low flow we are not considering the turbulent motion. To ensure the laminar flow the Reynold number has to be brought down to a certain value which should be less than 2300 is a very crucial point for a flow transition from laminar to turbulent. We know when the Reynold's number is more than a certain critical value then the flow laminar flow will be converted into turbulent motion and that turbulent motion flow very difficult to measure. So in that case then we have to see first what is the Reynold number of that particular structure and it is given by row VD by mu where row is the density of the fluid, V is the velocity of the fluid, capital D is the diameter of the flow channel and mu is the dynamic viscosity of the fluid. For a particular example, particular tube flow measurement and flow measurement inside a tube of diameter is a shown here 0.01 meter and row value if we assume 1.18 kg per meter cube. That is for air flow so and we calculated it is a 637.84 which is well below 2300 for this kind of structure. So we are ensured that flow is laminar. So after that we can go for certain analysis and certain simulation are measurement flow and either by this technique or other technique and those analytical simulation as well as design of the flow sensor I will discuss in the next class. Thank you.

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Preview of Next Lecture

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Lecture # 19

Micromachined Flow Sensors

Micromachined Flow Sensors

Today we will continue our discussion on flow sensors. In last lecturer I remembered I introduced the flow sensor and there are two basic techniques of measuring the flow of the fluids and those two techniques we will be discussed in details and some of the experimental results and some of the design aspects of the flow sensors also will be discussed.

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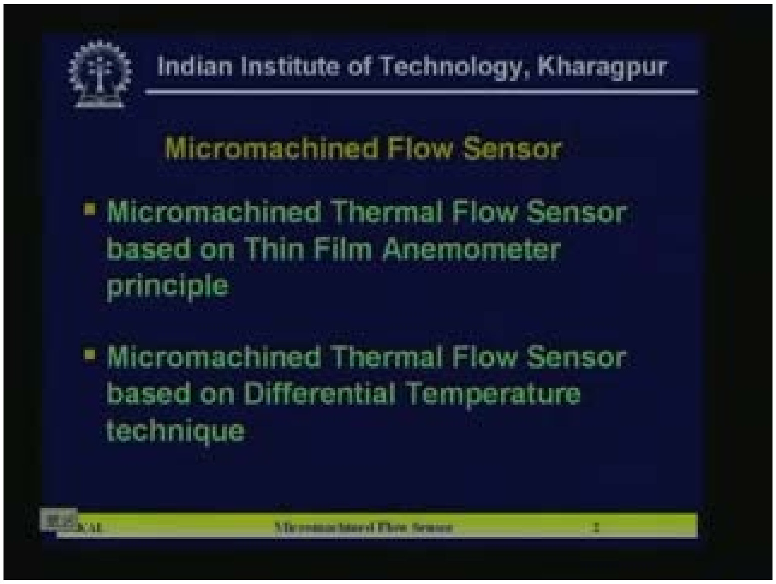

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Micromachined Flow Sensor

- Micromachined Thermal Flow Sensor based on Thin Film Anemometer principle
- Micromachined Thermal Flow Sensor based on Differential Temperature technique

Now there are two techniques which are used for designing micromachined flow sensors are namely thin film anemometer principle and other one was differential temperature technique. Both of the flow sensors belong to thermal flow sensor. Basic principle behind this, heater will be there and the heat will be dissipated from the heater with flow if the fluid flows, depending on the flow pattern and depending on the flow velocity, the heat dissipation will change and because of the heat change some of the properties are materials are also will change and that will be the measure of the flow. That means it is not direct flow measurement, it is indirect flow measurement. Flow pattern is going to change the heat dissipation, the first phase and second phase the change of because of heat dissipation the temperature of that particular sensor will change and that will change the materials properties.

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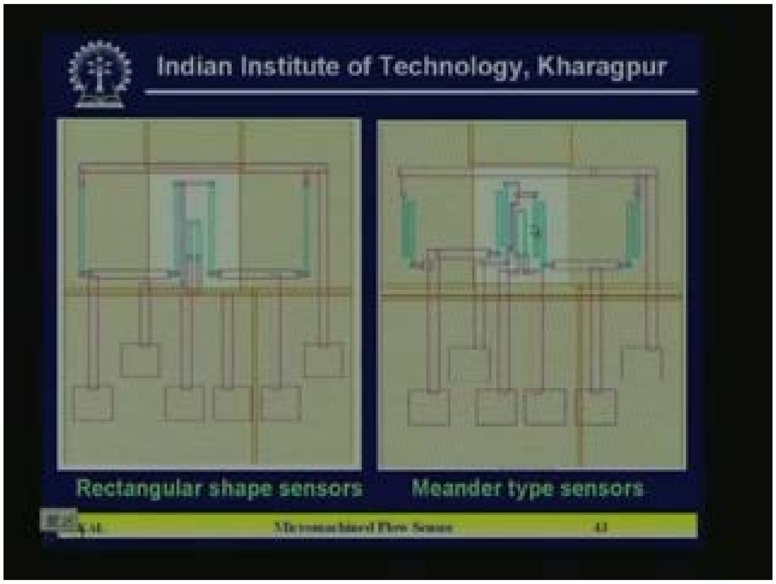

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Rectangular shape sensors

Meander type sensors

So you see here, so this is portion and this portion resistance are meander line. Here is one is state line, one single line; here you can see three lines. All four resistances in the layout are same one, two, three, and four; here only the meander and here is single line. So that will be much more sensitive because total areas of the surface area of the resistance are more here. So there are the mask layouts of all the layers you can see here.

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Conclusions

- For flow sensor based on Anemometer principle, with increasing flow rate the drop in voltage due to heat convection increases linearly.
- This sensor has number of qualities, particularly a small sized sensor and an easy implementation.
- The main drawback of the this flow sensor is its high operating temperature as well as its high sensitivity to variations in the fluid temperature.
- Moreover, this is a local measurement which has to be reproduced many times in order to get a profile of velocity allowing the determination of a volumetric flow.

Next is the comparison given between the anemometer and these differential for measurement and number of qualities particularly in case of the anemometer principle is the small sized sensor and an easy implementation. The main drawback of this flow sensor is its high operating temperature as well as its high sensitivity to variations in the fluid temperature. It is a local measurement which has to be reproduced many times in order to get a profile of velocity allowing the determination of a volumetric flow. This is local measurement of major problem. There is the heating and sensors element are same which may create problem in anemometer principle.

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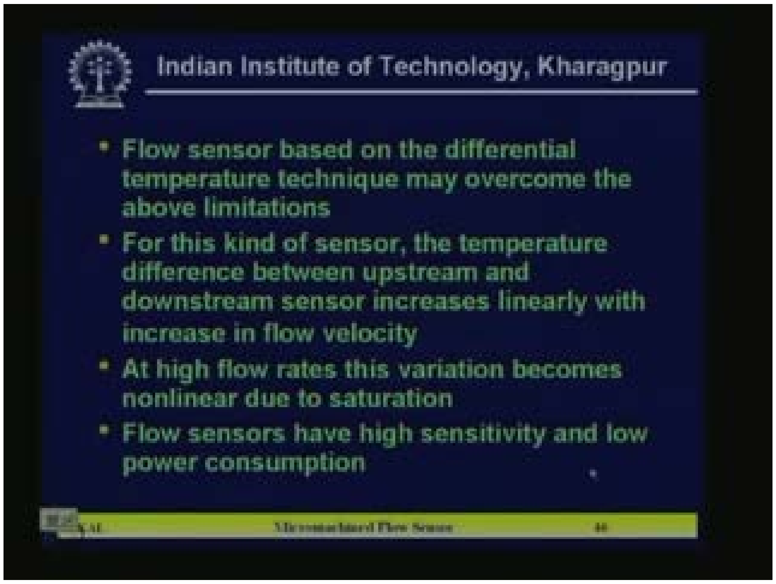

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- Flow sensor based on the differential temperature technique may overcome the above limitations
- For this kind of sensor, the temperature difference between upstream and downstream sensor increases linearly with increase in flow velocity
- At high flow rates this variation becomes nonlinear due to saturation
- Flow sensors have high sensitivity and low power consumption

But the second one is also promising the differential flow sensor based on differential temperature technique may overcome the limitations of the anemometer principle. For this kind of sensors, the temperature difference between upstream and downstream sensor increases linearly with increase in the flow velocity, this is the observation at high flow rates. This variation becomes non-linear due to saturation. So that you have seen over the simulated gap which saturates at high flow sensor have high sensitivity and low power consumption in this particular the micromachined and cases. So thank you very much. Let us stop here today.