MEMS and Microsystems
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Lecture No. #19
Micromachined Flow Sensors

Today we will continue our discussion on flow sensor. In last lecture I rememberedI have introduced the flow sensor and there are two basic techniques of measuring the flow of the fluids and those two techniques we will discuss 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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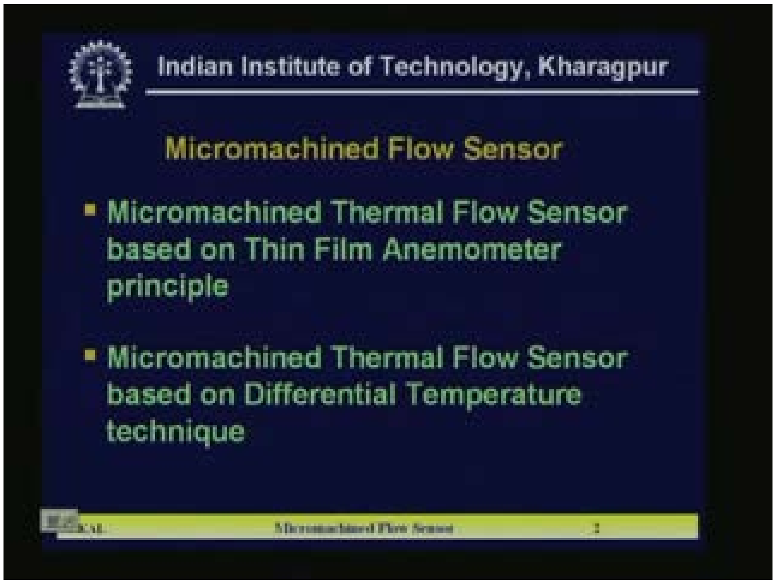

Now there are two techniques which are used for designing micromachined flow sensors are namely thin film anemometer principle and other one was differential temperature technique. Both of the flow sensors belong to thermal flow sensor. Basic principle behind this,a heaterwill be there and theheat will be dissipated from the heater with flow. If the fluid flows depending on the flow pattern and depending the flow velocity the heat dissipation will change and because of the heat change some of the properties of 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 distribution.

The first phaseand second phase the change of because of the heat distribution the temperature of that particular sensor will change and that will change the material properties. That means it is two-step process. So out of those two-stepsthose first one thin film anemometers have got certain advantage, disadvantage. But the second one differential temperature technique is well acceptable. Because there the individual temperature of the heater or sensor is not important but difference of temperature between the two heaters is important which will automatically eliminate the environment. Lot of environment effect;effects mean the room temperature or radiation from outside sources which are coming on to the sensor. Those effects automatically will be neglected in the second class of the thermal flow sensor which is differential temperature technique.

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Now I will directly go to the principle which is based on thin film anemometer. Designsperspective of the thermal flow sensor based on thin film anemometer principle. In the design perspective what is to be done? First a thin dielectric layer of silicon dioxide of 1 micron is thermally grown on the silicon cantilever. Why this is required? Because if you want to have a sensing element. That is in this particular case, is basically a thin film resistance and directly the thin film resistance if you make on silicon. Silicon is also a semiconductor material. It will have certain conductivity. So that means the silicon as well as the thin film resistance which change you are going to measure, that will be combinedphenomenon. So you, order to isolate these combined effect, we normally put an insulation layer or isolation layer in between the metal filmand the semiconductor material, then what is the purpose you can ask me.

The purpose of using the semiconductor material is that we can micromachine that semiconductor material in particular region where the thin film metallic resistance is placed. So that its thermal mass will be less, so absorption of that base material. What absorption? Heat absorption or heat distribution by the base material will be less. Sowhatever the distribution of the film, that distribution is only due to the flow pattern. There is convection if the liquid or the gas flows over the film so there is convection and due to the convection the flow will be thereand as I told you, in last class also,that another effect of heat distribution is due to radiation and that heat distribution due to radiation. And thatheat distribution due to radiationdepends mainly ontemperature if temperature is very high, then heat distribution will be more. It is asigma t to the power 4, this Stefan'slaw you know. So there is a fourth power of temperature.

So if we restrict the temperature of that sensing element low so distribution due to radiation will be minimum. I should not say 0, so it will be low and may be neglected in compression due to distribution, due to the flow. That is the convection conduction, convection and radiation. These are three methods by which heat can be distributed. So out of that in this particular case we want only the heat distribution should be with respect to the convection of the fluid, convection phenomena. That means fluid flows over the thin film resistance and or thin film heater and then accordingly the property will change. But conduction should be as minimum as possible. So in that case if I put directly the metal film on the semiconductor that means the base material or the substance material also will be a conduction of the heat from the thin film to the substrate material and from there it will be distributed, that we want to avoid it.

That is why it is better if you design the whole thing or fabricate the whole thing on an isolation material which is that isolation material is either silicon dioxide or silicon nitride. It will have good isolation property; heat isolation as well as electrical isolation. Electrical isolation is also necessary because you are sensing the current through that thin film resistant. So it is a placed on semiconductor. So the current will be distributed not on the thin film resistor,it will be distributed throughout the semiconductor also. So that will also create problem in estimating the actual current change and after that you are going to measure the voltage change across that thin film resistanceif you send a constant current. So for that we have to have an isolation layer and that isolation layer is made here by a thin silicon dielectric layer and which is 1 micrometer and is thermally grown on the silicon cantilever. Silicon dioxide provides electrical isolation between the sensing element and the bulk siliconas well as to some extent, thermal isolation also. A very thin membrane is created and the free hanging end of the cantilever on which the sensing element is placed. That reduces the mass of active area that just now I told you.

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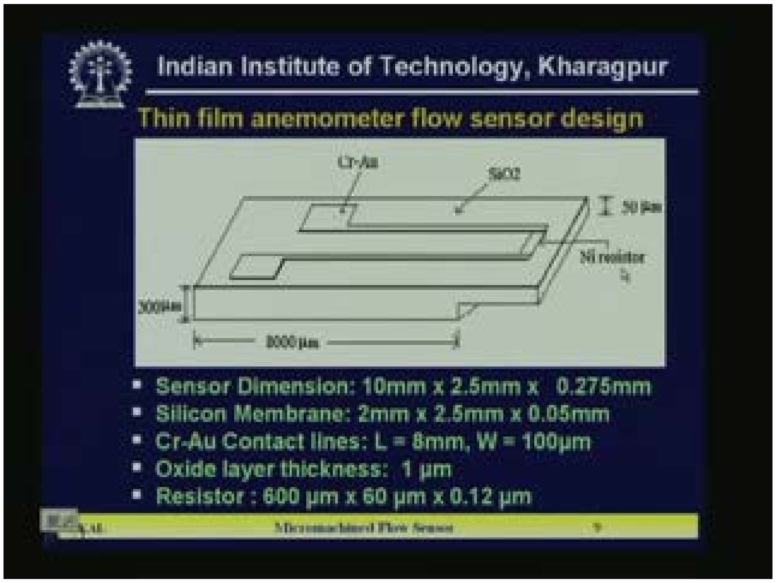

Now this is the structure of theanemometer flow sensor device. So here you can see here, so this whole, the top surface is a silicon dioxide SiO_2 and this is thecantilever or which from the bottom of that cantilever we have etched silicon although here is 300 micrometer. So this cantilever is only 50 micrometer and in this region you have design and fabricated this nickelresistance and for ohmic contact you have used the chromium and gold. They are two end of the resistance is a chromium and gold connected and this is the bonding pad. The total dimension of the sensor is 10 millimeter; here is 8 millimeter and from here to here another 2 millimeter. So 10 millimeter 2.5 millimeters is the width here and 0.275 micrometer millimeter. So that means 270 micron is the total thickness here. So that means total piece of the silicon rectangular which we are using for the sensor is a 10 millimeter across 2.5 millimeter across 0.275 millimeter. Silicon membrane is basically, this portion is there,2 millimeter 2.5 is the width and 0.5 millimeter is the thickness. This is 50 micrometer here. Chromium gold contact lines are8 millimeter length. This is chromium gold contact line and w width of this chromium gold is 100 micron.

Chromium is used you know I mentioned earlier also. That for proper addition of the gold film on to the silicon or silicon dielectric substrate is chromium necessary. Otherwise the addition of the gold will be very poor and subsequent processing the gold may be peeled off from the surface of the silicon dioxide.Similarly nickel, below nickel also we have to you some chromium layer which will very thin layer is may be 100 to 200angstrom unit, not very large amount. So that will help addition of the nickel with the substrate which is,said for silicon dioxide below that film. Oxide layer thickness is 1 micrometer. On that you can get it by thermally grown oxide, 1 micrometer and resistor which is here, the nickel resistor which is placed here, this nickel register is 600 micrometer is the length and 60 micrometer is the width and 0.12 micrometer is the film thickness. So that is the sensing element or the heater here, heater and sensing elements are both same in case of the anemometer flow sensor. But in other case those two are different. We will explain that also. So this is the basic the design structure or structure of the thin film anemometer flow sensor.

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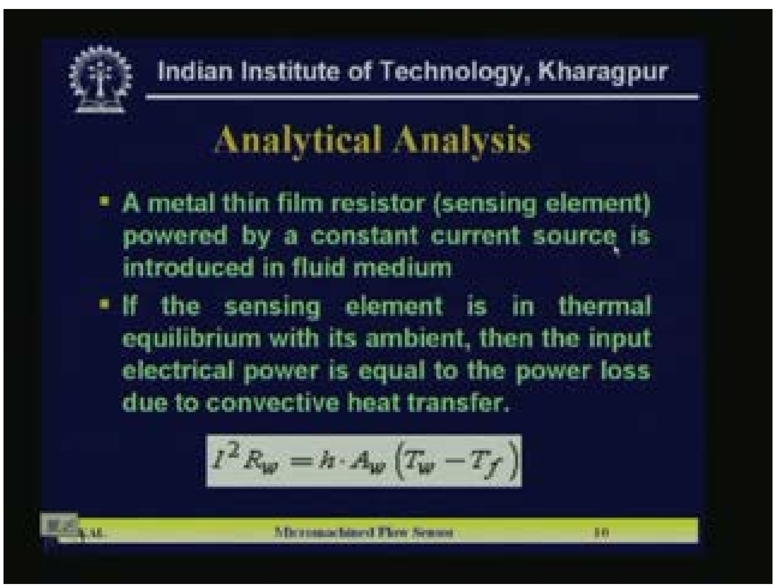

Now we will discuss on the analytical analysis of this metal thin film resistorand this resistor is powered by constant current source is introduced in the fluid medium. That means a thin film resistance which is putinto the fluid medium, either it is a gas or it is a liquid. So a constant current is sent through that thin film resistance. If the sensing element is in thermal equilibrium with its ambient then the input electrical power is equal to the power loss due to the convective heat transfer. We mentioned we have to design the total things so that the heat transfer is mainly due to convection for fluid flow. Now when this in thermal equilibrium,if the power through the resistance is I square $R_{w,}R_{w}$is the resistor, value of the resistance of the metal thin film which is nickelthere. I square R the power, now this must be equal to h into A_w into T_w minus T_f.

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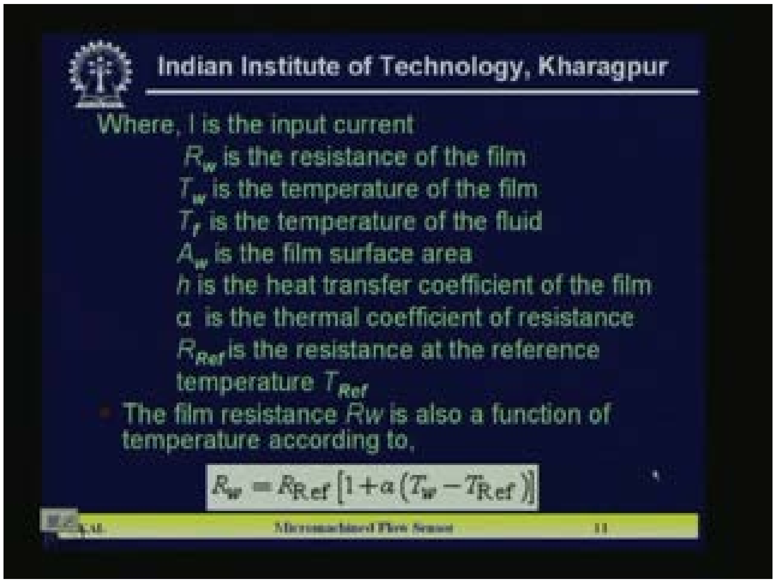

So this h stands for the heat transfer coefficient of the film. T_w is the temperature of the film and T_f is the temperature of the fluid. So T_f is the temperature of the fluid and T_w is the temperature of the film and h is the heat transfer coefficient of the film. R_w is the resistance of the nickel resistor which is the sensing element it is R_w and now some other parameters are mentioned here is alpha. Alpha is the thermal coefficient of resistance. R_{Ref} is the resistance at the reference temperature $T_{Ref,}$the film resistance R_w is also a function of temperature. According to R_w is equal to R_f1 plus alpha T_w minus T_{Ref}. So $R_{Ref}$and $T_{Ref}$are the reference. That means if we use the reference is room temperature so there so after that the R_w which is the film resistance will change according to this relation where alpha is known as the temperature coefficient of resistor. And I mentioned also temperature coefficient of resistance should be very high to increase the sensitivity of the device.

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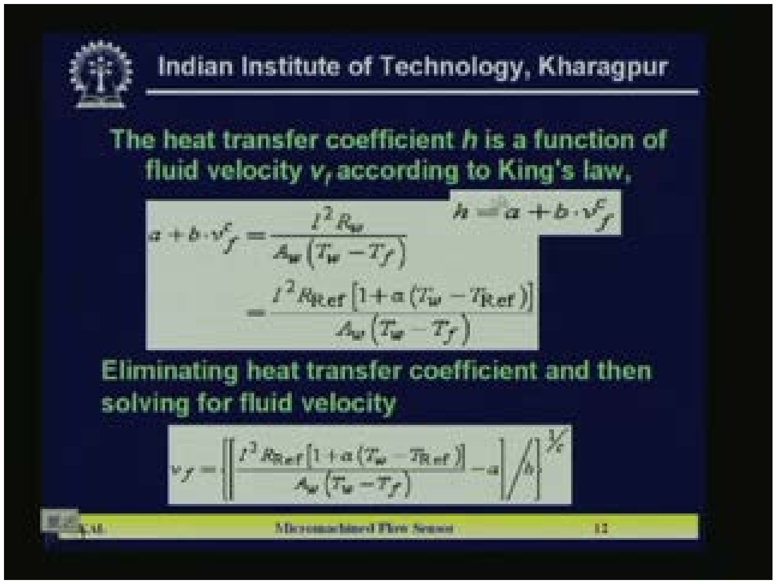

So these two relations later on we will solve to find out the velocity.Heat transfer coefficient h is a function of fluid velocity v_f. According to the King’s law and this is the King’s law. Here is the King’s law; this one is the King’s law. So that is what h is equal to a plus b v_f to the power c where a, b, c are constants, which is we found out from the design structure and physical parametersand v_f is the velocity of the fluid and h is the heat transfer coefficient. Now the h is equal to a plus b dot v_f to the power c, that will be equal to in the earlier equation if you see in this.

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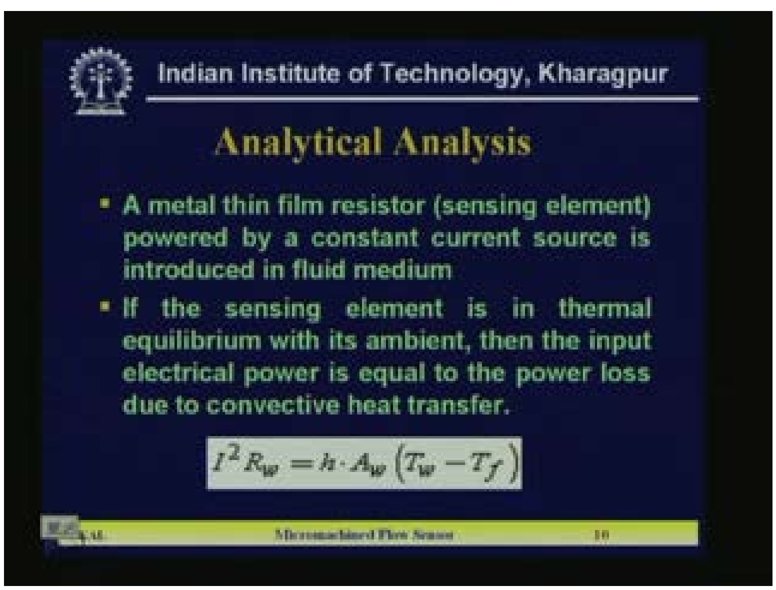

So you can see this equation I square R_w is equal to h dot A_w, T_w minus T_f. So this equation h will be given by I squareR_w divided by A_w, T_w minus T_f. So there the h value is substituted, here you see then you are getting I square R_w divided by A_wT_w minus T_f and which is again in thesecond equation R_w is put because the second equation R_w is equal to R_{Ref}, R reference into 1 plus alpha into T_w minus Treference. If you put this value here R_w the expression looks like this. So now what we did basically here we eliminate theheat transfer coefficient hand then if you solve the equation, then fluid velocity from this equation will come like this. V_f fluid velocity is equal to I square R_{Ref} into 1 plus alpha into T_w minus T_{Ref} divided by A_w T_w minus T_f minus a slash b whole to the power 1 by c. So that is the fluid velocity which we found is basically the, I square R is 1 parameter. A_w the area is known and the you see T_w minus T_f fluid temperature and the resistance temperature difference will be there and we have to have alpha more to getting more sensitive and fluid velocity and the current through the constant current which is flowing through the film heater as well as sensing element is related with V_f like that.

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So now if you now discuss on the fabrication steps, it will be like that. The starting material which we have started is 2 inch diameter, double side polished silicon wafer. Why double side polish because, we have to align both side, means front side as well as back side also. If it is not both-side polished, that alignment will be difficult and it will not be properly done. So that is why we have to use two side polish,both side polish silicon wafer, it is a n type resistivity, 4 to 6 ohm centimeter, thickness 275 micrometer. Here the type of the substrate is not that much important because you are not going to diffuse any kind of the dopant into the substrate or you are not going to make diffuse resistance. You are going to metal thin film resistance and the silicon is basically the container or is a substrate into the silicon. You are not going to make any active components or nothing. Only the some portion you are going to etch.

To get this thin structure and other portion we will keep it as it is. So that the mechanical rigidity will be there. So now step one will be thermal oxidation which is a normally we use dry wet dry is a 20 minute 120 minute and 20 minute at 1100 degree centigrade. Silicon dioxide thickness is approximately 1.2 micrometer. Next step is photolithography for patterning of front side oxide which is grown in step one. Using the front etch maskwhile protecting backside oxide with photoresist. What did you do in this particular step? Basically there, the front side patterning means the total area of the sensor you are defining. Rest of the portion you are removing the silicon dioxide. So that when you will etch backside from the top side also, those layers, boundary layer will also etch. So that easily at the end of the process you can break the wafers or break the samples from the wafer easily. Sample means sensor devices easily you can break it.

That is why this step two front side patterning is requiredand what patterning you are doing it is oxide patterning and some of the periphery of that each sensor some line which is also we call it as scribe line the oxide is removed. Next is third step and in third step we will do for photolithography which patterns the back side oxide and while protecting front side oxide with photoresist, this step requires both side top and bottom alignment. So here in the backside patterning means you are defining the etch area where you are going to make the membrane as well as theperiphery boundary. That means you can see the periphery boundary of the sensor either step 2 and step 3 both places you are open and now if you etch, then the periphery of the sensor will be etched. KOH will be etched from the top as well as from the bottom and as well from the bottom only the membrane area or the cantilever area it will etch, but top surface it is protected. So this is the normally they did the silicon oxide removal for micromachining of the silicon itself. That is this two steps they did it. Next is a thermal evaporation of chromium nickel film to form resistors.

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The chromium film thickness 150 angstrom nickel film thickness nearly 2000 angstrom. Now this kind of the chromium nickel chromium is required for addition and nickelis basically your thin film metallic anemometer. That is which is the basically sensing element, so this kind of structure if you want to pattern, you can face little bit problem. What problem? Because already you havenot etched but oxide you have patterned. Oxide pattern means there on the surface top and the bottom there is some uneven places where you grove, you have made itby removing silicon dioxide from the top and bottom. The next phase if you do for lithography then you may face some problem. Because photo resistor will not uniformly cover the entire surface and their photoresistthickness may value over the entire surface top and bottom and then exposure will not be uniform over the entire wafer and development and subsequent process you can get some problem.

So for that in this case you can sometimes go for. If you face the really problem then you can for the direct deposition of the metal film. That means either lift-off technique or you can go for the direct vacuum mass technique. You can deposit chromium nickel film and there one advantage is you are going to bother of the chromium nickel. The etching solution directly you go for that. But if you find that the top surface, the scribe lines or etches are not very deep at all, only 1.2 micron or 1 micron silicon dioxide etching will be there. So you can easily spin photoresist, then you can go for the normal photomasking step,photomasking process and that is why step 5 is written photomasking of chromium nickel patterning. Thenstep 6 thermal evaporation of chromium gold film to form the contact. This is the materialization,metal contacts the chromium film thickness is 150 angstrom.

As I mentioned that chromium is basically the addition metal with gold and nickel with silicon dioxide and its thickness is very small of the order of 150 angstrom. Then you go for the chromium gold patterning. That photomasking from chromium gold andstep 8 silicon etching which is micromachining of silicon with 44 weight percent KOH at 25degree centigrade from backside only while protecting front side with black wax and silicon 1 1 wafer silicon 1 0 0 thickness etched only from the back side approximately 200 micron. That means here what you are doing? So if you need longtime etching the front surface, since the chromium gold or the chromium nickel has already been patterned on the top. So the KOH solution may damage the gold or chromium or gold or nickelchromium nickel film. So in order to prevent those damages normally top side is covered protective layer and that protective layer in many cases we use the black wax and on the top of black wax you can if you press 1 1 1 oriented some silicon wafer which normally does not etch by KOH.

So top side to be protected and from the back side you can pattern and so that you can get cantilever or membrane. So after that you remove the black wax and other things. Then very thin layer will be there, the separation layer. Wherethat is basically the scribe line for small amount of time you again you dip it in KOH solution which will not damage the gold or chromium film. But the silicon will be separated. So that is normally done. Otherwise you have to go for some other the etching technique micromachining technique, not KOH. Those are basically TMAH etching. So TMAH etching is not available in most of the laboratories. That is why you are using KOHalso people design theprocess flow so that easily you can get the complete structure.

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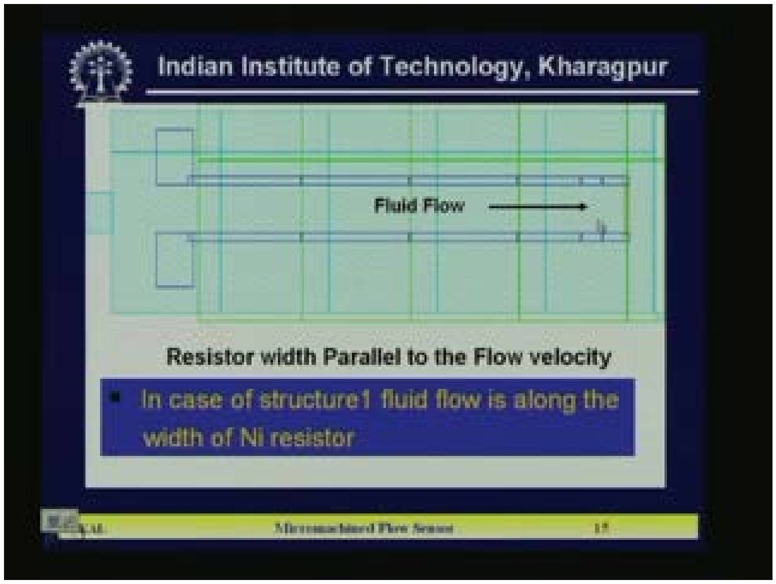

Now these are the fabrication step and this is the structure, mass structure of the thin film anemometer. So these arethe, you see bonding pad here,this is the line, gold line and this is the resistor nickel resistance here. Now there are two kinds of designs. In one design the resistor width parallel to the flow velocity the fluid flow is in this direction. Then this is the width, these basicallyno, this is afluid flow is along the width of the nickel resistor. This is the, this along the width of the nickel resistance. But width, this direction along the width is right, along the width of the fluid. Fluid isalong the width of the nickelradiation nickel resistor. So there is another structure where fluid flow is along the length of the resistor so andthat structure is a second one you can see here. If you make the design like that and fluid flow in the direction, so that means the flow is in this direction, width is in this direction. So automatically it is in the length. Then two things you can do. Flow is along the length or flow is along the width.

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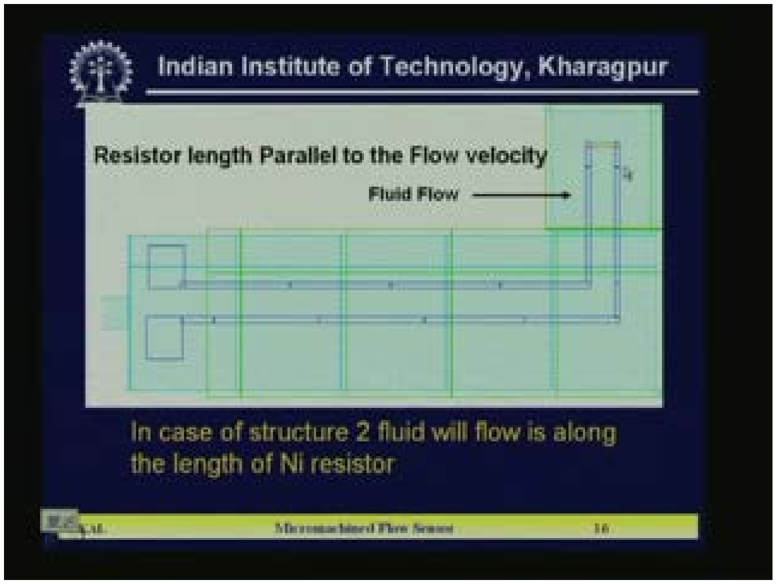

And here this is along the width, this is here is the resistance, this portion is the resistance and here is along the length, this is the length. So in a both design has been made so that you can measure along the length as well as along the width the resistance change.

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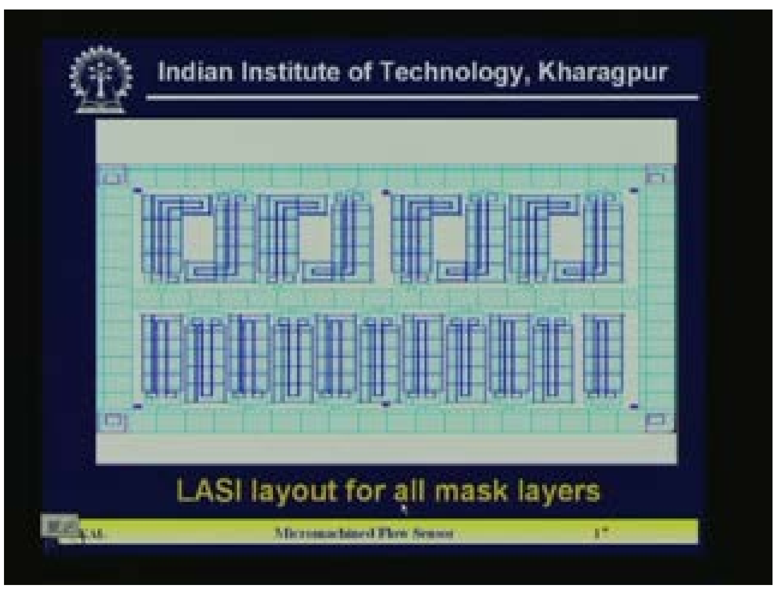

Now here are the complete structures of the sensor. LASI layout of the mask together here so you can see here,in each case you can see1, 2, 3, 4, 5, 6, 7, 8 are the structure 2 and here 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, the structure 1. S both structure 1 and structure 2 has been madeand now you can see the top surface, the white region, the white region, this is white, white and this region basically oxide is removed. So that here you can etch from the top and from the bottom you will etch only the region where yourfilm is there. That means in this particularfilm is nickel film is here. Here nickel film is here, here is here similarly here in this caseand the structure 1 case nickel film is only in this portion.

Here is in this portion, here in this portion, so there from the bottom sidemembrane is there and this white gap between one sensor to other sensor is kept basically for breaking the samples from one to other which will be easy. If thoseportions are etched from top as well as from the bottom, it will thin down drastically and it is held over some point. For example here is a joint point you can see here green. Here is a joint, here also is a joint,and here also is a joint. Similarly in this case here is a joint. So only this joint point it is held with the substrate at the end of the etching. So that just gentle pressing each of the sensor you can get separated from each otherso that you can easily go for mounting of individual sensor. So accordinglymaskhas been made.

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Now here you can see the diagram of the fabricated micromachine flow sensor. Here both the sensor, this is structure 1, this is a structure 2. You can minutely notice here. So the tip is different color which is the nickel and rest of the line is coming as gold and that is soldered here with some small PCV. So that you can place you can just cover the whole thing in a tube and which is fitted in the measurementchamber, measurement setup so here also structure 1 here is a tip is the nickel resistor, here in this tip is a nickel resistor. So this is the fabricated devices.

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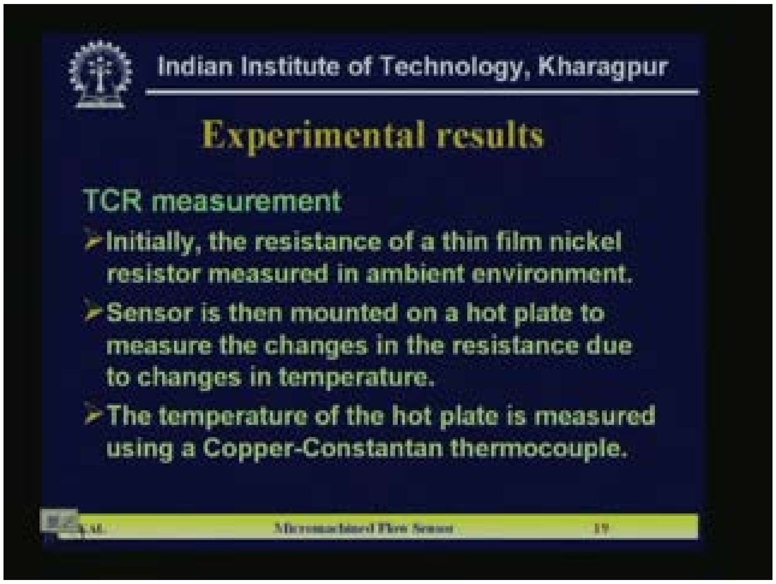

Now the experimental measurements. So forthis kind of sensor you have to go for first measurement is temperature coefficient of resistance of the nickel film. Then you will measure the velocity versus the change of resistor. So first is temperature coefficient of resistance measurement, there what you have to do, the thin film nickel resistor is basicallyall the measurements are done inambient environment or room temperature. To increase the temperature because for TCR you do notneed the fluid flow just temperature coefficient of resistance you have to increase the temperature of that particular film and you have to measure the resistance change. So that is the objective. So there the sensor is mounted on a hot plate. To measure the change in the resistance due to the change in temperaturetip of the resistance, you put a very stiff heater, small stiff heater, so that the accurately you can change the temperature and then temperature can be measured use using thermocouple attached closely to the tip. Then the temperature of the hot plate is measured using the copper constant thermocouple.

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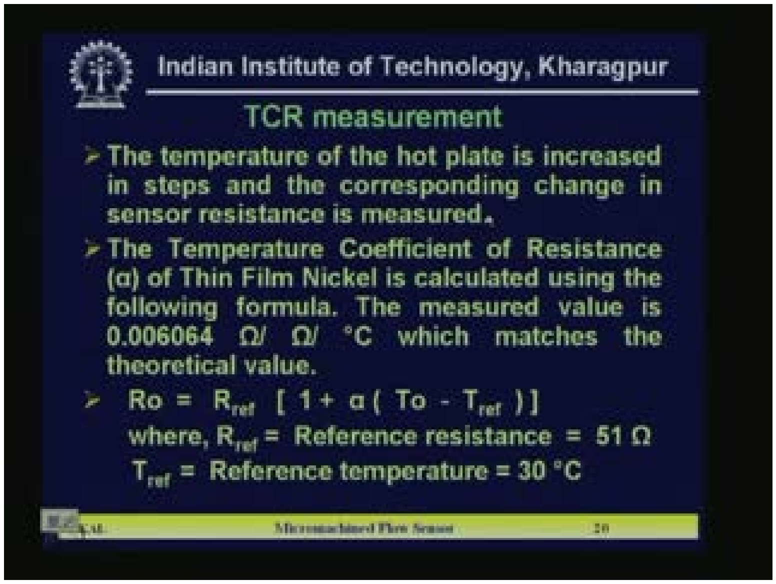

So now after that and the corresponding change in sensor resistance is also measured. The heater you can hot plate basically you can change itsinput power. So that it will be more and more hot and the sensor is attached to the hot plate and then sensortemperature will also increase and resistance change is measured simultaneously at different temperature. The temperature coefficient of resistance alpha of the thin film nickel is calculated using the relation which is given here. Which is $R_0$is equal to Rreference R_{ref} into 1 plus alpha T_0minus T reference where R reference and T reference are the reference temperature and resistance. And that means reference temperature we assume its ambient temperature which on that particular day may be 30 degree centigrade and at that temperature the resistance of thenickel film is 51 ohm. So now you put that $R_1R_0$is known reference is known $T_0$and T reference is known, so alpha you can calculate easily from this relation.

So the alpha measured value is obtained as 0.006064 ohm per degree centigradewhich matches theoretical value theoreticalvalue is nearly 0.0064 or 67 something like that up to third order it is matching properly. So slight diffusion is there because here whatever heating I am giving, exact measurement of the temperature of the film is very difficult. Because lot of heat loss due to the ambient temperature difference with the heated temperature, if the heated temperature is large compared to the ambient, there will be heat loss due to radiation and exact measurement of the temperature of the film is not possible. So that is why some error will come into the picture and at the same time another deviationis due to because you are measuring the TCR of the nickel film and you are not expecting the TCR of the nickel film will be as that of the bulk. So the reported result in the literature is the bulk nickel TCR value. So that is 0.0064 or 65 something like that. But here we are getting very close to that and deviation is because of that.

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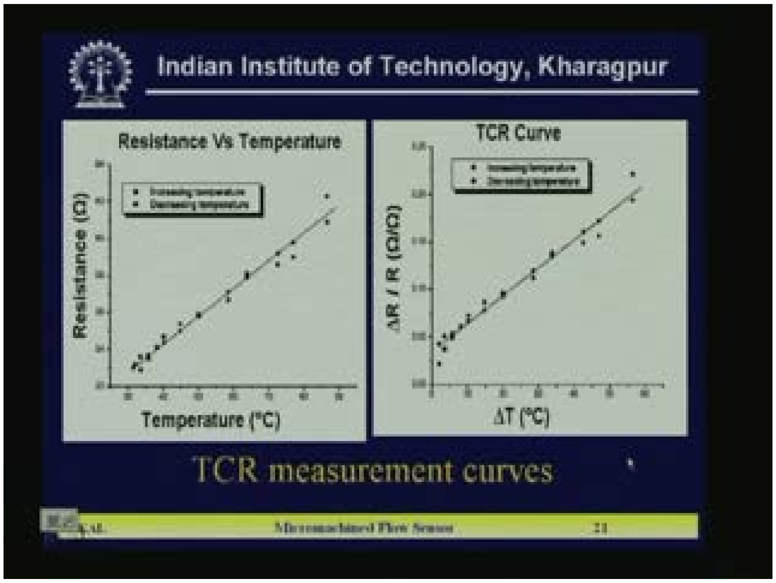

Now these are the measured values of resistance versus temperatureand here you see we have measured for increasing and decreasing. Both ways because when you increase the temperature then you can see the resistance value is going to increase and at the same is a metal. Isn't it? So with temperature increase, resistance value will increase and again if you reduce it will follow the same path reduce it. So that we have you can see the square and the dot it, is its almost close, some average curve we have takensome small variation because you are taking spot measurement and during that spot stabilization is another problem power supply has to be stable because you are sending constant current source and that has to be stable. So because of thatminor fluctuation may be there. So for measuring the TCR so the second curve is plotted is basically the derived curve from the first one delta R by R where R is the reference temperature or temperatureat resistance value,reference resistance which is resistance value at room temperature or ambient temperature and delta add is the chain. So if you take the delta R by R S Uand the change of temperature with respect to the ambient is delta T where it also straight line and from there you can easily calculate the alpha value and that is obtained as 0.006064 so like that.

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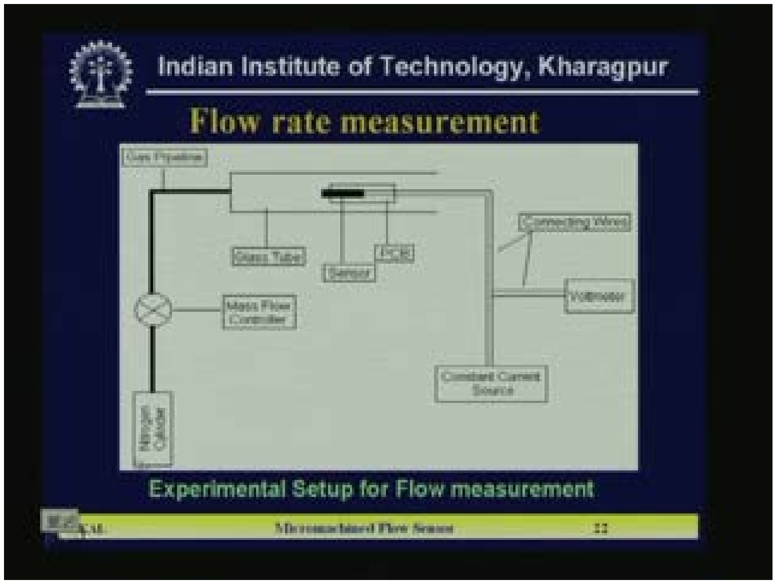

Now the flow rate measurement. This is the setup which is used for measuring the flow and here is the nitrogen cylinder because we are measuring the nitrogen flow. With just basically you can say is a calibrate calibration carp. So the flow of gas is the gas flow that is nitrogen is used and from the cylinder. This is a mass flow controller which can control the direct gas flow from the cylinder the gas pipeline is connected to a tube, narrow tube and inside the tube we put the sensor and this is the sensor and the PCB is here. The PCB fixed inside the tube at a particular point. This is a glass tubeand now this sensor point is connected to a constant current source and now across these two points if you measure the voltage, then you can measure the change of voltage with respect to the flow because you change the flow here.

So automaticallydistribution will be there and if you send a constant current through that, so because of the heat distribution thetemperature of that particular tip will vary and because of the resistance value will vary and this resistance value itvaries. Then you will get a voltage drop and that voltagechange is because of resistance change as we have sent a constant current v equal to ir. If i is kept constant, so directly v is will be theproportional to R. If R changes, so accordingly the voltage drop also changes. We assume that iremain constant. That is why we need a constant current source. So with this measurement setup we measured thedelta v voltage change for different values of the flow of nitrogen gas.

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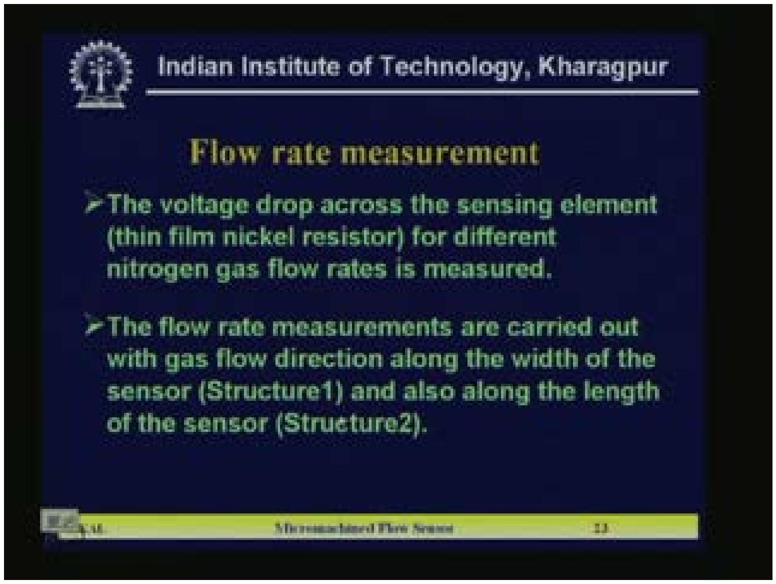

So that is measured for different nitrogen gas flow. Flow rate measurements are carried out with gas flow direction along the width of the sensor. That is structure one and along the length of the sensor. That isstructure two both the sensors are fixed inside the tube.

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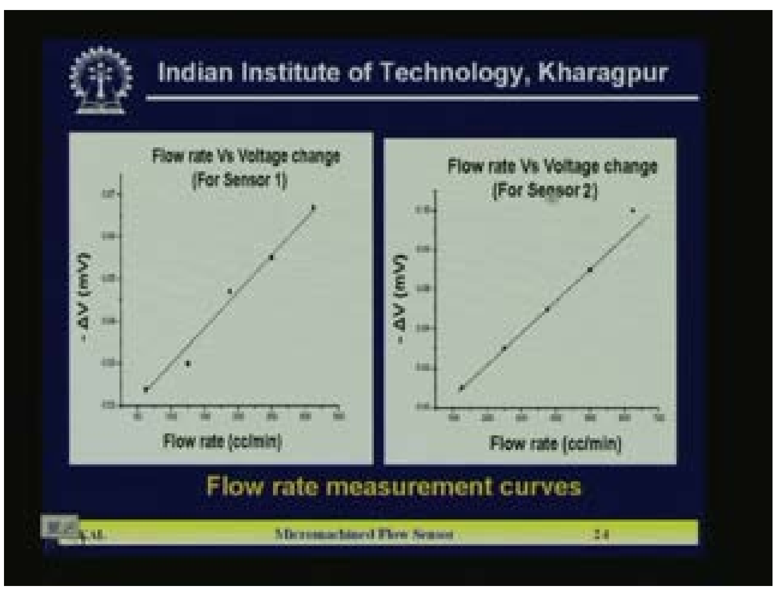

And we measure the flow versus the change of the voltage. So we can measure by mass flow controller which is connected at the mouth of the nitrogen cylinder. So from there you will get the flow and delta v you can measure from the voltmeter connected across the anemometer. So now the delta v versus flow rate is this is a measured value for sensor 1 and sensor 2 is a structure 2, the delta v versus the flow rate. You can find here up to the 100 to 700 cc per minute and here for sensor 1 the 50 to 300 you can get very linear curve. The nature is linear and due to the minus delta v because, whether your resistors changes or resistors increases or decreases. Depending on that voltage will also change either positive or negative direction. Means whether it is increasing or decreasing. That will depend on the positive temperature coefficient or negative temperature coefficient. So in case of metal it will be the voltage drop will be less and less because resistance change will be in such a fashion so that you will get the sign because of whether positive or negative. Now the flow rate versusthe change of voltage that may be the calibration curve and later on you can use the similar curve and directly from the delta v change you can measure the flow. You can estimate the flow from the calibration curve.

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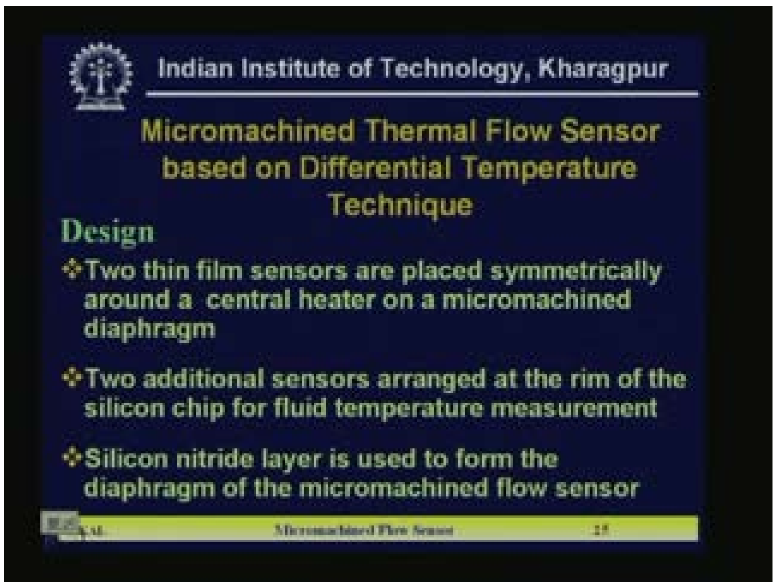

Now this is the anemometer principle. The second one is the differential temperature technique. So in this particular case,2 thin film sensors are placed symmetrically around the central heater on a micromachined diaphragm. Two additional sensors are arranged at the rim of the silicon chip for fluid temperature measurement. That is not changed. This additional sensor and here we will use some Wheatstone bridge. So that with respect to some reference resistors which are kept at the rim we can see the change of the sensing element and accordingly you can get the output by balancing a bridge which is the Wheatstone bridge and there you can get much more accurate measurement. Silicon nitrideis used in this particular case to form the diaphragm of the micromachined flow sensor. Because silicon nitride is a better insulation property than silicon dioxide in both with respect of heat andthe electrical conduction.

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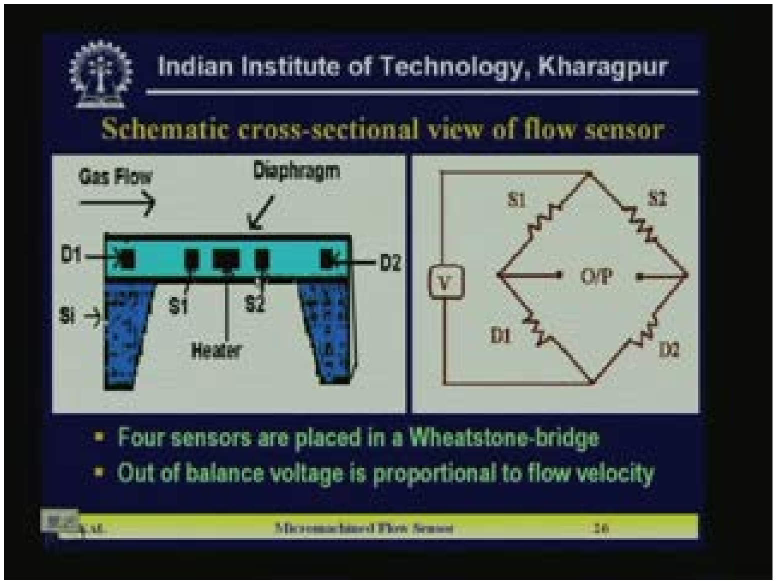

So now here the structure looks like this. This is the membrane structure basically here you are going to measure going make 4 resistances D1, D2, S1 and S2. Similarly almost resistancesyou have made and in the central portion is a heater. This is the heater portion, heater is here, this is the because here in this particular technique the heater and sensing elements are different heater is placed at the middle and the D1 and D2 is a far array from this sensor part far away. So that it can measure these two resistance will basically the ambient resistant, it will measure and that since we are not going it is far away from the heater,these two will not are not going to change. Now this is the D1 and D2 we can call it is a reference resistance and now the S1 and S2 are kept here and here. So when there is steady state and no heater is there. So then all the resistance is D1, S1, S2 and D2 will be the same. At the steadystate under the ambient condition. No heating will be there, if you are not heating is all kept at room temperature.

Even then if you at a steady state flow condition, what will be there? Both flow resistance will be equal and in under that condition the bridge will be perfectly balanced; bridge will be perfectly balanced output will be 0. Now what is done here the whole, the 4 resistance along with the heater, heater is nothing but is also resistant is put on the silicon nitride is a black region is a silicon nitride is not cross section. This top part is not cross section, basically it is like that this is, the thing you can see is here. So now here is the top surface is shown and the black region is basically the insulation layer nitride on top of your making these 4 resistances. Now what will happen? If you power the heater, so during the flow from the heater,the fluid will absorb the heat and it will flow in this direction. So accordingly what will happen? This S2 will be the down steam. This S1 will be in the cool region and S2 will be in the hot region because the flow is gas flow is in this direction.

So now when the gas flow will be here, this will be from here the gas is flowing heater from the heater some of the temperature will be transferredinto the gas and the gas will be hot and because of the gas this S2 will be at the hot region and this will be the cold region. Temperature difference will be there and because of that you will have the unbalancing the bridge. Bridge will be unbalanced because there S1 will not be the equal to S two one is the down steam and another is the up steam. So one will be the in the cold region other will be in the hot region. If the flow is more and more, so then more heat will be transferred into the S2. So that the S2 change will be more compared to the S1 chain. So there is a gas flow velocity. Depending on that if it is a more so difference of the resistance change S1 and S2 will be more and more. So accordingly bridge will be more and more unbalanced if you estimate. How much it is unbalanced, so based on that you can have an idea of the flow velocity. So that is the basic principle.

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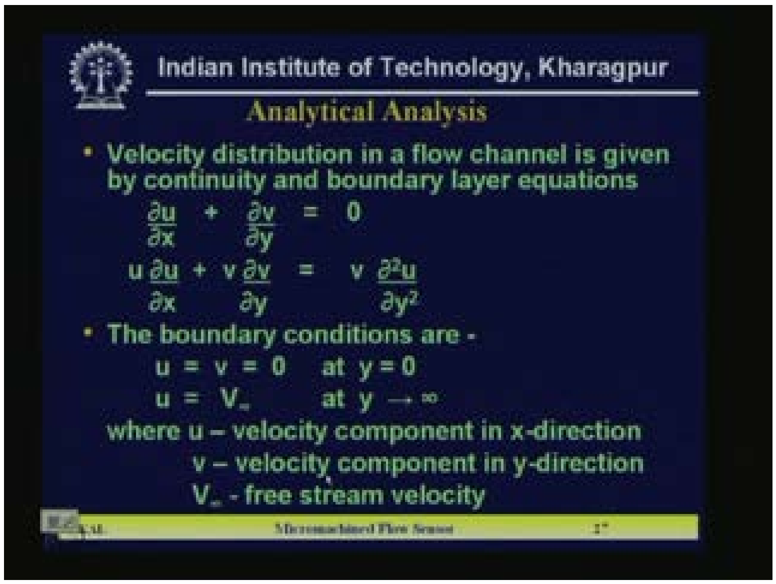

So now if you go for analytical analysis, then it is like that. Velocity distribution in a flow channel is given by continuity and boundary layer equations and these two equations are given here,del u by del x plus del v by del y is equal to 0 where u and v are the velocity component along x and y direction inside the fluid medium. So other equation is a del u del x ah del x v del v del y equal to v in del d 2 u d y square del y square the boundary conditions are like this and where u is the velocity component,x direction, v is the velocity component in y direction and v infinityis the free stream velocity is it. Free stream velocity means when the Norman laminar steady state velocity of the fluid not in the x component and y component y and x direction normal free stream velocity is v infinity.

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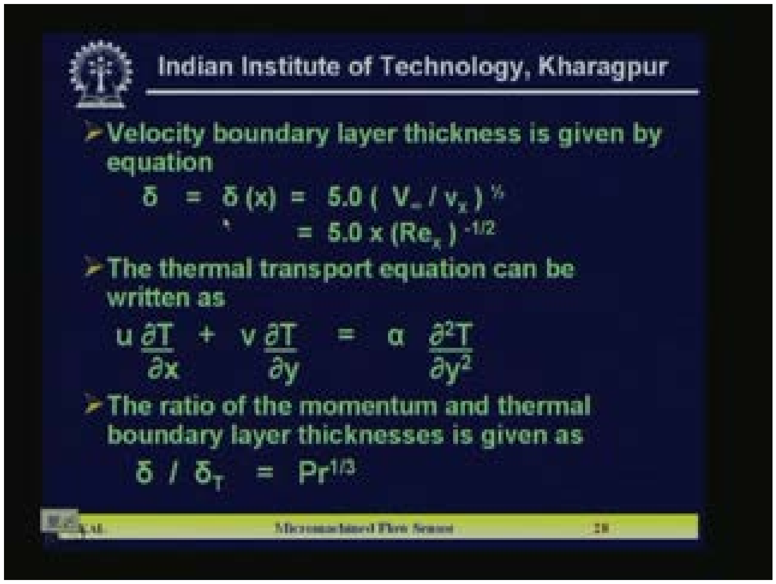

The velocity boundary layer thickness is given by this because if the velocitysince there is obstruction,there will be a boundary layer will be formed and this boundary layer if it is a delta, then delta at x is a delta x will be given by 5 v infinity. Thereby that is a free velocity by vx to the power half and other will be 5 into Re_x to the power minus half $Re_x$is the Reynold numbera Reynolds number. The thermal transport equation can be written as this and the ratio of the momentum and the thermal boundary layer thickness is given by del by del t is equal to Pr to the power one third and Pr is known as the prandtlnumber.

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Here is given Pr which is known as prandtlnumber. Nu is the nusselt number. So heat transfer coefficient which is convection in nature, convection coefficient can be calculated using the Nux which is a dimensionless number which is given by hl by k and is equal to 0.664 Rex to the power point 5Pr to the power 0.343 where Rex is basically you know is a Reynolds number is a row V L by mu and Pr is prandtlnumber which is mu Cp by K where the row V L mu C and Pr given by are given here. Row is the density of the fluid in kg per meter cube. V will be the velocity of the fluid meter per second. L is the length of heated plate, mu is a dynamic viscosity of the fluid, K is thermal conductivity of the fluid, Cp is the specific heat of the fluid, Re is the Reynolds number, Nu is the nusselt number and Pr is the prandtlnumber. So these are the relation.

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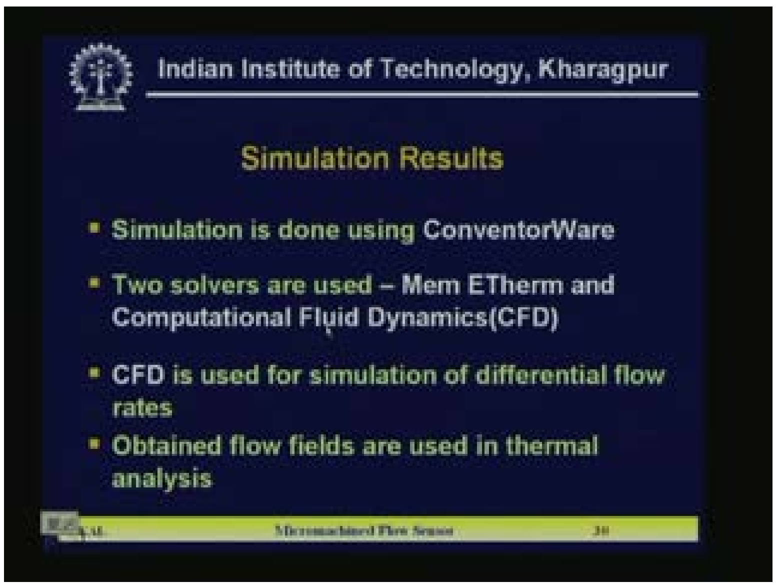

Based on those relation you can do some simulation and also we have tried to simulate the flow in a simulator which is a conventorware is a renowned the MEMS simulator tool and there two solvers are there for fluid flow. One is MemETherm and other is CFD which is computational fluid dynamics. Two module is there using both the module MemETherm and the CFD some simulation has been carried out and the results will be given. CFD is used for simulation of differential flow rates. The obtained flow fields are used in thermal analysis. The flow field which is obtained from the CFD analysis can be used for the MemETherm analysis.

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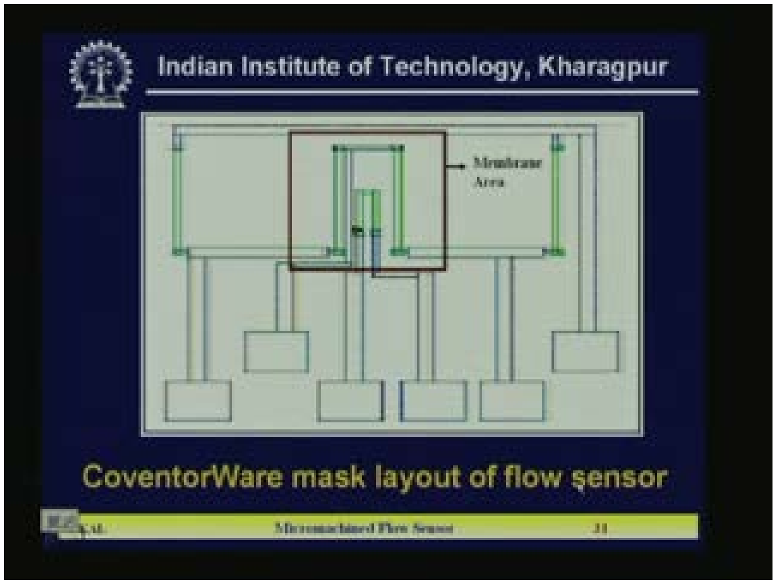

Now this is the structure you can see here. Soyou can get this is the basically the heater in the central place you can see this is a heaterand the 4 resistances are onehere and this is another here and these two are wide apart from the sensing elementand this portion is a membrane you can see this region is a membrane,this region is a membrane here and here is the reference resistances. This region is one and this region is one. There is a wide apart from the sensingand the central is a heater for heater there are 2 bonding pads. So you can heat the heater and these are the upstream and downstream sensing element one is kept these are very close to the sensor. So that it will be the heat, will be directly transferred from this heater to the sensing element.

So you will get much more sensitivity if you can make this heater very close to the make this sensing resistor very close to the heater. So another structure may be thought of there you can have the meander line of resistant. So total surface area of the resistance is more. So that the change of resistance due to the heat absorption or heatfluid flow which converted into heat, the heat chain will change the resistant. That will be much more effective if the total area of the resistance is more and that can be done by using the line meander lineresistances. So that you can see, this is basicallythese two are heater bound pad, other four;1, 2, 3, 4 are the Wheatstonesbridge. There are four bonding pad requires 2 are the power cell supply and 2 are theoutput. So all resistance are connected wired in such a fashion the four resistance will fit in to the Wheatstones bridge.

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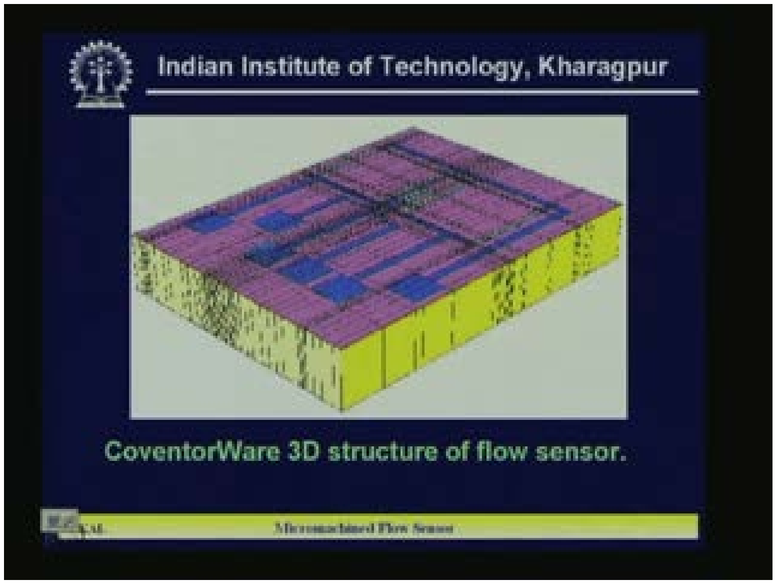

Now you can get this is the conventorware,3D full sensor structures, the whole structure you have to define the structure in conventorware. So this you can see the bonding pads are here the total 6 bonding pads and these are the resistances 1, 2, 3, 4 and in the center is the heater, here is the heater this is generated by conventorwarefor simulation.

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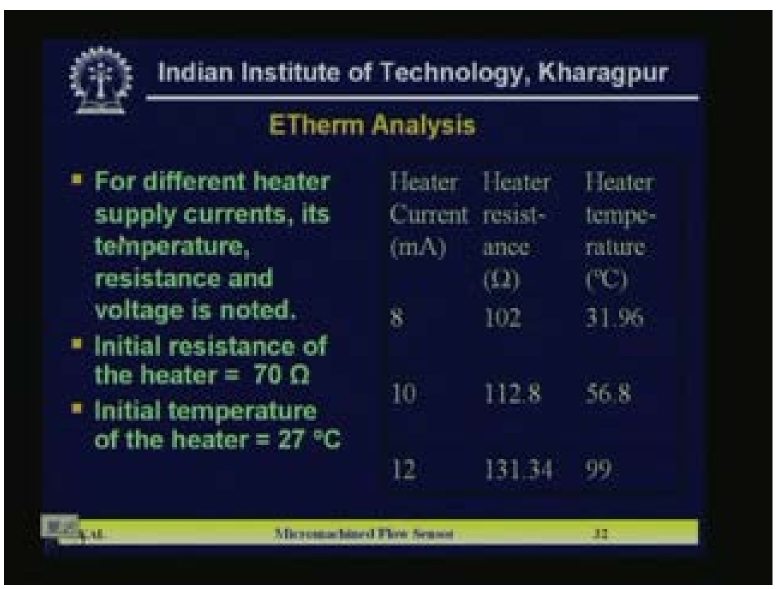

And ETherm analysis has been carried out and there the parameters are like that for different heaters supply currents its temperature resistance and voltage is noted and initial resistance of the heater is 70 ohm and initial temperature is kept 27 degree centigrade. Now these are the changes heater current there will be power supply to the heater. If you change from 8 milliampere to 10 to

12, accordingly heater resistance also will change and heater temperature is 31.96 or 50 degree 6 degree centigrade,99 degree centigrade that you can get from the ETherm analysis.

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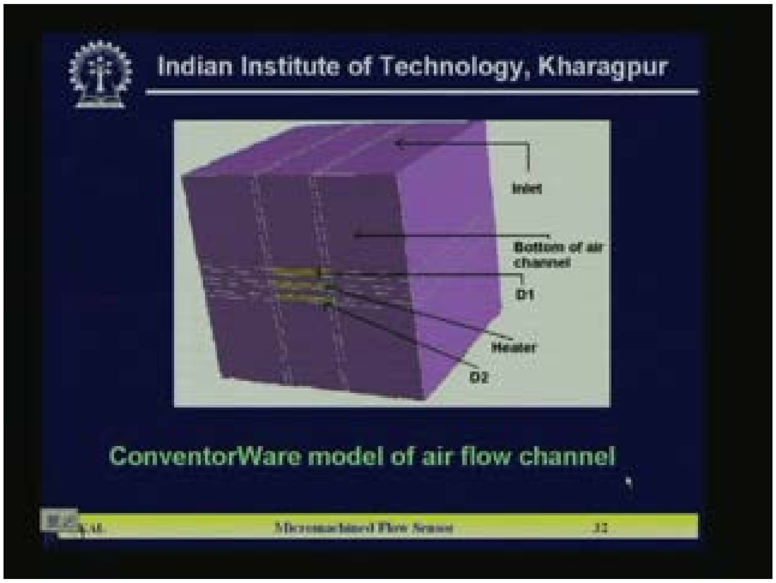

And later on you can for CFD analysis the flow channel, there also you have to design the whole in a 3D structure of the whole sensor is to be done and there you have to define the inlet through which the gas is flowing and the heater location and the flow channel through which it is flowing. It is not looks like physically how you are getting it and how you are fixing it in the measurement setup rather some hypothetical the structure you have to define into the simulator. So that it can simulate using the boundarylayer technique and again it will do some kind of the finite element on finite difference analysis to get the flow pattern.

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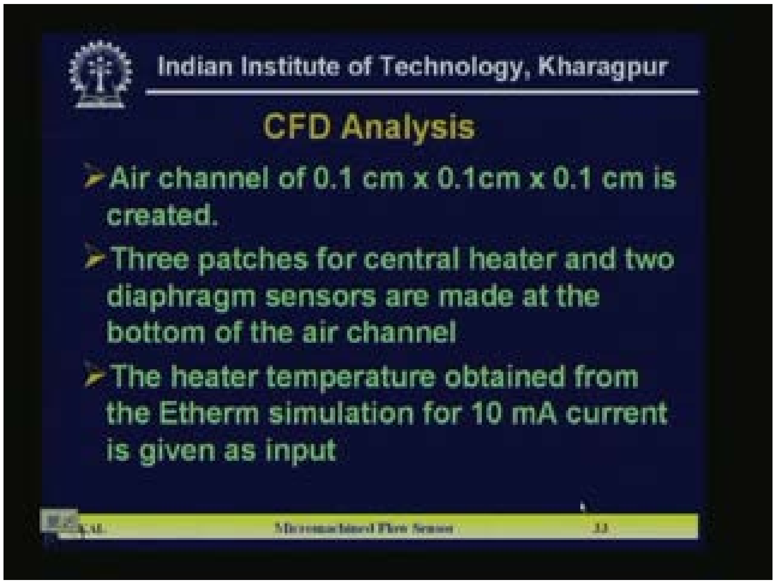

So now the CFD analysis, the assume channel is a 0.1 centimeter,0.1 centimeter into 0.1 centimeter cubic structure is created what you have seen. Three patches for central heater and 2 diaphragm sensors are made at the bottom of the air channel. The heater temperature obtained from the Etherm simulation for 10 milliampere current is given as the input for CFD and this 10 milliampere what is the temperature, that is obtained from Etherm analysis in earlier.

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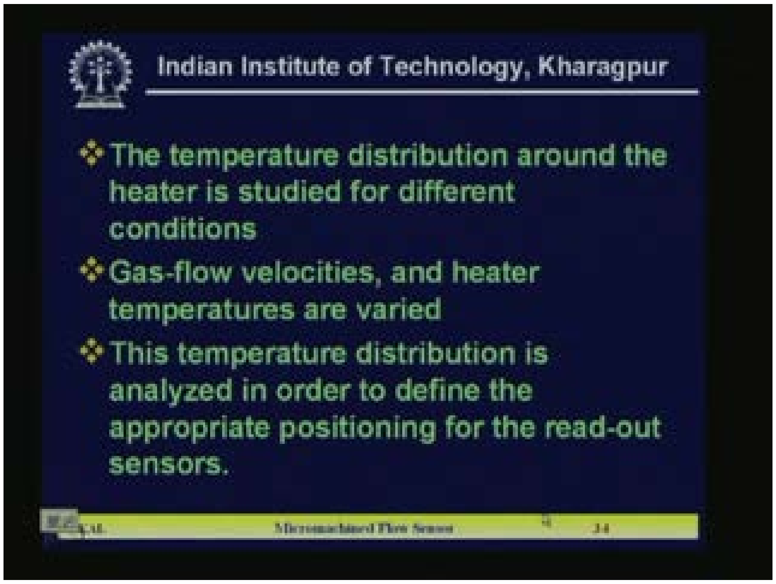

The temperature distribution around the heater is studied for different conditions. These are the steps how to go for simulation. Gas flow velocities and the heater temperatures are variedand this temperature distribution is analyzed in order to define the appropriate positioning of the read out sensor. So these arerequired for designing means the proper positioning of the sensor and the heater on the silicon surface so that you can go for making the mask.

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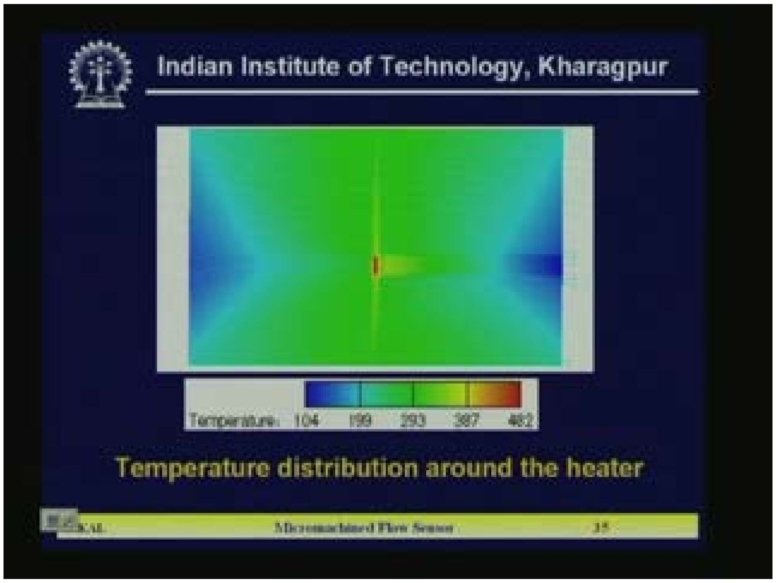

So these are some temperature distribution around the heater, the color chart is given by 104 degree centigrade 482 centigrade. So this is the heat distribution around the sensor. So we have to choosecertain location where you will put the upstream and downstream resistances.

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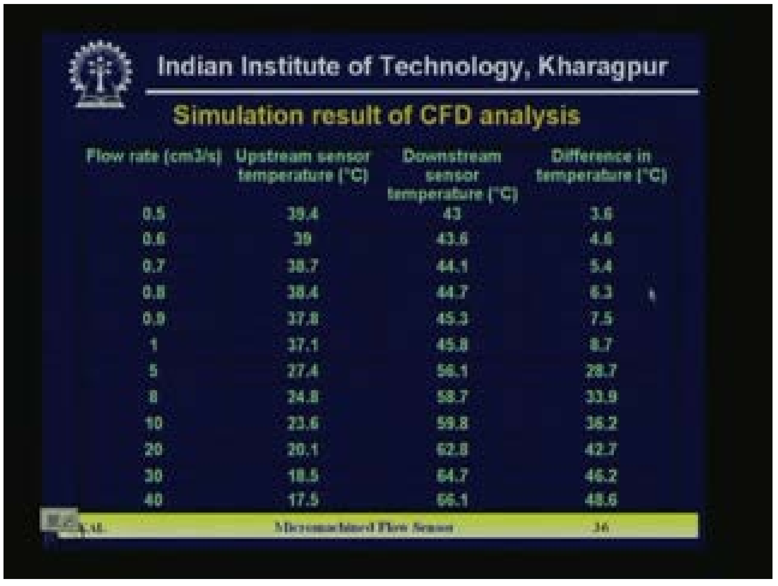

Flow rate (cm3/s)	Upstream sensor temperature (°C)	Downstream sensor temperature (°C)	Difference in temperature (°C)
0.5	39.4	43	3.6
0.6	39	43.6	4.6
0.7	38.7	44.1	5.4
0.8	38.4	44.7	6.3
0.9	37.8	45.3	7.5
1	37.1	45.8	8.7
5	27.4	56.1	28.7
8	24.8	58.7	33.9
10	23.6	59.8	36.2
20	20.1	62.8	42.7
30	18.5	64.7	46.2
40	17.5	66.1	48.6

Now here are some simulation results of the CFD. These are the flow rate is a cc per second is upstream sensor, downstream sensor you can see the temperature difference here is calculated.

So the downstream means after downstream temperature will be more than the upstream. So there temperature is 39 here,43 here, you can, if you go, if you see the flow rate changes, so if the flow rate changes. Then you can find the temperature difference between the downstream or upstream also differ. Because lot of distribution will be there for higher flow rate. So because of that temperature difference from the upstream and downstream will be more and more. Isn't it? Lot of flow means more heat is going to the downstream sensor. So downstream sensor resistance is going to temperature is going to increase. So that is why you see here 17.5, 66.1, here you are getting 48.6 and the beginning if the flow is low, so both the downstream and upstream sensor temperature will be almost same. Not much difference from 3.6 to 4.6 to here 48.6 if the flow is 40 centimeter cube per second. Now these are some simulated values.

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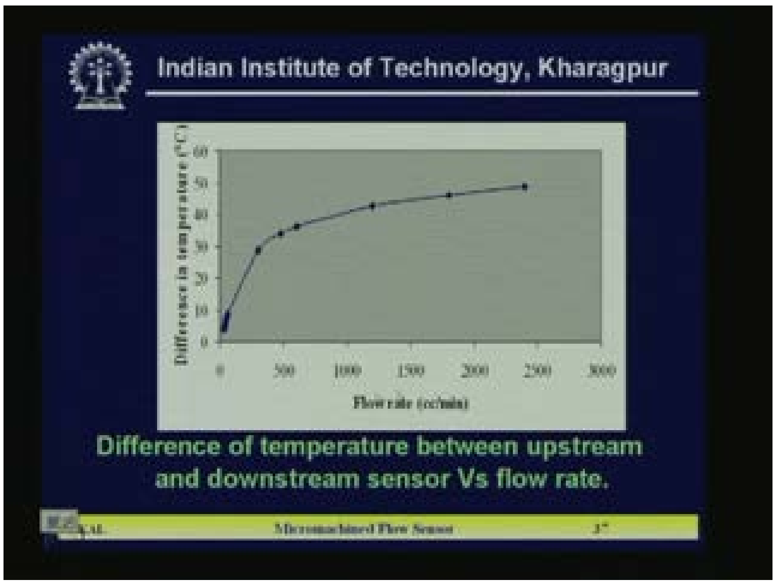

And those are plotted here. You can see this is basically cc per minuteand here difference in temperature, this is highly linear after that is saturated, after this saturate meansifthe flow rate is very large, so then the difference of temperature is almost constant. But is low flow is from laminar flow. You can get the linear nature and this nature is useful for measurement of the flow.

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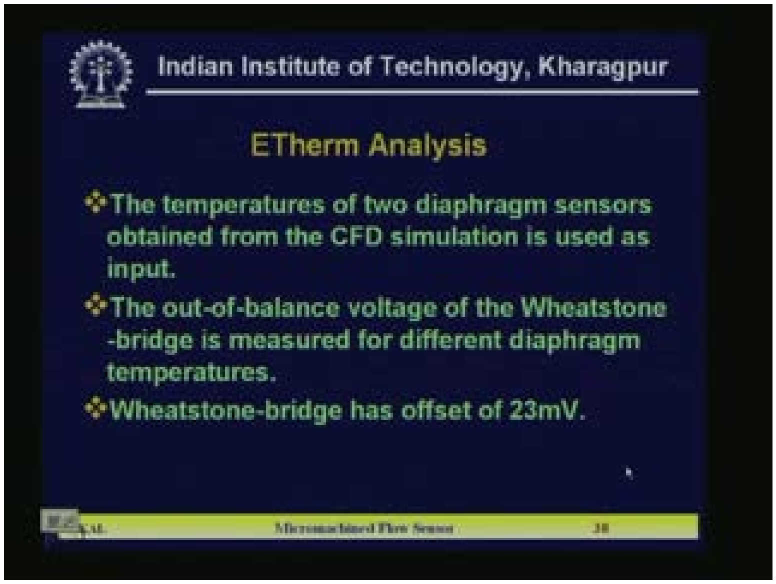

And Etherm analysis also you can get the dip distribution.

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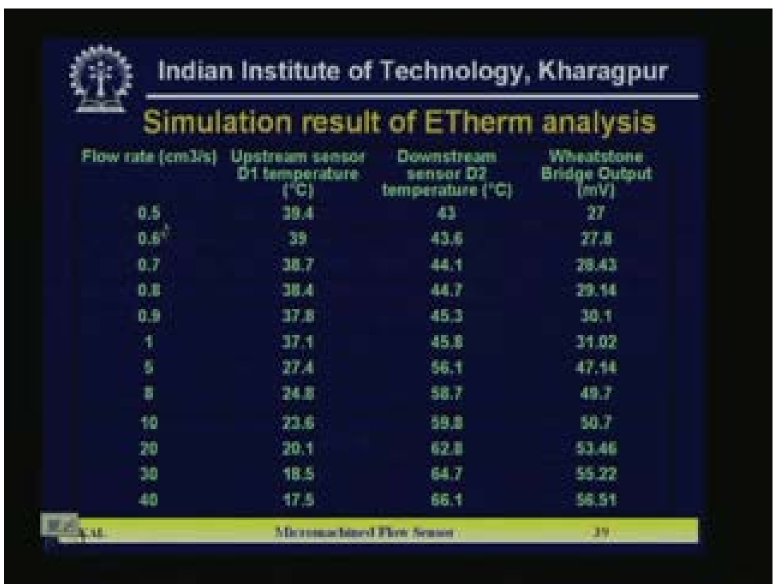

Here the flowrate upstream and downstream of Wheatstone bridge. Because after that you are getting Wheatstones bridge output. Earlier you got the temperature difference. Now that is reflected into the resistance change and after that if you have supply of the bridge is constant then you can get the offset voltage and that you also you are getting here. So with different flow rate what is the Wheatstones bridge output voltage that is given here?

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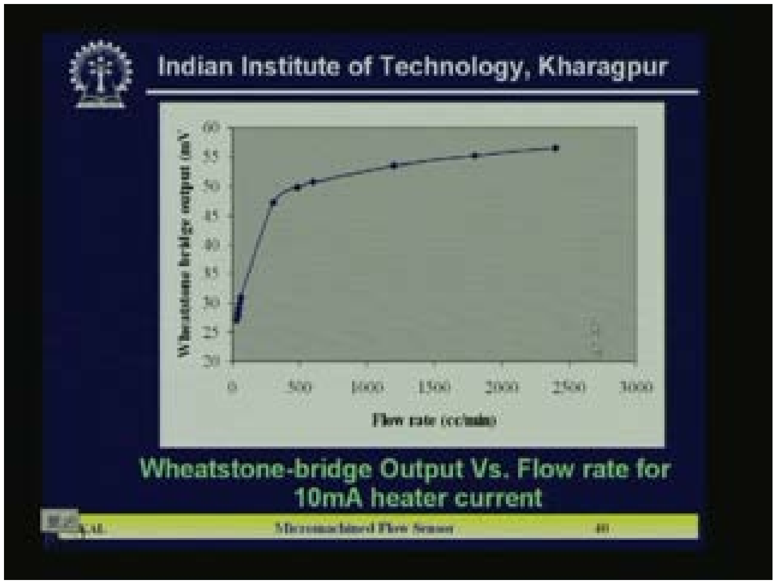

So that plot is also shown here. You can see this is also up to certain flow. It is linear, after that it saturates almost. So this linear region is may be used for the flow sensor of this differential temperature technique.

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Now here the fabrication steps are almost similar to other one. First you have to grow the thermal oxide and then photolithography of the front side oxide, then photolithography and patterning of the backside oxide. Only difference here is that it was single resistance. But here you are using 4 resistances along with the heater.

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Now the step 4 is thermal evaporation of chromium nickel film. Then pattern it then you deposit chromium gold film, then pattern itand last step is the backside etching of the silicon substrate from the diaphragm structure, to get the diaphragm structure. So that is the total fabrication step.

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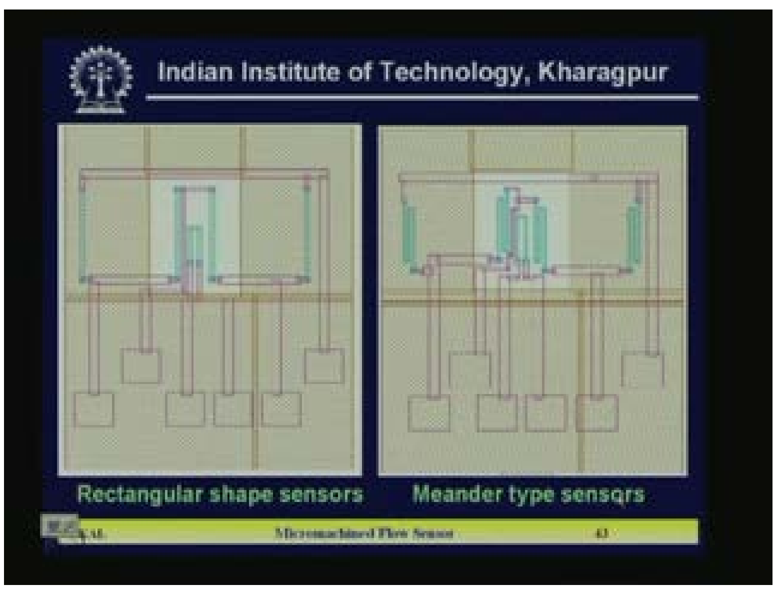

And now these are the two structures; one is a rectangular shape, another is a meander line shape. Meander line shape will be much more sensitive. What is the difference? As I mentioned few minutes back, so you see here, so this is portion and this portion resistance are meander line. Here is only straight line, one single line. So here you can say 3 lines. All the four resistances in the layout are same. 1, 2, 3, 4, so here all is the meander here is the single line. So that will be much more sensitive because total areas of the surface area of the resistance are more here.

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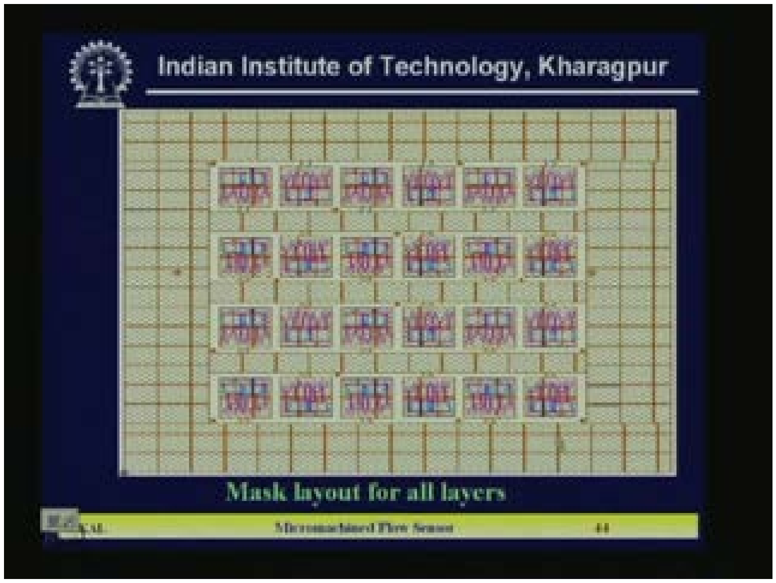

So these are the mask layout of all the layers you can see here.

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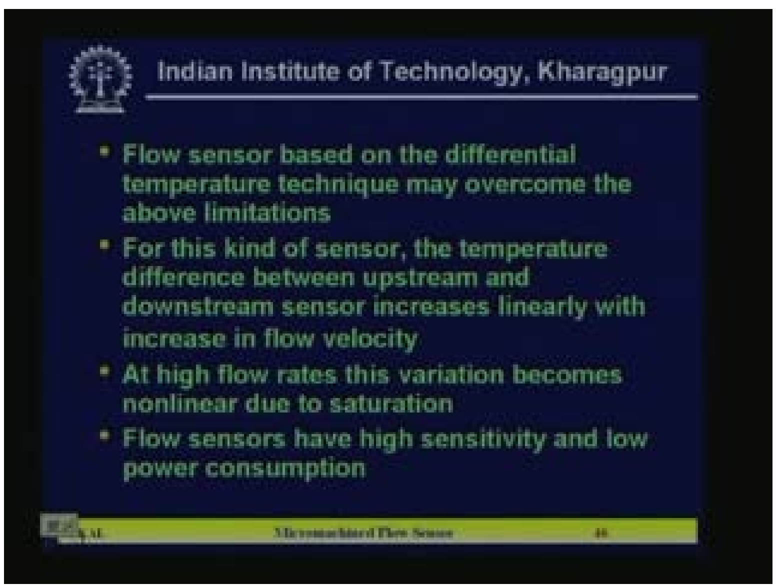

So thank you very much. Let us stop here today.