Micro and Nanoscale Energy Transport
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Lecture - 42
Measurements Techniques in Micro & Nano Scale Heat Transfer-Part II

We were looking at experimental measurement techniques at micro nano scale; you know, what are all the things that you have to start with this first the dimension of the micro channels for example, including the surface roughness. So, we looked at some of the techniques there then we looked at how we measure the pressure difference, because as we talked about the construable part of the differential pressure will include also the expansion and contraction losses.

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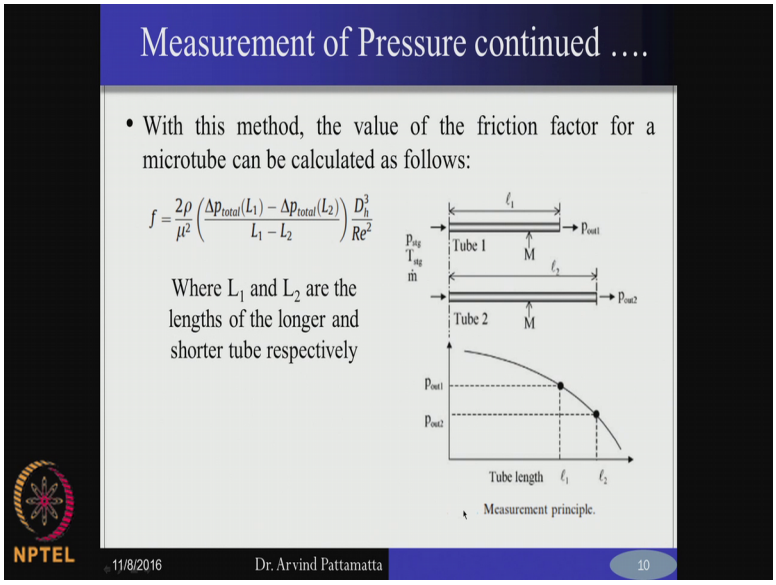

So, therefore, if you want to calculate only pressure difference within the micro channel and not you know usually, we keep the pressure tapings outside the chance. So, the inlet and outlet ports are the convenient locations to fix the tapings and unfortunately, that includes additional contraction and expansion losses. So, we have seen a few methods one is the tube cutting method, where you take the difference between longer tube and shorter tube to eliminate the expansion and contraction pressure losses.

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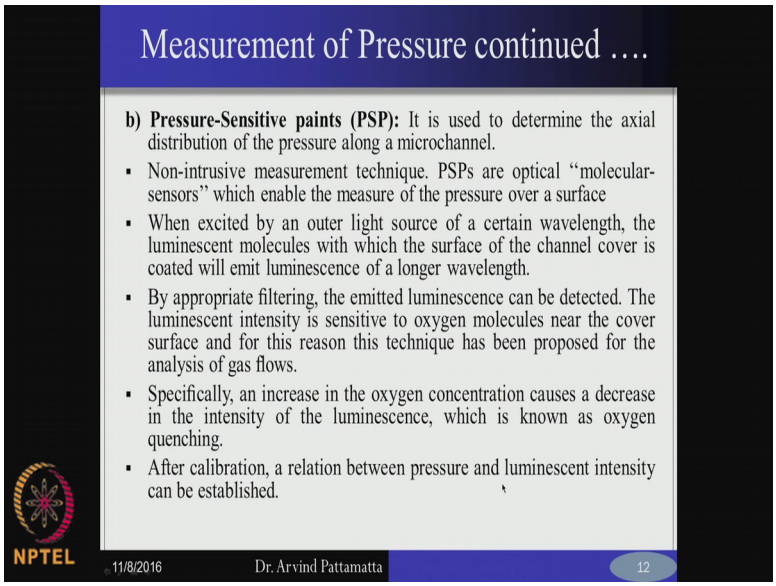

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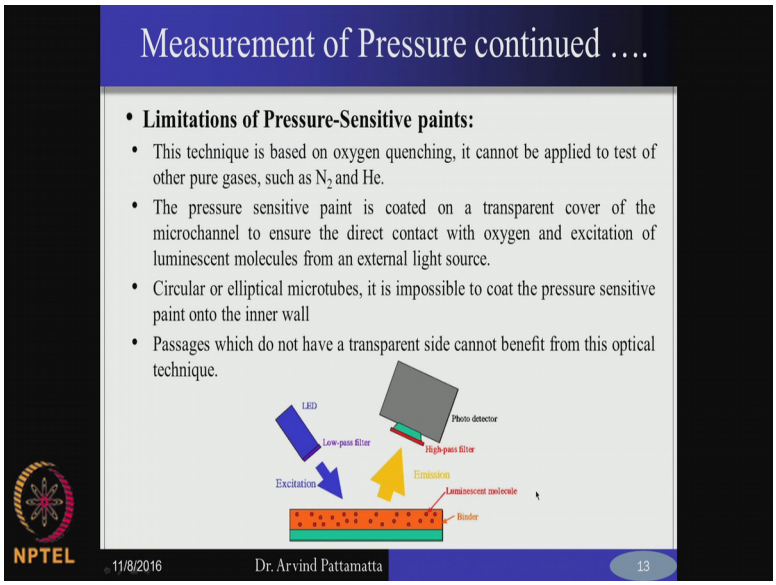

There are also other methods of direct measurement of pressure like, using pressure sensitive paints, so, all these covered in the last class, and also the optical lever methods. The optical lever method is more expensive technique.

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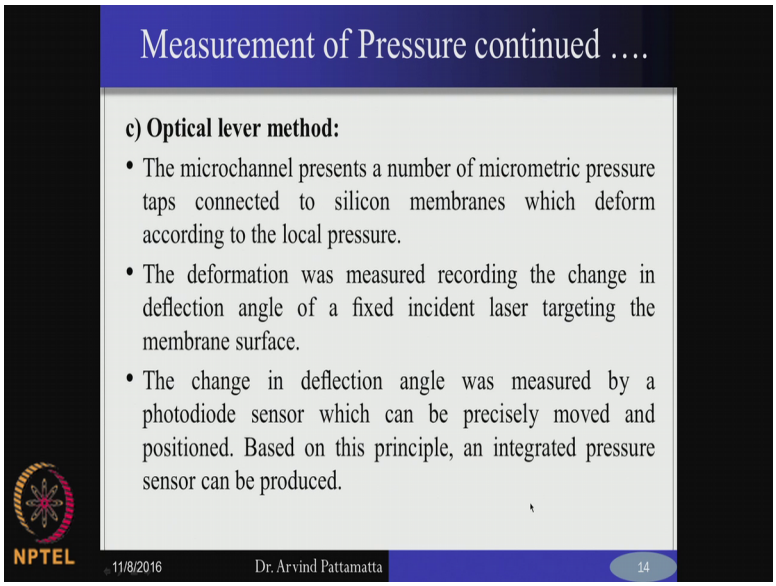

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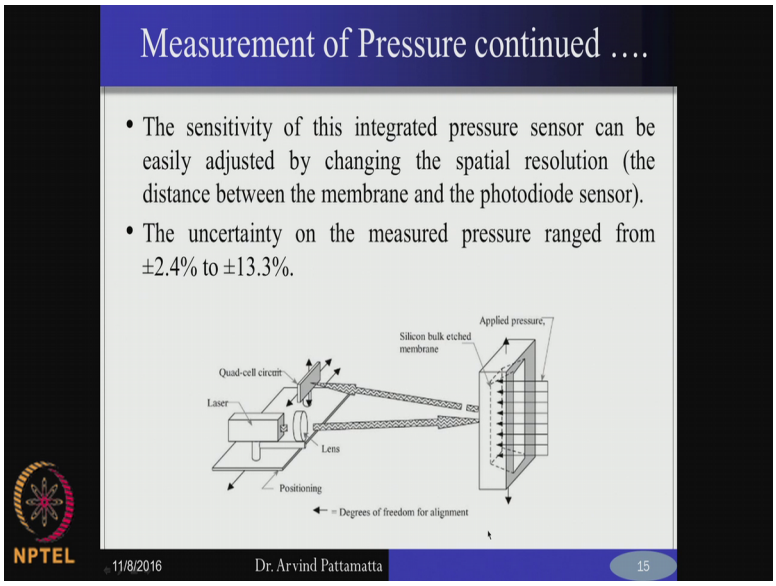

So, you need a laser mechanism, so, this will eliminate laser on to a flexible membrane made of silicon. So, this silicon membrane is connected to the pressure tapings and micro channel. So, depending on the deflection of this membrane, so, the reflected intensity of laser will have different angles deflection angles will be function of the deflection of the membrane. So, therefore, you calibrate it in the beginning as a function of the deflection, you know what is the pressure. So, using the calibration you can actually use it you know in the experiment and get the values of pressure. So, these are very, very accurate ways of getting it, but of course, you need a more expensive unit in terms of a laser and also

sensor unit which can detect the reflected beam of laser and the sensor beam also should be traverse mechanism which can move you know, different of degrees of freedom.

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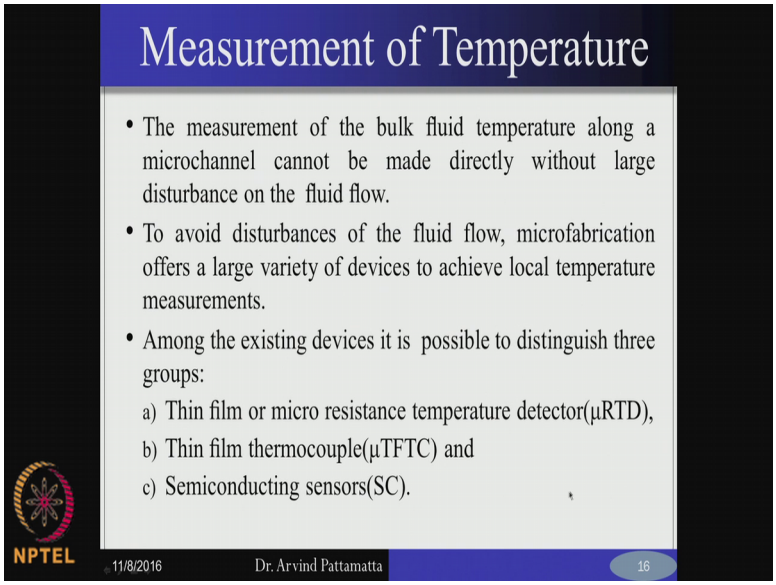

So, we have looked at this, now in this today's class we looked at the other 2, which is the tem which are the temperature and flow measurements right. So, at micro nano scale you know nano scale of course, there is no point in defining or measuring temperature, but the micro scale of course, you know, so, when you are talking about conventional thermo couples you know you have junction of basically the chromium aluminum.

So, you have different thermo couple elements which you make junction you create a junction which produce an e m f based on what is the see beck coefficient of this particular thermo couple junction so; that means, as a function of temperature you generate an e m f and depending on the alloy that you have you know, you get different response to temperatures, so, this is denoted by see beck coefficient. So, now, similar principle can be used, also at micro scale, but the differences that the d diameter or the junction that you make, now should have diameters of the orders of microns. So, otherwise if you put a bulk thermocouple into a micro channel you are going to intrude the flow. So, this is an intrusive way of measuring the temperature which is not preferred.

So, if you put a thermo couple it is also likely the flow is getting disturbed flow pattern will be different. So, which you do not want therefore, if you take the case of micro

channel of the order of one millimeter or less so, the b diameter as to be quite small of the order of few microns. So, therefore, there are different possibilities of measuring the temperature in the micro channel so, or any micro element. So, one of the methods is using what is called as a micro RTD. So, resistance temperature detector, so, you have conventional RTD's, same way in a micro channel, you can also miniaturized it and you can call this as a micro RTD. The other common method is the micro thermo couple. So, apart from this you also use, what is called as a semi conducting senses.

So, in essentially, all of this the basic principle is you do not measure temperature directly right, unless you have thermo meter thermometer is the one which maintains the thermal equilibrium and use measured directly something in degrees Fahrenheit or degree Celsius, but in all the conventional measurements that we are using in a heat transfer, using RTD or thermo couples or some sensitive paints temperature sensitive paints, we do not measure temperature, but the response to the temperature in terms of a current or resistance or voltage. So, this is how we indirectly get it and we know the calibration of the current verses temperature or voltage versus temperature that is the behavior of how the current or voltage or resistance changes sometimes, it is a material property; for example, the resistance is a material proper depending on the kind of material you choose. So, you know the temperature coefficient of electrical resistance.

The other way, other case you have to do calibration. So, you know how much voltage will be produced for example, for a corresponding temperature difference. So, you know the see beck coefficient which will essentially, define this and based on that you can calibrate it you know with a standard ice bath, where you know the reference temperature and you can get the values of voltage right. And, so, this can be used for other temperatures as well.

Student: (Refer Time: 06:39) Sir, is a function of temperature and then how will be (Refer Time: 06:42) of temperature (Refer Time: 06:45).

I think, this is where the calibration comes into this picture. So, you calibrate; that means, you know the actual temperature in a; that means, you use a bath you use a thermo static bath or constant temperature bath whose temperature is fixed. So, that is already done by another thermo couple which you know that it is a accurate thermo couple and you dip this into reference temperature you know one, one and the other can

be some ice which could be 0 degree this is always fixed. So, this temperature difference is now going to produce a voltage. So, although you make use of see beck coefficient this is a function of temperature.

So, you just take that information to build a materials, junction of materials and depending on the operating temperature therefore, you use different junctions. But during the calibration you do not use this information, you actually measure the e m f produced verses you know what the actual temperature that is there, so is, that will give you the calibration. And now to get back the temperature you now actually sense the voltage because, in the real case when it measures the temperature it is only producing a voltage. So, and from a calibration you invert and get back the temperature right. So, this is basically the conventional way we do not directly sends temperature, but indirectly using current or change in the resistance or corresponding change in the voltage and which is quite accurate. So, if you look at the RTD for example, in RTD you know the temperature coefficient of the electrical resistance.

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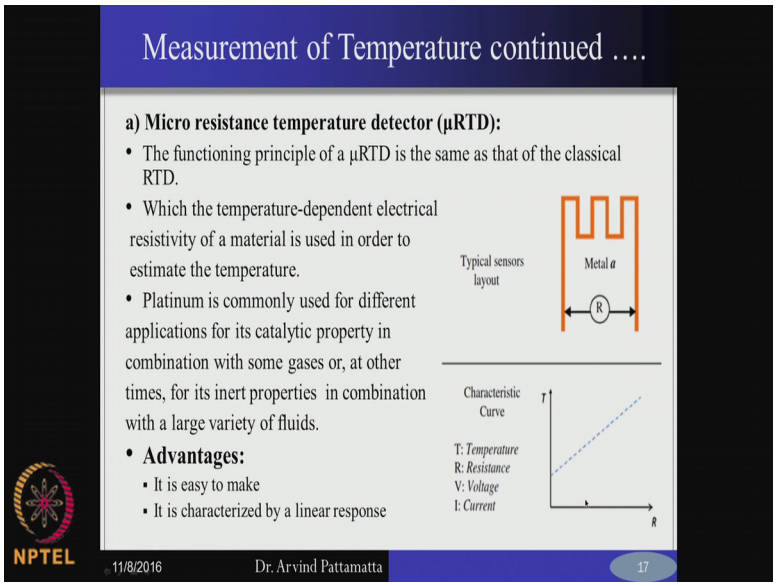

So, therefore, as a temperature changes you know increases for example, the electrical resistance could increase, so, depending on this calibration you know what should be the change in resistance for a given change in temperature, you know you can draw the calibration curve and when the actual element, the RTD element senses the particular value of resistance you know what is the corresponding value of temperature from this

particular calibration. So, it is a fairly straight forward procedure. Sometimes, you do not even have to calibrate because, the value of d t by d r is constant and it is given to you over temperature range by the manufacture, we will give you over this temperature range what is the value of temperature coefficient of electrical resistance.

So, directly you have to use it and then make sure within the temperature range and you can directly get the value of temperature. Sometimes, it give you the table this temperature this resistance this temperature this is the, so, you interpolate it if you get resistance get it somewhere in between and you can find out a corresponding value of temperature. So, this is one of the simplest way to you know get there is no junction form it is only metal metallic element which has a very high coefficient of electrical temperature coefficient of electrical resistance. So, the more common ones which are commonly used which is platinum, because it also you know inert and does not react with most of the gases right. So, advantages are it is fairly straight forward to fabricate and it is characterized by a simple linear response like this. So, the same RTD is used for the macro scale can also be a miniaturized. So, we can have a very, very small sensor probe of the order of microns, so, that fabrication is quite challenging, but once you miniaturize it, it exhibits a similar proper.

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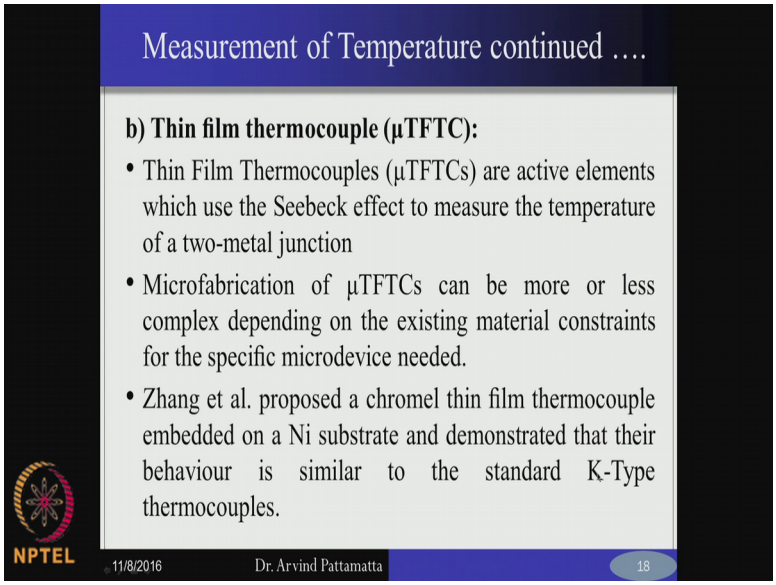

So, the other one is the miniaturizing the conventional thermo couple. So, what we call as now, thin film micro thermo couples you know this principle is the same as the

conventional thermo couples the use see beck effect to measure the temperature of a by metallic junction. So, you have 2 metal elements they make 2 junctions. So, one is the sensor were you connected to the object to measure the temperature, the other is the reference, which you keep it in ice bath or whatever. So, you measure the voltage correspondingly this will be use to you know the calibration is used to get the temperature. Now the manufacturing of the micro thermo couples are more difficult then RTD s namely, because in making this junction with micron size bead is going to be the biggest challenge. So, making junction 2 conventional materials of the order of millimeters or so, it is quite common, but making it of the order of 5 microns or 10 microns is going to be the biggest challenge.

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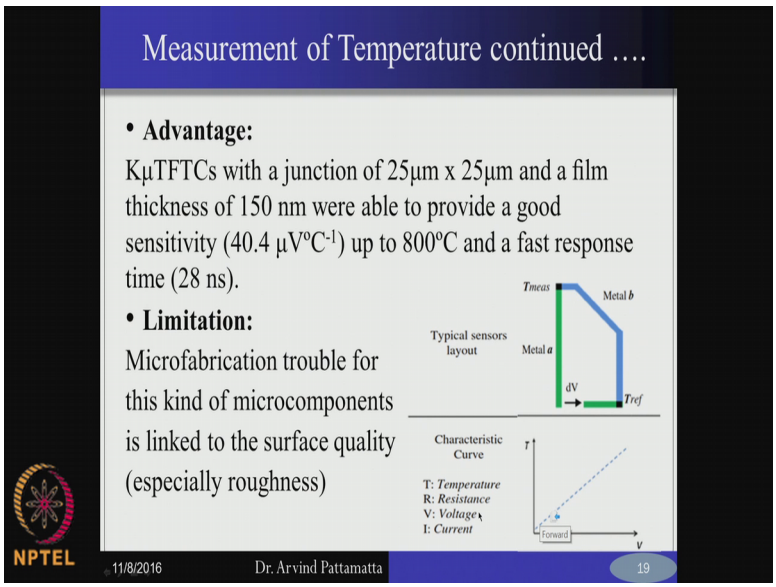

Some of the common ones, you know which are used is the Chromel Chromium film you know you have a nickel substrate and you have a Chromel thin film thermocouples. So, these are some of the materials that can be used as k type thermocouples. So, you know if you want to make a junction of 25 micron by 25 micron, you know this is the biggest challenge actually. So, therefore, principle is similar you have 2 metals and you make a junction on one end where this is to be pasted on the sensing side and the other is kept at a reference temperature, but the sensing side should have a bead junction which is of the order of may be 25 microns or 25 less you know this is where the challenge, and also you have to select a material which gives a good sensitivity, this is measured by the Seebeck coefficient. So, that is the kind of the voltage that you generate for a given a temperature

difference ok.

So, and also the other important challenge with micro thermo couples, is the high response time, very good sensitivity. Very good sensitivity means; that means, the response time has to be very fast, it cannot be of the order of standard thermo couples. Standard thermocouples can wait with few micro seconds or milliseconds, but micro thermocouples have to be response to the order of nanoseconds. So, inherently, all this processes are small scales are not only small lens scales, but also small time scales. So, therefore, any attempt to measure the flow or pressure or temperature should also consider this quick response, so, this is another challenge. So, the material selection also depends on not only in the Seebeck coefficient, but also on a kind of response that you get, you know the there should be able to get response of the order of nanoseconds.

So, the biggest limitation is, the fabrication trouble for this kind of micro components and especially, you know the quality of the surface or micro roughness now place will become a big role when you are creating this junction the inherent defects in the material and the material roughness now will get amplified right. So, sometimes you may not have a perfect junction, and sometimes this junction may not be able to be uniform in sensing particular temperature, some parts may be you know rough corrugated, some parts will be better contact, some parts will have a may not have a sufficient contact, this will again lead to problems in accurate temperature detection. So, therefore, fabrication of micro thermocouple is actually a more challenging, but of course, you know in terms of response time and also the range of temperatures that you use we are more versatile then the RTD, this RTD have a very limited range of temperature.

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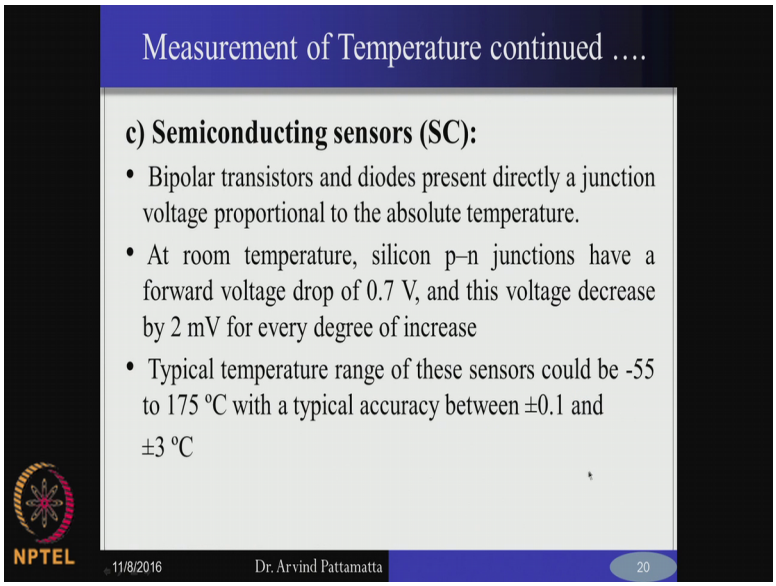

Apart from that you also have what are called as semi conducting sensors, so, again you know. So, this based on using rather than using metallic elements you use semi conducting devices, where the junction temp voltage is proportional to the junction temperature.

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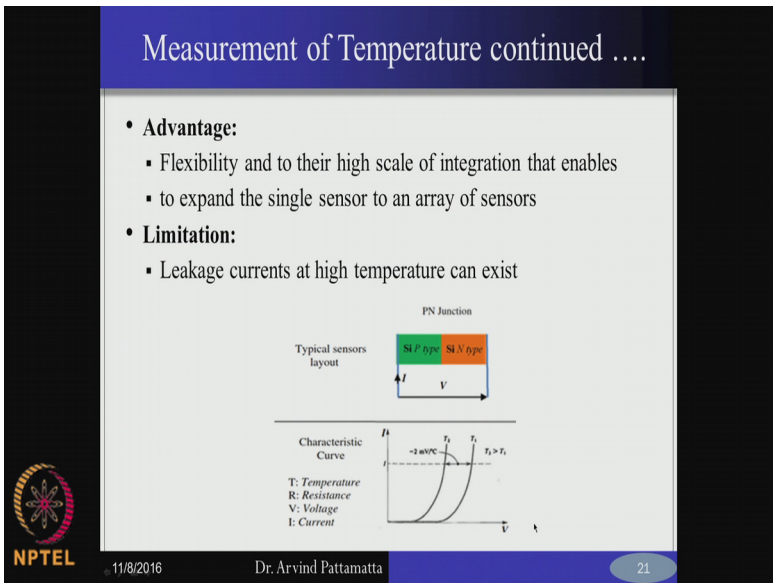

So, at a particular junction suppose you make a p n junction diode, the voltage that you measured across this p n junction will be direct function of the temperature at which you maintain this. So, therefore, you can do a calibration at different temperature you can

calibrate the voltage that you get and then it can be used to measure the actual temperatures. So, this could also be used provided you have a good response, you know the response time also as to be considerable fast.

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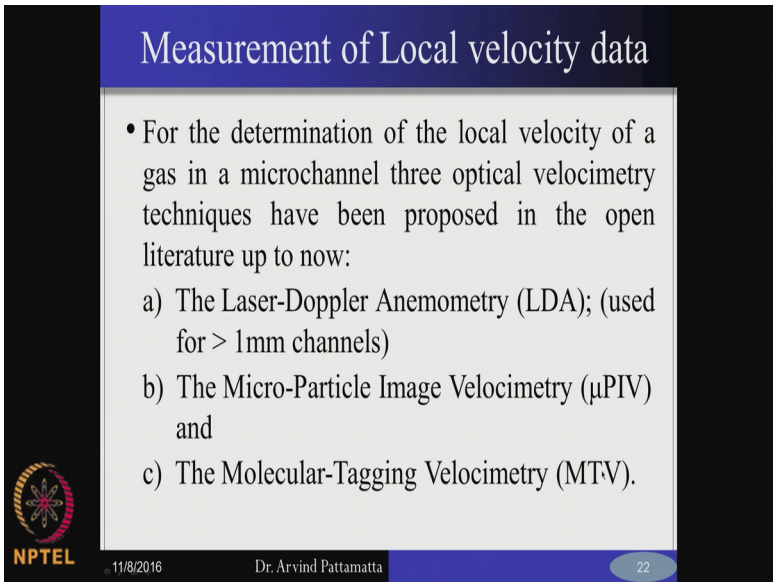

So, this wills kind of completely the temperature measurement now will quickly move on to the other important component which is measurement of velocities. Now when you talk about velocities this are not flow rates, because the flow rates are average values, so, we are going to look at local velocities that is the velocity field. So, I mean if you are talking about micro channels, you know flow patterns of the order of you know millimeter size field. So, then; that means, you have to resolve the field within the order of few microns in order, to get the local velocity field local velocity data. So, therefore, how do you do this? So, then again you have to rely on laser based diagnostics.

So, the more common ones now a days is, the micro PIV micro particle image velocimetry and LDA is used LDA is also an anemometer, but used using a laser and this is used for larger channel dimension, but if you are really looking at small channel dimensions the, we have to look at the same PIV which is there at conventional measurements and this as to be scaled down to capture micron size resolution.

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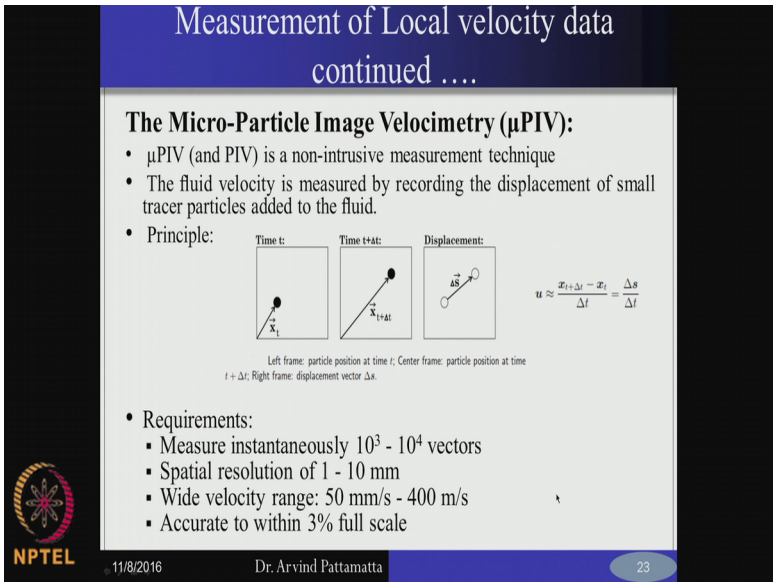

So, apart from that you also have an expensive method call the molecular tagging velocimetry. So, I think many of you know how the PIV set up works right. So, it is basically you should have an experiment which is optically accessible first of all and; that means, you should be able to have a construct optical access from where you can put the laser source from one end and other end, it should be able to capture by high speed camera. So, it should have optical access for both the laser to penetrate the system and also for the light which is scattered and coming out of the system to be captured by a camera.

So, it should have a two way optical access number 1 and number 2 is, it should also have seeds seeding particle which are negligible density, compared to the actual fluid of which you are measuring velocity and so on if the density is high then you know this will it have own momentum which is different from the that of the parent fluid and therefore, this will not give you an accurate velocity field. So, therefore, it should be quite light at the same time the property is should be luminescent; that means, once you radiant it with the laser of a particular wave length, it should start glowing right it should be captured by the high speed camera.

So, apart from that the principle is very simple, you know you just add these tracer particles into the main element fluid element of the systems, so, you add several millions of these particles into them, and then you just keep pulsing the laser. So, pulsing the

laser, you have to have a pulse laser. So, every few nanoseconds or micro seconds depending on the time scale you pulse it and this will correspondingly respond by glowing you know so. So, this glow will give you the track of the particles. So, you keep recording the images with a CCD camera at different time intervals you know every few micro seconds or nanoseconds.

And by looking at the snap shots in times you have 1 image, where particular particle would have been at a location position vector x x t after time delta t, this particle would have bored x plus you know x at t plus delta t. So, by just simply taking the 2 images, looking at the position vector of particle at t plus delta t and particle time t you take the difference between them divided by delta t will give you the velocity magnitude right. So, this is the very, very simple method, you know like that you look at each and every particle and you will be able to calculate the corresponding velocity vectors.

So; that means, you have a local velocity vectors all over the entire systems, form this images if you need a 3 dimensional snap shots, then you have to have a holographic theory; that means, you should have 2 cameras, you know taking 2 different planes, so, that you can construct a 3 dimensional motion of this particles. So, that will give you a complete 3 dimensional velocity field so, but basically this is the principle and in the case of micro PIV all this as to be much more you know smaller, you tracer side should be now really, really small number 1 number 2 again, you know the response time has to be very, very quick and again from the laser side point of view also the laser pulse which should be now really small in the camera point of view it as to be a really high speed camera to take you know images at very high frames per second. So, therefore, all of these now become you know technologically more demanding for example, if you are talking about, so, let us look at the comparison between the conventional PIV and micro PIV.

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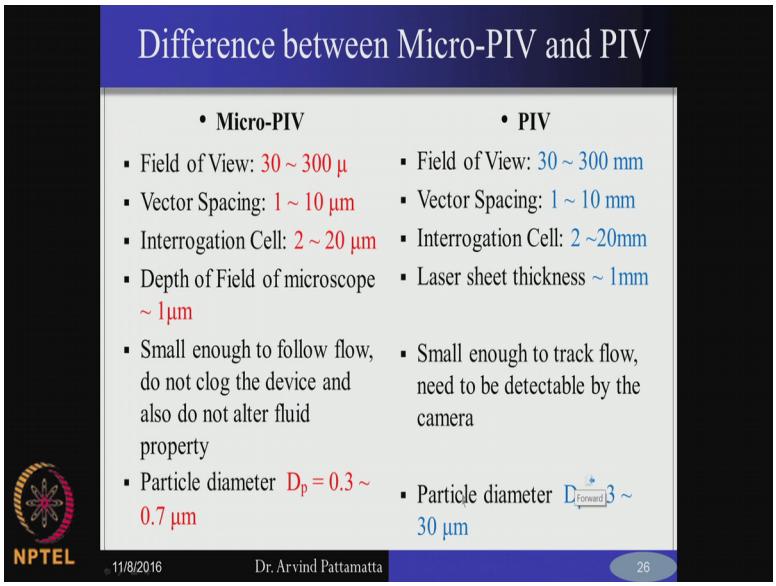

So, in the micro PIV looking at field of view of the order of 30 to 300 microns compared to conventional PIV which is covering 30 to 300 millimeters. So, the interrogation the interrogation cell is this particular unit cell, across which you are tracking a particular tracer within a delta t. So, over a delta t this particular tracer can move from one point to another within the interrogation cell. So, if you are interrogation cell width is too small this will escape the cell within delta t or if a delta t is too large, also will not be able to capture this tracer within that particular interrogation cell. So, therefore, the interrogations cell size also has to be very small in order, to resolve the local velocity data more accurately. And therefore, the particle diameter has to be even smaller then the interrogation cell size right.

So; that means, if you are talking about interrogation cell size of 2 to 20 microns the particle diameter should be of order of the point 3 to point 7 microns you know less than a micron talking about 300 to 700 nano meter particles, this are nano particles essentially right, where as in the conventional PIV; you are looking at micron size particles. So, for 1 they will be not too much affected by gravity, because of inherently you know very small particles size, but at the same time you need a smaller interrogation cell you need a small field of view and also the laser thickness the laser sheet should also be very, very small. So, here it should be of the order of micron for example, in the conventional case the laser sheet thickness should be of the order of the millimeter.

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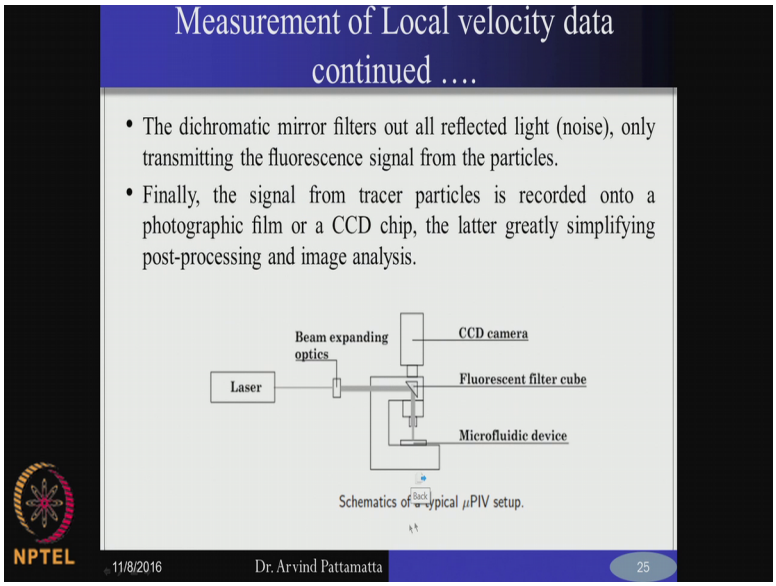

And also the pulse of the laser also should be considerably smaller. So, therefore, you know, so, in the case of, so, this is how you know the typical micro PIV arrangement can be used. So, you have a laser which goes through an optics, which will make this laser is actually a point source you know. So, this particular expanding optics will convert this point source into sheet of light. So, this is the beam expander. So, this sheet is sent through a filter cube; that means, it is just going to then, change the angle of this beam by 90 degree and you have a micro fluidic device, sitting at the bottom you know you pass the sheet directly through this device, now this were interact with the seeded particles inside the device and there is a camera sitting right at the top. So, this will take the snap shots of the seeded particles, at regular time intervals this is basically how you have that you have a laser, you have the optics, you have the CCD camera and your system also should be seeded with this kind of nano particles.

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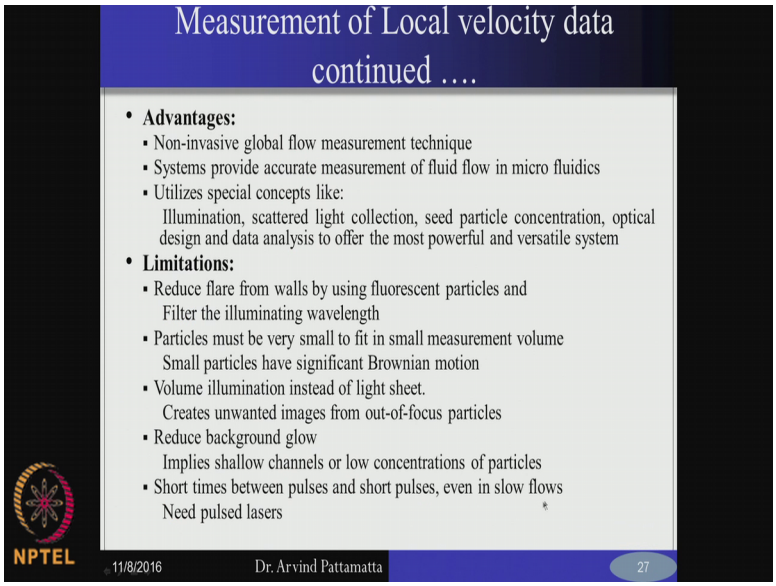

So, therefore, you know so there are, so many problems just simply scaling down the conventional PIV. So, all this limitations list these problems, you know for example, you need very, very short times between pulses and short pulse lasers. So, therefore, you know the cost goes up, you need a high short pulse laser, you need also very high speed camera; you need specialized nano particle tracers. You need also good optics which can basically convert the sheet into a much smaller beam.

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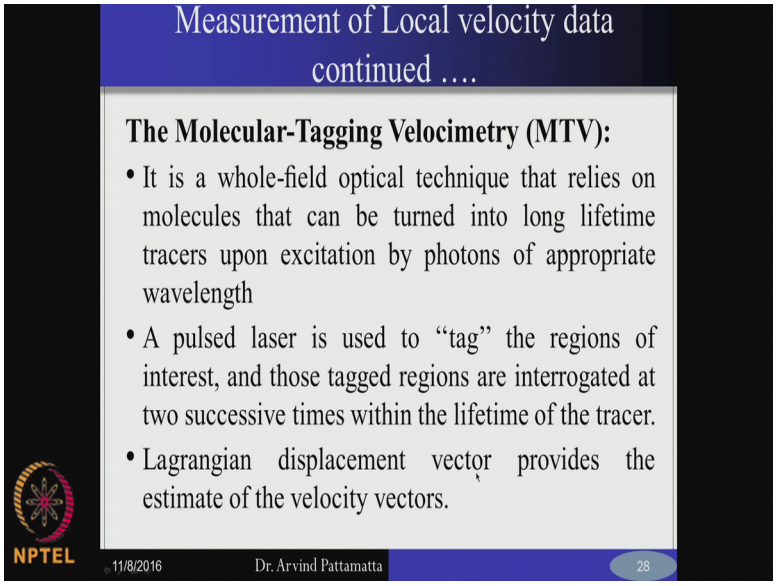

So, all of these together will make your cost definitely much higher than a conventional

PIV. So, the conventional PIV itself is quite expensive, it is not very cheap; at top of micro PIV will also make it more expensive.

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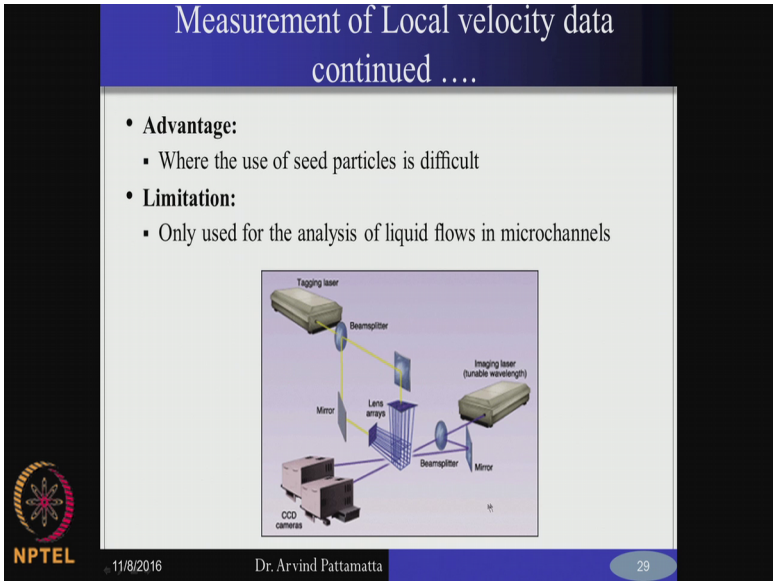

So, apart from this, there is also a method called molecular tagging velocimetry. So, this is similar to the PIV where you have a tracer particle, but in this case you use the molecules of the working fluid itself respond to the incoming laser pulse.

So; that means, pulse laser used to tag region. So, if you have a system, so this you use one of the laser having a tagging laser and you mark region, over which you want to calculate the velocity field. And then and you have a imaging laser, the imaging laser is now going to send a sheet beam of light, through the tagged region and the molecules will there now change their color, you know responds to the incident laser and then you use this as a signature to track the you know velocity vectors of this particular molecules. So, it is a similar expects that you do not use a tracer here. So, you use the molecules of the working fluid themselves as the, you know elements to trace the fluid velocities. So, the advantage is that where you cannot use the conventional seeding particles you use this of course, you know this can be only used for liquid flows, because most of the liquid molecules are more responsive to the lasers where as the gas molecules are not.

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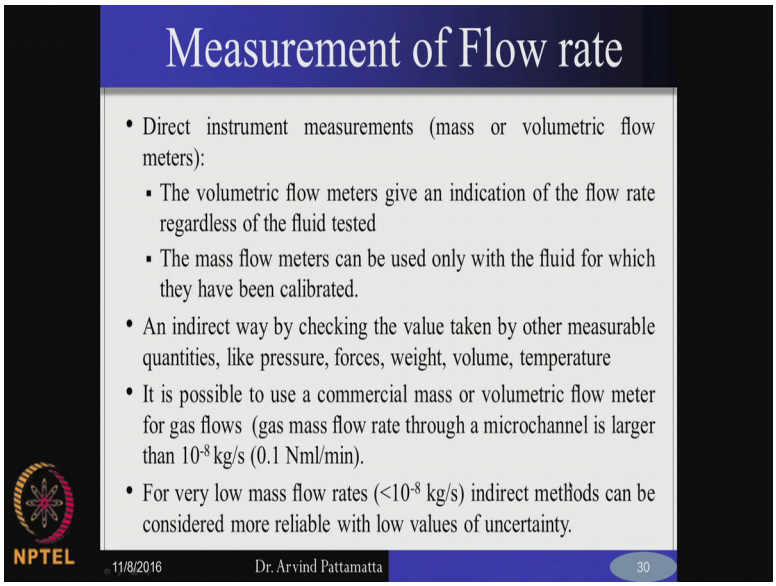

So, and again so, that was with the velocity, now coming to the flow rate measurements, flow rate is the like, you know connect to a flow meter somewhere, at the inlet or exit to measure the actual flow rate now even that is challenging because, now you are talking about flow rates which are the order of less than 10 power minus 8 k g per second. So, very, very small flow rates, sometimes it is like a trickling flow. So, how do you resolve such small flow rates with mass flow meters? So, therefore, there are different methods which are used there are indirect methods to also check the mass flow rate. So, what is commonly done is you sometimes way so, you collect the amount of flow in a small beaker over a period of time and then check the weight the difference in the weight and then you know how much volume is actually flowing.

So, this sometimes this may be more accurate than putting mass flow sensor, because the order of mass flow rates so small, but instantaneous flow rates may be very difficult to detect, but a over a period of time once you let it collect to the order of few you know milliliters and then from that you know, judging what is the low rate might be more accurate. So, it is not very uncommon for people to just relay on very simple methods, like collecting in a beaker over a period of time to calculate mass flow rates you know rather than using expensive mass flow meters.

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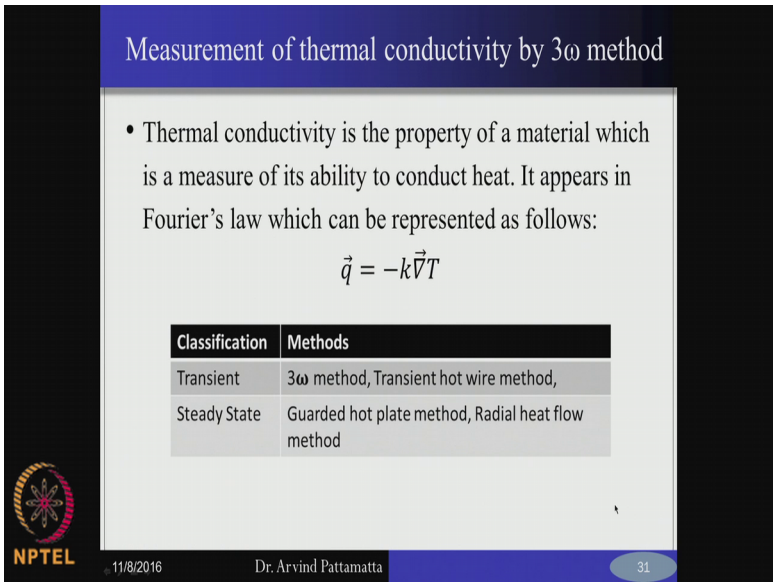

So, all these are with respect to the micro channels, where you know look at the fluid pressure measurements, temperatures measurement, flow rate and velocity measurements, and so on. Now, if you go to the nano scale, so, we are interested in the thermo physical properties right, such as the thermal conductivity thermal conductivity heat capacity. So, these are things which are required for you to for example, solve the Boltzmann transport equation and therefore, find out what is the size effect on thermal conductivity. So, you have the bulk thermal conductivity you know.

So, use that calculate the relaxation time of the phonons and so on; when you use the Boltzmann transport equation and then find out reduced size, what is the effect of thermal conductivity. Now how do we verify this how do we verify the value of thermal conductivity coming from the solution, so, you have to also have experimental methods then only you can verify your theory, right? So, and very, very small nano scales, you know nano meter sized films you cannot measure thermal conductivity the way you measure in a conventional set up. So, one of the most common ways of doing is called guarded hot plate technique. So, it is a steady state measurement technique, where you simply sandwich the material between two metallic junctions. So, 1 at a high temperature, 1 at low temperature you measure the temperature difference, you measure the heat flux and you know what is the effective thermal conductivity right, on one side, you basically know what exactly is the flux the heat flux applied.

The other side you maintain at a constant temperature. So, therefore, the temperature difference now will be a function of thermal conductivity. So, then you measure the hot side temperature, cold side temperature heat flux, so, then using the Fourier's law you can directly estimate thermal conductivity. But when you go to nano scales, you know you cannot measures temperatures, so, nano films thin films. So, therefore, how do we indirectly, measure thermal conductivity without measuring the temperature, is the actually challenging part. So, for this one of the most common methods which have been proposed by David Khail, you know in the 90's is called the 3 omega method. So, the 3 omega method is a very novel innovative technique of measuring thermal conductivity of either could be bulk material or nano scale material without having to measure any temperature.

So, I mean, if you generally look at the thermal conductivity measurement techniques, either you can do measurement at steady state or transient. So, the steady state method is one of the methods I described guarded hot plate method transient method includes the transient hot wire method. The hot wire method was the one I talked about the nano fluids. So, when you immerse a probe you know lines pointed line sensor, heated sensor into the nano in fluid you actually, look at the response period of time. So, how the temperature of this probe changes? So, depending on that you can find out the thermal conductivity of the liquid.

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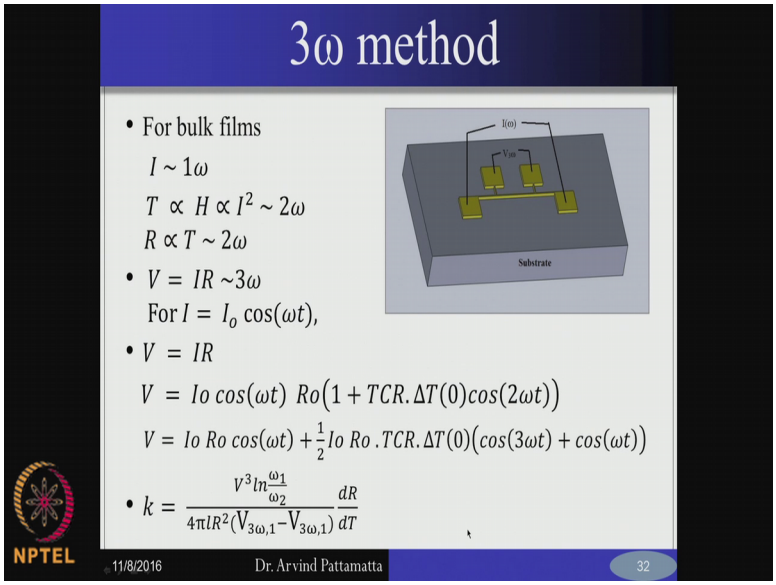

Now, when it comes to nano scale films, so, even this method cannot be directly used. So, therefore, 3 omega methods is used. And this 3 omega falls in the transient measurement category. So, it is not a conventional steady state method. So, how does this works? So, for example, for this we have to do some photo lithography; that means, you have to carry the sample to MEMs lab, where they have this photo lithography machine. So, you have to prepare a mass and then you have to h and you have to deposit some gold film. So, the finally, you will get what is called a 4 point probe. This 4 point probe will have four contact pads. So, across 2 contact pads you basically supply the input current that is I at a particular frequency. And, so, this is basically the supply pad.

So, there are 2 more contact pads from which across which you measure the voltage. So, therefore, the same probe acts like both like, heater as well as a sensor just like transient hot wire. The hot wire is also heating at the same time, it was also sensing the temperature, the same way this 4 point probe itself acts like heated when you are supplying the current through 2 ends of this probe. So, you are actually rising the temperature, because of the resistance going to heat the surface of the particular sub straight and this will cause a change in the temperature over a period of time, and this will now induce voltage across the other 2 contact parts. So, the concept, if you are supplying current of frequency 1 omega that is basically some frequency, the temperature responds will be according to I square which is of the order of 2 times omega and the resistance will also be changing as a function of temperature which is also 2 times omega.

So, now, when you take product of I into R, Ok. So, therefore, you are talking about 2 components, so, 1 can be 3 omega; 1 can be 4 omega, now what is special about this 3 omega component is that, if you extract the 3 omega component, it will directly give you a what is the temperature rise at the surface of the material and directly you can calculate the thermal conductivity with that particular value. So, therefore, if you take the product of I into R, So, you have components which is coming from omega here and the component which is coming from 3 omega. So, only this amplitude of 3 omega component is called the v 3 omega. So, this is the voltage corresponding to third harmonic 3 omega. So, we take the measurements at 3 different frequencies. So, 1 at say omega 1 we supply a input frequency omega 1 measure v 3 omega 1 then we supply another frequency omega 2 corresponding velocity at 3 omega at the second frequency

and then we take the we use this particular expression d r by d t is nothing, but the coefficient of resistance to temperature.

So, based on this, you can directly express; what is the thermal conductivity of the bulk film. So, this method is a method which is used for the bulk film that is; films of the order of say micron size 10 above, but what if really go to nano scale.

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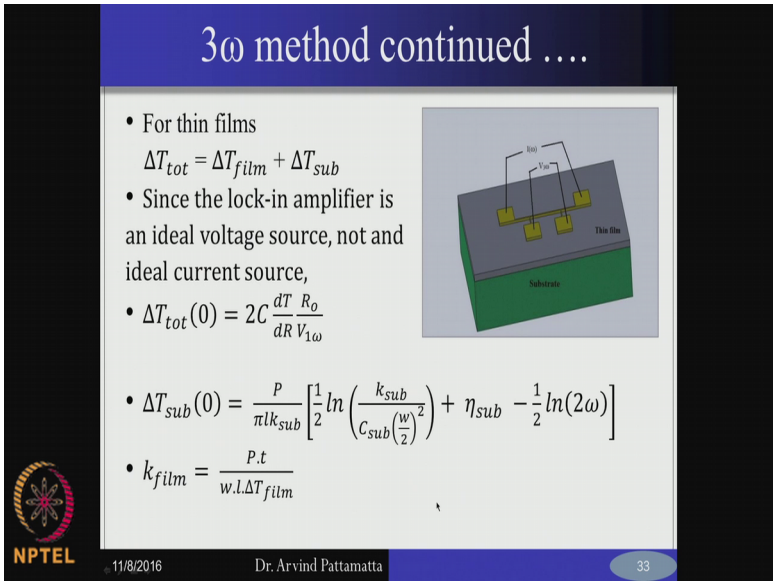

So, how do you will modify the set up? So, for that; you have to deposit this nano scale film which is called the thin film here, on to the top of the bulk material which is electrically insulating. So, also the film that sample that you measuring also be kind of electrical insulator otherwise, what will happen is apart from the heat conduction you will also have a electric conduction through the film and this will corrupt the data. So, for now thin films what you are going to measure is kind of a total temperature rise for both the film as well as the substrate and you have to subtract the contribution of the substrate, because first you do the experiment for the substrate like this; you know what is the temperature rise for substrate and now you do the experiment for the both the film, along with the substrate and you know the total temperature rise. So, if you subtract this will give you temperature rise only due to the thin film from which you can calculate the thermal conductivity.

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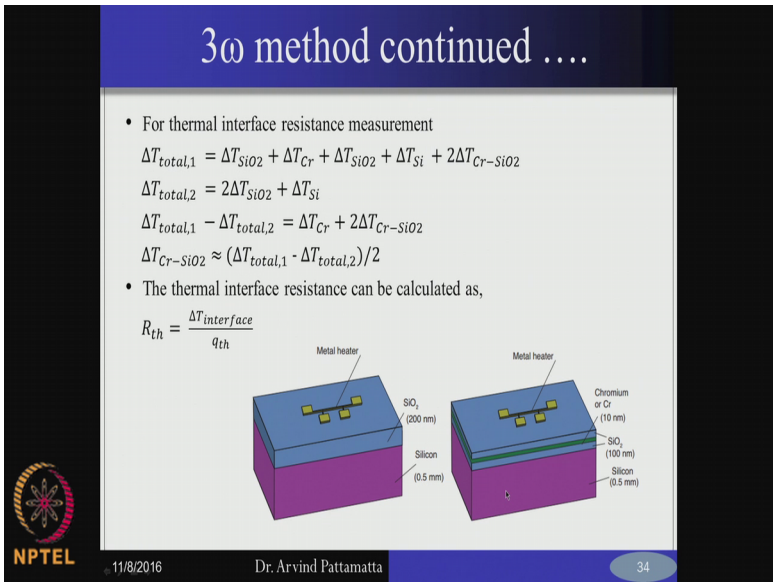

So, this is how this has been adopted for thin films, now we can also use this to calculate another interesting thing which is the thermal face resistance. So, if you have the sandwich of metal and semi conductor, there is a temperature drop at the interface of these 2 different materials. So, we can use the same method extended to also calculate the thermal resistance of multiple materials.

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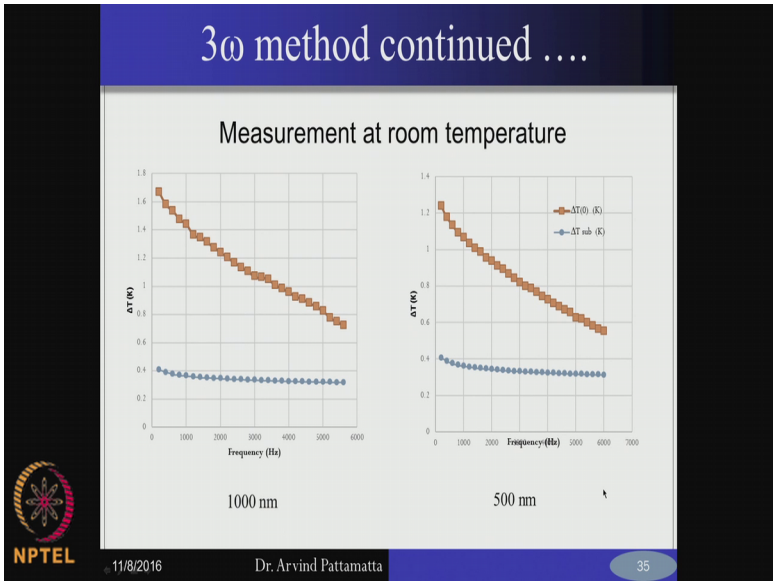

So, we have done some of these measurements at our laboratory, at room temperature as well as a say at room temperature as well as elevated temperatures. And this kind of

gives you an idea how the thermal conductivity varies as a function of film thickness and also as a function of the temperature.

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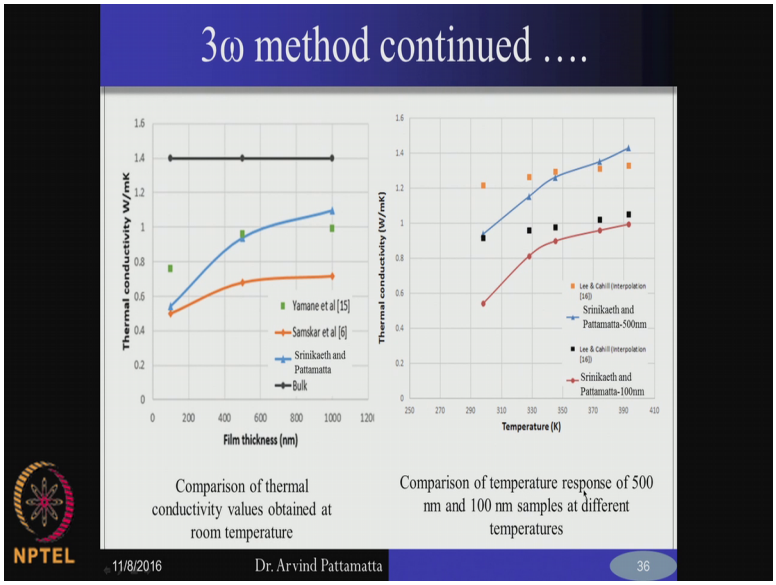

So, we have some standard experiments experimental data available in the literature and our student you know Samskar and Shriniketh. So, they have independently carried out measurements you see very strong size effects as the size of the film become smaller and smaller the temperature the thermal conductivity drops, and depending on the kind of preparation of the sample so, you may have the 2 different values of thermal conductivities you know, so the bulk values themselves are quite different. So, at film thickness of 1000 nano meters you see these 2 values are quite different from each other whereas, at the nano scales they both converged. Similarly, they also exhibit strong functional dependence on temperature. So, for a given sample for example, if you have 100 nano meters and 500 nano meters sample. So, they display different dependence on temperature. So, all this can be measured using this method very, very accurately.

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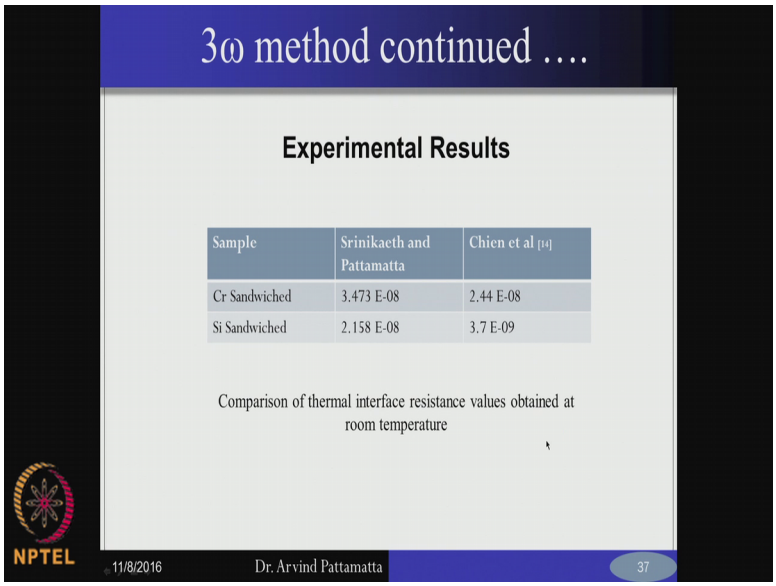

So, also this can be extended to measure the thermal interface resistance we have done some measurements where we have chromium sandwich between to silicon dioxide substrates and also for silicon sandwich between to silicon dioxide substrate. So, we have got the values of thermal interface resistance, we have compared also with the order of magnitude with some measurements before.

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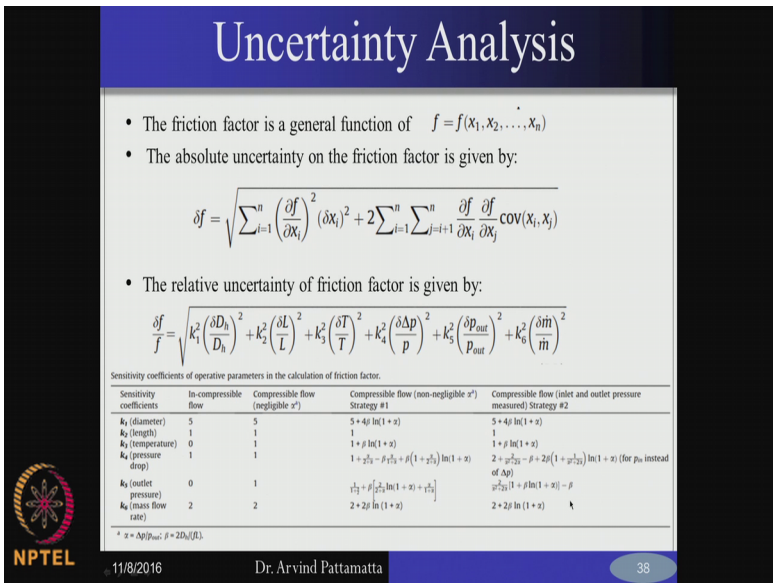

So, finally, so, after doing all these measurements a very important analysis is called the uncertainty analysis. So, you have to tell what is the confidence of your experiments;

confidence levels. So, in your experiments are never 100 percent accurate, because they all come with uncertainty in every stage. So, it could be uncertainty with your probe or the uncertainty you know in the setting itself. For example, if you take friction factor, now friction factor if you want to calculate from experiments. So, what are the things that you have to measure you calculate the friction factor. So, one is your pressure drop, the other is your velocity, the other is your density and others your dimensions length and diameter. At micro micron size now the uncertainty associated with even calculating dimensions become more, because you are dealing with micron size diameter now accurately are you going to measure that that is what we had seen in the first part how to calculate the dimension accurate. So, you have to use one of the methods, but this method itself will have a certain uncertainty.

So, you have to know, what is the uncertainty of measuring each parameter? Such as; length, diameter, pressure drop, density, velocity, so, independently, you measure each of that you should know what is uncertainty and then from this we use the procedure call the uncertainty analysis to calculate the global uncertainty in friction factor. So, the method is pretty simple, friction factor is a function of parameters x 1 x 2 up to x n. So, the absolute uncertainty in friction factor is the some of the squares of all the individual uncertainties multiplied by the derivative of this particular factor on that parameter. So, for example, if you know d f by d x 1 you take the square of that you know multiplied with the square of the uncertainty, so, you sum them all the uncertainties and then you take square roots, this will give you the absolute uncertainty. Now for the friction factor, so, this is function of you know your length, your diameter, so it could be a function of temperature, it is a function of delta p, it is a function of for example, pressure losses at the outlet it is a function of mass flow rate. Because mass flow rate is related to your velocity, out of which you know you can rule out.

So, you can give weight age to certain factors for example, if you feel that that is no dependency on temperature you can give that coefficient to be completely 0 similarly, with the pressure at the outlet. So, you can give that to be completely 0. So, you can give certain weight ages, which are called sensitivity coefficients to certain parameter is more than the others, if you feel that this parameter plays a much bigger role in determining friction factor then the other. So, therefore, from the absolute uncertainty we can write down expression for what is called the relative uncertainty.

So, this will tell you what is the percentage uncertainty; in determining friction factors. It could be plus or minus 5 or 10 percent. So, when you say plus or minus 5 or 10 percent, this is usually, relative uncertainty. So, that particular value you basically multiply that value by plus or minus 5 percent of that value, so that will give you the uncertainty right. So, that will be finally, if you calculate it will come out to be nicely a function of each parameters uncertainty, uncertainty divided by the value of the parameter square some over all the parameters and takes square root. So, that will give you the relative uncertainty. And you can also give weight age by including these sensitivity coefficients, if you want to give more weight age to one parameter than the other.

So, this is the standard procedure used by across all measurement analysis, uncertainty is very, very important thing that you have to report, when you do measurement you have to say what is the confidence level of your measurements whether, it is within plus or minus 5 percent or within plus or minus 10 percent. So, that will error bars. So, you also plot your data with this error bars sorry. So, you also plot these error bars and then when you plot these error bars you present to the research community that, you have done these measurements, but these measurements are not 100 percent accurate, but could be accurate anywhere between these error bars. So, this kind of completes what I want to talk about measurement techniques. So, I hope with this you understand at least some important measurement techniques to be used at micro nano scales.

So, with this we will conclude this particular lecture and also the course if you have any doubts or. So, you can email me.

Thank you very much.