A Brief Introduction to Micro Sensors
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Lecture – 19
Pressure Sensor – III

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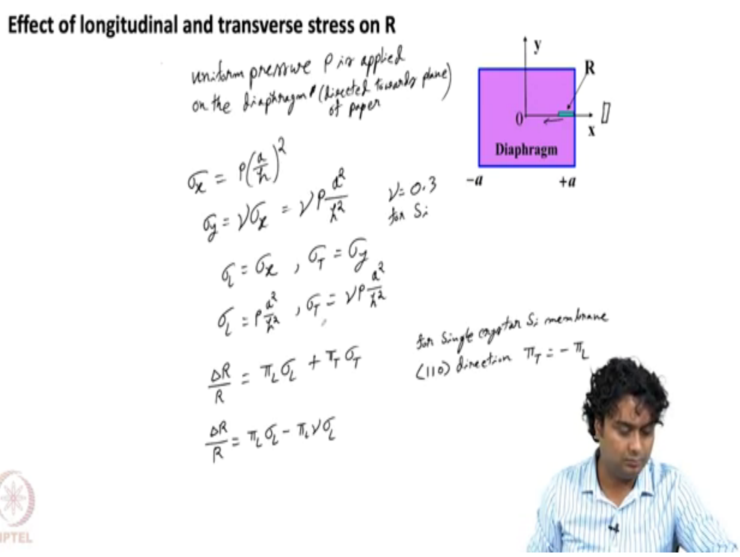

So, as we are discussing about this pressure resistive sensor and we already know that the arrangement or the alignment of the resistor actually matters like; however, whether this is aligned along the radius or in transfers direction to the radius right. And let us say this is the membrane and uniform pressure. Uniform pressure P is applied on the diaphragm. There from pointing to the like normal to the paper. Now the stress component that is let us say sigma x. So, sigma x is the stress in x direction which is working radially which is directed in this direction right. Sigma x is in this direction.

So, that sigma x is equal to P into a by h whole square. And that we find that we are writing from this expression right from the plate theory.

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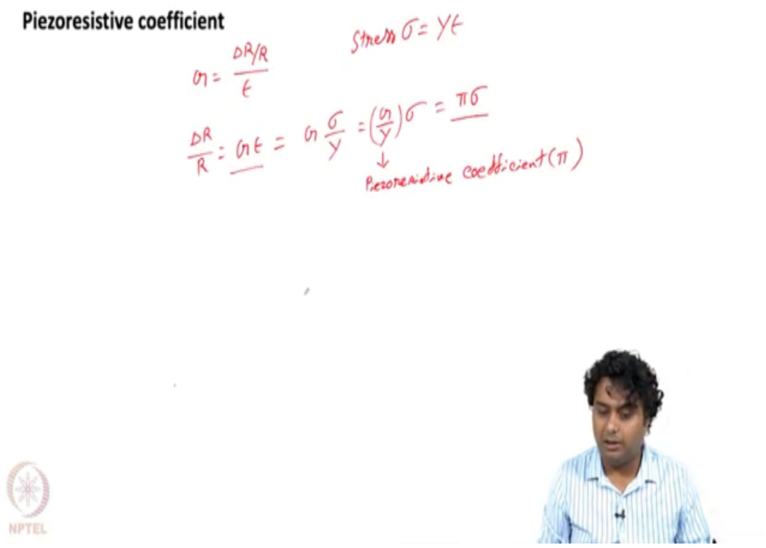

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COMPARISON OF GAUGE FACTORS

TYPE OF STRAIN GAUGE	GAUGE FACTOR
Metal foil	1 to 5
Thin-film metal	≈ 2
Diffused semiconductor	80 to 200
Poly crystalline silicon	≈ 30

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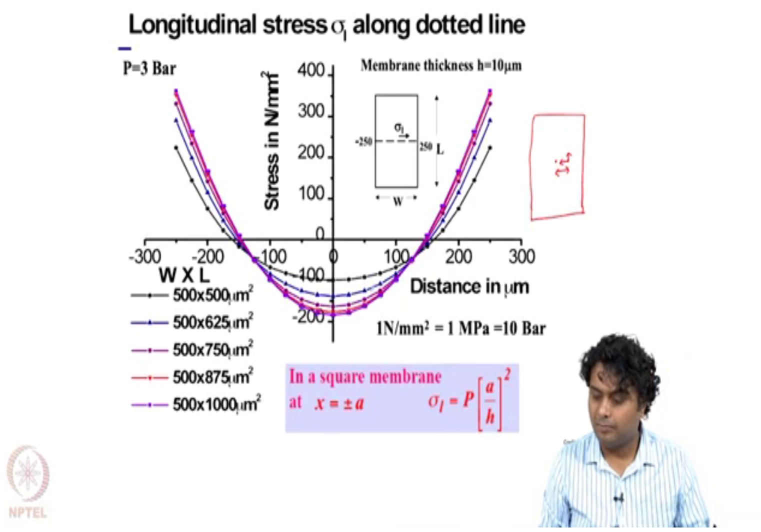

Now as we have discussed for Poisson ratio, that whatever is the stress in like in x y direction will be just a Poisson constant into sigma x. So, sigma y, sigma y is equal to Poisson constant nu to sigma x. That is nu into P into a square by h square. Now nu is 0.3 for silicon.

So, if it is a silicon membrane we can consider nu to be 0.3. Now this is a sigma x and as you can see the direction of the resistor also, it means it is the longitudinal direction of the resistor. So, longitudinal stress sigma L is equal to actually sigma x right. And transfers state sigma T is equal to sigma y, but let us say if the resistor was mounted or fabricated like this in this arrangement, then sigma L would have would be equal to sigma y actually right, if the arrangement was like this.

So, this actually does matter because sigma y and sigma s x it is not same right. So, sigma L and sigma T is also not same. So, we can write that sigma L is equal to P into a square by h square and sigma T equals to nu P into a square by h square. Now earlier we have seen that delta R can by R can be represented as the gauge factor in to strain or the piezo resistive coefficient in to stress right. So, we have already the stress values. So, we can write.

So, as I mention that this piezo resistive coefficient is have a directional property. So, along the length the piezo resistive coefficient along the length and like in the longitudinal direction or in the transfers direction are not same. So, delta R by R will be having both the components. So, this is a longitudinal component. Which is piezo resistive coefficient in the longitudinal direction in to stress in the longitudinal direction plus piezo resistive coefficient in the transfers direction into stress in the transfers direction.

For single crystal silicon membrane along 1 1 0 direction. We can consider that pi t is equals to minus of pi L. So, delta R by R becomes then pi L sigma L and then this minus will come minus pi L nu to sigma L right, because sigma T is again nu into sigma L.

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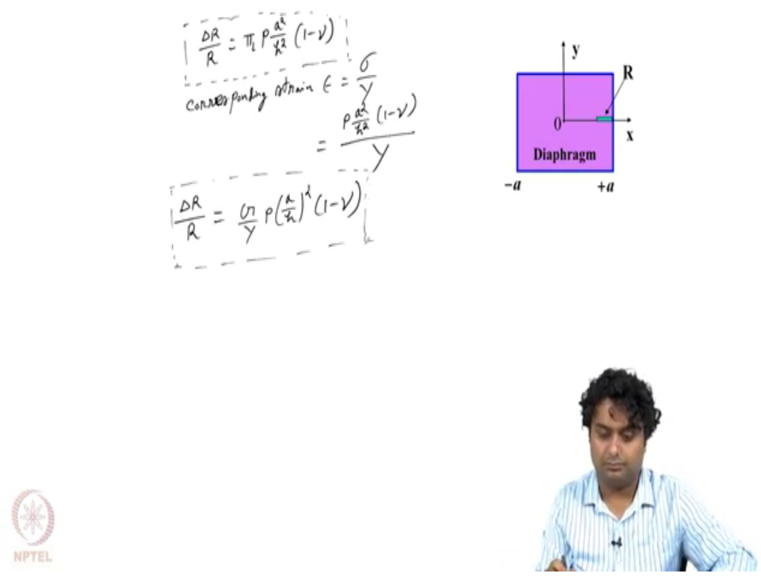

Delta R by R is equal to pi L P into a square by h square into 1 minus nu right. So, we are putting sigma L value, sigma L value is pi P into a square by h square and then we are taking pi L into P into a square by h square common. And we have then 1 minus nu. And what will be the corresponding strain? Then is equal to sigma by Y and Y is our Young's modulus. So, this becomes P into a square by h square into 1 minus nu divided by Y.

So, in terms of gauge factor delta R by R in terms of gauge factor will become g into epsilon. So, that is G by Y into P a by h whole square into 1 minus nu. So, both the piezo resistive both the expression piezo resistive coefficient as well as the with the gauge factor are important.

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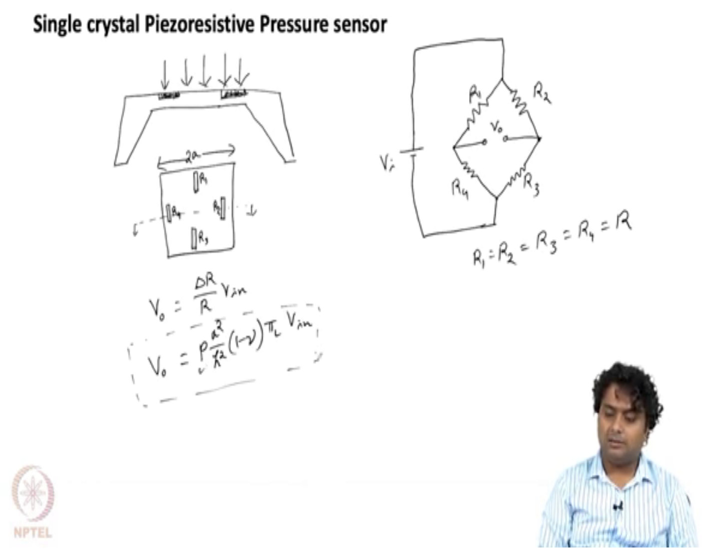

Now, we know that this is our membrane say this is our membrane. And we have the piezo resistive elements here right four different resistors actually put here. Here the pressure is coming and because of that the membrane will deflect right. And this is the top view of the membrane. This side is let us say 2 a and then we have four different resistors piezo resistors which is let us say R 1, R 2, R 3 and R 4.

We have measured the stress and strain along the along this axis right. And then it is connected like a Wheatstone bridge. So, this is where I am measuring the output voltage V 0. And then actually I applying some voltage ok. This is V in now what we have taken that this all the initial resistances are same so, R 1, R 2, R 3, and R 4.

2 equals to R 3 equals to R 4 equals to R let us say ok. Then V naught the output voltage is equals to delta R by R into V in right. And now I know what is delta R by R. So, delta R by R

is P into a square by h square to 1 minus nu into pi L V in. So, by measuring the output voltage V naught we can calculate the P.

Now in this expression we are actually applying this V in and then measuring the V naught right. And we using V naught we know that how much is the pressure we can back calculate the pressure. Now, if the pressure changes then also V naught changes and if the V in changes then also V naught changes right.

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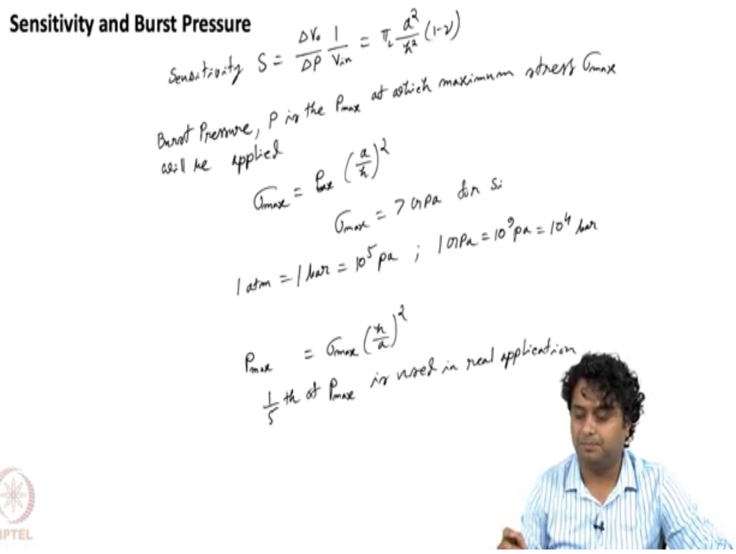

So, the sensitivity is defined as S is equals to delta V naught by delta P. Technically it should be the sensitivity that how much is the output voltage changes with per unit change of delta P, but here will be on V in term also because, if we change the V in then also we can get higher V 0, like if we increase the V in then we can get higher V 0.

So, which is per unit input voltage sensitivity per unit input voltage. Sense is equals to pi L into a square by h square 1 minus nu on this a and h are our geometric depends on the geometry of the membrane and then this pi L on nu r like depends on doping concentration material properties etcetera. So, these are all this all we can decide and accordingly we can select the sensitivity of the pressure sensor.

Now in this context we need to know another term called burst pressure. Burst pressure is the pressure where the what is the like burst pressure is the pressure what maximum pressure can be applied on the membrane. So, if we apply more than P burst or burst pressure then the membrane will get damaged or membrane will burst or membrane will break. So, burst pressure sigma max.

So, definitely that burst pressure or the maximum pressure the stress will also be maximum, like just before breaking. And then sigma max is equal to P max to a by h whole square. At this pressure this will be the at the burst pressure the stress will also be maximum. And this sigma max is equal to 7 GPa for silicon the 7 giga Pascal. So, the point is here that we know the material sigma max or what is the maximum pressure material can withstand.

So, accordingly if we know the material geometry then we know how much can be the maximum pressure this pressure sensor or this membrane can with stand, because we if we apply more pressure than that then the membrane will burst and other point here to note here is that this P burst or P max is different for different geometries of membrane ok.

So, it is not a constant term for a material. Constant is sigma max like what is the maximum stress it can with stand, but depend even if the sigma is constant for different silicon membrane can be of different sizes. Size like 1 membrane can be of 10 micron with 1 micron thickness, another membrane can be like 100 micron with 1 micron thickness. And both the cases the maximum capability of withstanding the pressure will be different. Just to mention here as we are mentioning about the pressure come that 1 atmospheric pressure or 1 atm is equals to; is equal to 1 bar.

And that is equals to 10 to the power 5 Pascal ok. And again 1 GPa is equal to 10 to the power 9 Pascal 1 giga Pascal 10 to the power 9 Pascal. So; that means, 10 to the power 4. So, another thing what we need to understand from this that if we decrease the edge that is the thickness of the membrane then sensitivity is more and more higher or even if we increase the size then also sensitivity is higher, but if we make the membrane very thin if we make the membrane very thin then sigma max is constant, but here so, P max will P max will also decrease.

So, the burst pressure will also decrease right. So, it is kind of trade of we need to do like what is the maximum we can make it thin. So, that we have a significant amount of sensitivity and without making the membrane to get damaged right. So, here you see P max only equal to sigma max into h by a whole square. So, you can see that even though the sensitivity will increase if we decrease h, but the P max will decrease.

So, the range of pressure for which it can be used will be lesser. So, sensitivity and range this two we need to kind of we need to optimize. That what is the max for which range we want? And for that what kind of sensitivity we can achieve? By controlling the other terms also like area then the piezo resistive coefficient etcetera and also V in is also in alright.

And another thing is usually whatever is the maximum pressure the membrane withstand we use 1 by 5 times of that. So, even though let us say it can withstand it can withstand 10 atmosphere pressure, but we will not push the membrane to be used for like 10 atmosphere pressure let rather we will work in like the range will be decided as like 2 atmosphere maximum.

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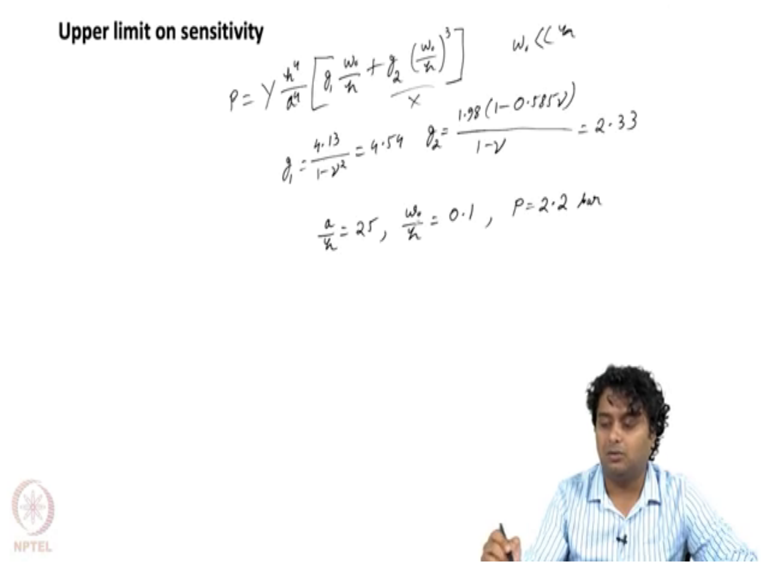

Now, another problem in reducing the thickness too much is that actually the pressure and the deflection membrane is related by this expression. So, P is equal to Y that is Young's modulus in to h to the power 4 by a to the power 4. Where h is the thickness of the membrane and a is the like each side of the square membrane is equals to g 1, which is a coefficient in to W 0 by h plus g 2 in to W 0 by h whole cube. So, this W 0 is the deflection of the membrane.

And for all the real cases where we actually deal with small deflection we can neglect this term we can neglect this cubic term, because W 0 by h will be like W 0 will be very very less than h. So, W 0 by; so, W 0 by h whole cube will be even much much smaller than 1 so, we can neglect we can neglect that term. But if we make the membrane very very thin then this non-linearity kicks in because then we cannot neglect that term.

So, this will add extra complexity to our device. And this g 1 is equals to 4.13 divided by 1 minus nu square. So, if you put silicon value then it will come as 4.54 and g 2 is equals to 1.98 into minus this will be 2.33. And if you put different values like let us say I put some particular value like a by h. Let us say equals to 25 and then W 0 by h equals to 0.1. Then we get pressure equals to 2.2 bar. This is for silicon.

So, for Y you will use silicone value. Now you see why I wrote this actual numbers because a by h is like 25. So, if your membrane if our membrane thickness is like 1 micron then the side is 25 micron. So, it is pretty reasonable assumption. Then we have W 0 by h equal to 0.1. So, in usual case we will consider that the deflection is maximum one tenth of the thickness.

So, W 0 by h will be 0.1. That is also very reasonable assumption for non-linear cases right. So, in that case W 0 by h cube will become 0.001 so, that we can anyway neglect. Now this itself gives 2.2 bar. And 2.2 bar means 2.2 atmospheric equation means whatever is your our ambient pressure now 2.2 times like 2 times more than that pressure is can be achieved with this kind of configuration itself. So, we can pretty reasonably assume that if our deflection is not much that we are in the linear job.

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So, this is the pressure sensor we are talking about. Now how we can make it. So, first there is step by step process we need to follow for that. One is first step is anisotropic etching of top silicon. Anisotropic etching of silicon to realize the membrane. Then boron implant in particular regions using lithography as we have discussed in last module of the piezo resistors.

Then connect the connect the resistors in Wheatstone bridge Wheatstone bridge and finally, bond bottom wafer. So, bonding is a technique by which we can actually join two different silicon wafer. We have not discussed it in the course of in this course, but this you can consider as like gluing two different wafers though it is not we do not use physically any glue we use anodic bonding or like high temperature high pressure bonding where two silicons.

So, will 2 silicon wafer will be joining to each other. So, here as you can see this top wafer is the where the membrane is there right. Top wafer has the membrane and it has all the resistors all the devices made that, but the bottom side of the other half the bottom half is actually containing that pressure port. And how they are connected? Like we cannot h material from inside.

So, first we make this material this wafer and then we separately make the other black bottom wafer. And then we just join them together let us you can think it like clamping two wafers together. And then we have a vacuum or like a trap space in between which will be like a trapped gas and then the top site of the thin site act as a membrane. Now how we can make it? Now we will discuss.

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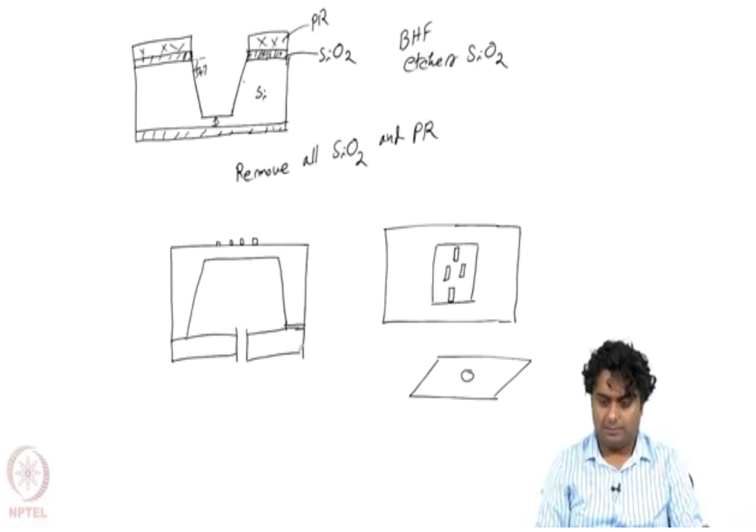

Now, we will start we will start with a simple 100 silicon wafer. And then we will deposit oxide in thermal oxidation technique. So, then in thermal oxidation technique what will happen? The oxide both the sides same thickness of oxide will grow. So, let us say this is oxide. So, this is oxide. And then we will spin coat photo resist as we have discussed during the lithographic class.

So, we will spin coat the photo resist let us say this is the photo resist. And then we will use the mask to exposed a particular region of the photo resist. Let us say this is the region or the photo resist what we are exposing. So, after exposure of 2 u v and then development what will happen? This region of photo resist will go away as we have discussed right. So, then we can remove this; we can remove this region of photo resist. So, we get something like this.

Now so, this is P R or photo resist and this is S i 0 2 silicon oxide and this is silicon. Now we use H F or buffer HF. Which is a solution of hydrochloric acid and that etches S i O 2. So, S i O 2 which where it is exposed that region will get it H F by the buffer HF, but the this region will not get etched. So, then HF. So, from this region the HF will get etched and sorry S i O 2 will get etched and the other two sides which is suppose protected by PR they are save to with their.

Now what we will do we will do anisotropic etching using k o h or t m h. And after anisotropic etching we will get anisotropic h profile. So, how it how will it look?. So, this sides this sides will not get etched because this is protected by the S i O 2 right, but from the middle it will it is like anisotropic way and this is a 54 degree angle 54.7 degree angle which it creates. Now, we will stop the etching at a certain distance from the bottom. So, we have a thin membrane in between the other side negative top side and the bottom side and this cavity right and this will act as our membrane.

Then we will use again we can use again buffer HF and like acetone to swipe up all the S i O 2 and PR. And we remove all S i O 2 using h f or that kind of solution and PR. That we can remove PR by using acetone. And then we get only the silicon structure like this. And this is the membrane. Now on top of the membrane, now let us say this is the causational side and this is the top side and this is the membrane.

So, we radiate this sample from the bottom and then we can see the light coming out of the membrane. And like that we can actually identify the membrane and then on top of that we can again put photo resist and lithography and put all the piezo resistors. And how do you put the piezo resistor? That is we will open few spaces using lithography and then we will just doped boron into those spaces right.

And then this will become this places of silicon membrane will become piezo resistors. So, you can align it like this or and put them we can put the piezo resistor according to our design requirement.

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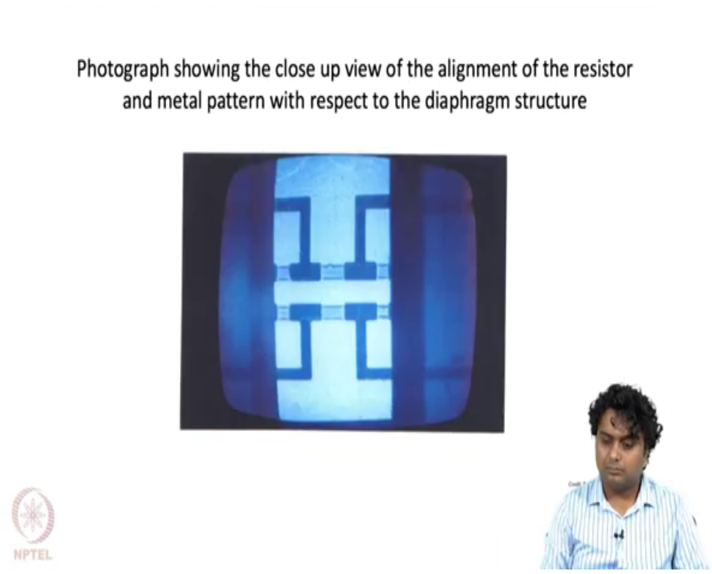

So, this is real image which was made by Professor K N Bhat, Professor K N Bhat from IIT Bangalore which is the real optical image of the top side of the diaphragm. And these are the piezo resistors here you can see these are the piezo resistors.

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And this is from the bottom side and here you can see the cavity. This dark space is the cavity or light is not reflecting. So, that you can understand and this is the membrane. Now, once we have this structure with like I want to have this structure with piezo resistors made on the top like this, let us say here the piezo resistors are made. Then we take another we take another silicon wafer or glass plate where we have a hole in the middle.

And that wafer actually we can put at the bottom. So, that wafer we will put at the bottom and then there will be a pressure port actually like bond this wafer to the top wafer. So, this is like the all the silicon all the piezo resistors and etching has been done and on this plate. And then we have a cavity at the bottom and then we just take another plate and stick it together or clamp it together bond by bonding and then we have the full pressure sensor.

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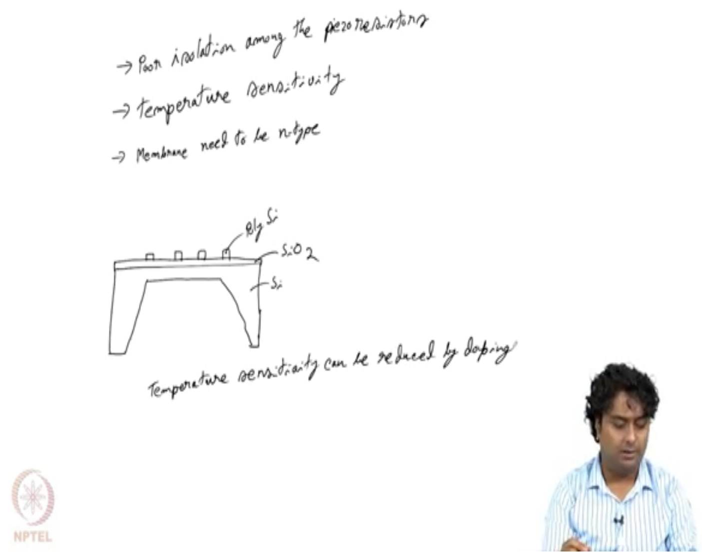

Now, there are some important points we need to remember regarding this single crystal silicon single crystal piezo resistive elements. That is like while we are doing this on single crystal silicon and they are very good conductor of electric current right. So, the there is poor insulation very poor isolation. So, as I told that the piezo resistance need to be connected like a Wheatstone bridge circuit, but in that case like it happens is as all the piezo resistors are made by doping silicon in different different regions of the same silicon membrane.

And if the silicon is not very good insulator like if we as we know the silicon is basically a semiconductor, and then there is electric like charge carrier flowing in between one piezo resistor to another piezo resistor then this will hamper the actual result. So, this is one of the issues then temperature coefficients of sensitivity. So, this nu, pi all this factors actually depends on temperature also and also the resistance itself like resistivity etcetera it also depends on temperature.

So, this is another problem with this kind of piezo resistors and as we use always like most of the time we prefer P type piezo resistors because they have very good gauge factor. So, the membrane need to be n type n type. So, one kind of solution can be thought for this purpose is polycrystalline piezo resistors on oxide. So, what we do we have the membrane like this as we have already discussed.

So, this is the membrane this is the membrane and then rather than putting the piezo resistor on top of the membrane directly we put a oxide layer. And then on top of that we put the piezo resistors like polycrystalline piezo resistor. So, these are the four piezo resistor. So, now, this piezo resistors are actually on S i O 2.

So, these are properly insulated from each other only where we will make the connection there only they will be connected otherwise it is not and, but the problem here is that this poly silicon piezo resistors have low gauge factor like 30 or so whereas, the use a single crystal piezo resistors have a gauge factor around 80. So, that is one problem, but an one kind of advantage is there is the temperature sensitivity can be reduced by using 0 doping. But one advantage of this take another advantage of this technique is temperature sensitivity can be reduced by doping. I mean it reduce to almost 0 by doping.

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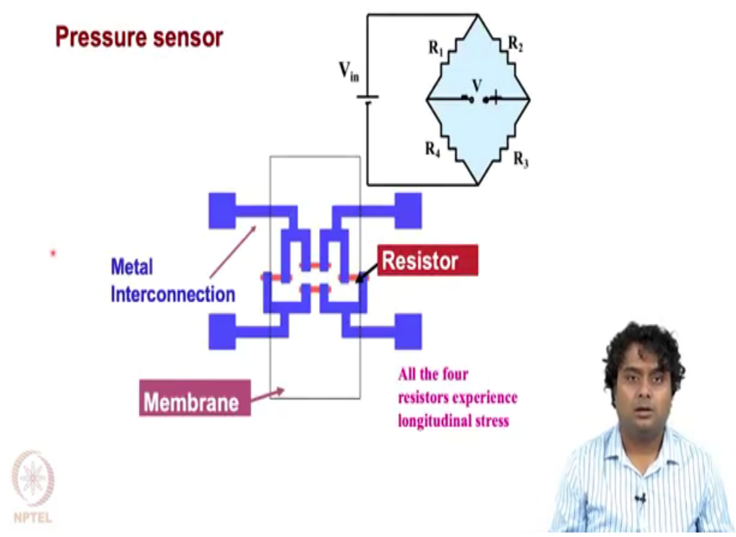

So, now we have seen that have a pressure sensor can be made from scratch. Starting from a silicon wafer then doing silicon etching, then lithography and then finally, bonding two wafers to make the pressure sensor. And this is we have already seen this is how the resistors are connected in Wheatstone bridge connection and this is the membrane. And then all this resistors according to the Wheatstone bridge are actually connected to some external pads where from the electrical contacts will be taken.

So, these are like metal contacts. So, this metal contacts are made by sputtering or wave physical wafer deposition whatever we have already discussed. And then in this pressure sensor will be ready.

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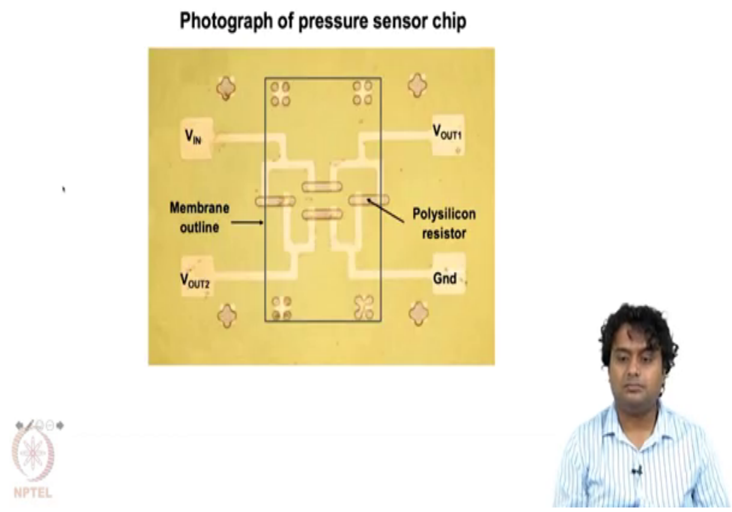

And this is the photograph of the pressure sensor chip. So, this is optical micro graph actually here you can see the resistors. So, these are the actual boron doped resistors. And then these are the metal contacts which are they connected to its contact pads and this is a membrane region and there you can see some mass which are actually for alignment because as you have seen that the etching of the membrane happened from the bottom whereas, the top side actually this resistors are made.

So, because of that to match the membrane and the resistor. So, that it is exactly place at the space where it is required when need this alignment marks.

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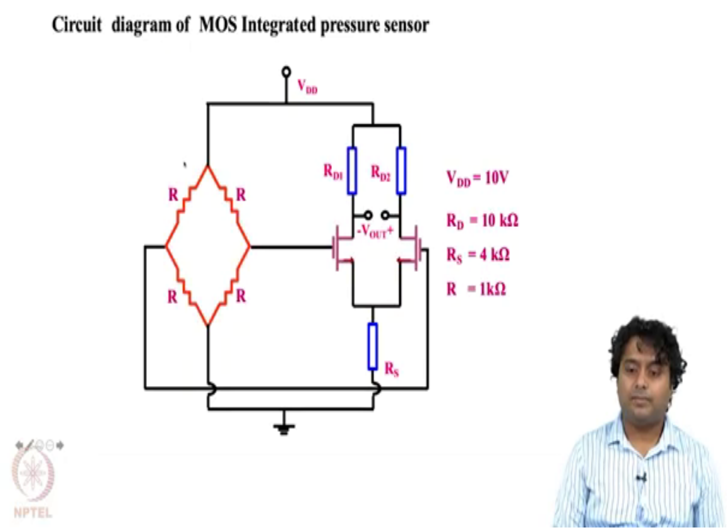

This is circuit diagram of the most integrated pressure sensor. So, this is the Wheatstone bridge we know that this is the voltage output what we are getting right. And this voltage output actually like we do not need much electronics for to measure that, but still we can use a simple differential amplifier and amplify the gain amplify the voltage output.

Let us say if you are using 10 gain amplifier then if you are getting like 2 millivolt output from the Wheatstone bridge then ultimately well the measure end we will see 20 millivolt. So, this kind of electronics also we can put with the photo with the pressure sensor. And this will actually increase our sensitivity from by electronically.

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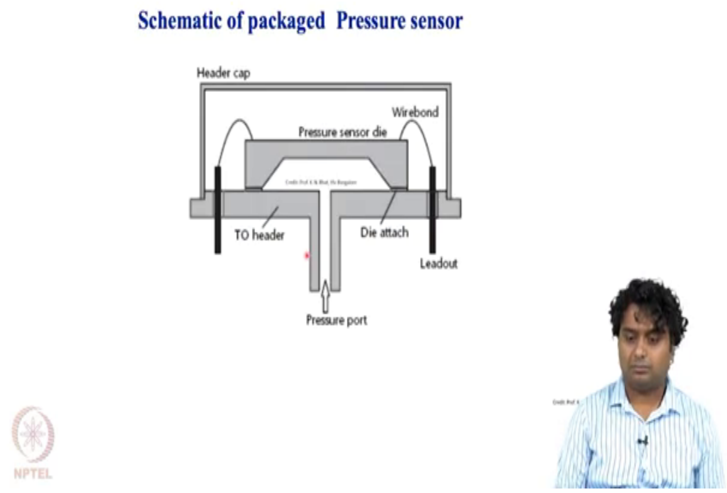

And then we can we will actually package the device. So, this is the schematic of the packaging and there we have put a header cap. So, that we can remove it like a if air or moisture is not will is not harmful for our device and we can remove the air or moisture from this part. And then like we can package it under vacuum and we can take the leads out where for our applications.

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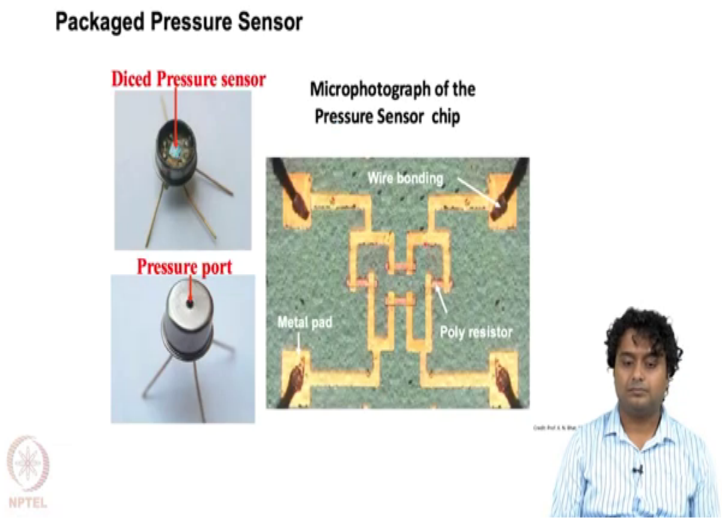

And this is the final device package device which are made by Professor K N Bhat in IISC Bangalore, and also in IIT madras. So, there you can see the actual photograph of the image of the pressure sensor. So, this are the; this are the wires which are going out actually solder wire and this are the poly silicon resistors.

So, this is actual optical microscope image and this is the metal pad which are actually gold pads consider gold pads here and this is the package device. So, this is the top cap is open here you can you. So, you can see the die and then this die is connected to different different contact points at the pressure port will be connected here. So, this is the final device.

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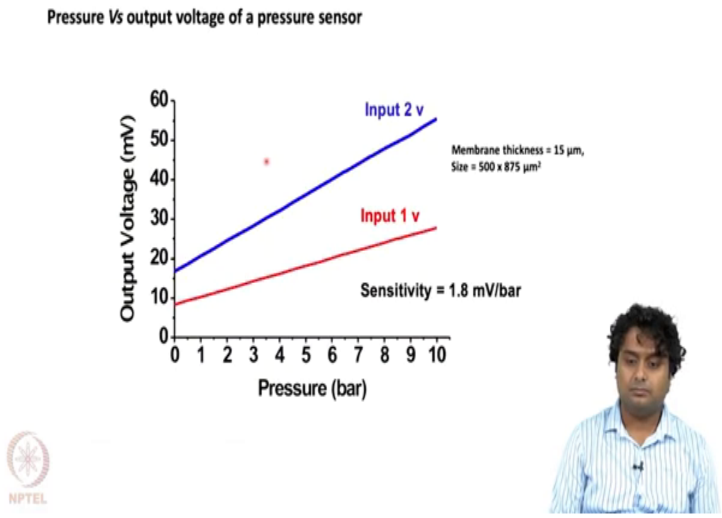

And this is the output voltage verses pressure. So, as you can see that with input voltage of 1 millivolt you can get a sensitivity of 1.8 millivolt per bar. So, if our output is about 1 millivolt. Then we know if our output is about 10 millivolt then we know that the pressure is about 1 bar whereas, if it is about 20 millivolt. And we know that it is about 10 bar pressure.

So, the sensitivity is 1.8 millivolt per bar whereas, if you are using 2 millivolt then you can see that the slope is little bit increased because as we have seen that the in the sensitivity part V in also come. So, if the input voltage is 2 volts then in that case sensitivity is 3.6 millivolt per bar and this is the membrane. So, this graph are drawn for this membrane thickens. So, this that is all for pressure sensor means pressure sensor.

Thank you.