Micro and Smart Systems
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Lecture - 37
Pressure Sensor Design Concepts, Processing, and Packaging: Part - 1

Okay, so we have seen the signal circuits and also we have gone into the details of the integration of Microsystem and microelectronics. Now, we take up some special cases like the pressure sensor, it is design concept, processing and packaging.

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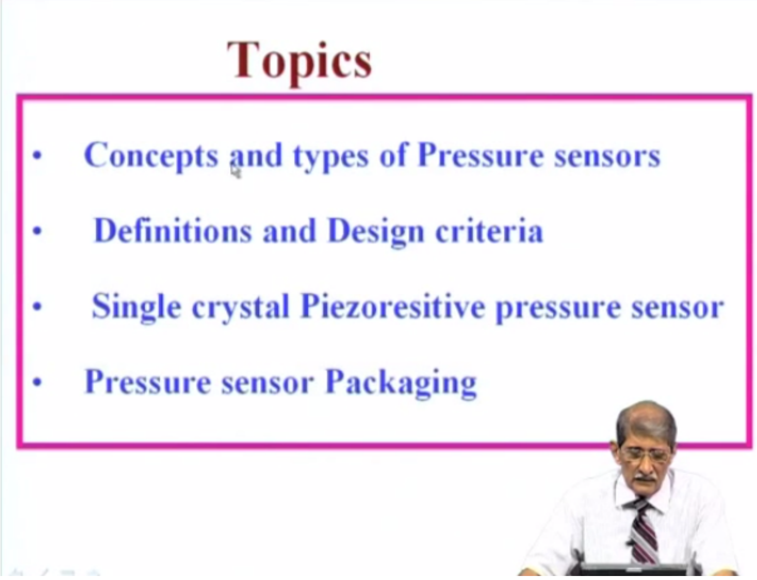

Topics

- Concepts and types of Pressure sensors
- Definitions and Design criteria
- Single crystal Piezoresitive pressure sensor
- Pressure sensor Packaging

So in this presentation, we will discuss concepts and types of pressure sensors, definitions and design criteria, single crystal piezoresistive pressure sensor, then pressure sensor packaging, a glimpse of that I will give you also

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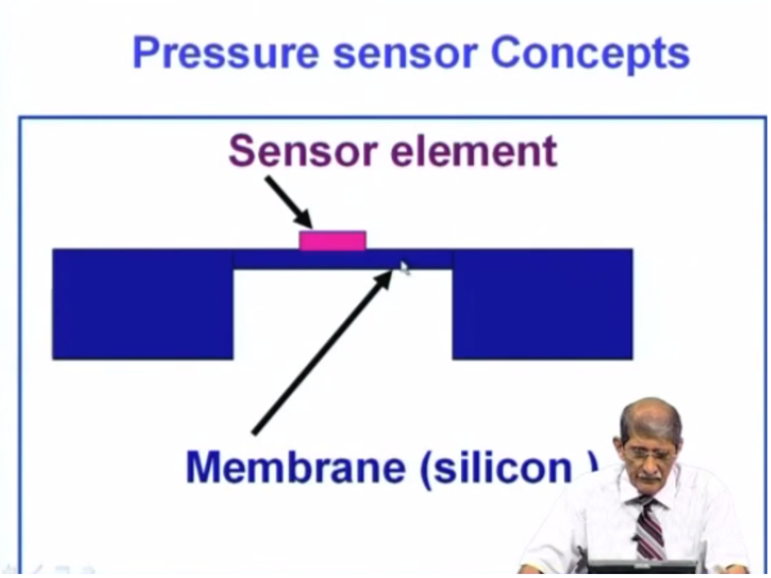

Pressure sensor Concepts

Sensor element

Membrane (silicon

So the pressure sensor involves or it requires a membrane, thickness desired by your pressure requirement and membrane is anchored all around in these portions to a thick frame, so that it is free to move up and down when it experiences fluid pressure and that membrane is usually is micromachine devices, it is taken and you have a sensor element. We will discuss what are these 2.

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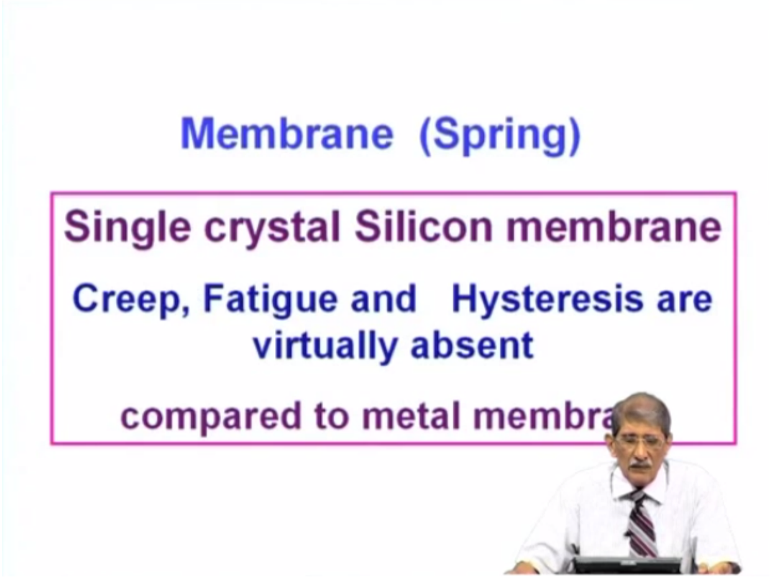

Membrane (Spring)

Single crystal Silicon membrane

Creep, Fatigue and Hysteresis are virtually absent

compared to metal membra

So the membranes or you can call it has a spring also if you like is usually or invariably made of single crystal silicone material. That is because the silicone is a very good material mechanical material, it has high (()) (01:53), high yield strength, all those advantages are there, even comparable to or better than steel, excellent mechanical material, the added advantage is unlike some of the metals, metallic membranes, silicon is free of creep, fatigue, hysteresis, virtually free.

The creep meaning, what is implication of creep, if you heat most of the materials like metals, you heat it to almost slightly above half that melting point, there is a chance of it is being, there will be a warpage of that membrane. Whereas, silicone, melting point is 1410 degree centigrade, you can go right up to 1000-1200 degree centigrade, there is practically no warpage, so that is what is meant by there is no creep.

That is why it has made it possible to make integrated circuits by processing at very high temperatures using silicone. Then, you can keep on if you are using it as a membrane, you can keep up and down, large number of times you can operate it, million times, there is no fatigue. And there is no hysteresis in the sense, if you apply pressure and if you release the pressure, it will quickly come back to its original position.

In metal membranes, it takes a while to come back to it is original position, so during that time, you will have some signal coming out of the pressure sensor. These are some of the main advantages of using silicone as a membrane and you can process it very easily using the conventional integrated circuit technology.

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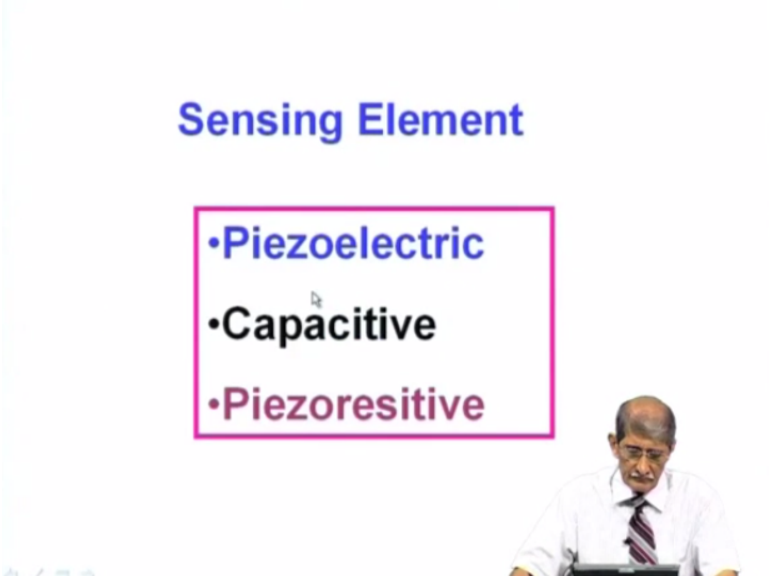

Sensing Element

- Piezoelectric
- Capacitive
- Piezoresitive

Now the sensing element that you put on the membrane, okay, they can be of different types. The most popular ones are piezoelectric, capacitive, and piezoresistive. I will just go through what they are quickly.

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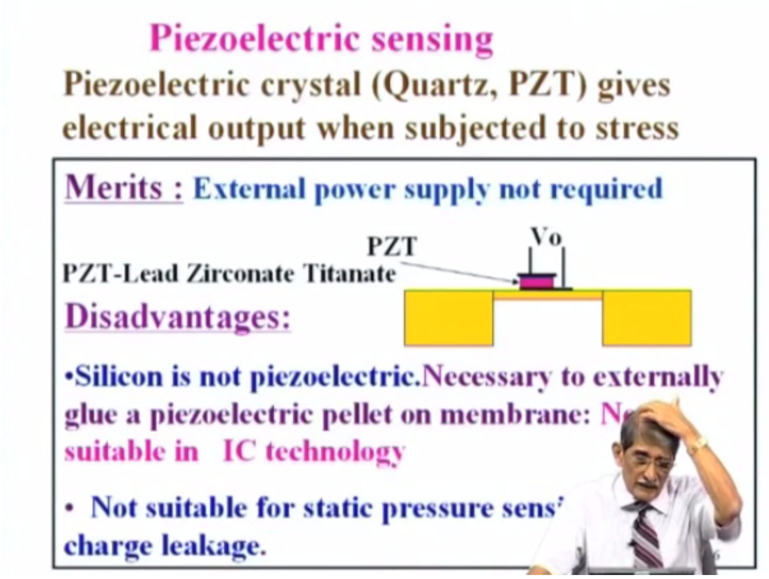

Piezoelectric sensing

Piezoelectric crystal (Quartz, PZT) gives electrical output when subjected to stress

Merits : External power supply not required

PZT-Lead Zirconate Titanate

Disadvantages:

- Silicon is not piezoelectric.Necessary to externally glue a piezoelectric pellet on membrane: N suitable in IC technology
- Not suitable for static pressure sens charge leakage.

The piezoelectric sensing, here a piezoelectric crystal like quartz or PZT, PZT is lead zirconate titanate, so these are very good piezoelectric materials, these crystals give electrical output when subjected to stress. So you can mount them on the membrane, okay, so when these membrane is subjected to pressure, let us say from the bottom end, then the membrane will deflect up, this is anchored here, the membrane will deflect up and there will be strain in the membrane, that strain will be transferred onto this, strain and stress transferred on to the PZT or piezoelectric crystal.

And then a voltage will develop across the 2 terminals of that PZT or piezoelectric crystal, top metal and bottom metal, we have output voltage. Okay, you can see that you are not using any power supply for this. Straightway you will get the output, when you subject it to pressure the device is subjective to pressure, you will get the output straightway, excellent for usage in remote places okay.

But, the problem is this PZT has to be glued, it is externally glued onto the membrane, okay. The pellet of PZT is glued onto this and this is not part of the conventional integrated circuit technology, so that is not disadvantage, but still you may say, I can deposit some PZT, polycrystalline materials and use it but the sensitivity will go down if you use such materials.

Now, but more serious disadvantage is, it is not suitable for static pressure, because if you have static pressure, the membrane deflection is constantly there and the strain is constantly there and constantly the charge developed across this piezoelectric crystal will be leaking. It is like a capacitor being charged. The capacity charger leak, so for static pressure measurement you cannot use it, but for dynamic measurement you can use it.

If the pressure is continuously varying, then this is a very good method. It is like vary in the voltage across the capacitor, then you can see the capacitance changes, so this is the drawback of that.

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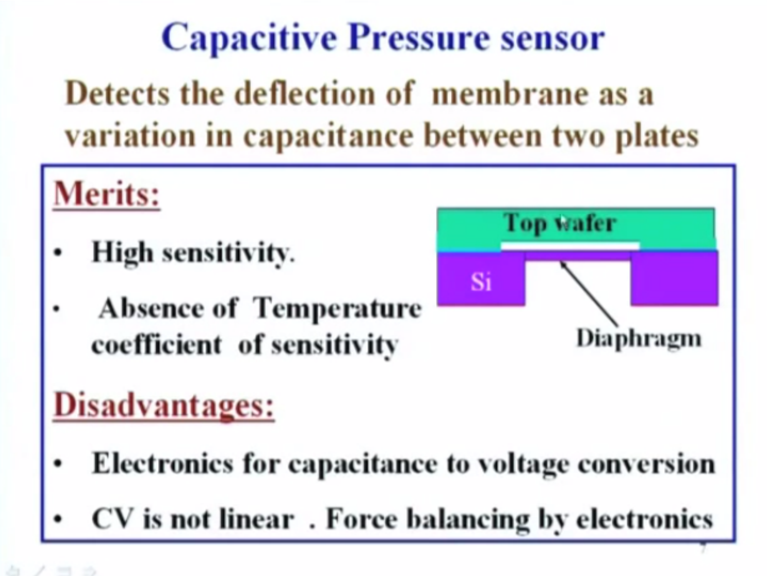

Capacitive Pressure sensor

Detects the deflection of membrane as a variation in capacitance between two plates

Merits:

- High sensitivity.
- Absence of Temperature coefficient of sensitivity

Disadvantages:

- Electronics for capacitance to voltage conversion
- CV is not linear . Force balancing by electronics

Now, let us take a look at the capacitive pressure sensor. The capacitive pressure sensor, you can see, the membrane is here and you put another top wafer, bonded onto this wafer, with a gap, so that when this membrane experiences pressure from the bottom, okay, that will deflect up, then the gap between the top wafer and this membrane is reduced, the capacitance will go up, okay.

So, this is operating on the principle of changing the capacitance due to change in the distance between the 2 electrodes. So, how much distance changes depend upon the pressure. So, it is very good for, it is sensitivity in this type of sensor, capacitive sensor, pressure sensor is excellent and also this capacitance change is practically independent of temperature.

So, temperature coefficient of sensitivity is absent. On the disadvantage side, the main thing is the capacitance voltage characteristic is not linear. So, this capacitance change will not linearly vary with the displacement. So, it not a linear function of the pressure, so you may have to do linear racing circuits to accommodate large range of pressures and you definitely need electronics in this system because you have to convert capacitance to voltage.

So, these are added requirements for capacitor sensing, otherwise, it is very highly sensitive and it is temperature insensitive, that is the biggest merit.

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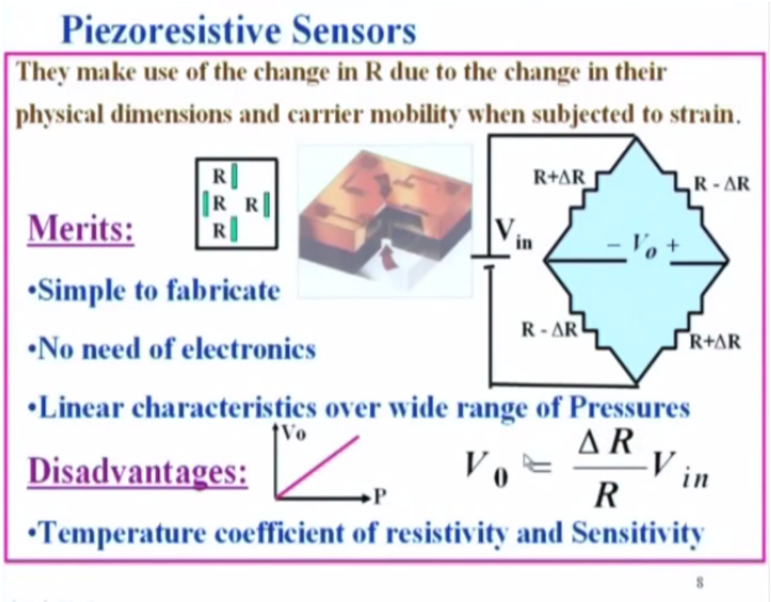

Piezoresistive Sensors

They make use of the change in R due to the change in their physical dimensions and carrier mobility when subjected to strain.

Merits:

- Simple to fabricate
- No need of electronics
- Linear characteristics over wide range of Pressures

$$V_0 \approx \frac{\Delta R}{R} V_{in}$$

Disadvantages:

- Temperature coefficient of resistivity and Sensitivity

So, you can see the third one, piezoresistive sensors. A piezoresistive sensor, here what you do is, I have shown here a 3-dimensional picture, where a membrane is present, which is anchored here onto a glass substrate, so this portion, center portion of the membrane is free to move up or down, when it experiences a pressure. So, that membrane will experience stress and it will undergo stress, suffer the stress and the stress will be transferred on to the resistors, 1, 2, 3, 4 resistors, which are located like this on the membrane.

This is the membrane top view, you have these 4 resistors which are located. We have discussed little bit about that in the previous lecture, okay, so these resistors experience a change in the resistance when it is subjected to stress. For example, as I mentioned already in the previous lecture, the resistance are which is mounted perpendicular to this edge, will experience longitudinal tensile stress and it is value will go up, if it is a P type resistor.

These are semiconductor resistors. Then, if it mounted parallel to this edge, it will experience transfer stress, that is perpendicular to its length, then if it is a P type resistor, the resistance value will go down, okay. So mount these resistors, whose values go up, we go onto opposite arms of the bridge, once it go down, you mount to ups and down of the bridge. So that, where there is unbalance, this bridge will give an output voltage.

The unbalance comes because of the delta R, delta R, delta R present here. You will get an output voltage which is equal to if all the delta R and R same, it will be delta/R*input voltage. So you can see the sensitivity of this sensor would depend up how much is the delta R/R and how much is the delta R/R would depend upon the strain experienced by the resistor due to the strain on the membrane.

Now on the merit side, before you go to that, this change in resistance takes place because of 2 things, one due to the dimensional changes which happens in the conventional strain gauges, plus secondly in the semiconductor piezo-resistor, the resistance change takes place also due to the change in the resistivity. So that change is dominant, chance in the resistivity, okay. We are not getting down into fix of that, it is due to change in the mobility of the carriers whether it is subjected to stress.

The merits, simple to fabricate, all that you need to fabricate a membrane, on that (()) (11:12) resistors, how to do that, we will see as you go on, no need of electronics. For example, if delta R/R is just point one percent, input voltage is one volt, you will get one millivolt, if it is 10 volts input, you will get 10 millivolts, which can be easily measured, but you may need electronics for further processing, that will be different issue.

Linear characteristic, okay, the output voltage will be linearly related to the change in the resistance, which is linearly related to the strain which again is linearly related to the stress or the pressure, so that is the main advantage of this piezoresistive sensors. You do not get everything free, what you have to pay for this is, what will on the disadvantage side is the temperature coefficient of resistivity and temperature coefficient of sensitivity is finite in this type of sensors.

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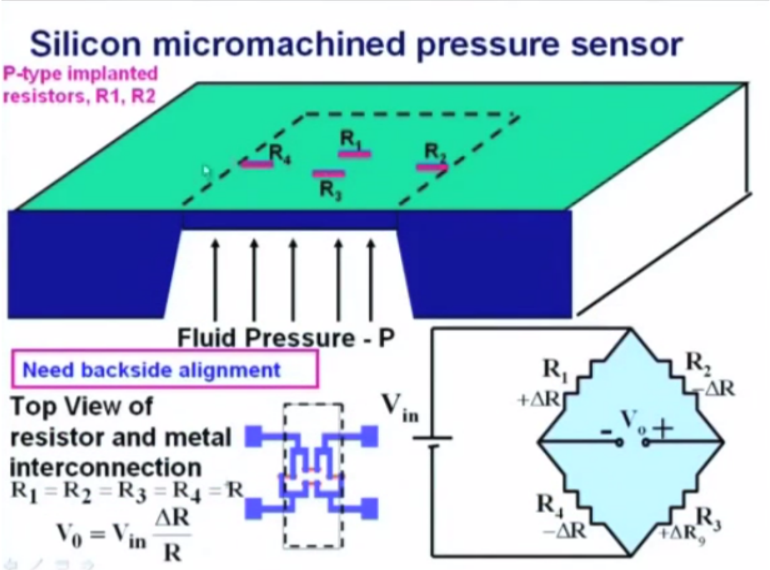

Silicon micromachined pressure sensor

P-type implanted resistors, R1, R2

Fluid Pressure - P

Need backside alignment

Top View of resistor and metal interconnection

$R_1 = R_2 = R_3 = R_4 = R$

$V_0 = V_{in} \frac{\Delta R}{R}$

Okay, seeing these things, we will go into some of the details of this piezoresistive sensors. So I have shown the isometric view of the silicone, micromachined pressure sensor, the membrane is realized by micromachine technique, you can see that angle between the bottom surface which we saw on 0, 0 wafer and this 1, 1, 1 plane which you have discussed in your technology lectures, so you have the membrane.

Thickness can be precisely controlled based on your design. Then, these red colored ones are the resistors, R1, R2, R3, R4 are put like that. You know, this is different location that I have shown here, R2 and R4 are arranged, perpendicular to these dotted line, which is nothing but the location of the membrane, so those 2 resistors experience longitudinal tensile stress and the values will go up, R2 and R4, okay, R2 and R4 the values will go up.

The R1 and R3 will go down in this particular case, so these are the edges here, will go up, these are center of the membrane go down, resistance, okay.

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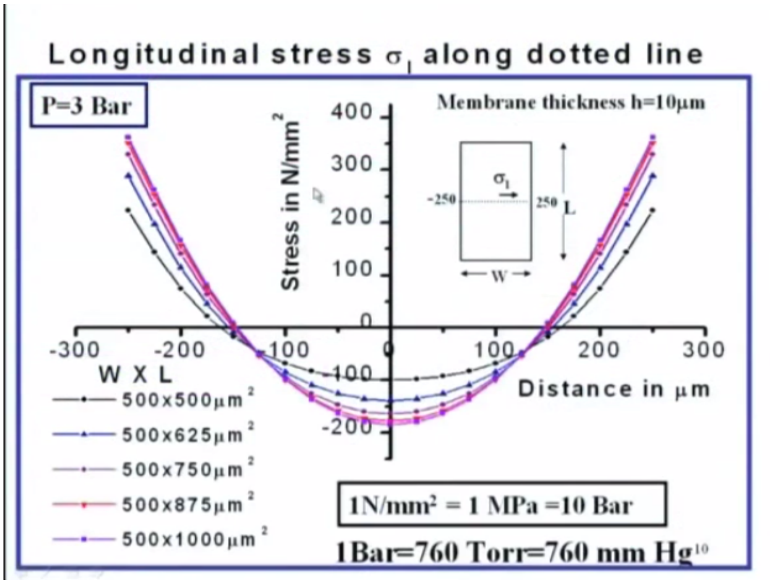

Longitudinal stress σ_l along dotted line

P=3 Bar

1N/mm² = 1 MPa =10 Bar

1Bar=760 Torr=760 mm Hg

Because, at the center, you will see that the, if you plot the stress around this line, center line of the membrane, it will be tensile at the edge, is positive meaning tensile, has it moved from left to right around the center dot. What happens is the stress is tensile here along that direction, you can see she square type of membrane, W is 500 micron, length is 500 micron, this is the lateral dimension of the membrane.

So at the edge, -250, the width is 500 microns, I take the center at 0, so -250, 0 is here, -250, the stress is 200 Newton per millimeter square which is actually, one Newton per millimeter square, is 10 bar, 10 atmospheres, this is 2000 atmospheres. When the membrane is subjected to a stress, perpendicular to the plane, is subjected to stress of 3 atmospheres, 3 Bar, 1 atmosphere is 1 Bar, 3 Bar is 3 atmospheres.

So, if you are familiar about other dimensions for the pressure, 1 Bar is 760 torr, which is 760 mmHg or 1 Newton per millimeter square is 1 Pascal, so mega Pascal is 10 Bar. So, if you have 3 Bar of pressure on the membrane, all over the membrane, okay, you subject it uniformly all though the membrane like that perpendicular, then the stress will vary from the edge to the center and to the edge.

At the edges on the both edges, -250 and +250, the stress is maximum and what we are talking of is stress in that direction, I you put a resistor there, you can call it longitudinal stress, around this direction, so that stress for 3 Bar pressure is 2000 Bar, you can see that the applied pressure of 3 Bar is amplified in terms of stress at the edges. So this membrane virtually acts as a pressure or stress amplifier, so that if you put a resistor at this edges, you see the amplified stress.

So for a small pressure, there is large amount of stress experienced by these resistors, which actually is transfer from the stress on the membrane. So as you go from the left hand side to the right hand side here, it varies from 2000 Bar, somewhere here, somewhere about middle of between center and the edge, the stress is 0, on the top surface of the membrane. As you go down further to the center, the stress is negative.

Meaning, it is compressive, so go to the right, it becomes less compressive 0 than tensile. So you have got the stress variation, tensile, less tensile, compressive, less compressive, tensile and maximized edge. So, you can place the resistors at the edges here, they will experience tensile stress. The resistors at the center, because that is compressive, they will experience compressive stress, those values will go down, okay.

Now, you can just go further, I just have to point out here, this R1 and R2, they actually go up and R1 and R3 go down, so that if these 2 go up, okay, if this go down and this goes up, R3 goes up, the voltage will be positive here, and if R1 goes up, the polarity, R4 goes down, the polarity will be negative here. Okay, one more thing that I want to point out here to you is that if you keep the width constant and if you keep on varying the length of the membrane, the stress concentrations all through will increase.

For example, if I make it double, width 500 micron, length 1000 microns, the stress will actually become much larger than that, you can see it goes up from 200 Newton per millimeter square to about 350. Same is here, the compressive stress also goes from 100 to about 200.

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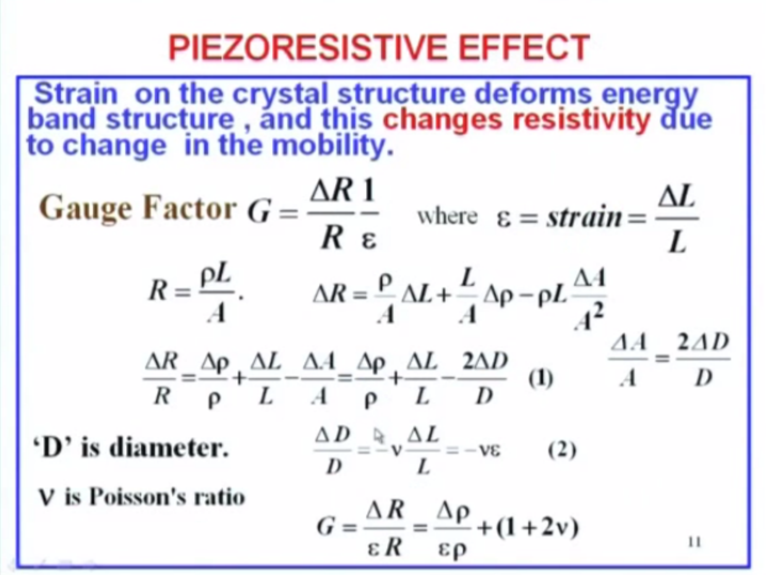

PIEZORESISTIVE EFFECT

Strain on the crystal structure deforms energy band structure , and this changes resistivity due to change in the mobility.

Gauge Factor $G = \frac{\Delta R}{R}\frac{1}{\varepsilon}$ where $\varepsilon = strain = \frac{\Delta L}{L}$

$$R = \frac{\rho L}{A}. \qquad \Delta R = \frac{\rho}{A}\Delta L + \frac{L}{A}\Delta\rho - \rho L\frac{\Delta A}{A^2}$$

$$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A} = \frac{\Delta\rho}{\rho} + \frac{\Delta L}{L} - \frac{2\Delta D}{D} \quad (1) \qquad \frac{\Delta A}{A} = \frac{2\Delta D}{D}$$

'D' is diameter.

$$\frac{\Delta D}{D} = -\nu\frac{\Delta L}{L} = -\nu\varepsilon \quad (2)$$

ν is Poisson's ratio

$$G = \frac{\Delta R}{\varepsilon R} = \frac{\Delta\rho}{\varepsilon\rho} + (1 + 2\nu)$$

Okay, now is the definitions, the strain in the crystal structure, deforms energy bands that is why the resistivity changes. That is the physics of that. The gauge factor, you have certain parameters which you have to define. That is the gauge factor. Gauge factor is delta R/R, change in resistance divided by original resistance divided by strain. Strain is delta L/L. So the resistance R is actually rho L/A, okay.

So delta R change takes place due to change in rho L and A, okay. So, delta R can be written in terms of all these changes as rho/A*delta L, L/A*delta rho and rho*L*differential of A, 1/A that is delta A/A square -. Now, there is one term one has to remember, delta L/L is actually the strain epsilon. Delta A/A is the change in the transverse direction and that you can put in terms of diameter as twice delta D/D.

So, we will rewrite this whole thing as delta R/R/R, when you divided it by R, what you will get will be delta rho/rho, delta L/L, -twice delta D/D. Now, in mechanics, you have got another parameter to remember that is the Poisson's ratio nu. When the subjective device to a stress, in the longitudinal direction, and you pull it, there will be a change in the lateral dimension, that change in lateral dimension is defined as the nu, so the ratio of this change in lateral dimension, to the change in the linear direction is defined as nu.

So if that goes up, the lateral it goes down, so that is the negative sign that is put, so what you do is substitute for delta D/D as –delta L/L that is –nu*epsilon, so put them altogether, you get G=delta R/R/epsilon, which is equal to delta times, delta rho/rho+, this is nothing but, delta L/L is nothing but epsilon, minus-minus cancel and plus twice nu.

Okay, it is dividing by epsilon that goes off. So here, nu is actually due to the change in the dimensions, delta L/L, okay. Now due to the physical dimension changes but the first time is due to the change in the rho. In metallic, piezoresistors, meaning change in resistance delta R/R takes place due to change in this physical dimensions, okay and delta rho/rho in metals is negligible. So in those metallic strain gauges, the gauge factor, which is actually first time is negligible, you get 1+2 nu, if I take nu as 0.5, this will be 2, 1+2*0.5 that is 1+1 that is 2.

So, you will get a gauge factor anywhere to 2 to 5 or so for metals. Whereas, in semiconductors, this term which is due to physical changes almost similar to the metal small 2 or 3 due to that the gauge factor, for delta/rho, delta rho/rho/epsilon is large quantity, that will be, so total number will be close to 100. So the benefit of using semiconductor resistors, is that the gauge factor that is the change in resistance due to the change in strain, will be extremely large compared to metal strain gauges.

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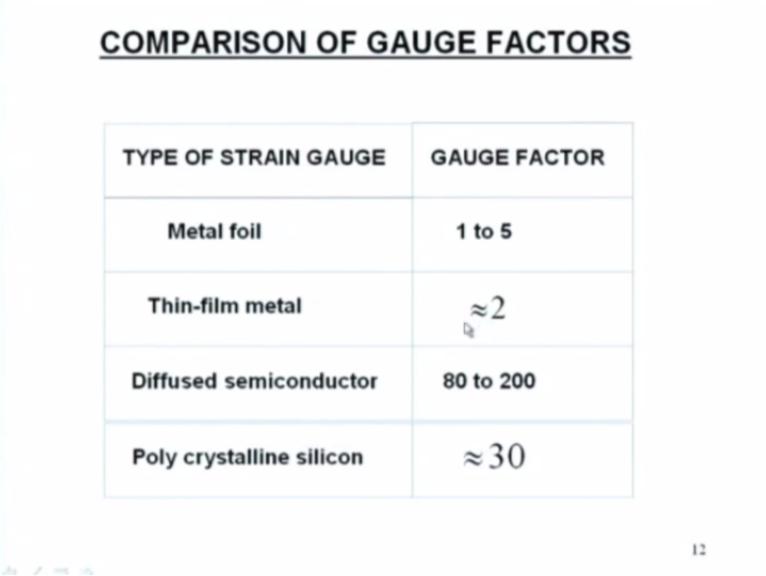

COMPARISON OF GAUGE FACTORS

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

Okay, to take a look at some numbers, a metal foil will have a gauge factor of 1 to 5, so this gives you an idea how much delta R/R for a given strain, so you can measure delta R/R, you can get information on the strain and if you obtain the information of strain, you can obtain the information on stress which can be correlated to the pressure. Thin film metals 2 is the gauge factor.

Diffused semiconductors that is single crystal it is 80 to 200, very large. Poly crystalline, that is not single crystal, made up of number of single crystal structures that is about 30 that is the gauge factor okay.

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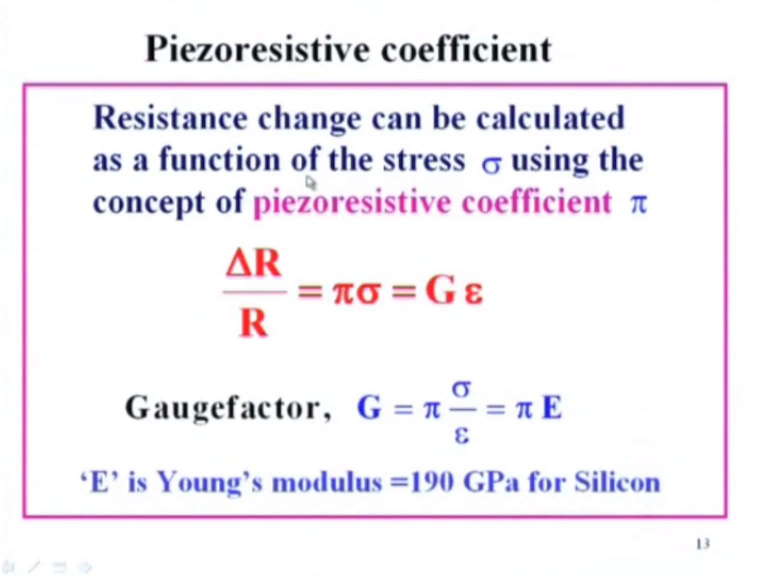

Piezoresistive coefficient

Resistance change can be calculated as a function of the stress σ using the concept of piezoresistive coefficient π

$$\frac{\Delta R}{R} = \pi\sigma = G\,\varepsilon$$

Gaugefactor, $G = \pi \frac{\sigma}{\varepsilon} = \pi E$

'E' is Young's modulus =190 GPa for Silicon

Now we take a look at further on the piezoresistive, see this term that I have introduced to you here is that gauge factor which tells you delta R/R related to strain, delta R/R by strain is the gauge factor. Now, there is one more term similar to the gauge factor, which relates the change in the resistance delta R/R to the stress, that is the piezoresistive coefficient, okay.

Delta R/R is related to stress sigma through this proportionality constant coefficient pi, pi is the piezoresistive coefficient, okay. Now, you recall, we define delta R/R as gauge factor G*strain and in this we define delta R/R as piezoresistive coefficient into stress okay. So you can define it, delta R/R with respect to stress through piezoresistive coefficient or delta R/R related to strain through the gauge factor, both are allowed okay.

You can remember one of them, you can correlate, because sigma/strain, stress/strain is called Young's modulus in a planned mechanics all of know that this is Young's modulus, so gauge factor is related to the piezoresistive coefficient pi through the Young's modulus sigma/epsilon and that is Young's modulus usually defined by a symbol E, do not confuse with the electric field but this is general symbol that is used E.

The gauge factor is related to the piezoresistive coefficient through the Young's modulus. Okay but without confusion, delta R/R is piezoresistive coefficient into stress or delta R/R is gauge pattern into strain. The Young's modulus is about 190 gigapascal for silicon. Gigapascal is 10 to power of 9 Pascal, one Pascal is one Newton per meter square.

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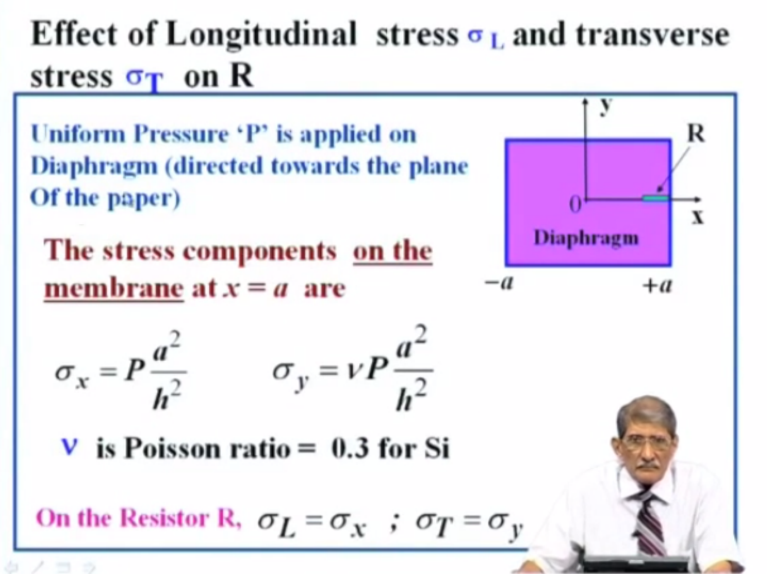

Effect of Longitudinal stress σ_L and transverse stress σ_T on R

Uniform Pressure 'P' is applied on Diaphragm (directed towards the plane Of the paper)

The stress components on the membrane at $x = a$ are

$$\sigma_x = P\frac{a^2}{h^2} \qquad \sigma_y = \nu P\frac{a^2}{h^2}$$

ν is Poisson ratio = 0.3 for Si

On the Resistor R, $\sigma_L = \sigma_x$; $\sigma_T = \sigma_y$

Okay, now let us take a look at further. The effect of longitudinal stress sigma L and sigma T on R. We will see where these resistors will be located, to further, supposing this membrane shown by color is subjected to stress perpendicular to that from the top, with the pressure P, whatever unit you say, if you say in Pascal, if you subject it to the stress, and from the analysis, you can see formula is available for you, to correlate this applied pressure to the stress at this edge of this membrane in that direction, X direction, okay.

If I put the resistor there in the direction, perpendicular to this edge of the membrane, that will be longitudinal stress that we are talking about stress in X direction is along the direction of resistor where the current flows that is longitudinal, so sigma X for a pressure P will depend upon the ratio of the membrane dimension, for example, if I take a square membrane or side to a, if I take at 0 at the center of the membrane, this is +a and other edge is–a.

So if 0 are the center, the stress at the edge here, near this edge of the membrane is applied pressure multiplied by a divided by thickness h whole square. H is the thickness of the membrane, okay. So you can see if the pressure is 1 Bar, 1 atmosphere, applied on to this perpendicular, the stress at the edge of this membrane is 1 Bar*a/h whole square, if 2a is 500 micron, that is the width or the side length of the membrane is 2a = 500 micron and if h thickness if 10 microns, 1 micron is 10 to the power of -4 cm.

So thickness is 10 microns, this is 250/10 is 25, 25 whole square is 625, so if I apply 1 Barr pressure for this membrane, perpendicular, the stress at the edge will be 625 atmosphere, 625 Bar and in a y direction, whatever stress is experienced there, x direction, multiple by the Poisson ratio, that is 0.3 times of that okay, for silicon is 0.3, it would depend upon the material, it will be of that order.

So on the resistant R, which is mounted like this, sigma L is P*a/h whole square, sigma transfer perpendicular for this direction along the length of the longitudinal is, if I have the resistor like this located, that the current will flow in that direction, you call that direction as longitudinal and perpendicular to that there is a width of the resistor so that is called transfers. So if I have a resistor located like this, longitudinal is P*a/h whole square, transfer is nu times that, okay.

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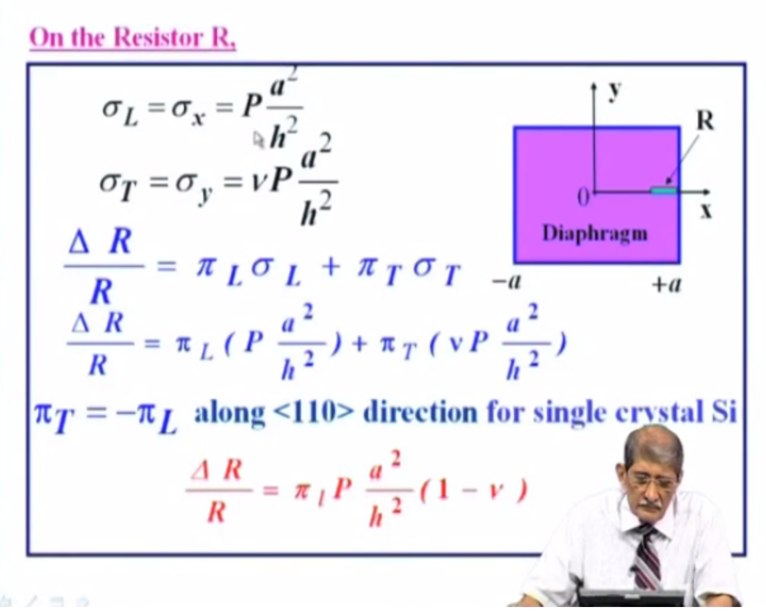

On the Resistor R,

$$\sigma_L = \sigma_x = P\frac{a^2}{h^2}$$

$$\sigma_T = \sigma_y = \nu P\frac{a^2}{h^2}$$

$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T$$

$$\frac{\Delta R}{R} = \pi_L \left(P\frac{a^2}{h^2}\right) + \pi_T \left(\nu P\frac{a^2}{h^2}\right)$$

$\pi_T = -\pi_L$ along <110> direction for single crystal Si

$$\frac{\Delta R}{R} = \pi_l P\frac{a^2}{h^2}(1-\nu)$$

Now, let us put this in terms of the piezoresistive coefficient, okay because for the material you will know how much is the piezoresistive coefficient or how much is the gauge factor you will know, so therefore we will see, sigma L is P*a/h whole square and sigma T is nu times P*a/h whole square, so that total change in resistance is due to the combined effect of these 2 which is longitudinal piezoresistive coefficient into the stress.

Notice delta R/R is somehow the effects of longitudinal stress and transfer stress, pi L*sigma L, longitudinal resistive coefficient multiplied by longitudinal stress plus the transverse value. Now delta R/R you can put it as now pi L*sigma L is P*a/h whole square plus transverse stress*nu*P*a/h whole square, okay. Now this pi L and pi T are opposite, for single crystal membrane, the pi transverse a negative of pi longitudinal because of simple fact that their longitudinal stress is increase the resistance or of P type, transverse stress will decrease that.

So that is why this is negative and take care of that, substitute to that you will get delta R/R is pi L*a/h whole square which is common and pi L plus pi T which is pi L*1- nu. So you can see the whole thing is pi L*P*a/h whole square is 1 –nu, delta R/R. so you can now tell very comfortably that if you know the delta R/R pi L would be you will know other dimensions are known, you can tell what the pressure is. That is how the pressure works.

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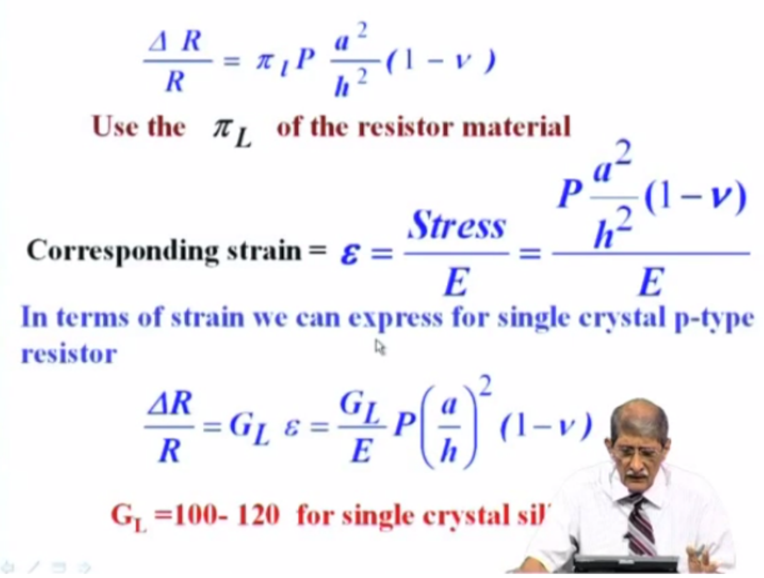

$$\frac{\Delta R}{R} = \pi_l P \frac{a^2}{h^2}(1-\nu)$$

Use the π_L of the resistor material

Corresponding strain = $\varepsilon = \frac{Stress}{E} = \frac{P\frac{a^2}{h^2}(1-\nu)}{E}$

In terms of strain we can express for single crystal p-type resistor

$$\frac{\Delta R}{R} = G_L\,\varepsilon = \frac{G_L}{E}P\left(\frac{a}{h}\right)^2(1-\nu)$$

G_L =100- 120 for single crystal sil

So delta R by now from here is pi L into pressure*a/h whole square, a is half of the width of the membrane size by h whole square*1 –nu, nu is Poisson ratio about 0.3. So we can express, this is in terms of the pressure resistive coefficient, you can express it in terms of the gauge factor also because you know that the pi L and GL are related through the Young’s modulus.

So it is just divide this by this entire thing is a stress divided by Young’s modulus using by strain so GL into strain gives me delta R/R, either way, this way or that way you can express it. The key thing is you must know the stress or the strain, stress divided by the Young’s modulus is strain, then you multiply it by GL or pi L, gauge factor or the piezoresistive coefficient.

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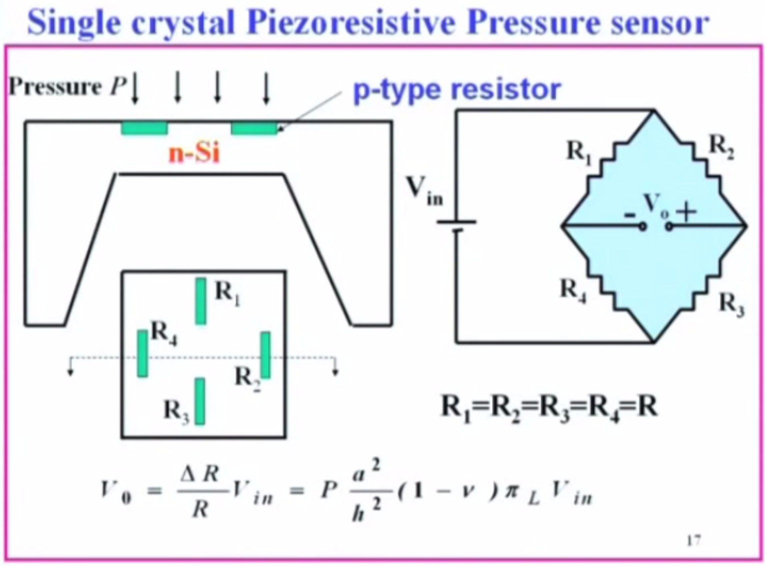
Single crystal Piezoresistive Pressure sensor



R_1=R_2=R_3=R_4=R

$$V_0 = \frac{\Delta R}{R}V_{in} = P\frac{a^2}{h^2}(1-\nu)\pi_L V_{in}$$

With that we have discussed with the definitions. Now let us get back to the single crystal piezoresistive pressure sensor, how it works. So you have already seen this, this is the membrane which is created as a cross section of the membrane which is prepared by etching silicon from these portions by the anisotropic etching which is already well known to you and on this membrane, I have shown 2 here, because if you see a top view, the membrane will be here and if I take the cross section here, I can see only these 2 resistors.

So the 4 resistors are located like this, R1, R2, R3 and R4 because at the edges, in the middle, at the edges the stress is maximum, longitudinal here, longitudinal here, transverse here, transverse here. That is the key thing. 2 of them should increase, other 2 should decrease, that is why you change source on the locations. So in this case, if all the R values are same, then you can put V0=delta R/R*Vin, we have said this number of times and delta R/R you can see here, we can measure V0 in terms of Vin, both V0 and Vin will be known, delta R/R is known.

From delta R/R you can determine what is this quantity is, okay you can calibrate it actually, you will see, for a given sensor, you find out what is V0 by Vin and computing delta R/R, you got V0 versus pressure then you will see, we will go and see into that. So delta R/R is measure of this entire quantity, okay. So, here this entire thing is the stress into the piezoresistive coefficient.

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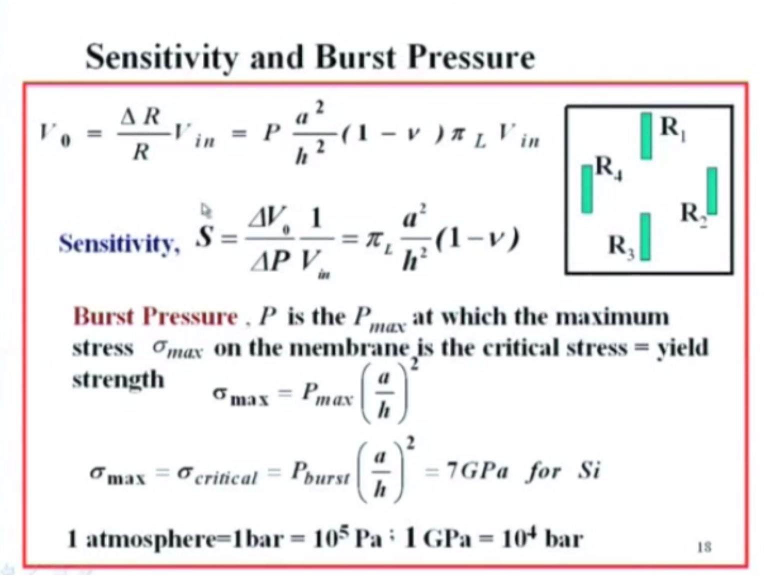

Sensitivity and Burst Pressure

$$V_0 = \frac{\Delta R}{R} V_{in} = P \frac{a^2}{h^2}(1-\nu)\pi_L V_{in}$$

Sensitivity, $S = \frac{\Delta V_0}{\Delta P}\frac{1}{V_{in}} = \pi_L \frac{a^2}{h^2}(1-\nu)$

Burst Pressure, P is the P_{max} at which the maximum stress σ_{max} on the membrane is the critical stress = yield strength

$$\sigma_{max} = P_{max}\left(\frac{a}{h}\right)^2$$

$$\sigma_{max} = \sigma_{critical} = P_{burst}\left(\frac{a}{h}\right)^2 = 7GPa \quad for \quad Si$$

1 atmosphere=1bar = 10^5 Pa ; 1 GPa = 10^4 bar

Let us take a look at the sensitivity burst pressure. What is sensitivity? Sensitivity is V0/pressure okay. V0 is delta R/R*Vin, which is P*stress, this is this quantity into input. Now in this term, you see the pressure P, so a sensitivity is delta V0/delta P, delta V0 depends upon delta P and of course for a given voltage, divided by that, so this is the quantity. That is pi L*a square/h square*1–nu, straight away that will give you.

So to tell you, in other terms, sensitivity will depend upon the material that you chosen, longitudinal piezoresistive coefficient and a/h ratio, a is the half of this side and h is the thickness. If you want to increase the sensitivity, choose for a given dimension, you may recall making the thickness less and less, it will become more and more sensitive, more output will be there for a given input voltage for a given changing pressure.

But there is upper limit on this sensitivity, that comes up from the burst pressure. See for example if I keep upon increasing the pressure on this membrane, the maximum stress is experienced at the edge which is applied pressure into a/h whole square. So I can go to a maximum pressure, at a particular maximum pressure, the stress at the edge will reach a maximum value which is the critical pressure, that is the point at which the membrane will yield, it will burst, okay.

So, that critical pressure is 7 gigapascal for silicon that is 70,000 atmospheres, okay. So the maximum pressure will be decided by when is the critical pressure is reached. So if h is smaller, this pattern will become larger and larger and for the given pressure, the sigma maximum will be reached at the lower pressure. So the maximum pressure that you can use will be less if the sensitivity is more.

So the guideline is thinner the membrane, your sensitivity will better, but the maximum pressure that you can use will be lower because it will be burst at a lower pressure, okay. But, can you go right into that maximum stress that is decided by what is the other upper limit?

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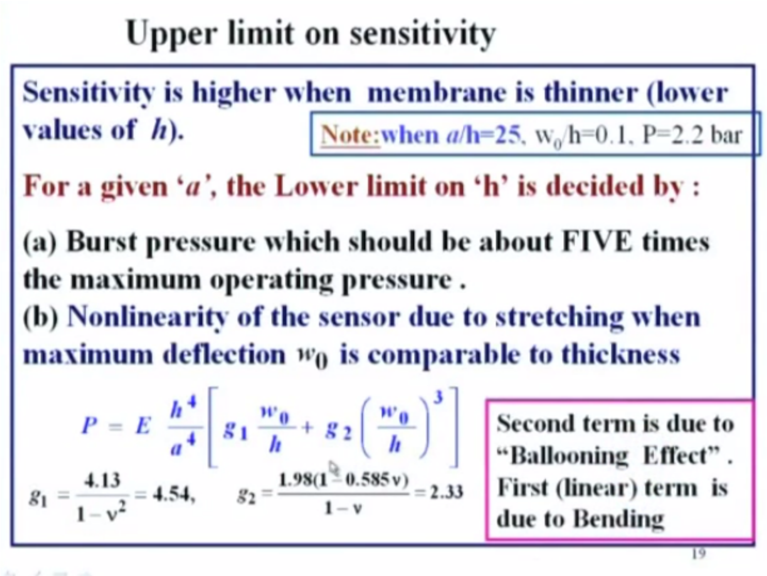

Upper limit on sensitivity

Sensitivity is higher when membrane is thinner (lower values of h).

Note: when $a/h=25$, $w_0/h=0.1$, $P=2.2$ bar

For a given 'a', the Lower limit on 'h' is decided by :

(a) Burst pressure which should be about FIVE times the maximum operating pressure .

(b) Nonlinearity of the sensor due to stretching when maximum deflection w_0 is comparable to thickness

$$P = E\,\frac{h^4}{a^4}\left[g_1\frac{w_0}{h} + g_2\left(\frac{w_0}{h}\right)^3\right]$$

$$g_1 = \frac{4.13}{1-\nu^2} = 4.54, \qquad g_2 = \frac{1.98(1-0.585\nu)}{1-\nu} = 2.33$$

Second term is due to "Ballooning Effect". First (linear) term is due to Bending

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See, there is a relationship based on the series of plates, the pressure is related to the deflection W0/h by this relationship, a/h is the membrane dimension okay. So, if I keep a constant, if I keep on reducing h, this equation tell you that first term is linear, W0/h is linear, if second term is negligible, the pressure and deflection are linearly related. So your delta R/R or the sensitivity will be linear function of pressure okay.

If you increase the pressure, the output voltage will increase linearly. Now if I keep on increasing the pressure, the deflection will become more and more; at a certain point, the deflection will become comparable to the thickness, for example, if the deflection is 0.1 times the thickness, that is if h is 10 microns, if the deflection is 1 micron, you can see the second term will become some factor, it become comparable to this first term about 10% of that okay, at the pressure of 2.2 bar.

In other words, you must stop using the sensor when the deflection becomes, W0 becomes comparable to the thickness, so for this example, where a/h ratio is 25, then at a pressure of about 2 bar it becomes, like second term becomes comparable to the first term, so that means you cannot use it beyond 2 bar, though your burst pressure will be much higher than that, you do not go on using until burst pressure, so the ultimate limitation comes up from this linearity concentrations okay.

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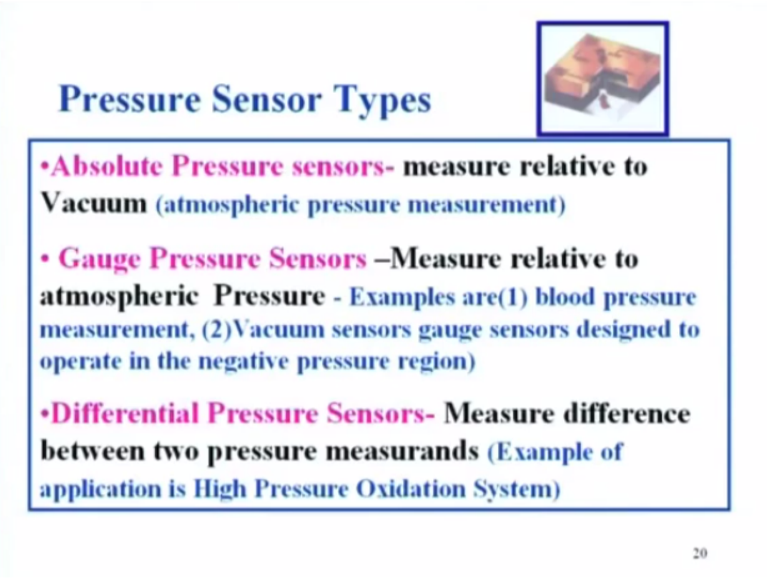

Pressure Sensor Types

- **Absolute Pressure sensors- measure relative to Vacuum** (atmospheric pressure measurement)
- **Gauge Pressure Sensors –Measure relative to atmospheric Pressure** - Examples are(1) blood pressure measurement, (2)Vacuum sensors gauge sensors designed to operate in the negative pressure region)
- **Differential Pressure Sensors- Measure difference between two pressure measurands** (Example of application is High Pressure Oxidation System)

Now, there are different types of pressure sensors, so one to understand this concept, we will take a look at the different types of pressure sensors. Absolute pressure sensors, you measure the pressure relative to vacuum, that means you have a cavity which is completely sealed and there is vacuum inside the cavity and the membranes gets deflected due to the external pressure that is absolute. You are measuring the pressure with respect to vacuum.

The second type of pressure sensor is the gauge pressure, you see in the gas cylinders you put a gauge, that gauge is measuring the pressure with respect to atmospheric pressure, so for example if the cavity is filled with 1 atmospheric pressure air, then whatever you see outside is over and above that pressure how much is the pressure, that is the gauge pressure. So it is called gauge pressure sensor if you are measuring for example blood pressure.

To measure the blood pressure relative to atmospheric pressure, so when you say the blood pressure is 80/120, during systolic and diastolic, that means it is 80 mmHg and 120 mmHg with respect to atmospheric pressure okay. So vacuum gauge, you measure vacuum, that is also a gauge pressure, with the respect to the atmospheric pressure how much it is, so you call it as minus, 10 to power of minus or -2, you see, that is the fraction of the atmospheric pressure.

Then, you have got differential pressure sensors, which measures actually the pressure on top and bottom, on both sides of the membranes, these are used when you want to monitor the pressure from both sides and you want to keep pressure constant across the membrane and if you want to vary the 2 pressures, inside pressure 1 bar, outside pressure 1.5 bar, the inside pressure becomes 1.5 bar, outside pressure also increase it by 0.5 bar, so difference is maintained 1.5, that is the differential pressure.

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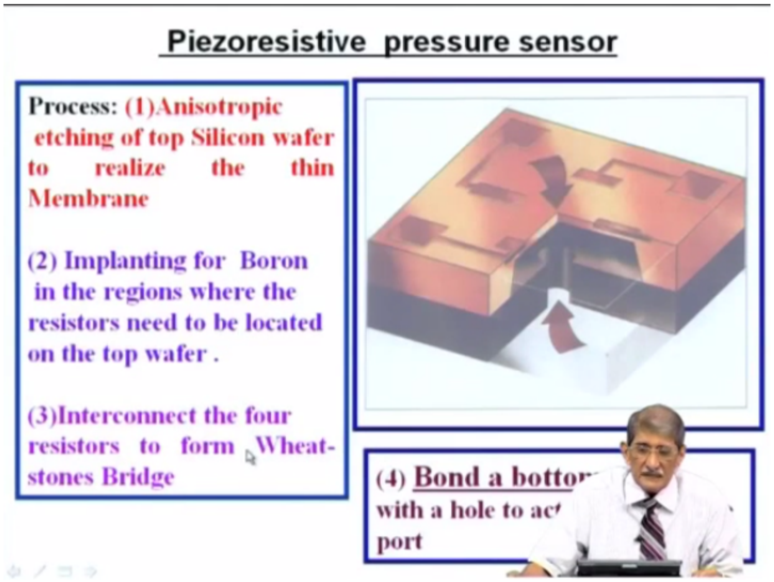

Piezoresistive pressure sensor

Process: (1)Anisotropic etching of top Silicon wafer to realize the thin Membrane

(2) Implanting for Boron in the regions where the resistors need to be located on the top wafer .

(3)Interconnect the four resistors to form Wheat-stones Bridge

(4) Bond a botto
with a hole to ac
port

Now, this is the piezoresistive pressure sensor which is 3-dimensional picture, you put this 1, 2, 3, 4 resistors, cross section has shown here, this is anchored in these portions, this silicon membrane is stuck to this glass in this edges so that this is rigid and this can only move, the way you make that is make a membrane, realize the resistors, okay, first anisotropic etching of the silicon wafer to realize the thin membrane.

Implant or diffuse boron, into these regions, to realize the resistor. Then, interconnect the 4 resistors to form Wheat-stones Bridge, then bond this glass on to this.

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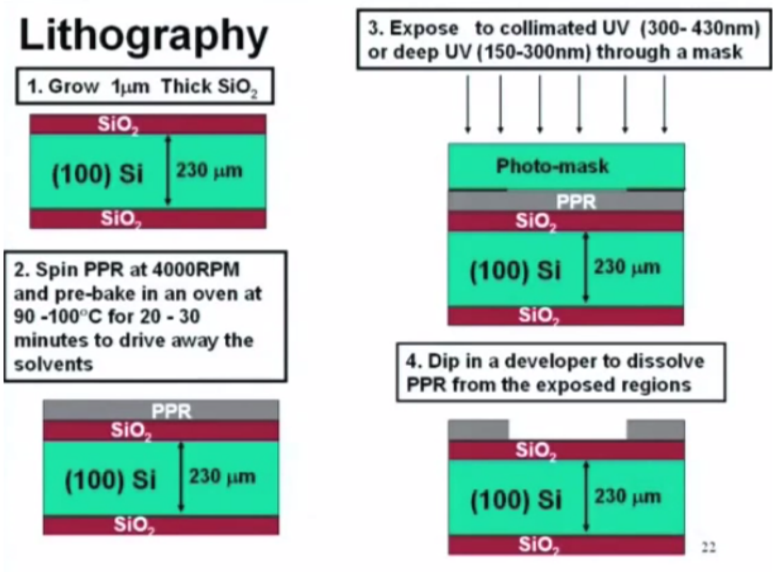

Lithography

1. Grow 1μm Thick SiO_2

2. Spin PPR at 4000RPM and pre-bake in an oven at 90 -100°C for 20 - 30 minutes to drive away the solvents

3. Expose to collimated UV (300- 430nm) or deep UV (150-300nm) through a mask

4. Dip in a developer to dissolve PPR from the exposed regions

Now to go through quickly, I do not have to this very detailed for you because you have done the lithography. So I have shown the cross section, take 100 silicon, that is 230 micron thickness, grow oxide, spin photo resist, export that photo resist through these are mask, photo mask, where there is a pattern here, so light can though this pattern, will get exposed here, positive photo resist, you can develop it, the photo resist is removed from here, so you got the photo resist here.

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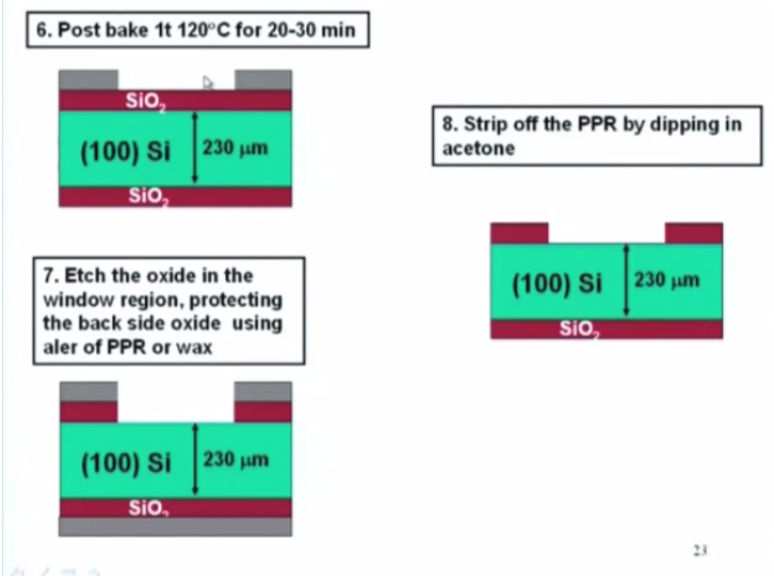

6. Post bake 1t 120°C for 20-30 min

7. Etch the oxide in the window region, protecting the back side oxide using aler of PPR or wax

8. Strip off the PPR by dipping in acetone

I show it once again here, I am quickly going though this lithography stills because you already know, so you have the photo resist here, we have removed the photo resist from here, post making etc., you do at 120, to harden the photo resist, then using the photo resist at the mask, these are cross sections, etch the silicon dioxide using dilute hydrofluoric acid, so you got the photo resist, below that oxide, this oxide is removed.

You protect the back side oxide because do not remove the photo resist, then after this, once you have etched this oxide, strip off the photo resist from both sides, starting from the oxide all over, you have ended up the oxide removal from here.

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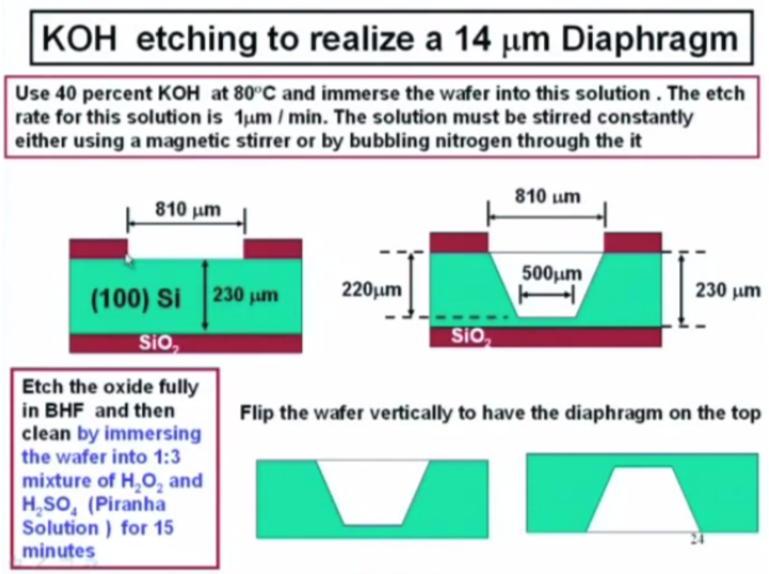

KOH etching to realize a 14 μm Diaphragm

Use 40 percent KOH at 80°C and immerse the wafer into this solution . The etch rate for this solution is 1μm / min. The solution must be stirred constantly either using a magnetic stirrer or by bubbling nitrogen through the it

Etch the oxide fully in BHF and then clean by immersing the wafer into 1:3 mixture of H_2O_2 and H_2SO_4 (Piranha Solution) for 15 minutes

Flip the wafer vertically to have the diaphragm on the top

Now this one you put it in the potassium hydroxide etchant, so in this portion you can etch silicon and from your knowledge of this KOH etching you will see that it will go in this direction, controlled by the 1, 1, 1, plane, if you etch up to 220 microns, the size left out here is 500 microns, but you etch to 220 microns, you can calculate the size of this opening here is 500+220/0/.7 that is 810 microns.

So, on the design what you have to do is, in the pattern, you must design 810 microns pattern size, when you have that pattern open and etch it to a depth of 220 micron, you will end up with a membrane of thickness if this is a 230, 10 micron thickness and 500 micron immersions. I strip off this oxide, you will get this, okay and flip it upside down, you get the membrane. This is the cross section.

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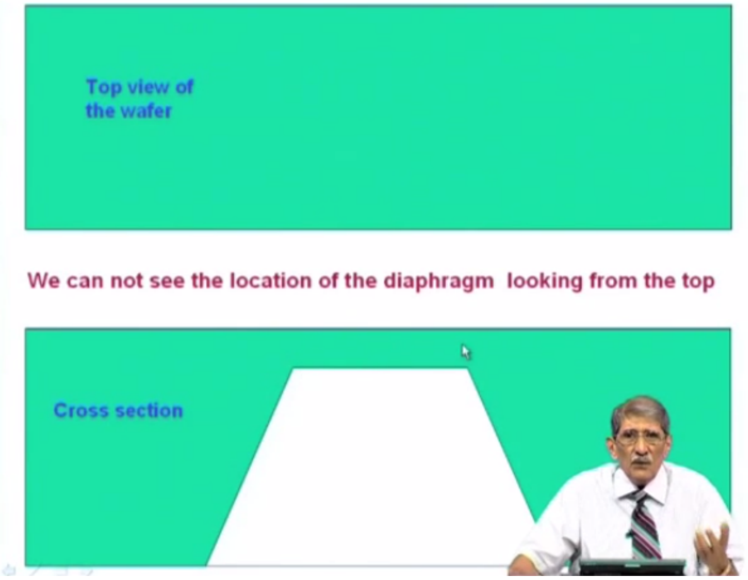

Top view of the wafer

We can not see the location of the diaphragm looking from the top

Cross section

Looking at the top of this, if you look at that, I am showing one device, number or devices will be there on the wafer, I am showing you one part of the wafer, that will look like this, nothing will be seen. The cross section is like that, so you have to put the resistors in top of this membrane, for that you may do lithography. From the top when you see, you will see where the membrane location is.

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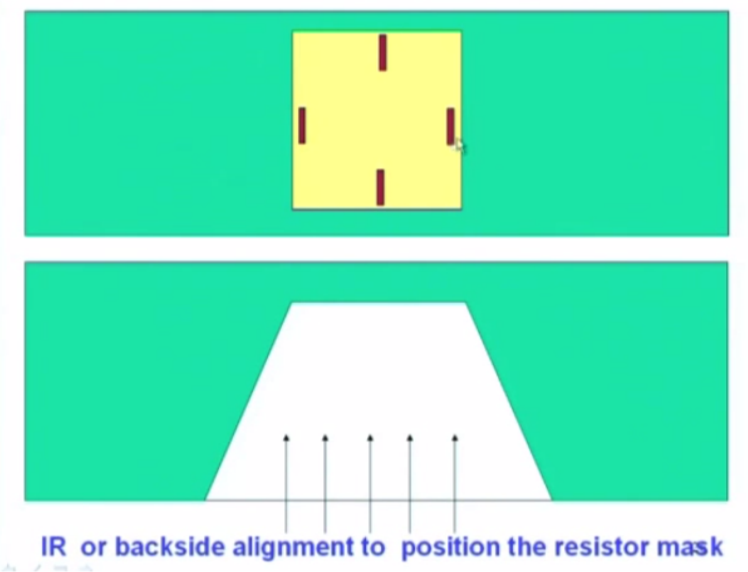

IR or backside alignment to position the resistor mask

One way of doing that is shine infrared light, IR light, from the backside of the wafer, then you can see this particular thing transparent like that. Because IR can go through from bottom and if you put a video camera on the top, you can see this membrane, okay. And then by lithography technique from the top, you can realize you can grow oxide open window in the oxide in these portions and diffuse resistors here, that is the technology part of it.

Okay, you can put the resistor in this portions and then you can make connections between the 2, so this is IR lithography, or you can have a machine where you can have facility for backside aligning using storing the backdoor pattern on the backside and ability to see from the top.

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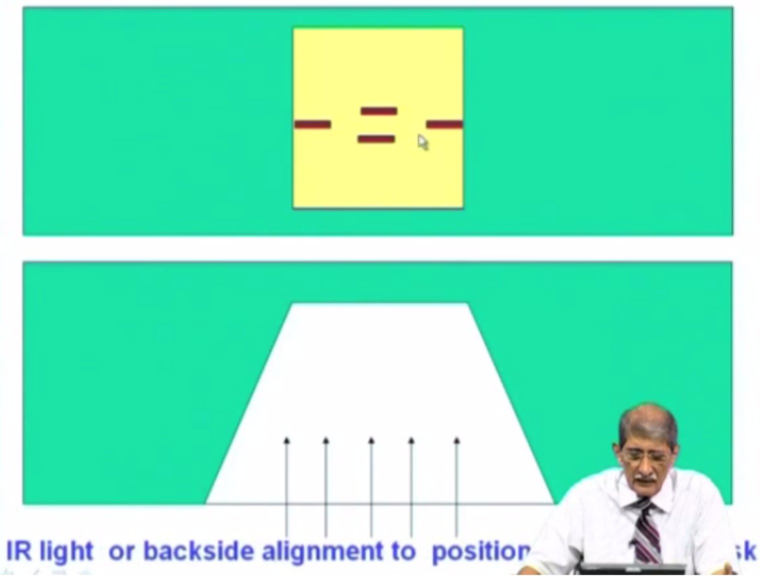
IR light or backside alignment to position

So, you can put that resistor like this or like this, either way, here this will experience longitudinal stress, tensile stress, these 2 transverse, here, these 2 will experience longitudinal and tensile stress, these 2 will experience longitudinal compressive stress, these 2 will go up and these 2 will go down. Here, these 2 will go up and these 2 will go down in value.

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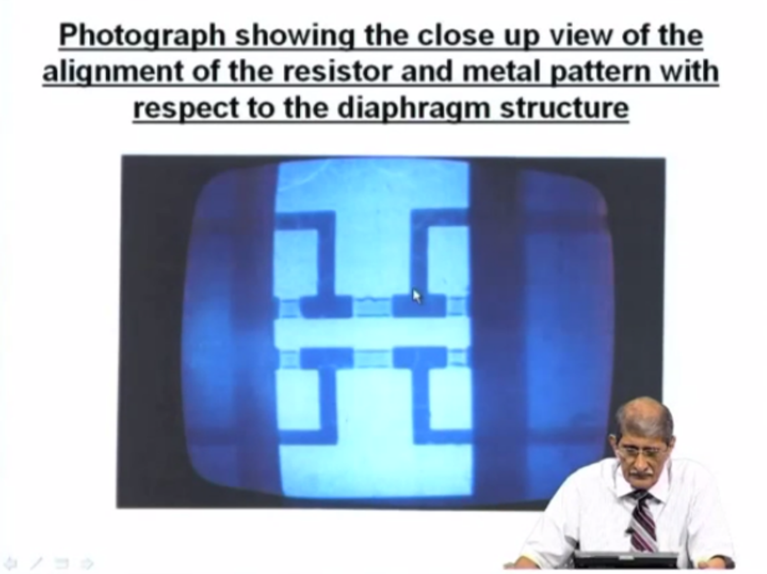

Photograph showing the close up view of the alignment of the resistor and metal pattern with respect to the diaphragm structure

Okay, now we will see from the IR aligner, this is what you will see, this is the membrane is, these are the resistors which you can see, so you precisely see where to locate these resistors, just I have taken the photograph from the video camera.

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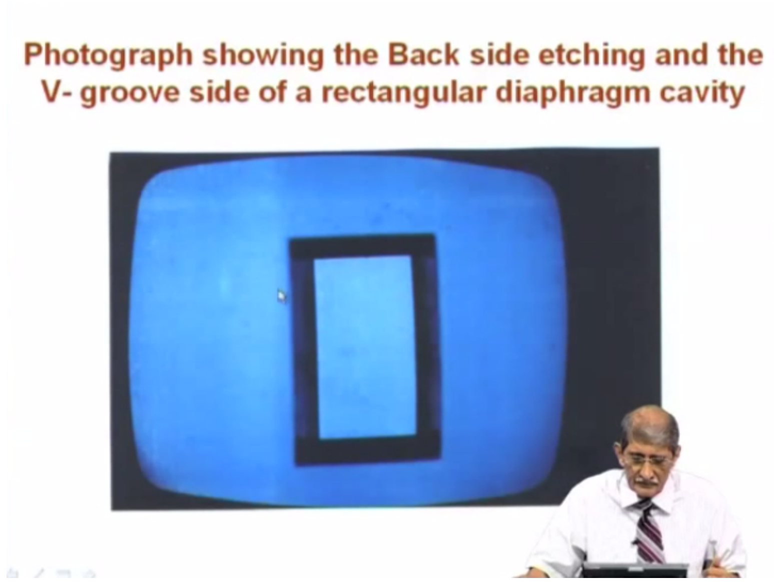

Photograph showing the Back side etching and the V- groove side of a rectangular diaphragm cavity

And if you look at the backside of this membrane, look from that side not IR, through microscope you see that is how it will look. This is the etched, this is the sloping side and because it is sloping, when you see under microscope, this portion looks dark because light will not be reflected there. When the light is not reflected, it will look dark.

So this is the bottom of the etched portion, that is the membranes looking from the back side, this is the top of the wafer from the back side okay. So, couple of things I want to point out here, this particular thing I just kept that, see you can actually either do IR exposure or throughout this pattern focusing from back side, store it on the video camera, then look from the top, have a pattern on this side, align them together, then you can bring this resistor in their side, that is the another way of doing that.

Anyway, what I am trying to point out is if you do not have the ability to align these resistors, with respect of these portions, that will move away from this membrane, and that will not experience the stress okay.

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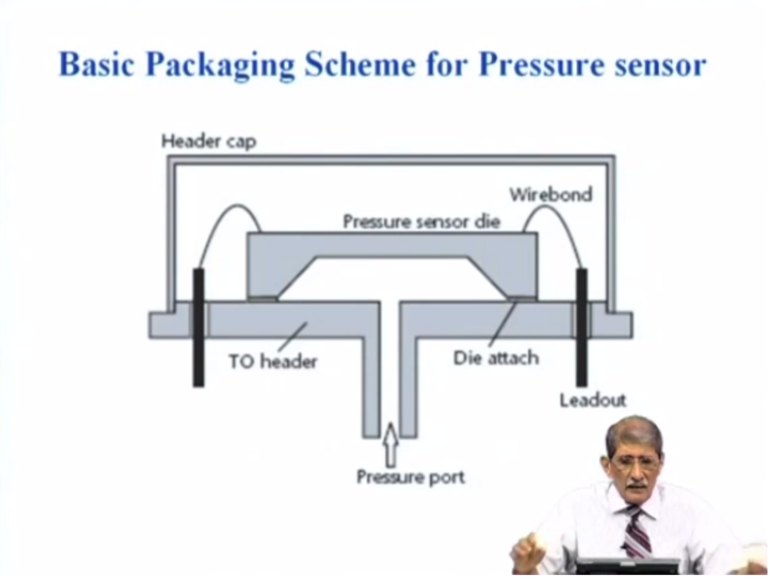

Basic Packaging Scheme for Pressure sensor

Now, part of this thing is the how to package this. I have come almost to the end of my discussion today, because the more details about these we will discuss in the next sessions including the packaging. See what I have shown here, is the cross section of the one device okay and I have not shown the resistor here, resistor is kept on the top, somewhere here, it is there and the wires are there on the top, that are not shown.

So what you do is you mount this dye on header, this is actually a thick metal plate which is gold plated onto that you can mount this either by a technique known as the eutectic bonding that is just keep the silicone in contact with this gold plated plate and just heat the temperature to about

400 degree centigrade. The gold gets leached into this silicone to form an alloy of gold and silicone.

That alloy is a continuous transformation from gold plated material to silicone, so this pressure sensor dye will be rigidly held to this header, metal plate by this bonding or you can solder it, there is an alternate way, so once you mount it on that, see this cap would not be there at that point, you will have this header, on that you have mounted this, then in header itself there were will be leads.

In my next presentation, I will show those full details of those leads, the leads going through this holes through this header and this is metal, this is metal, in between them there is some insulating material, so that there is no sorting between the header and this wire, this lead metal, this is a thick metal. So using a machine, there will be a pad on this region, okay, you can bond wire onto this so using a machine called the wire bonding machine, take the other end of the wire which is just about 25 microns, take it an bond onto this, you can do this by ultrasonic bonding.

The ultrasonic bond is actually you have the wire bonded here then taken to the other end here and just you mount it on that point, that will be vibrated like this. When we vibrate it, any little oxide that may be present on the surface will be removed, these wires will be either aluminum or gold wire, okay and this post will actually be gold coated.

So, when you, just hold it onto that and vibrate it like that, local temperature will rise and there will be a plastic flow, it will be just bonded onto that. If you take 2 surfaces, just rub it like that, the local temperature will rise and it will bond, that is the trick that is done here. There is no solder is being used, so one end of the wire is bonded here, other end is taken and bonded onto the other end.

So with that, you have mounted this dye and all the wires you have connected to the 4 bond parts of this piezoresistors connected here, then you have to close this, so that from the outside atmosphere of the cap and this resistor, I am sorry this is actually completely sealed so the pressure on the other side of the membrane is not changing, you can change the pressure by means of this opening here, you can apply pressure through this.

So the membrane can deflect on this side. Okay, there are more of these details in my next lab presentation, you can see, okay.

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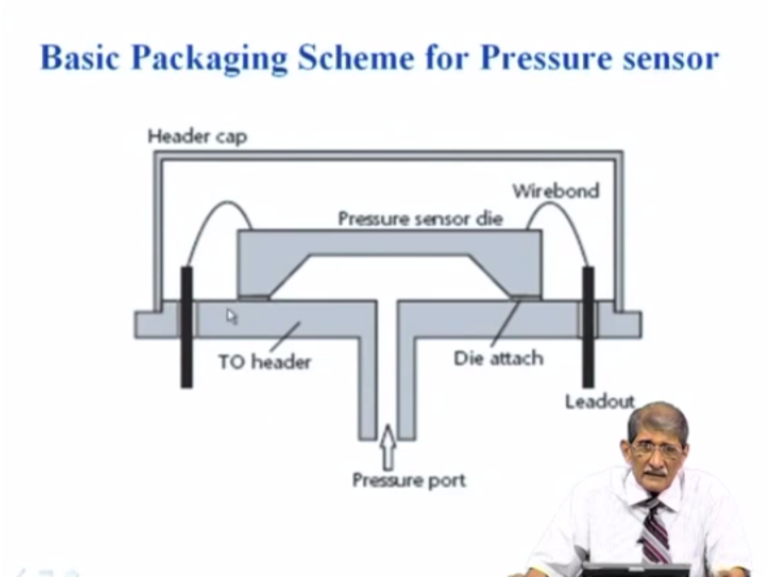

Basic Packaging Scheme for Pressure sensor

Now other way is actually you can also use instead of mounting it directly like this, first mount this on a glass plate and the glass plate is attached onto the header through this.

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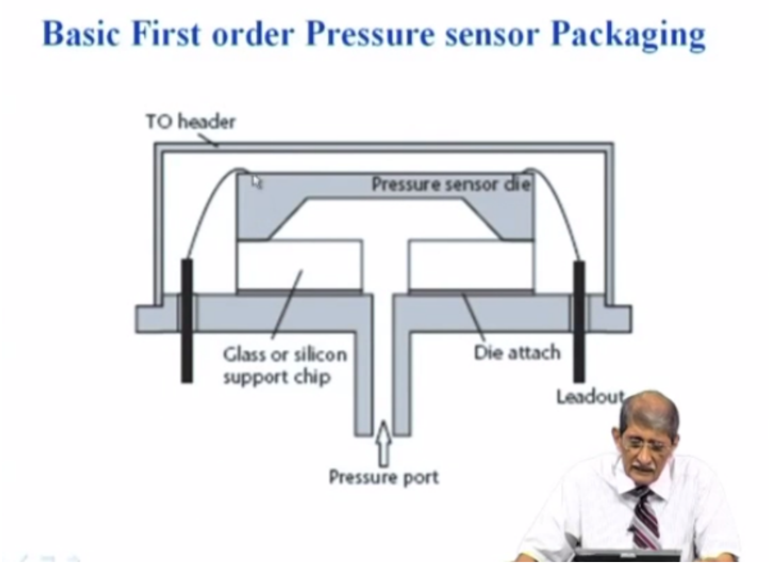

Basic First order Pressure sensor Packaging

This is just bit more sophisticated technique compared to this. Now to see here, more of this, I will just take you through some other region, the top of this particular, this is I am not showing the die here, you can see the die is put on this, the die will look like this, for example, you will have, see here, these are the bond pads, this is the resistor and the wire is connected on the top out surface of this wafer itself, that is a pad onto which you will do wire bonding.

You will do the wire bonding on to that and take it out from their outside, okay, you bond it onto that and take the wire out from there, bond onto the post on the header, so this is what I mean by bonding pad. So this is what is shown here, one pad is there, resistors are located on the membrane, from the bond you can connect to this one.

So with that I think I will close my discussion today, we will continue on this, on a particular case study of pressure sensor with more details of this, making use of polysilicon piezoresistive pressure sensors. Thank you.