A Brief Introduction to Micro Sensors

Dr. Santanu Talukder
Department of Electrical Engineering and Computer Science
Indian Institute of Science Education and Research, Bhopal

Lecture – 18
Pressure Sensor – II

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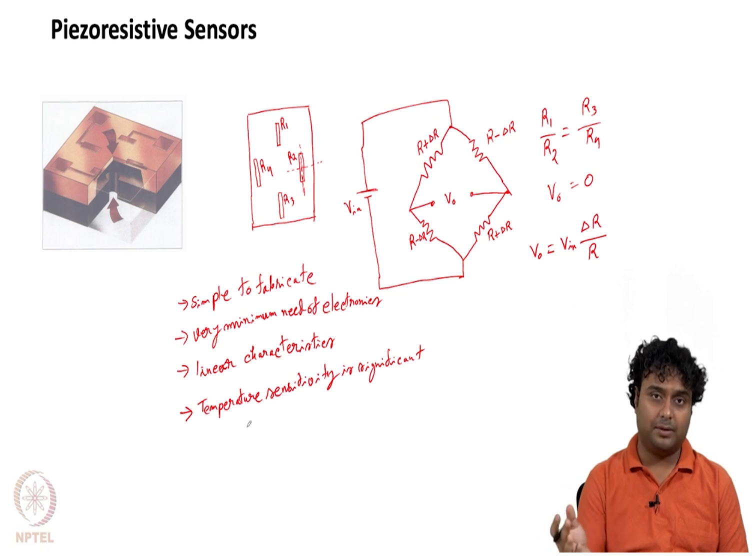

Hello. So, today, we will talk on piezoresistive sensors. So, the last two sensors like Pressure Sensors we discussed is one is piezo electric sensor and another is capacitive sensor, and now we are going piezoresistive kind of sensing. Here I have put a picture of usual kind of a pressure sensor like a piezoresistive pressure sensor and there you can see that this is the top side is the membrane right, you can see the cavity here. So, below this top layer the there is no material or this is empty.

So, this is like a membrane or and the pressure port is from here right, you can see the pressure port from here. So, any gas which pressure we need to measure will come through this port and then that will apply some amount of pressure on this membrane which will then bulge. It will be like a paper right if you like a balloon. So, this like this let us say you have this kind of membrane. You can think this paper sheet as a membrane and then it is clamped at all the edges.

So, all the four edges it is clamped and from bottom some pressure is coming from the whole membrane right. So, accordingly it will bend or bulge now we have put four different resistors which are not simple resistors these are piezoresistors. What does it mean? Means it changes its resistance when it is under some kind of stress or strain. What is stress? Stress means that if we apply some force then what is the force per unit area that is the measure of stress right.

And, then what is strain? Strain is like any amount of deflection part unit length or per unit area like that right. So, any kind of deflection from its original amount that is strain. So, if this membrane is under stress then it will bend or bulge and then it will be under it will there will be a strain also right. And, this four resistors so, one is this and then you can see how half this resistor and this resistor.

So, this all this four resistors will be under the pressure or the stress and because of that that resistivity will change. If we see that top view of the membrane then the resistors are put like this. So, let us say this is the top view of the membrane and then you have resistors like this, like this, like this ok. So, let us say these are four resistors which are like R 1, R 2, R 3, R 4 let us say.

Now, this arrangement and the placement of resistors are important and how these are important that we will come in few slides because the stress is at different region of membrane is different ok. And, also whether the resistor is under tensile stress or under a compressive stress accordingly this resistance changes also different and also whether it is stress is across the axis of the resistor along the length of the resistor or it is along the breadth of the resistor according to that also resistance change varies. So, this things are important.

Now, these resistors are connected like a Wheatstone bridge circuit. So, I hope that all of you have already know what is a Wheatstone bridge circuit which is actually taught you in 12th standard. So, in the Wheatstone bridge circuit you have four resistors connected like this. This is let us say one resistor ok.

So, these are the four resistors and then we apply some amount of voltage and measure the output voltage across these two junction. So, let us say this is the input voltage and this is the V naught or output voltage. So, let us say now I put the resistance names R 1, R 2, R 2, R 3, R 4. So, let us put this resistances R 1, R 2, R 3 and R 4.

Now, according to Wheatstone bridge principle if R 1 by R 2 is equals to R 3 by R 4 then the bridge is balanced; that means, the voltage at this point and this point will be same. So, V 0 will be 0 V 0 will be 0. And, from this Wheatstone bridge circuit if we apply in the normal Kirchhoff's current law or voltage law then we can show that according to if we change any of the resistance then accordingly the voltage output voltage will change.

So, for our piezoresistive circuit what we will do, we will use the same Wheatstone bridge we will use the same Wheatstone bridge, but we will use all the same resistors; all the resistance values are R now. Now, in this case the bridge is balanced; that means, that the output voltage will be 0 because R by R equal to R by R right.

This resistances or the piezoresistors are placed in such a way that because of some kind of a pressure or applied stress both the opposite resistors will have same kind of change means that if this resistance increases by delta R, then the. So, this is let us say R 1 and this is R 4.

So, if R 1 increases by delta R then R 4 will also increase by delta R and R 2 is increases by like decreases by delta R, then R 3 will also decreased by delta R. So, say this is has because of some kind of pressure pressures because of some kind of pressure it resistance has changed to delta R. So, then the other resistance the opposite resistance of the bridge will also changed by delta R.

The other two resistance are designed such that this resistances will decreased by the same magnitude; that means, this resistance will decreased by minus by delta R and this resistance will also decreased by delta R. And, in this case we apply Kirchhoff's current law or voltage law from our basic electronics then we can show that the output voltage V naught will be equal to V in into delta R by R.

So, these R what we are putting the resistance of the piezoresistances we already know. This V naught is what we will measure and V in is what we are applying because this is the battery we have put in the circuit, so, we know how much is the V in. So, we know V in, we know R we measure V naught and then we can get the value of delta R get the value of delta R. So, once we get the value of delta R then delta R is related to the deflection of the membrane.

So, we can back calculate the deflection of the membrane again deflection of membrane is related to the applied pressure. So, then we can measure the pressure. So, what are the advantages of this circuit? Advantages will be like it is simple to fabricate, then very minimal use of electronics, many minimum need of electronics, linear characteristics.

But, one important disadvantage or limitation is temperature sensitivity. So, these circuits are simple to fabricate because we can actually make piezoresistor by doping the silicon membrane itself so, that we will come later. And, then we need very minimal use of electronics because at the output voltage you can easily use and then we can maybe we can use some kind of a simple amplifier to amplify the output signal and accordingly we can measure.

This is linear characteristics. Linear characteristics means we can see that the output voltage linearly varies with the change in resistance. So, that is also one advantage and what another. One limitation of this technique is temperature sensitivity it means that the whether the resistance of the piezoresistors or sensitivity towards strain towards the stress or strain is all these things are dependent on temperature.

So, if we design that a sensor for a particular temperature it is difficult to keep the same characteristics for some very different temperatures also ok. So, this kind of temperature sensitivity is not appreciated.

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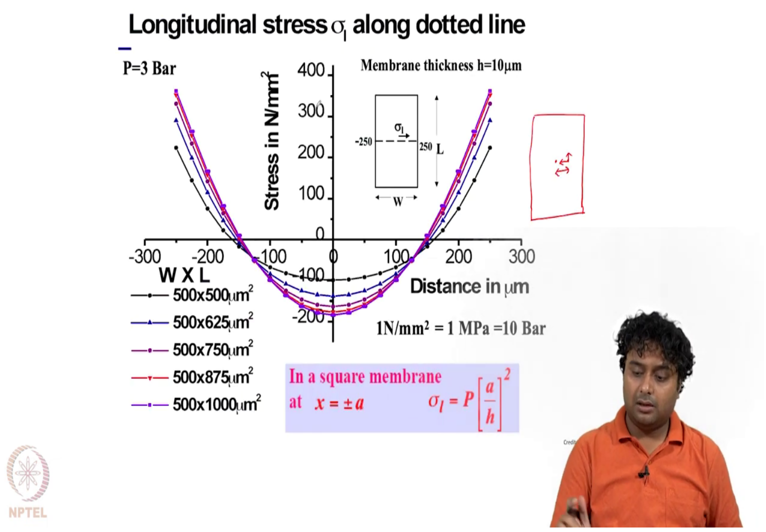

Now, we will show the stress distribution on the membrane. So, membrane is not a simple case like what we have a studied in module 1 and 2 for cantilevers etcetera, cantilever or simple beams; then in that case we have actually calculated stresses at different points right and what is the deflection or what is the stiffness constant but, in case of membrane stress is different and in different position of the membrane.

So, as it is shown in this graph so, as it is shown in this graph that this axis is the distance; is the distance shown in micrometer. So, let us say this is the membrane this is the rectangular kind of membrane and then you have you are like moving along this axis right moving along it is; along it is width. So, this is center, there the here somewhere will be the center and then you are going to let us say 250 micron on this side and also 250 micron on the other side.

Now, if we measure the stress at different different point in on this line then you will get very different stress response. So, you will see that the at the edges the stress will be high, and then as you move towards the center stress starts decreasing and then after certain distance somewhere here it will go to the negative side; that means, here it is tensile stress where here it is compressive stress right.

So, here it is tensile stress and here it is compressive stress and then competitive stress becomes become maximum at the center of the along this line at the center of the membrane then if you move towards the another the other side of the edge then it is it again starts increasing and somewhere it crosses 0, and then it will again have positive stress value; that means, it is tensile stress.

So, we are not like a derivation of this curve or the actual expression derivation of the actual expression of pressure of the for this curve is not a part of this course, but you can actually intuitively understand this phenomena it is like this. So, this is the membrane and which is clamped at the edges right and the middle part or rest of the part is free to bend or move.

Now, as it moves towards let us say upper side or lower side whatever it is, now as it bends or moves then this side as it is clamped the stress will be maximum because here only it is trying to pull the membrane it is like balloon. So, if you can consider it is like a rubber membrane like a balloon you have bend at the edges and then you are applying some pressure from the bottom.

Then what will happen that at the edges where it is clamped there will be maximum tensile stress right because it is trying to move away from that fixed junction, but that material whatever is moving that is trying to accumulate at the center right and then here it will be compressive stress. So, as you move away from the fixed junction the stress becomes smaller and smaller and then you at the center you have more stress more like a more compressive stress.

And, for the like simple case you can write this equation that for a square membrane at any distance which is x from the center let us say which is x equal to plus minus a, the tensile stress will be P equal to a minus a by h whole square. So, here if you think to here if you think we need to understand that is this is distance from the center. So, let us say I am at a distance a. So, I am at this point ok. So, this is my a.

So, at this point; at this point tensile stress or the longitudinal stress is P by a P into a by h whole square ok. So, towards the center; towards the center so, in so, as you know that stress is a the a vector right. So, it has different direction. So, let us draw the picture. So, as you understand for this membrane if I take this membrane like this and then this is my center let us say and I am measuring the stress at this point. So, this is the distance a from center.

Now, at this point the stress will be adding all the diff all the directions right. So, it will be have it will have one component here in this direction as well as in this direction and these two components are not same. This sigma l is the longitudinal component and that it is saying that it is towards this direction and what is the transverse component?.

So, that, we will come later but for this direction it is sigma l into sigma l is equal to P into a by h whole square. And, also as you can see this is not a simple expression and with changing the different with changing the membrane dimension it also changes like it becomes if it becomes from 500 cross 500 to 500 cross 1000; that means, from square membrane to rectangular membrane the stress characteristic with distance also changes.

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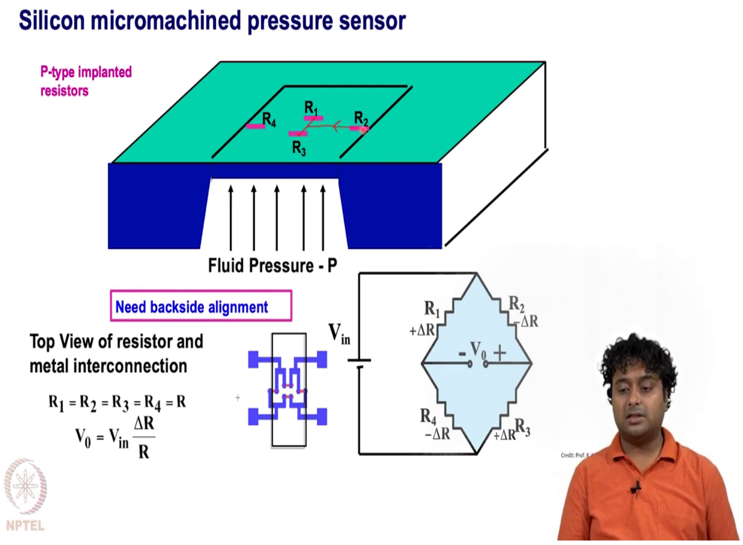

Now, as I was showing so, this is the membrane this is the like the device or the pressure sensor and then this part is which you which can freely vibrate or deflect. So, this is the membrane and then on top of that we have put this four resistors like R 1, R 2, R 3 and R 4 and fluid pressure is applied from the bottom and then accordingly the membrane will deflect.

And, as we have seen in the last slide that according to the pressure or according to the distance from the center there will be for the same pressure there will be different different stresses right and then accordingly this resistances will change. Now, as we put this resistors in such a way that R 1 and R 3 will have same kind of so, you see the position of R 1 and R 3. So, these are like symmetric from the center and the arrangement is also like that it will have;

it will have the same kind of deflection because it is under the same stress. So, like here for let us say this R 1 if we draw; if we draw the line center is somewhere here.

Now, the radial direction for R 1 and R 3 both are this right radial direction is like towards the center. So, this is like this line is going through the center. So, center is somewhere here. Now, the arrangement is like that the stress towards the center is transfers for both R 1 and R 3 ok, but this R 1 this R 2 and R 4 for R 2 and R 4 if you see then this stress which is towards the center this is actually longitudinal stress for R 2, but the, but at this point this is actually transverse stress for R 1.

So, R 2 and R 4 with the so, R 2 and R 4 are with the same kind of stress direction ok. So, if the resistance changes it will have the same sign; R 2 and R 4 both will be negative let us say and for R 1 and R 3 both will be positive and of the same magnitude because it is from the same distance from the center.

And, as you have seen the stress versus distance curve it is also symmetric across the center. So, at a distance let us say a 50 micron from one side and 50 micro on the other side have the same sign of the stress and also same magnitude. So, that is why the resistances are put like this. Now, this we have already told that then output voltage will be equivalent will be equal to V in into delta R by R.

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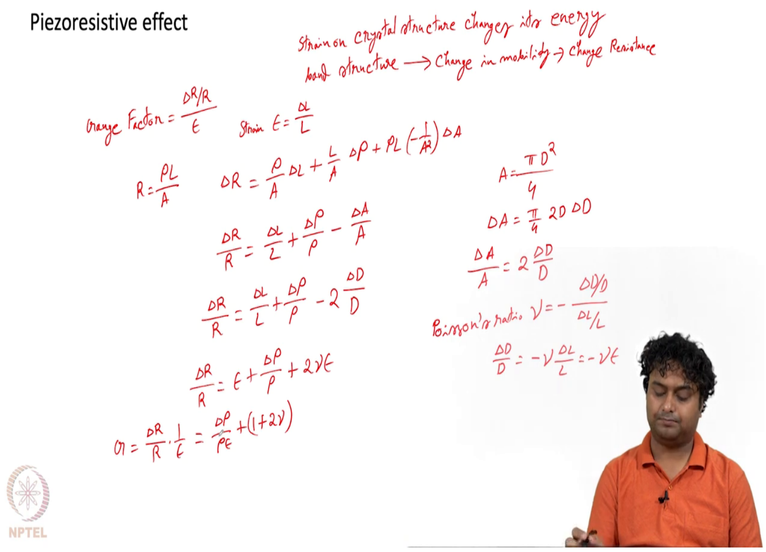

Now, till now we have discussed that how placing on a different region or different domain of the membrane have different kinds of stress and accordingly the resistances will also change. Now, how the resistance and the stress is dependent, resistance change and the stress is dependent so, that we will discuss in the piezoresistive effect.

So, what is piezoresistive effect? So, what happens is the stress or strain on crystal structure. So, whatever is your piezoresistive material let us say it has some crystal structure like it is usually single crystal silicon doped with some p-type or n-type material and accordingly it has a crystal structure. So, strain on crystal structure changes its energy band structure.

Because of this energy band structure change we have change in the mobility; mobility of carriers like electrons or holes and that actually change resistance that change resistance.

Now, one important parameter in this context is gauge factor; gauge factor. What is gauge factor? Gauge factor is measure of change in resistance with respect to the strain right.

So, what is the change in resistance? Change in resistance is delta R, but for different R value it is also different right because ultimately what we are interested in it how much percentage of R is changed right. If we are using 1 kilo ohm and if we are using 2 kilo ohm resistance then both the cases delta R will be different. So, gauge factor is measured by what is the per unit change of resistance. So, that is delta by R for unit strain that is epsilon and what is epsilon that we have already discussed before right epsilon is equal to our strain and that is delta L by L where delta L is the original length of resistor.

Now, from basic physics or electronics we know that R equal to rho L by A, where rho is the resistivity, L is the length of the resistor and A is the area cross sectional area of the resistor right. Now, let us assume this is a like a cylindrical resistor or a like an wire circular wire and then. So, A will be something like pi D square by 4 like if D is the diameter of the wire and L is the length of the wire.

Now, what is the how on each of these parameter actually R is dependent on each of this parameter. So, for that what do we need to do we need to take first derivative of R with respect to all this parameters. So, then we will get delta R equals to. So, it will be like let us say first we are taking with respect to L. So, for that we can consider rho by A constant. So, delta L plus let us say with respect to rho.

So, in that case L by A we can take outside and then this is delta rho and then with respect to 1 by A which respect to A. So, if we do derivative with respect to A then we will get rho L will be constant 1 by A will become minus 1 by A square into delta A. Now, if we calculate ultimately we need delta R by R.

So, if we calculate delta R by R so, that is we divide by rho L by A then we will get delta L by L rho by rho by A will cancel out delta L by A L plus delta rho by rho minus rho L by A if we consider then it will become minus delta A by A and here. Now, so, rho L by A rho L by A will cancel out.

So, it will become delta A by A now A equal to let us say pi D square by 4 where D is the diameter right. So, delta A will be pi by 4 into 2D into delta D. So, delta A by A will be equal to 2 into delta D by D. Then we can write here that delta R by R equal to delta L by L plus delta rho by rho minus 2 delta D by D, where L is the length of the wire or the resistors, rho is the resistivity of the resistor and D is the diameter of the resistor.

One concept I suppose that you have already you already know that is if we elongate any wire like a if I elongate this wire let us say then it is length increases right. So, if the length increases, then the diameter have to decrease because otherwise material will not be conserved right because you are not actually adding new material in that all you are not changing the density let us say then in that case diameter will sync accordingly.

So, what is we see that diameter will also decrease as we increase the length right. So, this is related by Poisson ratio related by Poisson ratio Poisson. Let us call it nu and nu equal to minus of delta D by D divided by delta L by L. So, the ratio of change or the strain of in the diameter divided by strain in the length and there will be a minus sign definitely because if the length increases if delta L is positive then the diameter decreases that is delta D is negative.

So, there is a there will be a negative sign. Now, so delta D by D can be written as minus of Poisson ratio into delta L by L equals to minus of Poisson ratio into epsilon because delta L by L is epsilon right. So, here we can right now a delta R by R equals to delta L plus delta L by L that is our epsilon plus delta rho by rho and then. So, it will be minus minus will become plus 2 nu epsilon.

And, gauge factor; gauge factor G equals to delta R by R into 1 by epsilon right delta R by R divided by epsilon. So, this will become as delta rho by rho epsilon plus 1 plus 2 nu. So, this epsilon is the strain that we can measure or we will know, nu is the material property that also we will know and then delta rho by rho rho also we know. So, accordingly we can just measure the epsilon and can like can calculate the gauge factor.

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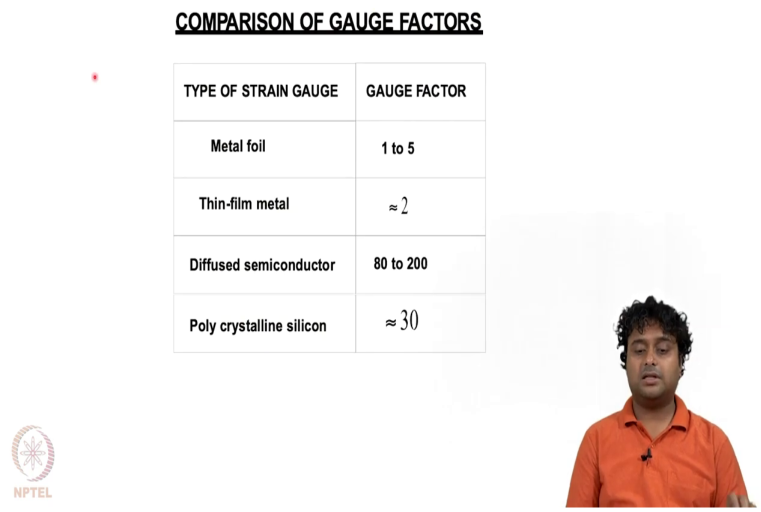

This gauge factor is a measure of like how much is the will be the change in resistance per unit strain ok. And, depending on the material this delta rho value like the resistivity value or the epsilon and the nu all this things changes and accordingly gauge factor also changes. So, for like metal foil it is about 1 to 5. So, it gauge factor is not very high ok.

Thin film metal – so, there is a difference between metal foil and thin film metal because metal foil are still the thickness will be like a few 100 micron or so, whereas, thin film metals can be even few nanometers. So, in that case the metal film has very less very low gauge factor around 2. Diffused semiconductor – diffused semiconductor means let us say p-type doped silicon or n-type doped silicon they have a high gauge factor of 80 to 200.

And, polycrystalline silicon; polycrystalline silicon means which silicon is deposited by severity technique and or by some other technique; it is not single crystal silicon rather it is a poly crystal silicon in that case gauge factor is about 30. So, diffused semiconductor this is mostly used or doped silicon is mostly used for even poly crystalline silicon is also used for making piezoresistive pressure sensors because the high gauge factors.

So, same amount of strain if we use a dope semiconductor then it will give a much higher amount change in the resistance or in the resistivity of the sensor whereas, if we use a like thin film metal or metal foil then it will be way much lesser.

So, this is the advantage of doped semiconductor that the gauge factor is very high. However, there are some advantages of metal also the like the metal films can be in case of metal film the signal to noise ratio is lesser or metals have low resistivity. So, the amount of current will be higher, but we cannot use those advantages because the gauge factor which is our prime requirement that itself is pretty small for metal film. So, that is why we use doped semiconductor. Like in this picture we are showing p-type implanted resistors so, this resistors are p-type doped.

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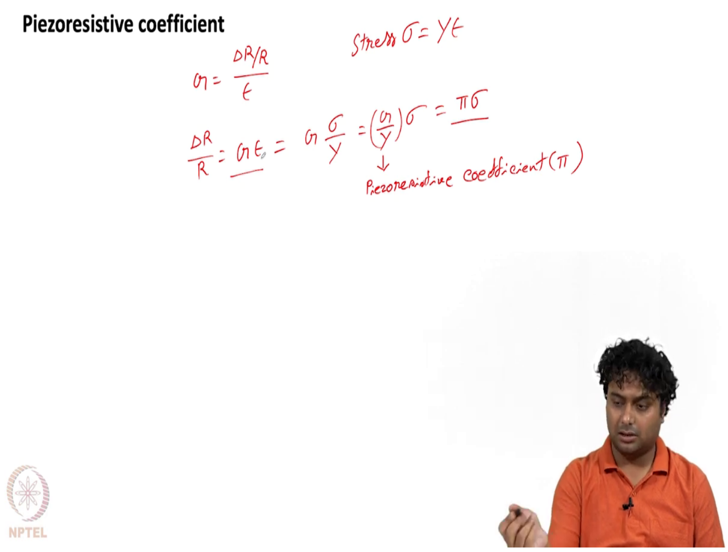

We have seen that gauge factor G is equals to delta R by R divided by epsilon ok. Now, this epsilon is a our strain. Now, stress and strain is related Young's modulus and stress sigma is equal to Young's modulus let us say if it is if we set that to Y then sigma by sigma by epsilon is equal to Y or Young's modulus.

Now, if we put that then we can write that delta R by R is equal to G into epsilon is equals to G into sigma by Y. So, sigma by Y or Young's modulus is our epsilon right so, can be written as G by Y and into epsilon into sigma. These G by Y this term that is gauge factor by Young's modulus this called piezoresistive coefficient piezoresistive coefficient and we can call it pi. So, it can be written as pi sigma.

So, delta R by R can be written in terms of a gauge factor and strain as well as piezoresistive coefficient and stress and for a piezoresistive element we will know either the gauge factor or the piezoresistive coefficient and accordingly you can calculate what should be the delta R by R if we can measure the epsilon and or the sigma that is the stress.