Micro and Smart Systems
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Lecture – 36
Signal Conditioning Circuits and Integration of Microsystems and Microelectronics

Okay, we talked our discussion on Signal Conditioning Circuits which we were doing last time, we continue on that and we will also discussed integration of microsystems and microelectronics because after all this are mechanical structures which are realised to sense or actuate and also electronic circuits, microsystems will consist both of them. Now we are going to see is how do we put them together, that also we will discuss here.

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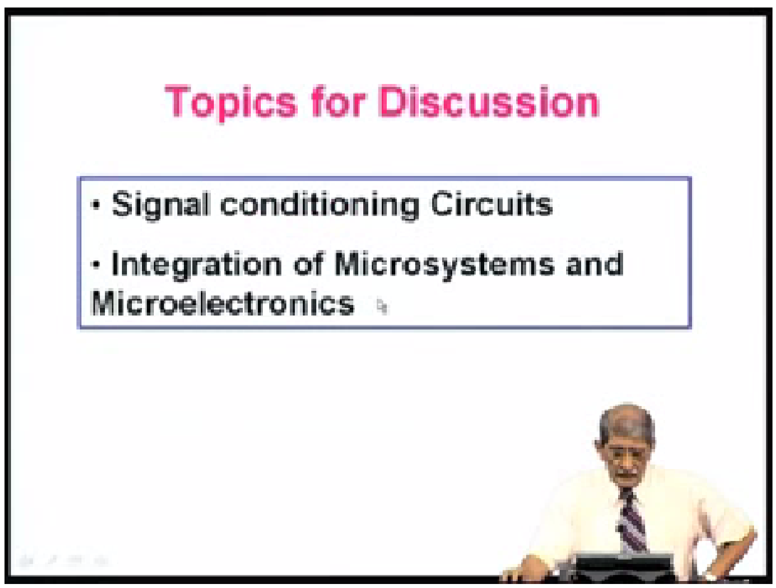

So the topics of discussion today will be signal conditioning circuits, integration of microsystems and microelectronics.

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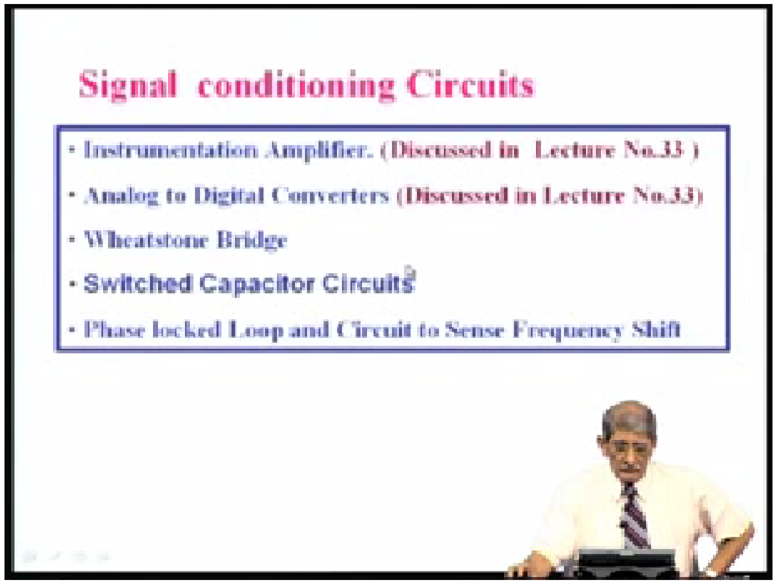

Now under the signal conditioning circuits, we have already discussed instrumentation amplifier in our last lecture no. 33 and also analog to digital converters, ADC, this also we discussed in our lecture no. 33. So today under heading signal conditioning circuits, we will discuss Wheatstone Bridge which is very useful in piezoresistive sensing devices like piezosensors and even in accelerometers.

We will also discuss switched capacitor circuits which is used for sensing outputs from capacitive sensors like capacitor accelerometers or capacitor piezosensors. We will also discuss the phase locked loop circuit to sense frequency shift which will be useful in many of the vibration circuits, vibration devices.

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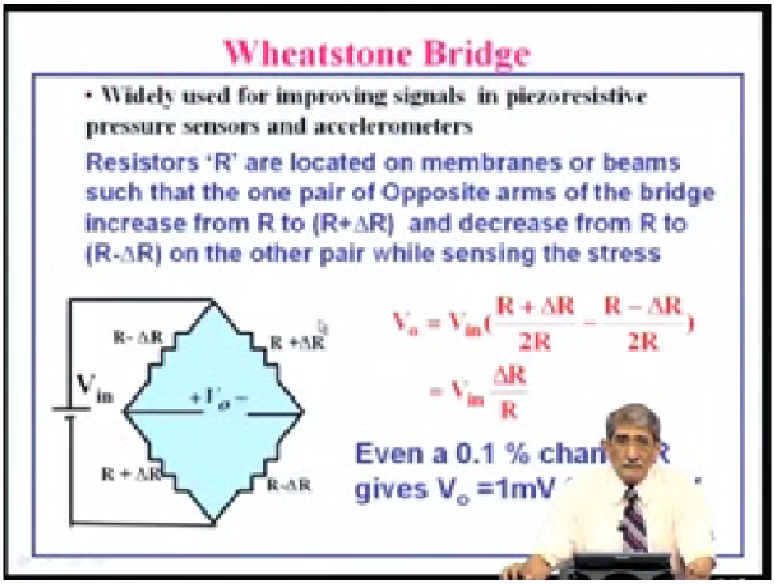

So first we start of with the Wheatstone Bridge. It is very widely used for improving signal in piezoresistive pressure sensors and accelerometers. After all piezoresistive sensor is resistor whose value changes when it is subjective to stress, okay. Now after the change in resistance is so small that it will be difficult to measure the resistance as it is. For example, if there is a1K resistor and if it changes just about 1 ohms due to the stress, you can hardly measure that change, 1 in 1000, that is very difficult.

So to take care of that aspect, Wheat-stone Bridge is used. Here 4 resistors are connected, they are located on the membrane or a beam such that these locations are ranged such that the resistors on the opposite arms, here, this arm and this arm, on the opposite arms of the bridge increase from R to delta R, R+delta R and on the other opposite arms, it will decrease from R to R+delta R. here it is R+delta R and R+delta R. On the left hand side, here, this R will be delta R and R by this delta R.

Other quiescent conditions that is when there is no stress on the membrane, all the 4 resistors are equal to each other, they are 1 kiloohms, normally its value will be used. So while sensing the stress, these bridges become unbalanced because R will become R+delta R, this also will increase, these 2 resistance will form. They are located in such places that these change takes place and the delta R are taken it to be equal in all the cases. It need not necessarily be equal, okay. So we apply voltage Vin and is no stress, output voltage taken across other 2 terminals is 0.

So due to this stress experienced by the membrane, that stress is transfers a strain on these resistors and the resistance value changes. Now looking at this bridge, we can see that the output voltage in the unbalanced condition will be Vin into this voltage minus that voltage, voltage gets at this point a, this point right-hand side point is b, I have not written b but a and b, let us say. So voltage here on left-hand side is actually equal to Vin divided the sum of the 2 resistors which is 2R multiplied by this resistor which is 4+delta R.

So the left-hand side voltage is Vin and the R+delta R will take over this divided by the sum of the 2. If the voltage is better and voltage on the right-hand side is actually sum of the resistors is R+delta R+R-delta R which is 2R and voltage across this will be input voltage divided by the total resistors, 2R, multiplied by the resistance which is R-delta R that is what I put here. So V0=Vin*R+delta R divided by 2R-R-delta R by 2R which simplifies to Vin*the R R cancels and it 2delta R/2R which is delta R/R.

Therefore, V0, now you can see V delta R*V input, now you can see. If delta R changes by 1%, that is R is 1K and if delta R is 1 ohm, this is 1/1000, the resistant was -3, so input is 1 volt, output is 1 volt*1/1000, that is 1 millivolt. So that is a measurable quantity. If I have 10 volts input, it will be 10 millivolts output. So that is a measurable quantity, okay. So that is the benefit of using Wheatstone Bridge.

Now let us take a look at the location of these resistors, in fact we will have very detailed discussion on pressure sensor in subsequent lectures but today, I will just give the principal.

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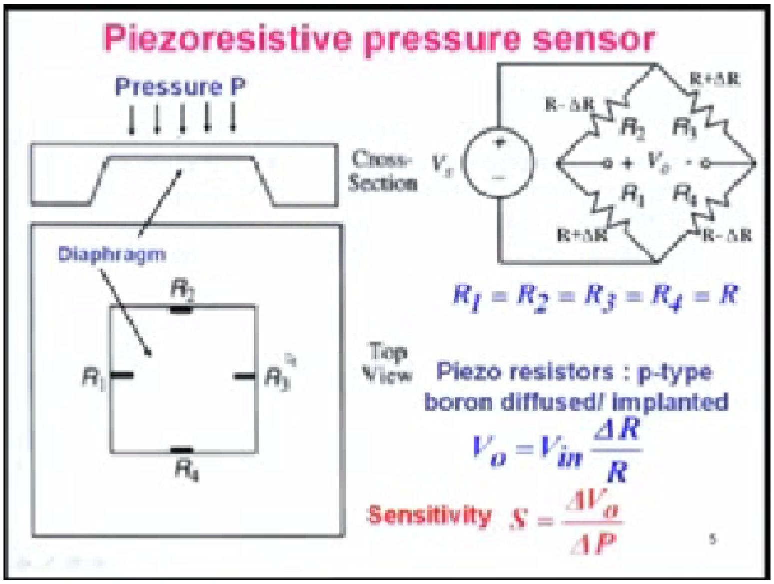

Here, this is a bridge, I have shown it as R1 R2 R3 R4, in fact all of them are equal to R. Just to distinguish between the 2 resistor locations, I put them R1 located here then R2 here, R3 here, R4 here. R1 R2 R3 R4, okay. Now we can see, this is the membrane, may be 10 microns thickness of the membrane, dimensions may be something like 500 micrometer by 500 micrometer. This is look at the top, this is the membrane location, membrane which is may be 500 microns by 500 microns.

Now this membrane is made up of silicon in micromachining and you remember technology course lectures, you have gone through these, If I can etch through this and reduce the thickness by using what is known as anisotropic etching. This will be 1 1 1 plane and this will be 1 0 0 plane. So if I etch it down in a controlled way using potassium hydroxide etchant to get the thickness of 10 microns or 15 microns or whatever you will like to have and what is the thickness etc. decided by the design criteria and which we will discuss in our subsequent lectures.

So now focussing on the location of the resistors. You see the membrane, okay. This quadrant brain is subjected to stress from the top that is perpendicular to the membrane, okay from the top into the plane of this paper if I subject it. There will be stress, maximum stress will be at the edges that is why I located this R1 R2 R3 R4, all of them at the edges where as for given pressure, the stress is maximum at the edges and the center of the edge but R1 and R3, will experience longitudinal tensile stress.

That means it will get pulled out, it will get stretched, as a result of that if it is a p-type resistor when it is touched, this is also a diffuse resistor, when it is touched, the resistance value increased by delta R. That is why I put here R1, R1 will go up by delta R, R3 also will go up by delta R and R2 experiences transverse stress, that it gets stretched in the lateral direction perpendicular to this length.

It will be stretched in this direction, that means in the transverse direction when it is stretched, it experiences the strain, it is the traverse strain or transverse stress and then effectively you can look into task the area increase, (()) (10:07) is the change in resistance, area increases resistance decreases, so these 2 resistance will decrease that is R2 and R4 will decrease.

In fact, in a piezoresistor, you will see that it is not only the area increasing that is the rho also changing that contributes with any resistance that part we will see when we go to details of the pressure sensor, okay. So because of the tensile stress here, these 2 will increase, transverse stress and longitudinal stress because of transverse stress, R2 and R4 decrease, therefore, these pressure sensor works.

So if in a p-type resistor, you will have V0 will be equal to delta R/R*V input. For the sensitivity of this pressure sensor will be given by delta V0, change in resistance due to a change in pressure by delta P that is the definition of the sensitivity. So more about this pressure sensors, we will see later when we go into the design in to the case study of a pressure sensor.

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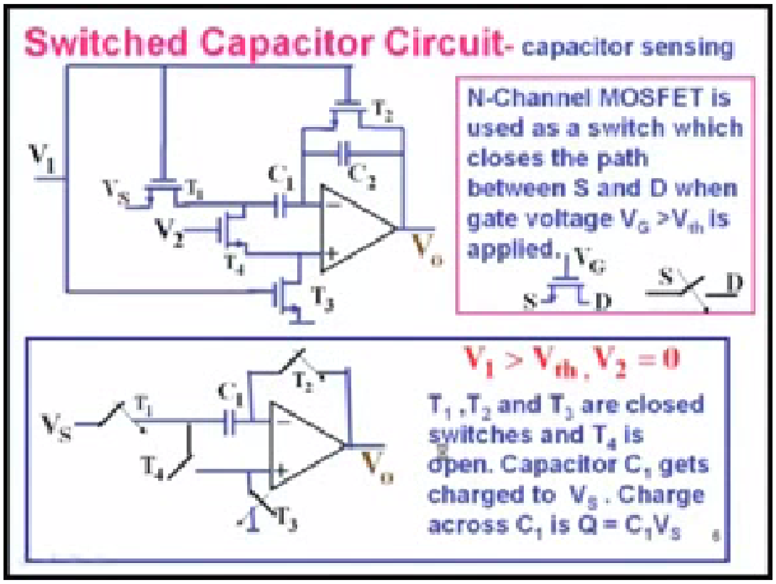

Now let us take a look at another circuit which is very useful for capacitive sensing devices. When you take a look at it, it looks complicated, it is not at all complicated. But all that is done is there is an off on care to the inverted terminal, you connect a capacitor C1 and between the inverted terminal and the output terminal or capacitor which is C2.

C2 may be the capacitance that we want to measure which is output of a capacitive sensor and C1 is a known capacitor. Ultimately what we are doing is comparing the C2 with C1 in terms of the signal voltage. How it is done is by charging this capacitor C1 first by means of V OF S and transferring, okay, the charge is capacited by means of V OF S, the charge across C1 will be C1*V OF S.

Now if that is completely transferred out to the C2, the charge across the capacitor will be same as C1*V OF S but here you will see that it will become C2 times V0. So both of them are equal. C1 and V OF S are known, okay, V0 you can measure, so C2 can be measured. That is the principal of that. Here it is done by means of the switched capacitor circuit. You can see transistor T1 T2 T3, all of them have their gates connected together to a voltage V1.

That means whether I apply voltage V1, that is actually gate voltage to T1 T2 T3, whenever I apply voltage to T1 greater than this threshold voltage, minimum voltage required to make the switch on, that is V threshold, VG greater than threshold voltage Vth, the T1 T2 T3, they are acting switchers, so they will close as soon here.

T1, T2, T3, they are switches and apply gate voltage, then the property in the source and drain will be complete that means the switch is closed. You can see T1 T2 T3 are shown as closed switches when V1 is greater than threshold voltage but V2=0, when V2=0, this switch is open, T4 is open and T3 is closed that means the circuit now is path is like this to V0 and this is connector ground.

So T3 is connected to ground because of the switch, that means voltage here is 0, as we have seen earlier in the inverting circuit, if the plus terminal has got voltage 0, since the difference between the 2 voltage is practically 0 or negligible, this voltage also will be 0. So on the other side of the plate C1, the voltage is VS; on this side, it is 0. So capacitor C1 gets charged to a voltage VS, so charge across that capacitor C1 is C1*voltage VS. Q=C*V, okay, so Q is C1*VS across this, okay.

Now, at this point, the output in such will be 0, because this is connected to this point. This is just charged. Next what we do is, open all these 3 switches whichever was closed, that is I reduced this voltage V1 to 0 and apply a pulse or voltage to V2. When V2 is applied, T4 closes and circuit will be like this.

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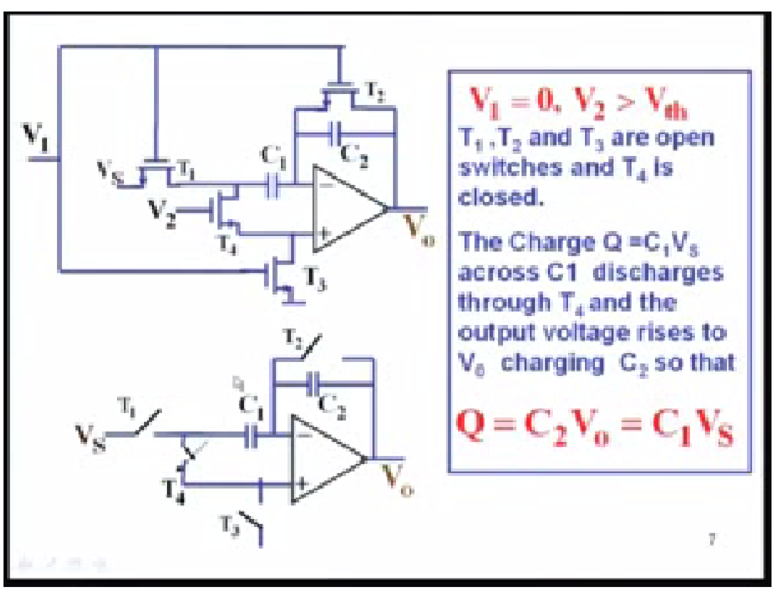

So same circuit I have shown here. All that you do is T1 T2 T3 are open that is now voltage is applied to V1 but V2 is, we apply voltage greater than threshold voltage, therefore, V2 will be closed. Now we can see what we have is, this is open, at the end of the first phase as I turn off V1 and when I turned down V2, the remain T4 was closed, at that instant there was a voltage charged, C1*VS across C1 that was charge.

Now once this is closed, this capacitor discharge is through this terminal to the plus terminal, that means this plus, if we apply into this and immediately the output voltage starts rising, going towards higher value, then the entire charge is transferred, this output voltage reaches the value V0 where C0*V0 is equal to the charge deposited on this capacitor and if C2V0 is the charge deposited, that has come from this capacitor C1 that is C1*VS. So output voltage rise to a value V0 till C2*V0 is equal to C1*VS.

What we are telling is by closing the switch, the entire charge through this positive terminal has got transferred on to this capacitor C2, okay.

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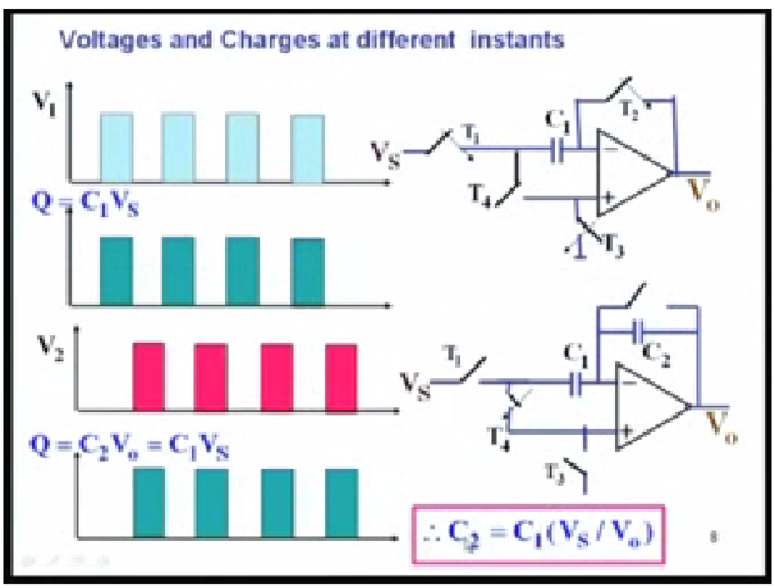

So if I know the value of C1 which is a known capacitor and VS is a known signal and I can measure V0 and I can get the value of C2 because of this relationship. So now C2=C1*VS/V0. Everything else on the right hand side is known. I can measure C2. So this is used in the capacitive sensing, accelerometers or pressure sensors.

To investigate whatever I have discussed earlier now, we go through that. V1 in this circuit, V1is applied for these 3 switches are closed and then C1*VS is a cumulative deposited on this capacitor so long as V1 is present, that is like this, okay. V1 is that one, the charge is here corresponding charge is C1VS, C1VS, C1VS everywhere else if nothing happens. But we are doing is at the end of this pulse V1 we are switching on this V2.

So what are charge just happened here during this phase when the V2 is switch on, this switch is closed, T4 is closed, therefore, that charge is transferred on to the capacitor here. So V1 is closed, charging takes place; V2 is closed, discharging takes place on the C1 to C2. SO this is charging discharging charging discharging is done and because these are digital output which are available for you.

So that is the way you get where you can use this switched capacitor, you are switching this capacitor from on to other one. So a switch capacitor circuit can do that.

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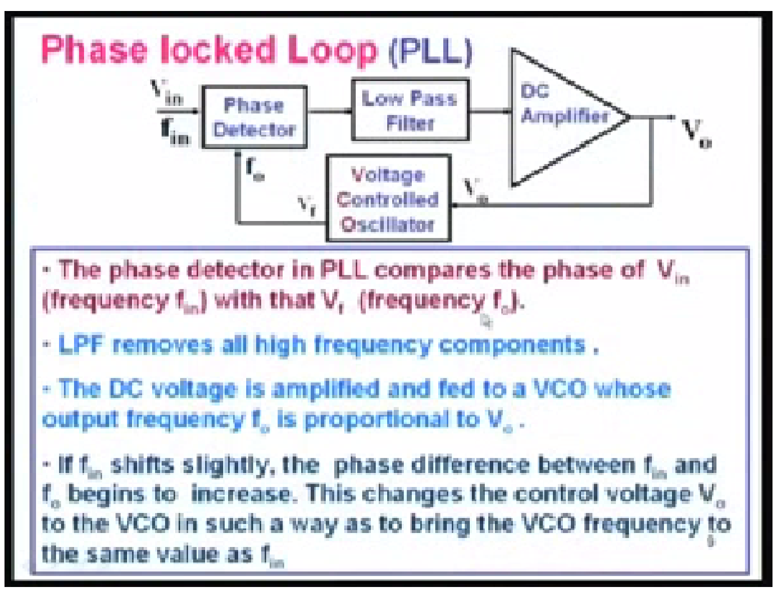

Now we will discuss the phase locked loop circuit. In the phase locked loop PLL, it is a very popular circuit.

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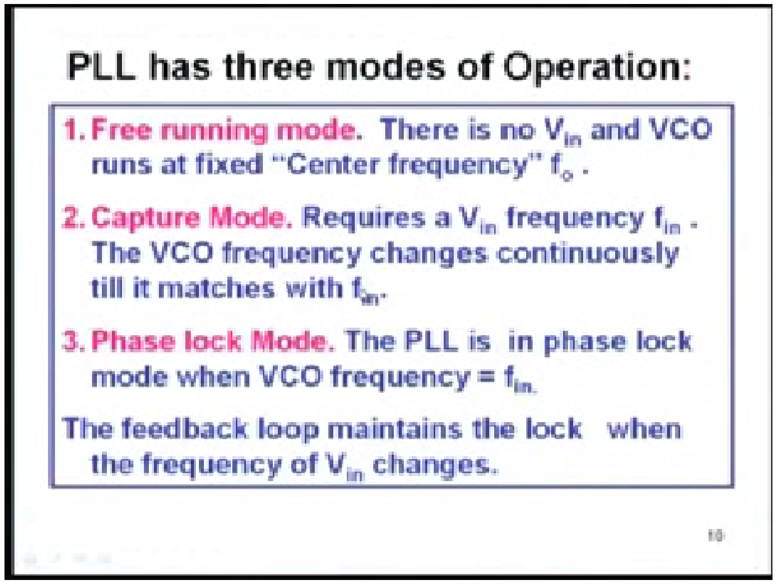

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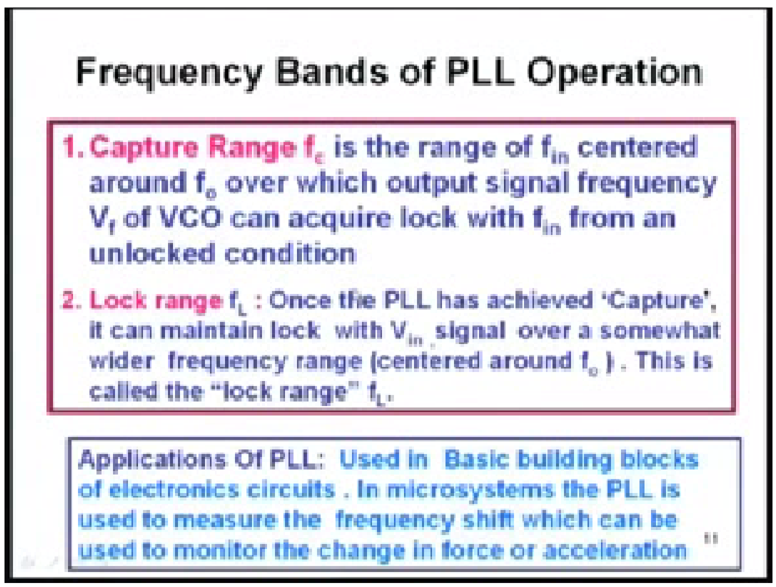

It is used in many applications as you will see little later. What it has is a phase detector which has input signal Vin and another input signal is Vf that is feedback voltage from this entire circuit Vf. These are the 2 inputs. Fin is input frequency of the input signal, f0 is the frequency of this voltage control oscillator if the signal is not present. If the input signal is not present, f0 is the free running frequency of this particular oscillator, okay.

Now phase detector is actually is looked upon as a multiplier, okay, so that you will have DC plus AC signals which are sum and difference of these 2 frequencies. So we will have DC and high frequencies. So that is filtered using low pass filter. All the high frequency components are removed so that the only DC is present and the DC output is amplified using a DC amplifier, shown on circuit and not shown what it is.

So this is amplified and this amplified output V0 is input to the voltage controlled oscillator. This voltage controlled oscillator gives AC signal whose frequency depends upon the DC voltage, okay. Where the DC voltage is absent, it will have a free running frequencies and oscillator which has a particular capacitance inside, LC circuit and it will give us a certain frequency f0. But if there is a DC voltage input there, the f0 will change.

Okay how much is f0 changes, depends upon V0. How much V0 is available depends upon the difference between the 2 frequencies. If the difference between the 2 frequency is there, that will result in a voltage V0 so that the f0 is gets locked on to fin. In another words, this circuit will track the f0, the frequency of this voltage into oscillator will track whatever frequency is there at the input.

So this will give you actually the frequency from the circuit that is being tested or used, a vibration sensor for example, if its frequency changes due to some force, we can measure the frequency using this particular circuit or we can calibrate this V0 to get that frequency, okay. That is the measure of the frequency change and the change in frequency is a measure of the force that is experienced in that sensor.

So just to go through it quickly, phase detector compares the phase of the input signal whose frequency is fin with that of the feedback put in frequency f0. Low pass filter removes all high frequency components. The DC voltage is amplified and fed to the voltage controlled oscillator, VCO as popularly mentioned as whose output frequency f0 is proportional to V0. It is a linear function of V0, okay.

Now if fin, if the signal frequency changes slightly, the phase difference between fin and f0 begins to increase. The phase difference changes the controlled voltage V0 to the VCO in such a way as to bring the VCO frequency to the same value as fin. So all that this V0 does is, it senses the phase difference between the 2 and the voltage developed here is such that it brings the frequency of the oscillation of the VCO back to the beam, that is it gets locked on to the fin, therefore, it is called the phase locked loop circuit, okay.

Now there is the operation of the phase locked loop few terminologies, okay. It has 3 modes of operations. One is the free running mode that means there is no signal here. If there is no signal input, the output frequency of the voltage controlled oscillator is f0 that is called as the center frequency f0.

Next, one more mode of operations is the capture mode and this requires a signal frequency fin to be present. So when that is present, the moment we apply that, okay. Before you applied the frequency of f0. Now the moment we apply this signal here, fin will settle will be different from the free running frequency because of this fin difference, there is voltage developed and f0 will begin to change or increase continuously till it matches with fin. So that is called phase locking, okay.

So the PLL is in phase locked mode when the VCO frequency is equal to the input signal frequency. So this is the phase locked mode. Now let us see the one more aspect of this. There are couple of frequency bands of interest for PLL operation. One is the capture range fc. It is the range of the input centered around f0 over which output signal frequency of the VCO can acquire locking with fin.

Say for example, this f0 is let us say 100 kilohertz, just for example, is 100 kilohertz and if this intake range 100 kilohertz plus or minus the 10 kilohertz, so then the 10 kilohertz is called the capture range, okay over which the VCO is able to acquire lock-in. So that is the limitation of that particular phase locked loop circuit. If the frequency difference is exceeding fc that is the capture range, there will be voltage cut-off, it will not be able to lock in owing to that, okay. That is limitation of that.

Now there is some a more band which is called the lock range. Say for example, if the capture range is 1 kilohertz and f0 is 10 kilohertz, okay. So that 1 kilohertz is the capture range. Now once it has locked on to let us say 10.5 kilohertz, the PLL once it has achieved capture, it can maintain lock with Vin signal over a somewhat wider frequency range then fc.

It need not be just 1 kilohertz, it can be slightly beyond that 1 kilohertz. What I am trying to point out is if f0 is 10 kilohertz, fc is 1 kilohertz, the lock range after it had locked down to the frequency within that range fc, it can maintain that lock in position just like a wider range, that is implication of that.

Applications of PLL, used in all basic building blocks of electronic circuits. In microsystems, the PLL is used to measure the frequency shift which can be used to monitor the change in the force or acceleration. In fact, you will see when you go to the accelerometer etc. or beams, vibrating beams or you must have already seen it. There is some frequencies depends upon the fin constant and mass, okay.

So depending upon that it will have a certain frequency of oscillation as a result of frequency. Now if there is a change in the mass or fin constant or when it experiences a force, there is some change in the frequency if it occurs due to some electrostatic force, that can be sensed here. So you can measure the force by measuring the frequency shift in beam. We will see some of these details when we go on to the accelerometer chapters, okay.

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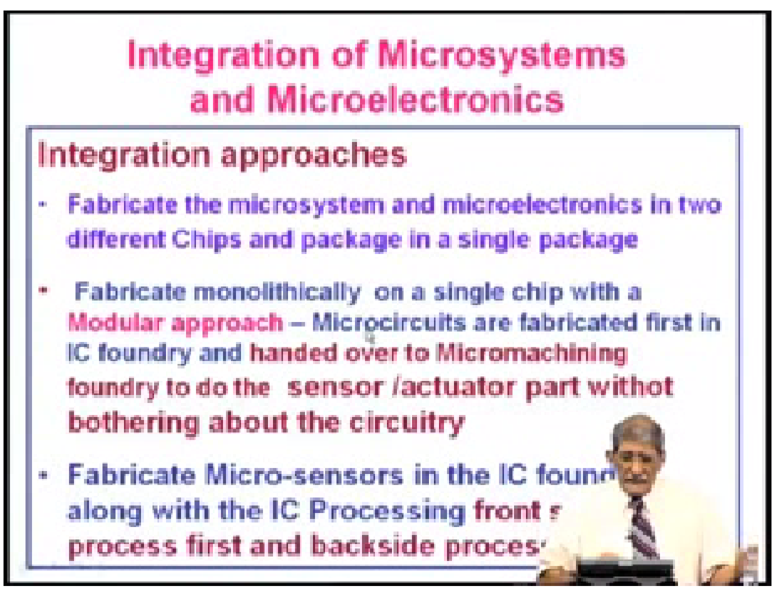

Now next we will see through that course of discussion on the signal conditioning circuits. Now we will take on the much more difficult task. On paper, it looks quite simple but it is a much more difficult task that of integration of microsystems and microelectronics. In another words, you can have, see what we are talking of now is in a microsystem or fuel system, we will have micromachine devices as 1 chip and also you can have electronic circuit as a separate chip, okay.

So one way of having this integration of these 2 separate circuits is fabricate the microsystem in the sense a MEMS device or number of MEMS devices in 1 chip and the required electronics as we saw electronic circuits are required for sensing or for actuating. So you realize that electronic circuit in a separate chip, okay and once you have these 2 separated, all the metalisation everything is done on them and mount them on the same header or the same plate and close it.

Close it meaning, package it under one capsule. That means both the devices exists separately but they are interconnected outside the chip by wire bonding connecting wire from one chip to another chip, you run external wire, okay, to connect them together. It is actually a thin wire which is bonded on to one device on one wafer or one chip and other end of the wire bonded on to another bond pad of another device, another chip. So these 2 chips are interconnected by means of the wires interconnected.

Okay, so this is the hybrid integration, 2 separate chips mounted on a single package connected internally by means of external connection. The problem with this type of thing is the processing cost will definitely be more because we are processing 2 separate chips independently. Advantage is the electronic circuits, VLSI circuit people can make their electronic circuits and MEMS technology can exist completely in a separate location and independent of them.

It will take independently design and independently fabricate these 2 chips and then bring them together to a separate foundry where it can be packaged. So you can see this is the hybrid mode. Apart from the cumbersome packaging or the cost involving these all these things interconnecting the 2 separate chips outside.

The other difficulties that are associated are stray capacitances and stray inductances which comes from the interconnecting wire and interconnecting capacitor because these lengths of the wires definitely be more than 2 millimeters within the chip. You need to reduce those length of those. You have to do that, you have to bring them, you have to put the 2 chips together in 1 chip that is monolithic formation of the chip, okay.

So that is you can, an alternate approach, better approach would be not have, do not fabricate 2 separate chips, fabricate 1 single chip where entire electronics and also the entire MEMS device is put on the same chip which will require smaller things compared to 2 chips, number 2 and all these interconnections will be in the 2 devices that is the MEMS chip and also the electronics that is done by running better connections on the chip itself.

That length can be very small and the capacitance, inductors everything can be reduced, okay. That is the biggest advantage of fabricating these 2 devices in 1 chip which is known as monolithic fabrication. Monolithic means fabricated on the same stone or same chip, okay. So you can have different approaches for this monolithic integration that is one of the approach is the modular approach.

Here what we do is the 2 foundries that is the microelectronic foundry and also the MEMS foundry, these 2 can be totally different foundries. So what you do is, take a wafer, in some portion of the wafer, you make the electronic circuit. Leaving some space very near to that electronic circuit, space required for we keep the MEMS. So we go through the entire processing of this microelectronic circuit, complete it even with metal connection, etc. within the device, then seal it so that it is safe to transfer from 1 place to another place, okay.

And send it off to another foundry where the microfabrication will be done, okay. So there the second company will adjust this microfabrication, does not bother about electronics. All that it does is, it operates only the place located for that industry to make those MEMS devices. We just take a look at the different approaches used for that. So modular approach is actually do it in one place, take it to another place, fabricate that device.

But another approach is, do both the things, okay. The microsensor and also the microelectronics, fabricate them together in the same foundry, same internet circuit foundry, that will be the best.

So people may have some hesitations to use the some of the etching techniques in the VLSI technology because you can use potassium hydroxide for etching the silicon to realise the MEMS device, that may not be accepted in some places. Then you have to change your method of etching that. That is how people take it to the acceptable level, okay.

So I will discuss these 2 approaches now here, one is the modular approach which I have actually done first demonstrated by Berkley where microcircuits are fabricated first in IC foundry and handed over to micromachining foundry to do the sensor or actuator part without bothering about the circuitry. That we will see first.

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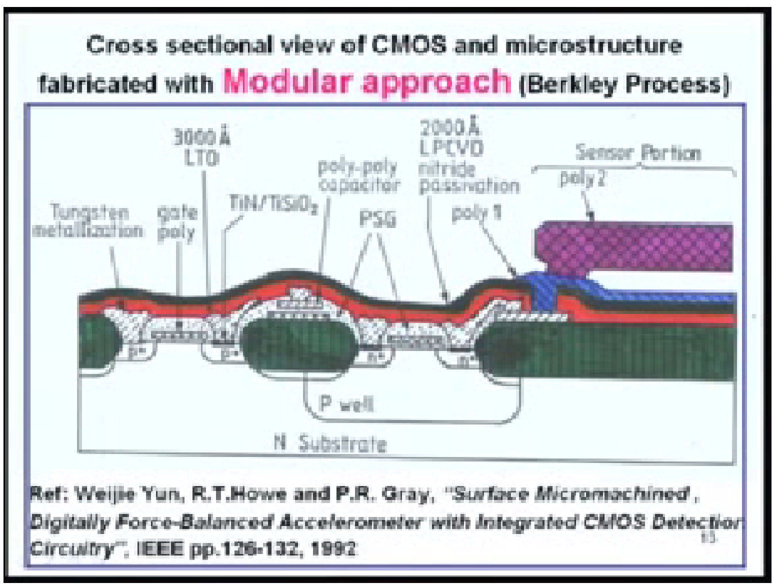

So do not be frightened about appearance of this. What I am showing here is the cross section. Cross-sectional view of a CMOS and a microstructure that is actually accelerometer, fabricated with the modular approach wherein you have fabricated, see this portion on the left hand side here, what I am encircling here, that portion is representing the electronics portion.

Here what we have shown is only the CMOS inverter that is you have p channel MOSFET here on the left hand side and you have these n channel MOSFET here and place source and drain, p-type source and p-type drain. So as you may recall that we discussed the CMOS inverter, p channel is connected to the drain of the n channel, that is done within the circuit itself internally and the source is grounded and this source is connected to power supply, okay.

So here I am not going through the process just right now. In one foundry, you do all these processes of doing this P Well, doing this n channel of MOSFET, carrying out the p channel MOSFET, all these field oxide and the get realisation, number of processes, all of them are carried out to complete this CMOS inverter and the CMOS based intergraded circuit.

And then what you do is before transferring on to the other industry where they make use of this portion on the right hand side, okay, this portion here, that was left blank when this portion was done and it was transferred on to the next industry. So before doing that we will ensure that this region is not disturbed by these people with the next industry. So how that is done, that is done by using, putting a coating of a low temperature oxide.

LTO is low temperature oxide, 3000 Angstrom for oxide you will deposit this red color things, all over including the region where the other company is going to process, okay. So use the low temperature oxide and then on the top of that, you have a low pressure chemical vapour depositing technique to deposit nitride. What happens is if I just send it to only with this oxide layer, when we transport from one place to other place, the oxide is very hydrophobic, it will absorb moisture.

So to avoid that, and also to avoid any contaminants entering this device portion, you put a coating of nitride, all through. So you can see that as you send it from this industry to this industry, this portion is blank, okay. This portion is blank and this portion is covered with the low temperature oxide, LTO and also the chemical vapour deposition nitride, low pressure CVD nitride which I think is passivating it making it less reactive, okay.

You do not worry about all these terminologies, you would have seen already in the integral technology, phosphosilicate glass which is actually P2O5, phosphorous pentoxide and SiO2 which is present in one of the gate which is needed for making the MOSFET technology and this is the gate region, all that done in the first phase of the process, the first industry. The only thing that is first industry should take care is while it is being processed, everything is complete.

All that we have worked is space provided for this sensor in this case, it terms out to be accelerometer structure, capacitive sensing accelerometer, you can see one electrode here, another electrode here with the gaps so that it can move up and down, okay. So from here when you take it to the next foundry, they will open this oxide here and nitride here deposit a polysilicon on that portion.

They will not tamper this portion, deposit a polysilicon completely on this portion and then deposit some oxide and then deposit polysilicon, removes oxide in between the 2, this is called the surface micromachining technique where top polysilicon which is separated from the bottom polysilicon, poly 1 with a gap, air gap so that if there is acceleration, the mass can, the top body can move up or down depending upon acceleration experienced by the top poly.

It can move up or down, depending upon that, the capacitance between the 2 will change, you have to sense the capacitance to sense the acceleration. The friction of the top mobile, moving electrode tells you how much is the acceleration or the force, that part we will discuss while discussing the accelerometer. So important work here is when you transfer it, when you do the process, you will have high temperatures for depositing the polysilicon, okay.

So you feels high temperatures are involved, the industry which does this initial process, should ensure that whatever high temperature that rest industry subjects the wafer to, should not hurt this device. Suppose you use aluminium for interconnecting the devices in this first stage, first industry, when it is subjected to 650 degrees centigrade, if this were aluminium, that will melt and aluminium flow all over. So you cannot choose aluminium for interconnection.

You have to use refractory materials like tungsten for metallization. See this is the tungsten metallization or you can use titanium nitride etc. for the contact regions and interconnections can be done with the chrome gold which can withstand high temperature. So you have to be careful with your process in the first stage itself if you are transferring on to the next industry to go through the process.

This is the problem in this type of modular approach where you do is some CMOS first and take it to the next stage for the MEMS device to separate location, so one has to take care of these things very carefully. This was done way back in 1992 by Berkley by these people who published already and accurately.

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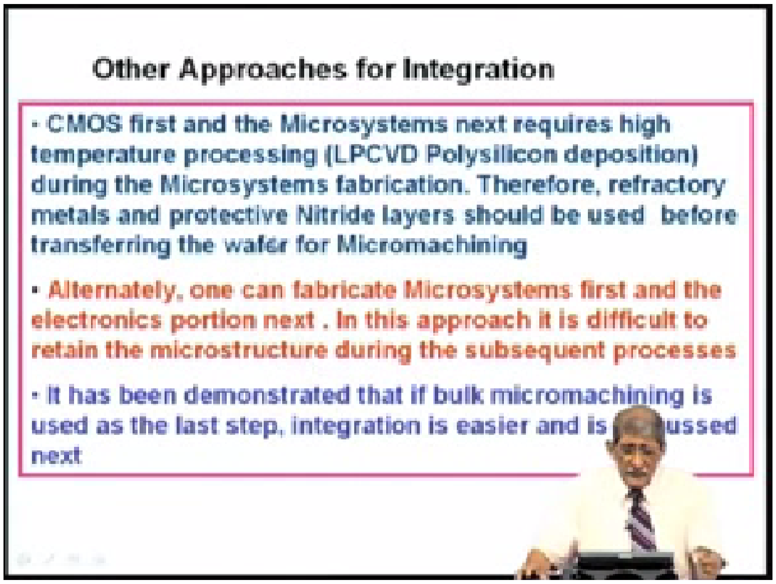

Other approaches for integration are apart from this, one that will be discussed is CMOS first and next this process that we have said already that it requires high temperature processing during the microsystem fabrication, therefore, refractory metals and protective nitride layers should be used before transferring the wafer for the next stage.

Alternative, one can fabricate microsystems first, do that mechanical device first and electronics portion next. In this approach, it is difficult to retain the microstructure during subsequent process. For example, if I release the accelerometer structure, already which can move up and down, like that, then if they transfer it on to another industry, or even in the same place if you are doing the processing.

During the processing, those vibrating structures may move and during the spinning processing of wafer, photolithography, etc., those moving parts will break. So this is one of the difficulty one has to take care extreme care, though you have taken care of the high temperature portion first, okay. But a slightly better approach has been demonstrated in technology with the R&D sectors that if bulk micromachining is used.

You are already familiar about bulk micromachining where you etch some portion of silicone to realise the structure and then integration, you carry out integration, okay together. So you use the bulk micromachining as a last step.

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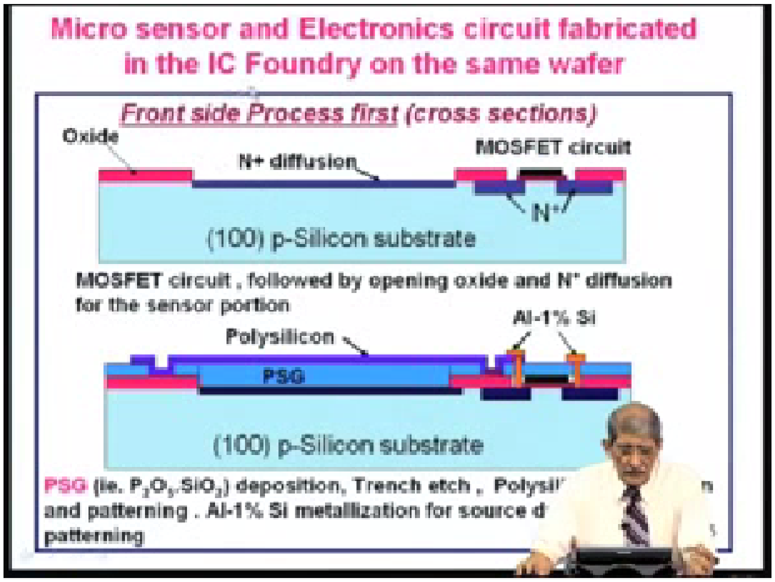

First you carry out the circuit portion, next you do the micromachining portion. Please note, this is a very interesting thing, people have demonstrated where you can actually see. I am just giving you the process which is different from the one that we have discussed just now, okay. Microsensor and electronic circuits fabricated in the same IC foundry on the same wafer. This is the integration.

I am showing you the one transistor here. It will be, may be a CMOS circuit or it will be number of transistors together to realize that circuit portion. So what is here, you have done earlier this portion of the wafer. I am showing you 1 device. There are number of such devices side by side on the single wafer. Ultimately you have to dice them to realize single device. So I am showing that single portion of the device.

So what you do is first front side process is carried out first. You carry out this portion up to realizing this MOSFET. Nothing is protect this portion completely where your sensor comes, this portion, protect it completely. Focus only on this particular portion, make this particular device that the (()) (48:07) and do this gate oxide, gate poly, all this thing is completed, this field oxide will be present everywhere.

After completing the electronics portion, do not complete their interconnection portion, that is done ultimately. So here what you do is take it to next stage after this open, at the next stage you will have oxide everywhere here protected, remove the oxide where (()) (48:34), open this window, carry out N+ diffusion, N+ is heavily doped enter, phosphorus diffusion you carry out to serve as one electrode of a capacitively pressure sensor.

After all a capacitive pressure sensor will have fixed electrode, okay, that is the center of region what we are showing and another electrode which can experience the pressure and can move up or down. So the change in the capacitance between the 2 is the one that you are sensing. So the bottom electrode is decided by this N+ region, almost like a metal instead of talking of a metal, you talk of N+ diffusion.

After this what you do is, I have just skipped various steps, but I will show you what is done. First MOSFET circuit followed by opening the oxide and N+ diffusion for the sensor portion is done. We are processing only the front side, the top side of the wafer. Then what you do is, deposit this PSG shown by the color all through everywhere, phosphosilicate glass which is P2O5.SiO2, deposit that which can be done by the chemical vapour deposition techniques by reaction of (()) (49:58).

Then you etch out this trench portions. What is this portion, right up to the bottom so that you access up to this bottom. You have opening here carried out and deposit polycrystalline silicon here, this color on the top is the polycrystalline silicon, okay. And then after doing that, from all of these portions and these portions, the trenches, deposit the poly everywhere, etching out the poly from everywhere except this portion.

So you have got this polysilicon over this sensor region and you have got metal also, aluminium 1% silicon metal to make contact on to the source and the drain region of the MOSFET. This is a metal oxide silicon metal then a PSG here, okay. So with that, you have got the front side portion completed.

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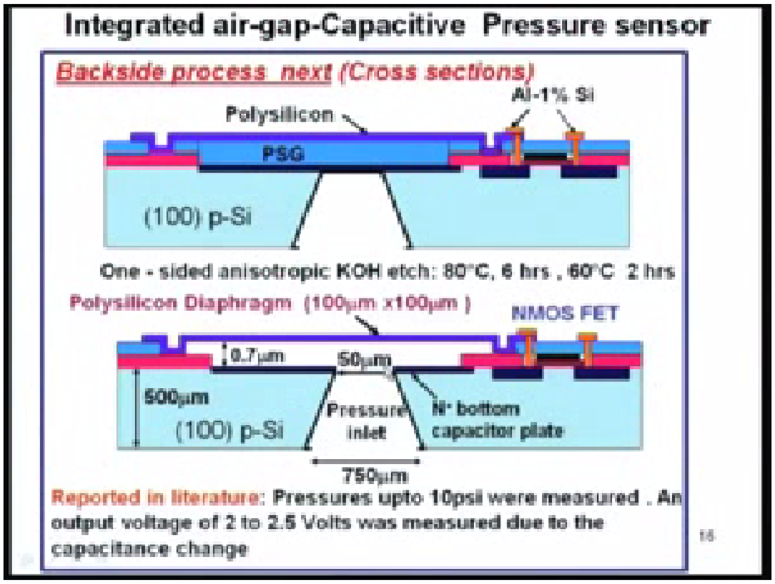

Now you come back to the backside portion processing. How is that done. To take it to the next stage, you oxidize the backside fully completely and deposit oxide on this, do a lithography, open window on the backside here. You must be able to align this portion with this to the top so that this is a exactly located below that portion. For that you have got special equipment called backside alignment machine, they can locate this window here in the oxide precisely align it to this center of this portion.

And then etch out this silicon from here using KOH etching. So one sided anisotropic KOH etch, 80 degrees Centigrade for 6 hours, that is a fast and drop the temperature to 60 degrees, etch for another 2 hours, x-ray till reduced so that you have got etching from this end to that end till this hits this particular N+ region rate that also down, okay. So what you did is you have etched out this backside completely right in this portion.

Now with that you reached, you can remove this PSG from here, everywhere, okay. You can remove that PSG from these portions, polysilicon is present on this portion. So you can put it in the buffered dilute hydrochloric acid agent, that will remove this PSG from here and there is access from the bottom which will be about the MOSFET and also you have ensued that, this source drain is connected to this polysilicon during this metal contact.

And to this great contact, you will take contact somewhere laterally on the top surface of the wafer which cannot be seen in the cross section, okay. So at the end of this process, you have realized the MOSFET with the connection from this drain to this polysilicon, you can see it is very close already done and this polysilicon is separated from this N+ region which you have realised here, this portion, okay.

This N+ region is here, that N+ region and this polysilicon are separated by means of the air gap in this example it is about 0.7 micrometers, okay and this hole is about 50 microns only and this is about 750 microns. How much you get here size depends upon how much window you open here. For a 500 micrometer thick silicon wafer, if I use about 750 microns, then you will get about 50 microns. So the size of this hole is decided by this how much area you want to open.

For the capacitancy, it is actually between this polysilicon which is movable and this fixed N+ region. So when it is subjected to pressure, for example like an applied pressure from the package we can see how it is done, we can apply pressure from the bottom, this is the pressure inlet, you can put it in atmosphere where there is some higher pressure, you need not worry whatever is the pressure depends upon the design here.

We will discuss this subsequently, you have subjected to stress, pressure is there, this membrane will deflate up and it is fixed up the gap between the 2 increases from 0.7 to may be 0.71 micron or of that order. So because that if it dropped the capacitance between the 2 electrodes will decrease because the gap is increased. Capacitance is (()) (54:40) a/d, if d increases, capacitance falls. So the change in the capacitance is sensed using the circuit like the sensory capacitor circuit.

We can change determine the change in capacitance or some other circuits, electronics is used, that circuit is present here. We will sense that capacitor change, let us say it is connected together. This is the one way of making a pressure sensor, integrated with electronics, monolithically in the same industry. You can see that this KOH etching is done as a last step here.

No high temperature, it only just temperature is about 80 degrees Centigrade, you do not have to worry about this IC getting damaged, okay. Now the one that is reported in literature for these type of devices is actually pressure up to 10 PSI were measured, very low pressure. Output voltage of 2 to 2.5 volts was measured due to the capacitance change and that is this capacitance change is converted into a change in voltage using the electronics.

Now before I windup on this, one small thing that I want to show is, this hole is etched from here right up to this, you can use a circular window to open the oxide here. There is oxide usually below this that is open that and if wherever oxide is present at the bottom, the KOH will not etch it or the etch rate will be very small, you can etch through this.

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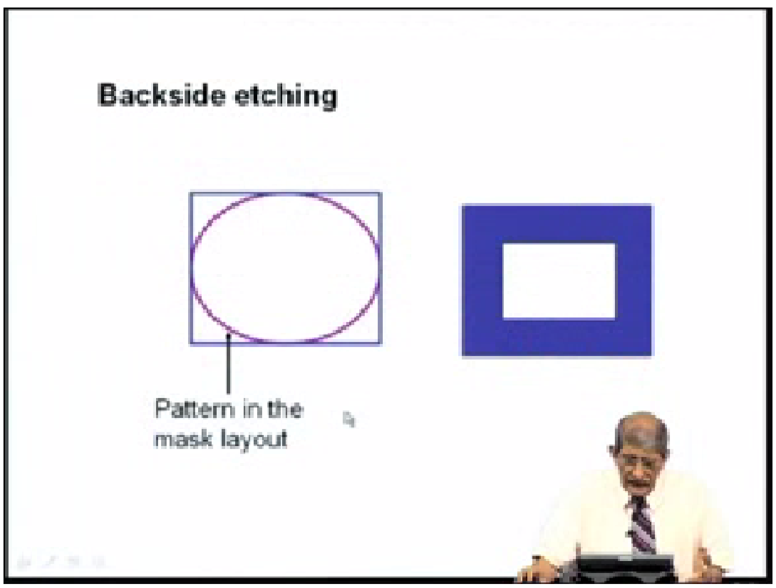

So if that is whole mass in the window is, wherever is oxide, you retain this oxide everywhere except in the circular portion. Now you put it to etchant. The etchant will etch through this oxide, but it will go over this so that it becomes a square because if this is 1 0 0 wafer, this will be 1 1 0 planes, it will end up with that. So if I start with the square thing, I will end up more of these we will see in our subsequent lectures.

This is the square opening that result as a bottom and when it go up to the other end, that is here, this is square window and here you have square window of this, this is the opening that has resulted in and this was as we saw earlier, there was 750 microns, this width and this way should be 50 micron by 50 micron. So that is the way you can, all that you have to do is put a circular thing, etch through it, you will get a square thing if you want square. We will talk about it later on circular things.

So with that it is closed for discussion on the integration of the sensors or microsensors, microdevices along with electronics. What is the approach and also approach in the same industry or hybrid approach whichever is available to you, one can use it. Thank you very much.