MEMS & Microsystems
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Lecture No. # 25
MEMS Capacitive Accelerometer

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Today we will discuss on MEMS capacitive accelerometer. In my last few lectures I spent on MEMS piezoresistive accelerometer a case study. That is particularly for avionics application we just described how accelerometer is designed and then how do the technology, fabrication steps and its characterization. And today I want to spend on another case study that is MEMS capacitive accelerometer. That is for generalized application for defense and many other automobile sector also you required such accelerometer. So MEMS capacitive accelerometer, a case study that is the topic of discussion today.

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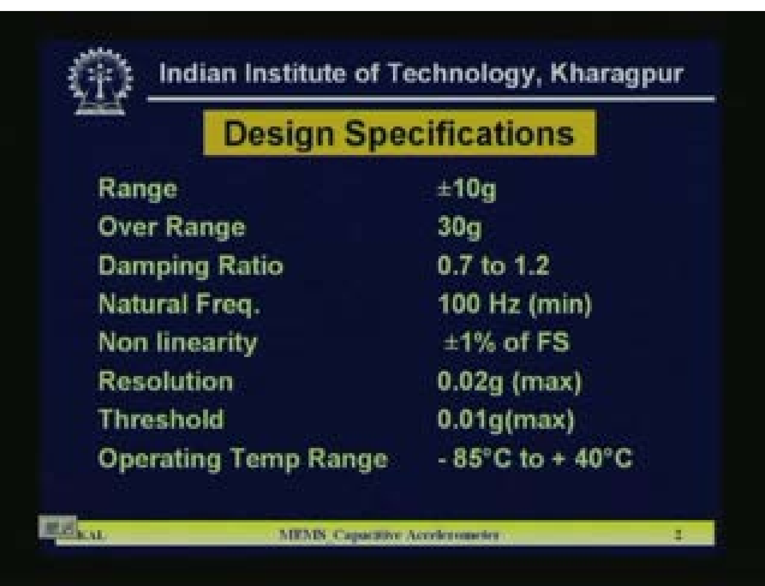

Now the design specifications of that accelerometer is range of the accelerometer is plus minus 10g. Over range is 30g; that means up to 30g there is no destruction of the device. It should withstand; damping ratio is 0.7 to 1.2, natural frequency is 100 hertz. Non linearity plus minus 1 percent full scale, resolution 0.02g maximum and threshold is 0.01g maximum, operating temperature range is minus 85 to plus 40 degree C. So now with these specifications how do you proceed to design an accelerometer which is based on capacitive sensing?

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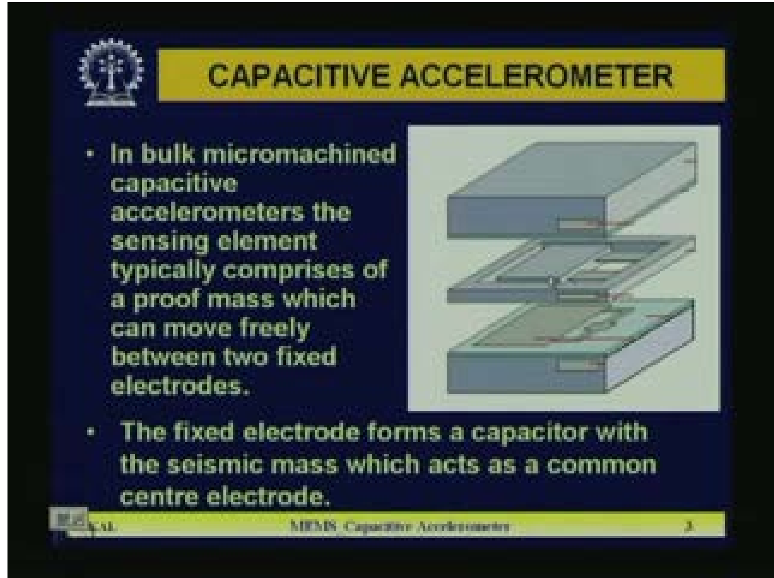

Now, the structure of the capacitive accelerometer is shown in the figure here you can see and this figure has 3 modules. You can see in the middle piece is basically the sensing element and it comprises of a proof mass which is also known as seismic mass which can move freely between 2 fixed electrodes. What are the two fixed electrodes? One is held at the top and another is held at the bottom. And there you can see in the bottom piece which is a fixed and a parallel plate electrode is configured here and you can take the contact from the side wall or may be some bond pads are ejected at the outside and from where you can take outside external connection. Similarly at the top fixed electrode also there is a metalized plane which acts as electrode.

So then the fixed electrode top and fixed electrode bottom will form capacitances with the middle sensing element. Now middle sensing element you can see here a movable seismic mass because of the movement of the object whose acceleration we want to measure. So this proof mass or the seismic mass will move either up or down and accordingly the capacitance between the seismic mass and top electrode and bottom electrode will change. So that change of capacitance will be the measure of your acceleration. That is the capacitive accelerometer principle which we are going to follow in this case study.

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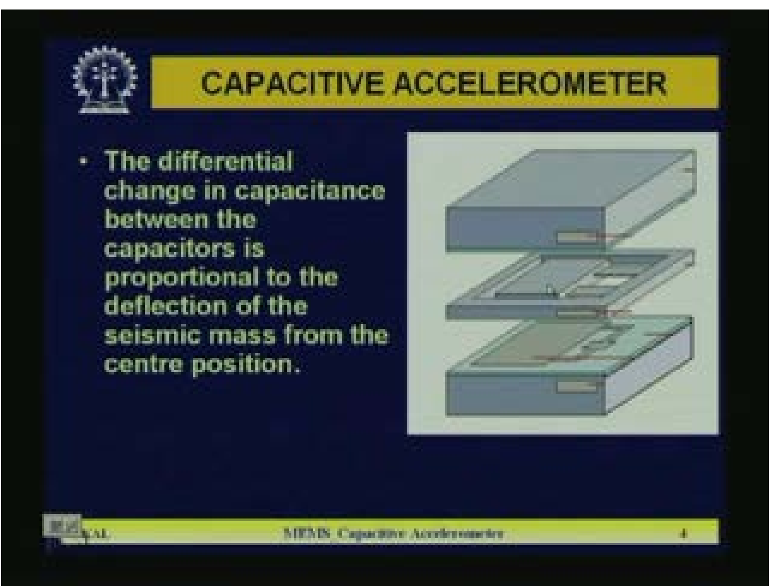

Now the differential change in capacitance between the capacitors is proportional to the deflection of the seismic mass from the center position. So obviously if the seismic mass which is at the central position, if it moves upward then the gap between the top electrode and seismic mass will be less and the gap between the middle seismic mass and bottom electrode will be more. So that means in one case capacitance will increase, in other case will decrease. So this differential change we are interested so that we can eliminate some of the parasitic things. So the differential change obviously is proportional to the movement or to the g value of the object on which this accelerometer is fixed. So that is the basic idea and basic principle.

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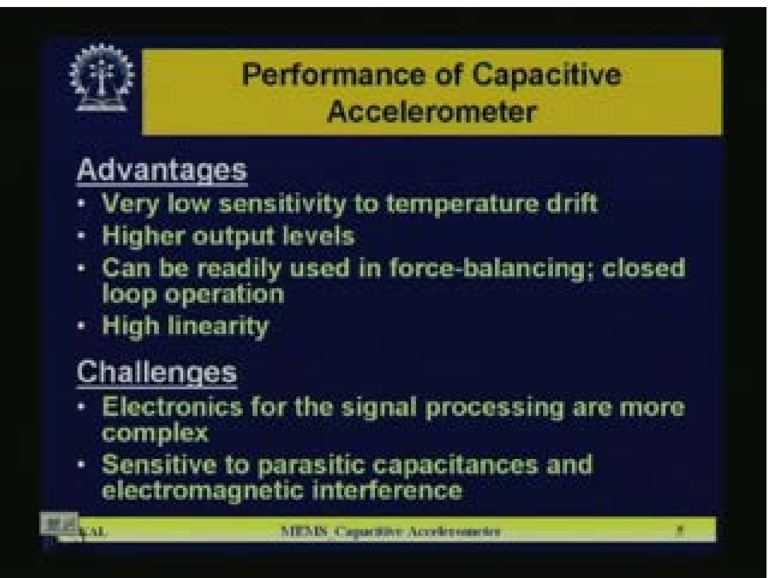

Now, the advantages of such kind of structure are meaningful such as very low sensitivity to temperature drift. That is the basic property of the capacitive accelerometer we now. Higher output levels it can be readily used in force-balancing. If you connect this accelerometer in a close loop operation so you can use it for force balancing mechanism and high linearity is achieved. On the other hand there are certain challenges on this kind of accelerometers. These we can say it is limitation of capacitive accelerometers. What are those? There electronics for the signal processing are more complex. In case of piezoresistive accelerometer we saw that simple Wheatstone's bridge is sufficient for pick up the signal due to the acceleration change. But here the signal processing because capacitance change directly you cannot measure. You have to have an arrangement or interface electronic so the change of capacitance is reflected either change of voltage or change of frequency in the output which you can further process for your application. That electronics is done is available. But it is not so simple like piezoresistive accelerometer.

Second point is sensitive to parasitic capacitances and electromagnetic interference. Because electromagnetic interference, that is why nowadays people want the electromagnetic compatible. Compatible circuit devices are required because lots of electromagnetic radiations are available in your surroundings. So they may induce some electromagnetic field and because of that you can get some sensing voltage which may hamper your the actual signal coming out from the sensor because of the g variation. So that is why it is sensitive to electromagnetic interference, also as well as parasitic capacitance that I have already discussed many times in earlier lectures. Now this structure which is shown here, the three pieces, this is basically fabricated using bulk micromachining technology. There is another kind of capacitive accelerometer available which is basically fabricated from surface micromachining. Those are comb structure capacitive accelerator; comb like structure that I explained in earlier lecture also. The case study which I am going to discuss today is based only on bulk micromachining technology.

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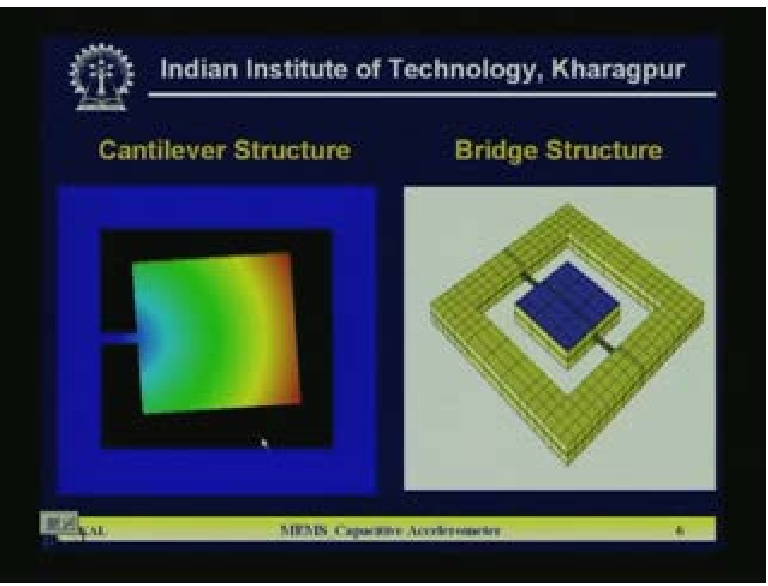

Now there are several kinds of structures available; one is known as cantilever structure, other is known as bridge structure. You can see here 2 diagrams; in one case the seismic mass is held with a cantilever; single cantilever. In other case the seismic mass is held with a frame. With the help of two cantilevers supported in the opposite side so that it is just like a bridge. Now there are some advantages, disadvantage of both the structure and that we will see which structure is better for all respect means performance technology fabrication in all aspect which is better so cantilever structure and bridge structure if you compare.

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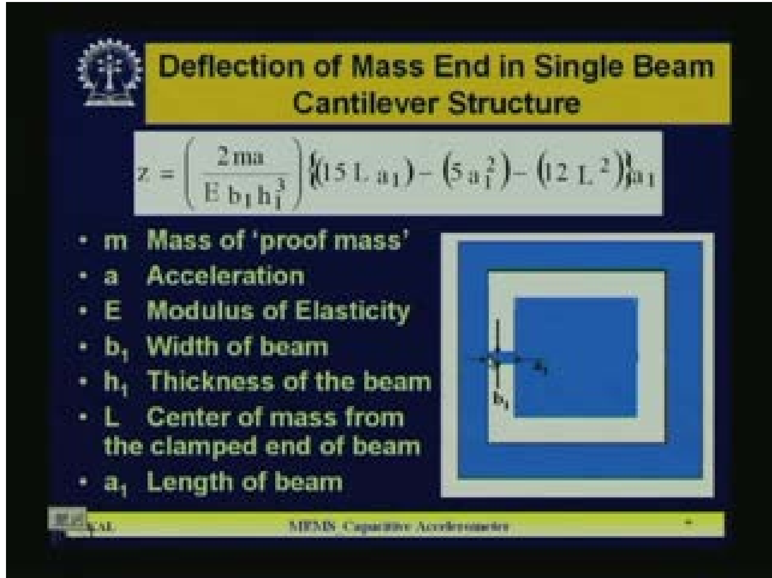

Then first let us concentrate on cantilever structure where I am going to use a single flexure beam. The whole seismic mass is held with a single flexure beam. So the single flexure, its width is b_1, its length of the flexure the cantilever is a_1 which is shown in the diagram you can see here. So a_1 is the length, b_1 is width and h_1 is the thickness of the beam. So a_1, b_1, h_1 is known, m is the mass of the proof mass, there seismic mass in the center which is there and E is the modulus of elasticity. So that I defined earlier what do we mean by modulus of elasticity and L is the center of mass from the clamped end of the beam, centre of mass of the seismic structure; seismic mass structure from the clamped end of the beam. This is a clamped end of the beam from there say the centre of mass if it is here, so then that is the length L. So if a is the acceleration then with acceleration a the seismic mass along z direction, if we accelerate the whole structure then the seismic mass will move, some displacement will take place and that displacement is z which is given by this relation.

Twice ma E b_1 h_1 cube into 15L a_1 minus 5 a_1 square minus 12L square whole multiplied by a_1. So that is taken from literature and with some analytical calculation, you can make using this relation. How the relation is derived details I am not discussing this has been taken from some references. Now if we know the z movement, basically of the mass, then we can easily calculate how much change of the gap. Because top and bottom electrodes are fixed. So if we know the z, so in one case the gap between the two electrodes, that will be reduced by z; in other case the gap will be increased by z. So accordingly parallel plate capacitance easily you can calculate so that capacitance change also easily you can calculate. From there you can get the delta C which is change of capacitance.

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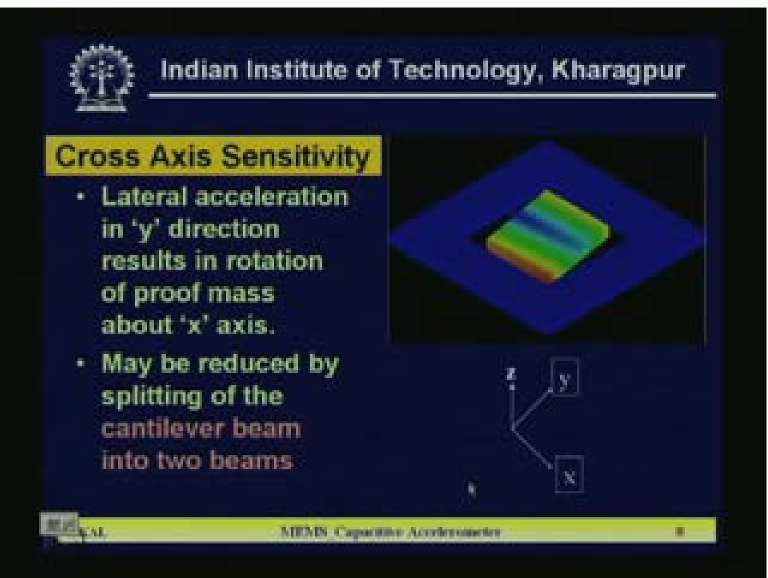

Now in this kind of structure there is a problem. What is that problem is the cross axis sensitivity. So now if this is the single flexure single cantilever structure, now if you make acceleration along y direction, say y direction is shown in the bottom in the diagram, z is the vertical and x, y in this plane of this table for example. So there if we move this whole structure along x direction, then the movement or the position of the seismic mass will be

will be along z also. If you move along x axis, x acceleration, x direction, the rotation of the proof mass will be, this is the x along vertical. So there some movement will be there along z also. So that means this kind of structure will not give you that less cross axis sensitivity.

So along if you desired or if you design the whole thing for z acceleration, so because of this structure it is also sensitive to y direction acceleration also. So you can see the configuration. So if you push it along y direction, it will just tilt and because of that so the gap is also going to change, gap basically if you move the structure along y direction, along x direction so parallel plate capacitors say that gap should not change. But here it is going to change because you see this portion of this proof mass or say seismic mass will go up and this side will go down because it is trying to rotate along x direction. So this kind of structure is not very good so far as cross axis sensitivity is concerned.

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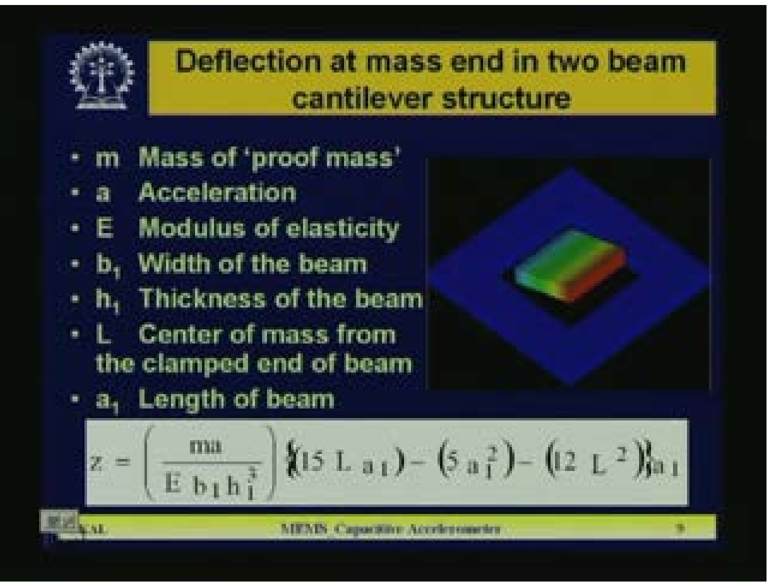

So we thought of a different structure which is double flexure, double flexure the cantilever structure. So here instead of 1 we have used 2 flexures. So under that condition if you move along y direction or x direction, this whole seismic mass will not rotate along that direction. So that mean whatever the movement is there will be along z direction either upward or downward. So if you move it along this direction then it will not show any upward movement or downward shape change. So because of that you can reduce the cross axis sensitivity problem. So now here again the displacement of the seismic mass is shown in the relation which is given below: ma divide by E, E is the modulus of elasticity, b_1 h_1 cube 15L a_1 minus 5 a_1 square minus 12L square whole multiplied by a_1. The relation if you find, then I think only difference is here. It is only ma in earlier case I think it is twice ma you can see the relation is a twice ma here. So that is the difference in the expression and all the parameters ma E b_1 h_1 L a_1 are known. So if you know those, that is basically dimensional parameters, so then easily you calculate z from there you can calculate the parallel plate capacitor. Now this kind of structure is is advantages so for as a cross axis sensitivity is concerned.

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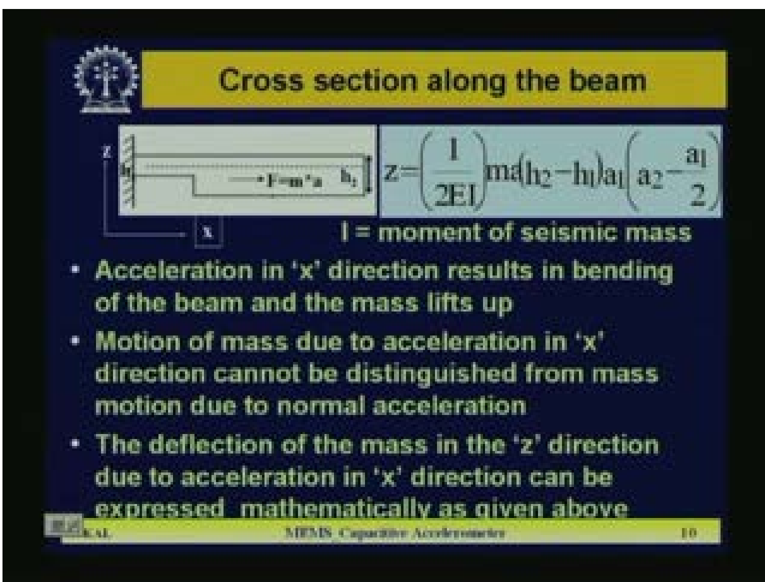

Now here if you look into the cross section of the structure then also you can calculate the z displacement from this relation also. That is here you can see the thickness of the, this is a cross sectional diagram, h_1 is the flexure thickness mentioned there and h_2 is the proof mass thickness which is basically the wafer thickness and F equal to mass into acceleration is a force and I is the moment of the seismic mass. So in terms of moment of the seismic mass, so Z the moment along the or the displacement along z axis of that proof mass is given by this relation and acceleration in x direction results in bending of the beam and the mass lifts up. If you use single flexure, motion of mass due to acceleration in x direction cannot be distinguished from mass motion due to normal acceleration. The deflection of the mass in z direction due to acceleration in x direction can be expressed mathematically as given above. That is for the cross axis displacement z. So if you move this structure along x direction how much in z direction, it will move that expression is shown here.

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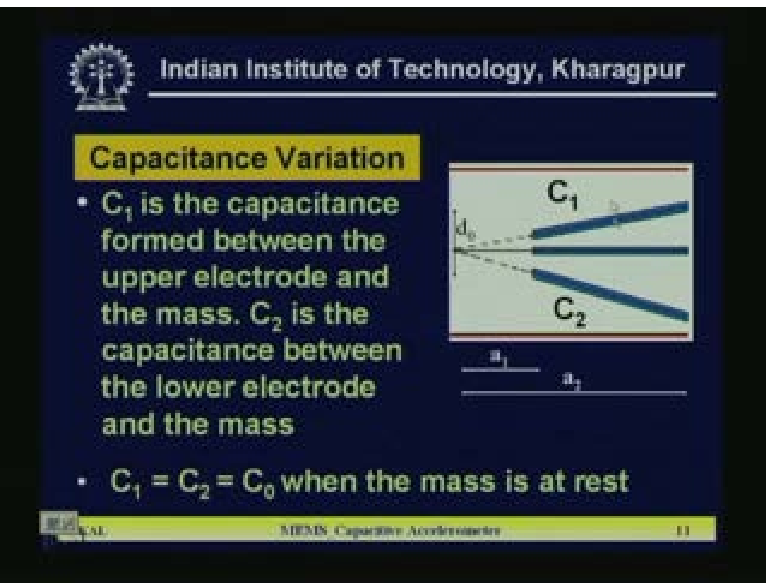

So this will give you some idea about how much fraction of the cross axis sensitivity is achieved with such kind of structure. Now as I told you the there are two capacitances. How the capacitance changes, that is shown in the diagram. The red lines top and bottom are the two fixed parallel plates. That is top electrode and bottom electrode and the middle one is a sensing element. So now with the movement of the whole structure, the seismic mass will go upward or downward. So depending on its acceleration or deceleration and then the d_0 is the maximum deflection from this point to this point. For its maximum deflection d_0 average displacement is shown here. Average displacement of that means gap change between the fixed and the bottom. Because this how much moves in up and down that average value is d_0 basically. Now C_1 is the capacitance with the top electrode and seismic mass and C_2 is capacitance with the bottom electrode and seismic mass. So now the C_1 is equal to C_2 is C_0 when the mass is at rest that is obvious. So when this is there is no movement of the structure which is a rest position the C_1 will be equal to C_1. So if you move or you under g only the C_1, C_{12} will vary. So this is the capacitance variation how it varies you can see from this diagram.

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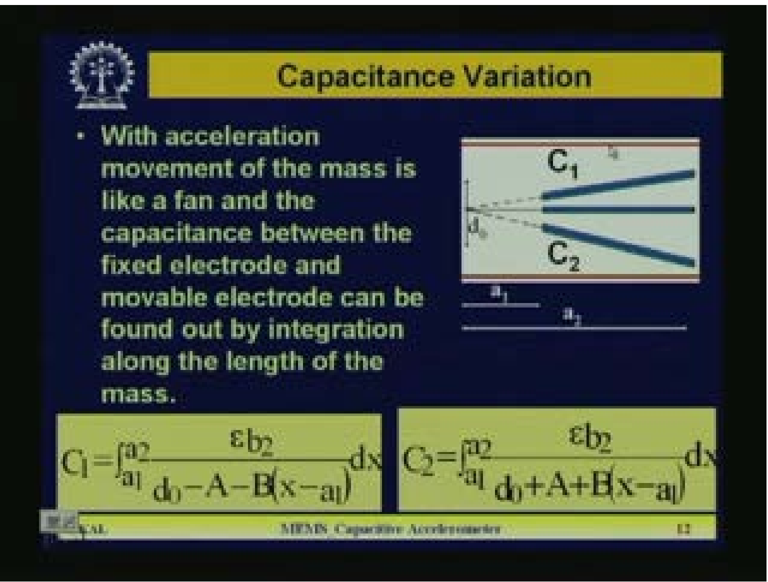

Now with acceleration movement of the mass, that is basically like a fan, this will move up and down and between the fixed electrode and moveable electrode can be found out by integration along the length. Now the one point is very evident here that you see although we are telling parallel plate capacitance, the gap between top electrode and the middle is not same everywhere it varies. So that is why the capacitance is calculated by integrating from a_1 to a_2 where a_1 is distance and a_2 is from this point to this distance. So from a_1 to a_2 if we integrate this relation that will be the average value of the capacitance C_1. Similarly C_2 is also a_1 to a_2 and it is given by this expression. So it is not exactly parallel plate. So directly step forward is a simple relation and you cannot use it. Isn't it? So that is why the d_0 is some average from there how much it is deviating, so that is given by this relation.

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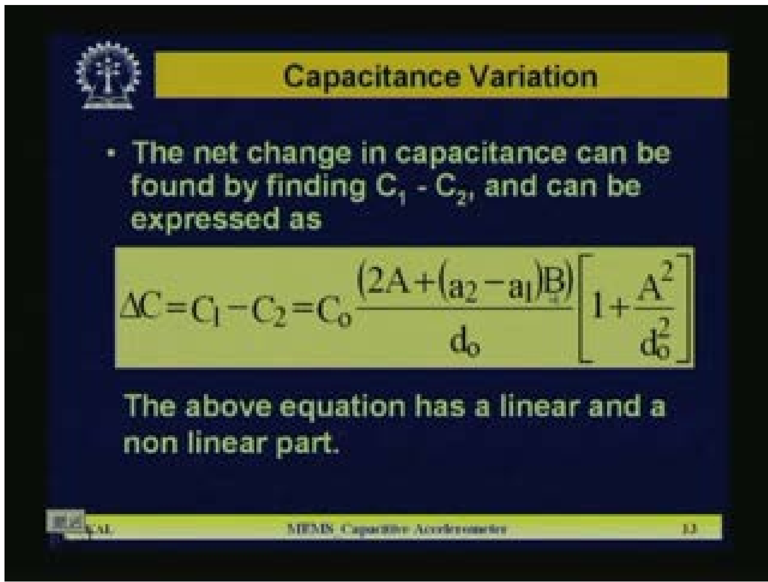

Now the net change capacitance can be found by finding C_1 minus C_2 and it can be expressed as delta C which is C_1 minus C_2 is given by this relation. C_0 into twice A plus a_1 minus a_1 in to B by d_0 where a multiplied by a plus A square by d_0 square. So this equation has a linear as well as a nonlinear part. The second term is a quadratic term is not exactly linear.

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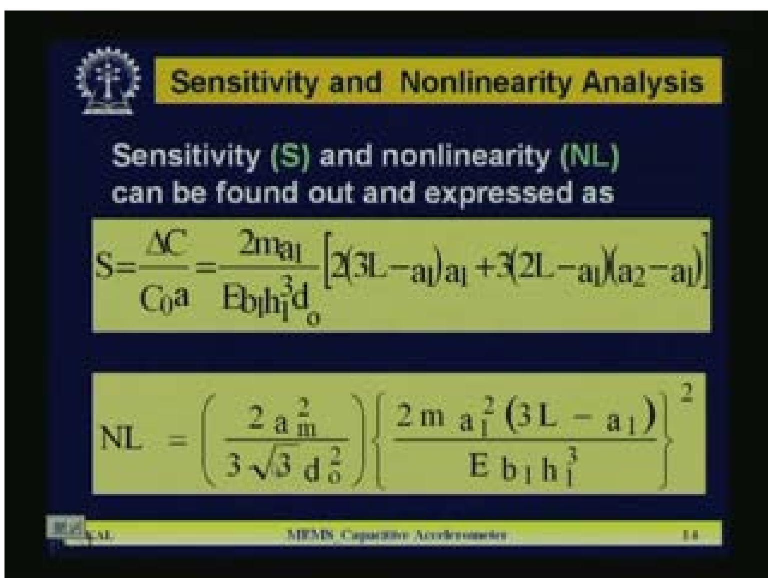

Now the sensitivity and non-linearity. These are another two parameters which we are also interested because in our design specifications nonlinearity has been expressed as less than 1 percent of the full scale, sensitivity is 0.02g. So for that also we have to calculate the

sensitivity as well as non-linearity of the devices. So those are analytical expressions for those are given in this viewgraph here. So it is sensitivity is $delta_0$ divided by C_0 into a where this if you put the value of the delta C which is given in earlier expression then the sensitivity expression comes like this. Similarly in non-linearity is given by twice a square m 3 root 3 d_0 square multiplied by this factor. So these are the sensitivity and non linearity expressions from where you can easily calculate the values of sensitivity and non-linearity.

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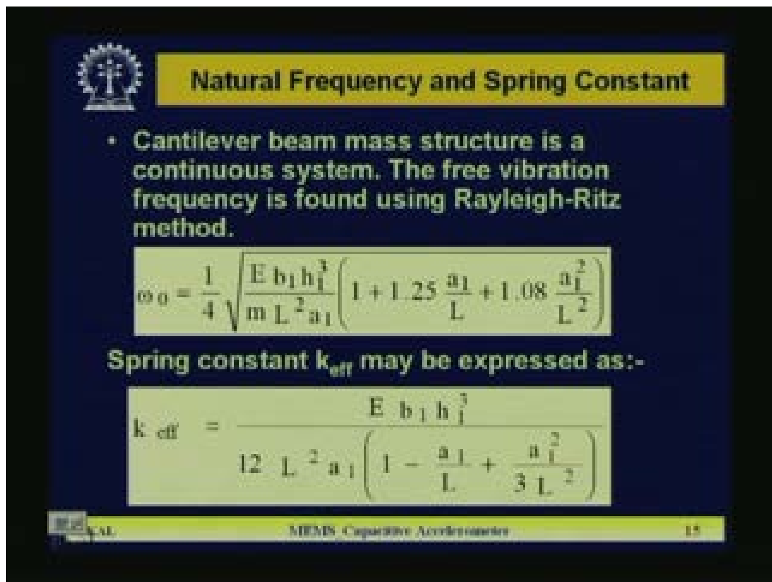

Now the cantilever beam mass structure is a continuous system. The free vibration frequency is found using the Rayleigh-Ritz method and the whole structure has got some natural frequency. That frequency depends on the dimension of the structures, thickness, mass and the area. That means length and breadth and modulus of elasticity. All those things depend, all those things will decide the natural frequency or vibration frequency and that $omega_0$ is given by this relation. One fourth the under root E b_1 h_1 cube divided by m L square a_1 multiplied by 1 plus 1.25 a_1 by L plus 1.08 a_1 square by L square. Spring constant k effective may be expressed as k effective because from there you can calculate under root. The relation of the mass and spring constant will give by the acceleration so that is equal to E b_1 h_1 cube divided by 12L square a_1 into 1 minus a_1 by L plus a_1 square by 3L square. Detail derivations of this expression are given in literature. You can find those literatures or any book on the mechanical vibration book and there you can get this expression of the natural frequency and the spring constant.

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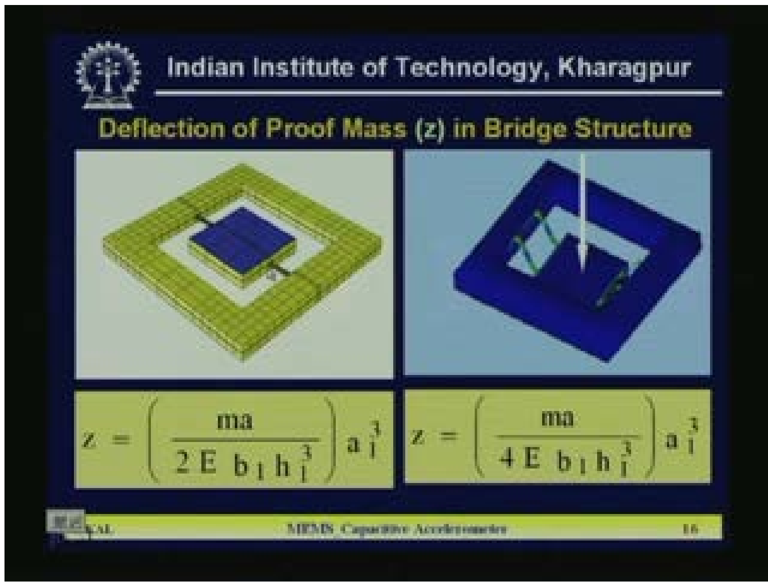

Now the deflection of proof mass in case of bridge structure. So bridge structure is basically the seismic mass is held between 2 flexures. Now you can see the flexures which is connected the seismic mass with the frame that is not always at the top surface or at the bottom surface. The diagram shows it is at the central position. Similarly here also and it has been observed by analytical calculation or the finite element analysis that if you make the flexure at the middle of the construction of the seismic mass it gives better response compared to the flexure fabricated at the flat top surface. So there are different kinds of bridge structures available; in one case it is held by 2 flexures and in other case it is held by 4 flexures like piezoresisitive accelerometers. Now in both the cases the deflection of the proof mass which is given by the z is given by the simple relations which is shown here and here also the h_1, a_1, and b_1 are respectively the thickness and length and width of the flexures, m is the mass of the proof mass and a is the acceleration, E is the modulus of elasticity. So the simple relation for the deflection proof mass deflection for 2 flexures bridges and 4 flexure bridges is shown below.

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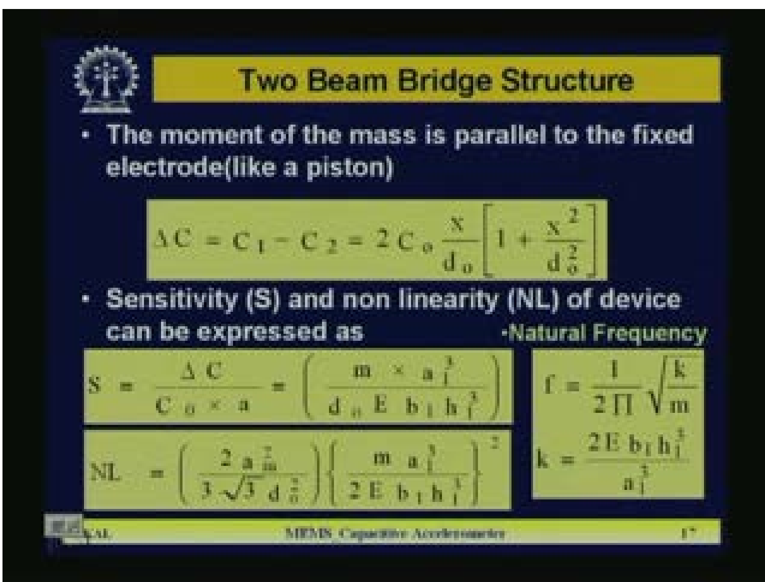

Now in this kind of structures the moment of mass is parallel to the fixed electrode like a piston because it moves up or down like piston. Because it is held by 2 flexures. So it is not the bending, is not asymmetric, is a uniform if you held by 2 flexures then either thing will go up or down like piston. So now there delta C is given by C_1 minus C_2 which is again shown by this expression twice C_0 x by d_0, 1 plus x square d_0 square and sensitivity and non linearity are also shown in by this expression for this kind of structure. Natural frequency f equal to 1 by twice by k by m and the stiffness constant k is given by this relation twice E b_1 h_1 cube by a_1 cube. These are the relations of sensitivity non linearity and change of capacitance. That is differential capacitance in case of 2 beam bridge structure.

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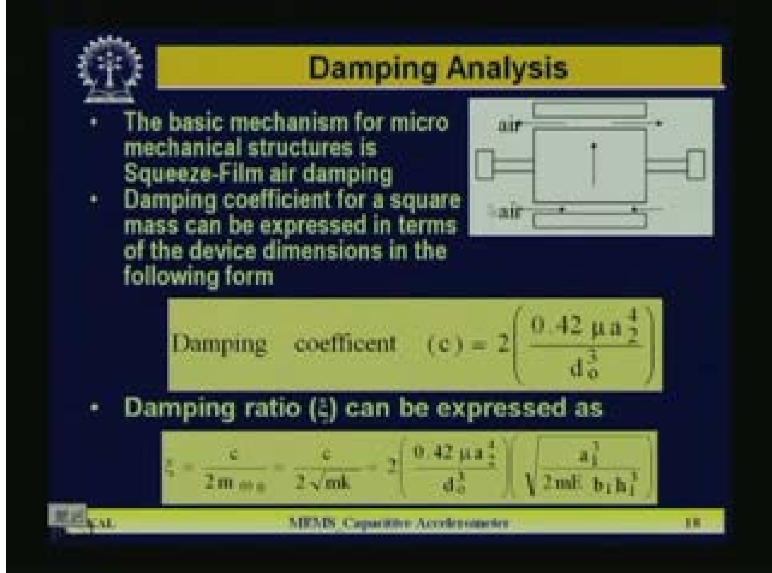

Now next is coming, the damping analysis. So damping analysis is also important for stability of the structure and there always we think of that the Squeeze-Film air damping. These are top electrode, that is the bottom electron and this is the middle. These are constructional structures, this is middle seismic mass. So that is filled with air. So air will flow in this direction. So automatically the air pressure will obstruct the movement and damping will be exerted on this structure. As a result of which it will settle after sometime. Otherwise if it is resonance, there is no damping. It will not stop the vibration, it will continue. So now damping coefficient c has been calculated as 2 into 0.42 mu a_2 square divided by d_0 cube and the xi which is damping ratio is c is a damping coefficient divide by twice m, m is mass of the proof mass, $omega_0$ is a frequency natural. Frequency of the structure which is again expressed c by twice under root mk and is given by this relation where mu is the viscosity of the damper, here which is the air and all other parameters a_1 h_1 b_1, mE are known. Now this is the damping expression, the damping ratio xi should be in the range of 0.7 to 1 in that 0.8 or 0.85 is the some desired value. So with this expression you can calculate the damping coefficient as well as damping ratio of the complete structure.

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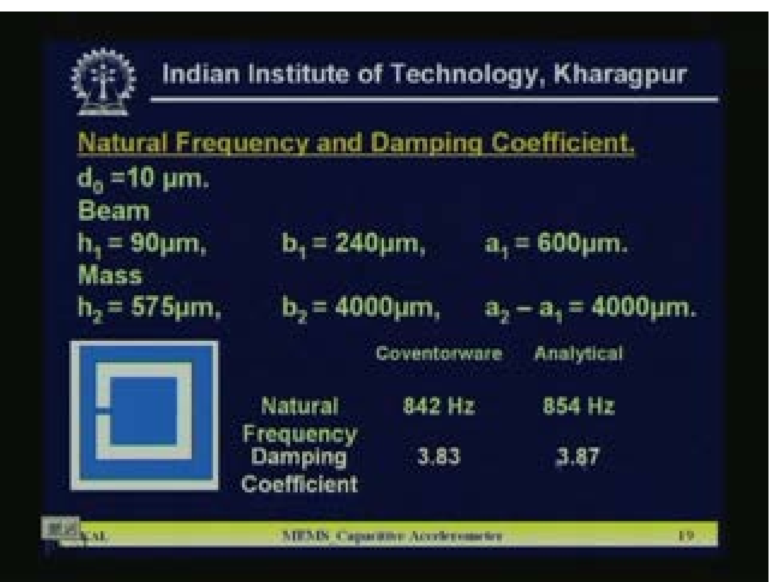

Now with certain values we have calculated using this analytical relation and also we can calculate using Coventorware software. Both are done and we have seen how close they are. So for a structure where the beam is the 90 micron h_1, that is thickness of the flexure b_1 is 240 micron is the width and a_1 is the 600 micron is the length of the beam and proof mass is thickness is 575 micron that is 570 micron thickness, this is the wafer thickness, b_2 and a_2 minus a_1 is basically b_2 is the width of the mass 4000 micron and a_2 minus a_1 you can see the length of the proof mass which is again 4000. That is square seismic mass you are using 4000 by 4000 and its thickness is 575 micron. So this kind of structure, here you can, natural frequency is calculated using CoventorWare. It is 842 hertz using analytical technique is 854 hertz.

So analytical means the expression which I gave you in my earlier slide using that relations and taking the value of h_1, d_0, b_1, a_1, you can calculate easily the natural frequency in damping coefficient. In both the cases either you go for finite element structure or the analytical structure, you can get the values like 842 and 854 which is not wide apart. In damping coefficient 3.83 and 3.87, this is very close but this damping coefficient is not acceptable because it is not our design value. Design values are of the damping coefficient should be nearly 0.721 or 1.1 and in this is may be accept in natural frequency. One it must be greater than 100 hertz it should not be less than 100 hertz. So it is greater than, so it may be acceptable but other two are not acceptable. So this kind of structure for the single flexure the capacitive accelerometer we do not use because it does not meet our design specification.

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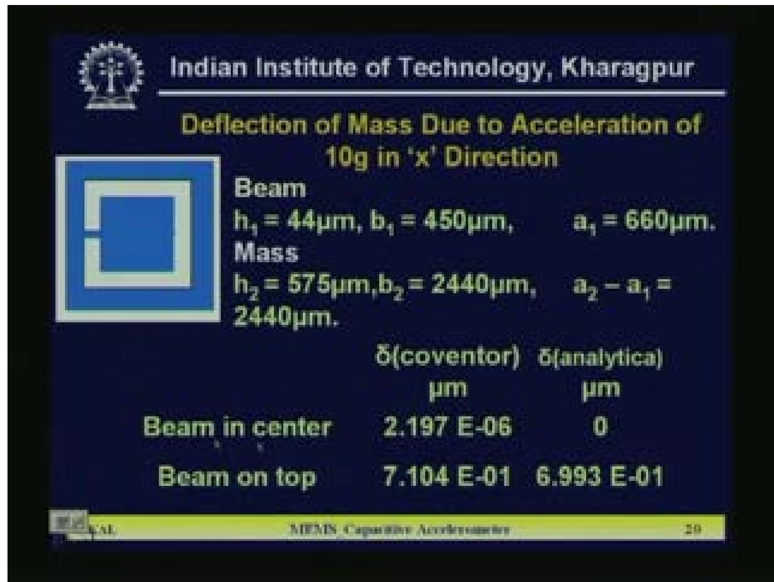

Now for 10g again we have calculated the two cases where the beam, in centre beam on top just I mentioned earlier that the beam which is connected with a proof mass and the frame it may be at the top or it may be in the center. So on the top you can see here the 7.1 so that is delta is this one and this 6.9 although calculation wise is equal but beam in the center you can see this is 2.1 E minus 6 and here it is 0. That means here is a 10g in x direction try to understand this is not on z direction. So in x direction means we do not want any delta. Delta is what the displacement along z direction. If we apply the acceleration along x direction that should be as minimum as possible. So that we found in beam in the center it is E minus 6 and beam on the top E minus 1. So obviously the top one if beam is at the center it is better and in analytical it is almost 0.

Because it is analytical straight forward, the relation if you use, so the movement along that if you apply x direction we assume that z direction is 0. So that is why it is 0, but some movement along z will be there if you put x direction acceleration. So that is why in coventor accept that, so there you are getting some value which is very small delta is the displacement along deflection to the mass due to acceleration change in x direction, that is

the delta here. So obviously if you compare this two value then always whatever the structure you use either single beam single flexure or double flexure, so you found that a beam is in the center and center means, I mean to say not the centre of the length center, mean in the thickness wise, not at the surface; but at the center of the cross section. So there if you do it, so this is a better, so far as the displacement as well as the up axis sensitivity is concerned.

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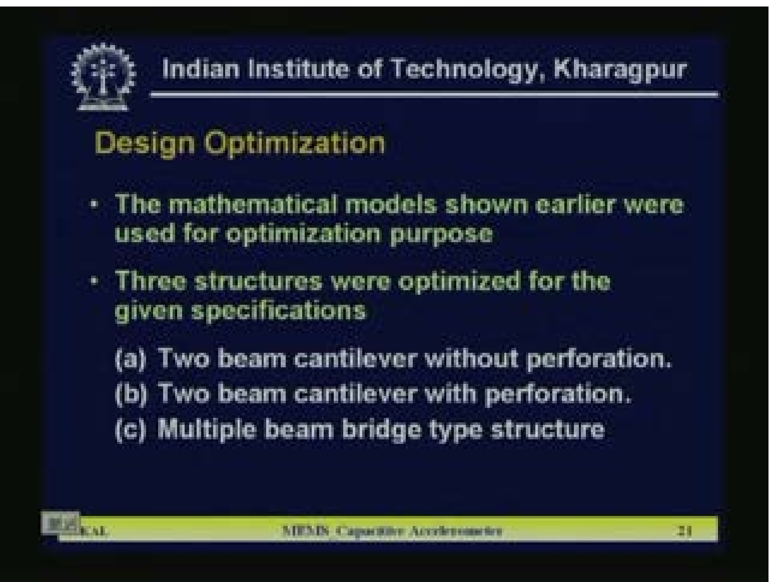

So now, so far till now I have discussed all the optimization all the different kinds of structures, either bridge or the cantilever, single cantilever, double cantilever also. Now we have to optimize the things. So out of the 3 structures, 2 beam cantilever without perforation, 2 beam cantilever with perforation, multiple beam bridge type structure. The width perforation without perforation why it is coming? Perforation means what? We have seen in the earlier viewgraph that you can summarize a damping coefficient. You see damping coefficient here is a 3.83, 3.87 so that is not at all acceptable that you can improve by making some holes on the seismic mass. So now the holes are in the periphery; blank spaces are at the periphery. Now you can put some holes at different location of the proof mass that is known as the perforation.

Then these with through that holes so air can flow from bottom to top cavity, top cavity to bottom cavity; so that will also help the damping coefficient. So that is why it has been mentioned that a 2 beam cantilever without perforation, 2 beam cantilever with perforation, multiple beam bridge type structure, there are the 3 structure now optimized. Single beam cantilever is not acceptable as I have shown earlier because that is the also in off axis means x and y axis also z displacement is enormously high so that is discarded. We go for 2 beam event in 2 beam and we have to see which structure gives you better damping coefficient. So from there and multiple beam bridge type structure is again complicated. So if I get almost similar kind of performance with the 2 beam structure with certain modification, so we will

always opt for that simplified 2 beam structure with certain modification whose performance may be very close to the multiple bridge type structure.

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Design Optimization

	Two Beam Cantilever		Eight Beam Cross Bridge Structure
	Without Perforation	With Perforation	
a_1	660μm	900μm	1400μm
b_1	225μm	200μm	250μm
h_1	44μm	120μm	40μm
b_2	2440μm	4000μm	5300μm
h_2	575μm	575μm	575μm
d_0	19μm	10μm	3μm

Now these are some optimized values or we have 2 beam cantilever without perforation and 2 beam cantilever with perforation the a_1, b_1, h_1, b_2, h_2, d_0, these are the parameters and for 8 beam cross bridge structures these are the a_1, b_1, h_1, b_2, h_2, d_0. So with this kind of the optimized value of the dimension, we can achieve the targeted value, simulated targeted value. So that is why here, since we will not go for the complicated 8 beam cross bridge structure we can without perforation of 2 beam cantilever. We can concentrate on that and we can make the design using this physical dimension.

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Design Optimization

	Two Beam Cantilever		Eight Beam Cross Bridge Structure
	Without Perforation	With Perforation	
Mass Length	2440 μm	4000 μm	5300 μm
Sensitivity	0.00125	0.00120	0.00158
Nonlinearity	0.927%	0.89%	0.934%
Natural Frequency	933 Hz	1.31 kHz	2.31 kHz
Damping Ratio	0.835	0.8**	404
δz at 10g	4.12 μm	2.12 μm	0.466 μm

Now this is the mass length using the other the a_1, b_1, h_1, b_2, h_2, d_0, these parameter we have calculated the values, the sensitivity, nonlinearity, natural frequency, damping ratio and delta z at 10g. Delta z at 10g means the the displacement of the seismic mass. So that we found that the mass length if you use, the mass length is the centre of mass and there are fixed L. The L value without perforation is this one with perforation is 4000. Sensitivity we found almost in both the cases very close and nonlinearity is a 0.927 is a 0.89 here is because desired value is very good value is 0.8. But its 0.9 slightly different, 933 hertz 1.31 kilohertz and this is the damping ratio. Here is a 0.835 is a 0.8 here and delta z 10g is 4.12 with perforation is a 2.12 micron.

That is the displacement along z direction. So here displacement along z direction without perforation is more compact to with perforation. So displacement is more that means you will have the capacitance change also more. Isn't it? So under that condition although damping ratio is same and nonlinearity you are getting very is a less than 1 in both the cases, here it will be more, that means not that bad as with perforation. But so far as the displacement, this is better. So we can concentrate on this without perforation 2 beam cantilever structure, that after optimization of different parameters with different dimension we can now stick to that structure, with those values.

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Now next is how with perforation looks like, there is one picture shown is a basically the not bridge type cantilever typed with 2 flexure and the centre some holes is made and there with acceleration how it moves, how is the movement along z direction, it is shown. That is basically the structure with perforation. In cantilever structure the damping is within limits and can be tailored to meet the specifications by perforation. Hence it can be used in open loop configuration. On the other hand in bridge type structure air damping is very high and hence force feedback configuration is must. You have to go for force feedback configuration in order to settle the open bridge structure. Besides measure structures the sealing is required to control the air pressure inside the device. Sensitivity of a bridge type structure is more as compared to the cantilever structure. If you go for a comparison of cantilever versus bridge these points are coming in to the picture.

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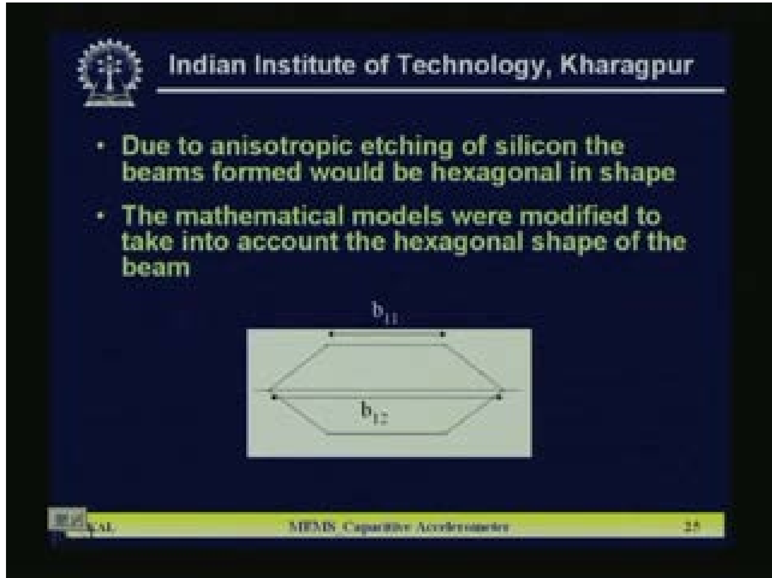

Now due to the anisotropic etching, the silicon anisotropic etching of the silicon the structure of the beam is not exactly rectangular. But it will take the form of the hexagonal shape like the figure it was shown here. The mathematical models were accordingly modified to take in to account the hexagonal shape of the beam. So whatever the analytical expressions given in earlier slide that is assuming that all the flexure and proof mass are exactly rectangular in structure; not the irregular geometry hexagonal or other kind of complex geometry. That complex geometry if it is there you have to go for the finite numerical technique which is the finite element analysis and that can be done using Coventorware. There you cannot use the close form relation analytical expression which is shown in earlier viewgraph.

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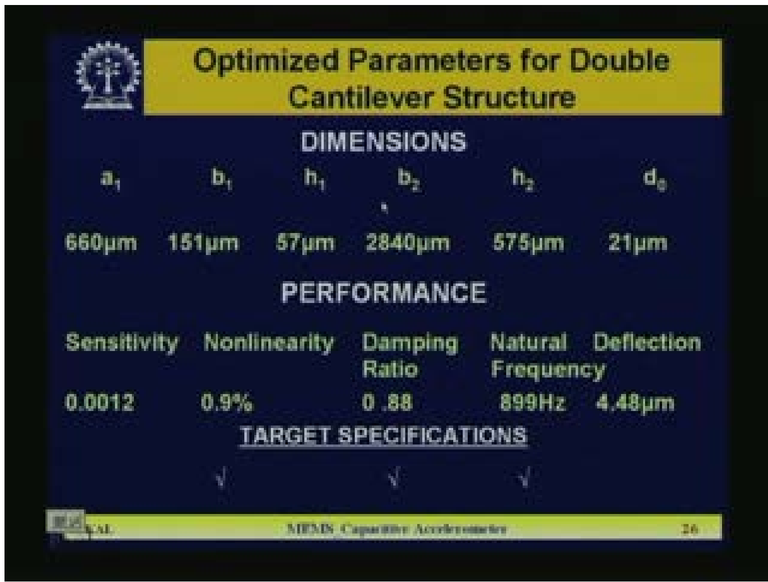

Now the dimension we confine in to this these values. So a_1 will be 66 micrometer b_1 is 151 that is the width that is the length of the flexure, h_1 is thickness 57 micrometer and b_2 2840 h_2 this is b_2 h_2 is related to the seismic mass. There b_2 and a_2 are same because square structure we are using 2840 and h_2 is a 575 micrometer. That is the substrate thickness the seismic mass. But the flexure it is 57 micron thickness only. So that has been edged bulk micromachining we restricted to 57 micrometer. So if you concentrate at the performance of the structure its like that sensitivity 0.001 to nonlinearity 0.9 percent, damping ratio 0.88, natural frequency 899 hertz, deflection 4.48 that, all those values are shown in earlier table also, say with without perforation column. So now target specifications has been achieved in the nonlinearity, damping ratio, natural frequency and sensitivity is also very close we want there, similar kind of sensitivity.

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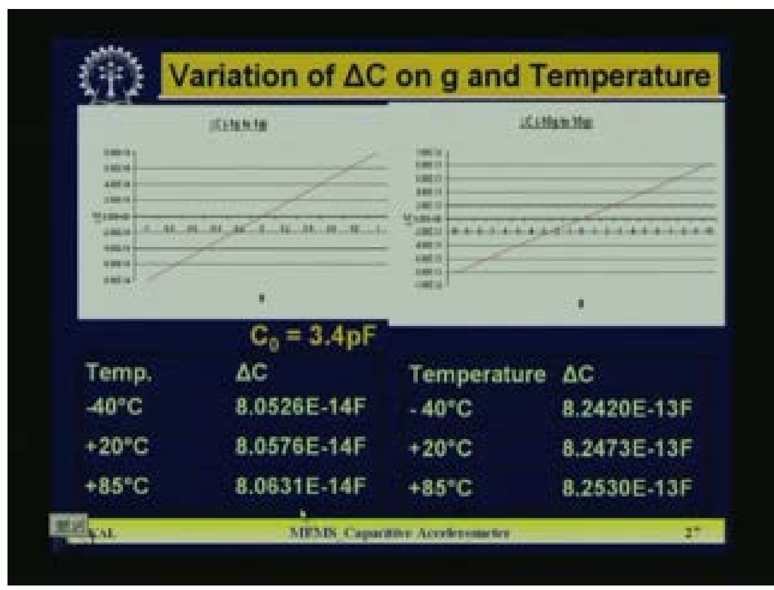

So we can just go for designing and the delta C for this structure for minus 1g to plus 1g and minus 10g to plus 10g is plotted. So that is shown at say room temperature is nearly 8 into 10 to the power minus 14 farad delta C change and for minus 1g to 1g and for minus 10g to plus 10g, that is acceleration is plus 10g and deceleration in minus 10g is almost these are simulated value and there we got these the relations here. With those relations, regular structure we got the delta C values like that, it is of the order of 8024 into 10 the power minus 13, for minus 10g it is 8.05 10 to the power minus 14 farad in case of 1g. So 1g and 10g, in both cases the two designs has been calculated and simulated and the values are so near. C_0 means at the rest position the capacitance is 3.4 picofarad and these are the delta C with temperature calculation has been made and there also you can find there is hardly any difference with temperature. That is the beauty or advantage of this capacitive accelerometer compared to piezoresistive. You can see in both the cases the variation is almost negligible may be in the third decimal place in 10 to the power minus 13 farad in that ring and almost negligible.

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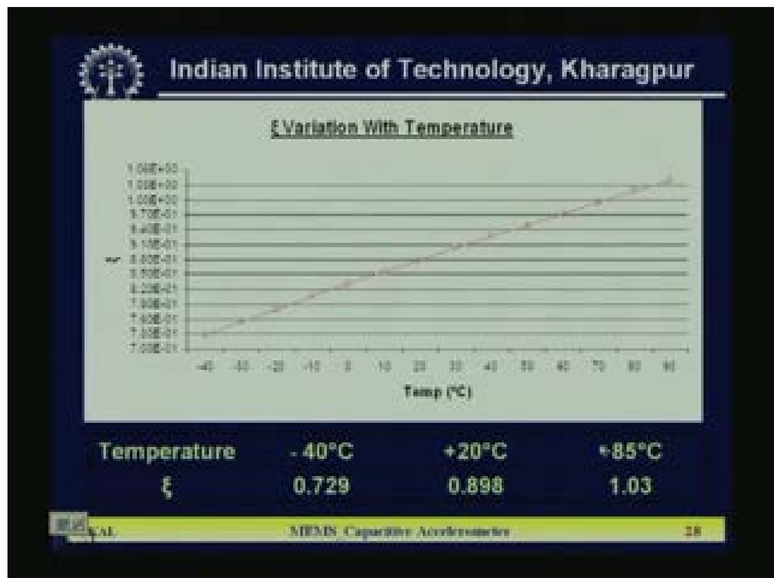

So now the variation of the xi that is the damping ratio. That variation is also shown or at different temperature plus 40 degree C, minus 40 degree C, plus 20 degree C, plus 85 degree C. So about the whole temperature change we found it is in minus 40 C it is a 0.7 to 9 plus 20. That is room temperature is 0.898 and plus 851.0 C. That means we found that it is not wide variation and these, that is our targeted value of xi was given in the first slide, that was 0.7 to 1.2 and the whole temperature change is minus 40 to plus 85 it is within that range so we can go for that particular design which we have stated earlier.

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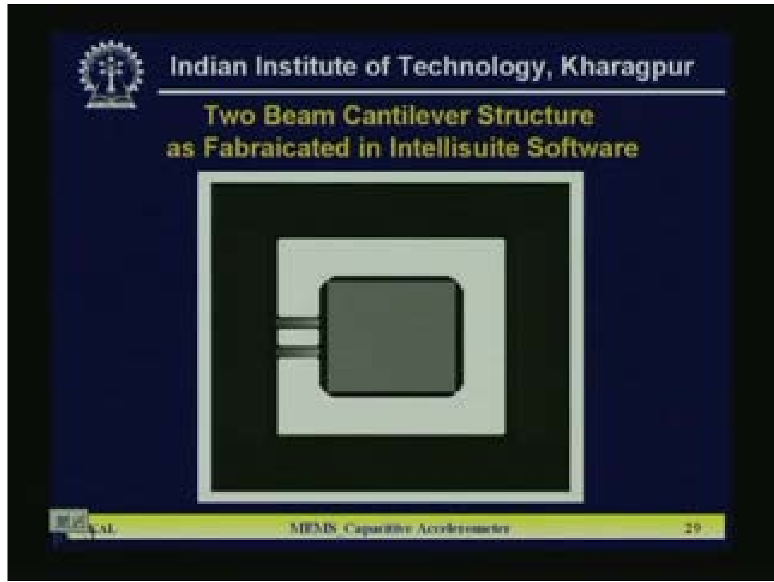

Now the two beam cantilever structure has been simulated and fabrications part has been simulated using Intellisuite software that is software, it is not CoventorWare. So Intellisuite software you can give this process steps and dimension and there you can see the how the structure comes after fabrication. So there with those dimension what we suggested earlier in our design that has been applied and some tentative process steps has been given and after the process is over the complete structure senses structure looks like this. Here one point I would like to mention that here this kind of structure has got the 4 corners. So all the 4 corners will be etched faster with the parallel as compared to the parallel plane structure parallel or this either the along the length, along the width. So in that case sometimes here some compensation is given as corner compensation so that although it is first at the end, so it should be, it should look like almost a square frame. So that is why some compensation like rectangle piece is added here so that after etching it will be almost the whole structure will be as rectangular as possible. If we make it square, as square as possible and this is at the centre of the cross section flexure.

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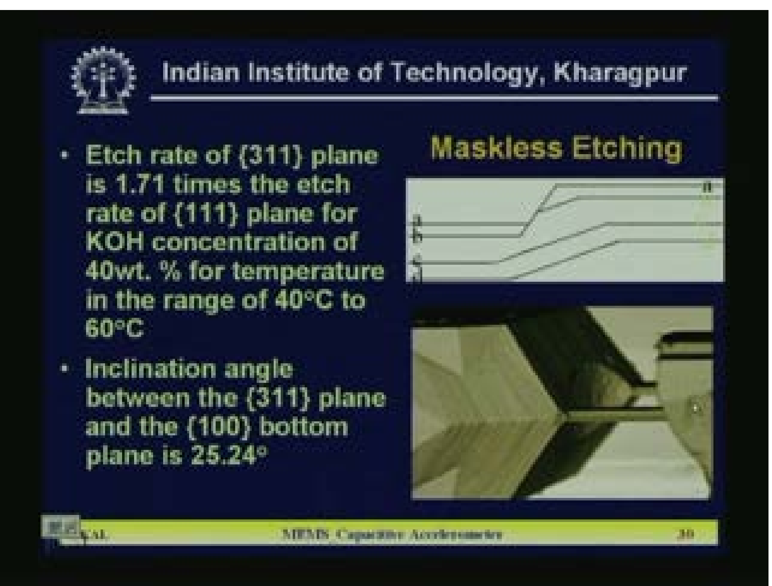

Now the here if you want to have at the centre you see this is some diagram is shown. This is one side is a frame, another side of mass and you can see how it is held at the center. So how can you get that structure? That is again we can use the micromachining step which is mask less etching some kind of things. So you can see here if you etch in this direction, so it will come, it will reduce dimension from here to here and this side also, there to there and that is the crystallographic plane dependence of etch rate. So that I mentioned in my micromachining class so that use the KOH the anisotropic etching. So that will not etch in a equal rate in all crystallographic orientation of the silicon and we have found the etch rate of 311 plane is 1.71 times the etch rate of 1 1 1 plane for KOH concentration of 40 weight percent for temperature in the range of 40 degree C to 60 degree C.

So that has been observed and the inclination angle that means this angle between 3 1 1 plane and the 1 0 0 bottom plane is 25.24 degree. So this kind of etching, how to get this kind of structure is again one important issue which you have to practice and we are doing so in our laboratory to get the flexure at the centre of the cross section. Earlier in piezoresistance case this kind of flexure is not coming to the picture. That is at the top surface because there we diffuse piezoresistances on the surface of the single crystal silicon. So you cannot make the flexure at the middle or middle of the cross section. That is that case we fabricated everything as the top surface but here as we found that this kind of structure gives better performance. So we can have certain technique, we have to involve it and that is being done to get the structure at the center of the cross section.

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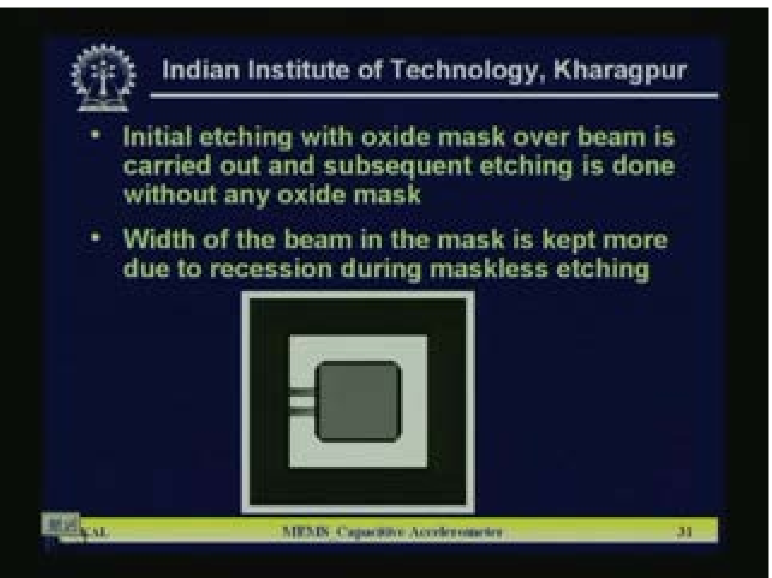

This is the thing, so initial etching with oxide mask over beam is carried and subsequent etching is done without any oxide mask. So one, first few minutes the etching is done with oxide mask and after that if you remove oxide, then that rest portion is the maskless etching. Maskless etching means some of the crystallographic axis I as I mentioned 1 0 0 or 3 1 1 and 1 1 0 the difference is there etch rate. So that will automatically give you similar kind of structure. Width of the beam in the mask is kept more due to a recession during maskeless etching. So you have to think little bit more how the maskless etching is used the no mask is required to get the flexure at the centre of the cross section. So that has been exploded and it can be done.

We have seen now in our laboratory this kind of etching is practiced and I hope within few practice we will be able to get similar kind of structure. Now after designing the next part will come is the fabrication. So that fabrication again what will the steps you can see the fabrication there are 3 pieces. One is middle sensing piece, another is a top electrode, and another is the bottom electrode. So all the 3 pieces are separately fabricated and at the end you have to bond all the 3 pieces and at the same time you have to think contact. How will take the contact with the top electrode and the middle and bottom electrode and the middle.

So that fabrication details and the making contact of the each electrode and the substrate bonding mechanisms we will be discussed in the next lecture. Thank you.

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Preview of the next Lecture

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In my last lecture I was discussing on a case study on the MEMS sensor that is MEMS capacitive accelerometer. Some specification we defined and from there how these specifications are achieved we discussed on that. Two methods we followed; one is analytical treatment and the other is the simulation using standard simulation tools and we

compared the results. I remember I also discussed various structures of the capacitive accelerometer which are bridge type some are the cantilever flexure type. So out of that we found a particular structure which is double cantilever beam structure is quite sensitive and without much difficulty of technology and with that we achieved our goal by certain simulation, certain parameter variation. And after satisfying those parameters our next step will be how to go ahead for fabrication of those devices and basically the structures contain 3 pieces and how the 3 individual pieces are fabricated and then how they are assembled that I will discuss today.

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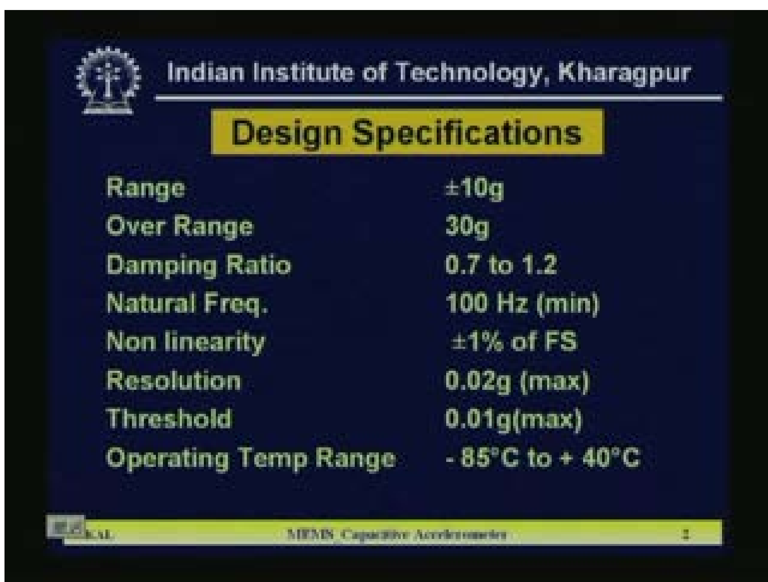

The design specifications which I mentioned in my last lecture are range 10 minus plus minus 10g, over range 30g, damping ratio 0.7 to 1.2, natural frequency 100 hertz, and non-linearity plus minus 1 percent of full scale; resolution 0.02g threshold is 0.01g operating temperature range minus 85 to plus 40 degree centigrade.

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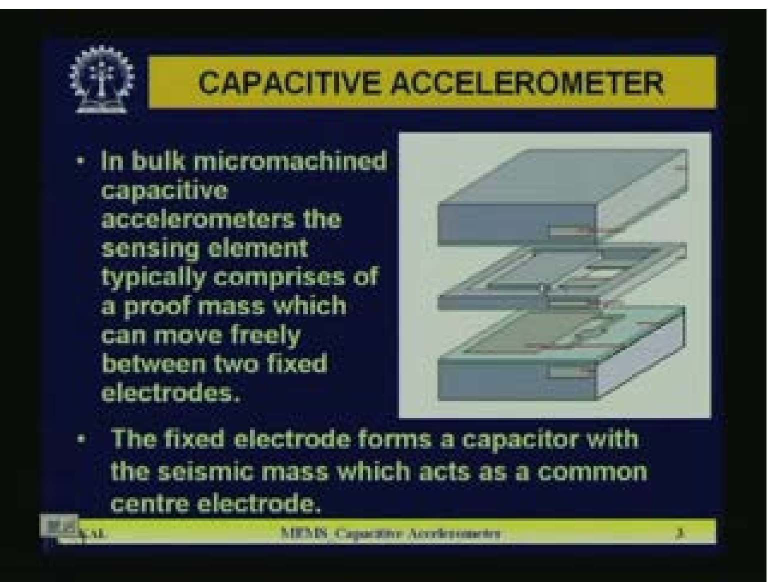

So with that we confined to this structure which is shown here 3 pieces; middle piece is basically the sensor and the top and bottoms are two fixed electrodes which form parallel plate capacitance with the central piece and the central piece is comprising of a proof mass which can move freely between the electrodes and accordingly the capacitance between top fix place and middle, the sensing electrode and that with the bottom fixed electrode will vary. And we will are going to measure the differential change of capacitance of this particular structure. And as we used a proof mass and that proof mass will displace according to the acceleration. And as a result of which the gap between two plates will change and capacitance variation will be detected and which is the measure of the acceleration.

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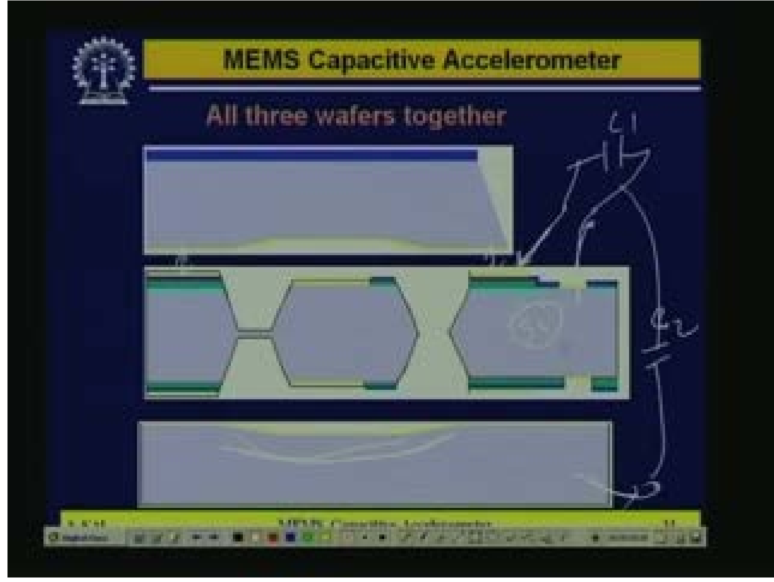

Because in the bottom of this bottom, bottom electrode it does not have any insulating layer at the bottom side of the wafer. You have delineated this portion, but this side is intact. So that means one you can take here, one you can take here and the third you can take either side or from the bottom. That means middle is fixed from middle and this will give you the one C1 and similarly this and this you will give another C2, this and this will give because this is the common contact you are making. So in this way you can get after the 3 wafer bonding you can get the complete thing.

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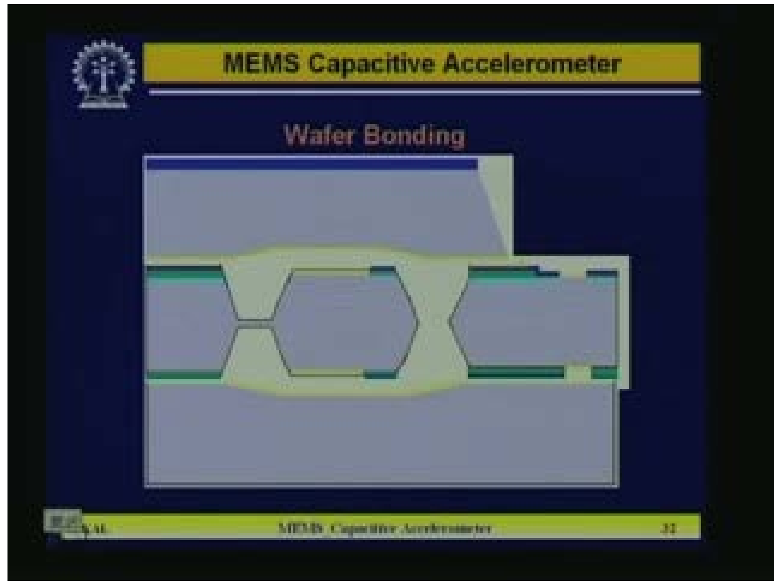

The wafer bonding has been taken place both top and bottom are joint together you got the 3 structures. So in this way one by one you fabricate separately. Now the assembly is another very important point in this particular the capacitive accelerometer fabrication where you have to have the both C1 and C2 top and bottom capacitance contact should be proper and then you will. Because you know these the C1 C2, both capacitance structure top and bottom will help you elimination of any parasitic or some noise pick up. Because you are giving stress on your differential capacitor difference delta C C1 minus C2. That is proportional to g, that variation will be with g, will be there and that we are interested. So in that way because you see here a lot of the conducting planes are there and if you use the conducting silicon wafer there is also going to create problem.

Because the conducting wafer with any other ground plane it will have some parasitic also and that are the major concern in case of many capacitive accelerometers. So there we have to see certain design modification certain techniques so that those parasitics can be removed completely. So this is the complete process sequence of this capacitive accelerometer structure and I am not going to discuss further on this and now we will discuss another inertial sensor. So that is the gyro sensor. So we covered two case studies; one is the piezoresistive accelerometer, the second one capacitive accelerometer with certain goal and how we design it and after design how we fabricate also, that also we discussed in both the cases. Now I will give some stress on another kind of inertial sensor. That is the gyro or rotation sensor and there I would like to give some stress on the quartz gyro sensor with little introduction of silicon gyro. So next class we will discus on gyro sensors, MEMS gyro sensors. Thank you very much.