

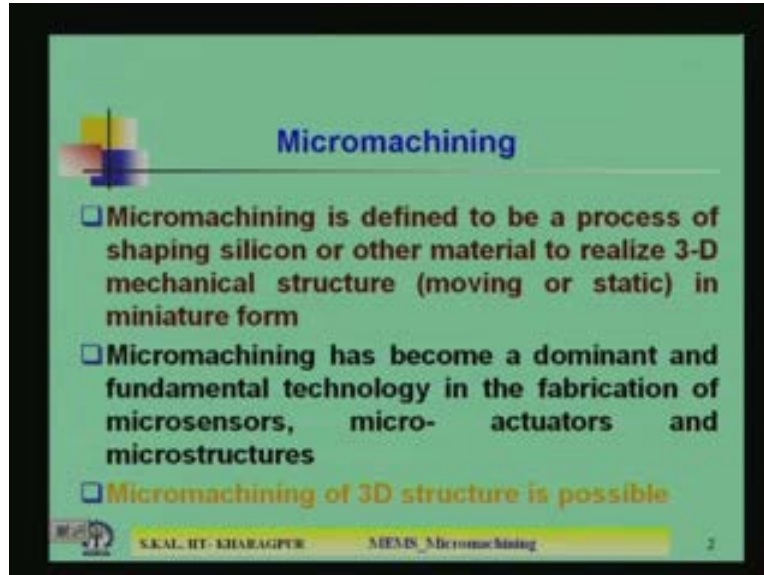
MEMS & Microsystems
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Lecture No. # 10
Micromachining Technology for MEMS

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I welcome you for today's lecture on micromachining technology for MEMS. You know that MEMS is full form microelectromechanical systems and in MEMS we need lot of microstructures like flexures, cantilevers, membranes, nozzles and many other structures which may be symmetric or asymmetric. But to get those structures, mechanical structures normally in mechanical engineering we made the structure by using certain machines which are lathe machine grinding, polishing, and etcetera. But in MEMS technology we may see materials like silicon, quartz and many other materials using certain technique which are compatible with the VLSI processes and those techniques are mainly the etching techniques and in particular anisotropic etching technique is used for making microstructures in MEMS. So machining here are done to obtain very fine structures of the order of say micrometer range several 100s of micrometer range and that is why the name is called micromachining.

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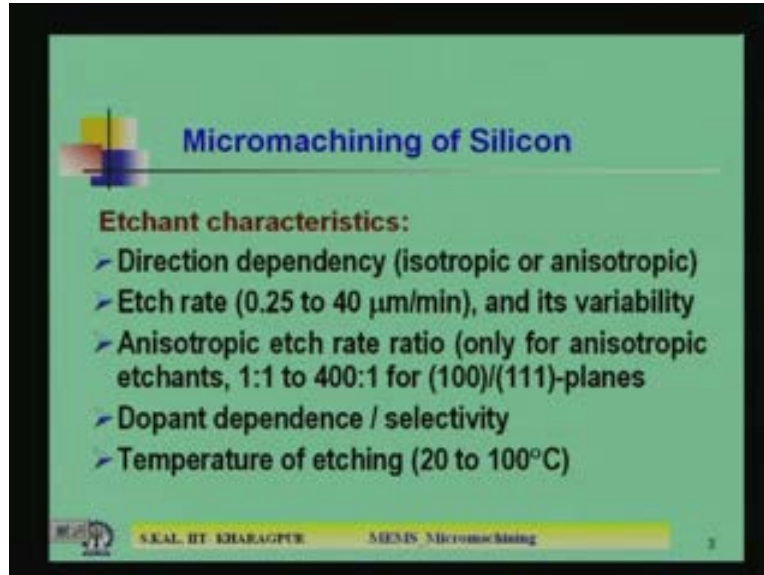
Micromachining

- Micromachining is defined to be a process of shaping silicon or other material to realize 3-D mechanical structure (moving or static) in miniature form
- Micromachining has become a dominant and fundamental technology in the fabrication of microsensors, micro-actuators and microstructures
- Micromachining of 3D structure is possible

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Now the micromachining definition is like this. It is a process of setting silicon or other material to realize 3D mechanical structures and these 3D mechanical structures may be moving or static. Here is the difference with the VLSI etching or machining and MEMS machining. In a MEMS machining the microstructures some times move, but in case of VLSI the structures are static. That is why it is known as micro electro mechanical systems. Micro machining has become a dominant and fundamental technology in the fabrication of microsensors, microactuators and microstructures. It is basically a process by which you can get a 3D structure. Normally in IC technology we use 2 dimensional structures by either wet etching or dry etching. But in MEMS the structure will be 3 dimensional, so that you can make certain actuators or sensors in the complete micro system.

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Now silicon micromachining has certain characteristics and what are those? First one is direction dependency. What do you mean by direction dependency? That means if you etch silicon, etch rate of the silicon is not uniform in all direction. That means if you dip the silicon wafer into the etching solution, the vertical etch rate, a lateral etch rate will in the silicon bulk we will not be the same. If it is same, then this is known as the isotropic etching. If it is not same, then this known as anisotropic etching. That means etch rate depends on the direction. On the other hand some times this etching is also depended on crystallographic orientation. That means the etch rate of 1 0 0 plane of silicon is not same as etch rate of 1 1 1 direction of silicon; crystal plane of silicon. So when the etch rate of different crystal planes are different, then that is also known as anisotropy or crystallographic anisotropy of etching.

Second point is etch rate. Etch rate also varies with the concentration of the etching solution. It varies with the temperature and many other things and this etch rate varies from 0.25 to 40 micrometer per minute. In many cases we have to control the etch rate. So we need some times the etch condition or etch bath temperature or mechanical stirring all has to be perfect means has to be standardized to get certain etch behavior. Now the third point is etch rate ratio. Just now I told you that etch rate of 1 0 0 crystallographic plane and 1 1 1 crystallographic plane of silicon are not same. For anisotropic etchant this may vary from 1 is to 1 which is the isotropic to 400 is to 1 also depending on which type of the etching solution you are going to use and what are the conditions of etchant bath you are maintaining and fourth characteristic is the dopant dependence of etching etch selectivity.

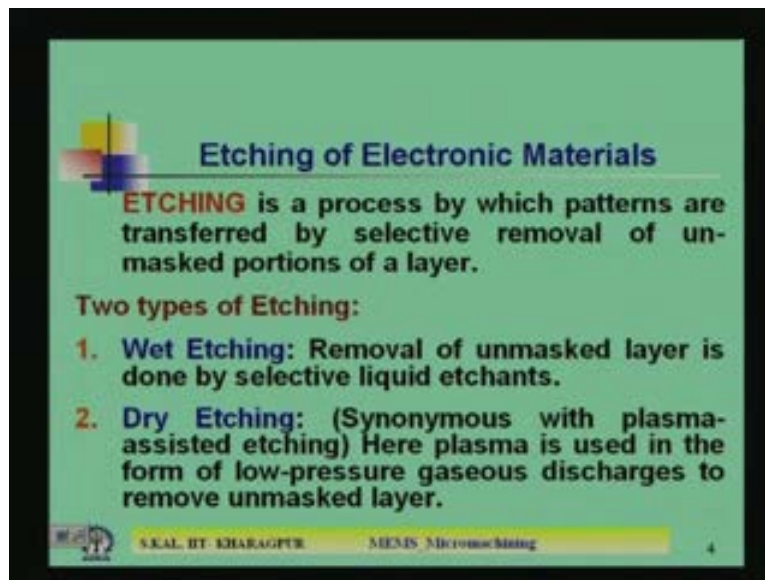
Etch selectivity is also very important aspect because if you want to etch a certain a region, so you have to passivate the other region which you do not want to etch. That means here, you are putting some passivation layer and those passivation layer will not be affected by the etchants or etching solution. That is known as the selectivity. That means let me give you one example. So if you want to etch silicon and if the silicon passivation layer is silicon, etch passivation layer is silicon dioxide. Then when we put the complete wafer covered with silicon dioxide, some

portion and some portion no silicon dioxide. That means the region we want to etch. So when we deep it into the solution, then the etch rate of silicon will be very high compared to the etch rate of silicon dioxide in the same solution it is known as selectivity.

So this selectivity is very important aspect when you want to make some microstructures and that means, it depends selectivity is basically coming from the material properties as well as the etching chemical properties. At on the other hand in some times we can see that this etching is also dependent on the dopant. That means if a silicon wafer is doped with for example say boron and if the concentration of boron are varying over the entire silicon surface or say along the bulk of the silicon material, then we have seen that if the doping is very high then the etch rate reduces, the etch rate is very small. On the other hand in doping is very low doping so there are easily it etches. That means the etching behavior is also dependent on the concentration of the dopants inside the silicon bulk material so last characteristics of etching is the temperature of etching.

So obviously the etching bath temperature has an important role on the etch characteristic. In most of the silicon or silicon dioxide etchants, they depend on the temperature of the bath. In many cases we found if the temperature of the bath increases, its rate also increases. So that mean etch rate depends on temperature also. So keeping in mind all these aspect we have to design or we have to make certain process so that we can get our desired microstructure from silicon. The process is known as micromachining of silicon.

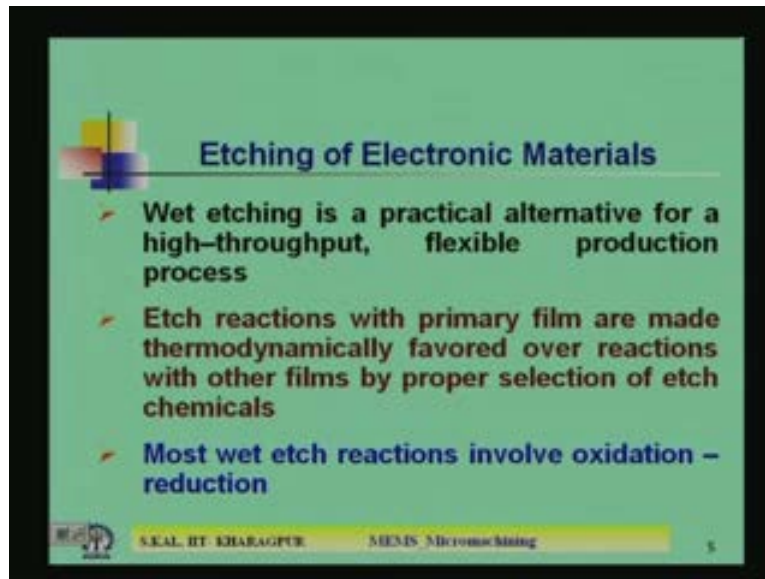
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Now etching is an important process in IC technology. What is etching? It is a process by which patterns is transferred by selective removal of un-masked portions of a layer which are masked, those portions will not be etched; which are un-masked; those portions will be removed selectively in the solution. There are two types of etching. One is known as a dry etching and the second is known as the wet etching. So dry etching and wet etchings are extensively used in IC technology also. In wet etching we remove the un-masked layer by selective liquid etchants. That

means wet etching is done in some liquid solvent. On the other hand dry etching we do not use a liquid solvent, here we use plasma. Plasma in the form of low pressure gaseous discharges is used to remove unmasked layer. So these are the two kinds of etching.

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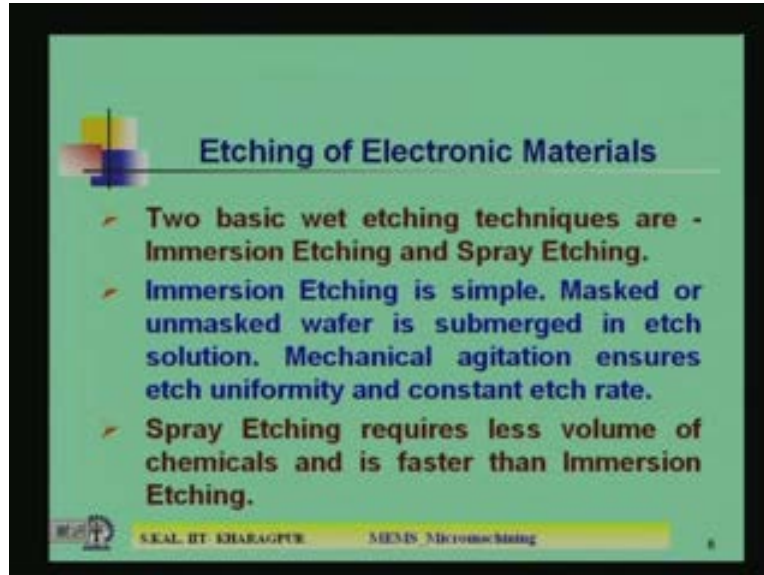
Etching of Electronic Materials

- **Wet etching is a practical alternative for a high-throughput, flexible production process**
- **Etch reactions with primary film are made thermodynamically favored over reactions with other films by proper selection of etch chemicals**
- **Most wet etch reactions involve oxidation – reduction**

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Some other aspects of wet and dry etching are also mentioned here. Wet etching is a practical alternative for a high-throughput flexible production process. What does it mean? Throughput is a parameter which always you have to keep in mind when you are going for in industrial process. Throughput means in a certain step, certain etching process, how many wafers you can etch at a time. So in case of wet etching the number of wafers may accommodate in the etch bath depends on the size of the etching chamber and it can be very large ranging from 50 to 100 wafers can be etch at a time in case of wet etching. That is why in wet etching process the throughput is very high and it is a very flexible production process. Etch reactions with primary films are made thermodynamically favored over reactions with other films by proper selections of etch chemicals. Here is basically coming the selectivity aspect. That means primary film we want to etch secondary film which is the passivated layer is known as the secondary film. So, primary film will be thermodynamically favored for etching, whereas a secondary film is not favored for etching in the same etching solution. Most wet etch reactions involve oxidation-reduction reaction.

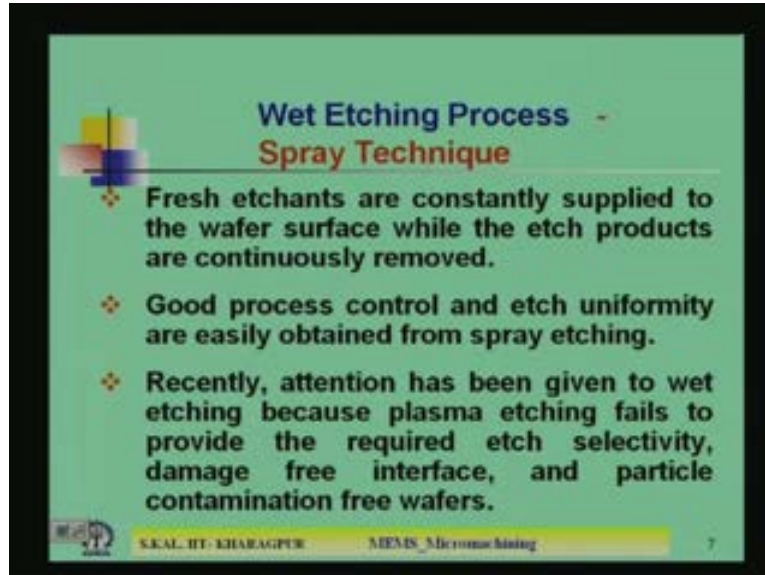
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Two basic wet etching techniques are immersion etching and spray etching. What is immersion and spray etching? Immersion etching is very simple technique and here masked or unmasked wafer is submerged in etch solution. Mechanical agitation is given during the etching process. Why? Because it ensures etch uniformity and constant etch rate. That means in immersion etching you required a huge amount of chemicals in which you can put the 50s or 100s numbers of wafer and it is submerged, the all wafers are submerged into the solution and you have to apply in mechanical agitation which give you etch uninformative. Why? Because during etching sometimes some gas evolves and the gas bubbles will stick on the surface of the wafer which will hinder for further etching process. So that is why a continuous mechanical agitation is established in the etching solution so that the gas bubbles bubble cannot stay on the surface of the silicon wafer.

Rather it will lead the etching solution and it can be exhausted from the etch bath. So this is very important aspect and if you make proper agitation then etch rate will be uniform and you can get constant etch rate. On the other hand spray etching technique requires less volume chemicals and is faster than the immersion etching. That means in spray etching we are not going to immerse the whole lot of wafer, rather on the etch bath we spray the etch solution. So that the etch solution will fall on the surface of the wafer and at the same time the etching will take place and because it is done or because of the spraying. So what will happens, automatically some mechanical agitation is ensured. So in that case we find that etch is etching process is very fast and here obviously you need less amount of chemical. Now the spray technique

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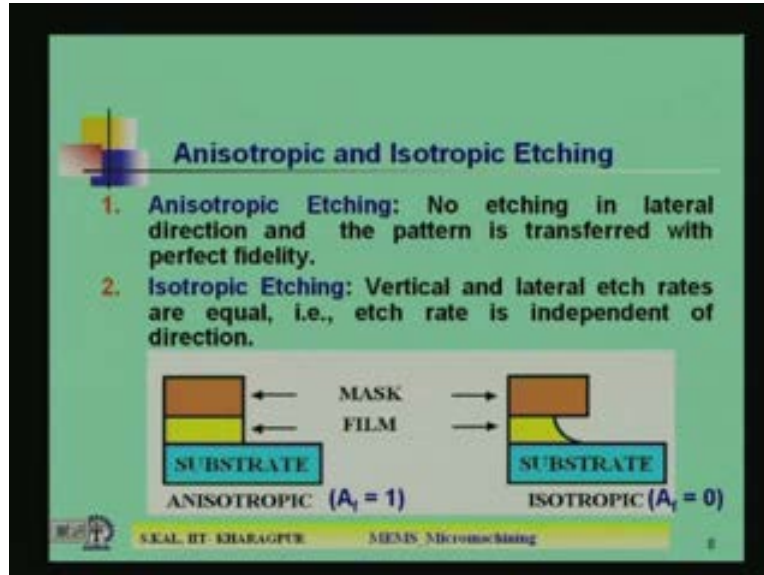
**Wet Etching Process -
Spray Technique**

- ❖ Fresh etchants are constantly supplied to the wafer surface while the etch products are continuously removed.
- ❖ Good process control and etch uniformity are easily obtained from spray etching.
- ❖ Recently, attention has been given to wet etching because plasma etching fails to provide the required etch selectivity, damage free interface, and particle contamination free wafers.

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Here fresh etchants are constantly supplied to the wafer surface while the etch products are continuously removed. That is one advantage of the spray technique compared to the immersion technique. Since you are placing fresh solution, your wafers are freshening. Always the fresh amount of the etch solution and the etched by products are continuously removed, which is not possible in the immersion kind of etching. Good process control is ensured, etch uniformity are easily obtained from the spray etching. Recently attention has been given to wet etching because plasma etching fails to provide the required etch selectivity damage free interface and particle contamination free wafer. So at some point of time people preferred the dry etching process which is based on the plasma, blow discharge of plasma. But later on we found that this plasma etching techniques are not highly suitable for microlithography or micro etching process. Because that plasma creates some damage at the interface which is not there in case of liquid agent either spray or immerse. So that is why nowadays again people are giving much more importance in wet etching process compare to dry etching process.

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Anisotropic and isotropic etching, I told you there are two kinds of etching. Now we will see the difference between anisotropic and isotropic etching. How it is defined? Anisotropic etching, basically the etch rate etching is not done in all direction uniformly. That means no etching in lateral direction and the pattern is transferred with perfect fidelity. On the other hand the isotropic etching case vertical and lateral etch rates are always equal. That is etch rate is independent of direction. Now you can see the diagram, so one is anisotropic, here you can see the layer, one is mask, the red color is mask, the yellow is the film and the bluish color is the substrate.

Now in case of anisotropic etching you can see the vertical etch rate is more and there is no lateral etch rate. So you can get the perfect fidelity here. But in case of isotropic etching we found vertical etch rate and the lateral etch rate are same. That is why there is an amount of undercut, below the mask in case of isotropic etching process. Now there is a parameter which is known as the A_f . You can see here A_f is known as degree of anisotropic. Will define now the degree of anisotropic which is 1 in case of anisotropic etching and which is 0 in case of isotropic etching.

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Anisotropic and Isotropic Etching

Degree of anisotropy,

$$A_f = 1 - \frac{R_l}{R_v} = 1 - \frac{B}{2h_f}$$

$R_l \rightarrow$ Lateral etch rate, $B =$ bias
 $R_v \rightarrow$ Vertical etch rate, $h_f =$ film thickness

For anisotropic etching, $R_l = 0$, $B = 0$. Thus, $A_f = 1$
For isotropic etching, $R_l = R_v$, $B = 2h_f$. Thus, $A_f = 0$
In general, $1 \geq A_f > 0$ represents anisotropic etching

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Let us see where, how degree of anisotropy is defined. Degree of anisotropy A_f is defined as 1 minus R_l divided by R_v where R_l is lateral etch rate and R_v is the vertical etch rate and which is again equal to 1 minus B divided by twice h_f where B is known as the bias and h_f is film thickness. Now for anisotropic etching we have seen that lateral etch rate is 0. There is no lateral etch rate, only vertical etch rate will be there. So if the R_l part is 0, then automatically the bias will be 0. So in that case A_f becomes 1. On the other hand for isotropic etching you can see lateral and vertical etch rates are equal. So if R_l is equal to R_v then obviously A_f becomes 0. To make A_f equal to 1 the bias has to be twice h_f . So in isotropic etching, the bias is twice h_f , thus A_f equal to 0. Now what is the bias? Bias means how much the lateral encroachment or say undercutting below the mask layer. So the undercut below the mask layer is basically the measure of bias. Now we found that anisotropic etching A_f equal to 1 and isotropic etching A_f equal to 0. So two extreme cases, now in general a the anisotropic etching we found A_f is in between 1 to 0 it is always because an ideal case A_f equal to 1 which is not possible. So it is always less than equal to 1 and is greater than 0. So that is the case for degree of anisotropic.

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Etch Selectivity

❖ Suitable etch recipe is to be searched so that the film etches much faster than mask material or substrate

Film-to-mask selectivity :

$$S_{fm} = V_f / V_m = \frac{\text{Etch rate of film}}{\text{Etch rate of mask}}$$

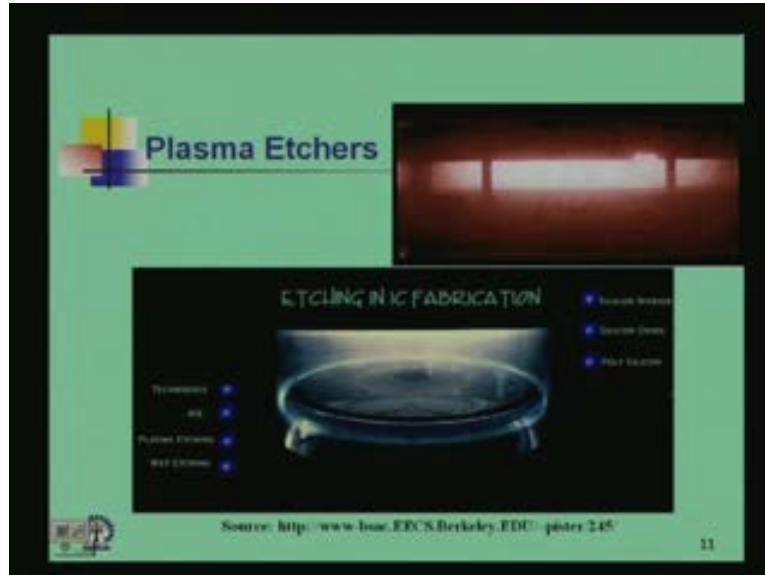
Film-to-substrate selectivity :

$$S_{fs} = V_f / V_{Sub} = \frac{\text{Etch rate of film}}{\text{Etch rate of substrate}}$$

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Now etch selectivity. What do you mean by etch selectivity? Etch selectivity means that some layer that is primary layer is favored for etching and the secondary layer or mask layer will not be etched. So suitable etch recipe is to be searched so that the film etches, that is primary films etches much faster than mask material or substrate. So now you see in the earlier diagram you can see, here you can see one layer is a mask, one is substrate and yellow layer is the film. If you want to etch the film only, so we need protection of the mask as well as substrate. Why? Because after etching is finished so then the etching solution will face the substrate so you want that substrate also will not be etched. So that means we need the selectivity of etching with respect to the mask as well as with respect to the substrate. That is why the etch selectivity is defined as film to mask selectivity and other one film to substrate selectivity. So film to mask selectivity is define by S_{fm} which is equal to V_f by V_m . V_f stands for etch rate for the film and V_m stands for etch rate of mask, V is the etch rate, f stands for film and m stand for mass. So etch rate of film and etch rate for mask ratio is known as S_{fm} which is film to mask selectivity. On the other hand film to substrate selectivity is defined as S_{fs} which is V_f divided by $V_{\text{substrate}}$ which is equal to etch rate of film divided by etch rate of substrate. So both are important in order to get perfect microstructure.

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Now there is a picture here, which shows the plasma etching process. So plasma etching process we mention is basically dry process. Here the throughput is less. Why? Because you can see the etch chamber. Here you can have to keep the wafers on this substrate holder and the substrate holder will not contain large number of wafers like 50,100, is not possible. So that is why here the etch throughput is less and here we use the plasma etching or reactive ion etching process and with this we can etch silicon nitrate, silicon dioxide or polysilicon. Now on the top figure you can see, basically there are two plates separated by a small gap. Now if you apply potential, large amount of voltage between the two plates and if a gas is inserted into the chamber, so then because of the electric field, the gas inside the chamber which is normally use some organ in a gas or in some oxygen plasma. We can use oxygen or some reactive gas also. The gas will be ionized in presence of the high electric field. Once the gas is ionized they will start discharging and you can see the glow which is basically the plasma and because of this glow, this plasma, it will hit the surface of the wafer and in the plasma discharge process some of the material or primary film which you want to etch will be removed from the substrate. That is the plasma etch process which is again a dry etching process.

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Crystallographic Orientation Dependent Etching

Isotropic Etching:
Removes material equally in all crystallographic direction, results in undercutting and uncontrolled etch features

Anisotropic Etching:
Crystallographic dependent etching, where etch rates vary according to the type of crystal plane exposed to the etchant

Isotropic Etchant for Si: Hydrofluoric acid

Anisotropic Etchant for Si: EthyleneDiamine
Pyrocatechol (EDP) Potassium Hydroxide (KOH)

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Now the isotropic and anisotropic etching we defined earlier slide as the lateral and vertical etch rate difference. Now there is another definition of the isotropic, anisotropy with respect to crystallographic orientation dependent etching. Now in this particular case the isotropic etching means here removes material equally in all crystallographic direction and it results in undercutting and uncontrolled etch feature. Because if in all crystallographic direction the etch rate is same. So obviously there is a possibility of undercutting. What is undercutting? Below the masking layer the etch will continue etching will continue. So that is the undercutting, which is not a desired phenomena in either IC technology or in MEMS courses. Also on the other hand, there is another is anisotropic, isotropic etchant is basically the etch rate of silicon in different isotropic planes are different. In some plane etch rate is much faster with respect to the other plane.

So that is hystorographic and isotropic. Now if I give certain example isotropic etchant for silicon is hydrofluoric acid. On the other hand anisotropic etchant for silicon is ethylene diamine pyrocatechol which is known as EDP. Another example of anisotropic etchant for silicon is potassium hydroxide, which is a very common micromachining etching solution which is used in different laboratory. So potassium hydroxide and EDP are being used quite a lot of time since over several years for getting the micro machine structures in anisotropic etching process. There are very recently another anisotropic etchant is used for getting microstructures that is TMAH. TMAH is highly CMOS compatible and we will discuss the TMH etching process in detail in future classes.

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Acidic Etchants (Isotropic Etchant) and Etch Masks

Hydrofluoric (HF) + nitrite (HNO_3) + acetic acid (CH_3COOH) → does not show crystal orientation dependency

- 1:3:8 ratio of HF: HNO_3 : CH_3COOH mixture at room temperature etches heavily doped ($75 \times 10^{19} \text{ cm}^{-3}$) Si between 50 – 200 μm / h with a selectivity over lightly doped ($<10^{17} \text{ cm}^{-3}$) being 150.
- Dopant dependent selectivity is opposite of that of strong alkaline system

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Now let us discuss on the isotropic etchant. There are various kinds of isotropic etchant. Some are acetic, etchants and one example is hydrofluoric acid plus nitric acid plus acetic acid. HF plus HNO_3 CH_3COOH mixture, it does not show any crystal orientation dependency. So if it does not show crystal orientation dependency, obviously it is isotropic etchant. Another example is 1 is to 3 is to 8 ratio of HF, HNO_3 and CH_3COOH mixture at room temperature. So it etches heavily doped there is 7.5 into 10 to the power 19 per cc, heavily doped means silicon between 50 to 200 micron per hour with a selectivity over lightly doped being 150. That means if the doping is of the sort of 7.5 into 10 to the power 19 per cc then etch rate is 50 to 200 micrometer per hour. But if the doping is less than 10 to the power 17 per cc, so etching is much more and the ratio of selectivity is 150 time more compared to highly doped region. Dopant dependent selectivity is opposite of that of strong alkaline system. So in acetic etchant the behavior of the dopant dependent is opposite to that in alkaline etching system.

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Acidic Etchants (Isotropic Etchant) and Etch Masks

- Acidic system can be used as complementary etchant to enhance the flexibility of creating chemically etched structures
- Acidic system etches SiO_2 slowly ($\sim 2\mu\text{m/h}$)
- SiO_2 mask can be used for brief etching time while Si_3N_4 or Au are used for longer etch times

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Now acidic system can be used as complementary etchant to enhance the flexibility of creating chemically etched structure. Acidic system etches SiO_2 very slowly of the rate of 2 micrometer per hour. On the other hand you have seen that in silicon the etch rate varies from 50 to 200 micrometer per hour and since in acidic system silicon dioxide etches very slowly, so we can use silicon dioxide mask as a mask material for brief etching time. But if you need long etching process that means, if you want to etch silicon of the order of say 200 micron thick silicon you want to etch. In that case silicon dioxide may not be a proper mask material then we use silicon nitrite or gold layer as mask material for long etching times.

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Anisotropic Wet Etching of Silicon

The diagram illustrates the anisotropic wet etching of silicon, showing the formation of a self-limiting etch. It includes a cross-sectional view of a silicon wafer with a $\langle 100 \rangle$ surface, a 54.74° angle, and a 70.5° angle. The etching process involves a frontside mask, a boron-doped Si membrane, and a backside mask. The etching is self-limiting, forming a $\langle 111 \rangle$ surface. A top view shows the $\langle 111 \rangle$ surface and the $\langle 110 \rangle$ surface. The diagram also shows a self-limiting etch and a boron-doped Si membrane.

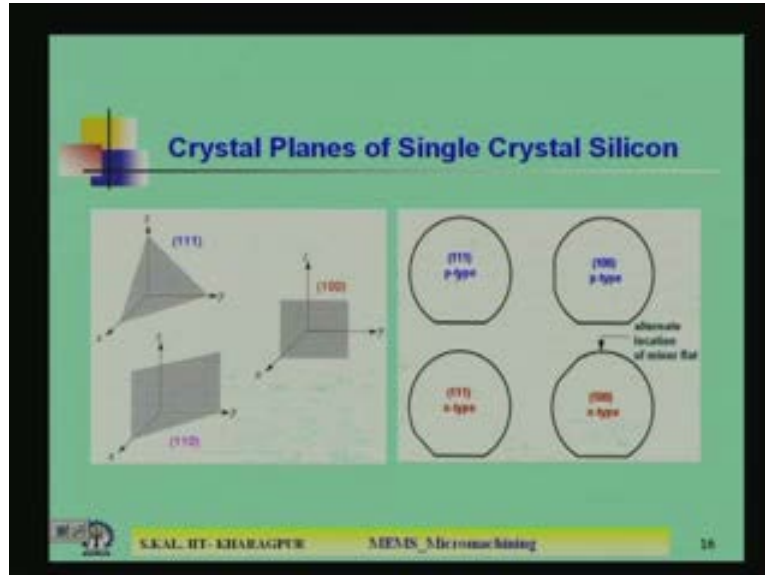
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Now here you can see a picture and this picture is basically anisotropic wet etching, how it proceeds. So here you can see in the first figure, the yellow color is basically the mask material. Front side and back side are covered by a mask material and then windows are open to etch silicon. Now the silicon is 1 0 0 silicon. What is meant by 1 0 0 silicon, in the next slide I will show you. So here we found after the masking layer is removed from the desired etch portion then if we deep the whole wafer into a solution, then we will find the 1 0 0 etches very fast compare to 1 1 1. So that we will get a slant surface and the slant surface will make 54.74 degree with the top surface the slant etch will make 54.74 degree angle. So, now as it proves that etch rate of 1 1 1 plane is not same as 1 0 0 plane. But if the structure depends on how much area you have opened for etching on the mask layer.

Now at some point of time you can see here, in this particular portion, there 1 1 1 plane has touched a particular point, so that it looks like a v group. In the left side it will not a v group, may be after certain amount of time it will end up with 1 1 1 plane and it will join here and so that also it will take form of v group. Now in the back side here you can see if you open the windows of etching to a largest end then you may end up till the backside so that the etch feature or etch the group will be totally different. Now if we make a boron-doped silicon membrane here highly doped, so after reaching that interface where the layer is highly doped the etch will automatically stop so that you can easily get a membrane at the end of the etch process. Now here is another picture which is 1 0 0 and this is basically the 3 dimensional view you can see and you can have a feeling how the structures looks like after etching.

So the mask layer has been removed and in the same wafer, for example and then you can see the cross section as well as top view so that you will have some idea regarding the shape of the structure. Here you can see the 1 1 1 layers are, this layer, this layer and this layer and this layer etch rate is very slow and in case of 1 1 0 wafer you can see the etched group shape is not similar to 1 0 0. That means, in 1 1 0 will not have the same etch rate with 1 0 0 and here you can see the shape of the etch group is completely different from the 1 0 0 wafer. So that means this picture shows that the etch rate is highly dependent on the crystallographic plane. So that you can get certain specified picture of which we shape after etching.

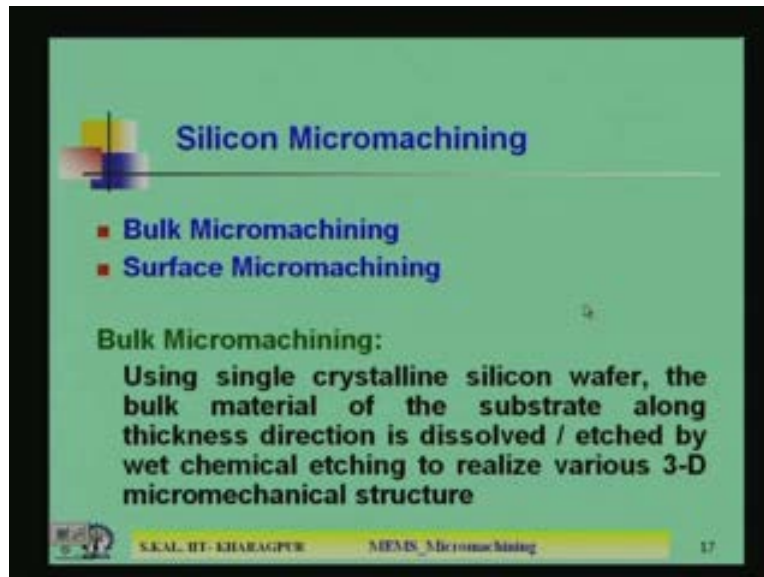
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Now what is 1 0 0 or 1 1 1 and 1 1 0 that is shown here. So in a crystallographic plane xyz 3 dimensional three 3D axis are shown here coordinates. So now 1 1 1 plane is if you connect a line like that. So in x_1 , y_1 and z_1 and if you join these two points it will look like that and 1 0 0. That means x is one, so total plane is parallel to yz plane, so it is 1 0 0. Similarly 1 1 0 the x it is one here, y it is one here so it is basically parallel to the z axis. So this is 1 1 0 plane and how do you identify a particular silicon wafer whether it is 1 0 0 or 1 1 1. So that is basically identified with certain nomenclature. Manufacturer of the silicon wafers they have decided to give certain shape of the silicon wafer. So that by observing that particular shape which are globally accepted.

One can identify the type of the wafer and the cut only which which crystallographic plane the wafers are cut. For example p-type 1 1 wafer there is a notch here similarly p-type 1 0 0 wafer, there are 2 notch which are perpendicular each other, one notch here, another notch here, which are perpendicular. But in p-type 1 1 1 only 1 notch whereas in 1 0 0 p-type there are two notch. Similarly 1 1 1 n type there are two notch which are at an angle and 1 0 0 n type similarly there are 2 notches are there which are not perpendicular to each other, it is in certain other location. But from the physical verification of the notches one can easily identify whether the wafer is a p-type or n-type, whether it is a 1 0 0 or 1 1 1 like this.

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Silicon Micromachining

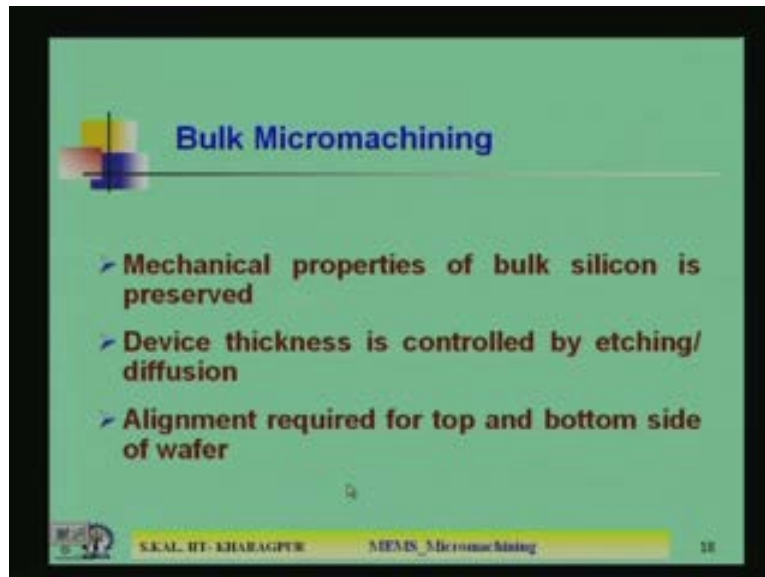
- Bulk Micromachining
- Surface Micromachining

Bulk Micromachining:
Using single crystalline silicon wafer, the bulk material of the substrate along thickness direction is dissolved / etched by wet chemical etching to realize various 3-D micromechanical structure

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So now there are two kinds of silicon micromachining. One is known as the bulk micromachining, other is known as the surface micromachining. So bulk micromachining means the whole silicon crystal, bulk silicon crystal we want to machine and we want to have certain microstructure. On the other hand surface micromachining means on the surface of the silicon wafer you want to have certain microstructures, not the whole bulk material is used. So obviously the surface micromachining microstructure is much more sophisticated and much more attention is required to get the microstructure. But in bulk, the structures are heavy and you can have the larger structures heavier structures, by etching complete bulk solution you can get the structures in case of bulk micro machine. So using single crystalline silicon wafer the bulk material of the substrate along thickness direction is dissolved and etched by wet chemical etching to realize various 3D micromechanical structures.

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This is the bulk micro machine and what are the specific features of the bulk micromachining after micromachining completed when you get the micro structure the following points is to be ensured. What are those? Mechanical properties of bulk silicon are preserved. Mechanical property should not change means the elasticity its Young's Modulus, CR elasticity all those things should not change. Device thickness is controlled by etching and diffusion. Because if you use a time etching, so thickness will be different or by diffusion means the highly doped region will etch less. So that means thickness of the device may be controlled by proper use, by proper diffusion. Proper diffusion means what? Certain spaces diffusion spaces and the concentration of the dopants we can tailor to we can use different amount of concentration of the dopants so that the thickness of the device will be different.

Alignment required for top and bottom side wafer. So that is one important to make microstructure using bulk micromachining. That means when you are going to etch certain material, so may be some portion already etched at the bottom and you want to etch some other location at the top surface. So obviously top and bottom should be aligned properly, so that you can get the exact etch behavior or to get exact shape of the microstructure. So alignment mark is to be given on top and bottom. So here, you have to use a special kind of machine for this particular purpose which is a double sided mask alignment.

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Bulk Micromachining

The following microstructures may be fabricated.

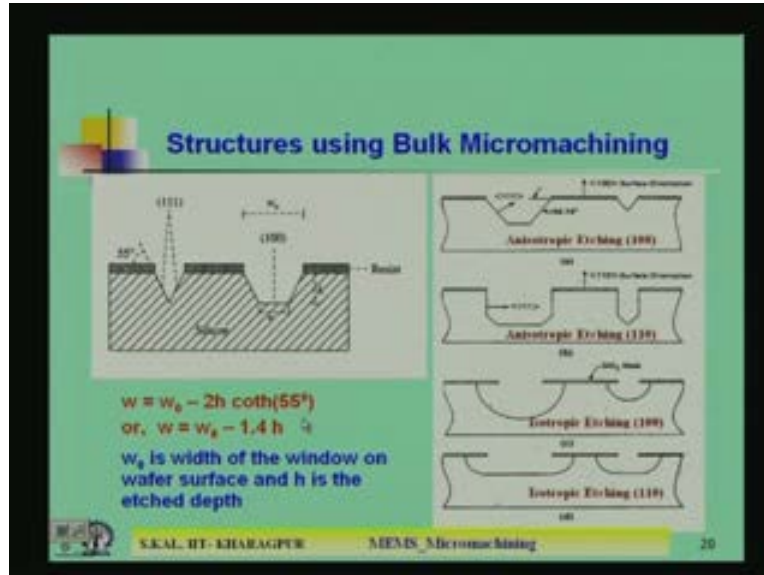
- Membrane /Diaphragm
- Cantilever
- Nozzle
- Silicon stencil mask
- Tuning forks

The diagram illustrates the fabrication of a silicon membrane. It shows a cross-section of a silicon wafer with a silicon dioxide (SiO_2) layer on top. The wafer is etched from the bottom side to create a cavity, leaving a thin silicon membrane at the bottom. The top surface is protected by the SiO_2 layer. Labels include 'SILICON WAFER' and 'SILICON MEMBRANE'.

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Now here one example is shown how the microstructure can be fabricated. That means how a membrane can be fabricated. So here the silicon dioxide wafer passed here, the silicon wafer is oxidized to get silicon dioxide top and bottom, so top side silicon that side is preserved. But bottom side we open a window by using lithographic technique. Now after that we etch the wafer using a either KOH or DP solution so that silicon will be etched and silicon dioxide here will prevent the underneath silicon from etching. So the etch will proceed in this direction so that you can get at the end of etching a thin membrane depending on how long you have etched. But other regions are protected by the silicon dioxide. So in this way a membrane can be made. Other microstructures made also bulk micromachining or cantilevers, nozzles, silicon stencil mask, tuning forks structures; those can be made using bulk micromachining.

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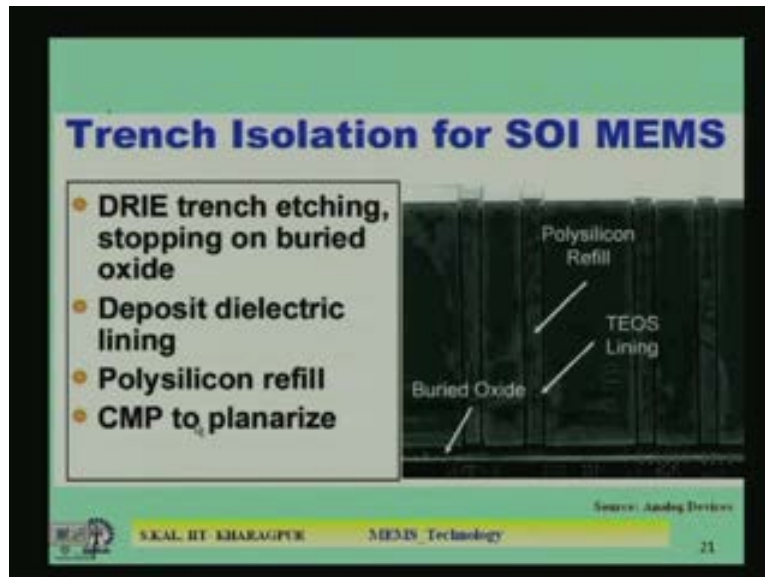
Here is another structure using bulk micro machining techniques. How different structures are made? Now here you can I just now previous slide I mentioned that there is a relation between the window size and the shape of the structure. Now that relation is shown 55 degree is the slant surface, one surface with the surface that angle 44.74 degree which we took here is the 55 degree. Now if the window size is W_0 and a after certain etch, the surface, the window ended with W here in the picture it is shown. What is W and what is W_0 ? Then there is a relation which is given below which is W is equal to W_0 minus $2h$ coth hyperbolic 55 degree. If I put the value of coth hyperbolic 55 degree the relation becomes W equal to W_0 minus $1.4h$ where h is the h depth and W_0 width of the window on wafer surface. So W_0 is the width of the window at wafer surface h is the h depth and and W is the window size after etch.

So this relation is valid and this is used for making a design or to making the mask for different etch process an anisotropic etch process of silicon. Now in the right hand side there is a picture you can see. That is a one surface this is anisotropic etching of silicon 1 0 0 surface window size is small ended with the v look, window size b . So we will get this shape and 1 1 0 anisotropic etching case you can have the same window, you can see same time of etching the structure is different. Because 1 1 0 and 1 1 1 the etch rate ratio is different compared to 1 1 1 is to 1 0 0. In the c diagram is an isotropic etching 1 0 0 where etch rate in the vertical and etch rate in the lateral direction are same. So because of that you can get a complete round shape, one structure with the window is like this and silicon dioxide mask material and then isotropic etching of 1 1 0. So both 1 0 0 and 1 1 0 are used here both isotropic etching and anisotropic anisotropic etching are also shown.

So in that case in isotropic etching 1 1 0 it the shape looks like that for the same opening. So that means the etch rate here is the shape of the h structure will be defined one by the crystallographic plane selection and another is by the opening of the windows at the surface. Now so this is the structure normally we use in many of the micromachining process, micromachining technology

for making MEMS devices. Now this relation W equal to W_0 minus $1.4 h$ is very useful for designing mask in in different kind of the microstructure

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Now here one picture is shown there is trench isolation for SOI MEMS. So SOI is silicon on insulator, so this is becoming very popular in many of the micro machine devices which we exposed in many harsh environments. For example, in space or in hostile environment where lot of radiations are there, the sy is the alternative for silicon, silicon mean insulator because this radiation hard deviser. So MEMS technology you know the microstructure means their sensors and actuators we made using that micromachining technique as well as some signal conditioning circuits are integrated together to get the complete microsystem. So there obviously if this micro system is used in such kind of harsh environment, so then we need such precaution so that the complete microsystem is radiation hard. So that means the after exposure of radiation nothing will happen on the performance of the wafer.

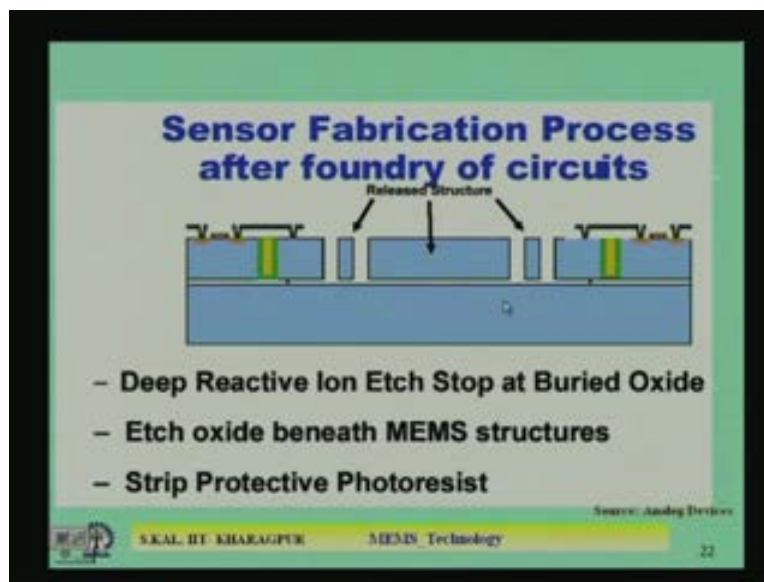
Now here one example is shown where a DRIE so deep reactive iron etching is used and trench etching. So you can see the trenches and here like that trench is made by reactive ion etching and bottom is buried oxide, this is oxide so after etching silicon and then at the oxide level it is stopped. So now after the making the holes then we need a dielectric lining. So this dielectric lining how we can make by TEOS lining. So the TEOS oxide we make it these again a CVD method by which we can make a thin layer of oxide at the surface of the group. So after making that TEOS lining, then we have to refill the group using the polysilicon and that is done if you that is also CVD process. By CVD technique we fill the complete trench in the all the trenches and obviously it will not finish at the surface of the silicon wafer. So some protrude will be there some extra portions will be there on the surface.

So how do you make it planarize so after refilling the polysilicon then we go for a process step which is known as CMP that is chemical mechanical polish, the CMP full form. So you have to chemical and you have to apply mechanical energy also, through in that case the chemical

mechanical polishing if you make then the extra portion on the surface which is coming due to the CVDT position of polysilicon refilling step that will go away and you can have the complete plainer surface on this on this wafer. So that means the trench is made by machining, here is a machining, is a deep machining and for that deep machining here we use a DRIE and you can see the narrow trenches are already made here and etch stop layer we will put it as a buried oxide which is normally used in the bulk of the silicon to have all SOI devices, silicon on insulator devices. Now then refill and then CMP means chemical mechanical polish planarize. The planarization technique is an important step which is being used nowadays in all VLSI process.

Because you see gradually the size of the cheeper down and down so are going less and less and vertical also. Because lateral dimension if shrinkage, so vertical dimension is going to be more. So there, all the layers are vertically stat. So as a result of which you need some isolation between from one layer to other layer and conventional isolation techniques already we know in IC technology or VLSI process are oxidation solution lucos or say p junction isolation which are also called diode isolation. But that takes lot of surfaces or areas all the silicon wafer so we need a to make very narrow area consumption and in that respect trench isolation is a very popular choice and this trench isolation is used with the help of the deep RIE and depositing the filling is electric lining. Because insulation you required otherwise if you fill with the polysilicon the trenches. So polysilicon and this dielectric will polysilicon and silicon there is a conducting layer. So the trench wall has to be isolated so we need it the TEOS lining so that it will be isolated dielectrically isolated and then you again refill with polysilicon.

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So now the sensor you can see in the picture has been fabricated using this deep reactive ion etching that means dry etching process. Normally the sensor a micro system. Normally what we do that all the devices are made and devices means circuits are made after making the circuits then we go for fabrication of the sensor using the MEMS technology and here you can see this portion some transistors are there, some interconnect lines are there, here is a the trench isolation, some trench are made and filled with the polysilicon. We can see the yellow color here. Here a

certain devices, transistors, MOS transistor and some the interconnects has been done. Then we go for releasing the mechanical structure and deep reactive ion etch stop at buried oxide. So it is here we said buried oxide we made before going to make the device then etch oxide beneath MEMS structure.

So if you etch the oxide beneath MEMS structure, they will strip protective photoresist. So you can get some a structures release certain structure which are movable, which can be moved. That means cantilevers or flexures or some membranes which can be formed with external pressure or external vibration and that movable portions are made using this. This technique means first you make the circuit and sensor devices and then you go for etching. That means micro machining, so that you can a release the structure as you desire. So this is one example of how the micro machining is going to use to get certain structure which are not static, but which can be moved depending on our requirement. So with this let me a stop today. That means today we discussed regarding the basics of etching certain definitions of the etch selectivity or the anisotropy or isotropic etching with respect to both crystallographic direction, depended etching as well as the liquid etching.

There is vertical and lateral etching with respect to that direction also and the two kinds of etching also we discuss bulk and surface micromachining. Bulk micromachining part we discussed little bit at length but surface micromachining just we defined it. In the next lecture we will concentrate on the surface micromachining part and then we will follow other micromachining techniques to achieve certain microstructures which are used in case of MEMS and micro system MEMS and micro sensors or actuators to make certain microsystem. Thank you very much.

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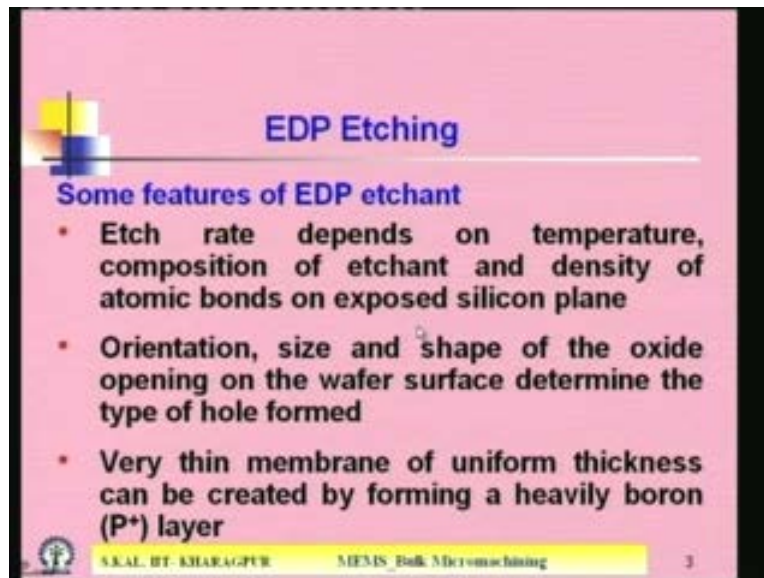
So we will continue our discussion on micromachining of silicon. In my last lecture I told you there are two micromachining processes. One is bulk micromachining and other is surface micromachining. So out of those two processes today I will discuss in detail bulk micromachining process for silicon. So this particular technology there are various chemical agents we use for bulk micromachining. So one of such chemical used or agent used for bulk micromachining is ethylene diamine pyrocatechol or in short EDP etching. So here we use three chemicals. One is ethylenediamine, another is pyrocatechol and the third is water. So they are mixed in a certain stoichiometric ratio and then we go for etching silicon at a particular temperature.

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This particularly technology has got certain advantage. One is highly selective over materials like silicon dioxide, silicon nitrides, chromium and gold. So all these three materials can be used for masking purpose. That means it can be protected this particular layer can be used for protection of silicon where you do not want to etch that material means silicon material. So it is a very good masking material and in this particular technique EDP etching etch stop technique is very simple it is not that much complicated. So these are the few basic advantages for EDP etching. So now some other features are there for EDP etching. Those features are mentioned here one by one.

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EDP Etching

Some features of EDP etchant

- Etch rate depends on temperature, composition of etchant and density of atomic bonds on exposed silicon plane
- Orientation, size and shape of the oxide opening on the wafer surface determine the type of hole formed
- Very thin membrane of uniform thickness can be created by forming a heavily boron (P⁺) layer

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Etch rate of the silicon material depends on temperature composition of etchant and density of atomic bonds on exposed silicon plane. What does it mean by that? Density of atomic bonds on exposed silicon plane means it will depend on crystallographic orientation. Because in different crystallographic plane the atomic density of the silicons are different. That means the etch rate will be different for 1 0 0 oriented plane, crystal plane in silicon, 1 1 1 and 1 1 0 the etch rate of these three planes will be different.