

Bio – Microelectromechanical Systems

Prof. Shantanu Bhattacharya

Department of Mechanical Engineering

Indian Institute of Technology, Kanpur

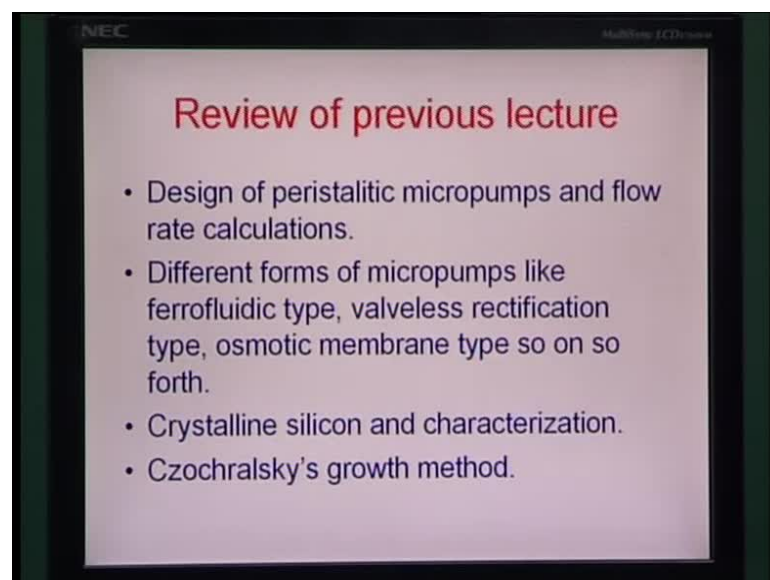
Module No. # 01

Lecture No. # 35

Hello and welcome back to this 35 lecture on Bio-Microelectromechanical systems. Let us do a quick preview of what we did in the previous lecture.

We started designing of peristaltic micro pumps and their flow rates through an integral technique wherein, we would take a radial area and try to use the deflection of a thin membrane and then try to integrate the whole deflection saying that what would be the amount of volume change Δv because of this deflection. The deflection would be cause by some kind of energy mechanism and thus, this volume change is multiplied by the low frequencies would actually give you the tentative flow rates for the particular micro pump.

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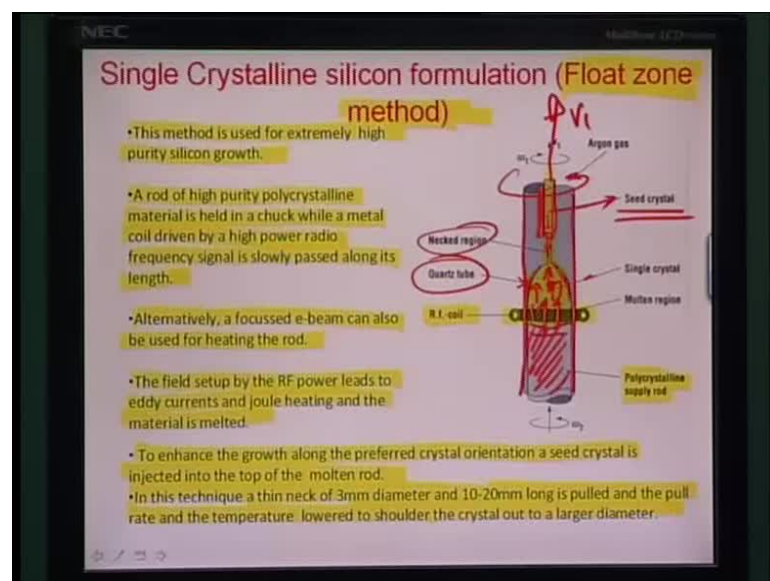
We also talked about different forms of micro pumps especially, the non-conventional types like Ferro fluidic types of pumps wherein, they were two geometries. One was just

a simple planner mechanism, where with an external magnet; another was a circular path of fluid flow with two parallel placed magnets, where the magnets would flow with or move with respect to one another; with one fixed, another moving and it would drive the fluid inside the pump as a plug.

We talked about valve less rectification pumping systems and osmotic membrane type of pumping mechanisms so on, so forth. Then, we went into the fabrication processes and try to look into basically, silicon because silicon was essentially the primary MEMS material that was translated from the silicon industry. You may recall that the MEMS processes were essentially fallout of the microelectronic processes, which were generated by the semiconductor industry. Due to the integration density problems those processes were made obsolete, so MEMS kind of took it up.

Silicon definitely was the most prominent material which could start with building MEMS and also BIOMEMS. We talked about crystalline silicon and their characterization modes and various notations, which would be representatives of the directions in the planes or the group of planes. We talked about this famous Czochralsky's method of growth of single crystalline silicon, which is normally used in the industry for producing wafers.

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Today, we will be looking into another aspect of silicon crystalline; semi crystalline silicon formulation and that is essentially also known as the float zone method. As you

can see here, in this particular example or illustration, the float zone method is really different than the Czochralsky's growth method. Essentially, this is used for making crystals which are lower in diameter or size than, what Czochralsky's can normally make.

The way you make it is essentially by taking a polycrystalline supply rod as you can see here in this figure (Refer Slide Time: 03:10). This rod is pushed through the small RFS in this region and while it is being pushed and immediately before it is being pushed, it is superheated in this particular zone by using either some kind of an RF coil, which is around this region or using infrared radiations to a great extent or using laser for example, so all these heating modes are non-contact in nature. Therefore, there is a tendency of more thermal gradients to be caused within this mold, which would be an important advantage of this method over this Czochralsky's growth method, where the heating is done essentially through the sites of the crucible.

Now, as this is heated up and this outer is essentially a quartz tube that is how this whole outer is made up of. You have this necked region through which the liquid flows and on the other side here, you have a seed crystal. Essentially, this part here as you are seeing is a seed crystal. As you are actually depend the crystal down all the way to here and you have the silicon melt going in, you essentially take this away now with a certain velocity V_1 while, this other outer is rotating. As you are feeding the liquid material through the necked region into this **radiant**, the seed grows the material around it in the same direction as the seed crystal. Therefore, you have this wafer which comes out in this end totally of the same type as the seed crystals were (Refer Slide Time: 04:05).

The advantage in this method is that it is free of any thermal gradients, which may happen due to the other form of heating in Czochralsky's. Number two is that the material has a higher purity of silicon because a few silica, which is melted essentially passing only through a quartz environment as opposed to the Czochralsky's, where you can have. Also, there is no question of any of the whole process is carried out in vacuum, there is no question of any gas entrapments here, because the melt essentially is formulated in the backside or as a plug and this particular thing is the solid material which is a plug. There is no inclusion of gases really and it is more pure or it is a high purity crystal that you can obtain by using the float zone method.

In a nutshell, this method is used for extremely high purity silicon growth. Rod of high purity crystalline, polycrystalline material is held in a chuck while a metal coil driven by high power radio frequency signal is also slowly passed along its length. Alternatively, a focused e-beam can also be used to heat the rod or then RF frequency is used normally. The field setup by the RF power leads to eddy currents in joule heating and the material is melted away.

To enhance the growth along the preferred crystal orientation seed crystal is injected into the top of the molten rod. In this technique, a thin neck of 3 millimeter diameter and 10 to 20 centimeter long is pulled and the pull rate and temperature lowered to shoulder the crystal out to a larger diameter thereby, making a large diameter crystal at the other end. Organ gas of course, is flown through the tube for maintaining the inertness and the non-inclusion of oxygen or any other moiety into the crystal.

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Wafer specification and preparation

- The boule is first characterized for resistivity and crystal perfection.
- Then seed and tail are cut off and the boule is mechanically trimmed to proper diameter.
- The diameter at this point is slightly larger than the final wafer diameter, since additional etching will still be done.
- For wafers 150mm or less, flats are ground the entire length of the boule to denote crystal orientation and doping type.
- The largest flat called the primary, is oriented perpendicular to the $\langle 100 \rangle$ direction.

Cleanliness (particles/cm ²)	< 0.03
Oxygen concentration (cm ⁻³)	Specified $\pm 2\%$
Carbon concentration (cm ⁻³)	$< 1.5 \times 10^{16}$
Metal contaminants bulk (ppb)	< 0.001
Grown in dislocation (cm ⁻²)	< 0.1
Oxidation induced stacking faults (cm ⁻²)	< 3
Thickness (mm)	≈ 1.50
Wafer (μm)	625 or 675
Global Flatness (μm)	10
Coat (Å/cm ²)	3
	0.2

Diagrams show crystal orientations: (100) p-type, (111) n-type, (110) p-type, and (100) n-type. A diagram also shows a wafer with a primary flat and a secondary flat, with a red arrow indicating the direction of the primary flat.

This is another form of making silicon polycrystalline or single crystalline silicon from polycrystalline silica material. Essentially, this piggybacks the other Czochralsky's process, whenever purity is in question and high pure material is needed. Let us now look into some of the specifications that such wafer outputs would have from both the processes. Essentially, the silicon bowl that is finally, emanated from both the process whether it is float zone or Czochralsky's is first characterized by its resistivity and crystal perfection.

There may be point effects which may alter the resistivity significantly. There may be **dopends**, which are introduced in the melt for getting P type or N type material generally. So, this is one first aspect that what is the resistivity of the crystal and what is the level of perfection of the crystal? Are there many defects or there lesser defects? So then the seed and tail are cut off and the bowl is mechanically trimmed to proper diameter.

Essentially, now this proper diameter is the diameter of the wafer that there is in question. Diameter at this point really is slightly larger though than the final wafer diameter, because you have to have some allowance for polishing the sites, additional etching probably has to be done and then that is followed by chemical mechanical polishing.

The wafers less than 150 millimeters flats are ground the entire length of the boule to denote the crystal orientation on the doping type. Therefore, there is flat site on one end of the bowl, which can denote what kind of crystal orientation the silicon crystal would have or what is the doping type. Basically, the largest flat called the primary is oriented perpendicular to the 100 direction that is what you have to remember.

Any silicon crystal is denoted by this largest flat on the side which is perpendicular to the direction of the 100 crystal. This can be evaluated by lattice diffraction methods at the very beginning. This is an industrial standard that they put you to figure out what a certain direction would be of a particular crystal if you know, what is perpendicular direction to the 100 direction or 100 planes?

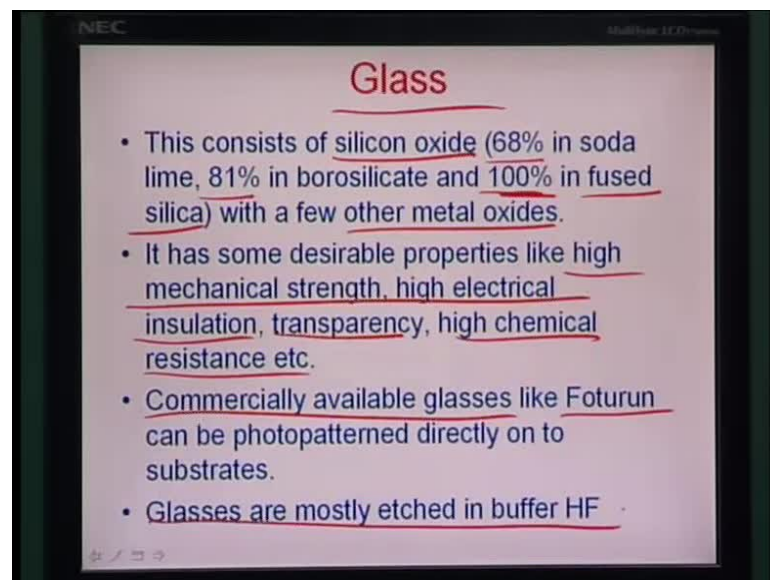
You can see here, this is really the top view of such a wafer and you can see at this end particularly the flat is grounded, which means that this is probably the plane which is perpendicular to the direction 100, so the direction 100 really is perpendicular to this; that is what essentially means. Also, this can be used to denote other about the resistivity like for example, this is a 111 P type, this is 111 N type, this is 100 P type this is 100 N types so on, so forth. There are different specifications which the silicon industry would give for denoting these wafers (Refer Slide Time: 09:48).

Other important aspects here are the full specs, where it considers, what is the cleanliness and particles per centimeter square. What is the oxygen concentration, the carbon, the metal contaminants in the bulk in parts per billion? You can also talk about growth in or grown in dislocations per centimeter square of surface area of the wafer. You could talk

about oxygen induced stacking faults, you could also - this is in the volume of course, stacking is an effect in the volume.

You could talk about diameter in millimeters; you could talk about thickness in microns. The bow of the wafer how much the bowing happens or the whopping happens, the global flatness, which is in micro meter and then the cost. These specifications are normally specified on the characterization box associated with any new wafer which comes in.

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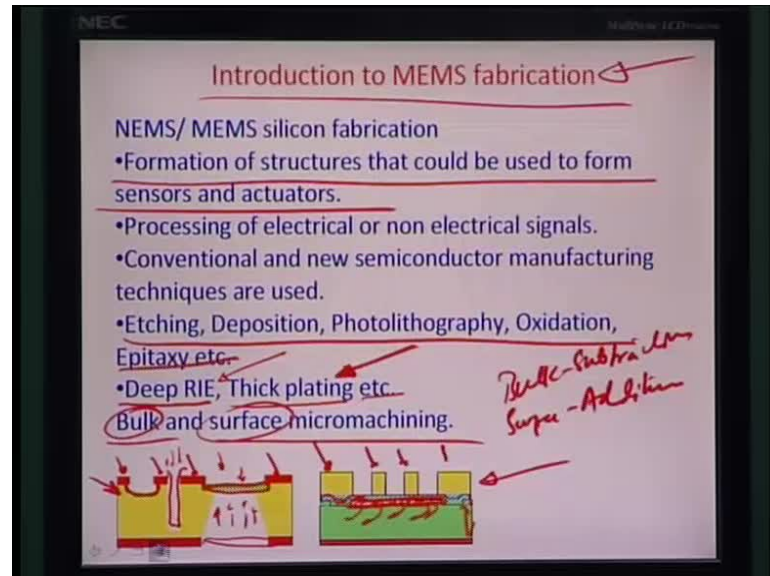


On the other hand, some of the other materials like glass normally consist of silicon oxide, which is about 68 percent in soda lime, 81 percent in borosilicate these are different forms of glasses and 100 percent as you see in fused silica. So, fused silica essentially is the cleanest form of glass that is available. It has this silicon oxide in combination with some other metal oxides normally. It has desirable properties like high mechanical strength, high electrical installation, more optical transparency and high chemical resistance etcetera.

In case of photolithography and other kind of techniques, there are some commercially available glasses which you could actually photo pattern. One of them available commercially is known as Foturun, it can be photo patterned directly onto the substrate wherein can be used either as channel material, where particularly sandwich such a layer and photo pattern it and then cover it with another layer on the top and then thermally

bond may be, so there are embedded channels this way that you could make within a wafer. Glasses are mostly etched in buffer HF solutions.

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This slide really gives you some of the introductory processors to MEMS fabrication. Really, this is all about formation of structures that could be used to form sensors and actuators that is all about MEMS. One shot MEMS is essentially, how small structures can be fabricated and realized, so that they can be used the sensors or as actuation mechanisms.

These sensors really do some transduction processing of one form of signal into another. So, the signal can either be non-electrical or electrical; in non-electrical signals are particularly like **piezo** base or vibration base signals. We also know that most of the MEMS are used or realized by using conventional and new semiconductor manufacturing techniques things like etching, deposition, lithography, oxidation, epitaxy, so on, so forth.

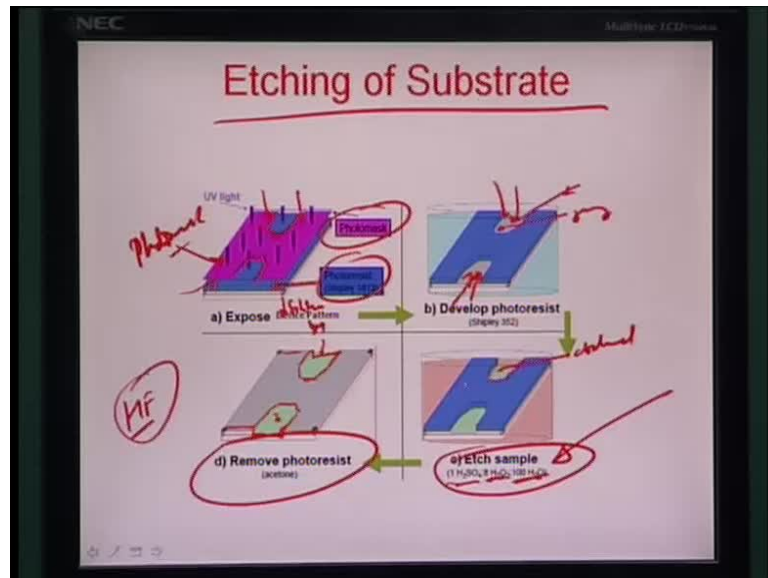
You could also talk about some other specific to MEMS processors, deep RIE is one of them were you actually build very high aspect ratio straight etched channels. You can talk about thick plating particularly electro chemical plating, where a very thick metal layer is deposited and etched, characterized, etcetera. Really, if you divide this whole this machining, you can categorize them into bulk and surface micro machining.

The bulk as you know is more related to the volume removal or the bulk removal of the material, this right here is an illustration (Refer Slide Time: 13:40). This is the cross section of the silicon wafer and you can use this particular red layer here is the masking layer. You can actually etch away material underneath at using an etching solution homogeneously or isotopically. You could actually do deep RIE based etch, where you can have very straight aspect ratio geometry of this particular channel. You have opened a etch window at the top here in order to accomplish this. This plasma driven process and we are going to cover the details of what plasma is in this particular topic or section in a few slides from now.

This is another very interesting illustration; you are talking about depositing a p plus layer here, so this is p plus silicon in green. You opened another etch window and then you etched the material in the bulk manner outside, so that you can realize this freestanding membrane like a flat beam. Therefore, these are really bulk micro machining process, where it is a subtractive method it is removed from the volume of material.

The surface on the other hand is the additive process, so bulk essentially subtractive and surface is additive. As you are seeing here in this particular process, you can see your growing pillars posts; this is a very fine illustration here, so this was a sacrificial material as I am showing on the red shadowed region. After depositing a layer of poly silicon on the top of it, you are removed this layer out sacrificial, you can dip it in acetone or something, so you can formulate an embedded channel in the poly silicon layer in between this glass. Whatever it is, you are building it on the surface of a wafer, the wafer really is not subtractively etched out, and it is additively built upon. So that is what surface micro machining is all about.

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We talk about etching first, so etching as you see is a process which is now illustrated here. You actually introduce a blue layer as you are seeing here of a photoresist material. As you can see, so this is the photoresist material and this is the positive photoresist, so wherever there is an exposure to light there is going to be a creation of via or a capillary. You add up photo mask as you are seeing from this region here made up of violet color, so this is the photo mask. You are exposing this whole assembly to the UV by after putting the photo mask jet directly over the photoresist.

As you actually heated with light and then I will later on develop it; it creates two vias here on the resist, so the remaining portion is still the resist as you see in the blue. This portion showed by the two red arrows here are really the resist which are removed or the vias are created. Therefore, whatever was there on the photo pattern as you are seeing here as open areas, these two areas which were open here, have been translated in terms of this vias on the photoresist. Therefore, light fell on them and it got debonded and it could be removed or etched away. Therefore, one more interesting factor is that it has exposed the underneath silicon surface here, which was the base wafer to etching action then, other portion is actually a sacrificial cover over the silicon surface.

Now, you could use some kind of an acid may be, HF or aqua regia or some of the etchant to etch off this particular layer up to certain depth and then essentially remove the photoresist over it. This is the etching process so let us say, in this case, you are using

1 part of H₂SO₄, 8 parts of H₂O₂ and 100 parts of H₂O by volume. When you have etched away this particular layer which was earlier grey as you can see here, now this is the etched part, so it is denoted by this light green (Refer Slide Time: 17:36). You are left with etched holes or vias and then you can remove the photoresist away, so that you know the original wafer can be turned with two etches on both ends. These are the relatively lower H depths as you can see here on both sides. This can be a like etched structure or features within the micron surface, so this how etching is done with a sacrificial layer of resist.

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Subtractive Techniques

Wet etching:
Wet etching is referred to as etching processes of solid materials in a chemical solution.
Wet etching in microelectronics are mostly isotropic, independent of crystalline orientation.
 Because of the under-etching effect, isotropic etching has drawbacks in designing lateral structures.
 If the etch solution is well stirred, the isotropic etch front has a spherical shape.

Diagram illustrating isotropic etching: (a) Well stirred etch showing a spherical etch front, and (b) Disturb etch showing a flat etch front. A handwritten note 'Spherical' with an arrow points to the spherical etch front in diagram (a).

Examples of Wet Etchant Recipes for Thin Films of Functional Materials (After [7])

Material	Etchant	Solvent To
Si	HF, HNO ₃ , CH ₃ COOH	SiO ₂
Si	HF	SiO ₂
SiO ₂	NH ₄ HF	Si
SiO ₂	HF, HNO ₃ , H ₂ O	Si
SiO ₂	H ₂ PO ₄ , HNO ₃ , H ₂ O	Si
Si ₃ N ₄	H ₂ PO ₄	SiO ₂
Al	H ₂ PO ₄ , HNO ₃ , H ₂ O	SiO ₂

Let us talk about subtractive or bulk techniques first. The first kind of bulk technique is also the wet etching process. As the name refers it is essentially a process of removing solid materials by dipping it in a chemical solution, which can voluntarily react and create groups or move away groups thus, etching is performed in that manner. Wet etching in microelectronics is mostly isotropic, independent of the crystalline orientation, etcetera. It is done with very simple methods which can homogeneously go on etching by using chemical reaction though the bottom of the silicon surface.

Wet etchings in microelectronics again are isotropic and independent of crystalline orientation but, then there is a potential pitfall to this problem and that is basically under etching. I would just like to illustrate here, how these affect comes. Let us suppose, you have a sacrificial layer here, which is also like masking or a protective layer. You are

using etch solution to pass through this particular etch window into this particular silicon and it starts etching away, because it is a homogeneous etch process, etching would be same in all directions and therefore, this part which is away from the window is also starts to get etched.

Therefore, the overall etch shape is really much more in size than the etch window, so this is really known as the under etching effect. Let us actually see, how it happens? This is actually the mask window again and you have this layer of material removed from under the mask window. Essentially, this particular area is also known as the under etch of this particular feature or structure.

Now, one thing which is important to be noted here is that if suppose, the etch solution is well stirred, as the etching continues the shape would be most spherical in nature as you can see here, because then the homogeneity of the etch is maintained, the solution is continuously recirculated across the edges of this particular illustration. Supposed to where it is not properly etched then of course, there will be a preferential etches direction which is more in the side than in the bottom.

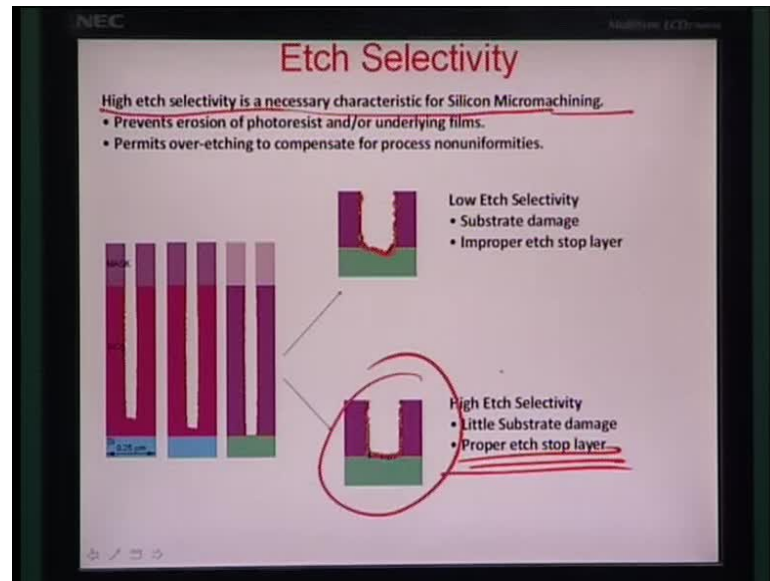
Essentially, you can consider that more area is being exposed to the etch process in the bottom due to which there is more amount of material dissolved from the bottom. There is a concentration gradient which is created **as opposed** to the sides probably, where very less amount of material is withdrawn from and that is because of the low etch rate in the linear direction.

Because of this reason as you see overall, sometimes after a while this etch gets flatter, because this is diffusion limited process; the one material, which is getting dissolved and coming out is of course, creating a concentration and then this becomes slower and slower as it goes down. As compared to the other sides, where less material has to be removed and the concentration is probably lower. Therefore, etch can actually go ahead in properly.

Another important factor here is the type of materials and then what it is selective to and this has been is illustrated earlier also, what you mean by etch selectivity. Selectivity is essentially the stopping process to the particular material. Suppose, in this case, you have a silicon material and you have a Si O₂ layer which is a masking layer or a sacrificial masking layer.

You can say that this particular etchant HF, HNO₃, CH₃COOH that means acetic acid, nitric acid and hydrofluoric acid is in a certain ratio forms an etch top over the SiO₂, which means that is selective to this as opposed to silicon material, where it is not really selective to. Therefore, it etches away silicon but, whenever it approaches the SiO₂ process the etch stops.

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Similarly, for a potassium hydroxide it etches away silicon with selectivity towards SiO₂. This table here really illustrates what are the materials over which the etchants are effective and what is etch top layer for those kinds of materials (Refer Slide Time: 22:22). These are some of the wet subtractive etching techniques. This slide has been illustrated before, I would just like to put it back again that high etch selectivity is a necessary characteristics for silicon micro machining, this shows high etch selectivity, where there is a very low amount of substrate damage as the etch approaches an etch stop layer. So, really it is a very proper highly etch stopping layer of a certain chemicals.

Some chemicals do not give this kind of a property and it possess problem by etching off the sacrificial layer as you can see here (Refer Slide Time: 23:35). Therefore, the etch stop layer is really not one uniform and that creates problems over the whole aspect ratios feature sizes etcetera, for this particular technique.

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Some Common Etchants (for Isotropic Wet Etching in Silicon)

Material	Etchants	Selective To
Si	HF, HNO ₃ , CH ₃ COOH	SiO ₂
Si	KOH	SiO ₂
SiO ₂	NH ₄ , HF	Si
SiO ₂	HF, HNO ₃ , H ₂ O	Si
SiO ₂	H ₂ PO ₄ , NHO ₃	Si
Si ₃ N ₄	H ₂ PO ₄	SiO ₂
Al	H ₂ PO ₄ , HNO ₃ , H ₂ O	SiO ₂

One has to choose the etchant and the etch stop layer in very good faith, so that there is hardly any substrate damage which would take place at etch propagates. These are some of the common etchants for isotropic wet etching in silicon, as you can see here and what it is selective to. I have just compiled the table that was illustrated before.

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Anisotropic Wet Etching

Basic etching processes:

- For single crystalline materials such as silicon, etch rates of anisotropic wet etching depend on crystal orientation.
- In an anisotropic wet etching process, hydroxides react with silicon in the following steps:

$$\begin{array}{l}
 \text{Si} + 2 \text{OH}^- \longrightarrow \text{Si}(\text{OH})_2^{2-} + 4 e^- \\
 4 \text{H}_2\text{O} + 4 e^- \longrightarrow 4 (\text{OH})^- + 2 \text{H}_2 \\
 \text{Si}(\text{OH})_2^{2-} + 4 \text{H}^+ \longrightarrow \text{Si}(\text{OH})_4 + 2 \text{H}_2\text{O}
 \end{array}$$

Overall Reaction: $\text{Si} + 2 \text{OH}^- + 2 \text{H}_2\text{O} \longrightarrow \text{Si}(\text{OH})_4 + 2 \text{H}_2$

(dissolved)

Handwritten notes: $\text{Si} \rightarrow \text{Si}(\text{OH})_4^{2-}$

- In the steps of the reaction overall 4 electrons are transferred from each silicon atom to the conduction band.
- The presence of electrons is important for the etching process.
- Manipulating the availability of electrons makes a controllable etch stop possible.
- Because of its crystalline structure, silicon atoms in {111} planes have stronger binding forces, which make it more difficult to release electrons from this plane. This the etch rates at {111} planes are the slowest.

The second technique that I would like to point is called an isotropic wet etching. Essentially, this is the technique wherein, a certain hydroxide based chemical process is used for etching of silicon. In this particular an isotropic etching process, the only

difference that you have is that the etchant solution is a hydroxide based solution. Therefore, the process is really based on an electron transfer redox reaction, which happens with silicon of the particular hydroxide etchant.

As it is limited by a flow of electrons from the silicon structure, the problem that one would face in this case is that **during** as the etching propagates, as the etching continues, there are certain planes of silicon along which there may be a shortage of electron donation; electrons are more firmly bound in those planes, because of that there are certain planes over which the etch rate is effectively the slowest. As the process propagates and ultimately the feature which is carved in the silicon is totally based on such directions, where the etch rate is the slowest and etching takes place the slowest.

Eventually, the average feature which generates in silicon because of this situation is based on reflection of those planes, where the electron transfer is the slowest. Therefore, etches happen eventually in the 111 direction. We will be clearing this point in a little bit later numerical example, when we try to find out such etch planes regarding this process.

In a nutshell, for a single crystalline material such as silicon as you can see here, the etch rates of anisotropic wet etching really depends on the crystal orientation. In anisotropic wet etching process is essentially redox formulation, where hydroxides react with silicon and the following steps. You have in the first step the silicon getting coupled with hydroxide which is generated from the etchant material, so 2 OH^- and this gives Si OH_2^- with a 2 plus and 4 electrons here.

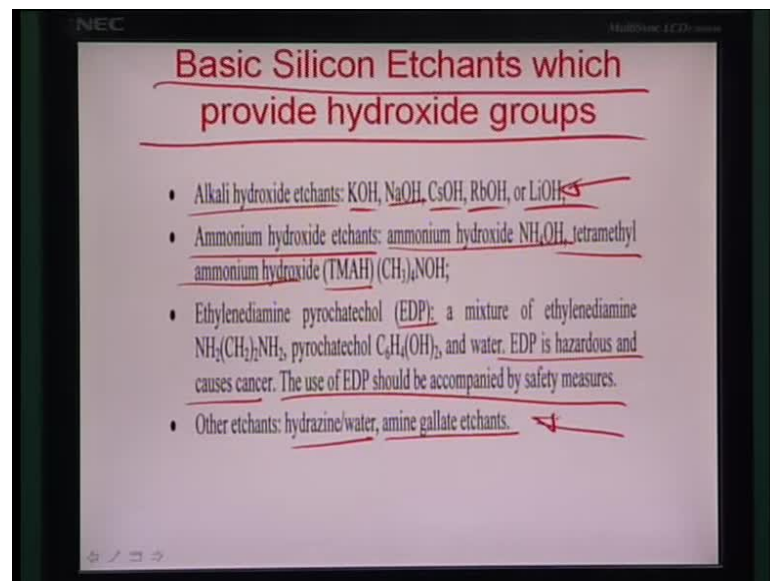
Then, these 4 electrons combined with the water which is present around which dissolves the KOH or whatever hydroxide it is and gives 4 OH^- and liberates hydrogen gas H_2 which bubbles out. Therefore, the 4 OH^- which are generated here and this is actually an H OH here. So, 4 OH^- which is generated in the previous step here, reacts with Si OH_2^- and this gives $\text{Si OH}_2^- + 2 \text{ H}_2\text{O}$ (Refer Slide Time: 26:00).

If you just write the overall reactions, so these three reactions taking place parallelly; if you react or if you write the overall reaction by summing over the left and right sides and thus electrons in some of the species get cancelled left with, $\text{Si} + 2 \text{ OH}^-$ from the hydroxide plus the carrier H_2O the fluid, the water which is around which would give $\text{Si OH}_2^- + 2 \text{ H}_2\text{O}$ and this is actually dissolved state, so this dissolves very fast; it is an ion which dissolves fast in the solution and it liberates 2 H_2 .

Therefore, the silicon is really removed as Si(OH)_2 plus 2e^- state inside the solution; it is the complex which is formulated inside the solution. Problem is that in the steps of reaction, overall 4 electrons are transferred from each silicon atom into the conduction band but, if you look at the etching process is really it is then a function of the presence or absence of the electrons.

Now, manipulating the availability of electrons can make controllable etch stop possible and that is happening because, in its crystalline structure silicon atoms in 111 planes of stronger binding forces. It makes the electrons to really lose their valence band configuration and get into that outer conduction band and thus their availability, the readily or their ready availability is very difficult. So thus, the etch rates at 111 planes are the slowest possible etch rates. Considering that to happen eventually, the sites of the particular channel get shaped towards the 111 direction, because that is a slowest removal rate of the slowest etch rate.

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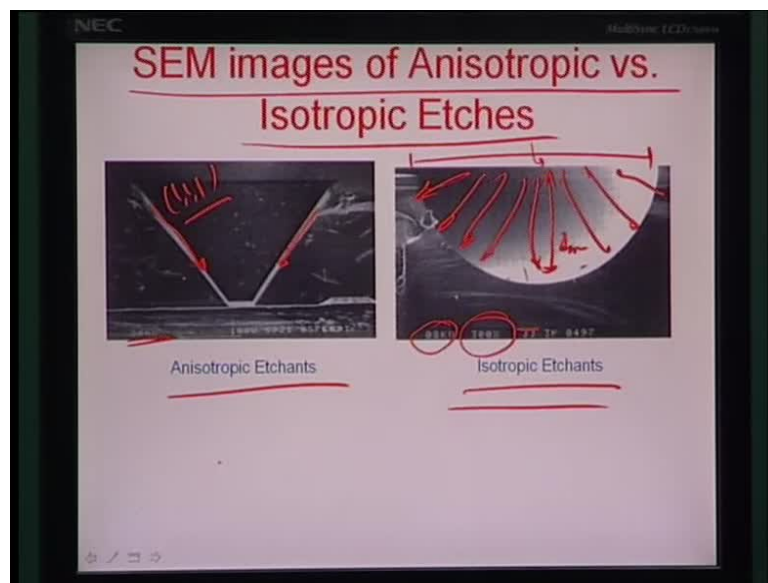


The basic silicon etchant some of which provide the hydroxide groups are alkali hydroxide like NaOH , KOH , CsOH , rubidium hydroxides, lithium hydroxides, etcetera. There are these ammonium hydroxide based etchants, one of the very popular etches that are used at TMAH based is called tetra methyl ammonium hydroxide or simply ammonium hydroxide based etching, so anything which can furnish hydroxyl ions easily. Then, you have this other mixtures, which can again give hydroxides, one of them is

EDP ethylenediamine pyrochatecol or mixture of ethylenediamine pyrochatecol and water which can give hydroxide ions readily.

EDP is hazardous and this causes cancer, so it is not a very environmentally friendly process and wherever, there is EDP performed and it is not very often used also because of this one factor, you have to have, proper safety measures to use it. Other etchants could include hydrazine water complex or amine gallate etchants etcetera, which can also just identically release electrons or release hydroxyl ions to initiate this redox process.

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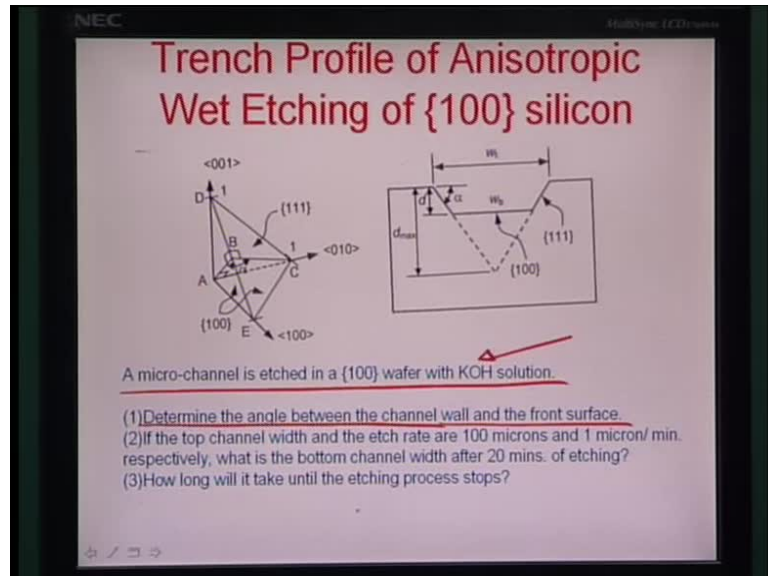


Let us look into what really the anisotropic etching shape would be and what is the comparison with isotropic process. As you can see here, in some of the etching images of anisotropic verses anisotropic etches this right here, as you see is a spherical etch were etching takes place uniformly across all the directions (Refer Slide Time: 29:59). This is blown up by about 300 times using an electric field of about is closed to 0.8 kilo volts. This right here is 33 microns which means that this would be a couple of 100 microns, let us say, about at least 600 microns or so along the etch window. The depth again could be close to about 500 microns or about 400 microns or so.

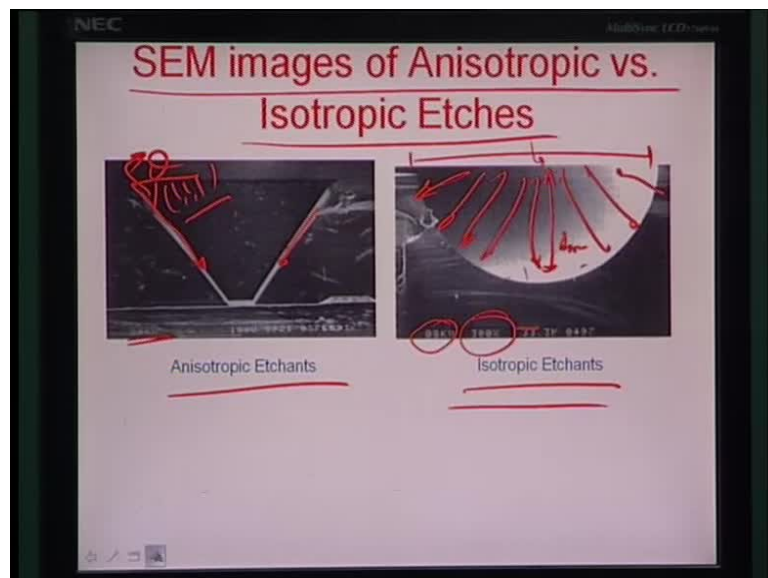
This right here again is done at about 20 kv and essentially, this is kind of an identically shaped corresponding anisotropic etchant used process. You can see that eventually the shape which formulates is dictated by the 111 plane, which is in this case, the least

electron releasing plane or electron donated. Therefore, it is an auto shaping technique of silicon the anisotropic etching process (Refer Slide Time: 30:38).

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Let us now try to understand this process a little more mathematically, a little more closely. We have a case where let us say, a micro-channel is etched in a 100 wafer with a KOH solution; the potassium hydroxide solution. We have to determine the angle between the channel walls and the front surface what really this angle would be.

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The slide features two diagrams. On the left, a 3D crystallographic diagram shows a silicon crystal with axes labeled $\langle 001 \rangle$, $\langle 010 \rangle$, and $\langle 100 \rangle$. Points A, B, C, and D are marked on the crystal surface. On the right, a cross-sectional diagram of a micro-channel etched into a $\{100\}$ wafer. The top surface is labeled $\{100\}$, the side walls are $\{111\}$, and the bottom is $\{100\}$. The top channel width is w_t , the bottom width is w_b , and the depth is d_{max} . The angle between the channel wall and the front surface is α .

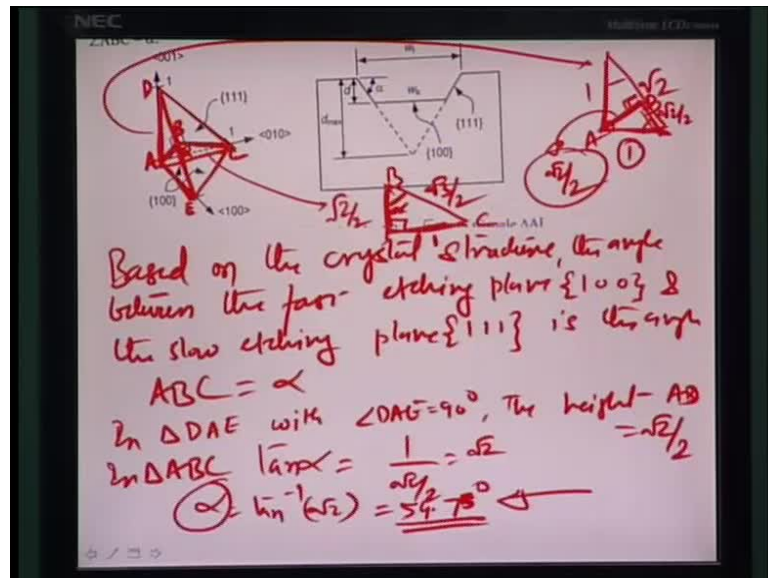
A micro-channel is etched in a $\{100\}$ wafer with KOH solution.

- (1) Determine the angle between the channel wall and the front surface.
- (2) If the top channel width and the etch rate are 100 microns and 1 micron/min respectively, what is the bottom channel width after 20 mins of etching?
- (3) How long will it take until the etching process stops?

We are talking about this particular angle θ that we need to detect here and then we also given that the top channel width and etch rates are respectively 100 microns and 1 micron per minute. We need to find out, what would be eventually the bottom channel width after about 20 minutes of etching process is over.

In the third question, we have to find out how long the etch process takes place till it stops. As both the planes meet essentially, because the 111 plane as you know is the slowest etching step that you have. So, eventually when you are going at a certain angle is almost always obvious to assume that they would kind of meet each other, when there is an abundance of no other planes but, the 111 plane. Therefore, the etch rate will kind of slowdown almost become negligibly small, 0 in that kind of a situation. We need to find out how much time it will take to arrive at that kind of a situation.

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Let us solve this problem one by one, based on the crystal structure the angle between the fast etching plane 100 and the slow etching plane 111 can be represented here, as you can see by the angle alpha. Alpha is the angle which is between the 100 plane and the 111 plane; 111 plane of course, being this one this is 111 planes (Refer Slide Time: 33:00), the triangle is the 111 plane and this is the 100 plane. So, the angle is really the angle between these two planes is accurately represented here by this angle alpha. Alpha is this angle between these two vertices or whatever you can call; let us try to determine this.

Based on the crystal structure the angle between the fast etching plane 100 and the slow etching plane 111 is the angle ABC, this is B, this is A, this is C, let us call it alpha. How do you find it? Let us say, in triangle DAE this is D and this is E vertex let us say, we have to see, what is essentially the characteristic feature of this A B, which is also a median of the triangle DAE (Refer Slide Time: 34:11).

In triangle DAE with the angle DAE really equal to 90 degrees, if you look at the angle here, this angle DAE is 90 degrees DAE is this one. It is like basically the two coordinates x and y perpendicular to or orthogonal to each other. Basically, the height in this case AB, so let us just draw this triangle out here. You have a triangle mind you, these both are 1, so this is root 2 and this is 90 degrees (Refer Slide Time: 35:38). Essentially, you are doing this in a manner that this is basically isosceles triangle with

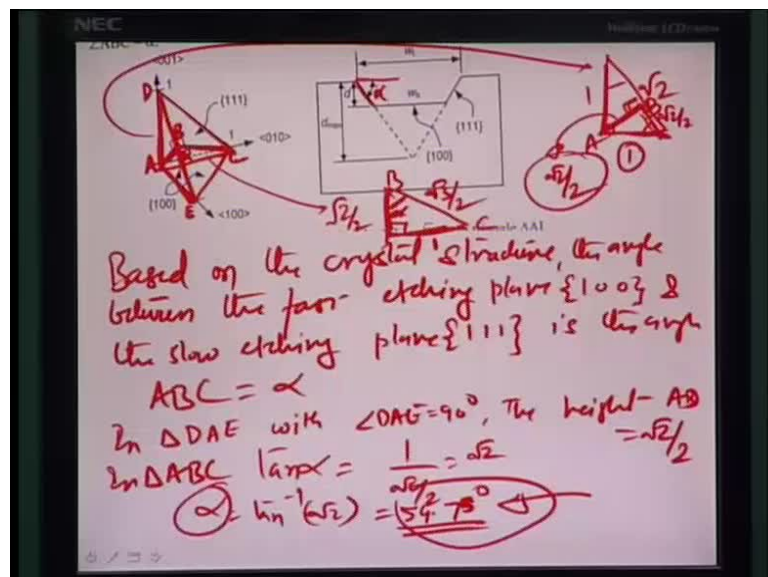
this angle equal to this angle equal to 45, so this median would be actually a perpendicular line, which is actually equal to.

You look at this particular triangle now, which this is root 2 by 2 this is 1 so naturally the other part here would be root 2 by 2. Really, AB, this is B, AB is root 2 by 2. The height AB here is root 2 by 2. Similarly, in triangle ABC this followed by this, which is the 0 1 0 directions basically (Refer Slide Time: 36:30).

You have another case here, which is very interesting let us say, you take this triangle of here and draw it. You have one side which is root 2 by 2 and other side which is 1. Essentially, the angle between this side and this side is alpha that is what this is about. So, I am actually taking this inclined triangle and trying to flatten up like this. So that is what is going to be, **so you have root 2, you have 1 sorry you have root 2 by 2 you** have a angle alpha and you have 1 here.

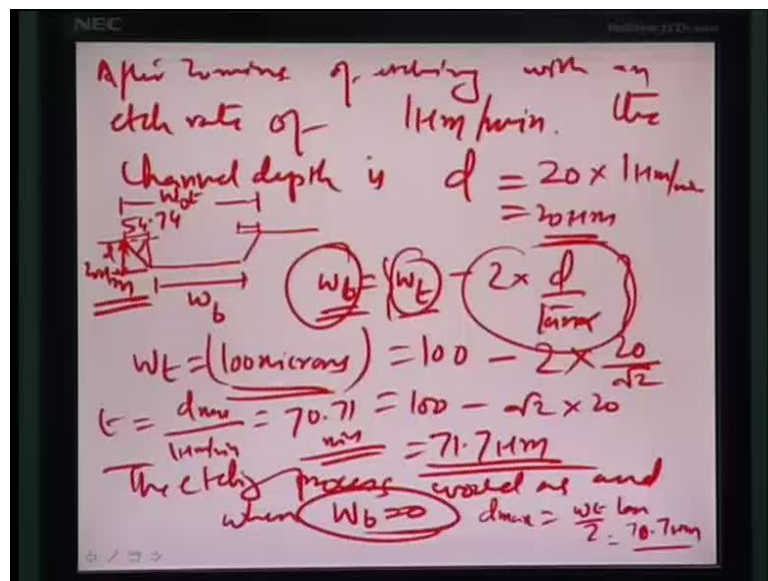
Naturally, if this is 90 degrees because this is going to be 90 degrees in any case, the site BC is essentially root 3 by 2, so the side is root 3 by 2. I am not really worried about that; what I am worried about what alpha is, so alpha essentially can be given by, so tan alpha is in this case 1 by root 2 by 2 or it is root 2 or alpha is actually equal to tan inverse of root 2 and root 2 is 1.414. So, the tan inverse of that is essentially equal to 54.74 degree it is more than 45 degrees tan 45 is 1. Therefore, the alpha value the angle here is 54.74 degrees.

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Now, we know that after 20 minutes; so the first part is answered, first part is basically, what is the angle of the plane finally formulating? The angle of the plane finally formulating in this anisotropic etching process with the direction of the phase of the wafer is really 54.74 degrees this alpha here. This is the phase direction of the wafer; this is the angle of the plane, so this is also 111 direction alpha is 54.74 degrees (Refer Slide Time: 38:40).

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Let us find out what happens after 20 minutes? After 20 minutes of etching with an etch rate of 1 micro meter per minute, the channel depth d is really nothing but, it is like 20 times of 1 micro meter per minute, which is actually the vertical etch rate which is given, so it is about 20 microns.

If it is about 20 microns then at the bottom channels – basically, you want to find out what is the bottom channel width? Let us draw this figure again, so you have a case here, where this angle right here and here is 54.74 degrees and this distance which has been etched off or etched away is 20 microns (Refer Slide Time: 39:57). Therefore, the bottom width here w_b and this is actually the top width w_t , which is equal to the bottom width w_t minus 2 times of d by $\tan \alpha$. That is what exactly the w_b is the bottom width is; so w_t minus 2 by d by $\tan \alpha$. Essentially, with the top width as you know w_t is nothing but, it is equal to about close to 100 microns as has been suggested by the question itself that the top channel width is about 100 microns.

Now, if that is so we have the bottom width here is 2 times of d by $\tan \alpha$; d is the etch depth, etch depth is about close to 20 micro meters and $\tan \alpha$ is essentially again root 1 by root 2 as we know. So, it is essentially nothing but 1 by - $\tan \alpha$ is root 2 I am sorry so $\tan \alpha$ is about root 2 essentially this whole thing boils down to root 2 we just rub this and rewrite this, so this whole thing boils down to 100 minus root 2 times of 20 microns which is actually equal to 71.7 micro meters that is exactly what W_b or the bottom width is in this particular case (Refer Slide Time: 40:55).

The etching process would stop again as and when the bottom width W_b is 0 as you can see here (Refer Slide Time: 40:08). Here, what happened is this was the top width W_t resource the bottom width, so W_t minus 2 times of d by $\tan \alpha$, so this is d , this essentially is d by $\tan \alpha$, so you are actually subtracting both ends $2d$ by $\tan \alpha$ in the process from W_t .

Here, if W_b is 0 then, the maximum etch depth that would be needed for the w_b equal to 0 is essentially equal to d_{\max} is w_t by $2 \tan \alpha$. In this particular case, as you see here, w_t by $2 \tan \alpha$ would be actually equal to about 70.7 micro meters and time t again would be equal to d_{\max} by 1 micro meter per minute, which is the etch rate, so it is about 70.71 minutes. That is what essentially the time until the etch stop if achieved would be. It goes all the way to about 70.71 minutes, which is also corresponding to 70.71 microns, where the bottom width W_b becomes equal to 0.

Now, I hope you are kind of aware of this whole etching business and the way that anisotropic etches can be accomplished. I would now like to move on to the dry etching processes by using plasma techniques. Essentially, dry etching is again a process where material is selectively removed by an agent, which may be in the liquid or in the gaseous state.

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Dry Etching

- Physical Dry Etching:
It utilizes beams of ions, electrons or photons to bombard the material surface. The kinetic energy of the ions knocks out atoms from the substrate surface.
The high beam energy then evaporates the knocked out materials.
Limitations:
Slow etch rates
Low selectivity because ions attack all materials
Trench effects caused by reflected ions
- Chemical Dry Etching:
Chemical dry etching uses a chemical reaction between etchant gases to attack material surface
Gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process
Chemical dry etching is isotropic. This technique is similar to wet etching and exhibits relatively high selectivity.

Here the dry etching can be categorized as physical dry etching or chemical dry etching primarily. Physical dry etching as you know it utilizes beams of high energy ions electrons or photons; photons whenever lasers are involved, electrons whenever EB machining is involved. This is essentially to bombard the material surface and the kinetic energy of the ions knocks out the atom, from the substrate surface in that particular case. High energy beams really then tends to evaporate metal atoms from knocked out materials and the basic mechanisms are ablation; basic mechanism of material removal is material ablation.

There are some limitations in this is high energy physical etching, physical dry etching process or the major limitations of the slow etch rates, because you have to individually ensure that all the atoms and all these molecules are knocked off and vaporize completely from their solid bounds towards where they are mean distance goes at least 10 times more than the distance of solid state or liquid state.

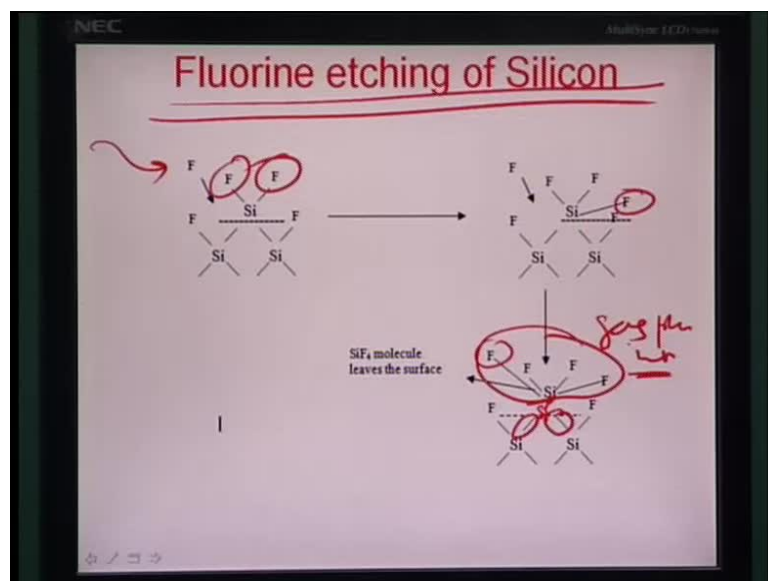
Low selectivity is also one of the major problems with this particular process, because the ions attack essentially all the material surface which is available, it does not distinguish between material which is covered versus material which is exposed; it is an ionic beam which were falling on the material. So, wherever it would hit the material, it would immediately start attacking the material selective non-selectively. There is nothing

called etch stop until you reduce the beam power to 0 the essentially the etch stop is when the beam power falls down to 0 it is only controlled by beam power.

There are other problems or issues one of the major limitations what we called trench effects, which are caused by reflected ions. So we have ions spotting into a let us say, you have this is the spot, where this high energy beam is being focused of this particular ion. You have sputters of material all around and this causes the trench effects, which means that some of the ions heating away from this sputter it actually starts heating onto the etches. Etches develop these trenches like features which is very common to this kind of physical dry etching.

The other kind of technique is chemical dry etching where you have actually a gas which is an etchant gas which chemically removes away the material. You have a chemical dry etching reaction between the substrate surface and the gas that you are supplying. Gaseous products are conditions for chemical dry etching because deposition of reaction products will stop the etching process. Basically, chemical dry etching is also completely isotropic in nature the technique is similar to other wet etching forms exhibits relatively high selectivity, because it is a chemical removal process the chemistry is actually the determining factors. If you make a different chemistry which is unsuitable to etching, it can act as a etch stop layer very accurately. That is what dry etching is about.

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Let us actually see how this dry etching process can happen? For example, in case of silicon atoms, if you hit fluorine inside a silicon matrix it starts immediately forming silicon fluoride, this is Si F_2 which has been formulated still it is unbound, this is another fluorine edition which happens and then finally, this Si F_4 is a gas phase material. Gas phase material which would leave this surface also, we have to see that you have satisfied all the bonds associated with silicon. So, the unsatisfied silicon is left bond in the lattice structure and the silicon here, which was initially there because of unsatisfied bonds now has been satisfied by fluorine and it leaves away as an independent entity or a gas.

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Recipes of Dry Etchant Gases

Recipes of Dry Etchant Gases for Thin Films of Functional Materials (After [1])

Material	Etchant gases	Selective To
Si	SF_6 , Cl_2 , BCl_3 , CF_4 , BCl_2 , CHF_3 , Cl_2 , CF_4 , Cl_2 , He , Cl_2 , CHF_3 , HBr , HFC_2 , HF , O_2 , HBr , SF_6 , He , F_2 , HBr , SF_6 , NF_3 , HCl , CF_4	SiO_2
SiO_2	CF_4 , H_2 , C_2F_4 , C_2F_6 , CHF_3 , CHF_2 , O_2 , CHF_3 , CF_4 , CF_2 , O_2	Si , SiO_2
Si_3N_4	CF_4 , H_2 , CF_4 , CHF_2 , He , CHF_3 , CF_4	Si , SiO_2
Al	BCl_3 , BCl_2 , Cl_2 , BCl_3 , Cl_2 , He , BCl_3 , Cl_2 , CHF_3 , O_2 , HBr , HBr , Cl_2 , HCl , SiCl_4 , SiCl_3 , Cl_2 , Cl_2 , He	SiO_2
Organics	O_2 , O_2 , CF_4 , O_2 , SF_6	

Physical Chemical Etching

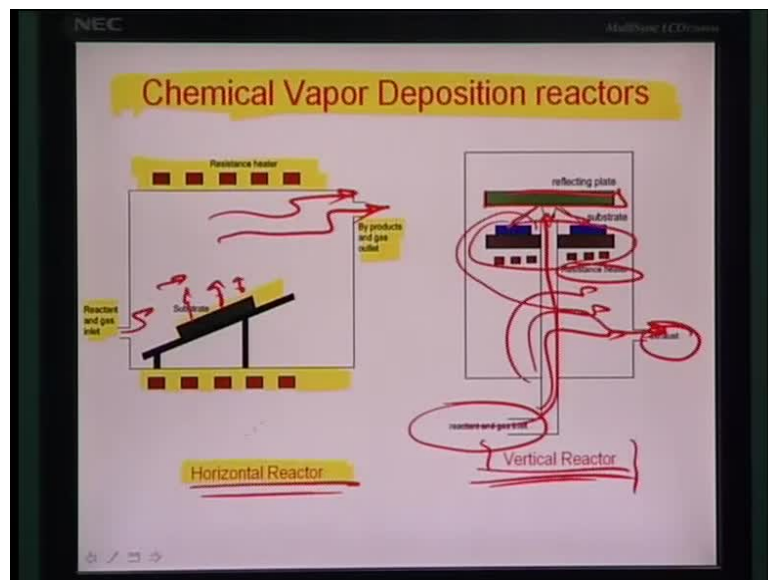
- Some Dry etching is referred to as a physical-chemical etching process.
- These are RIP (reactive ion etching), Anodic Plasma Etching (APE), Magnetically enhanced reactive ion etching (MERIE), Triode reactive ion etching (TRIE), and transmission coupled plasma etching (TCPE).

Therefore, wherever silicon covers off as Si F_4 , you have trenches or vias which are created and is essentially a chemical dry etching processes, as a reaction is happening it is a gas phase which is sending in and there is a dissolved gas phase of silicon which is coming out essentially of the process. Some of the recipes of dry etching gases are like for example, for material silicon with selectivity to Si O_2 , you have this different boron trichloride chlorine, boron trichloride carbon tetra fluoride, boron trichloride metal TRIE **trifluoromethene** trifluoromethane, you have chlorine and CF_4 so on so forth. Therefore, if you have to remove material Si O_2 , it is selective to Si O or aluminum layers, these are some of the gases which are used so on, so forth.

This table basically is a kind of complete recipe of dry etchant gases available for thin films functional materials, which can either use chemical or physical processes to remove off the material. Another very interesting dry etching process is of physical chemical it is a combination of physical as well as, the chemical dry etching.

These really are called reactive ion etching process and it depends on the pressure zone in which plasma has to be created over a surface. Essentially, there is a chemical gas phase reaction which is responsible for etching but, it is done within a plasma atmosphere, where there are ions and electrons of this gas. There is a certain drive pressure or an ionic momentum which is imparted to these species and it can drive into a substrate and start moving material from the substrate.

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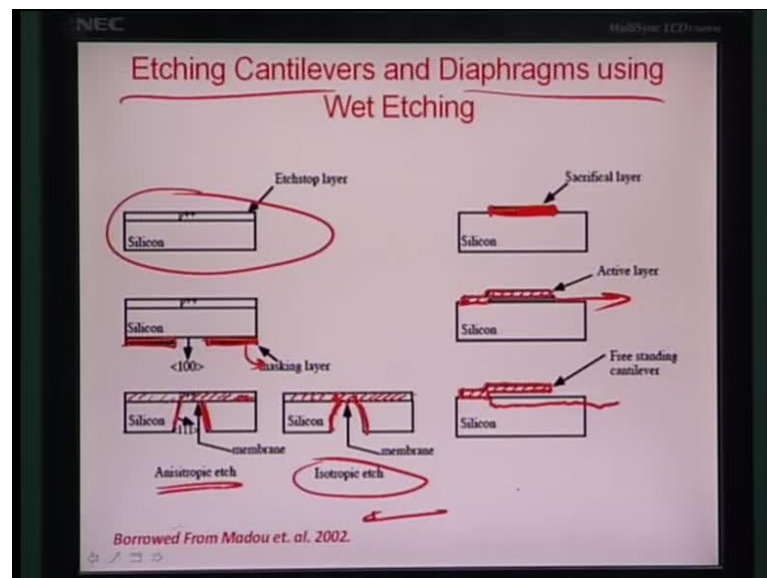


Therefore, based on this RIE processes there are different kind of sub processes like Anodic Plasma Etching, Magnetically enhanced reactive ion etching, MERIE triode reactive ion etching, TRIE and transmission coupled plasma etching TCPE. There are different kinds of reactive ion etching processes that one may think of in the physical chemical etching area. Some of the other important processes which are used are chemical vapor deposition reactors, where these chemical etching can be carried out. Typically, you have a substrate as you can see here and you have a set of heaters, which would be able to heat the substrate to a certain temperature ever in flowing reactant in a gas inlet and a byproduct gas outlet.

Heaters are actually on both sides so that you can uniformly heat the substrate and then definitely, this is actually what a horizontal reactor would look like typically. Then you flow in, flow out the gases which would cause the reaction on this substrate and there would be a gas state which is dissolved and the gas finally goes out from this outlet end.

Similarly, in case of a vertical composition of the reactor what happens is that you have a gas inlet which is thrown into this area, where there is a reflecting plate and the ions are reflected off and removes the material and this is highly heated zone with this resistance set of heaters. Therefore, whatever is removed here is or whatever is produced here is again removed by the exhaust system continuously. So, there is a flow between the reactant and the gas inlet.

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There is going to be sufficient amount of laminarity or turbulent switches introduced by the various flow velocities that are achieved within this particular kind of vertical reactor. You have a horizontal reactor and you have a vertical type reactor for chemical vapor deposition processes. This slide here illustrates how you can etch cantilevers and diaphragms using wet etching techniques and I have illustrated this before but, I would just like to go through it once more.

You have a p double plus etch stop on the top of silicon and you are actually opening a small window here on a sacrificial material masking layer, which is made in this black here (Refer Slide Time: 52:45). Through this window, you etch using anisotropic wet

etching so that you formulate on both sides 54 degrees angle of the walls. You typically put a hydroxide etch and then you are left with this p plus membrane here which is only a few nanometers and it is like a vertical membrane; it is simply supported beam or a membrane which can be used for various purposes.

If you could have used isotropic wet etching instead of anisotropic wet etching with slight amount of stirring then etch would have been spherical in nature. Therefore, you can actually get again the same formulation of thin membrane on the top of this semi spherical structure which is used or generated by isotropic etch, so this is how a diaphragm could be manufactured.

On the other hand, we want to manufacture cantilever the best way to do that is to put the sacrificial layer as you are seen here on the top of silicon and then you cover it with a poly silicon or an active layer by some deposition mechanism thereby, removing this material back, so that you are left with a freestanding membrane structure over silicon. You could use another masking alternately to remove material from this end, so you have a perfectly separated cantilever structure for different diagnostic studies.

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Photolithography

- Lithography is the most important technique for fabricating microstructure.
- Types of Lithography:
 - (1)Photolithography
 - (2)Electron beam lithography
 - (3) X-ray lithography
 - (4)Ion lithography.
- Photolithography consists of 3 steps:
 - 1.Positioning process
 - 2.Exposure process
 - 3.Development process

Optical Source

Aperture

Shutter

Mask

Photo-resist Wafer

Rayleigh Criteria for Contact Lithography:

$$b = 1.5 \sqrt{\lambda \cdot s}$$

Where, s is the distance between the mask and the resist and λ is the wavelength.

Rayleigh Criteria for Projection Lithography:

$$b = \lambda \cdot s / 2 \text{ NA}$$

Where, s is the distance between the mask and the resist and NA is the numerical aperture

Now, I would like to come to the next process which is photolithography. Therefore, we are towards the end of this lecture, we will try to introduce some more processes like photolithography and other deposition techniques like sputtering or ion implantation in the next lecture. Thank you.