Microsystem Fabrication with Advanced Manufacturing Techniques
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Lecture - 3

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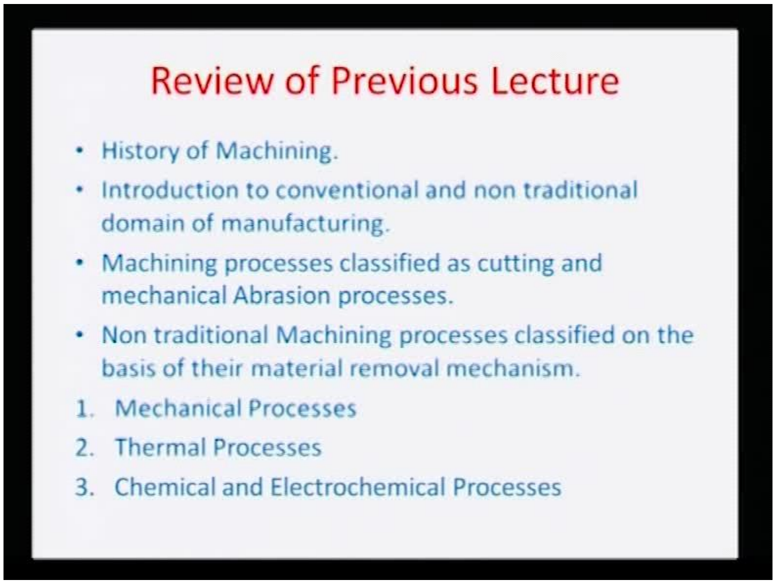

Review of Previous Lecture

- History of Machining.
- Introduction to conventional and non traditional domain of manufacturing.
- Machining processes classified as cutting and mechanical Abrasion processes.
- Non traditional Machining processes classified on the basis of their material removal mechanism.

1. Mechanical Processes
2. Thermal Processes
3. Chemical and Electrochemical Processes

So, welcome back. Today I would be talking on this Microsystems fabrication by advance manufacturing processes in the section. Then I would be dealing today is what is silicon and how do you process silicon using advanced manufacturing techniques. So let us look at some of these amenable materials, so review of the review of the previous lecture briefly.

So, in the previous lecture we really tried to get a historical prospective of machining and this was followed by description of the some of the conventional and nontraditional domains of manufacturing. Wherein you know the machining processes or metal cutting processes machining processes were classified as metal cutting processes or mechanical abrasion processes on one hand.

The nontraditional or the nonconventional machining processes were classified on the basis of material removal mechanisms based on either mechanical removal thermal removal or chemical electrochemical removal on another hand. And we also saw that, the course is basic intention is the synergism between the micro systems technology and the way to fabricate it and the advance manufacturing processes and the integration between the 2.

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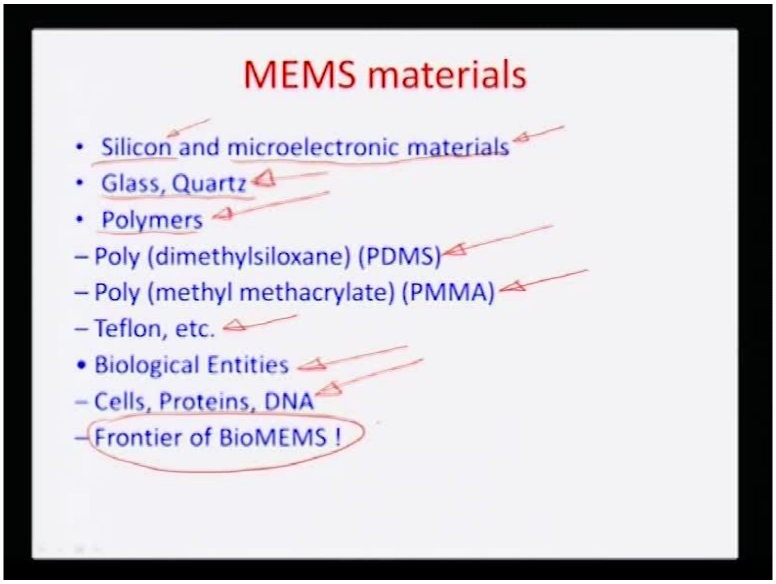

MEMS materials

- Silicon and microelectronic materials
- Glass, Quartz
- Polymers
  - Poly (dimethylsiloxane) (PDMS)
  - Poly (methyl methacrylate) (PMMA)
  - Teflon, etc.
- Biological Entities
  - Cells, Proteins, DNA
  - Frontier of BioMEMS !

So let us now, see some of the materials which are very amenable to the use you know and developing into their use of developing Microsystems. So silicon of course, is a 1 of the principle materials which are used for Microsystems fabrication, because as I mentioned earlier that the traditional processes really are the … The nontraditional processes on silicon are nothing but, borrowed from the microelectronic industry.

Therefore, being a microelectronic material the followed processes which really comprise of MEMS processes are amenable to fabrication of silicon. Then of course, quartz and glass, because in most of the cases of Microsystems you sometime need optical transparency and therefore, glasses and quartz are the next line of materials amenable to the you know can be classified as MEMS materials or the Microsystems materials.

Then another whole lot of class of materials which are nowadays increasingly used for Microsystems fabrication are polymers. And then polymers particularly this p d m s or poly dimethylsiloxane, which is considered to be a very bio friendly material is most used particularly in biomedical MEMS or biomedical micro devices.

Then of course, PMMA poly methyl methacrylate, which is also an e beam resists and it is used increasingly for e beam mythography and other applications. Then this material teflon, where teflon is actually commercial name of material available from and the teflon is very hydrophobic and it has excellent applications again in the biological world. So therefore, teflon is another very amenable material MEMS material which is used mostly for fabrication of Microsystems.

Then of course, there is this whole new domain of Microsystems which is using biological entities like: cells, proteins, DNA. And these are also some of the very frontier research areas in the bio-MEMS as to how to micro manipulate or nano manipulate sometimes the biological entities, for fabrication or advance manufacturing of MEMS at this particular scale.

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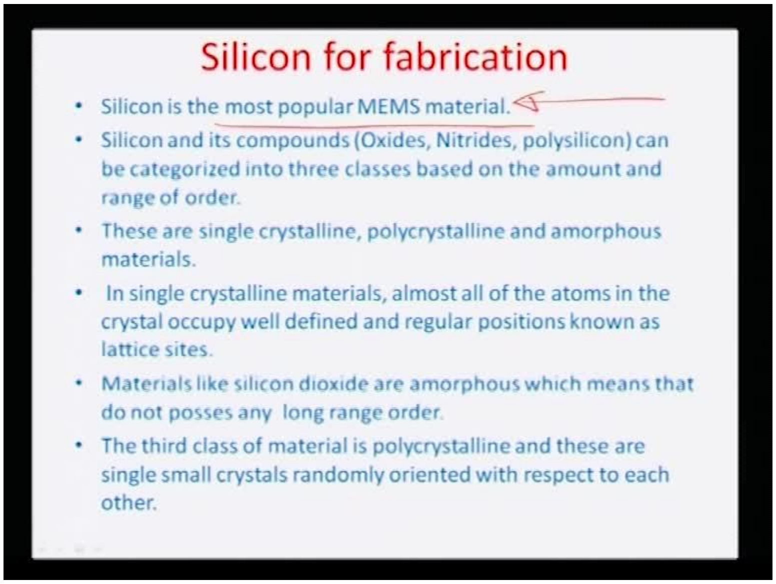

Silicon for fabrication

- Silicon is the most popular MEMS material.
- Silicon and its compounds (Oxides, Nitrides, polysilicon) can be categorized into three classes based on the amount and range of order.
- These are single crystalline, polycrystalline and amorphous materials.
- In single crystalline materials, almost all of the atoms in the crystal occupy well defined and regular positions known as lattice sites.
- Materials like silicon dioxide are amorphous which means that do not posses any long range order.
- The third class of material is polycrystalline and these are single small crystals randomly oriented with respect to each other.

So let us begin with silicon. So silicon of course, is a most popular MEMS material obtained, so far. And silicon and its compound, so variety of compounds like oxides, nitrides, polysilicon etcetera, can be very amenably used for Microsystems fabrications.

And not only that you can categorized these whole class of materials based on the amount of you know their range of order into crystalline, polycrystalline or amorphous materials. Where the in the definition of these terms are kind of parallel to whatever you know conventional definitions are.

Semi crystalline means, that there is one particular kind of crystal with the repetition of unit cells and there is no break of this crystal, what is, so ever. Polycrystalline is that the crystal growth takes place at the several centers and it formulates into cranes of different crystals, with grain boundaries in between. And amorphous is where the range of order is rather longer where shorter where there is no order and it is very randomly deposited. And so, these class of silicon oxide nitride and silicon as such polysilicon can be categorized into these various forms and domains. So, materials like silicon dioxides for example, are amorphous which means that they did not possess any long range order. So, that is what is basically the categorization of silicon?

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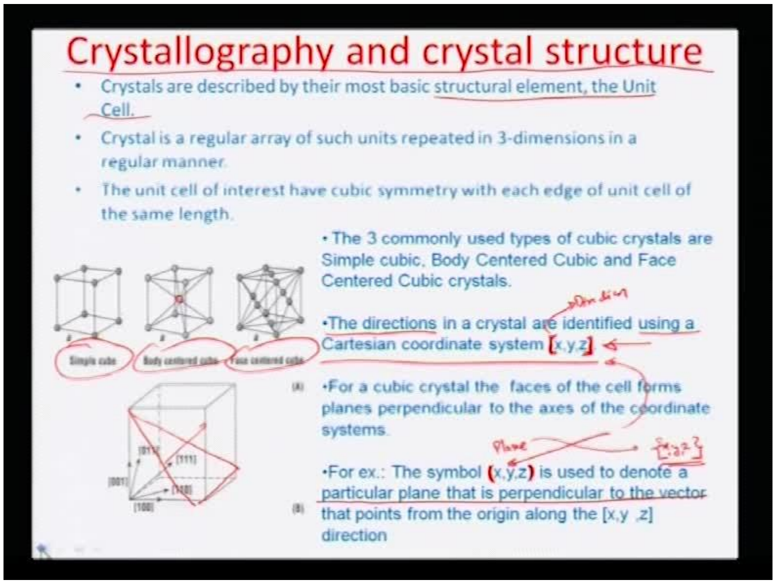

Crystallography and crystal structure

- Crystals are described by their most basic structural element, the Unit Cell.
- Crystal is a regular array of such units repeated in 3-dimensions in a regular manner.
- The unit cell of interest have cubic symmetry with each edge of unit cell of the same length.

• The 3 commonly used types of cubic crystals are Simple cubic, Body Centered Cubic and Face Centered Cubic crystals.

•The directions in a crystal are identified using a Cartesian coordinate system [x,y,z]

•For a cubic crystal the faces of the cell forms planes perpendicular to the axes of the coordinate systems.

•For ex.: The symbol (x,y,z) is used to denote a particular plane that is perpendicular to the vector that points from the origin along the [x,y ,z] direction

Let us look a dull into a little bit of crystallography and crystals structures. When we talk about specially single silicon crystals are described by their most basic structural element the unit cells as most of us know. And it is a regular array of such units repeated in 3 dimensions in a very regular manner which comprises of a crystal and unit cell of interest have. It is a cubic symmetry with each edge of this unit cell has the same length.

So, you can divide these into different classes of crystals like simple cubic where you can see there about 8 atoms on the 8 corners of this particular cube. Body centered cubic where you have atoms on the corners as well as one in the center of the whole cubic lattice. And this what one unit cell would comprise of a look like and repetition of all these unit cells in the 3 dimensions would typically result in, what you call as single crystal line in material. And then, you have face centered, where these faces also have some atoms apart from the corners and there is no atom in the center of this particular unit cell.

So, these are some of the classifications of how cubic crystals can be divided as and just to retreat or just to you know memorize some of the fundamentals, which you probably may have obtained earlier these the crystals are rarely represented by directions and they are identified using cartesian coordinate system and the square bracket here as you are seeing is indicative of the direction in which, so the crystal would grow you know, so it is the direction of growth of the particular crystal, so if I say that it is a 1 0 0 growth that means it is growing crystal is growing in the x direction if it is 0 1 0 is growing in the y direction similarly, if it is a 0 0 1 it is growing at the z direction and not only that if you know you can change the planes if their growth is along a certain plane then it can be a 11 0 and or it can be say you know 1 0 1 or a 0 1 1 which corresponds to different planes of of the growth and then there can be a very interesting growth along the 111 direction which means that it is something like a triangle here as you can see.

So the 1 11 direction typically is perpendicular to this particular triangle, so the direction of growth is perpendicular to this particular direction, so whatever it is the directions are represented by these square brackets and it is a sought of sign convention to do that and you know if you want to represent the plane a particular plane that is perpendicular to the vector square bracket xyz you represent that by this round bracket xyz which comprises of the plane of which xyz was a direction of...

So, this is the plane curved bracket and this is the direction square bracket, and then of course, a set of such plane is are represented by this third bracket and these set of planes would be meaning all planes of type round bracket xyz represented by the third bracket at xyz, so that is a sought of that you use for you know systems or for identifying silicon as such.

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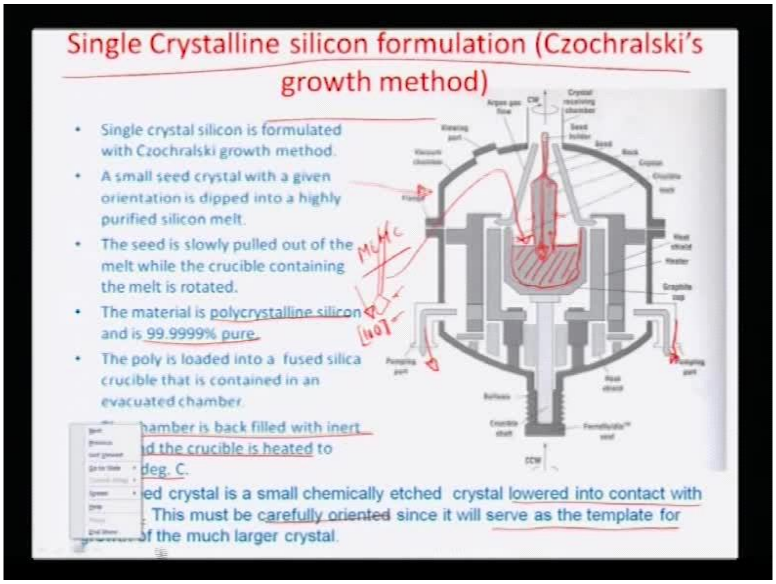

Single Crystalline silicon formulation (Czochralski's growth method)

- Single crystal silicon is formulated with Czochralski growth method.
- A small seed crystal with a given orientation is dipped into a highly purified silicon melt.
- The seed is slowly pulled out of the melt while the crucible containing the melt is rotated.
- The material is polycrystalline silicon and is 99.9999% pure.
- The poly is loaded into a fused silica crucible that is contained in an evacuated chamber.
- hamber is back filled with inert d the crucible is heated to deg. C.

ed crystal is a small chemically etched crystal lowered into contact with This must be carefully oriented since it will serve as the template for f the much larger crystal.

So let us know look into a little bit different aspect of how you can actually make a single crystalline silicon and in context of that the most important method that is illustrated in literature very often is Cochralski's growth method in which silicon can be obtained from polycrystalline Silicon and 99 point 99 in percent pure polycrystalline silicon which is fused and this fuse this fusion process is by thermal means there is a crucible which is indicated here in this figure which comprises of a central cavity and this cavity as I am illustrating by this border here contains the silica material

The silicon mate the polycrystalline silicon fused material and a this crucible, so called is basically capable rotation, so you can rotate the whole crucible and also it is inertly felt, so the chamber here is evacuated using pumping mechanisms as illustrated here and here and then you can fill the whole environment or atmosphere of this fused silicon container with organ or an inured gas, so that it ensures the non inclusion of material like oxygen or nitrogen into the silicon lathus. So it is extremely pure process and there are certain foundries in the world like one example is mem c which is based on which actually manufactures some of these silicon wafers high priority single crystalline silicon wafers.

So the way the processing goes is that when this crucible is rotated and then there is something called a seed crystal which has been obtained from an earlier process and the seed can be probably a very small a crystal of a certain direction or grown in a certain direction let us say the 1 0 0 direction. So, this seed has been grown from earlier process it is a pure crystal and this seed is inserted into this melt somewhere here as can be illustrated and as its illustrated here, and therefore, the the rotation the relative rotation between the seed and the crucible and you know can be varied by varying the the relative rpm and what is important here is that as the seed goes and dips into the material and the seed is slowly pulled out it tries to drag along with it apart with the silicon melt and the moment the silicon melt comes out into the open atmosphere it is no longer you know a part of the crucible.

Therefore, it can as well solidified, so only advantage here is that the solidification the rates of this pulling can be balanced with the rate at which the relative rotation happens between the crucible and the seed and many other parameters are in a controlled manner, so the rate at which the theta the solidification front sought of cool zarf you know you can really tailor it or fine tailor it in a manner, so that the growth takes place in the same direction as the direction of the seed crystal, so this is Czochralski’s crucible process.

So, the seed is the mother crystal which would eventually result in formulation of a bowl of material as can be indicated by this outline that I am drawing here and this all material in this bowl is grown in the direction of the seed crystal and the parent direction is kind of grown into this particular bowl. So once this bowl is extracted you can actually cut this bowl into pieces and you can find polish them and there are lot of methodologies like a c n c wire cutting idiom or some other instruments which are used for fine sizing or may be even band saw which are used for fine sizing these wafers.

Typically these wafers can vary between 400 microns thickness to about 900 microns thickness so,me other netigratity of this process is that the chamber is actually filled with you know it is back filled with inert gas and the crucible is a heat adapter 1500 celsius and this seed crystal is really small chemically etched crystal and lowered into the contact with the melt.

So, that the melt can grow in that all chemically etched crystal and lowered into the contact with the melt, so that the melt can grow in that direction it has to be carefully oriented, because this sought of serves as a template for growth of the much larger crystals later on, so that is how Czochralski's growth method or growth process is actually executed.

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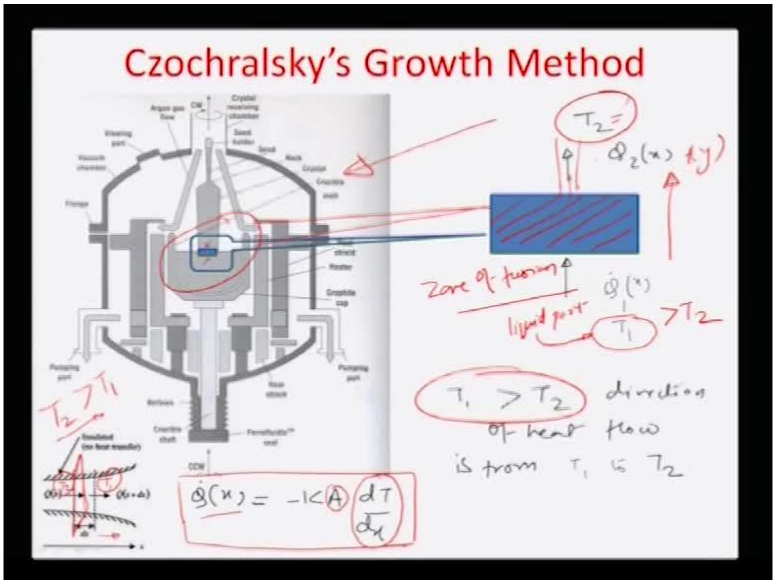

Czochralsky's Growth Method

$\dot{Q}(x) = -K A \frac{dT}{dx}$

$T_1 > T_2$ direction of heat flow is from T_1 to T_2

Now let us do some mathematical modeling for this processah which can give us an idea of how you know the liquid solid conversion can take place in terms of latent heat of solidification and we can just to a simple 1 dimensional heat flow analogy to understand the situation, so let us say you have a crucible here in this particular example and we are considering this particular zone here as you can see which is also called the zone of fusion zone of fusion, because the sought of you know this is the zone where the there is a presence of both the states liquid state which is in to the crucible and then the solid state which is a part of a seed which is getting withdrawn.

So it is a sought of semi solid semi liquid kind of zone that we are considering, so if you apply the furious law of heat conduction, so q of x or the rate of flow of heat as a function of x or in the direction of x is really proportional to the interfacial area across which the heat is flowing, so the interfacial area in this case can be thought of as going in to the plane of the slide, so this is a area across which the heat is flowing, so this is also known as the heat face and then its also proportional to the temperature gradient which exits in the material in the direction of flow of heat.

So in this case for example, if the temperature here is t 1 the temperature here is t 2, so temperature here is t 1 temperature here is t 2 and of course,,, in this particular case t 2 is more than t 1 which enables the heat flow from the direction of t 2 to t 1, so let us say in this particular zone of fusion that is in question we have a temperature t 1 which is actually higher than t 2 in this particular case which is that of the liquid part of the zone of fusion right.

So the temperature of the liquid part is t 1 and the temperature of the solid part of the withdrawn seed and the bowl formulated on the seed as a template is basically t 2 as illustrated here and t 1. Of course, is greater than t 2 which enables the direction of heat flow in the positive y direction as you can see here, because of the flows from t 1 towards t 2 and we need to just investigate how the rate of heat flow here into the zone of fusion from the liquid side and the rate of flow out of the zone of fusion in to the solid side would be balanced with each other and this heat loss which is happening you know is also a cause of the formation of the solid which means that you know in the solid state as you know the bond energy is always higher.

Therefore, there is a heat of formation of the solid which is lost you know its called the latent heat of formation of the solid, so the difference between the rate of heat flowing to the zone of fusion and out of the zone of fusion is really the quantity of heat which is lost in formulating the solid from the liquid state.

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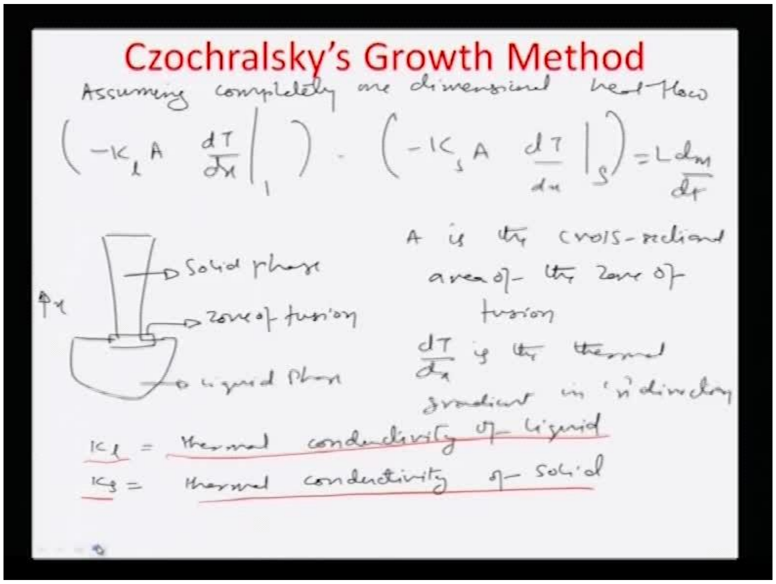

Czochralsky's Growth Method

Assuming completely one dimensional heat flow

$$\left(-K_l A \left.\frac{dT}{dx}\right|_l\right) - \left(-K_s A \left.\frac{dT}{dx}\right|_s\right) = L\frac{dm}{dt}$$

A is the cross-sectional area of the zone of fusion

$\frac{dT}{dx}$ is the thermal gradient in 'x' direction

K_l = thermal conductivity of liquid

K_s = thermal conductivity of solid

So if you model it in that manner let us say for example, if we assume completely one dimensional heat flow in this particular case we can write the heat equation as minus k l a d t by dx in the liquid side a minus shows that the heat is always from the higher the you know the towards the lower temperature from the higher temperature side which is also be defined by the law of thermos dynamic.

So, kl is the conductivity the thermal conductivity of the liquid melt is of course, the interfacial area of the zone of fusion and d t by dx is the temperature gradient available across that interface between the liquid on to the crucible. And the zone of fusion and of course, this heat goes into the zone and the heat which is lost from the zone of fusion into the solid can be defined as minus of minus k a where k s sorry, where k s is basically the thermal conductivity of the solid material aims of interfacial area between the zone of fusion.

the solid a you assume the area to be save in both the cases for simplicity of the model here times of d t by dx where temperature gradient in the solid while the heat flows from the zone of fusion into the solid, so that is the difference of heat flow into the zone of fusion and outside the zone of fusion and this net heat loss here is somewhere recorded as the solid formation and or the you know the heat of formation of the particular solid, so if we assume that the rate at which the the solid material gets formulated is d m by d t as you can see in this particular illustration here and l being the latent heat of formation which is in terms of how much mass per kg how much heat is lost in order to formulate the solid.

So, l d m by d t is really nothing but, they are the amount of heat the rate of heat the the rate of heat lost in terms of formation of the solid bond rate of heat lost can be equated in terms of heat going per unit timing to the zone fusion minus heat away from the zone of fusion per unit time.

So you can really equate both these equations and that formulates a bases of Czochralsky's growth process, because you know heat flowing in here represented by the first term heat flowing out here represented by the second term and in between whatever is happening resulting in this formation of the solid face d m by d t, so that is really what this Czocharlsky's process is about d t by d x, of course is a thermal gradient in the x direction from the either from liquid to the zone solid zone of fusion or from the zone of fusion to the solid and k land k s are respectively the thermal conductivities of the liquid state and the solid state of the silicon.

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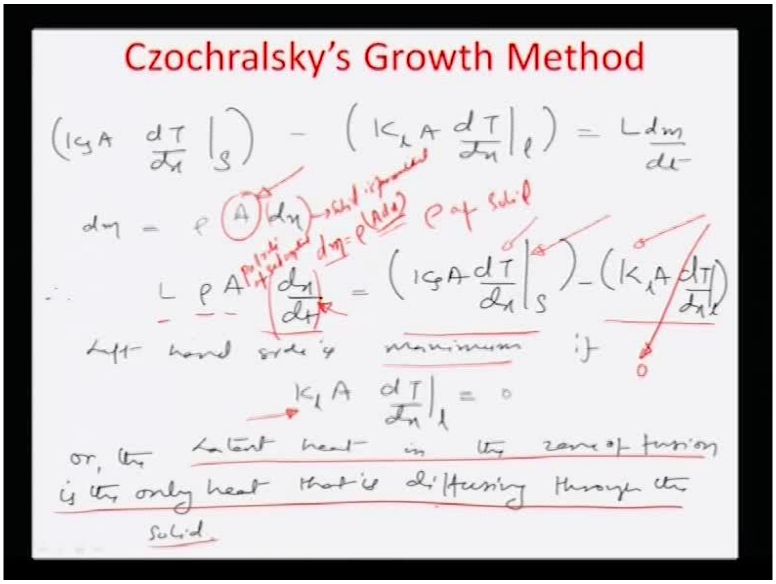

Czochralsky's Growth Method

$$\left(K_s A \frac{dT}{dx}\Big|_s\right) - \left(K_l A \frac{dT}{dx}\Big|_l\right) = L\frac{dm}{dt}$$

$$dm = \rho \boxed{A}\, dx$$

solid is formed

$dm = \rho(A\,dx)$

ρ of solid

$$\therefore\ L\rho A \frac{dx}{dt} = \left(K_s A \frac{dT}{dx}\Big|_s\right) - \cancelto{0}{\left(K_l A \frac{dT}{dx}\Big|_l\right)}$$

Left hand side is maximum if

$$K_l A \frac{dT}{dx}\Big|_l = 0$$

or, the latent heat in the zone of fusion is the only heat that is diffusing through the solid.

So let us refine this equation a little more by assuming that you have row as a density of the solid in this particular case and of course,,, a the area of zone of fusion defined by a constant a is the interfacial area and if you assume that dx length of solid material is formulated, because of this hip transfer process, so d m really the differential amount of mass is nothing but, the density times of the volume a d x which is created by virtue of pull out from the zone of fusion into the solid state.

So, if we equate the new term obtained for d m into the earlier equation we have l times of row times of a times of dx by d t which is nothing but, the pull rate the pull rate of the seed crystal in terms of the rate of displacement of the seed with respect to the crucible, so this is the pull rate, so l times row times of pull rate is nothing but, the seed transfer equation which is k x a d t by dx solid minus k l a d t by dx liquid you just taken the negative of negative therefore, that is why the equation has changed sign.

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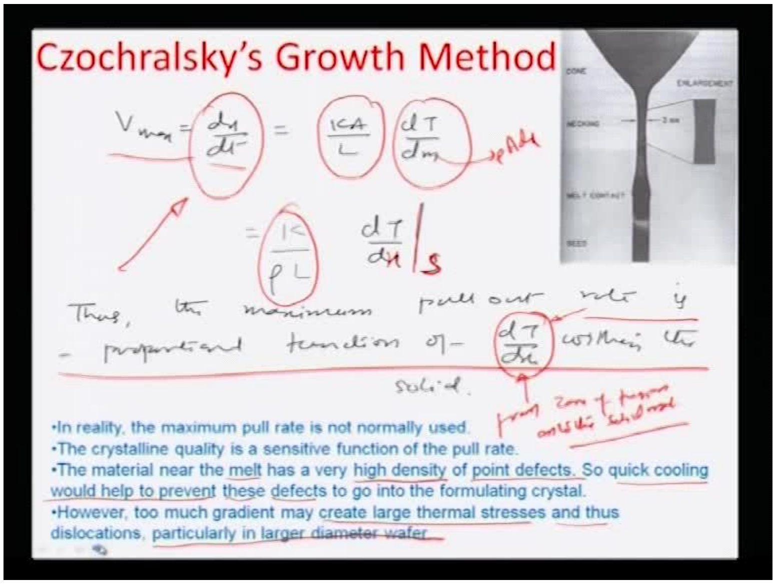

Czochralsky's Growth Method

$$V_{max} = \frac{dx}{dt} = \frac{KA}{L} \frac{dT}{dm} \rightarrow \rho A dx$$

$$= \frac{K}{\rho L} \frac{dT}{dx}\Big|_S$$

Thus, the maximum pull out rate is proportional function of $\frac{dT}{dx}$ within the solid.

from zone of fusion onto the solid mode

- In reality, the maximum pull rate is not normally used.
- The crystalline quality is a sensitive function of the pull rate.
- The material near the melt has a very high density of point defects. So quick cooling would help to prevent these defects to go into the formulating crystal.
- However, too much gradient may create large thermal stresses and thus dislocations, particularly in larger diameter wafer

So, if we were to assume that our pull rate is maximum for the purpose of high yield production we should have a situation where this negative component should go to 0 therefore, typically whatever is coming as heat into the the zone of fusion is really the amount of heat going away from the heat of fusion zone of zone of fusion.

So that is typically a case in one dimensional transfer, so this whole equation is a maximum on the left side only if this liquid heat transfer from liquid into the zone of fusion is 0 or the latent heat really in the in the zone of fusion is the only heat that is diffusing through the solid and therefore, this is a one dimensional case where you have the maximum pull rate w max represented by k a by l times of d t by d m or k divided by row l we are just putting the value of d m here row a d x times of d t by dx and this d t by dx mind you is in the solid domain as the heat emanates from zone of fusion into the solid.

So the maximum pull rate is really proportional to d t by dx or the temperature gradient from the zone of fusion on to the solid material and therefore, one may argue that if you have a very large d t by dx it would result in maximum yield or maximum pull rate which is actually not the case cut bloody, so normally the maximum pull rate is never used and that is, because if you give it very less time to formulate then there is always a tendency of a lot of point defects particularly in in the zone of fusion nearer to the melt.

Therefore, the point defect density would go up very high if the d t by dx increases, so quick cooling would help to sought of on one hand create a lot of defects into the next formulating zone from the liquid although the defects may not be going into the solid crystal, because you have a very less time given for the cooling process to take place or the solidification to take place.

However another aspect of this huge too much thermal gradient is also creation of large thermal stresses within the solid which would rather create dislocations and particularly this is true for larger diameter wafer if the dislocations are very, very prominent, because of that, so it is really a a tradeoff between the pull rate on the way that the defects would go into formulating the crystals or the amount of thermal stresses that the crystals can handle and this together would define how much pull rate is really needed.

That is really not a yield decision sometime yield based decisions sometimes it is basing itself on the purity of the material particularly where, because we are growing single crystalline silicon here purity of the material in terms of point defects I the density and also thermal stress created dislocation etcetera, so it is a it is a function of a lot of other quality parameters for the wafer apart from the yield, so that's how czochralsky's growth process works.

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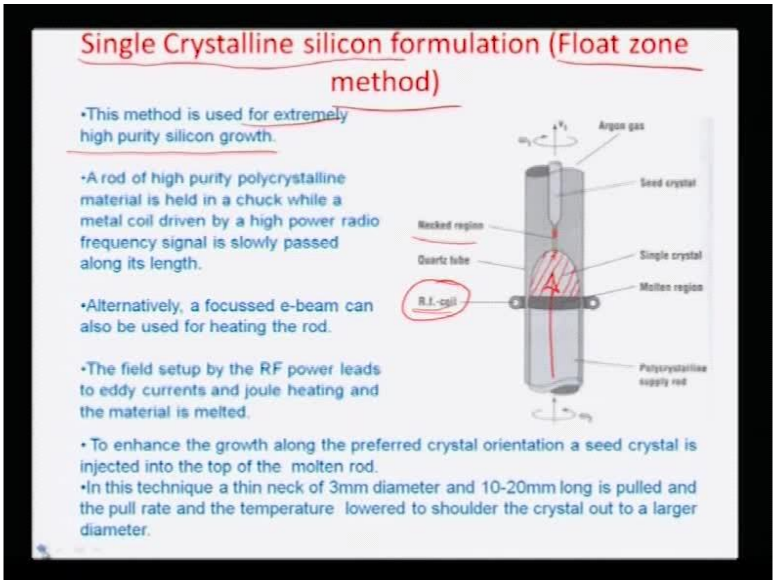

Single Crystalline silicon formulation (Float zone method)

- This method is used for extremely high purity silicon growth.
- A rod of high purity polycrystalline material is held in a chuck while a metal coil driven by a high power radio frequency signal is slowly passed along its length.
- Alternatively, a focussed e-beam can also be used for heating the rod.
- The field setup by the RF power leads to eddy currents and joule heating and the material is melted.
- To enhance the growth along the preferred crystal orientation a seed crystal is injected into the top of the molten rod.
- In this technique a thin neck of 3mm diameter and 10-20mm long is pulled and the pull rate and the temperature lowered to shoulder the crystal out to a larger diameter.

So the ,other method which is of some prominence is basically the you know is called the float zone method which is again another very important method for realizing single crystalline silicon, so in this particular method also called the float zone method you know it is a it is basically used for extremely high purity silicon growth although down side of this particular process is that you cannot really go above a certain diameter of production of wafer like Czochralsky's you can go up to any extent including 8 inches or you know 5 inches big size wafers are also possible.

In this particular case it is only limited to smaller size wafers and the process for production really is similar you have the concept of a seed crystal and this the method as well as we had in Czochralsy's however in this particular case as you can see there is a polycrystalline rod which is being pushed into the small and by means of noncontact mediate heating like an r f mechanism may be you heat this particular surface of the wafer to almost it is melting temperature while pushing the the polycrystalline rod all the way into the r f s.

On the other side you lower the seed crystal into the into the this r f s here and the seed crystal is actually used as a template for formation of growth of this polycrystalline material being pushed to thefts on to the other side, so from the naked region really in this particular region the seed crystal grows and make you know a single crystalline in silicon of the type of from the polycrystalline melt which you are pushing through this particular r f s the both the rod as well as the feeding rod as well as the wafers are moving at certain omega velocities and 1 good advantage here is the uniform heating.

So, there are very less thermal stresses and such no thermal stress related this location which is otherwise the case in Czochralsky's method where there is a huge thermal grade gradient available, because it is essentially a contact mode heating here most of the heating means are r f based, so that this noncontact mediated and there are no thermal dislocations what, so ever in the particular crystal, so that is another method of formulation of a single crystalline silicon known as float zone method.

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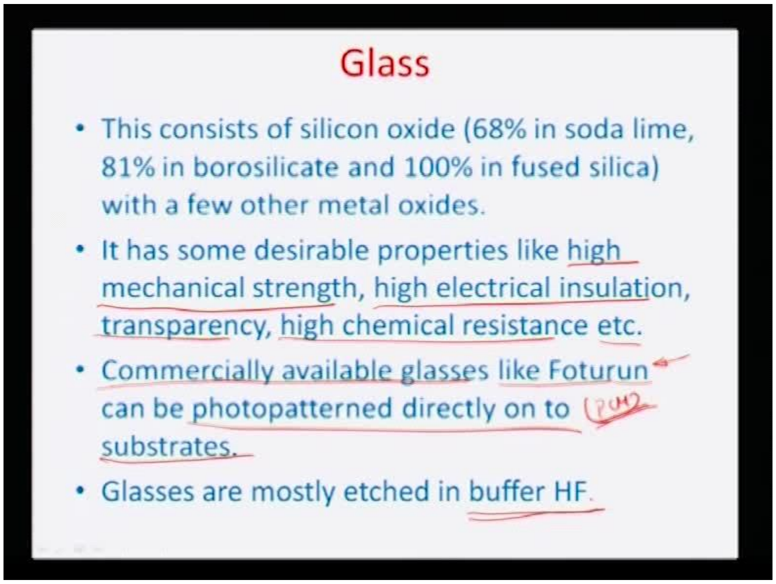

Glass

- This consists of silicon oxide (68% in soda lime, 81% in borosilicate and 100% in fused silica) with a few other metal oxides.
- It has some desirable properties like high mechanical strength, high electrical insulation, transparency, high chemical resistance etc.
- Commercially available glasses like Foturun can be photopatterned directly on to (PCM2 substrates.
- Glasses are mostly etched in buffer HF.

So the other material of importance of you know Microsystems fabrication is has been indicated is glass and glass is actually chemically silicon oxide and the content of silicon oxide however varies from different glasses for example, soda lime glass would contain about 68 percent of silicon oxide more of silicate another variety of glass would contain about 81percent and the highest and the purest form glasses is the quartz really its fuse silica which is actually100 percent silicon oxide.

Basically, there are certain other metal oxides along with silicon oxide which are present which would determine in the optical transparency or clarity of the glass to you know the whole u v vis u v visible region of the spectrum and therefore, certain characteristic metal oxides and metal ions would emit their own signatures making glass unclean and absurd at certain frequency. Whereas, quartz being the purest or the highest form of glass which is not absorbed in any of these wave lengths and would have a clean background as such, so glass itself has a variety of desirable properties for example, it has high mechanical strength it has high electrical insulation transparency high chemical resistance which are all amenable to Microsystems.

Therefore, glass sometimes can be used for packaging Microsystems typically and commercially available glasses are now available freely like you know which can be photo patterned fort run is one such class can be directly photo patterned on to the substrates and therefore, you know with glass also you can actually use photochemical machining or p c m to you know result in a variety of features and structures at the microscopic length scale.

So, for edging glasses for creating crevasses cavities features structures of the micro scale within such classes you normally use buffer h f solution which is actually a solution of h f along with ammonium hydroxide and water, so that is what glasses are or that is how glasses are important for the micro structure domains.

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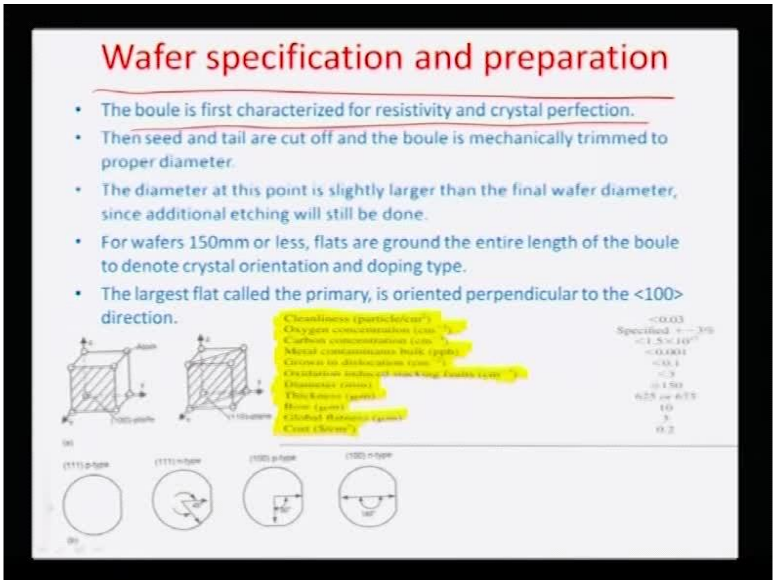

Wafer specification and preparation

- 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 <100> direction.

Cleanliness (particle/cm²)	<0.03
Oxygen concentration (cm⁻³)	Specified +−3%
Carbon concentration (cm⁻³)	<1.5×10¹⁶
Metal contaminants bulk (ppb)	<0.001
Grown-in dislocation (cm⁻²)	<0.1
Oxidation induced stacking faults (cm⁻²)	<3
Diameter (mm)	≥150
Thickness (μm)	625 or 675
Bow (μm)	10
Global flatness (μm)	3
Cost ($/cm²)	0.2

Let us also look little bit into the wafer specifications of silicon wafers and, so essentially how they are prepared from the bowl which are being obtain either by czochralsky’s method or by the float zone method, so the bowl is first characterized for resistivity and crystal perfectionand these are done by various electrical tests on the bowl then the seed and tail are cut off the bowl and mechanically trimmed to proper diameter and then of course,,, and then finally, there is a finish trimming operation on to the final wafer diameter since additional edging will still need to be done on those bowls.

So, for wafers 100 and 50 mm or less flats are ground to the entire length of the bowl denote crystal orientation, so if you have 1 0 0 direction you will have that flat pointing out as a plane towards the plane perpendicular to indicate the perpendicular direction as a direction of growth of the particular crystal, so most of the silicon wafers that you get from industry would have 1 or 2 cuts indicative of certain specifications particularly growth related specifications of the silicon wafer.

So, thing that has to be remember is the largest flat which is also known as the primary flat in such a circular wafer is oriented always perpendicular to the 1 0 0 directiontherefore, it is actually the x direction in a right handed coordinate system contains in coordinate system and the flat is always perpendicular to the x direction and that indicates the direction the other direction of the crystal, so comparison to that flat you can record what is the 1 11 direction or 1 0 0 direction or 1 0 1 direction or any other direction with respect this x direction, so one thing has to be very carefully seen or observed in any silicon wafer which comes from such a foundry you will have to first see what is the largest flat and that is called the primary flat and it is always oriented perpendicular to the 1 0 0 direction.

Apart from that there are several other specifications of a relative importance for example, you can actually have cleanliness in terms of particles per centimeter square or the surface area you can have indication of oxygen concentration per centimeter cube that means the per unit volume.

Carbon concentration per volume metal contaminates in terms of parts per billion within in the crystal lattice and then also you can have per unit area what are the growth or in dislocations sometimes these are very well measured using sophisticated noncontact mediated optical characterization tool like in the aerometry etcetera then you can also have an idea of oxidation in the and that can be in the bulk of the wafer.

so that can be per un it volume apart from that some normal specifications like diameter and thickness of the wafer or the bow which is nothing but, the way that the wafer is wrapped or bend sometimes and then aspects like flatness and cost these are all indicated in a wafer box which comes from such a manufacturer or a foundry of silicon, so these are some of the specifications which normally the manufacturer supplies and then with this specification on and the direction of the flat one can characterized is the wafer very well now once we have had good introduction to silicon and glass let us look at some of the MEMS fabrication techniques which are really available.

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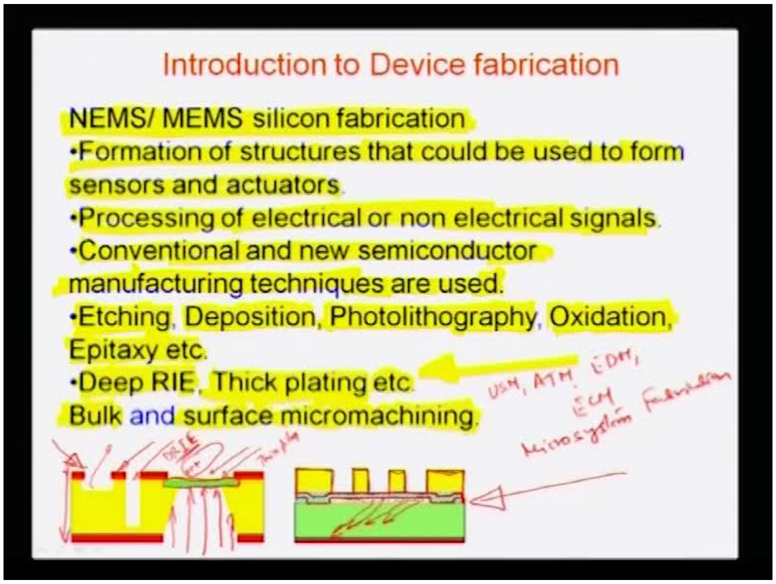

Introduction to Device fabrication

NEMS/ MEMS silicon fabrication

- Formation of structures that could be used to form sensors and actuators.
- Processing of electrical or non electrical signals.
- Conventional and new semiconductor manufacturing techniques are used.
- Etching, Deposition, Photolithography, Oxidation, Epitaxy etc.
- Deep RIE, Thick plating etc.

Bulk and surface micromachining.

So it is really all about fabrication of micro nano structures inside silicon or glass or some of the materials amenable for MEMS fabrication that means they are concerned with right, so it is formation of structures which could be actually used for sensing or actuation purposes at the micro scale, so that is the purpose of this kind of fabrication right and the idea is that this micro structure.

So, formulated should be able to process some signals it can be electrical signals or it can be nonelectrical like mechanical signals which can be somehow processed by means of transaction of these features or you know micro structure elements and for production of these you have to use some conventional and some new semiconductor manufacturing techniques for in the in the MEMS region.

Some of these manufacturing techniques could be something like chemical machining like etching it could be gas based or based on some chemicals it could deposition where you can deposit a metal film or a resist film on the top of some of these wafers, and then of course photo lithography where you can use a power of particle signals or light to actually carve and find out different features sizes and structures on to these films.

Then you can use a variety of other processes like oxidation epitaxy etcetera which are planned like for example, epitaxy could be used for growth of single crystal silicon or oxidation as a matter of fact is thermal process whereby you can actually entrap oxygen in silicon at the cost of silicon you can get a layer silicon oxide or silicon dioxide, so these are sought of conventional semiconductor manufacturing processes which have being merged in to the MEMS domain or micro systems fabrication domain.

Apart from that there are deep r I e or deep reactive ion etching which is a very new technique c I n the microsystems domain and then of course,,, thick plating which is also used this electroplating which is a sought of electro chemical machining abrasion where you can actually deposit films of certainsize and therefore, these are the 2 other domains which are very commonly used for systems or micro electro mechanical systems apart from that of course, there are the this nontraditional processes l k e u s m a j m e d m and e c m which have been very recently corporate for doing activity in fabrication or the micro system or micro manufactured components or devise.

So, if you look at all these machining processes in bunch they can be categorized either as bulk micro machining processes or surface micro machining processes and the bulk processes really are about the the the subtractive removal of material or subtractive processing of material from a wafer surface for example, in this particular illustration here or cartoon here you can see this right here is a section a cross section of the silicon wafer and you are trying to selectively h of the material from this wafer, so there can be for example, a protective layer here which you have etched out and created a small craves and a cavity.

So, another example is this particular h pit here which is a high expect ratio structure and this can be obtained by a process called deep reactive ion etching where the power of plasma can be used for driving atoms in a particular direction, so that they can look off the surface atoms here and then based on that high expect ratio structures can be formulated.

The third example as illustrated here is again a very interesting example where there is a p double plus a layer which has been impregnated here using ion implementation or some doping technique and then as tropic etch which actually goes on from the back side here and the material is selective to only silicon and, so p double plus therefore, whenever the the h and h actually comes and hits this area the actually lives a membrane here a thin membrane here, because it is not able to etch this part it is selective to p double plus as I already mentioned and the remaining silicon is etched away, so this is another way of getting what you can say thin film pressure censors and this is also known as bulk micro machine pressure sensors.

So, why it is bulk is, because you are subtractive removing material from the volume of this particular wafer and that is why bulk micro machining is an subtractive process it is a material removal mechanism on the other hand surface micro machining is an additive process where you do not really remove the material from the bulk of the wafer but, you keep on adding the front layers of materials on to the top of the wafer, because of which you can create this features and structures to exemplify some.

Let us look at this illustration here as can be represented, so here for example, this is poly silicon layer which has been put in a manner, so that you had a sacrificial layer in this particular region given by the dots it could be a resist layer, and then you have deposited the poly silicon layer on the top of this resist layer and the later on you can remove the resist layer away, because poly silicon is a high strength material, so that you can have a channel on the surface one side buried within in this poly silicon layer on another side, so you can remove away this resist later on it just goes off thus resulting in this channel into the plane of the paper or plane of the this transparency slide.

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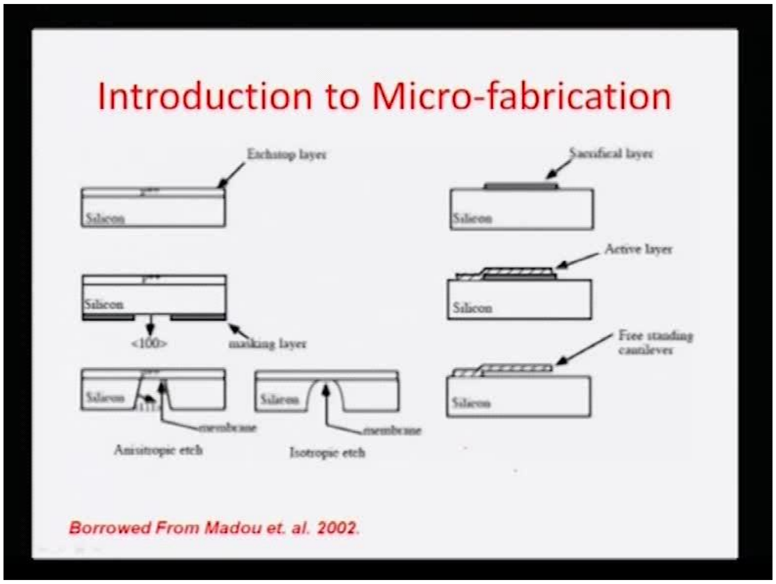

Introduction to Micro-fabrication

Borrowed From Madou et. al. 2002.

So, this is an example of surface micro machining or additive micro machining or other examples could be deposition of these pillars and pose by using either metals or photo resist where this structure, so realized can be of some significance for example, all the metallic inter connects in electronic microelectronic circuitry is actually made using such metal imprints it is called printed electronics and it is again a additive micro machining process or a surface micro machining process.

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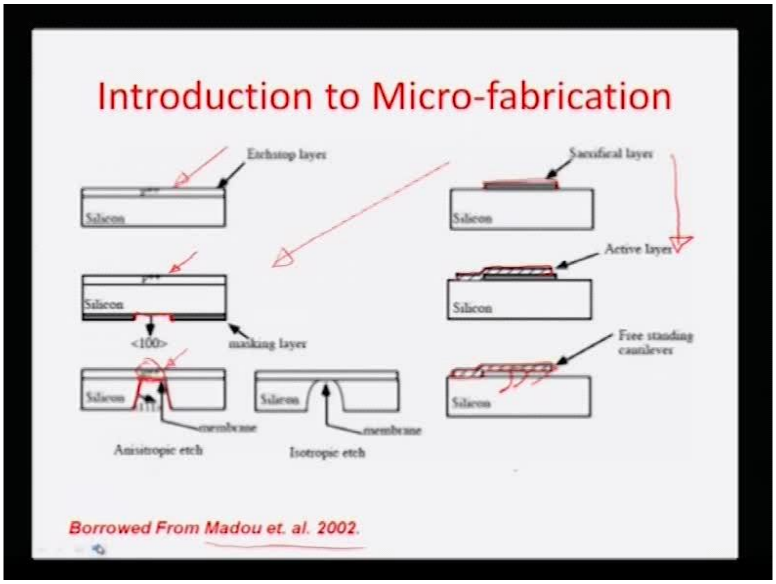

Introduction to Micro-fabrication

Borrowed From Madou et. al. 2002.

So in a nutshell machining can be divided into bulk where you are subtracting from the volume and a surface micro machining were you are adding material on the surface to do micro structures and features s these are the 2 broad categories of all machining processes that can be assembled to realize micro system or micro fabricated architectures for example, is a slide which has been borrowed from d r mark madou’s book on micro fabrication, so here it is showing how you can formulate a p double plus membrane and this is already been illustrated.

So, you can actually formulate a small cavity here using resist and, so this can be used as h window as and there can be a an etchant which can be selective to p double plus which is actually highly doped positive silicon on the other side and, so the material starts etching away in a anisotropic manner thus formulating a 54 degree angle and based on this the it just goes up to the selective layer here which is the p double plus layer and stops the etching process thus creating a membrane.

The other hand this side is showing how micro can be generated by additive micro machining where you have let us say a sacrificial layer over which you have put let us say a poly silicon layer like this and then you are removing the sacrificial layer away, so that you can have a small cantilever which you have illustrated here in this particular example, so these are some of the process flow charts or logic diagrams for formulating some of these micro features and micro structures different illustrations.

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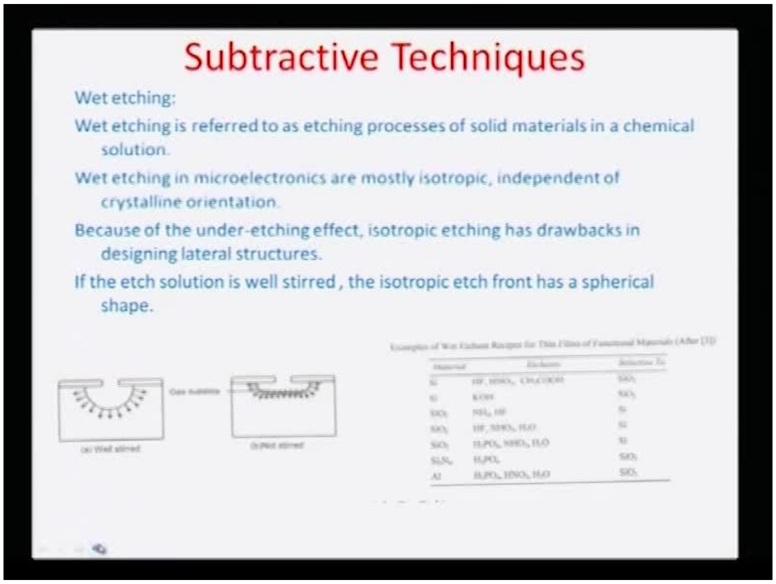

Subtractive Techniques

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.

So if you look at the bulk micro machining technique the first process that comes into existence is the etching and particularly wet etching where there is a chemical which is used for etching of the material, so it is a subtractive technique again the etchant is a highly corroding or eroding agent which engraves its wherever it comes in contacts contact with the wafer and removes the materials.

So, that you can have these features etcetera in printed and the etching solution is basically very often used in all the microelectronic processing and also in MEMS processing, so etching can be divided into 2 classes one can be isotopic or homogeneous etching where the material removal is uniform as a function in the volume and there can anisotropic etching where etching can be in a particular direction and the differences are in terms of h chemistries as I will illustrate in detail in the following slides.

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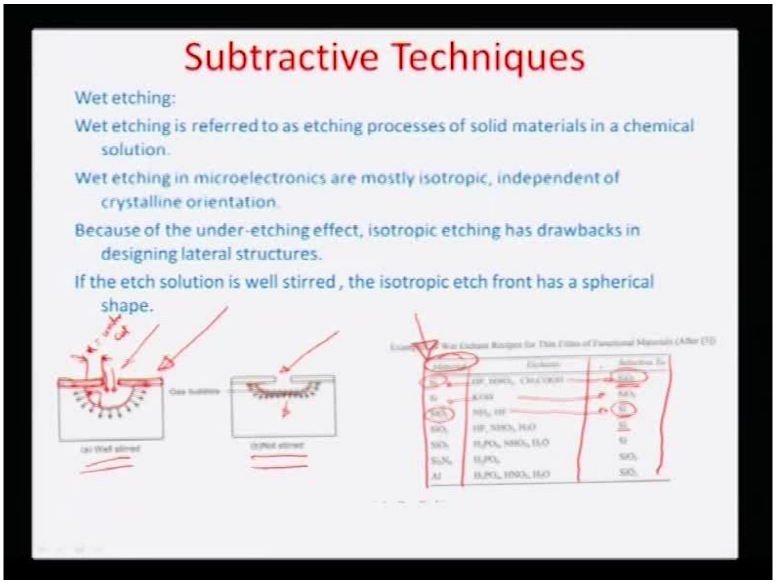

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So let us look at isotropic etching an isotopic etching really as I mentioned before the etchant is able to remove or erode away at uniform or homogeneous rate in all the directions this for example, is a illustration where there is h protective layer which is a now emboldened by the red highlight the red pen here, and so this window here of the h protective layer is able to give an access to the fluid to go into and start etching away a material which is underneath to this protective layer and in the process, because it is a homogeneous process the material actually goes into the into in to this h cavity and its starts etching in all directions resulting in this undercut.

So, this layer here which has been formulated let us say its distance is x this is also known as the undercut, because this was not really intended for it was not planned and, because of the homogeneity of etching the etching would happen in a lateral as well as the vertical direction which could always result in this kind of a undercut, so when you design micro system and the mask for the micro systems this undercut allowance has to be taken into account for the designing to happen if the etching was not homogeneous for example, as illustrated here the etching may be little more directional in this case for example, you can see the h rates are more towards the side.

So, lateral etching is more and the vertical etching it could result in different shapes based on what is the directionality of the etching. And so typically if you had a very well starred solution where whatever is coming out is going away from this h window it would result in a homogenous profile like this, if do not a starred very well starred solution it would rather result in this, because the amount of atoms which are coming out of this material would have a higher concentration here and that diffusional restrictions would prevent further etchant to move away.

So, the rate in the vertical direction would be reduced in comparison to the horizontal direction let us look at this some of these materials and the etchants which are used for the materials and what it is selective to, so h selectivity again is a term which is used in reference to the fact that you know the there are certain materials which may not be able to get etched away by the etchant solution and in that kind of a case this, this material l which is not effected by the etchant solution can be used as a protective layer to stop the etching process very accurately and therefore, an etched stopped layer or an h selective layer is always preferred as the layer which would prevent the etching from happening any further.

So let us look at this table back again here, so the material illustrated can be silicon silicon dioxide silicon nitride aluminum, so on so far, and then there are this etchants which are amenable to removal of this materials for example, h f or h n o 3 or c h 3 c o h or for example, k o h they can remove silicon very easily but, as soon as the etchant meets the surface of S i O 2 it is selective to S i O 2, so it will not etch S i O 2 anymore or it will not etch s I any more in this particular illustration where n h 4 and etch f combinations are used therefore, there are certain materials certain etches which are etching away this material is selective to silicon or it is etching away the silicon at selective to S i O 2. So the combination of these can be used for a variety of etching architecture that can be realized accordingly.

Thank you.