# Fabrication of Silicon VLSI Circuits
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## Lecture No. 4
## Crystal Properties and Silicon Growth (continued)

We are still under what about making Silicon from SiO2 event of 2 yesterday creation of poly crystalline (()) (0:28) using Siemens process and then we want to create now single crystal, Silicon wafers and we proceed further and the process which is possible in the case of Silicon most of the material can be grown into techniques.

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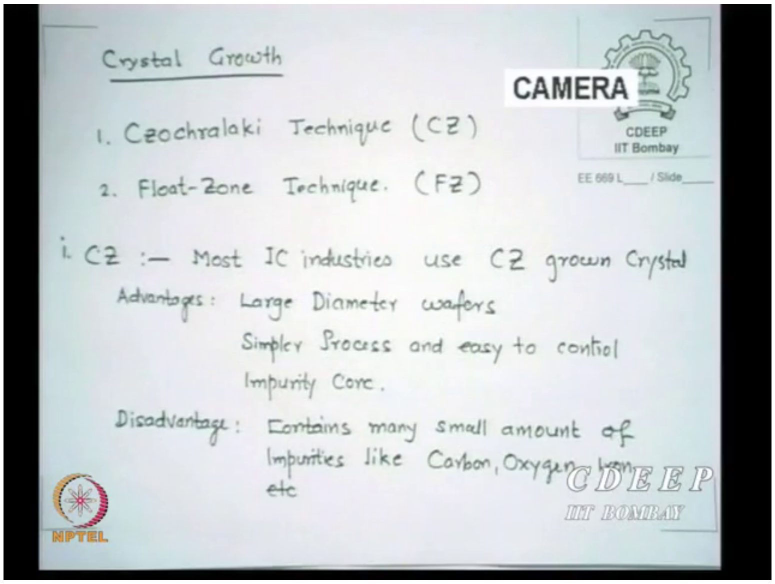

Crystal Growth

1. Czochralski Technique (CZ)
2. Float-Zone Technique. (FZ)

i. CZ :— Most IC industries use CZ grown Crystal

Advantages: Large Diameter wafers
Simpler Process and easy to control
Impurity Conc.

Disadvantage: Contains many small amount of
Impurities like Carbon, Oxygen, Iron
etc

There are 2 standard processes which allows single crystal highly pure Silicon rod to be pulled and these 2 techniques are called Czochralski technique and FZ technique though the full forms are different but short forms are similar CZ and FZ what is Czochralski technique and the other is float zone technique. In the case of Czochralski technique was integrated circuit manufacturing industries use CZ crystals and the advantages of this process there are very large diameter difference can be created, very very large size maybe as I said 16 inch wafers can be pulled.

Whereas in the case of the other FZ we shall see they may not be easier to be pulled than the second is the process is really very similar and much more easier to control the doping much more easier as I say. Of course there are disadvantages, it contains small amount of many impurities like Carbon, Oxygen, Iron, Bismuth, Lithium and many of them, okay. Of course not all of them in a large amount some of them are in parts per billion or less than part per billion, some are in parts per million and these are the ones which may actually create hell of a job to actually get rid of them.

You will be surprised to see that the oxygen which is sitting here is a bio product because the way the process is done, oxygen will always be present, so is the carbon and because of that any Silicon process which will do will have these 2 standard impurities carbon and oxygen both have some advantages and some disadvantages. So CZ essentially is a standard technique called Czochralski pull technique and I repeat larger wafers are possible only through this technique and therefore most integrated circuit manufacturing companies use CZ crystals.

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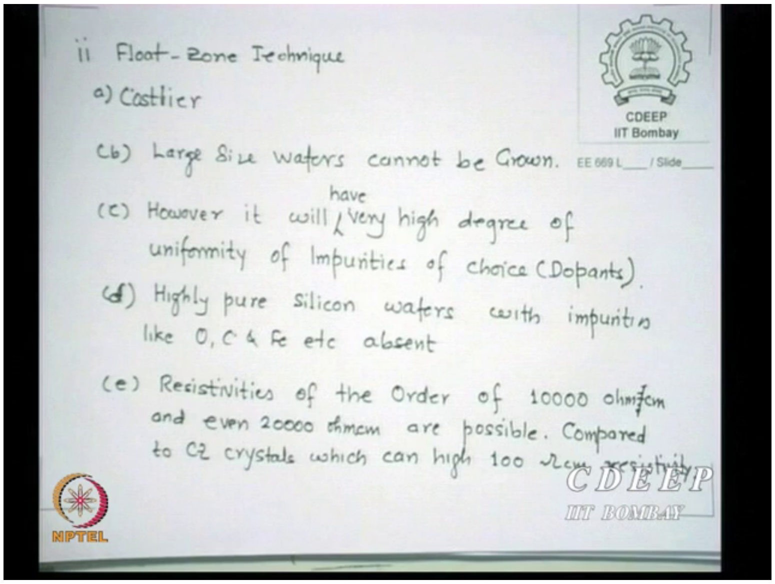

ii Float-Zone Technique

a) Costlier

(b) Large Size wafers cannot be Grown.

(c) However it will have very high degree of uniformity of Impurities of choice (Dopants).

(d) Highly pure Silicon wafers with impurities like O, C & Fe etc absent

(e) Resistivities of the Order of 10000 ohm/cm and even 20000 ohmcm are possible. Compared to CZ crystals which can high 100 $\Omega$cm resistivity

Then why we are really looking for float zone? Yes float zone is also important. Of course for the float zone you need CZ Crystal initially. So you can say it is an added process, it is damn costlier comparatively, it is impossible to grow larger wafers in this technique. Of course it as a feature and that is why it is used often. It has very very high degree of uniformity of impurities across the wafer and along the rod we shall see soon.

And they are very highly pure Silicon wafers and very low concentration of oxygen, carbon and iron and other impurities very highly pure material is possible in float zone and for example ICs may not require that much of impurity. Please remember most of the impurities and like either the donors or acceptors in a semiconductor. So if they are donors they will make it N type of their acceptors they will make it as P types.

And all over effort in the earlier ways is to dope a material to your choice but if intrinsically it is present there then it is difficult to control. However in the case of float zone these impurities can be easily wished off. Where do you release such a highly pure? So one can say purity of a wafer can be determined by this electrical property which will say the resistivity. Resistivity of a sample is decided by say 1 upon qmui n plus qmui to t, so if N and P are very very small from the impurities then the rows are very large, okay. Resistivity of a wafer is very large, so larger the resistivity pure is Silicon.

In CZ at best you can do 100 ohms centimetre wafers or maybe at best 150 o 200 sometimes but in float zone I can go up to 20,000 ohm centimetre wafers and that's fantastic about it. The reason why we are interested in such wafers with high resistivity 20,000 ohm centimetre one can say if I calculate the (()) (5:24) concentration out of 20,000 ohm centimetre will be around typically maybe 1 can say it is 10 to power. 5 into 10 to power 14 or 10 to power 14 or even sometimes less.

Intrinsic (()) (5:44) concentration of Silicon is 10 to power 13 per cc and since it is 10 to power 10 but 10 to power 13 is the smallest value which we use is called intrinsic semiconductor. Now we come very close to intrinsic value which means we have a wafer which is intrinsically doped and you need such wafers to create what we call power rectifiers we also need (()) (6:09) or rather (()) (6:11) Lasers many of these P ion based devices actually require I type of material and that means intrinsic wafers there is where large amount of expenses suspend by these people to get intrinsic.

Like avalanche diodes in the case of micro (()) (6:30) they also need PN kind of structure, so all those devices which are special devices and not IC group of devices they are actually many times require (()) (6:42) structure and in those cases float zone wafers are only possible. We are also trying that for solar cell to conclude efficiency and we will show you how I region does improve some efficiency if not great way. So please take it that float zone is one of the feature that it is highly pure wafer.

Now the problem starts how do we actually go through from the polycrystalline process? We have lot of rod has been created maybe since I can create rods of polycrystalline in the (()) (7:22) which I yesterday shown and then we actually break them into pieces and these pieces are called nuggets, okay. Now these nuggets are used to create highly pure Silicon rods which are shown here.

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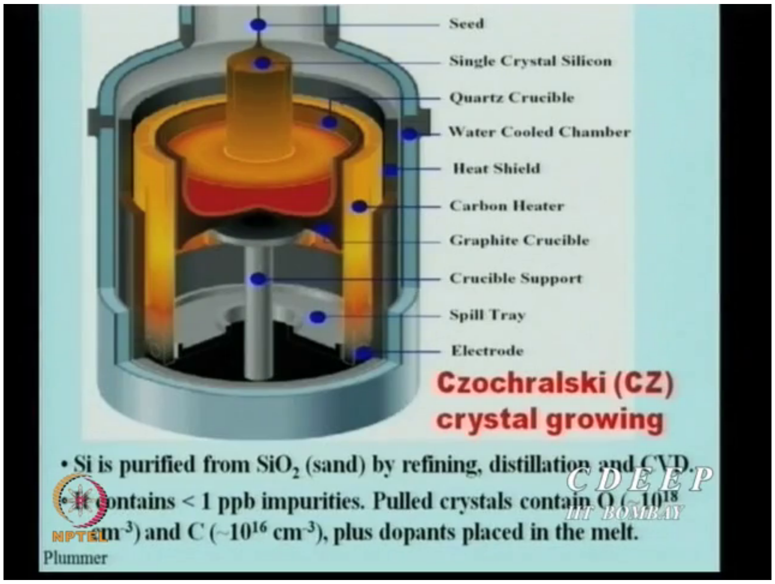

**Czochralski (CZ) crystal growing**

- Si is purified from $SiO_2$ (sand) by refining, distillation and CVD.
- It contains < 1 ppb impurities. Pulled crystals contain O (~$10^{18}$ $cm^{-3}$) and C (~$10^{16}$ $cm^{-3}$), plus dopants placed in the melt.

Plummer

This is a Czochralski reactor shown here the method is, okay maybe one can think of it, this is the rod being pulled, this is the seed crystal you can see a small, (()) (7:56) it is drawn in some kind of a crucible melt the nuggets at around 1412 to 1500 and then slightly cool it below 1400, so it is a molten state not fully liquid and then you put a seed crystal from the top and touch it and starts pulling, okay.

As it touches the molt, it picks up some molt to it’s because of the surface tension, as it starts pulling it becomes cooler and cooler so it becomes solidified. So crystal starts growing up as you start pulling the crystal, single crystal above and the orientation of whatever is grown by you is same as whatever starting single crystal you start with, so essentially this is just pulling of the rod from the melt and there are few things which we will discuss soon.

When we model it there is a rate of pulling and also during pulling we also rotate the, many a times there are some reactors in which the whole molt was rotated but molt is very high density material, so at times it breaks up (()) (9:06). So nowadays only the rods are rotated they have their own problems but essentially now rods are only rotated and also pulled up, okay.

So these are the 2 methods in which we control the growth as well as the impurity uniformity as we will see later. Now this one side I say from the polysilicon nuggets are put here please remember this chamber is a carbon chamber or rather Graphite chamber and which is lined with Silica. Now you can see the 2 materials I said Silica, Silicon dioxide and rather Quartz liner and also carbon crucible or graphite crucible.

So Carbon and Oxygen are only present in the molt itself even if their concentration is low because their melting point is higher but they are released in the (()) (10:04) and when you solidify something even part of this impurities will also go into solid. So give whatever there will be Oxygen and Carbon in the Silicon grown in Czochralski pulled crystal.

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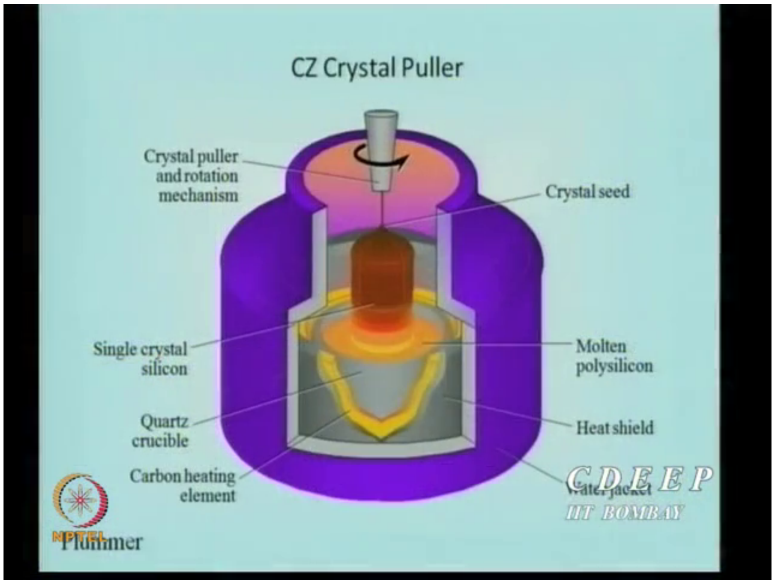

CZ Crystal Puller

Maybe better figure, all these figures not necessarily color ones are available in Plummers book, so if you please have a look at it someway.

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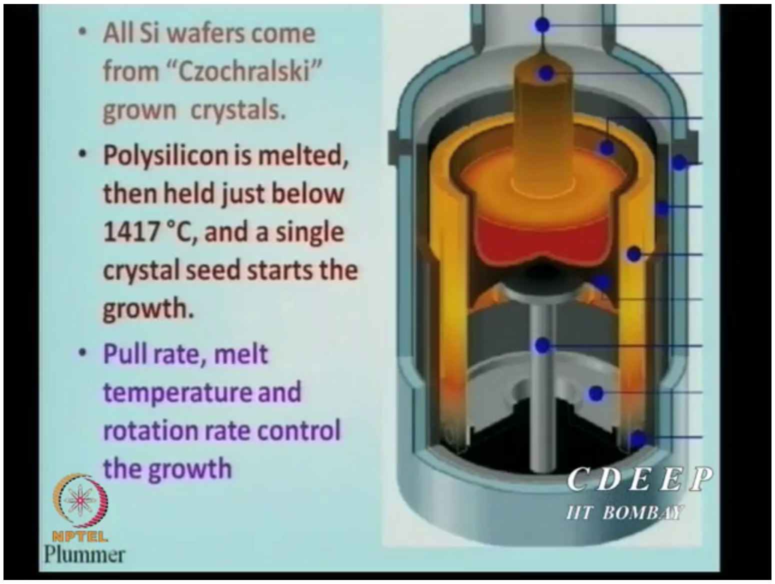

- All Si wafers come from "Czochralski" grown crystals.
- Polysilicon is melted, then held just below 1417 °C, and a single crystal seed starts the growth.
- Pull rate, melt temperature and rotation rate control the growth

I repeat this is rewritten again you can see slightly shown here. Earlier there used to be a bottom rod on which the crucible was kept and that was rotated and it was found that many a times crucible used to break. So in near cases this lower chuck is never rotated it is only fixed crucible sits on it you heat it on an arc furnace and as soon you start heating it goes up to 1417 degree centigrade and you start pulling and also rotating to control the growth, okay.

So these are all same figures differently shown to show you that how actually Czochralski pulled (()) (11:18). Please remember the worries are something like this if you see this we have the single crystal walls these solid which actually picked up from the melt has a much larger diameter because of the curvature it has. So depending on the kind of crystal size you initially start and kind of initial touch you do the size of wafer is different size of rod is different.

So how much you would allow it to grow along this and then start cooling, so there are tricks in that to increase the size. It is not very easy for outsiders but we will do it very routinely. Now the tip there is much smaller than the size of the crystal which you are pulling, okay. So once I was just telling if you spin too much with higher this, you will spin it definitely then it is possible that joint may not survive, okay between the single crystal and the green crystal. If you would pull it also will this very highly the melt will actually climb over.

So you don’t have to pull it very highly but you want to pull with certain rate because you want to increase the size of crystal, so you will pull it but at the same time you will have to decide how much hour and how much rotating speed you should have to have a good uniform single crystal coming out of this.

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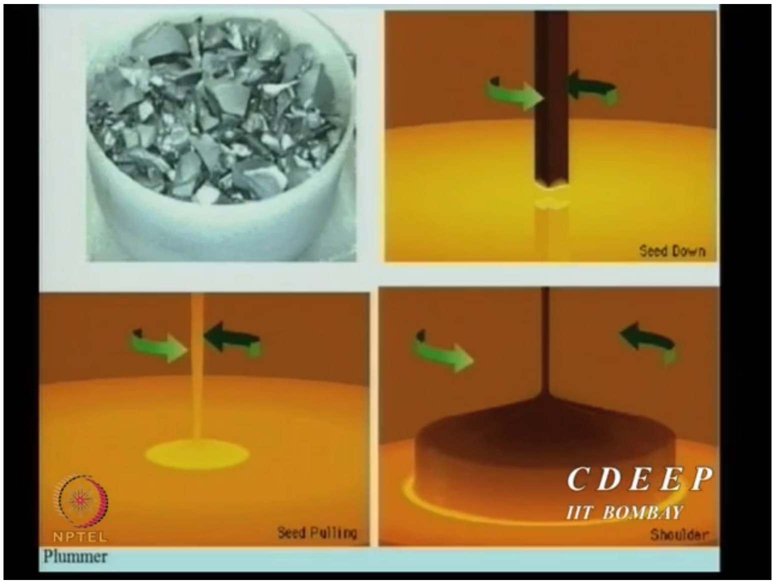

Here is the same figure, these are the nuggets you can see the better way of showing the figures this is speed being pulled and rotated and this is how it will look, okay and you can see the tip is too small. You can see the joint is, if you do too much this joint will break, so there are tricks in doing this which is not very difficult, okay but just want to show you how things happen.

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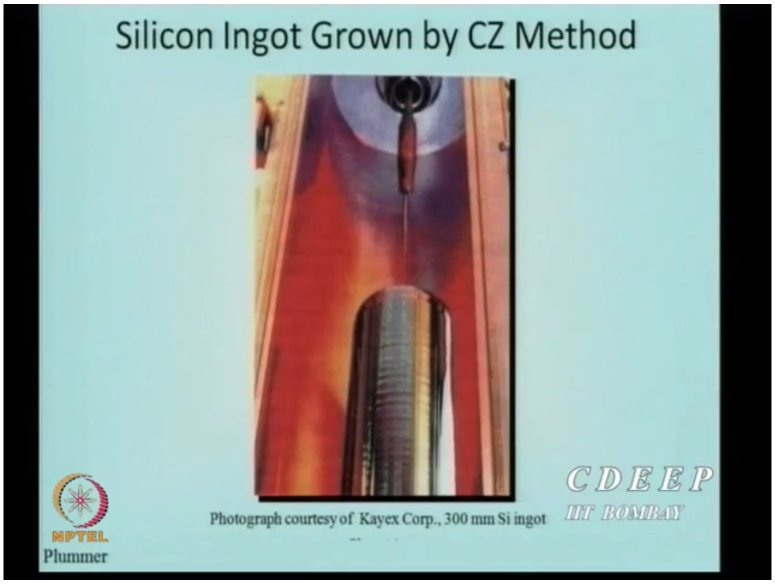

Silicon Ingot Grown by CZ Method

Photograph courtesy of Kayex Corp., 300 mm Si ingot

Plummer

This is another picture from the real-life Kayex Corporation wafer company which (()) (13:26) says 300 millimetre Silicon ingot, the larger rod is called ingot, okay and it can be as long as 1 meter to 1.5 meter to 2 meters depending on the reactor you have, please remember larger the rod you pull the machine require large heating because Molt has to be larger, so cost is very high. However cost to sell ratio decides how much size you should do.

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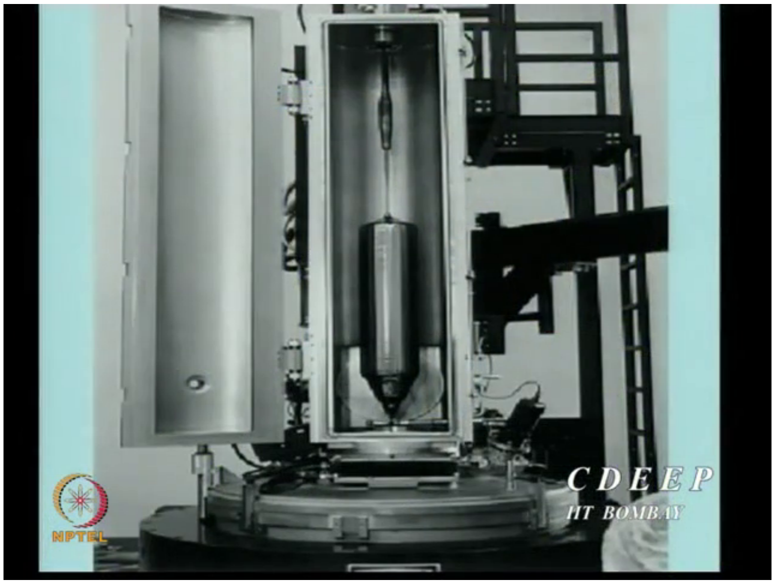

This is another picture for the same Czochralski pull this is a real-life picture which is taken, this is of course old plant in Germany from where this has been taken, okay.

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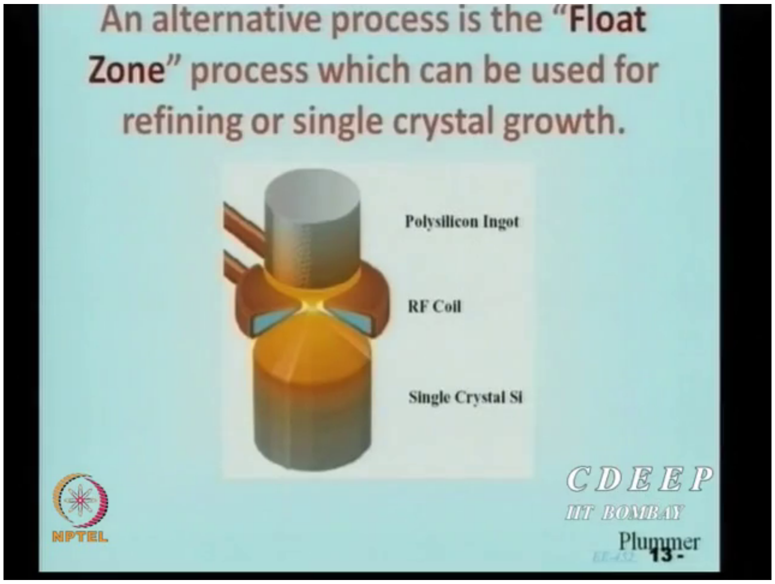

An alternative process is the "**Float Zone**" process which can be used for refining or single crystal growth.

Plummer

Okay, so before we go to the float zone we would like to show you that Czochralski poll crystals need to be doped, right now we have not doped anything, so how do we dope them? What we will do is, during this melt situation we actually add per gram of molt some amount of impurities which you want to dope, if it is P type you add Boron, Boron oxide in fact and in case of phosphorus you have P2O5 arsenic oxide, so this oxygen is anyway added by you by this whether you like or you do not.

Of course boron itself can be added because boron is a powdered material, it can be added but it is very hydroscopic, what does that mean? It picks up humid very fast, so it becomes jelly, so we cannot add that so much, so we normally use powder which is boric acid is available in market, it is not clear but it is available. So we activities and since the melt is dissolves that and when you start pulling the crystal some part of the impurities also go along the molt to the surface and then to the crystal rod, okay. This is how the impurities are added in the case of CZ.

Now we already said the problem with impurities incorporation is, that is the model we would like to see it how the impurities can be made uniform that is major worry for us. How the full rod has the same resistivity or the same concentration along the actual axis and along the real axis both side it should be uniform doping, okay then only I can say when I cut the wafers as I show you later on I have uniformly dope wafers.

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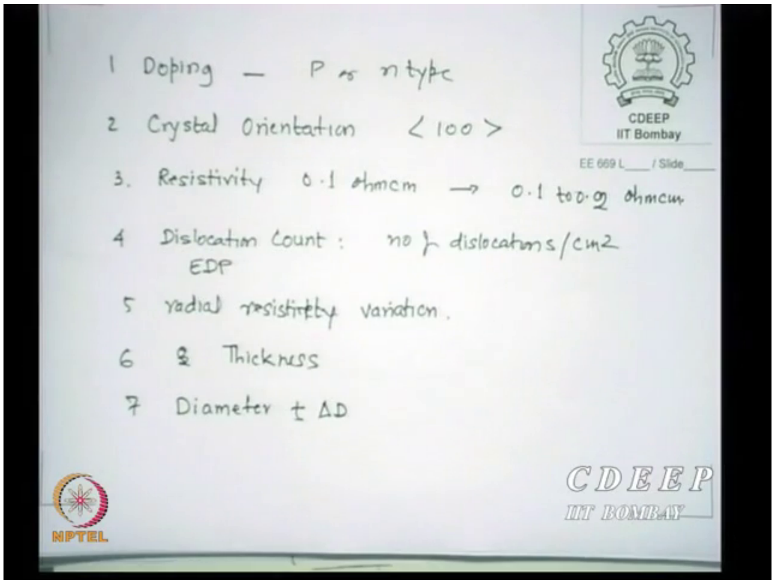

1 Doping — P or n type

2 Crystal Orientation <100>

3. Resistivity 0.1 ohmcm → 0.1 to 0.2 ohmcm

4 Dislocation Count : no of dislocations/cm2
EDP

5 radial resistivity variation.

6 Thickness

7 Diameter ± ΔD

If I go and buy a market the wafers many things we actually specify, one of them of course is for example one is doping, which is that is either P type or n type. The other thing they will say is crystal orientation likes a 1 0 0 oriented then they will also specify to you resistivity. Normally resistivity is never specified 1 value for example if I am buying wafer for integrate circuit which has 10 to power 16 per cc as concentration typically I am talking of 0.1 ohm centimetre but they will give you range 0.1 to 0.2 they themselves will not be sure of putting exact value.

So some wafer may have 0.1, some may have 0.2, sum in between, so you have to monitor each wafer before you actually load in. So you segregate those ones which have similar resistivity in one run and put in the others then they also specify what is called as dislocation count we will see this part little later maybe next when diffusion we start that is number of dislocations per centimetre square.

Actually it is called EDP, okay and this is very important larger the number of this worst is the wafer, smaller the dislocation counts greater will be the wafer. So one has to actually see how much EDC or EDP you are looking for before you buy there is also radial resistivity variation this is wafer to wafer, some companies give radial resistivity variation, this is also specified then they specify thickness and of course dia is you have (()) (18:31) but diameter and that also plus minus Delta D is specified.

So when you order wafers you have to specify in your indent itself everything depend on that they will give you quotations which you can then buy. Please take it larger the diameter of the wafer thicker will be the wafer requirement, why? Because larger the wafer means larger is the mass it has, if you take very thin wafer Silicon is extremely fragile material of course I do not say it but if you say it, it may break (()) (19:11) but if you handled with little not enough it breaks immediately, okay.

Our daily Silicon crystal breaks very fast, wafers break very fast, each crystal may cost you around 50 dollars to 100 dollars, so think of it if you lose one you may be charged for 100 dollars, okay. Therefore and link it is very important thing in this. The larger the wafer dia thicker will be the wafer thickness. Typically for maybe 6 inch wafers I may require 500 microns of thickness, okay.

12 inch I may have 1 millimetre thickness and 16 inch maybe little more than that because it should give physical support but unfortunate part in all this you should understand what economics is behind. If you have larger size wafer I will have some figure latter you will get larger number of chips in same run, okay. Larger space means larger chips will come initially in 3inch if you get 10, and 12 inch you will get 230, 250, 300, 500 chips.

The problem starts, any amount of thickness create it does not matter because the whole Silicon integrated circuit processing is within first few microns, 1 or 2 microns. So if you have 1000 microns of wafer and you only use 1 or 2 icons, now even it is less than that. Now in that case since it is planar process everything is in the top plane only few microns or even less.

So that means the rest of all of it is not doing anything is just getting wasted, okay. I do not say it is wasted it has some thermal SING issue, good sometimes but otherwise it is really wasting Silicon. So that is the main problem that larger the wafer you take, yes one side you may have larger number of chips but you will waste larger Silicon amount. So when I used to plan how much thickness, so depending on the company decide which product they are going to sell.

They decide which line they should have, if they do not have that they will actually go to a company which only manufactures these are called foundry. So will sell all of this to foundry to make for us we will not do ourselves anything, okay. Because that kinds of things we do not have, so we do not want to (()) (21:43) done from somewhere else, okay. So that is the trick in all the calculations of…

You know, when you set a line you have to think too many things before actually you are productive and at least within start of a company a line it takes at least 2 to 3 years before you are on equal basis, spend money, receive money and then profit starts by then if the technology changes some new products appear this whole line may go back, okay. And there is the issue that how much investment where decides the company's success, okay.

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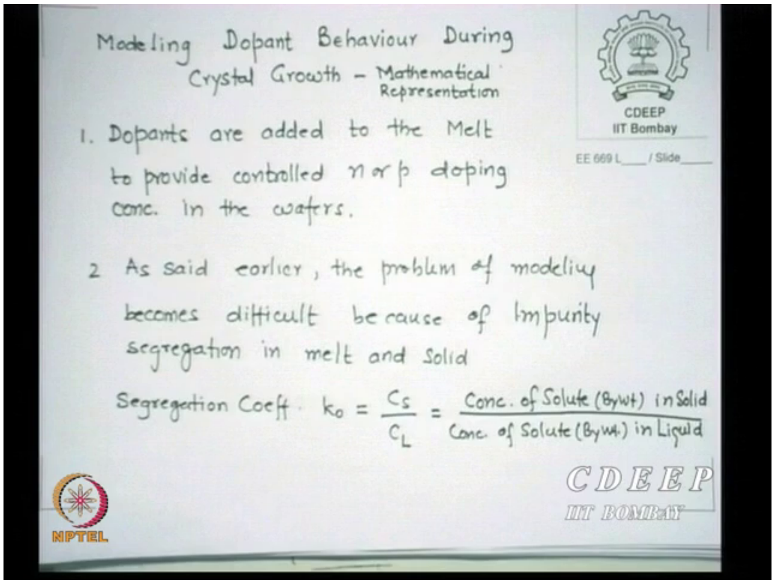

Modeling Dopant Behaviour During Crystal Growth – Mathematical Representation

1. Dopants are added to the Melt to provide controlled n or p doping conc. in the wafers.

2 As said earlier, the problem of modeling becomes difficult because of Impurity segregation in melt and Solid

Segregation Coeff. $k_o = \frac{C_s}{C_L} = \frac{\text{Conc. of Solute (By wt) in Solid}}{\text{Conc. of Solute (By wt.) in Liquid}}$

And that is why many of the people who may not be that intelligent in processing still may actually tell only go for this, this is what is going to survive, okay. These are managers who only manage and actually rule the world for doing nothing except telling, okay. Of course due regards to them I am not a manager may be a good manager at all either man or machine or anything.

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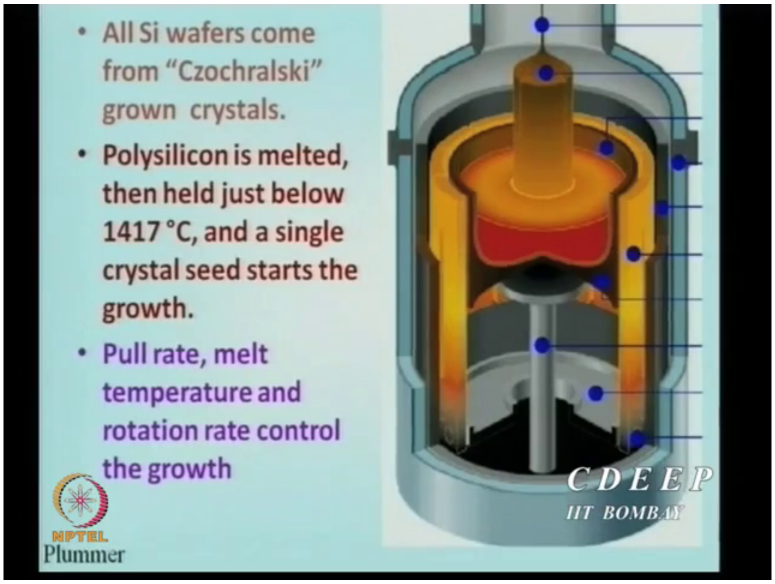

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Plummer

Before we go to this, let me do something more interesting about this because I am going to dope the crystal. Since I am going to dope the crystal, as I said already in the melt itself I will add impurities as per the doping I need, okay. Problem of moulding is very difficult, many varieties of reasons but very important reason if you see the maybe next graph little clear and then I will come back to this.

This is like the CZ process shown here, from the liquid or rather maybe you call it melt and the very close where the solid starts interface is the liquid that is slight difference between melt and liquid, okay. Melt has slightly low-density than the liquid, so we may differentiate but some books do not, so I may not also or I may or may not. Cle is the concentration of impurity.

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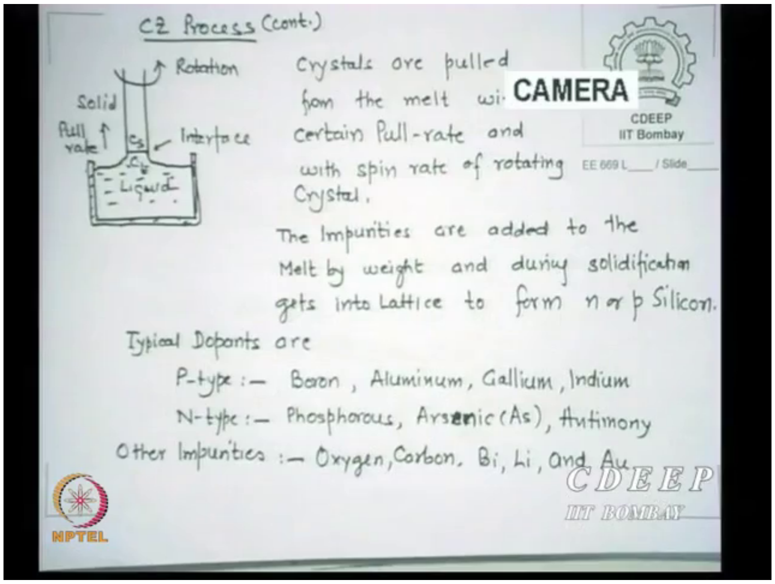

CZ Process (cont.)

Crystals are pulled from the melt wi… certain Pull-rate and with spin rate of rotating Crystal.

The Impurities are added to the Melt by weight and during solidification gets into Lattice to form n or p Silicon.

Typical Dopants are

P-type :- Boron, Aluminum, Gallium, Indium

N-type :- Phosphorous, Arsenic (As), Antimony

Other Impurities :- Oxygen, Carbon. Bi, Li, and Au

So this is Cl this is Cs we will define and do the modelling, so we can see I am pulling a crystal from this liquid as molt and we are pulling it and also as I said rotating it. Now there is a concentration of solid, concentration of impurities is going towards solid and part remaining in the liquid area. The problem is not that difficult if I know how much it goes I can recalculate I will say, okay how much impurity will go above?

The problem is the reverse process there, there is a word which is called segregation, okay. Some impurities like to be more in one region for example some more like to be in the solid than in the liquid or more in liquid less in solid. Normally when we have same material both sides the name given to this so-called coefficient called segregation coefficient is named distribution coefficients.

If we have 2 different materials Silicon and Silicon dioxide and impurities go through and also do reverse processing is called segregation. For example boron tends to segregate in oxide then in Silicon phosphorus tends to segregate more in Silicon then in oxide when I input the impurities down. The segregation is a process which is distinguishing impurity passing through each material.

Now in the case of solid and liquid also this process happens. Whatever you are pushing up partly it is coming back and so it segregates down, okay. Depending on of course the value of ratio of, solid to liquid concentrations, okay. This segregation is a major cause, how a segregation you will get and how much segregation coefficient as we shall define now we should have?

So that you have more uniform crystal available, please remember every time some impurities are pushed down then the concentration in the melt will increase and then it will rollover above. So there has to be some balance, the uniform amount of impurities go up, so that the wafer rod which is pulled as uniform dope, okay. This is our major worry and we will like to model how many impurities can go up uniformly, so that rod is uniformly doped.

Though as I said verily it is not but vertically it is mostly very good, okay. And as I said last time the P type impurities which I add are boron, aluminium, Gallium and Indium. N type impurities which I do maybe Phosphorus, Arsenic and Antimony. Other impurities are omnipresent which are Oxygen, Carbon, Bismuth, Lithium and Gold and even Iron, I forgot Iron, okay.

All these impurities can have segregation with solid to liquid when they are present. Please remember impurities do not differentiate when they go from liquid, they all will like to go above or comeback to the liquid again. So we should know what is a segregation for each of them means how many impurities will go actually in solid has to be controlled and this is the model which will allow us to find how do I do? But what rate I should pull? What spinning I should do? That uniformity is achievable, okay.

“Professor -Student conversation starts”

Student: Which parameter (()) (27:19)

Professor: Segregation coefficient is the material property which is decided actually by the band structure equivalently saying the atomic structure of the material. In case of amorphous material for example there is no actually atomic bonding, so the cruxes space charge available at any given time decides how many atoms can actually allow?

There is some kind of a shielding occurs, a wall is occurring, so I cannot go above, so I may pushed down. So segregation is a property of the sizes of the atoms as where the electrically the impurities are going they are stalled also by electrical fields then they will say what kind of bonding it sees to reflect back itself, okay. So these are essentially not very clearly told we only monitor it, okay that this is segregation.

Student: Sir, I am putting the melt.

Professor: We are not putting them. We are not putting any of these impurities except gold sometimes we do it probably but otherwise no impurity is put they are omnipresent, okay. As I say in Czochralski the Crucible is graphite, Silica cause liners, Silica is present there. I do not want to do anything but it will be there. Of course the traces are Bismuth, Lithium and iron is very small. I and sometimes is higher but other Bismuth, Lithium is very small but they are there.

So in float zone we actually see to it that they actually go away that is exactly what float zone allows us to do, okay. You remove those impurities at one end, the basic idea is if we segregate, all of them should segregate to one side then the rest of the crystal is only of one kind, so that is what float zone is trying to do compact to CZ, okay. The CZ nothing very much I can do, I can just control to some extent, okay.

“Professor-Student conversation ends”

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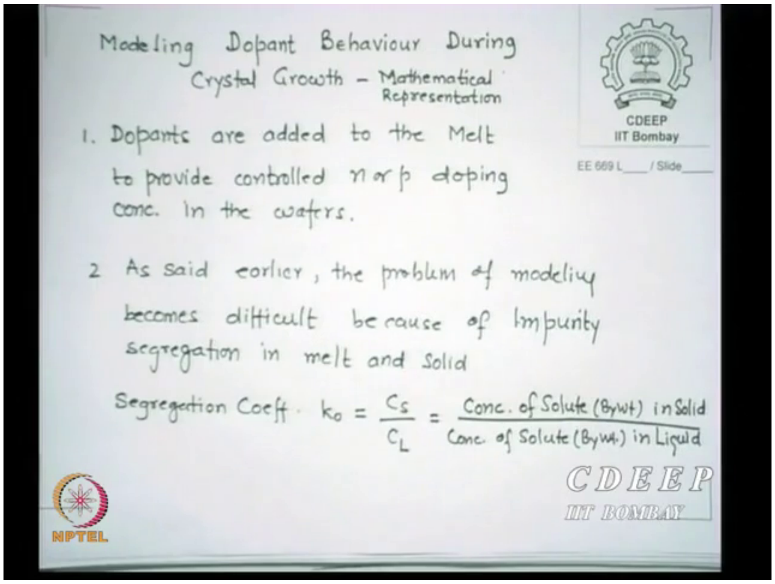

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Segregation Coeff. $k_0 = \frac{C_S}{C_L} = \frac{\text{Conc. of Solute (By wt) in Solid}}{\text{Conc. of Solute (By wt.) in Liquid}}$

Okay, so we define the segregation coefficient or as I say some books called distribution coefficient, as far as melt pull things re you can also call it distribution coefficient. It is defined as CS divided by CL where CS is the concentration of solute, solute means the impurities you are talking or solid Silicon itself could be one in solid divided by concentration of here of course I am talking about impurities, concentration of solute by weight in liquid, okay.

The ratio please remember if there are net amount of impurity and the crystal has some weight, so C is defined as total impurity divided by this weight is actually called concentration by weight, I will explain you little latter. Concentration is defined by net impurities divided by the weight of the available impurity, total weight of the impurity. The ratio of this is essentially called concentration. The concentration is always defied as per cc but it is not per cc it is per weight is what the concentrations are defined.

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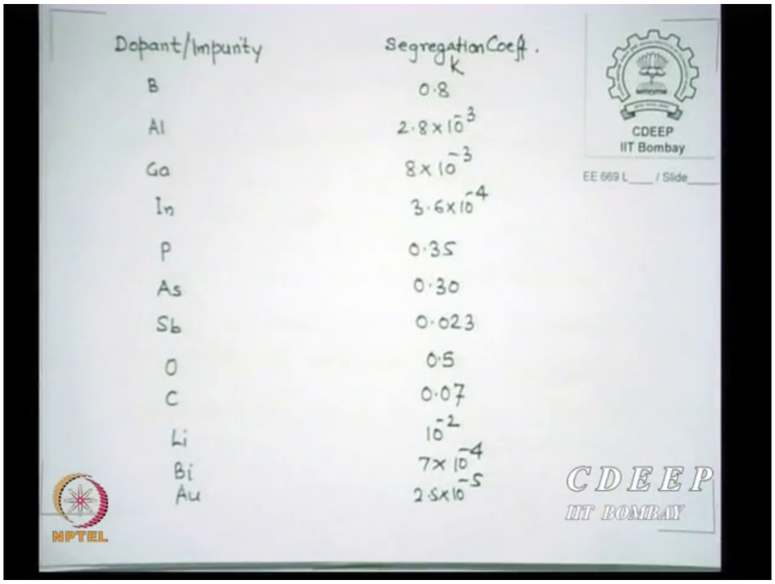

| Dopant/Impurity | Segregation Coeff. k |
|---|---|
| B | 0.8 |
| Al | $2.8 \times 10^{-3}$ |
| Ga | $8 \times 10^{-3}$ |
| In | $3.6 \times 10^{-4}$ |
| P | 0.35 |
| As | 0.30 |
| Sb | 0.023 |
| O | 0.5 |
| C | 0.07 |
| Li | $10^{-2}$ |
| Bi | $7 \times 10^{-4}$ |
| Au | $2.5 \times 10^{-5}$ |

Okay, so these segregation coefficients, if you look at it there are different segregation coefficients these are of course data available in many books, journals, papers, Google, anywhere. Most important thing why I show you is this. The impurities for P and N type which are our worrisome we can see from here someone who was asking for example Bismuth, Lithium has a very low segregation coefficient.

So they actually segregate more on the melt site and they do not go to this solid but which are boron for example you can see 0.8, so it will segregate the other side, okay. More compared to Bismuth and Lithium. Phosphorus for example as 0.35, Arsenic 0.30, Antimony is just the other way, Gallium has it into 10 to power minus 3, Aluminium please remember aluminium is a type 3 Dopant for Silicon, okay and that is very important because this word which I am using is very important because in many older ICs when we are making Aluminium as interconnect we never did lot many effort to get what we call me contacts (()) (31:50).

As soon as I changed over to copper, I have now a problem between copper material and Silicon to make an omnicity there whereas in aluminium because it was a Dopant, just doped it heavily there and it made contact there at least for P area, okay. So earlier technology is to copper has whatever they have created a fantastic interconnect comparatively that one process step has increased because earlier aluminium was never sintered it just went through, okay. So let us come to it later.

So these are some kind of impurities which are possible in Silicon and these are the actual into P type N type impurities. We will also see later when we do diffusions at antimony is rarely used accept some new sensors which are coming up now. There are varieties of reasons why antimony…

You know, these are also impurities decided by where they lie in the band gap, a will give some level for their own impurity level and depending on where that level lies the holes and electrons can be created. If the energy required for the whole to create is very small from the impurity level then we can say that boron is 0.08 for example ev, so most of the boron atoms can be ionised and it can give holes.

Phosphorus as 0.017 ev, so most of the electrons can go to the conduction band. So these are also choices made from electrical properties. Here we are not looking so much their electrical properties. So the decision of which impurity to use is now fixed either I use boron P type, 90 percent I will use boron may be boron plus Gallium these days that people are trying what to call complex.

People are only in P type we prefer to use arsenic compared to phosphorus, earlier we used only phosphorus N type, for N type we only used phosphorus for 30 to 40 years, off late 10 years or so we figured out that they will have to move to Arsenic, question can be raised why not Arsenic earlier? I mean what is so big, yes arsenic the way we will go to diffusion and we will show you the source of Arsenic whichever we create is Arsene and Arsene is extremely toxic gas if many of you were not born probably when the Bhopal tragedy took place the gas there was Phosgene or called MIC, these Gas the maximum allowed quantity was 1 ppm, 1 part per million whereas the death part for arsenic can be one ppb, so one can see even thousand times less amount of Arsene released in the air and we inhale you may not have time to tell I am no more, okay.

In phosphorus maybe you will say I am dying, okay. That is the job people used to do with (()) (34:58). No one could test Casein simply because by the time he realize he is no more to tell, okay but that is only a joke test is known.

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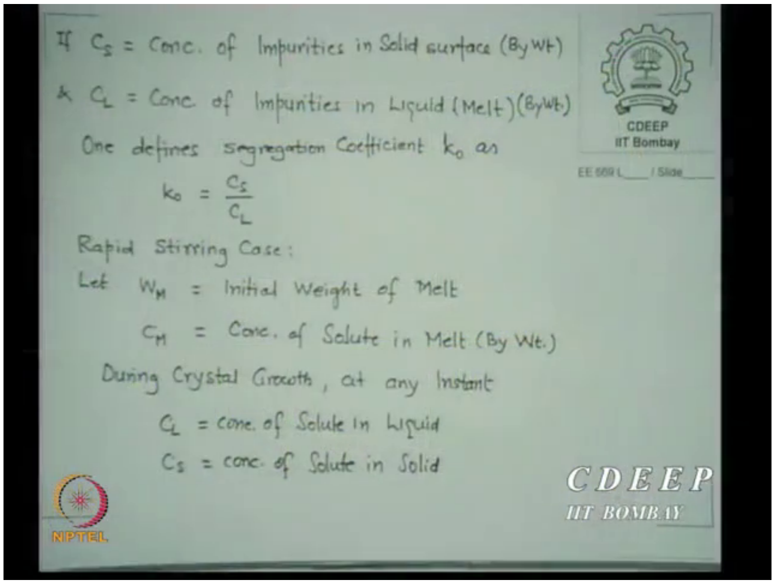

If $C_s$ = Conc. of Impurities in Solid surface (By Wt)

& $C_L$ = Conc. of Impurities in Liquid (Melt) (By Wt)

One defines segregation Coefficient $k_0$ as

$$k_0 = \frac{C_s}{C_L}$$

Rapid Stirring Case:

Let $W_M$ = Initial Weight of Melt

$C_M$ = Conc. of Solute in Melt (By Wt.)

During Crystal Growth, at any Instant

$C_L$ = conc. of Solute in Liquid

$C_s$ = conc. of Solute in Solid

Okay, I start with 2 cases we have discussed, one is called rapid stirring. So we are actually staring the liquid very rapidly other is called partial stirring very slow stirring, okay. The formulas which we want to create, we want to figure out what is k0? What do you expect k0 to be good? The concentration near the interface should be same as concentration in the solid so ideally I am looking for k0 to be 1. How much I get and how do I improve is all that technique is about, okay.

I normally will like to get one but it may not be possible and let see how much nearest we can reach there, okay. So we define, I think this is not given in the plumbers book this is my own old notes, as I say I am in 45years in this area, so some terminology is mine which may, may not be suited to new books or something may be some old books and so please pardon me if you can go and read Plummer's book change over to whatever names they are putting I have no objection but normally this problem is always worrying some for many of you.

For example in the case of MOS transistor its current is given by mui Cox W by L and I call it beta, this number I call it beta but beta is very popularly known is bipolar as a beta of the transistor most of the books give k, they call mui C...

But I have born in an era where we used to start it calling equivalent from bipolar to mass we say oh! This is a gain function, okay. So we started calling beta. Now when I teach, I teach beta and then people say then what is k? So I say, okay beta by 2 is k, that is true but the way I look at it and why many new books do not, probably is the age difference, so unfortunately my question paper will follow what I actually teach, so please follow what terminology I use maybe correct or maybe not correct.

Let say WM is the initial weight of the melt. CM is the concentration of solute in the melt, solute means impurities during crystal growth at any instance and remember there is a difference between CM and CL, CM is at initial time before it starts pulling, CL is when you start actually melting and going towards interface, okay. So any given instant near the interface value we call it CL and inside the molt initially what was available we call it CM.

CS of course as we have defined earlier is the concentration solute in solid other side of the when you pool, okay. There is an interface solid and liquid, okay. Is it okay everyone? I repeat this is my terminology but you have it because I will not change for your sake though I should and the current trend in the world is to change what students want but please help may not ask me to change it for you, okay. It is too late for me to change, okay. But this is a similar nomenclature is available in Plummer's book, so do not worry, Plummer is no different from me but I do not know he has use the modern names.

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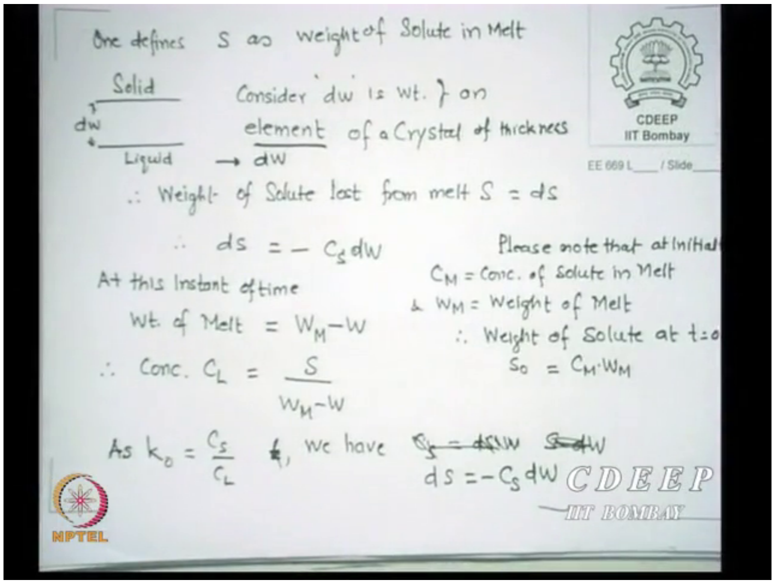

One defines S as weight of Solute in Melt

Solid
dw
Liquid

Consider 'dw' is wt. of an element of a Crystal of thickness → dw

∴ Weight of Solute lost from melt S = ds

∴ $ds = -C_S\,dW$

At this Instant of time

Wt. of Melt $= W_M - W$

∴ Conc. $C_L = \dfrac{S}{W_M - W}$

As $k_0 = \dfrac{C_S}{C_L}$, we have ~~$C_S = dS/dW$~~ ~~$S\,dW$~~

$ds = -C_S\,dW$

Please note that at Initial

$C_M$ = Conc. of Solute in Melt

& $W_M$ = Weight of Melt

∴ Weight of Solute at t=0

$S_0 = C_M \cdot W_M$

We define S as the weight of the solute. S is defined as weight of the solute, okay in the melt. Please note that at t is equal to 0 before the pull starts I am talking of this, CM is the concentration of solute in the melt, WM is the weight of the melt, so we define made of solute at t is equal to 0 as S0 which is CM times Wm this is how it is defined. I repeat CM is the concentration of solute by weight in the melt, WM is the weight of the melt by weight of course weight itself and weight of the solute at t is equal to 0 which I call it as 0 is CM times WM initial condition.

Because when I start pulling I need initial condition because some equations may come and then I will have to put initial value, okay. This is before I start I define it. Now consider between solid and liquid there is a layer which has dw as the thickness, crystal is this which is between liquid and solid, okay. You are pulling in between neither liquid nor solid something different that thickness we call it dw, okay.

Now how many impurities will be in that, the weight for that is concentration of solute into it that is dw in that small element I just now defined C into W is the net value S, so solute available in that dw is the concentration CS multiplied by dw the weight whatever you are talking about.

Why minus? Because this is lost from the melt side, you are actually transferring from melt towards solid. So this is minus sign is given to that, so that is lost from the actual melt, these impurities have been lost. Initial weight of the melt was WM, let say currently the weight is W at a given instance then the concentration of CL of the solute in the liquid is the total solute weight divided by the remainder of weight of the solute.

Okay, WM minus W is the remainder, upper part W has gone out WM minus W is remaining, S by this value is defined as I repeat this is concentration not per cc this is how it is defined in all metallurgical processes, okay. So I have CL which is S divided by W, please remember what is CL? Concentration of solute near the liquid surface which is total available impurities…

This has gone out of melt, so initially it was S divided by the new weight is some part is lost, so WM minus W, so this is the concentration near CL the ratio we have already set the k0 which is the segregation coefficient is CS by CL. However we have just now said dS is minus Csdw small change. Now when the all crystal grows we will go up to W, okay. Is that okay? Just write down, as I say this is available in Plummer's book in some other form but available this is my day I have done it myself, so I do not know whether they follow this, they do not I know.

As I said to you 83 December or rather 83 January to July to December I taught this course first time in IIT may be first time in India, okay. So since EDS (()) (43:13) starts in you, you start building on that and you say this is correct. So something may not be correct but it is okay.

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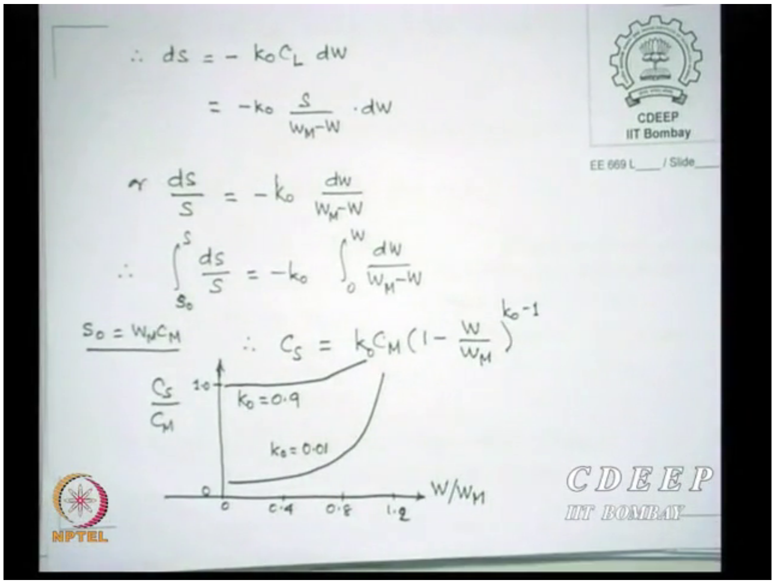

$$\therefore\ ds = -k_0 C_L\, dW$$

$$= -k_0 \frac{S}{W_M - W} \cdot dW$$

$$\text{or}\ \frac{ds}{S} = -k_0 \frac{dW}{W_M - W}$$

$$\therefore \int_{S_0}^{S} \frac{ds}{S} = -k_0 \int_0^W \frac{dW}{W_M - W}$$

$$\underline{S_0 = W_M C_M}$$

$$\therefore\ C_S = k_0 C_M \left(1 - \frac{W}{W_M}\right)^{k_0 - 1}$$

If I substitute this CS in terms of k0 then ds is minus k0CL dw I will just represent k0 CS by CL, so I put it there, I also represent CL as S upon WM minus W just now I wrote the whatever is remainder ratio, okay then I say ds by s is minus k0 dw by Wm minus W, How has the crystal grown? From initial concentration of k0 to any instant S, okay S is changing and how much is the weight in this changing in the solid (()) (44:06) in this 0 initially and it goes towards total weight of this w.

So if I integrate with this condition S0 is WMCM I get this relation which is CS equal to this minus sign comes because of minus W here, so k0 CM 1 minus w WM k0 minus 1. So now I have a concentration of solute in solid related to concentration in the melt, related to their weights, okay. Initial weight as well as current weight and segregation coefficient, this is a simple integral you can solve yourself.

What is interesting for me? I just now said for uniformity CS by CL, CS by CM or CS by CL that should be equal to 1 that is what my ultimate aim is. So if I plot W by WM versus CS by CM for different value of segregation coefficients k0 is 0.1, 0.2, how do I adjust k I will see later but as of now if I plot for different value of k0s, I find k0 when it reaches around 0.9k which is what we are looking for they melt liquid and solid are almost have universal concentration all 3 is same, okay.

Very close to this 1 1 1 for example, you can say there is a uniformity for melt to the liquid to the solid, so the doping is as good as possible you want to get. Smaller the k value you get worse will be the solid distribution, best you can get as close you reach k to the 1 you will get very uniform dope crystal, okay. Now in this process which we did just now, we like to do little more further processing on it and we will find that k cannot be really controlled because k is something constant for a given material for this but I can do little trick to vary the key, this is the whole game. From this I figured out that for Boron this case knows how do I change that case?

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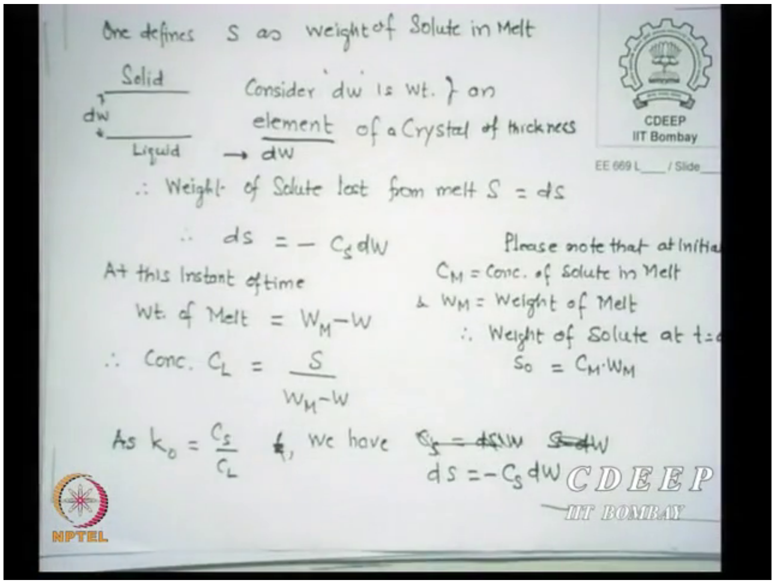

One defines S as weight of Solute in Melt

Consider 'dw' is wt. } an element of a Crystal of thickness → dw

∴ Weight of Solute lost from melt S = dS

∴ $dS = -C_S\,dW$

At this Instant of time

Wt. of Melt $= W_M - W$

∴ Conc. $C_L = \dfrac{S}{W_M - W}$

Please note that at Initia

$C_M$ = Conc. of Solute in Melt

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∴ Weight of Solute at t=

$S_0 = C_M \cdot W_M$

As $k_0 = \dfrac{C_S}{C_L}$, we have ~~$C_S = dS/dW$~~ ~~$S\,dW$~~

$dS = -C_S\,dW$

So I said, okay let me see if I get this value, if I reach k higher I will be able to achieve uniform doping. So I made a trick I don’t mean I, I means those who have done first may be Czochralski and others.

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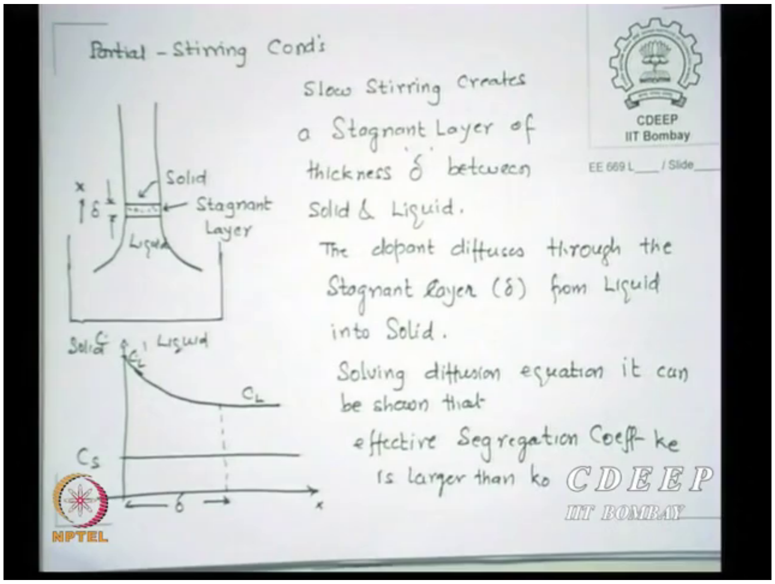

Partial - Stirring Cond's

Slow Stirring creates a Stagnant Layer of thickness 'δ' between Solid & Liquid.

The dopant diffuses through the Stagnant layer (δ) from Liquid into Solid.

Solving diffusion equation it can be shown that effective Segregation Coeff $k_e$ is larger than $k_0$

What we did? We said okay do not stir it with high speed, do it partial stirring, slow stirring that has some advantage, you can think of like this, if you pull it faster and rotate it faster the amount of liquid which it can stick will be smaller, is not it? But if you pull it slowly and rotate also to a more liquid can touch the solid area, okay and the rate at which you are pulling and the rate which you would segregate down is such that this layer remains uniform this is called stagnant layer.

If you have done anyone, some course in chemical engineering all our analysis in transport there is based on stagnant layer models, okay. Air is going through, particles will move or not, how much stagnant layer you have, every process in the life if you actually analyse is somewhere related to this stagnant layer, okay. So this same model has been picked up from chemical people.

Let us say the stagnant layer has a thickness delta, okay between solid and liquid and now you will say, since it is a stagnant layer there 2 things are happening, one is the impurities from the liquid are going to the solid by process of diffusion, what is process of diffusion? If there is a higher concentration, higher and lower it will try to defuse were looking at the gradient, okay.

(()) (48:38) it will start diffusing through stagnant layers; there is also segregation going on which is inverse of diffusion. In equilibrium there will be because it is a stagnant layer remain constant this will remain, this process will balance each other for a given time, initially it may be higher or lower but latter it will adjust itself. Now we want to see this can we solve the diffusion equation and also segregation related flux back.

If you solve this we somehow figured out and we will show this figure latter again. If this is my x and this is my concentration and plotting. On the left is my solid, on the right is my liquid and this is my Delta is a stagnant layer. CS is that solid concentration which you are actually looking for. Now we find from here near the solid liquid into phase or rather above the solid stagnant layer into phase.

Since the lower concentration is only possible because of segregation below but on the stagnant layer doing equilibrium the concentration there can be higher, okay that is the fun part because sticking there, so it is larger concentration here but below it cannot because it has no force to go up, this means CS dash at the interface is much large, is that clear? However as it goes towards process towards the liquid the concentration reduces to CL value.

When we calculated it rapid case this CL and CL dash were same, so k was decided by ratio of CS by CL but now this is not the value which is being used, which value I am going to use now? This value which is much smaller then this value, this exponentially decaying function, what does that mean? CS by CL will be higher than rapid pulling case, is that clear? Please remember if this is equal somewhere CS by CL dash or CL which was equal then k value was decided by whatever the distribution available for you.

In this case depending on the thickness of stagnant layer this concentration and this concentration will be different, okay. 2 processes, diffusion process followed by segregation process both will be trying to adjust each other such that depending on the delta use now my question is how do I control delta? The pull rate decides the delta, faster I pull delta will be larger and it will break also.

And how much I rotate, how much I allow it to stick, so depending on the pull rate and the spin rate I keep I can adjust the value of delta and delta will decide the ratio of CL dash to CL. So if I adjust this delta value then I have adjustment of ratio of CS to CL differently from different delta values, is that matter clear? As I change this the ratio will be varying, so is k will be varying and if I change k, I just showed in the last graph I can build the k then I will get more uniform crystal.

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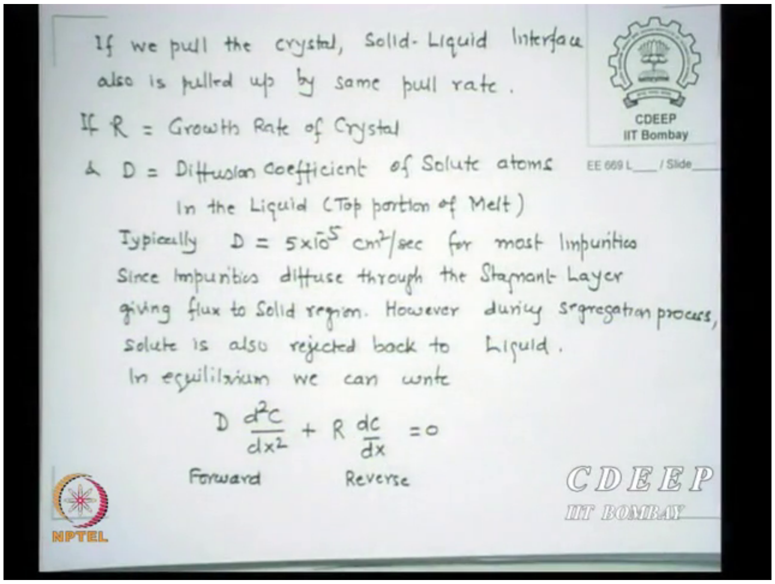

If we pull the crystal, Solid-Liquid Interface also is pulled up by same pull rate.

If R = Growth Rate of Crystal

& D = Diffusion coefficient of Solute atoms In the Liquid (Top portion of Melt)

Typically $D = 5 \times 10^{-5}$ cm²/sec for most Impurities

Since Impurities diffuse through the Stagnant Layer giving flux to Solid region. However during segregation process, solute is also rejected back to Liquid.

In equilibrium we can write

$$D \frac{d^2C}{dx^2} + R \frac{dc}{dx} = 0$$

Forward Reverse

Okay, here is maths. Maths is very interesting always, many of you may not think that this course will have maths, please take it this course will have 30 percent of maths requirements. Look of your differential equation solutions better different (()) (52:53) of equations may appear and we may have to solve them. So let us say if you pull the crystal solid liquid interface and it is pulled by simple rate, let say R is a growth rate of the crystal.

Please remember growth rate and pull rate are same because as much you pull that much solidifies, so growth rate and pull rate are almost same, exactly they are not but almost. The Diffusion coefficient of solute atoms in the liquid, top portion of the melt is normally for most impurities is given by 10 to power minus 5 centimetre square per second. Now we have in this stagnant layer.

Please remember infinity is diffused through stagnant layer into solid and segregation returns them back to stagnant layer and therefore to liquid. We read this is the followed reaction diffusion equation, D into d2C by dc is the concentration, D into d2C by dx square is the diffusion term, R into dc by dx is the segregation term, it returns back. Actually they are minis of that is equal, return means minus, total net value should be at equilibrium must be 0, some of this process plus this process must always be 0.

So forward pushing is balanced by reverse pushing, so there is a net pushes therefore when uniform, is that clear therefore uniform, okay. Is that equation clear? We will prove this again in diffusion process when we look into, right now you assume this is the diffusion equation which is giving dc by dx is the concentration gradient, second differential of that is essentially when I multiply by this, this is the diffusion term. This is coming from which equation? Continuity equation.

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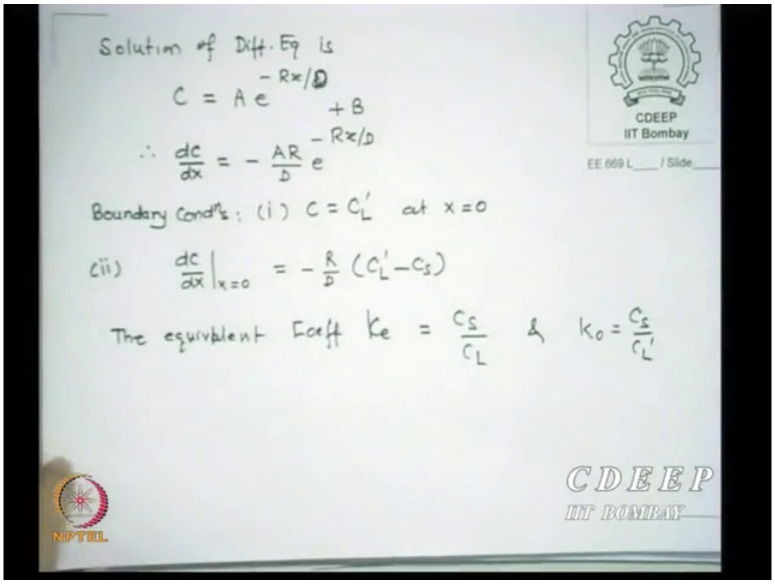

Solution of Diff. Eq is

$$C = A e^{-Rx/D} + B$$

$$\therefore \frac{dc}{dx} = -\frac{AR}{D} e^{-Rx/D}$$

Boundary Condn's: (i) $C = C_L'$ at $x = 0$

(ii) $\left.\frac{dc}{dx}\right|_{x=0} = -\frac{R}{D}(C_L' - C_s)$

The equivalent Coeff $k_e = \frac{C_s}{C_L}$ & $k_0 = \frac{C_s}{C_L'}$

So if I solve this continuity equation which I did, you can also solve. The concentration is Ae, e to the power minis Rx by D plus B, solution of a differential equation is simple and if I differentiate it dc by dx is minus AR by D e to the power minus Rx by D these are the 2, why I did this, i have 2 unknowns A and B, I need 2 boundary conditions to solve to get this value, okay.

I need A and B 2 unknowns, I need 2 boundary conditions, these are essentially one boundary condition but the other one of course I will come back to it. At x is equal to 0, what is the concentration?

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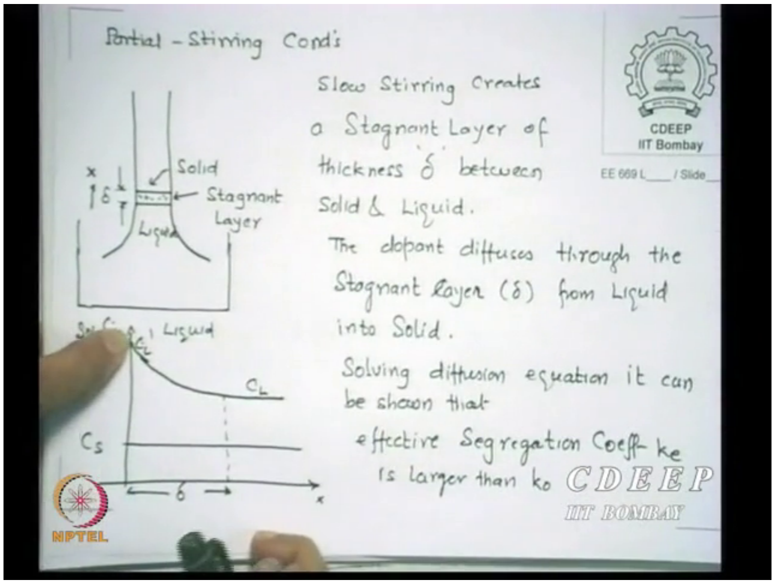

Partial - Stirring Cond's

Slow Stirring Creates a Stagnant Layer of thickness $\delta$ between Solid & Liquid.

The dopant diffuses through the Stagnant layer ($\delta$) from Liquid into Solid.

Solving diffusion equation it can be shown that

effective Segregation Coeff $k_e$ is larger than $k_0$

This figure we have just now, at x is equal to 0 concentration is CL dash whereas at the concentration gradient at x is equal to 0 by actually using this term is R by D CL dash minus CS I have not derived it but you can derive, in the night I finally got tired, so I wrote this. It is very easy to define from here and if I make these 2 equations and substitute to get A and B I get final term which I am looking for.

Please note down this, this is the solution, these are the 2 boundary conditions which are used to define the solution of this A and B can be found and once I find A and B, please note down because as I said I repeat whatever I am doing is possibly available in Plummer's book. It is not that it is different, only their names, nomenclatures may be different but the equation will change because diffusion and segregation physics cannot change, chemistry cannot change and maths cannot change.

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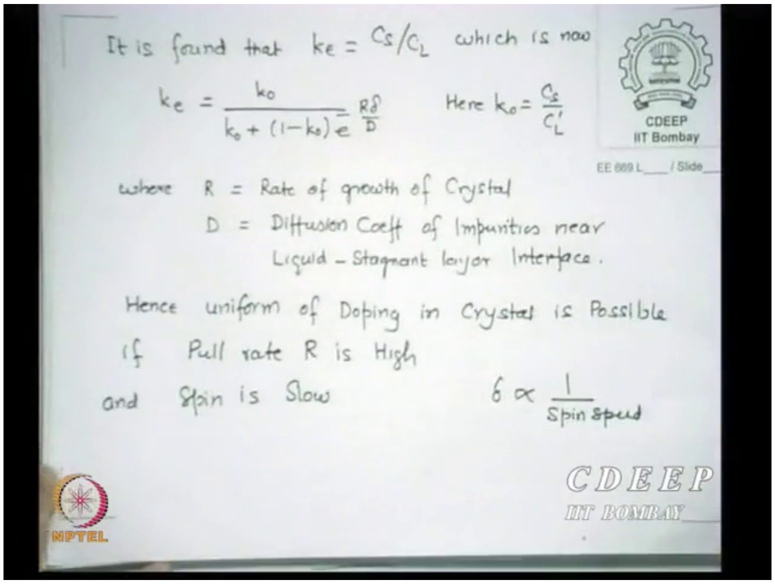

It is found that $k_e = C_S/C_L$ which is now

$$k_e = \frac{k_0}{k_0 + (1-k_0)\,e^{-\frac{R\delta}{D}}} \qquad \text{Here } k_0 = \frac{C_S}{C_L'}$$

where R = Rate of growth of Crystal

D = Diffusion Coeff of Impurities near Liquid – Stagnant layer Interface.

Hence uniform of Doping in Crystal is Possible if Pull rate R is High and Spin is Slow

$$\delta \propto \frac{1}{\text{Spin speed}}$$

So if we find new segregation coefficient which we call effective segregation coefficient which is called ke effective, this is not CS by CL dash but it is CS by CL, we solved those using the solution of that equation, we arrived at this term k is k0 upon k0 plus 1 minus k0 e minus R delta by D. So what is R? I repeat rate of the growth of the crystal, what is D? The diffusion coefficient for impurities near liquid standard stagnant layer interface.

So one can see from here I can adjust ke through which terms? Here are only 2 terms, R and delta, how delta adjusts? By deciding the spin rate and Ri adjust by (()) (58:12) pull rate, R pull rate, spin rate will decide how much is the delta for it? If I adjust this R and delta I can improve ke, is that correct? I can improve ke if you want ke higher one can say from here we should pull it with a higher this and spin very slow because delta is proportional to 1 upon spin speed, okay.

So if I want larger delta which I thought it will be good then one can see from here delta is 1 upon spin proportional to this. So slowly spin it has good rate, one can get higher ke and if I can get higher ke means what do i get higher uniform doping, all the game is to show that mathematically also I can show that either user tomorrow one of you, I may tell you now there is a possibility, other day there is a news report India may have first polysilicon plant which year and when only god knows and may be our prime minister knows, maybe I do not know even that.

But there is a proposal now which is almost going to be finalized; the problem with making a plant is simple. If I make 200 million ton plants a year, is there consumption of 200 million tonnes of poly Silicon in India? If it is not why do I put a plant? I have to compete with the world with the companies which are 50 years old and have already setup everything, my initial cost will be high, so I cannot sell cheap any poly Silicon, so I will never survive, if I have to market of but if I have internal connection, yes.

Solar cell this has come from solar cell department, so i hope it may be okay, it is not from IC group. The solar cell people a wanted policy and they are now negotiating I am told I am not very sure how would the news released to the press and available on other places is identical? But assuming it is so you may have a poly Silicon plant in India and as of now they are thinking of 500 million tonnes per year, hopefully yes.

So many solar cells may be made hopefully. So you may have a job latter are at least say, Sir, we have learned and we know, I have learned and I know remember me then.

“Professor -Student conversation starts”

Student: Sir, if we do not spin what will be the value of delta.

Professor: Oh! If you do not spin delta will be infinite, what does that mean? That solid liquid portion is now touching there is infinite delta essentially means there is no solid and there is no liquid and it will just jump down because such a large this, volume will trip down because the weight of solute would be so high on the top it will just fall down.

So too much lower spin and too much R, though R is also if I pull very heavily that small portion single crystal will break, so I have shown you 2 figures when I rotate very heavily and I pull it heavily I may actually lose the contact either side and therefore I cannot do too much, so ke cannot be made 1 any day may be 0.8, 0.7, 0.9 at best but even then ke 0.9 is good enough for us because it is giving relatively uniform crystals, okay.

So our CZ crystals are not greatly uniformed but mostly uniform and integrate circuits we do not bother too much about so much variation as long as variation is less than 10 percent, it is all fine. Why 10 percent? Anyone? Circuit math, this is circuit something doing circuit. Why it is 10 percent? If you see a particular in digital let us say, in a digital circuit your noise margins are half vdd, okay.

“Professor-Student conversation ends”

So you can see from here that if even if there is a variation of thresholds 10 percent is much lower than the available noise margins, only in analogue this may be killing, so there you may not be able to do this but in digital this is good enough. Of course in some speed it may affect to even then because the speed is depending on the essentially this value percentage vt because current is available to charge a capacitor. So there is a problem variability issue but otherwise it is sustainable as long as I know what is the variation? I will adjust my critical paths, okay.

But in analogue I may which wafers I should prefer even (()) (63:28) but then it will be so costly that no one will buy my chips. If I make it on CZ I am not doing well I am sure and also there are very few analogue chips are manufactured, purely analogue, how many 741 V buy or A2D, very few. All that people by is on chip analogue that is there is a digital block and some small 10 percent is analogue with signal.

There technology is not analogue it is a digital you work for the worse technology for analogue still want to give good results, okay. That is the trick that is why analogue designs are much more interesting because you are fighting every second, every nanosecond to get what you want, okay. And digital you sleep next day it may work, so that is what Digital is all about.

If I teach you digital I will tell you something else today I will not tell, okay. I will not go into detail of float zone you can read. Basic idea in float zone is the following I already shown you this float zone reactor maybe.

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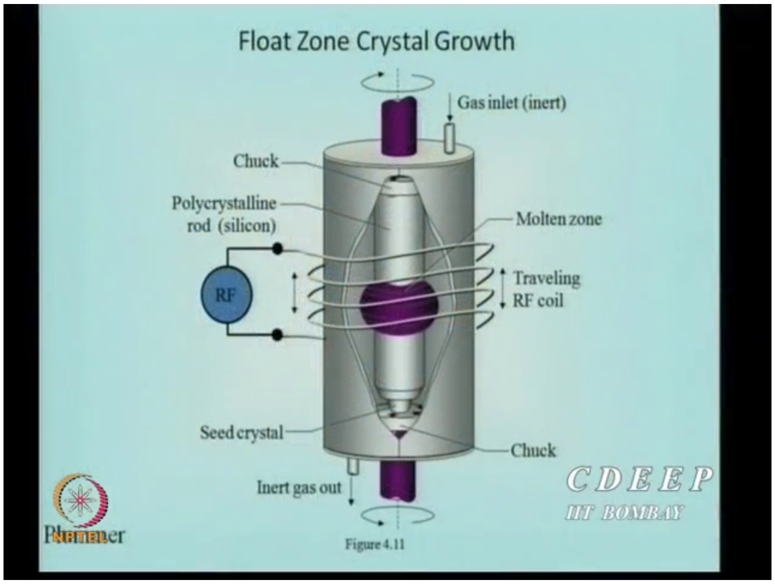
Float Zone Crystal Growth

You can see from here you have full ingot of single crystal available to you, okay. Full ingot, you hinge it on the top and also on the bottom and there is a coil you can see which is RF coil which is travelling it can move from one end to the other that is why wherever you apply RF to this coil by induction heating, the internal part actually also has a carbon rod there which actually receives the energy and heats, this is our induction heating is done.

So once that zone gets heated only that portion where that coil is sitting gets molten, the rest is still sorted. So what we do is, we start from say anywhere and keep passing this zone up and down, is that point clear? We start passing zone from up-and-down, too much speed is also difficult because if the molt moves very fast it breaks, if it is too slow it does not distribute well. So there is always catch optimiser, so this is called float zone.

Why it is called? Because the zone of heating is floating, so it keeps floating up-and-down. So what happens everywhere wherever it go there is a segregation, you come down another segregation, so number of passes you go through this because of the segregation and diffusion impurity is going through this zone part, impurity is finally after say 8 to 10 passes becomes uniform.

Since there is no quartz or anything inside here is no oxygen, of course carbon is but which is internally to it, so it normally does not interact directly to it and therefore this is almost impurity free. So pure crystals can be grown only...

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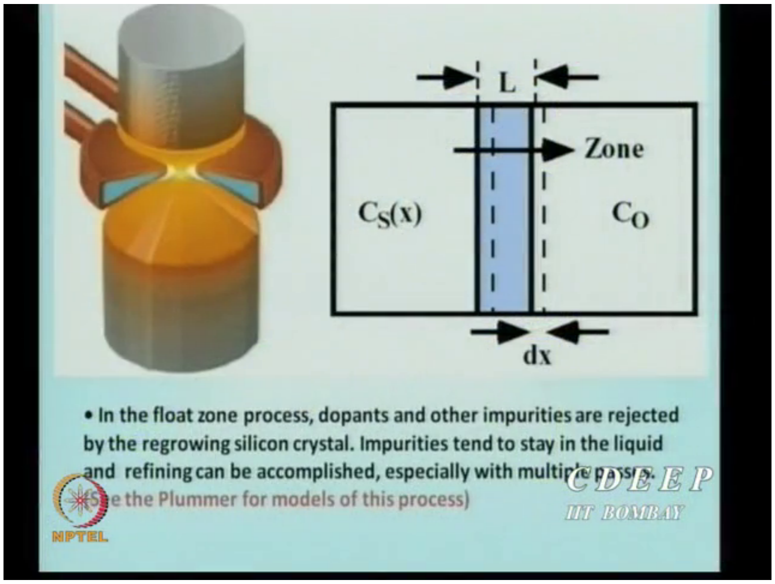

- In the float zone process, dopants and other impurities are rejected by the regrowing silicon crystal. Impurities tend to stay in the liquid and refining can be accomplished, especially with multiple passes.

(See the Plummer for models of this process)

So initially which crystal still I got CZ one, so I got a CZ crystal rod and I put it here and pass through number of zone passes and then you can see from here this is my zone, this is my solid, this is my melt or other side of this. What happens, impurity crosses this melt to the other side wherever concentration gradient is there you keep moving this when you come back the impurity starts moving the other ways.

If you keep going like this, like this you will get almost uniform concentration of impurities across the lot, okay that is how float zone's are actually made. Before coming here I may tell you where the carbon segregates. Carbon normally segregates on the surface, so we tried to remove that I mean that process I will show you.

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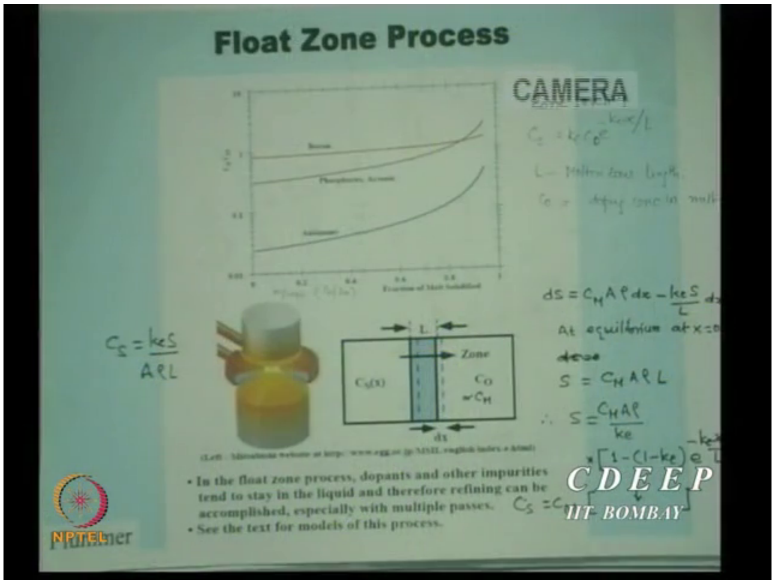

Float Zone Process

- In the float zone process, dopants and other impurities tend to stay in the liquid and therefore refining can be accomplished, especially with multiple passes.
- See the text for models of this process.

$C_S = k_e C_0 e^{-k_e x/L}$

L — Molten zone length

$C_0$ — doping conc in melt

$dS = C_M A \rho\, dx - \frac{k_e S}{L}$

At equilibrium at x=

$S = C_M A \rho L$

$\therefore S = \frac{C_M A \rho}{k_e}$

$C_S = \frac{k_e S}{A \rho L}$

By doing similar analyses which I did for CZ one, one can see CS to CM ratio can be 1 minus 1, similar like what we did for partially stirring case and you can see all 3 impurities, if I do number of passes, zone passes will reach maximum ke or uniformity. 8 to 10 passes of the length I have pushed everyone gets almost uniform concentration. Please remember this is the best possible crystal growth and since it has no impurities generally its resistivity is very high, is that clear?

That is why it is called intrinsic material, it is very few 10 to power 13 per cc or 10 to power 5, 10 to power 12 cc you can obtain using this method, okay. Normally in mass you require 10 to power 16 per cc, 10 to power 17 now maybe someday 18 and 19 as well. So 4 zone process is only used when you want highly pure crystals, with very high resistivity you can attain and you can always make doping.

To make a doping what do we do is, I just put a for example this is a good rod and this is the doping road which is doped by me, okay earlier fixed doping. So I put this rod which is to get doped with the one which is already available to me and keep giving with own passes. So the impurities from that concentration high will keep going and finally after 10 or 12 zone passes it will be uniformly distribute, this is called zone levelling.

Pushing an impurity from the source of rod to the whole remainder rod is called zone levelling. So you give number of passes impurities distribute all along, okay. So float zone is a very costly process. As I say a typical 12 inch wafer these days of course comparatively has gone down now but it is still 70 dollars where is the float zone? Of course no one makes that size of wafers. 6 inch wafers is available at 450 dollars, so it is a huge money differential, so unless you are working on something which gives you money on that side, do not go for intrinsic wafers.

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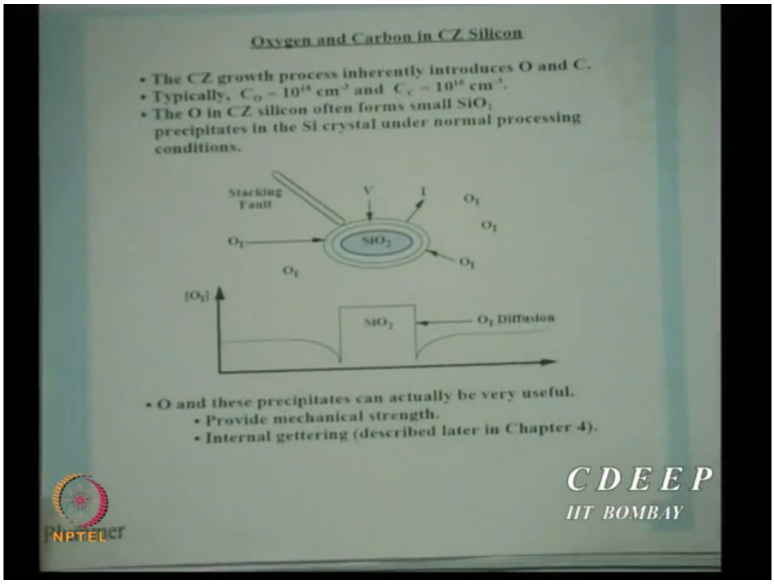

Oxygen and Carbon in CZ Silicon

- The CZ growth process inherently introduces O and C.
- Typically, $C_O \sim 10^{18}$ cm$^{-3}$ and $C_C \sim 10^{16}$ cm$^{-3}$.
- The O in CZ silicon often forms small $SiO_2$ precipitates in the Si crystal under normal processing conditions.

- O and these precipitates can actually be very useful.
  - Provide mechanical strength.
  - Internal gettering (described later in Chapter 4).

Okay, so this last but not the least, as I said these are the impurities which you see in CZ, as I said the other impurity segregation is very small and therefore very little goes into the actual crystal but Bismuth, Lithium, iron hardly go into it we will be there in traces but very little. However Carbon and Oxygen have a large content, you can see this oxygen concentration of carbon is 10 to power 18 per cc, okay which is very high, extremely high.

And carbon concentration is 10 to power 16 per cc which is also very high. However it looks as if the presence of oxygen also in carbon is not very good if we thought, yes (()) (70:53) it seems to be, no but it has some advantages also, okay. Since the oxygen is N type Dopant, it has a tendency to actually…

Silicon gets oxidised very fast, Silicon has the highest affinity for oxygen, so if the oxygen is there, Silicon gets oxidised it is called precipitates. Now these precipitates are more like amorphous material, no order of course I will not say 0 order but some less, much less order. Now when this place and if these contents are known where they are at the edges of the surface, okay then what happens that other impurities like let’s say material has carbon, what I should say gold or anything other impurities, they find there is a vacancy or possibility where they can occupy a site and stay there, okay.

So if you hit the wafer now with any other impurities this precipitate actually absorbs most of the other impurities, okay then you remove that area, okay and you now have a wafer which is free from most of the impurities as well as the precipitates. So many people thought that oxygen precipitate or carbon precipitate may actually harm us it really does not as much, in some areas if they are in the localised, yes those wafers will go away they have very low resistivity there they actually burn it then, these are called hotspots in chips. So very few areas burn but normally they do not, okay. So do not think that Oxygen and Carbon is all bad, think as if they are impurities and we do have a problem as such.

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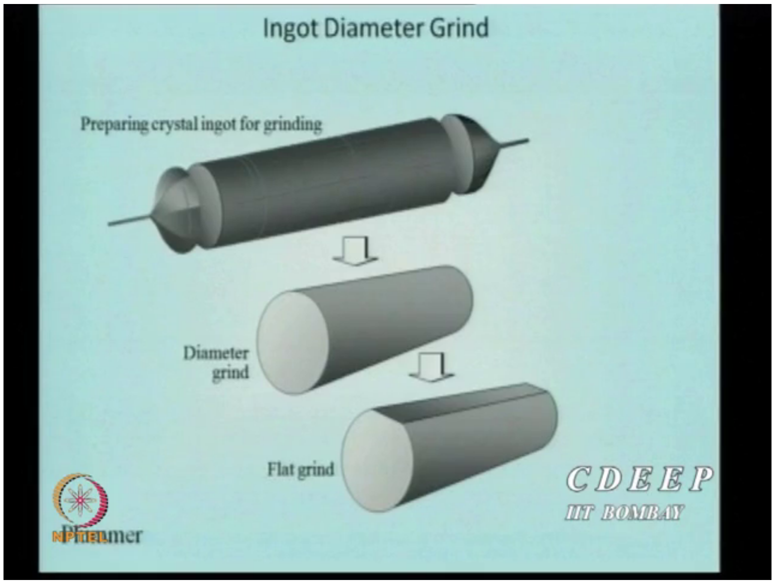

Ingot Diameter Grind

So this of course finishes the growth part, okay. Now few more things we will have to do for next time maybe we quickly see anything to be shown here on the figure, okay. Okay, this is what something we may show before because these are only show this is nothing to learn, this is an ingot and I actually grind the diameters, okay. The crystal ingot for grinding and then you actually grind it into a wafer something like this maybe better.

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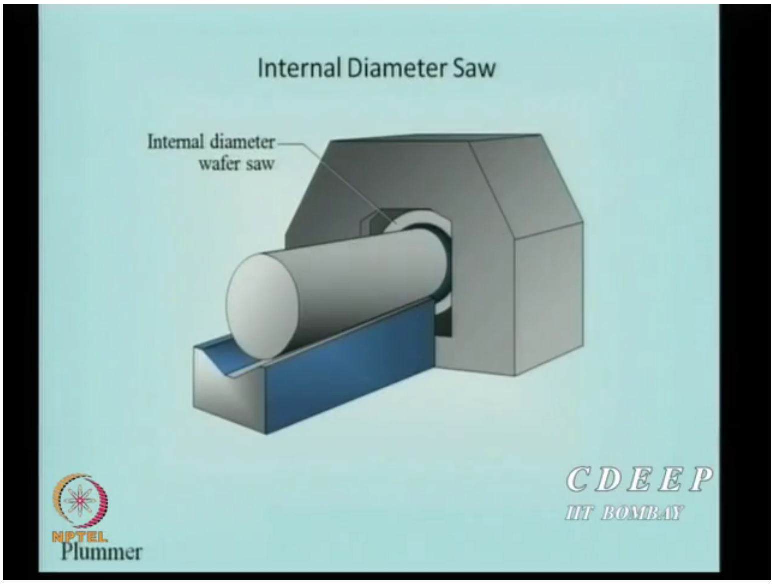
Internal Diameter Saw

You have a wafer saw as they call rod goes in and there is a rotating matrix of Nickel which actually grinds this upper surface. As I said most dislocation are on the surface, so they are actually removed, okay.

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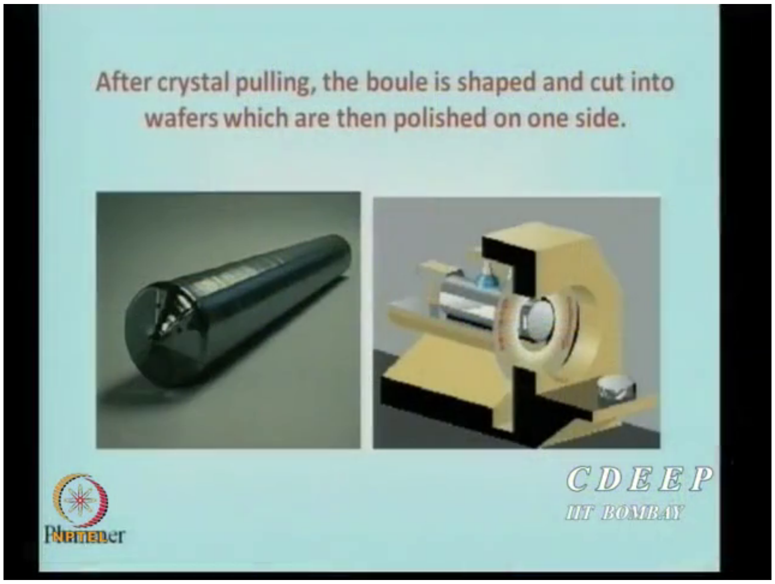
After crystal pulling, the boule is shaped and cut into wafers which are then polished on one side.

Same thing better figures after crystal pulling the boule is shaped and cut into wafers by using, this is how internal part of that, okay.

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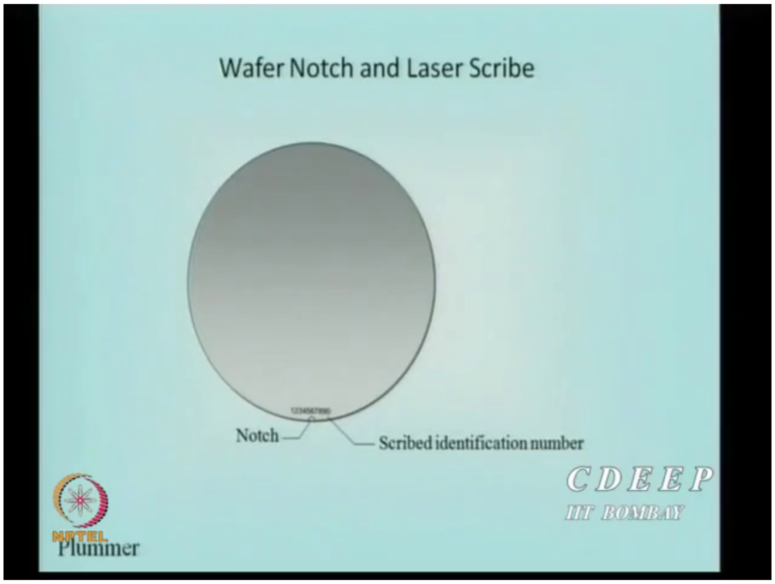

Wafer Notch and Laser Scribe

This is how you will get wafer, okay.

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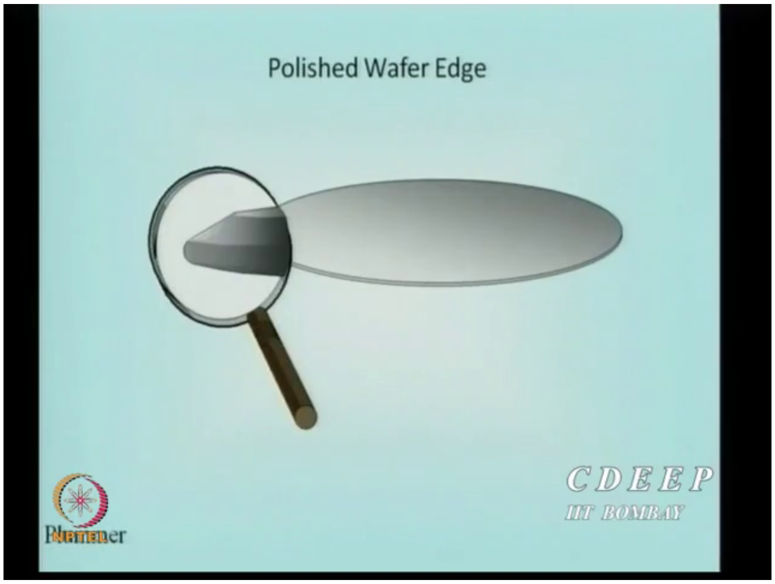

Polished Wafer Edge

This is the edge we see in the wafer magnified one.

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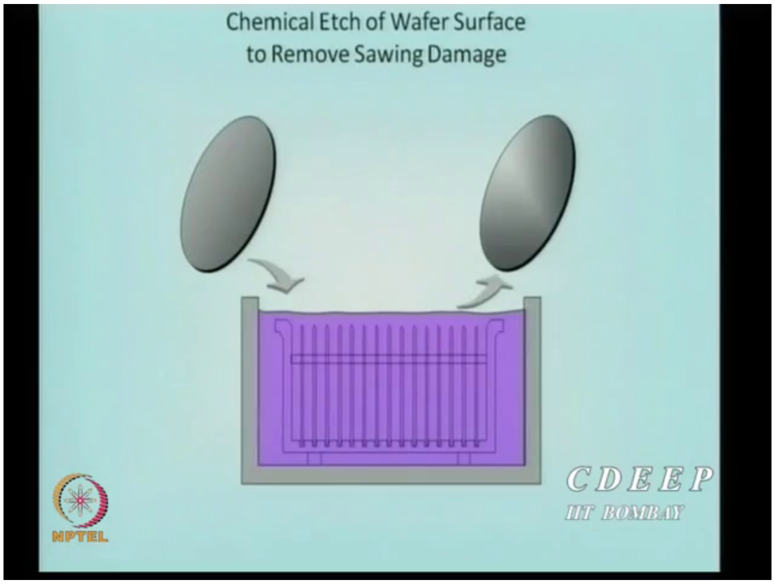

Chemical Etch of Wafer Surface
to Remove Sawing Damage

These are how they are actually handled to clean these are Etch in which wafers are handling putting in together inside, okay.

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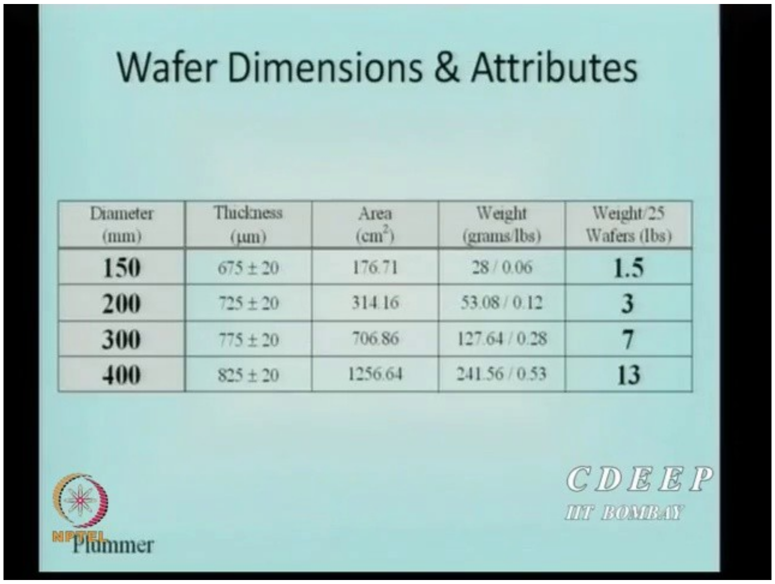

Wafer Dimensions & Attributes

| Diameter (mm) | Thickness (µm) | Area ($cm^2$) | Weight (grams/lbs) | Weight/25 Wafers (lbs) |
|---|---|---|---|---|
| **150** | 675 ± 20 | 176.71 | 28 / 0.06 | **1.5** |
| **200** | 725 ± 20 | 314.16 | 53.08 / 0.12 | **3** |
| **300** | 775 ± 20 | 706.86 | 127.64 / 0.28 | **7** |
| **400** | 825 ± 20 | 1256.64 | 241.56 / 0.53 | **13** |

Plummer

And typical dimension as I say is 150 millimetre to 400 and you can see weight per 25 wafers this is 13lbs 150milimeter as 1.5lbs, okay. So less than a kilogram here it becomes 6kilograms for 25wafers, so handling, can you understand the handling large the mass handling a wafer is a tough job and that it should not break, okay because one wafer break means one heart breaks, okay.

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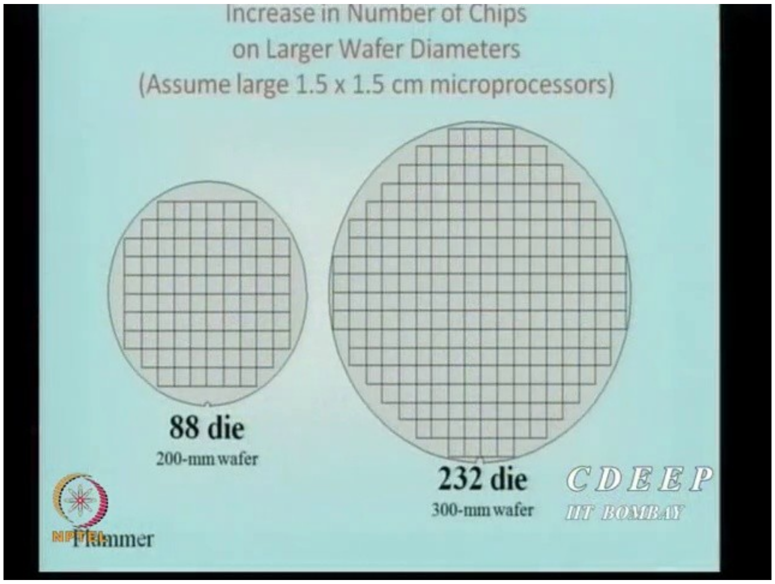

Increase in Number of Chips
on Larger Wafer Diameters
(Assume large 1.5 x 1.5 cm microprocessors)

This is an example if you have 200 mm wafer and whatever die side you have chosen which is 1.5 by 1.5 this may give me 88dies, if I have large wafer of 300 millimetres 12inch then it is 232 dies, so you have earned lot much good chips out of the same process. So the cost of wafer to the cost of processing depends which is higher or lower we will decide what size of wafer you should use, okay.

Okay, the polishing and everything maybe some other day, so essentially we are now having a wafer which is polished clean and it is always mirror finish the way I polish the wafer you can actually see your face much better than any mirror, okay. So it is highly polished wafers which we are actually going to use it is also highly hydrophobic.

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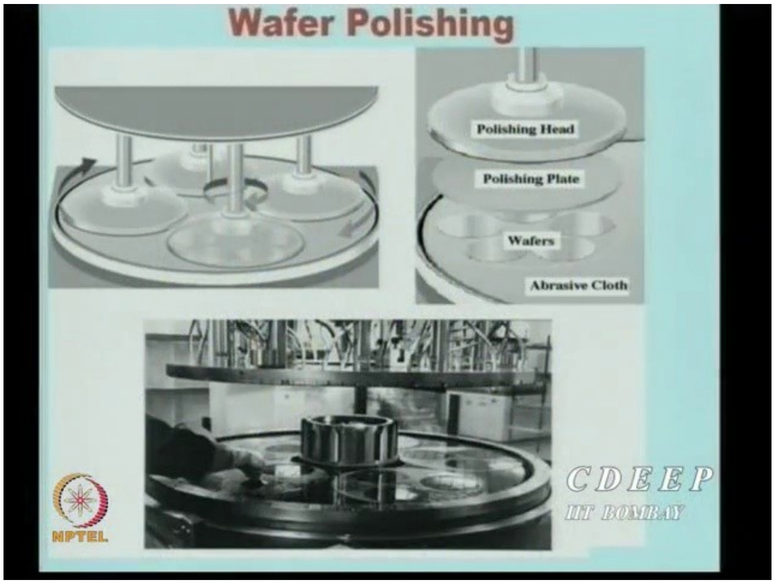

Wafer Polishing

No water can stick to Silicon but Silicon dioxide is highly hydrophilic, so as soon as Silicon is seen it will form an oxide immediately, so when you see a wafer you put into water sticks which mean it has an oxide on that. So the first thing you have to remove that oxide because I want Silicon surface, so this all has to be now done in an area all etching everything and an area which we call fab lab which is where clean rooms are required, okay.

So next time we start with clean rooms, how much clean is the cleaner? This room is called class trillion room, this is class trillion I am looking for sub class one. I am looking for a clean room which is sub one class whereas this is class trillion that means trillion particles of 0.5 microns per cubic feet floating here, I am expecting less than one particle one cubic feet, okay.

So the kind of purity we are looking for is very important and we will see next time what goes into (()) (77:02), thank you.