Fabrication of Silicon VLSI Circuits using the MOS technology

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We were discussing CBD. We also said that there are number of ways in which films can be deposited using chemical vapor depositions.

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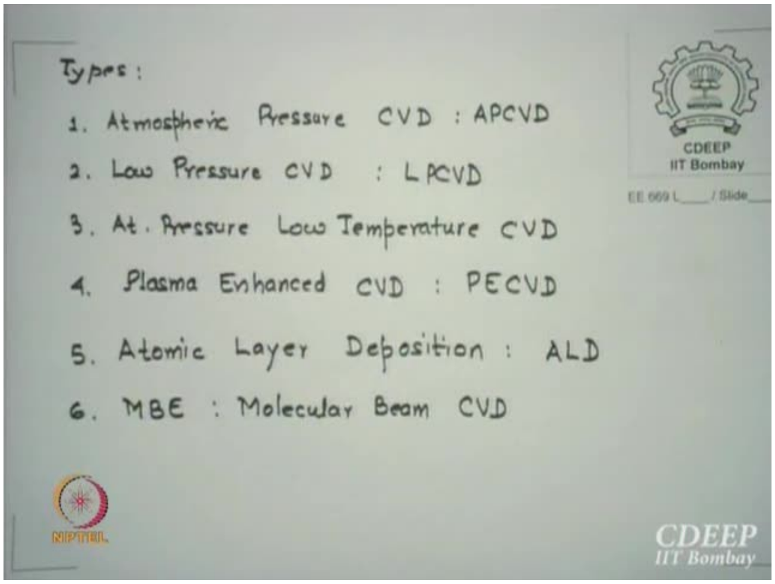

Types :

1. Atmospheric Pressure CVD : APCVD
2. Low Pressure CVD : LPCVD
3. At. Pressure Low Temperature CVD
4. Plasma Enhanced CVD : PECVD
5. Atomic Layer Deposition : ALD
6. MBE : Molecular Beam CVD

We have listed this different things. This is last time we did.

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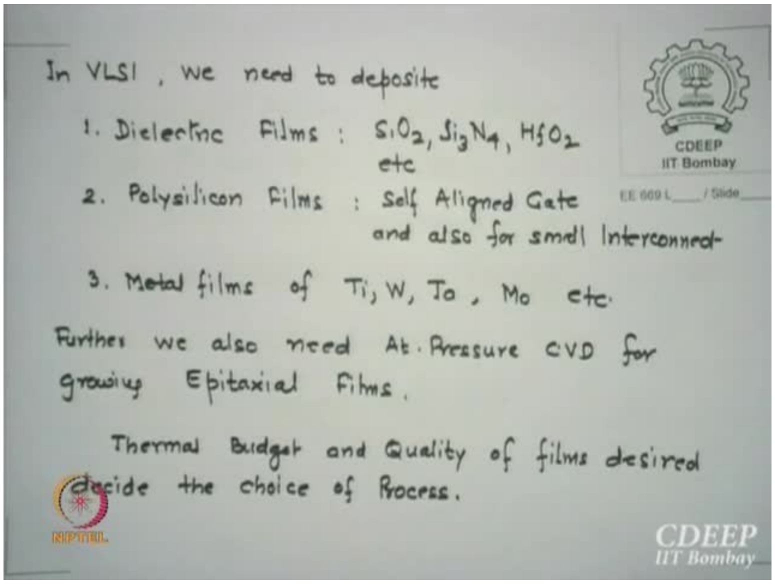

In VLSI, we need to deposite

1. Dielectric Films : SiO_2, Si_3N_4, HfO_2 etc
2. Polysilicon Films : Self Aligned Gate and also for small Interconnect
3. Metal films of Ti, W, Ta, Mo etc.

Further we also need At. Pressure CVD for growing Epitaxial Films.

Thermal Budget and Quality of films desired decide the choice of Process.

And in VLSI, we said we need to have metal films to be etched, dialectic films to be etched and also alloys to be etched. Also, we need atmospheric pressures CVD to deposit epitaxial films or grown, that is called grown films though it is actually deposition. The major important parameter which decides the growth or deposition is decided by the thermal budget. How much is what is thermal budget? In a process, whatever is the furnace or any other annealed cycles you go through, the time and temperature what use is called thermal budget because it consumes wattage.

So this thermal budget also decides which process to use because in processes the last end of processing is actually should have lower thermal budget because earlier process should not change. So thermal budget is a very crucial factor in decision where to use which kind of CVD. And of course quality of films to be etched after of quality firms of the film desired to decide the choice of process. We discussed last time, both APCVD and LP CVD. okay. So we have gone through all of it.

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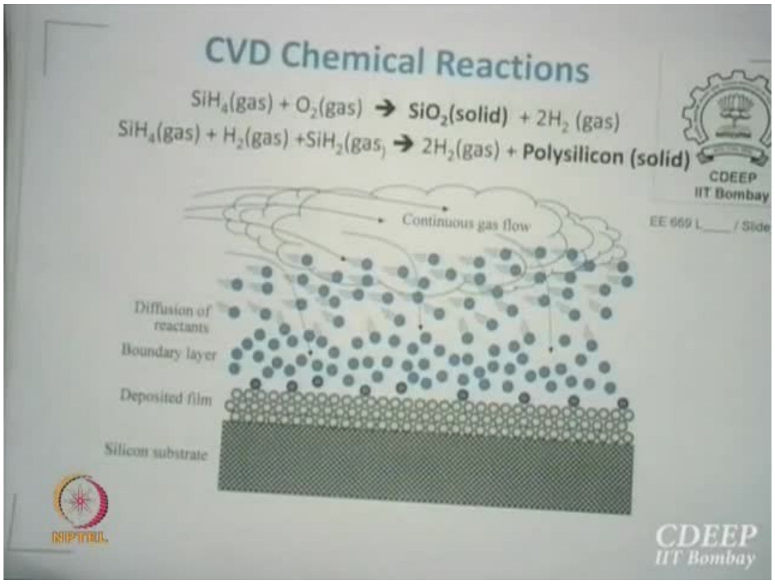
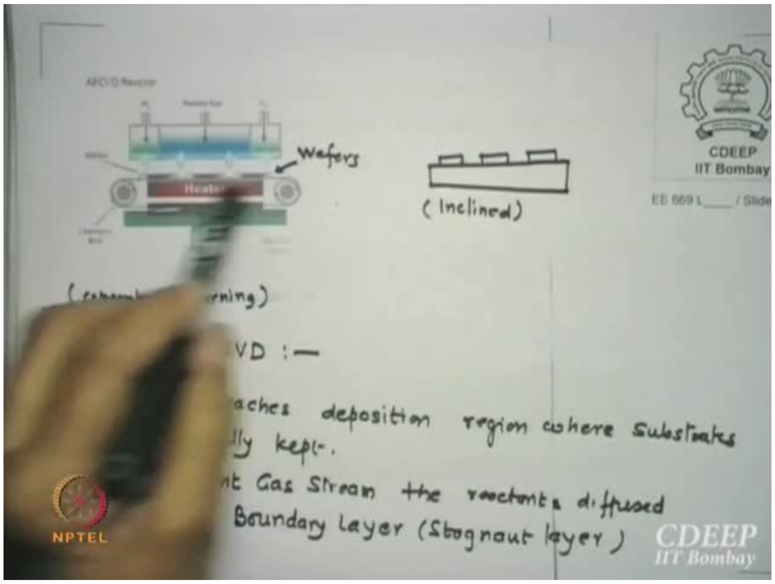


CVD Chemical Reactions

SiH_4(gas) + O_2(gas) → SiO_2(solid) + $2H_2$ (gas)

SiH_4(gas) + H_2(gas) + SiH_2(gas) → $2H_2$(gas) + Polysilicon (solid)



(…rning)

…VD :—

…aches deposition region where substrates …lly kept.

…nt Gas Stream the reactants diffused … Boundary Layer (Stagnant layer)

I just want to show where we were. And we were looking for the 1st process which is the atmosphere pressure CVD in which in a system in an AP CVD system, you have a heater on which wafers are kept. This need not be on a conveyor belt. It is good if they are because then you can have larger throughput. The basically may I have your attention now? You have a heater on which your wafers are kept. This temperature normally is around 400 degrees centigrade +. Okay. And you introduce 1st nitrogen for the clearing all began stream here. Sometimes you also pass through hydrogen to etch out few things.

That is called reduction and then you actually add the process K I think most cases it will be, if it is Silicon-based films, then it will be Silane or tri chloro dichloro Silane or something of that kind. What is the procedure? The procedure is reactant must reach the surface of the place where they want to be deposited and they must, they are kept horizontal. This is important fact, they are kept horizontally. From ambient gas stream, the reactant must through a boundary layer which we will discuss later. So there will be a thin boundary layer on the wafer and reactant must, oh yesterday I showed you the film, sorry.

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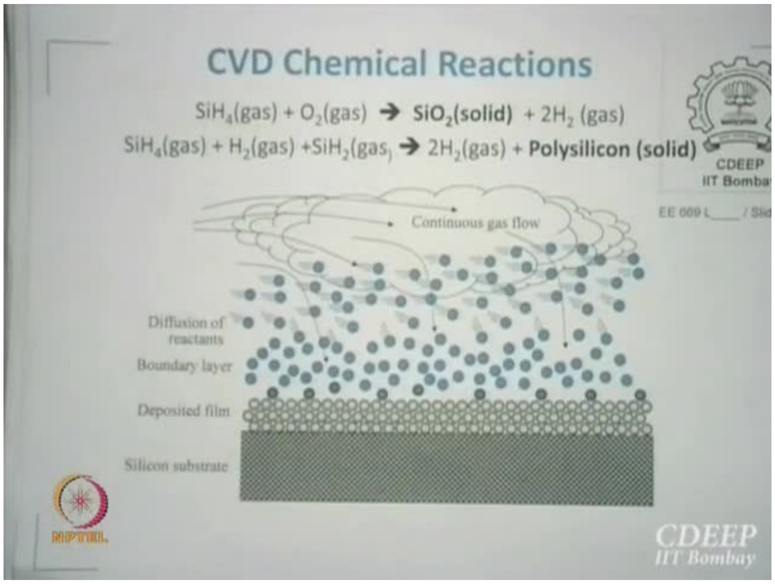

CVD Chemical Reactions

SiH_4(gas) + O_2(gas) → **SiO_2(solid)** + $2H_2$ (gas)

SiH_4(gas) + H_2(gas) +SiH_2(gas) → $2H_2$(gas) + **Polysilicon (solid)**

There will be a boundary layer, stagnant layer as is called and any new reactant has to diffuse through this to actually come and sit on the this. So this is an important thing which decides the mechanism of growth or deposition.

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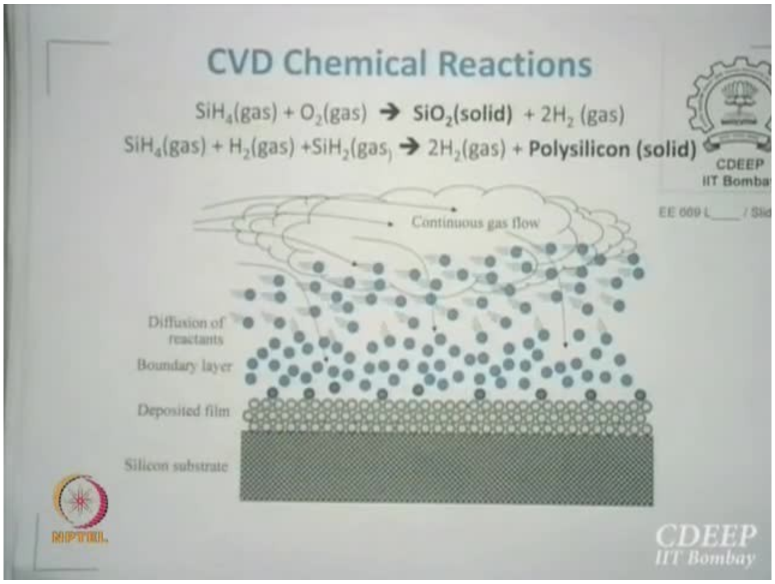

CVD Chemical Reactions

$SiH_4(gas) + O_2(gas) \rightarrow SiO_2(solid) + 2H_2(gas)$

$SiH_4(gas) + H_2(gas) + SiH_2(gas) \rightarrow 2H_2(gas) + Polysilicon\ (solid)$

Then what happens next is still what we did last time, so I am now going, this is what we start now. Once they passed through the deposition, this boundary layer, they are now at the surface of the wafer or substrate and there these reactant must get absorbed okay, to stick there. Okay. Surface reactions then can occur and remember the surface reaction is decided by the heater temperature. At that heater temperature, wafers are now held. So the reaction must take place at that surface temperature which is typically around 400 to 700, 800 degree in most cases but in epitaxial as I say, it may be as high as 1100.

Deposition occurs conformally. This is most important. Wherever the step is there, it will climb because gas can flow everywhere. So it will conformally actually deposit. It will also have something coming out of the wafer which is called emission and some may redeposit itself. So there is a combination of deposition, redeposition, etching or what we call emissions and at then some steady-state is achieved. So unreacted reactants and byproducts are adsorbed and they are actually removed out of the system by vacuum, vacuums pumps okay. We can have a kinetics of such deposition similar to groro-deal model and we last time discussed that this is what the model is something like.

This is what we did. I am just trying to go through quickly what we did and we see there is a gas film flux and there is reacting flux at the Silicon and in one is proportional to the CG - CS through a mass transfer coefficient and in steady-state, the reacting which is happening to proportional to CS must be equal. And then we derived this formula and we say okay, VY which is the growth rate which is F by N, number of atoms incorporated on surface is N, then VY is KS 1 + KS by HG to the power - 1 CG by N.

And then we also discussed last time that the gas reactant in a total gas system, whatever in a gas system and how much is available at the reactant surface, the ratio of that is called the mole ratio and that we defined as CG by CT. CT is the total concentration in the system okay. Based on this, we finally arrived at an expression which is KS HG upon KS + HG CT by N into Y. Y is the mole fraction. We also looked into last time, two cases, we say one possibility is KS is much smaller than HG.

The other possibility will be, HG will be much smaller than KS. Of course, so there will be a point where KS will be almost equal to HG and that is called the critical shift point. At that temperature, one process shifts over the other. So something below higher temperature it will be mass transfer and below that temperature it will be reaction rate limited.

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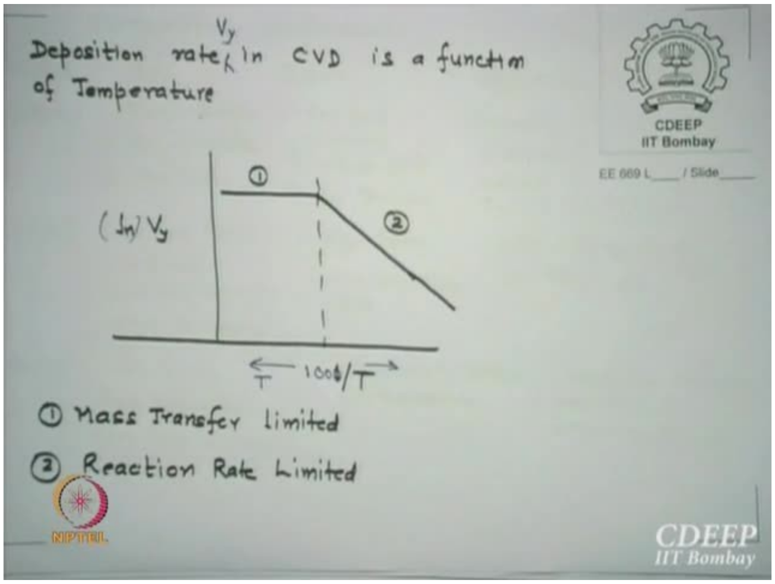

Deposition rate V_y in CVD is a function of Temperature

① Mass Transfer limited

② Reaction Rate Limited

If you see that graph which I showed you earlier figure, so you can see from here, higher temperature, it is constant with the temperature. Means mass transfer limited and below it is function of temperature which means it is reaction rate limited. Okay. And we then discussed, this is all that we did last time. I am just hurrying through them.

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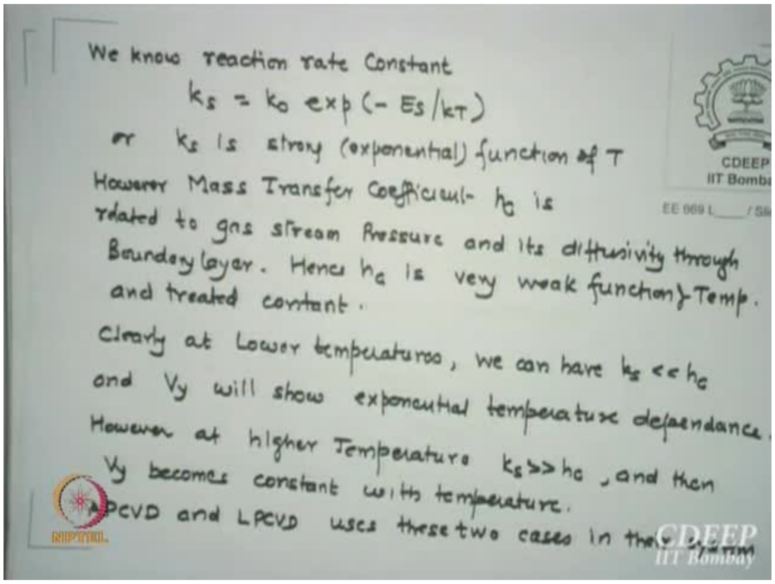

We know reaction rate Constant

$$k_s = k_0 \exp(-E_s/kT)$$

or k_s is strong (exponential) function of T

However Mass Transfer Coefficient h_G is related to gas stream Pressure and its diffusivity through Boundary layer. Hence h_G is very weak function of Temp. and treated constant.

Clearly at Lower temperatures, we can have $k_s << h_G$ and V_y will show exponential temperature dependance. However at higher Temperature $k_s >> h_G$, and then V_y becomes constant with temperature.

APCVD and LPCVD uses these two cases in their system

Now we say, the reaction rate limited KS as we know it is always function of activation energy and temperature, K0 is called its pre-exponent constant and please remember, KS is a very strong function of T as one can see from here and the activation energy for the process. However, we also said that the mass transfer coefficient HG is directly related to gas stream pressures and its diffusivity through the boundary layer. Since HG is a very weak function of temperature, though it is a function of temperature but very weak function of temperature, it is normally treated constant.

Please remember, HG is a function of temperature but it is a very weak function of temperature. So HG at after certain temperature we say it is almost constant. Though this can be verified by numbers and see how much it is but normally this assumption is fair enough. What we are trying to say essentially, if the gas is enough there, how much is reaction will be decided by the reaction but how much is made, I can react as much. But we are not providing. This mass which will allow me to limit it. So at higher temperature, what happens?

That the reaction rate is very high. Anything can come and react with it. But the amount gas will now decide how much you push okay. So is that physics clear that at higher temperature, reaction rate is very high. So anything, any amount you push, it may react. But how much you push will be limited by, that is the HG term. Whereas at lower temperatures, the react, you may have any amount of gas received at the surface but how much it can react will be decided by the temperature which you have at that point. So this shift over is very crucial. At some temperatures, the reaction rate limited process goes to mass transfer limited.

How much gas available for reaction. Okay, so one can clearly say, at lower temperatures, KS is much smaller than HG and at higher temperature obviously therefore HG is much smaller than KS. Now if I look at this term, I think you wrote down, if you look at this, the KS is much larger than HG and if you go back into that expression, you can see that KS term will vanish, 1 upon KS is very small, so it is only HG times something will appear there. It is only mass transfer coefficient, HG which will decide growth or depositions. Whereas if KS would have been much smaller, HG, 1 upon HG would have been smaller, so that would have gone and you will be only proportional to KS times other parameters.

So KS is decided by temperature, HG is decided by available gas stream pressure or available molecules there to react. This is exactly what we differ between APCVD and LPCVD. This is what we are trying. We want to make a certain process only temperature dependent. So what is the condition I am looking for? That at lower, if process is normally at lower, relatively lower temperatures where HG is much higher than, yes, is that correct? HG is much higher than KS and then we say it is only temperature dependent. So to make HG higher, we will see now the pressure, as lower the pressure you do, HG will start increasing.

So at lower pressures, HG could be made higher than KS, much higher than KS. So in low-pressure cases, it will be decided by what? Temperatures. Once I say it is only temperature dependent, what kind of wafers I can hold? I can hold vertical wafers. Why? Because I only look for their temperatures. In a furnace, I have hundreds of wafers but they all can be held at same temperatures, 200 wafers or maybe even 400. Depends on furnace size but all of them should have same temperature. As long as the furnace temperature is constant, the deposition rate will be limited only by the temperature constant there. If Delta T waves, yes, growth rate will also or deposition rate will change. Otherwise, any number of wafers can be depositing in one go.

So it has a large throughput okay. Normally poly silicon is deposited at low-pressure. So it is called LPCVD. Okay. Whereas most since like SiO2 or Si and silicon nitride which are mostly amorphous films, they are not really looking for structure. There is no real requirement for good structure. It is amorphous anyway. So I can deposit at much lower temperatures but then what I should do? Available gas should be sufficient for the thickness to grow okay. And therefore all mass transfer limited conditions, wafer should be flat because gas stream must come there and started depositing.

In the case of LPCVD, wafers can be held vertical. So what is the 1st difference between pressure changing? That the throughput of all mass transfer systems or low-temperature systems is very low compared to of course the belt system which I showed you, you say ya, I do increase it, I push it as fast as I can but after all, I have to go (inaudible 12:50). That much, some retention time I will have to give for the gas. So when it finishes that, then only I will move out. And the way it is done is that if there is a conveyor belt and as I said, 12 wafers are sitting and gas stream is moving like this and we maintain some velocity, we will discuss, we may not discuss this. So we move, when the gas is flowing, it is going all over. Okay. So growth is varying every point in sight okay. So the rate is so adjusted at this belt that at the end of the day, everyone gets the same thing. So there is a belt speed which is very crucial to decide uniform (inaudible 13:26).

Now among the most famous temperature not low-temperature, the mass transfer limited cases is the growth of epitaxial films. The word ‘epi’ stands for as it is, ‘taxi’ means whatever texture. If you have a silicon wafer of some kind of 100 orientation or 111 orientation and I want to depart deposit silicon over it, why do I want to do it? Because this EP player, I can deposit uniformly. That is, I can dope the wafer during growth itself. So I have a P type substrate and I can actually deposit N type silicon itself of my choice of (inaudible 14:09) okay, from my thickness requirement.

In a CMOS if you have seen, there is a P well and then another, I created another layer for a BT adjust. But this P well is sitting on a substrate okay. So I can make instead of wells, I can actually make 2 different epitaxial growths with thinness. This is done in what we call the process called

SOI process, silicon on insulators. Okay, so silicon can be deposited also on insulators as well as silicon. And these processes are very dominant now for the case of low-power, SOI in particular. The reason why SOI has not got the what I have applications and the (inaudible 14:52).

So this epitaxial growth is a very crucial requirement nowadays but earlier it was done only for the case of bipolar transistors. We start with a collector and try okay and then we deposit or rather grow epitaxial layer of P type which is constant base. Why we wanted that? Because we, any earlier we never used to control the profiles if there was no implants. So we want that doping of this to be constant. So base should be always epi-growths and then I will diffuse the emitter in that and I will have an NPN transistor which is vertical.

Those days, ICs were not used. It was only single transistor making and then we externally used to connect. So in those days, EP was major requirement for bipolar processes. Even now, bipolar process do use EP. But even in mass, for ultra-thin (inaudible 15:49) also there is a thin layer we want to have which is also epitaxially grown okay. So there are processes for low-power, low threshold processes, fast circuits, low technology load we still need EP layers. Only problem with EP is, it takes large temperature.

Now this fact is very interesting because if you say that the process is related to temperature, higher temperature because crystallinity is to be attained, one way of increasing the temperature without increasing this environment the temperature is to do plasma, okay. Plasma KT would be as 10,000 degrees centigrade it can get to, okay. So therefore now EP layers may be probably grown by plasma processes rather than the normal processes which is not I mean still some places, when 1st process is itself EP you do not have to worry. That is why plasma is costly and difficult to control.

This and number of wafers can be deposited in one go. So EP is cheaper in comparison to plasma. Throughput of plasma system is always smaller than throughput for epic reactors. So please remember, also there is one figure which may also have given you.

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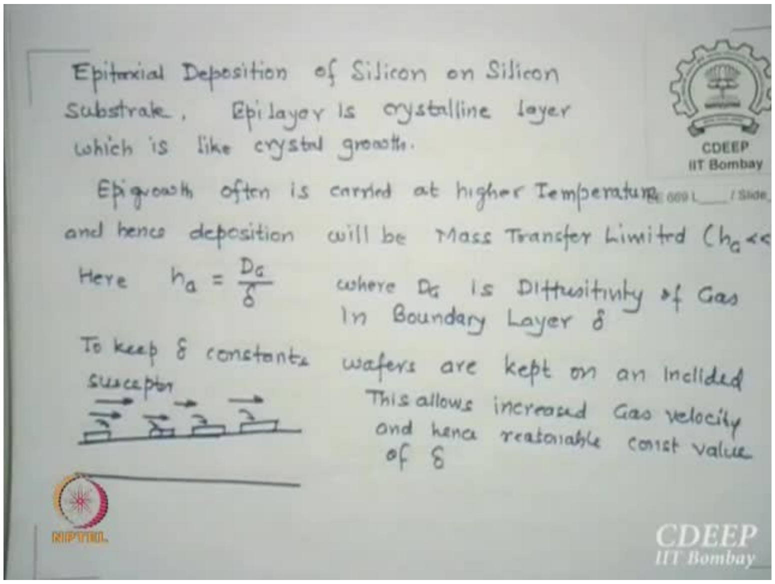

Epitaxial Deposition of Silicon on Silicon Substrate. Epilayer is crystalline layer which is like crystal growth.

Epigrowth often is carried at higher Temperature and hence deposition will be Mass Transfer Limited ($h_G <<$

Here $h_G = \frac{D_G}{\delta}$ where D_G is Diffusivity of Gas In Boundary Layer δ

To keep δ constant, wafers are kept on an Inclided susceptor

This allows increased Gas velocity and hence reasonable const value of δ

Since the gas stream is moving from say left to right in this figure, since the what is our condition? When the gas goes over the surface, it starts climbing. Why it starts climbing? Because the pressure there forces the gas to go up.so when you start here, the gas outside manoeuvre horizontally but when it touches the wafer, actually it starts climbing. But what is the condition I want to hold it this? I want mass transfer coefficient which is given by diffusivity of the gas to wafer through the boundary layer by the thickness of boundary layer.

So what is, when I can make HG constant? When delta is constant. Is that clear? PG is diffusivity which is known for a gas to gas. But what how can I make HG constant? If I make delta constant. What is delta? The boundary layers heating. If this moves away, that means delta will start increasing. Delta will start increasing but in my case, then HG will vary. So what I do essentially is I put the wafers on an inclined plane. Since it climbs here, so the actual difference between wafer and the gas stream is roughly delta all around. This is all EP reactors you find as susceptor which is kept at certain degree which is around 28 degree climb.

So this essentially makes this delta constant and if delta is made constant HG can be made constant and the growth is proportional to HG. Is that clear? Since it is a mass transfer limited process, HG is constant and therefore one can see, higher temperatures. So no KS related system. Everything is mass transfer and therefore EP growths are normally done at higher temperatures to get crystallinity and also we must maintain the angle so that uniform delta is achieved. Therefore uniform film thickness is also achieved.

Is that clear? This is something which is very important in EP layers. If you want to dope these EP layers, okay so there are certain things. You all write down, I will just give you what is how can you dope a film? It is always passing Silane for silicon. So I should also pass boron diborane for boron doping, I may pass phosphane or arsane during this. So that mixture of Silane and arsane will make N + kind of this. The gas mixture decides the concentration. Is that clear? How much ratio you keep will decide N or N +, P or P + K.

That is how it is adjusted. So all EP layers are uniformly doped. This fact has to be always understood. What is EP is difference between normal implant or anything, no profile. It is uniform doping and that is the feature of an epic growths. And I generally said where, where else the EPs are actually used now? For single crystal silicon solar cells, one of the method of making films of EP layers on substrate which is not necessarily silicon, but silicon dioxide is essentially EP growths because they are relatively cheaper compared to crystal growth.

I am not saying they are cheaper, related to and they can we have a belt system in which films of silicon can be deposits. And then it can make solar cells which are relatively cheaper, relatively. Is that what clear? So do not think cheaper. Relatively cheaper. So solar cell, people normally use all belt system because they want thinner films but they only want one junction and they want larger throughput, cheaper throughputs, so most of the time, films are used in their techniques. In VLSI, we need sometimes depletion region to expand, which means I need region there where it can expand.

So I will actually expand in the P sideways so that my depletion goes down. So there are difference in device characteristics MOS devices and in the case of solar cell which is normally a normal PN junctions. Okay.

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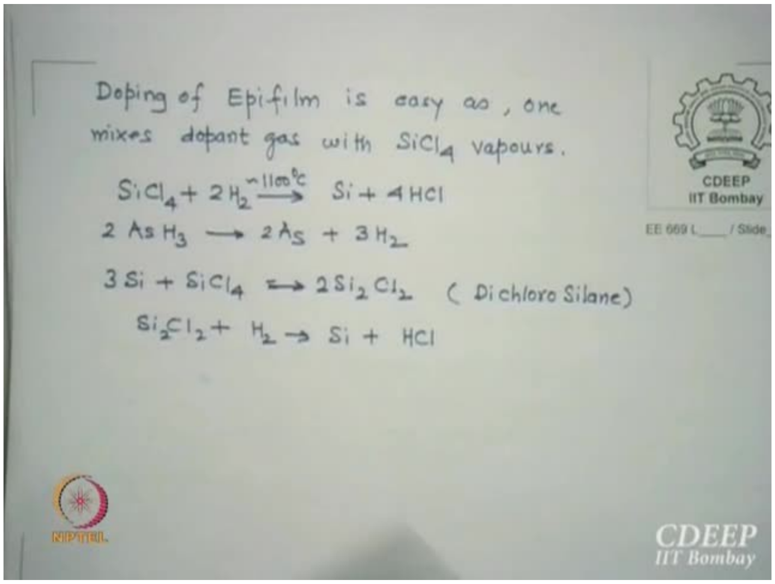

Doping of Epifilm is easy as, one mixes dopant gas with $SiCl_4$ vapours.

$$SiCl_4 + 2H_2 \xrightarrow{\sim 1100^\circ C} Si + 4HCl$$

$$2AsH_3 \longrightarrow 2As + 3H_2$$

$$3Si + SiCl_4 \rightleftarrows 2Si_2Cl_2 \quad (\text{Dichloro Silane})$$

$$Si_2Cl_2 + H_2 \rightarrow Si + HCl$$

Typically, if you have written down this, most cases, the process which does not use Silane, normally uses either use Silane or normally silicon tetrachloride which is actually a liquid, is used in most often. The reason is, there are silicon tetrachloride is very less toxic. So 2 achievements are getting. The liquid which I use can be priced by 100 degrees centigrade.

So I get a silicon chloride wafer and also, it is less toxic. Whereas if I use Silane, it is not that toxic but very little toxic but it is extremely highly flammable material. Little bit of heat extra and pressure increase, it will blast. So we avoid it and it is not that we do not use it. We use Silane as often as possible but just for the heck of it, we say why tetrachlorides? So silicon tetrachloride reacts with hydrogen to form silicon and HCL, HCL is taken out, one can see what many reactions actually takes place.

There is arsane actually decomposes into arsane and 3H2, arsane gets attached with silicon. At this temperature, there is sufficient diffusivity. Silicon + SiCl4 can form dichloro Silane. dichloro Silane will further react with hydrogen to create silicon and HCL and this of course there is another process which is trichloro Silane-based process. The cost of process is decided by what dichloro Silane, trichloro Silane are used. For example, to grow a poly films, the if you are using a dichloro Silane, it is the costliest process.

If you use trichloro Silane, it is cheaper. If you use silicon tetrachloride, it is even cheaper but since the throughput will be less with silicon tetrachloride, so normally trichloro Silane processes are used in crystals deposited poly films. All (())(23:35) in crystal growth was actually using trichloro Silane process. So you add arsane, you get phosphor arsenic. You add phosphane, you get phosphorus. You add diborane, B2H6, you get boron. So depending on the mixture ratio, one can decide the concentration and thickness of the film. Thickness is decided by the time for which gas stream moves in.

Okay so before we quit this area I may just tell you, some maths I did which maybe interesting for you. I said very casually I will say okay if you reduce the pressure, HG increases. So I will now prove that energy does increase this. In LP CVD, the pressure is reduced. Typically it is around 300 milli tors of pressure, 300 to 600 milli tors of pressure which is maintained. Somewhere LPCVDs are also being done at 1 milli tor but they are different processes, some other way. So obviously, we know the diffusivity of gas is proportional to total pressure, the gas stream there.

So we now want to look for this pressure dependence and as I keep already saying, I want to have HG increasing such that I became, I move away from this and I get some kind of constant HGs. Okay, this is what my game is. If I change the pressure, HG increases and then if you plot that same characteristics, HG becomes higher and higher and finally becomes flatter at lower temperatures. That is the ideal. Typical temperature of poly growth is around 300 to 700 degrees centigrade. 300 is not good films. Why 300 is not good films? Poly crystalline requires some crystallinity.

So lower the temperature, it will more amorphous material. So you will anneal it. Once you anneal it, you have already increased the temperature. Okay. So that whole purpose of reducing temperature may not be worthwhile.

Student1. (inaudible 25:47)?

Professor1. What? Annealing can be done anytime, anywhere. In the furnace where you are doing, you pass (())(25:56) anneal. You can take it out (())(26:01) through a RTP system or a RTA system, you can do anneal afterwards. Anneal is not a process which in general in situ is preferred because wafer takes out means you need to clean it again before you anneal. Inside furnace, you hold it actually. You change the temperatures or the way it is done as there is a different zone where anneals are performed in the same furnace.

So wafers are pushed there by attack, the temperature is different whatever you said and pass nitrogen heavily on that, anneal, whatever time you want okay. Then pull out the wafers. Numbers. I can stack 100, 200 wafers on a rack. Is that clear? Follow it. HG is limited what is the condition? It should go on the surface. So I have to keep wafers flat. So on a susceptor how many? 8 to 12 inch wafers I kept. Whereas vertically I can have a millimetre gap between them and I have 1 feet around 100 wafers.

If it has a 2 feet zone, I may have 300 wafers. So I I get in the same gas everything so many wafers can be deposited in one go. Whereas in other processes atmospheric pressure, they need to have mass transfers. Flat process, numbers are smaller.

Student1. Why cannot we have (())(27:27)?

Professor1. LPCVD. Okay there are 2 which I did not say but maybe you asked it so. The problem with all horizontal reactors is unless the temperature outside the wafer susceptor is very low, there is a contamination of particle from the walls so which actually sits on the wafer. So you have there is a belt system (())(27:51) actually stop the gas and pass the particles. So it is a difficult process to maintain. So preference is always given to vertical where even if it falls, hopefully it will not purchase the all wafers, every surface, may fall down.

So normally preference is always given to vertical holds. But wherever necessary, there is nothing else I can do, so I will try some best to see it is less contaminated but flat.

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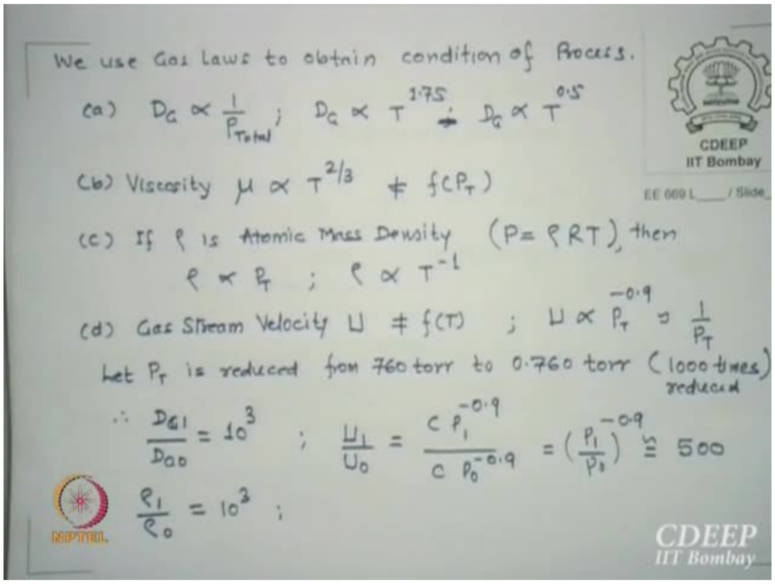

We use Gas Laws to obtain condition of Process.

(a) $D_G \propto \frac{1}{P_{Total}}$; $D_G \propto T^{1.75}$ ÷ $D_G \propto T^{0.5}$

(b) Viscosity $\mu \propto T^{2/3} \neq f(P_T)$

(c) If ρ is Atomic Mass Density $(P = \rho RT)$, then

$\rho \propto P_T$; $\rho \propto T^{-1}$

(d) Gas Stream Velocity $U \neq f(T)$; $U \propto P_T^{-0.9} \simeq \frac{1}{P_T}$

Let P_T is reduced from 760 torr to 0.760 torr (1000 times reduced)

$\therefore \frac{D_{G1}}{D_{G0}} = 10^3$; $\frac{U_1}{U_0} = \frac{c\,P_1^{-0.9}}{c\,P_0^{-0.9}} = \left(\frac{P_1}{P_0}\right)^{-0.9} \cong 500$

$\frac{\rho_1}{\rho_0} = 10^3$;

Okay having said so this is something more interesting. I said, I want to look for pressure dependence and I want to prove HGs are increasing. That is what I said. I said DG is proportional to total pressure and typically it is found for the most of the systems which gas systems we use, either DG is T to the power 1.75 and in some cases, it is T to the power 0.5. So in this range roughly DG is changes with the temperature.

We assume and DG proportional to 1 sometimes and say there is change it occurs. Then it is strongly function of total, this as I said DG is not independent of temperature, that is what I keep saying. So that dependency can be taken care through this term as well. Viscosity mew, why viscosity has appeared suddenly? Anyone? Materials science men, kahan se aaya viscosity? Whenever a gas stream (())(29:26) what is the mechanism of foot flow? It follows either the disturbed flow or it is called laminar flow. Laminar flow is decided by Reynold's number. Reynold's number is AUL by mew okay. So discuss means it will drag itself. 29:43.

So it will move with lower velocity. So stream velocity drops. So more chance of contamination and more chance of boundary layer not properly adjusted. So normally, the laminar flow is adjusted through the stream velocity and as well as the viscosity. Okay. This year I am leaving many, much of the chemistry but theek hai. Viscosity is given as proportional T to the power 2 by 3 and normally, it is not a function of total pressure. Okay, I will leave it to you to figure out PV is equal to NRT is the formula, ideal gas law says maybe I write here for you PV is equal to where R is the universal gas constant, N is the substance or amount of material reactant you have per mole and T is temperature, absolute temperature, V is the volume of the gas, P is the pressure.

Now think of it, this can be converted to P is equal to, actually you should write row R some dash you should write. Row RT. This is modified universal gas constant row R dash which is essentially R by M, some other day. Some gas law padho thoda. Whatever is PV is equal to NRT formula, who actually gave this formula? Clapeyron actually created this equation. After learning that pressure is proportional to temperature and volume is also proportional, he actually made this equation together from Boyle's law and the other law okay.

So please do not think it is actually Clapeyrons equation which is PV is equal to NRT. But somehow it always got to Boyle and everyone gave credit, everything to him okay but just to be history, I may tell you. Okay so row is atomic mass density. Row is proportional to PT and row is also inversely proportional to temperature. Gas stream velocity U, the net velocity of gas is going through in the system is not a function of temperature. It is only how much pressure, backside I push the wafer, gas in. However, it is function of pressure to some extent 10 to the power - 0.9.

Many a times, one can take it is inversely proportional to PT. Now let us do the game. I said okay, reduce the pressure. So 1 atmospheric pressure was there. That has been reduced thousand times, low-pressure. Okay. So 760 tor to 0.76 tor, 1000 times that is 760 milli tor kar diya. Ek tor se ek 1 atmospheric pressure se atmo (())(32:48) why we are comparing with that? Because earlier process was atmospheric pressure CVD. So 760 tors ko 1000 times pressure neeche le aaya.

Student1. (())(32:58)

Professor1. Ya ya ya, it is. Ya, it is for different gases, diffusivity is different. So it varies somewhere for etching. So in normally we may not even consider that but I just show you DG is not independent of temperature. (())(33:13) made a statement.

Okay DG is a function. So okay. In that case, assuming that temperature dependence is smaller, DG1 by DG0 is the ratio of pressures if I assume it is PT. DJ is proportional to only PT, 1st term.

So DG1 by DG0, G0 means atmospheric pressure, this is not the 1000 times less pressure. So DG 1 by DG 0 is 1000 times. That is what you reduced the pressure. So pressure is this 1 upon hai na? ulta. U1 by U0 is some proportional (())(33:52) CP1 to the power 0.9, CP1 P0 to the power 0.9. So it is P1 by P0 to the power roughly it is 500. So the ratio is 500 for U1 by U0 DG 1 by DG of course this I am neglecting, temperature.

We can add that if you wish. Then, similarly Row I know is proportional to this. So I say row 1 by row 0. In this, assumption is temperature is held constant. Only pressure is reduced. So I am only right now looking pressure dependence okay. So row 1 by row 0 is 10 to. Is that point clear? Temperature is held but pressure is reduced from 1 atmosphere to 0.76 tors. So row 1 by row 0 which is proportional to PT so it is now 1000 times.

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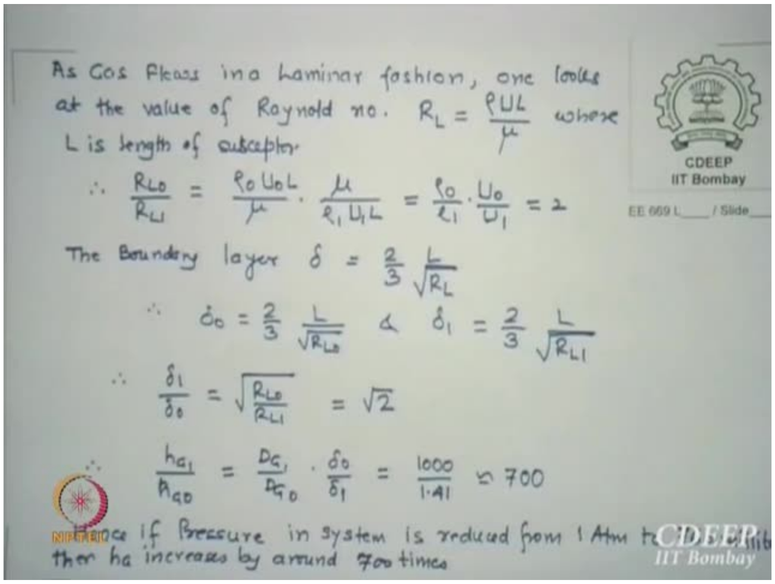

As Gas Flows in a Laminar fashion, one looks at the value of Roynold no. $R_L = \frac{\rho U L}{\mu}$ where L is length of susceptor

$$\therefore \frac{R_{L0}}{R_{L1}} = \frac{\rho_0 U_0 L}{\mu} \cdot \frac{\mu}{\rho_1 U_1 L} = \frac{\rho_0}{\rho_1} \cdot \frac{U_0}{U_1} = 2$$

The Boundary layer $\delta = \frac{2}{3} \frac{L}{\sqrt{R_L}}$

$$\therefore \delta_0 = \frac{2}{3} \frac{L}{\sqrt{R_{L0}}} \quad \& \quad \delta_1 = \frac{2}{3} \frac{L}{\sqrt{R_{L1}}}$$

$$\therefore \frac{\delta_1}{\delta_0} = \sqrt{\frac{R_{L0}}{R_{L1}}} = \sqrt{2}$$

$$\therefore \frac{h_{G1}}{h_{G0}} = \frac{D_{G1}}{D_{G0}} \cdot \frac{\delta_0}{\delta_1} = \frac{1000}{1.41} \simeq 700$$

Hence if Pressure in system is reduced from 1 Atm to

then h_G increases by around 700 times

So now I got this material science, pseudo-chemical, pseudo whatever it is, person should know is the Reynold's number which is described as row UL by mew. L is the length over which gas passes through, susceptor lengths okay. So row is the atomic mass density, U is the stream velocity, L is the length which is constant for a process and mew is the viscosity. So if I take the ratio and I want what kind of flow? Why I want laminar? Because if the particles themselves collide, then there is a diffusivity (())(35:28) at different angles. I want everyone to go through down.

So I want laminar flow and that is decided by Reynold's number. Typically, less than 8000 is expected. RL 0 by RL 1 is row UL by mew mew upon row L. Mew is independent of pressure we said, so it is row 0 by row 1 U0 by U1. L is same for both, susceptor lengths. So roughly, it is 2. If we require to figure it out, the boundary layer is proportional through these 2, Reynold's number is two third L by RL root RL. This boundary layer is related to laminar flow and susceptor lengths, okay. So it is two third L upon root RL okay.

So now delta 0 is two third 1 upon L upon RL 0, delta 1 is two third L upon under root of RL 1. So delta 1 by delta 0 is RL 0 by RL under root which is root 2 because we got this number 0 too. So delta 1 by delta 0 is root2. Now HG1 by HG0 is DG1 by DG0 delta 0 by delta 1. This is thousand. This is 1 upon root 2 means 1.41. So HG1 is 700 times HG0. Of course, these are not exact numbers but proportionality constants are not true in all pressures, all temperatures but assume right now.

The idea is to show you that if I reduce the pressure point thousand times, the mass transfer coefficient will be as large as 700 times the atmospheric pressure. So if just by a furnace, I reduce the pressure, I can increase HG and if I can increase HG then what is the process will be limited by? Temperature. Vertical stack and everything is possible. Uniformity is temperature dependent. How good temperature you maintain okay. In a vertical, you cannot create laminars. Is that point clear? The gas has to go like this like this, each vapour.

Laminar is always attained when you are in a surface. In a vertical, the gas cannot be streamlined very much because the wafer size and the cube size does not allow laminar systems. So kaisa gas jaata hai? Ek wafer ke andar jayega, fir bahar aayega, fir jayega. So it is unlikely to create any laminar flows okay. No, its not, that this what I say, depend on the size of the tube and the size of the wafers, laminar part length, susceptor lengths, so Reynold's number changes with this size. Ya ya so you have to worry all the time how to maintain laminar. It is not very easy but they are not dependent on mass transfer. So you need not worry.

I am only depending on available gas is not my choice. I want temperature, any amount of gas will react. Temperature will decide how much to react. Is that clear? That is the game. I want to see, it is only temperature dependent. So I must increase by HG somehow. So I figured out, if I reduce pressure, I will increase HG okay. So this is why I said earlier that how come I when I said HG will increase if I reduce pressure, I just did some calculations. There are some small mischiefs which you cannot find but truth still (())(39:03).

Again also the similar thing for temperatures and I did that. If you have written down, please. So is that clear that why the if I reduce the chamber pressure, the mass transfer coefficient will increase as much. If not 1000, but at least 700, 800 times which means K is dependent, depositions will start because HG will be much larger than KS. So that is the purpose of doing all this. So you can reduce the temperature, you can increase flow, increase this the pressure and then you have always temperature limited process. This is the method which is in mind. So anywhere I can use this, oh, I must reduce this, I will get this.

They have to. Even oxidation but there also, it is thermal limited. There also we will, the process when I started wafers, I said KS is much smaller than HG. So any kind HG is larger I will always do same. Luckily, in the case of this, the silicon dioxide allows you in the oxide rows, the diffusivity is another term which is helping you okay. So they were, that term is not available here.

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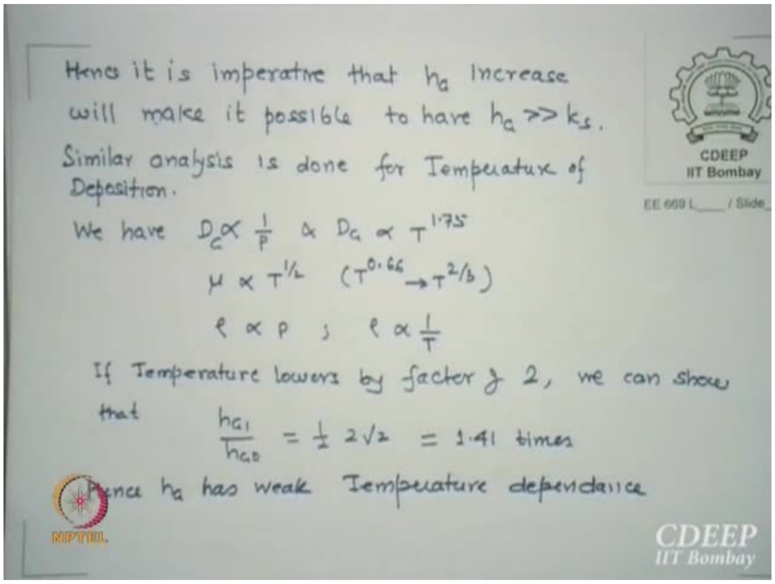

Hence it is imperative that h_G increase will make it possible to have $h_G >> k_s$.

Similar analysis is done for Temperature of Deposition.

We have $D_G \propto \frac{1}{P}$ & $D_G \propto T^{1.75}$

$\mu \propto T^{1/2}$ $(T^{0.66} \rightarrow T^{2/3})$

$\rho \propto P$; $\rho \propto \frac{1}{T}$

If Temperature lowers by factor of 2, we can show that $\frac{h_{G1}}{h_{G0}} = \frac{1}{2} 2\sqrt{2} = 1.41$ times

Hence h_G has weak Temperature dependance

So if I dope, it is imperative that HG increases when I reduce the pressure. Similar analysis was done by me and now I do not want to show every term. I only give you the data. DG is proportional to 1 upon P, DG is proportional to T into 1.75, the viscosity is E to the power 5. Actually it varies between T to the 0.66 to two third, many people have different versions. Row is proportional to P and row is also proportional to 1 upon T and if I now temperature is lowered down by T and if I do the same analysis which I did for pressure, DG, every calculation I performed, typically I get HG 1 by HG 0 root 2 times.

So HG is, so even if you reduce the temperature by half, HG will at least double. Is that point clear? Or at least one and a half times. If you reduce pressure, it increases enormously but with the temperature also, it actually increases but you can see, I told it is much smaller dependence. So it does change with temperature but not very strong quantity. Is that point clear? When I made a statement, I just wanted to you, the change is much smaller even if I half the temperature. From 900, if I go to 450, HG is hardly increased by 1.4, one and a half times.

Whereas in the pressure, if I reduce 1000 times, I am just going away 1000 times in pressure this HG. So this fact is actually used in all LP CVD, APCVD, every system which I actually used in my, this is in my mind. If I do this, this will happen. Is that okay? And I have done all this analysis for this also, I found (())(42:17) as a result, you do same thing which I showed you for all terms. Make division, row U everything and figure it out whether it occurs, which occurs and this is my result. So you can also do.

Student1. Sir (())(42:33)?

Professor1. No, there is no delta. HG is so high, that means delta is very small. That is exactly is the point. So almost all gas is available on the surface. So there is no diffusion required because gas is right now so much available, it is only how much it can react (())(42:56). Is that clear? HG higher essentially means there is no boundary layer pretty much, the gas velocity is good enough to actually make systems only temperature dependent. That is the way we do it. So typical pressure I said, LP CVD normally for polysilicon is done around 300 to 600 militors of pressure. 0.3 to 0.6 tors is all that pressure we maintain. Temperature is typically from 400 to 900 sometimes but 750 is all that we try.

Same way you can do silicon nitride. Instead of poly if you want, you add ammonia along with silicon okay and you can do same LP CVD. So you have depositions of silicon nitride. Anything can be deposited as long as make sure mixture of both, this figure is made at that pressures.

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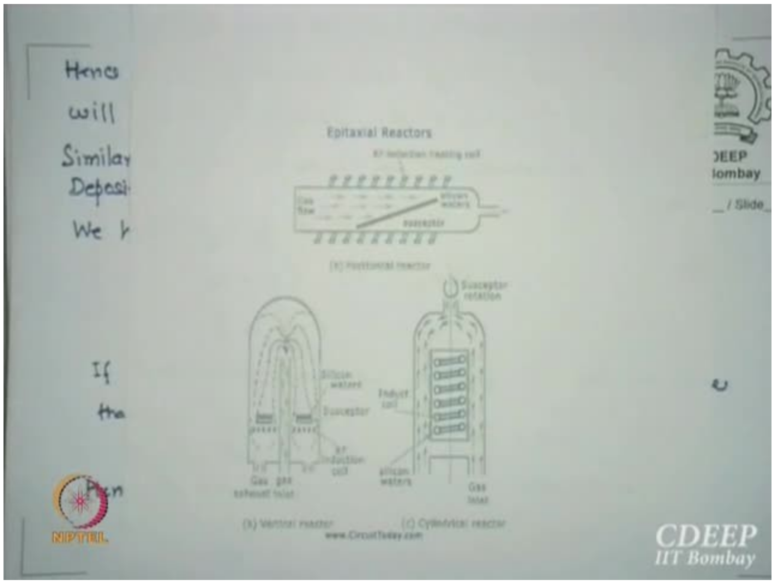

Of these are figures which are given taken from circuittoday.com website. I do not want to actually just I want to show you the actual there are numbers of kinds of, there is a horizontal reactor, there is a vertical reactor, there is a cylindrical reactor for each. The advantage of each system is, the throughputs are changed. Like there is some, in this actually there is a hexagonal system. The cylindrical system has hexagon or octagon. So each may have 6 wafers this and it rotates. So there are methods of improving throughputs.so this is available as I said, please note down this site which is www.circuittoday.com.

So this is a standard EP Reactor. Also okay I forgot but maybe most EP reactors do not use thermal heaters, okay. What is the purpose of this? I just want to pick it here, which I did not so far. I only want temperature of the susceptor to increase. I do not want the whole tube being has higher temperature. So if I make a resistive heating, what will happen? The whole furnace tube will get heated. Is that clear? So I now want only the place where I want reaction to be heated to temperature of my choice, and the rest should be cooled. It is called cool wall reactants.

Then how do I heat these wafers? The only possibility is through induction heating. So this is a grofide susceptor inside which there are rods which acts like a, and the resistor acts, grofide acts like a resistor across the transformer coil equivalently okay. And the outside, there is a transformer, other coil. You will actually create RF inputs there at high frequencies. This induction heating will allow this susceptor to heat okay. So what will be heated? Only the susceptor. Of course it will, some temperature will increase (())(45:58) something but most of the time, only susceptor is heated but the walls are cold. So these are called cold wall reactor, Cold War. Walls are at room temperatures. Same thing is possible in plasmas.

The walls are cold but the place where you want can have higher temperatures. So this whole process is sure to make it cold wall susceptor. Is that clear?

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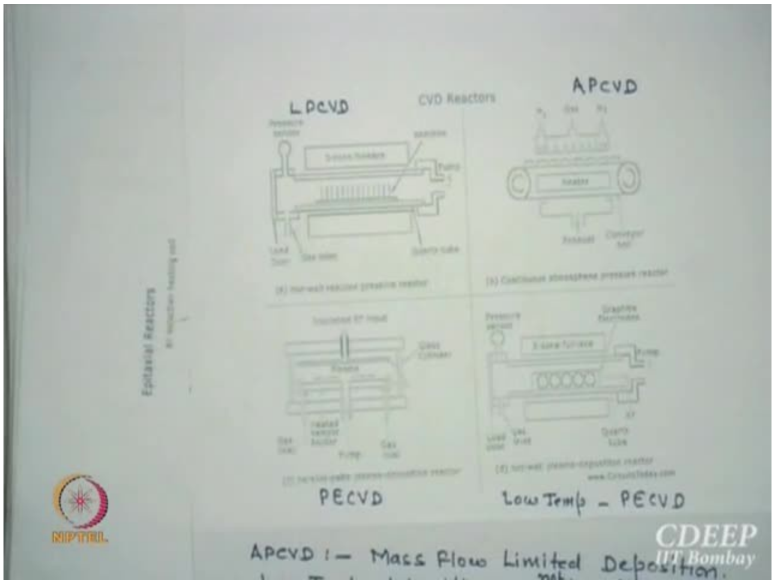

Okay, there are other, same from the same site, I have taken this figures of others. This is LP CVD, this is APCVD. You can see, vertically stacked wafers. So you see? All LPCVDs have vertical stacked wafers. This is of course belt system for atmospheric pressure. Then there is another process which is called PECVD, plasma enhanced CVD, now here, this susceptor kepts is here which is heated through a sample holders, these are wafers okay. This is a gas inlet and this is RF input at the other electrode. Using a plasma, I can actually create deposition of any gas which is ionised. Is that clear?

So this is a gas enhanced CVD. This is called low-temperature PECVD which has actually are normal zone and then you actually create at some point internally plasmas on the wafers okay. So it is a localised plasma reactors. This is very costly system which use actually called hot wall because the others are actually in furnace. So this whole track is pushed inside in a furnace. So if process allows you to make even crystalline silicates okay. Because higher temperature, you get it out. Plasma actually allows you to deposit and it anneals because of external temperature.

So you get actually EP growths. So this reactor which is low-temperature PE CVD is used for EP growths. Why this EP word I said? Because higher temperature externally will anneal it out. Internally at low-temperature, you will deposit it out okay. So it is one go or in same system, you can create and since they are flats, they can always be uniformly crystalline gravels okay. So this is one possibility.

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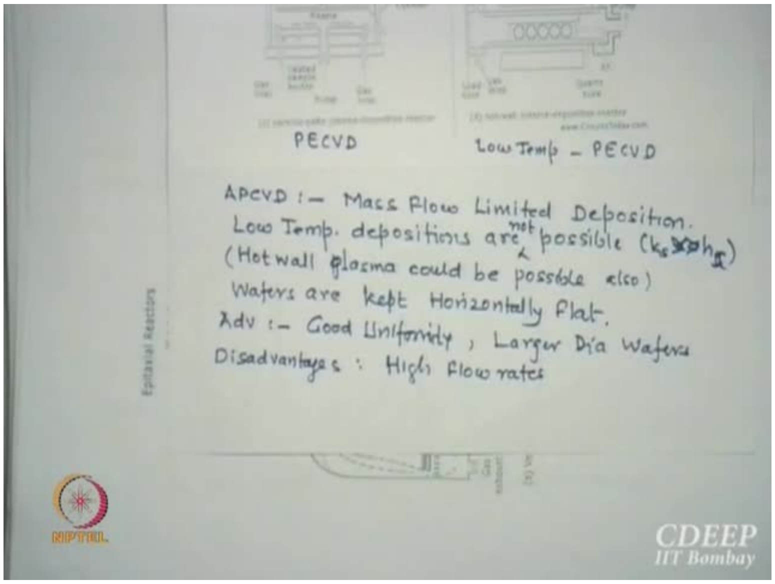

APCVD :- Mass Flow Limited Deposition.
Low Temp. depositions are not possible $(k_s \gg h_g)$
(Hot wall plasma could be possible also)
Wafers are kept Horizontally Flat.
Adv :- Good Uniformity, Larger Dia Wafers
Disadvantages : High flow rates

Just for the heck of it, I will quickly read through, APCVD is mass flow deposition system. Low-temperature depositions are not possible. Hot wall plasma could be possible. That is what I said. The biggest advantage of this is uniform growths or deposition, larger dia wafers and you need a lot of gas actually. You need huge amount of gas actually. Why you need larger gas? Because whole tube has to be filled up. Please remember, many I do not know anyone of you is doing any process in the lab and any time you are growing poly or anything, please see that what is the tube size and the and what is the volume of that you? What is the volume?

Pi R Square into length. At any time, amount of gas should be sufficient that it fills up this volume. Otherwise, there will be pockets and actually wafers may break because of stress. Okay. So even if you are doing in a any other gas stream, the gas requirement is very high depending on the size of the particles. 80 litres a minute to thousand litres a minute flow may be required. So really huge gas flow. And how much gas you will use? Very little, few ccs, 100 ccs. okay and the rest will be just going away.

But that is the cost. So APCVDs are costly in the gas systems. Rest the too much of gas requirement is smaller but it has to be maintained because it has to fill it up all the time. This is given in the circuit today. You can read this.

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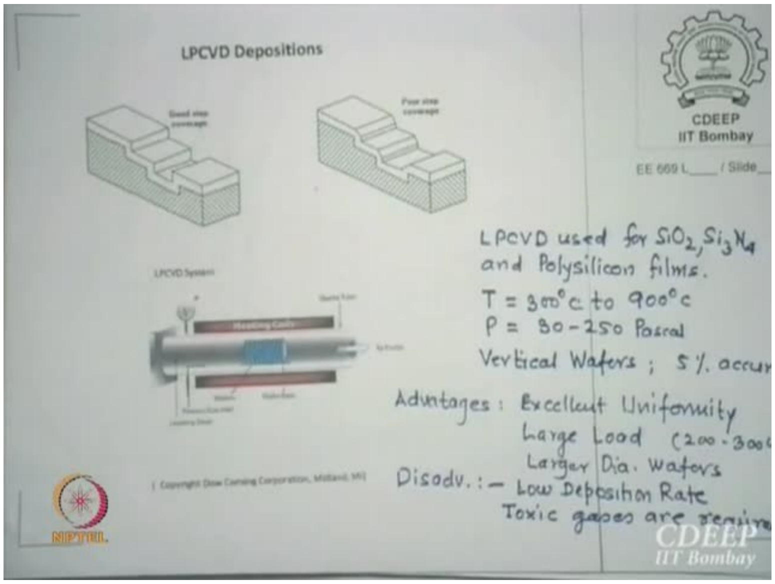


LPCVD Depositions

(Copyright Dow Corning Corporation, Midland, MI)

LPCVD used for SiO_2, Si_3N_4 and Polysilicon films.

T = 300°c to 900°c

P = 30-250 Pascal

Vertical Wafers ; 5% accur

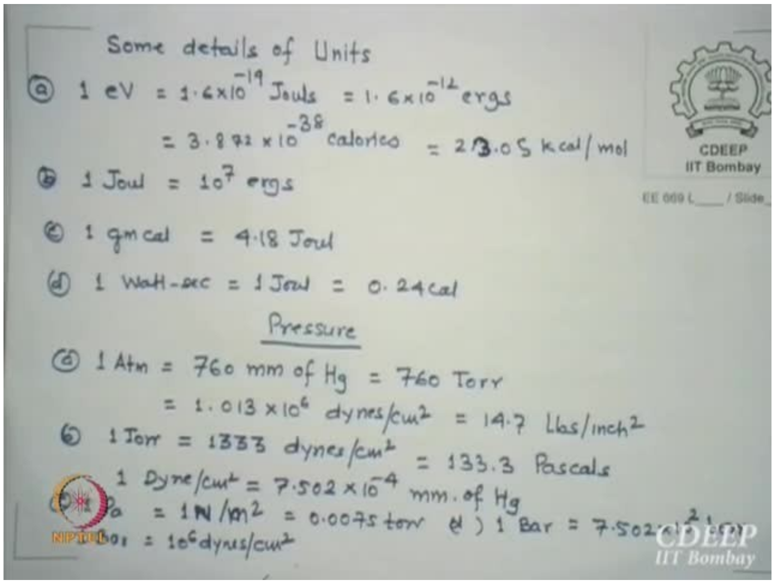
Advantages : Excellent Uniformity

Large Load (200-300

Larger Dia. wafers

Disadv. :- Low Deposition Rate

Toxic gases are requir



Some details of Units

ⓐ 1 eV = 1.6×10^{-19} Jouls = 1.6×10^{-12} ergs

= 3.872×10^{-38} calories = 23.05 kcal/mol

ⓑ 1 Joul = 10^7 ergs

ⓒ 1 gm cal = 4.18 Joul

ⓓ 1 Watt-sec = 1 Joul = 0.24 cal

Pressure

ⓐ 1 Atm = 760 mm of Hg = 760 Torr

= 1.013×10^6 dynes/cm^2 = 14.7 Lbs/inch^2

ⓑ 1 Torr = 1333 dynes/cm^2 = 133.3 Pascals

1 Dyne/cm^2 = 7.502×10^{-4} mm. of Hg

Pa = 1 N/m^2 = 0.0075 torr

(d) 1 Bar = 7.502×10^2

bar = 10^6 dynes/cm^2

For example for LP CVD, if you do AP CVD, there is a poor step coverage. If you do LP CVD, you have excellent coverage. Let me discuss LPCVD. Typical temperatures, okay before we finish this area, maybe I have a one interesting figure for you. There is something which I will put it on the web today myself. This should know but I know you do not know. So I have actually written down all units which are required in CVDs okay or anywhere else but at least more in CVDs or PVDs.

1 electron volt is 1.6 10 to the power - joules which is 1.6 to 10 to the power - 12 hertz or is equal to 3.87 10 to the power - 38 calories or 23.5 kilocalories per mole. 1 joule is 10 the power 7 hertz, 1 gram calories, 1 gram of calorie is 4.18 joules, 1 watt second equal to 1 joule is 0.24 calories. For pressure 1 atmosphere is 760 millimetres of mercury, 760 tor which is equal to 1.013 10 to the power 6 dynes per centimetre square as the pressure or133.3 Pascals. 1 dyne per centimetre is 7.5 10 to the power - 4 millimetre of mercury, 1 pascal is 1 newton by meter square which is 0.0075 tor, 1 bar is 7.50 to 10 the power 2 torr and 1 bar is 10 to the power 6 times per centimeter square. So the units in each processes is different.

Yesterday, I did give you some kilocalories conversion okay because specification from thermodynamics may come in one unit but for evaporation and whatever units we are using, we will have to convert to EV per mole okay. So whichever expressions I give, I do define which unit I am having. So I am maybe I will, this you can get finally in exam also. So that you must convert properly to the units. Is that clear? Otherwise that numbers will be awry. So this unit calculation, bar to pascal to to tor is very crucial because some people may say 2.3 bars. You will say what is this bar now? So I just tell you that there are number of ways in which pressures, temperatures, energies mentioned and therefore some conversions are actually needed.

So this is taken from variety of my old notes. I finally copied once for you so that you know now what is. So if I see just some expressions all these years, 6 months I am teaching 4 months different times, I have different units in that expression because (())(53:15) I want something in centimetre something something. So I always but this actual data may come from other areas. So they may give something so much dynes per centimetre. Now you are asking for is, you want now in terms of pressure. We must convert, we must convert okay. Is that point clear? Okay. So this is a LP CVD, typical pressure is 30 to 250 pascals, 300 can roughly say 1.3 so it is okay, 10.30 hundred to something like pascals tors, militors.

5 percent accuracy is only possible. Advantage is excellent uniformity, very large number of wafers can be kept, large throughputs, large loads, larger dia wafers can be kept because any size as long as tube can take that size, is fair enough. For a 8 inch wafer, what should be the tube dia? Then it will never fit. Do you know why? Because the rack, this is a circular tube. Rack will take one quarter of that. Is that clear? Then you have an 8 inch. Then you need 2 inch clearance. So

on an average, put 12 inches minimum required for 12 inch wafers. So you can see, 8 inch ke liye bara inch ka tube, bara inch ka tube kiya yane pi R Square badha yane aur length aapki toh badhi hai. So gas flow badha hai. So if I work on 1 inch wafer , I can get same result but if I have to transfer to this, I need huge system, lot of cost. This is the problem with our labs. We cannot shift to higher, someone may say, wafers of 3 inch are not available. So now convert it to 6 inch. They may say so but here all tooling if I have to change, next hundred crore kidhar se lana mujhe bhi nahi pata. Okay. Anyways, the deposition has, only problem is low deposition rates generally and there are toxic gases are involved okay. Wafer, aisa quartz rack rehta hai actually jiske upar slot slot me daalte hain. Slots rehte hain usme. So wafer uske andar atak (())(55:33). How do I hold the wafer? So there is slot in the rack. A flat rack rehata hai jiske neeche curved part rehta hai jo hole karta hai. Usme aise slots kate rehte hain. Wafer har ek wafer eke k slot me jaata hai. Ek you can't connect to each other na? gas kaise jayegi? Gap toh rakhna hi padega na. do slot ke beech me wafer jane ke liye gap toh rakhna hi padega.

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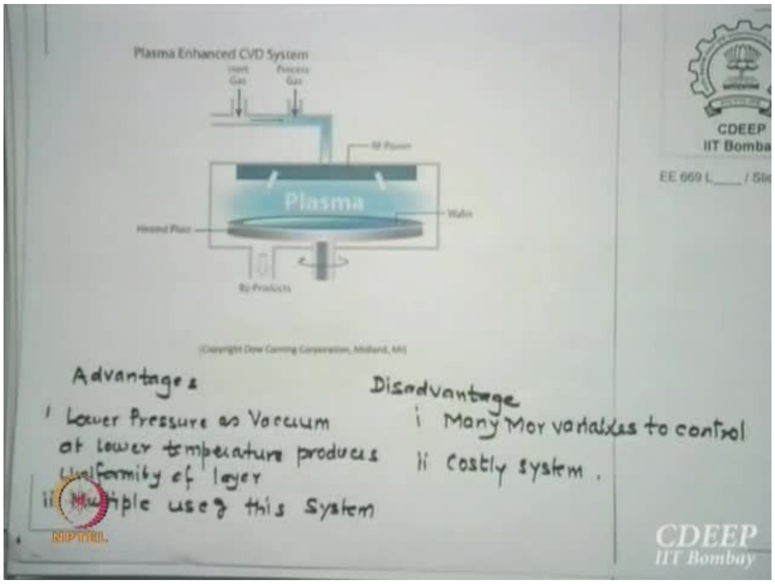

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Advantages

i Lower Pressure as Vacuum at lower temperature produces Uniformity of layer

ii Multiple use of this System

Disadvantage

i Many Mor variables to control

ii Costly system .

Oh, this is another system which we discussed. Plasma enhanced CVD. Normally it has a rotating wafer holder, then you have a processing glass, there is a RF system. We will discuss this a little later in etching. So I do not want to write now discuss. Advantages of PE CVDs are that low pressure vacuum should be as low as possible as higher. At lower temperature, it produces uniform layer. Multiple use of this system, it need not be 1 wafer, any kind of wafer can be used and it does not spoil very much because it is only plasma ions strike only targets. Ya, there are many more variables in the plasma system.

RF ka matching hona chahiye, distance hona chahiye, negative glow kitne door rakhna hai, there are many requirements to fit in and it is very costly. Sabse bura hai toh iska throughput is kam hai. These figure do not draw because these are available on circuits. No. Ya, it is all on the circuittoday with this. Though this model which I am showing is for Do Connor, ye aisa subsystem jo hai ab aapko dikhate hai ke actually dikhta kaise hai. This is air PCB. This is from plasma wares which is system 1200, so theek hai, subsystem 100. Ye exhaust pipe hai. You have to connect it out through a scrubber, toxic gas should not go out. Bahaut kuchh cheezen karna padta hai. But this is the system which is possible. The last but not the least of this process is very important nowadays and which is called atomic layer deposition. The last but not the least important is atomic layer depositions, very very important process these days because of all lower node technologies.

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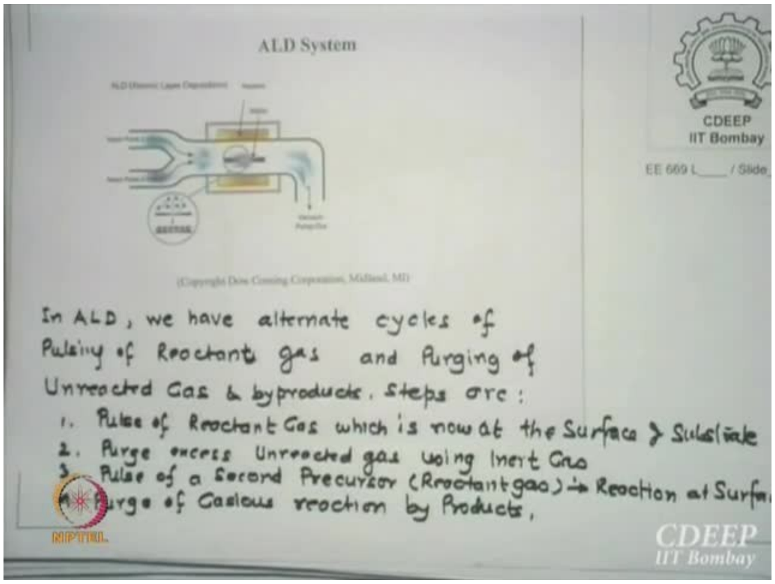

ALD System

(Copyright Dow Corning Corporation, Midland, MI)

CDEEP
IIT Bombay
EE 669 L____ / Slide_

In ALD, we have alternate cycles of
Pulsing of Reactant gas and Purging of
Unreacted Gas & byproducts. Steps are:

1. Pulse of Reactant Gas which is now at the Surface > Substrate
2. Purge excess Unreacted gas using Inert Gas
3. Pulse of a Second Precursor (Reactant gas) → Reaction at Surf
4. Purge of Gaseous reaction by Products,

This is essentially you can see a, there are 2 gas stream entry which is called 1 and 2. 1 is actually used for some purpose, I just discussed that. Then there are wafers okay. Then there is a susceptor, there is a some sort of system in which gas is passed and deposited. Now there is something which we do actually. 1st reactant gas is entered. This is called 1st process, step 1. Peulse of reactant gas which is now at the surface of the subsystem. I allow gas to come in.

Okay. So it reacts and it is temperature, everything is adjusted. So it actually flows over it okay. So some attempts are (())(58:39). There. Okay, we will come back to it.

Purge excess unreacted gas. Then what do I do it? I stop reactant but pass purging gas, nitrogen in many cases, argon in some cases. You can say here, the atoms are here and the rest of the gas is taken out. So it is called purge. Some layer is dissolved and the other part of the gas stream is taken out okay. So it is called purge. Then you have 2nd or, okay this reactant gas is also in actual AID system is called precursor. So I thought I should write the name. It is called precursor. The reactant gas, 2nd time you have a precursor. This is called phase 3.

So you purge gas again, reactant gas. Let further reaction take place and purge it again. Okay, this you may have to do more than once or more than 2 times for the thickness to be grown but this is essentially called purge this pulse 1, pulse 2, pulse 3, pulse 4, then react stem in which atoms actually go and sit, 1st absorbed, then react, then rest is going out and you get film is okay. This is called atomic layer depositions, ALDs. Now if you want to add something to this film, in the 2nd pulse cycle reactant gas, you can add another reactant gas. If I want phosphorus to be added, I can pass phosphine through the 2nd par, I mean 2nd pulse or 4th pulse.

So I can add also anything along with that. But it is one cycle, only one gas film pass. White is called atomic layer? Because atom by atom, it sits okay. And that is why, it is called atomic layer depositions, very important process of today.

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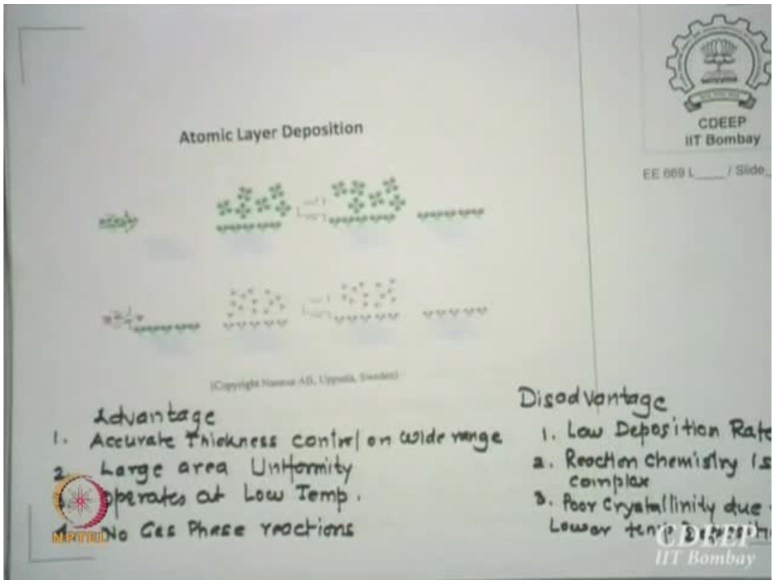

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Atomic Layer Deposition

Advantage
1. Accurate Thickness control on wide range
2. Large area Uniformity
operates at Low Temp.
4. No Gas Phase reactions

Disadvantage
1. Low Deposition Rat
2. Reaction chemistry (is
complex
3. Poor Crystallinity due
Lower temp

Okay, you can see here, 1st pulse, this comes in, some of them sit, then it is purged, so rest going away. If there are more suscepted, it keeps going. 2nd again, you enter new ones, then they purge. So everytime you purge, you add reactant gas. When you want to remove the, after desorption, you want to remove the rest, switch to purge it up. This layer by layer depositions you can see here, atomic layer depositions, so very thin films can be deposited using ALDs. Their growth rates can be as low as 10 amstrong per second. So it can be a monolayer. It can be deposited using ALDs. Accurate thickness control on a very wide range of materials, large area uniformity, operate at very low temperatures, no gas phase reactions, only adsorbed and then reacted deposition.

The advantage of force as low deposition rate but that is what we need. In fact, we need low deposition, it can be an advantage. I want a very thin films, so I will use this. Reaction chemistry is quite complex, poor crystalinity due to lower temperature. So silicon is not deposited for crystallinity. Films which are not crystalline are easy to deposit in this metal. Organic materials, all kinds of that non-silicon devices can be made using ALDs. Silicon, please remember this technology course was essentially highlighting silicon but that is not end of the world okay. Currently, there may be 30 percent effort in non-silicon devices. Whether they will complete silicon in the next 20 years or 50 years is only God knows.

People who are working there, they are not interested whether it would be technology or not. They want publication, so they will get it. But whether this will finally replace silicon is very much unknown. And I am not very sure. Possibly yes. Is that okay? So I have given you all kinds of CVDs. Okay, I have also shown you PVD as well as CVDs. So any deposition can be made. So if I want to deposit tungsten, what should I use? Tungsten fluoride is a gas which is available, WF6 and you can go through plasma, you can go through sputter, you can go through anything (())(63:04) and bombard that.

So any material can be deposited by either PVD or by CVD. PVD of course not all but CBD almost every thing okay. So CVDs are much more popular but why then PVDs? Because PVD deposits metals very uniformly. So most metalisation systems use PVDs if you have a target of that material, best way to do it. This is our last sheet which I discussed with you.

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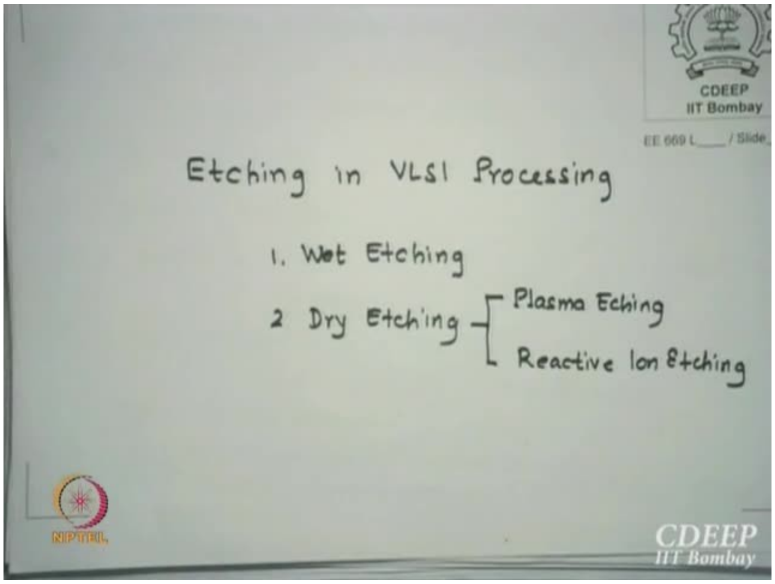

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Etching in VLSI Processing

1. Wet Etching
2 Dry Etching
  - Plasma Eching
  - Reactive Ion Etching

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So we will start with quickly some other area which is of more interest than the one which we did but we have now very little time to do it. Nothing can be done in VLSI unless you do etching. Unless you do, remove some areas and do some processing, so removal is more important many a times in real life. The whole technology is decided by how good etching you do okay. That is the major worry. So that is coming last as if .it is least important but it is very important process in all of that. So there are 2 possibilities in which one is called wet itching which we have been doing many years and of last 15-20 years, we are working on what we call as dry etching. In dry etching also, there are 2 kinds.

One is plasma etching which is essentially chemical etching but no ions there. Dry. Then there is a reactive ion etching. The ions are present but it can also chemically react. Of course 3rd one is another dry one which is sputtering, sputter etch maybe I should add which is actually bombarding this okay. So plasma also has 3 kinds of etching possibilities. These, both of them of course, this is less, this is isotropic, we will discuss this. This is very strongly anisotropic and this is also anisotropic but very low etch rates and much damage. Wet etching of course is isotropic. Isotropic word will come soon, that is my job today to show before we leave.

Typically as I said, we need to etch SiO2, silicon nitride, silicon, poly silicon, metals, aluminium, titanium, molybdenum, tungsten, vanadium, copper, then we need alloys and compounds like titanium oxide, titanium nitrate, silicides of molybdenum, Platinum, titanium, many many materials we need to etch. And of course, one which we did not right which we etch away now and then. What is it? Photoresist or resist. That is (())(65:42) every now and then. Every mask you go, you have to etch that. Okay, wet etching means solution-based. Whatever is the, you dip into solution and reaction will take place and etching will go.

For example, for silicon dioxide, hydrochloric acid, it is a very strong etchant for silicon dioxide. The typical reaction which I wrote is SiO2 + 6 HF H2SiF6 which is soluble + 2 water. If you have a nitride, same thing process, H2SiF6 + ammonia goes away and actually ammonia does not go. It actually acts like this. Ammonium hydroxide it is okay. You balance this, this equation is unbalanced. Whenever array is kept, it is unbalanced equation. It only shows forward reaction. Otherwise you make equal. Left is same as right. Number of molecules either side are equal.

Poly silicon is etched, polys silicon cannot be etched in HF because it is only I already started telling you that one of the test whether you have etched oxide is, you add water and you find it is not sticking. That means silicon has come. Hydrochloric acid, only HS silicon dioxide. It does not attack silicon. But I need silicon etching. Where? Where do I need silicon etching? STI. I will etch STI. So I need silicon etching. At silicon etching, I need something which is also of course poly silicon, if you have a gate of Poly, you will etch Poly.

So what we do is silicon can be etched in oxidised form. So what is silicon oxidation? Silicon + some oxidant will make it SiO_2 and then it will dissolve in hydrochloric acid. HNO_3 is a very strong oxidising agent or hydrochloric is not equally good oxidising. So I can convert HF + HNO_3 + water, dip the wafer in this. HNO_3 will oxidise the wafer to silicon dioxide and HF will remove it. Just for the heck of it, there is was still in chemistry there, the HF available in the which is called fully concentrated 100 percent HF is essentially 49 percent HF. What does that mean?

The most concentrated hydrochloric acid has 51 percent water okay. So please remember, when you calculate, you should treat 49 percent as HF when you say it is 100 percent concentration. So calculations this ratio is from 49 and not from 100 cc you take. So if you take 100 cc HF, actually you are using 49cc HF. This has to be because though you are doing chemistry, please remember this. This ratio is actual HF. So HF + HNO_3, this ratio is so adjusted that the rate of oxidation is matched by rate of removal. That is how the ratios are adjusted.

You can also use HCL H_2O for aluminium, you can also use orthophosphoric acid, H_3PO_4 which also uses HNO_3 + H_2O to etch aluminium. Aluminium is a strong metal which was used till very late. Now of course it is gone. So one need to etch hydrochloric I mean this H3 orthophosphoric acid. Of course there are, if you go to the Kramer’s book, there is a table given for all kinds of material, what kind of ratios of HF, NF, all acids, you must. Whenever you diluted some kind of HF, it is called buffered HF. Okay.

Normally, we add ammonium chloride to it and you also add acetic acid. Why? Anyone? Chemistrywala aadmi bol sakta hai. Why I add instead of water, I add actually acetic acid. What is acetate acid? CH_3 COOH. This hydrogen ion concentration changes what? The pH of the solution. So when you do any reaction, PH changes. For a uniform etch, PH must be maintained. Acetic acid (())(69:54) hydrogen so that PH is at least lower than 3 or 4 so that it is acidic in nature.

This are, this is chemistry thinking. What to add so I must maintain pH. In etching, one of the major requirement is what we call selectivity. That means I have 2 films and I am etching. I want once to be etched less and the other should be fully etched. Like I put a photoresist on something and I am etching oxide. So HN which is removing oxide should not attack photoresist. Otherwise the whole purpose is lost. Lithography kiya kyun? So selectivity of an etchant is very very crucial that 2 films, it should have very different etch rates.

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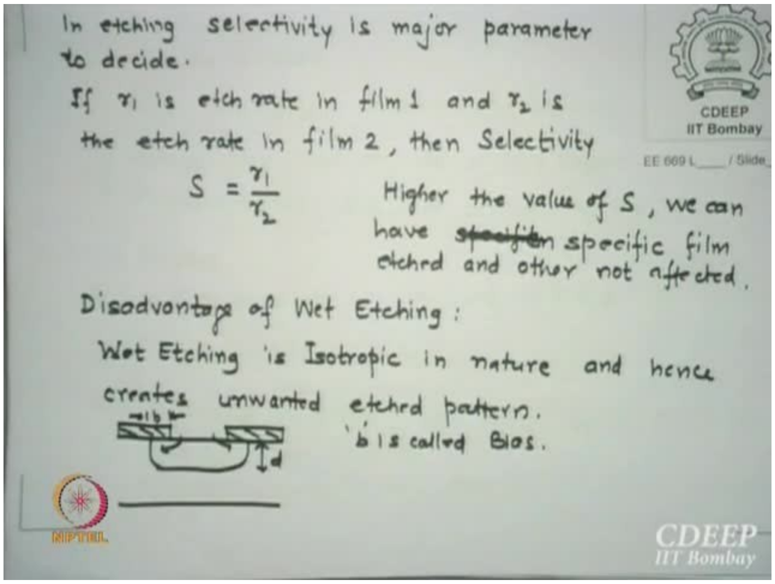

In etching selectivity is major parameter to decide.

If r_1 is etch rate in film 1 and r_2 is the etch rate in film 2, then Selectivity

$$S = \frac{r_1}{r_2}$$

Higher the value of S, we can have ~~specifim~~ specific film etched and other not affected.

Disadvantage of Wet Etching:

Wet Etching is Isotropic in nature and hence creates unwanted etched pattern.

'b' is called Bias.

So this selectivity is defined by from S and R1 is the etched rate in one and R2 in the other film. So the ratio of etch rate in 1 to etch rate of 2 is essentially called the selectivity. So if you want R1 to be etched faster than R2 then etch should be larger. If R2 should be more than less than R1, then etch should be less than 1. That is how you maintain the solutions or another problem with wet etching as such and this is the important figure. I started with a mask okay maybe resistor outside now, let us say anything it could be. This was the window I opened. Is that correct?

This this was the window I want to etch okay but when I was etching the area below, I figured out that okay this is not attack, selectivity is good. The resistor whatever the other film is not attacked but the lower film is getting attacked. So the solution which enters has no directionality. It will etch down but will also etch left side and right side. It is called lateral etching okay. So the solution comes, it etches this side, it etches going down also. So the kind of pattern which actually you wanted maybe this, was something like this. This is ideal pattern I wanted. Etch just below that.

Whatever the thickness, this is thickness (())(72:15). But what would it do it? Sideway etching it will do. Okay? That means the actual pattern which I wanted to print, has got extended. Is that clear? I want this much area. Now I have got this much area. So my next mass does not know that. I thought that this is what window you will open, I will put something there. Now it has gone out. The next connection here which is here, now actually touch this now. Because I have separated thinking that node allows me to separate by node minimum and I figured they are both are touching. So there is a risk involved.

So this additional lateral areas or lateral sides is called bias. What is it called? Bias. So one B here and one B here. So it has a bias of B, one B left side, one B right side and this is the film actually you want etched. So let us say this is SF, so what mask is SN but what is SF? SM + 2B. Is that correct? This is the mass. This distance is SM, mask etch okay but what you really got the film etched out is SM + 2B. So your pattern which you wanted SM has now become SM + 2B. Now there is another problem. The thickness of the film which you are etching, proportionally lateral etch will also increase, B will also increase. Is that clear?

So keep on etching down, you also keep on increasing them. So the film thickness also matters how much B you will get. Is that correct? Thicker film if you etch, B will be much larger. So your pattern will be almost not there what you want. However normally what we do is we will show you a figure. Even after I reached an etchant edge, I put this is up to what. I still etch over etch something. Why? I want this as flat as possible. Okay, this will be some circle no, so if I reduce further you can see. So I can get this area as flat as possible okay. So I did not do over etch but if I do over etch additional B will come okay.

So the problem is, I may get a good this, transfer of image but the larger size if I really do weightage. So do whatever it is, wet etching will always have higher size patterns than what mask is asking. So this is major worry in weightage.

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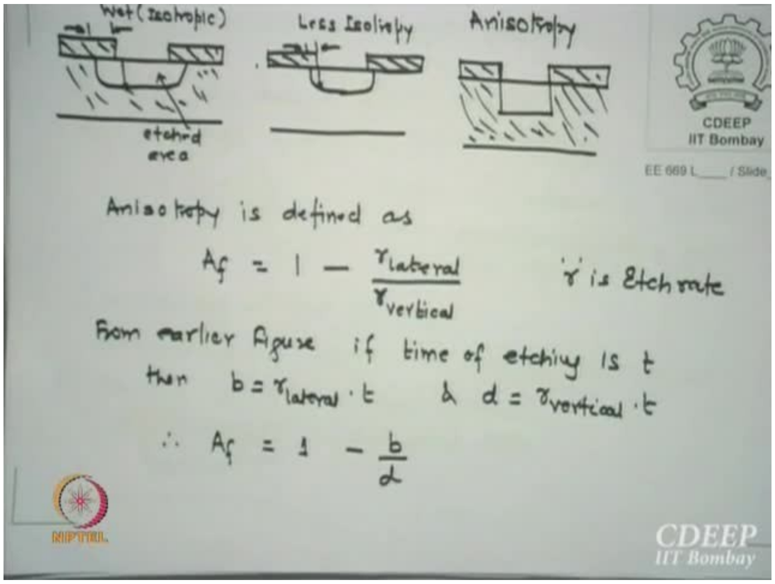

Anisotropy is defined as

$$A_f = 1 - \frac{r_{lateral}}{r_{vertical}}$$ 'r' is Etch rate

From earlier figure if time of etching is t

then $b = r_{lateral} \cdot t$ & $d = r_{vertical} \cdot t$

$$\therefore A_f = 1 - \frac{b}{d}$$

Typically to show you this, this last slide for the day at least, we define a term anisotropy okay. Anisotropy is defined as 1 - etch rate in lateral direction divided by etch rate in vertical direction. If lateral etch rate is 0, how much is AF? If lateral if it is 0, as in the 3rd figure, 1, so the highest anisotropy is 1. What is the lower anisotropy when the lateral etch rate is same as the vertical etch rate? So it is 0. So AF varies between 0 and 1. The worst case 0, best stage 1. Best stage, 1. So what is our ultimate aim?

To make AF as close to 1 as can you see the 3rd figure? The mask and the etch is same dimension. Is that correct? This is SF, this is SM. So SM is equal to SF. That is what I wanted. I may play some games. So that little bit bias appears. So now I SM + smaller side etching. So SF is not far away from SM but it is away outer of this. And here, SF is much larger than SM. So my whole trick in designing an etch system is from wet etching, I must try to reach this and ideally this. There is no system which is anisotopically 1.

What does that mean? Come what may, some lateral etching will be performed. Do whatever you do. Even with normal ion etching, you do, some lateral etching will occur. But our aim is that its rate the much smaller than the etch rate in vertical. If I do this, I will get highly anisotropic films etch rate etch areas. This is highest anisotropy, 1. Whatever is mass dimension, exactly same dimension is on the film okay. Is that point clear? So we would like to find out next time what is the actual film thicknesses you need and what is the limit you come, how close you can come.

Because after all, mask decision is decided by who? I say 14 nanometre nodes I am telling in this much separation can keep. Now if your separation, you told designer something. He has interconnect lines closer, what will happen? There will much or half or both of them will go. So my buddy started that whatever I have told designers, it must be conformal to what I should give him. So I am trying to achieve AF equal to 1. How close I get? I normally may try about 0.8, 0.85. 1 I will certainly never get. This is roughly what next time we will do and this is not very big one.

Last part of my course which is very important somehow I could not do anything fun that but some salient features I definitely tell and I said 50 percent of industry success is on the back end designs or back end processes. We are still not finished with front ends okay. So the back end technology make all the correctness of the designing work. Firstly, interconnects. All the process whatever you do is fine devised, how good is your interconnect is decides the success. That is your back end. So the back end processes, failures, testing is a huge area in itself. So I will not be able to do in 30-40 minutes.

So I will give you some salient features. Where do failures come from? Why do they come? Ek migration bola aaako. Aur bhi Junction fitting hai, there are many such issues. So I will just list them to you okay. So back end design, reading chapter 11 if you need, more seriously. For more details on etching, chapter 10, at least read 10.5, 10.51, 10.5, 10.53, where modelling has been done which I am not doing. Very small modelling. I may write also but model, model for etching okay. So we will like to show you how etchings are performed. Why I need models? Computer needs maths okay, so we must create models.