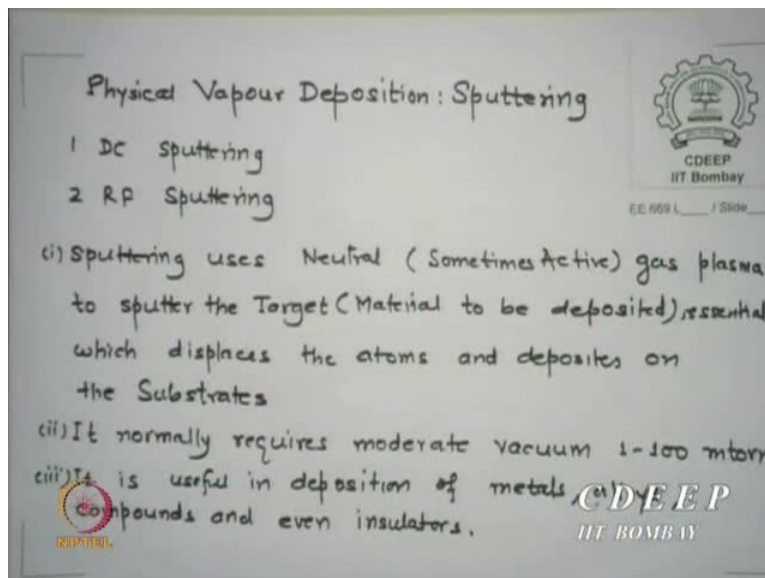


Fabrication of Silicon VLSI Circuits using the MOS technology
Professor A.N. Chandorkar
Department of Electrical Engineering
Indian Institute of Technology Bombay
Module no 01
Lecture no 26

Okay, here we go. Test for the case in case someone have forgotten. Mixed signal design is very interesting because most of the design currently required are mixed signals. So you will see that there is no deposition, there is something else I will start, I will talk about D to A converters, A to D converters, (())(0:39), all kinds of funny things, RF circuits, how do they interact? So this is the part of mixed signal. So we will see there something differently.

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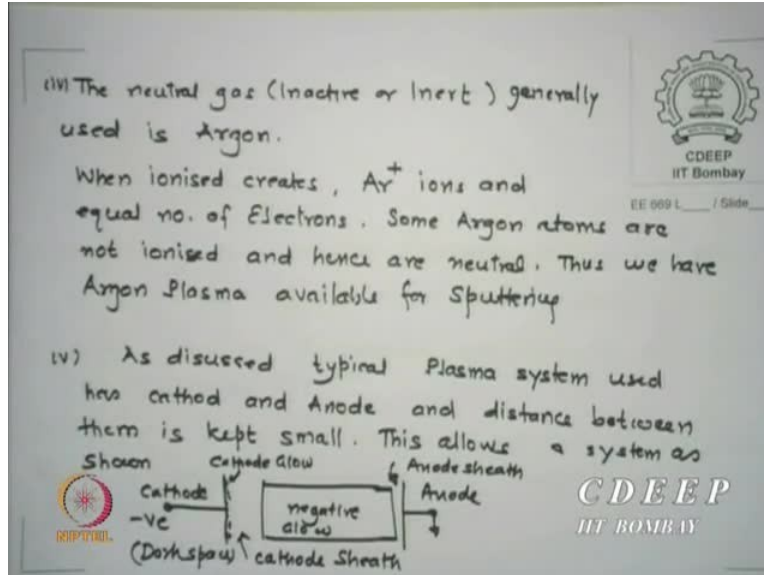
That time, I never said sputtering or any word of that but today I will say something more about depositions. We have done electron beam evaporation and normal resistive heatings evaporations, today we will finish up by sputtering. Basically, I already said sputtering uses sputtering is a plasma ions which can be energised and they hit the target okay. The target is a material which you want to deposit and substrate is where you want to deposit. So these ions actually hit the target and they somehow provide sufficient energy to stationery atoms and when they come out, there is something called momentum reversals and those species of target they get accelerated and actually go and hit the substrate.

And they lose the energy and therefore stick there. So that is the word sputter is okay. In most cases, sputtering is done with a neutral gas like argon but there is a possibility, you can add some reactive gases or you can add oxygen. So if you are sputtering and you also oxygen plasma, then you can oxidise them. So there is, this is called reactive sputtering. But most cases, people do neutral ion sputtering. Yes, I think that word will come soon and you will know why where in implant starts and where sputtering ends. There also actually we do not have that cathode glow there but there are also energetic ions, here also there are energetic ions.

The difference there and here is that there, the acceleration is very high. The column is so long and we accelerate to 300 KeV. Here we will not like to go that kind of energy. Okay. So sputtering uses neutral gas plasma to sputter target material to be deposited essentially which displaces the atom and deposits some substrate. It normally requires moderate vacuum, 1 to 100 Milli torr. Maybe sometimes 300 Milli torrs. It is useful in deposition of metals, alloys, compounds and even insulators. So that is the strength of sputtering. It can deposit anything actually.

Mostly it is used for deposition of metals and alloys okay. Where do you think alloys are deposited? For example, these days you may have required something called moly silicide or platinum silicide or titanium silicide, so these can be sputter films okay. High end metals like tungsten only can be sputtered because tungsten has a 3300 degree melting temperature. Electron beam uses targets which are of that temperature. So you cannot actually operate that much. So essentially, the material which has high-temperature melting points, they are normally sputtered. Okay.

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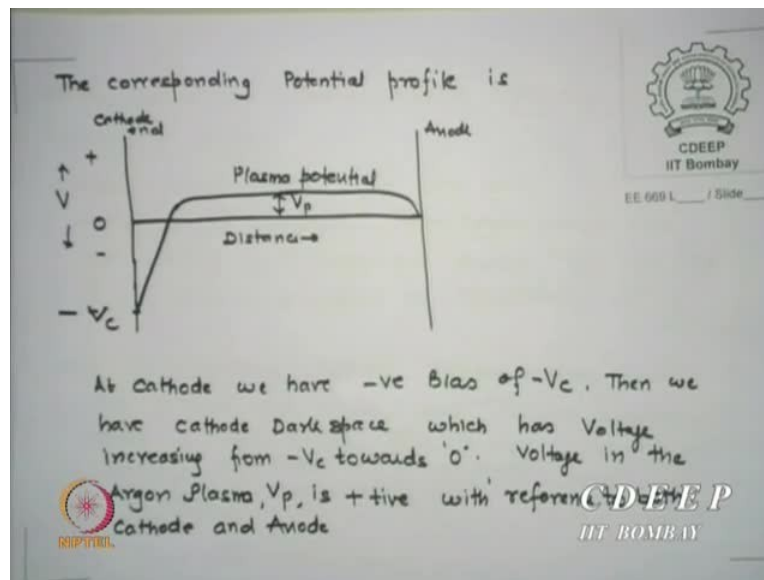
Okay. Please again, once all and are again, I have a argon gas which is neutral or inactive. Argon has atomic number of 18 and sufficiently large in size therefore. Please remember, I keep sitting when it is ionised, it will have equal number of electrons and neutrals. So plasmas are always neutrals okay. Thus we have argon plasma available post-sputtering. So instead of any other gas, if I have a chamber in which I have argon which is under vacuum to some extent, and I put DC bias against it, gas can be ionised. And the distance between 2 plates is smaller, there will not be a positive glow, there will not be any Faraday's space.

Only one dark space which we call sheath and the cathode. This is what the figure I have shown you, this is the kind of plasmas you will get. Earlier I had shown you anode. I also showed you in this case, normally anodes are grounded and cathodes are given negative potentials. Since there are negative glow available here which has plasma and some electrons are accelerated out of it towards anode, there is a small amount of voltage drop or dark space you can say even in the anode. That is called positive sheath or anode sheath. Now these 2 things are so in general, in a sputtering system, there is a small sheath at the cathode, a larger sheath at the cathode and a small sheath at anode as well.

Whereas from there, you can derive this. You have done an IV characteristics of a plasma system. If you have written down, I may just show you the figure which we have shown N times but once again I will show you. Since anode is grounded, the potential at the anode end should be

0 okay. Since it is negative potential at the, this end should be negative value okay which is the cathode voltage. I repeat. I am creating a plasma of argon by discharging it through a potential of $-V_c$ to ground and I expect some cathode drop here which I call sheath potential in the last page. Then there is a glow and there is a small anode sheath at the anode side. Is that okay?

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So the typical figure which we have been keeping showing you all the time, the voltage drop across cathode to anode, this is the $-$ cathode potential V_c and as the dark space, you go towards plasma, from cathode towards this, the potential starts rising towards 0 because in the glow, there is no much potential. But some potential is developed in the plasmas because electrons are leaving and ions are moving. So there is some moving charge which results in a equivalently saying there is a some charge in this which gives some kind of potential. That is called plasma potential V_p .

At the anode end, at 0 because you have grounded it. Which are the voltage, okay voltage in argon plasma is positive with respect to both cathode and anode. Now argon ions when accelerated towards cathode, where will they cross? Please remember, argon ions are in this and they are moving towards cathode and they are getting accelerated because of the electric field which you have applied. So these argons then will bombard cathode okay. So if I keep at the cathode a material which I want to deposit, let us say tungsten or any other material, so these argon ions will go and hit, that is called target. Cathode is normally a target area.

So if ions hit the target and they give their energy to them, and it so happens and which is what the word is, a momentum reversal takes place, a stationary atom of target is removed from the target area and starts moving towards anode area which is our, where we keep our substrates. Is it okay, figure? This figure we have been drawing it N times okay. This is why I actually discussed plasma in detail because plasma is a as I keep saying, 99 percent of the world is plasma and we do not talk about it okay. That is very funny.

Right now, I said DC sputtering. RF also will behave similarly, is not it? At high frequencies. It can, same can be used in RF. We will just show you the RF sputtering part. This is DC sputtering going on. DC has a problem which since he has said it, the target has to have some metallic system. Otherwise you cannot put a bias there. In RF, you do not have to be a metallic part because RF will just move back and forth. So the advantage of RF sputtering is not just getting a fields but it also allows you targets of nonmetallic materials. Okay, that is the only difference.

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(vi) Ar⁺ ions accelerates towards cathode crossing (cathode) sheath towards -V_c potential. Ar⁺ ions have sufficient K.E. now as they bombard cathode. In our case Cathode is the Target plate and Anode is the Substrate. Target atoms are displaced from cathode and due to process of reversal of momentum, move towards substrate (Anode) and deposits there.

(vii) We define a term Sputtering Yield S as

$$S = \frac{\text{No of atoms (molecules) ejected from Target}}{\text{Incident Ion}}$$

The slide also features logos for CDEEP IIT Bombay and NIPITRII.

The argon ions accelerated through cathode sheath towards - VC potential, argon ions are sufficient in kinetic energy and now they bombard the cathode. In our case, cathode is the target plate and anode is the substrate. Then the target atoms are displaced from cathode and due to process of what we call reversal of momentum, they move towards substrate and deposits there. More energy energy momentum transfers can be discussed but as I say, time is not enough to

really go through full theories, how reversal occurs can be proved. Just take it, the target atoms when released, they have still energy enough to come out and go towards anode.

We define a term sputtering yield. There is the most important term which we use. It is essentially defined as number of atoms or molecules ejected from target per incident ions. So if one incident ion of let us say argon, how many of this comes out of the target is called sputter yield okay, or sputtering yield. It has a I think my notation is S , just check what Plummer has. I think he has not used S as the same (10:54). Yes, that is what I say, argon ions hit the target, give energy to them okay and the target items get excited and come out.

Till they receive energy, how can they come out?

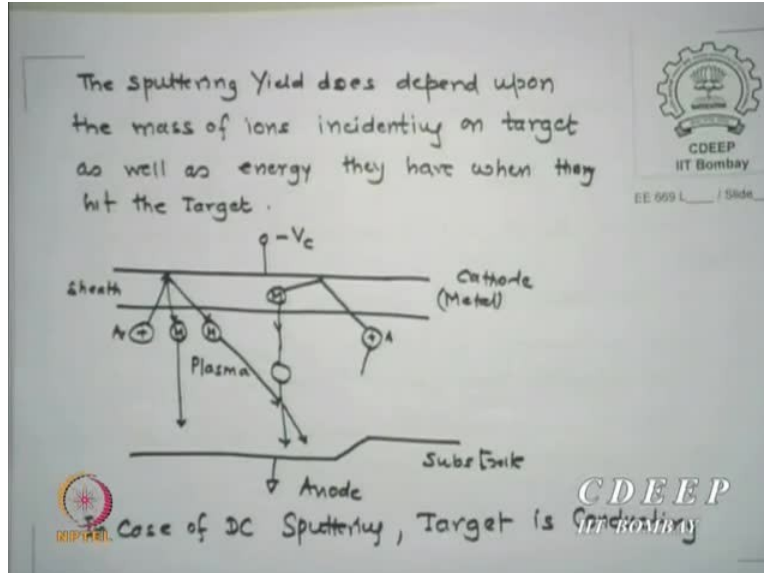
Student1. Argon ion (11:09) come out.

Professor1. Ya, but the mean free paths are so that that is a whole gain. That mean free path, so this is kept so high compared to this distance, so the collisions are minimum. I will not say there are no collisions. So there is scatter there as well but that is a small scatter. I will show a figure how it occurs for your sake. Here is a figure. I knew you will ask. I knew what figure I have to show you. So even if they this, they are still under field. They still both move. Not in same direction, actually momentum reversal is possible because they are not going in vertical direction.

Is it okay? Sputter wind is number of ejected atoms of target per incident ion. The sputtering, it does depend upon the mass of ions okay incidenting on tar, so argon is heavier. So if you have lighter, it is unlikely to actually do much damage actually. It may not eject (12:18). Also at what energy they strike okay, both energy as well as momentum is deciding how much kinetic energy it will have and how much it can transfer to stationary atoms. This is typically what you are asking, argon may hit, may come down, may hit another one but they again accelerate and there is some kind of a steady-state achieved, some angle where this and some target atoms will come down okay.

This is random process and cannot be explained in just one. This is only a figure just to show you. This randomness allows you to momentum reversals okay.

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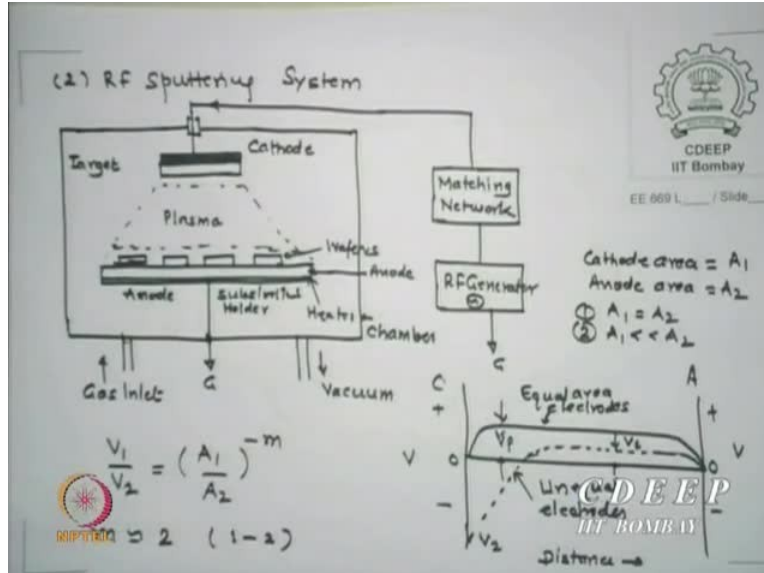


The intention is this is fairly given in Plummer's book. I do not realise but recollect. This is just to show you that even if there is a step somewhere, since the atoms are coming all angles, they will actually go what is called as conformal, it will climb on this, that is the biggest advantage this process allows because some will come somewhere and hit. If there is a step in the wafer, it will climb on that because some atoms may come like this, some may come like this, some make, this is a random process. It is uniform over the time but this process is random. So it is averaged out separately.

As I said, I am not doing lot of theory on it. There is another, full book on sputtering. So you cannot carry on that indeed. What is the difficulty that DC sputtering is that you need cathode to be cathode anode to be metallic plates. Because you need biased to be created there, they both are conducting plates okay. Whatever the target has to be have metal because otherwise it cannot receive the voltage. This is just a figure and this is not grown to the scale or in, this is just to show how random processes can occur and can create reversals.

Okay, here is something what is more relevant and which is, DC sputterings are rarely used except maybe we used to use in 1985-88, now we also do not use. I do not know whether we use it also but hopefully if we are using.

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This system which is often used in the VLSI technology is RF sputtering. We have last discussed the area ratios. Smaller area compared to this, please recollect what I did say. If cathode area is A_1 , anode area is A_2 , there are 2 possibilities. Either areas are same or cathode is smaller than anode which is 2 possibilities we can create. I applied to a cathode through matching network. What can, why you need a matching network? Because the matching impedance. So what kind of matching network it will be?

Student1. (())(15:10)

Professor1. LC, normally LC. Variable resistor there okay which is not really a resistor but a device which provides you resistor. Matching network system costs 6 lakhs in market. So you can see, it can have a just wired L and C okay, so just to tell you. And in our lab, if still existing old lab one of my students has designed and fabricated our matching network which we also spent two and a half lakhs but at least cheaper than this expense. So we have a generator which is essentially going to this. Then we have a, this is called susceptor or substrate holder which is normally heated okay around 300 degrees centigrade.

And then on this substrate, you keep your wafers, whichever number of wafers this. This is a circular disc okay on which you can keep number of wafers. Larger the surface area you have, larger number of wafers you can keep. This is grounded, so is the chamber is grounded okay. The

chamber is also of metallic, this, so both chamber as well as substrate holder is grounded which acts like a anode. There is a gas inlet, there is a vacuum. What we do? 1st we evacuate everything. We actually evacuate to the pressure of how much it should be?

As low vacuum as low pressure or as high vacuum possible to avoid oxygen or any other specie which may interact okay. 10 to the power - 6 torr is the minimum you should 1st go or better pumps available even - 9 should go. But generally, larger the vacuum requirements, costlier is the system but if your films are not that great, you do not put that money. So between these 2 as we have discussed, if the areas are equal, the potential at both will be some kind of $(\frac{V_1 A_1 + V_2 A_2}{A_1 + A_2})$ (17:21) at both ends and there will be a plasma potential VP.

In case the area of cathode is smaller than area of this, it will have a more drops because it will then, why it will be have more drops? Because the ion density will increase. Is that point clear? Area reaction means ion density will increase. Larger the ion density, more will be drop across J Sigma E okay. So it happens that if I push smaller area, I am actually increasing the potential at that end. So it will be like earlier one, DC kind and it will be some. But then, the net potential is applied average of other + DC which we have through matching. So average is same as what it was.

Area under the curves are same. So more potential at the cathode but lesser plasma potentials. The ratio of V1 and V2 potential here and here, this is $V_1, V_2 \times$ is essentially the area ratio and M is some factor which people believe it is around 1 to 2. Many people take it 2. It is area square. But it is not true. You have to figure out from different film measurements and find what is the ratio of A1, A2 which means the ratio of V1, V2. By V1, V2 ratio I am interested in? Because how much is the plasma potential and how much is the cathode potential will decide the acceleration of ions.

How many available and how much acceleration I can give will decide by VC and VP. So that adjustment I will have to do for a given species which I want to evaporate or did this. So what is the advantage of RF system compared to DC? I am not saying it cathode has to be metal. I can put an insulator there. That place, I may metal but I would I am not because if both side RF is moving + and -, it does not really matter much and therefore even insulators can be sputtered in

the film RF systems. Insulator has a problem. Like SiO₂, when the ions when it will hit it, it should be less than the binding , I mean it should not be larger than the binding energy of SiO₂.

Otherwise, silicon and oxygen will separate okay and this oxygen ions may go back to the silicon upper target than rather going to the below target. So the catch is that is how much single reactive sputtering should have which will allow you to do silicon dioxide, silicon nitride deposition. So there is a process has a different methods and so much pressure and so much V₁, V₂ is adjusted okay. The advantage of all this sputtering is conformal sputtering. What is conformal? The shape of the surface, it will pick up all the shape of the surface.

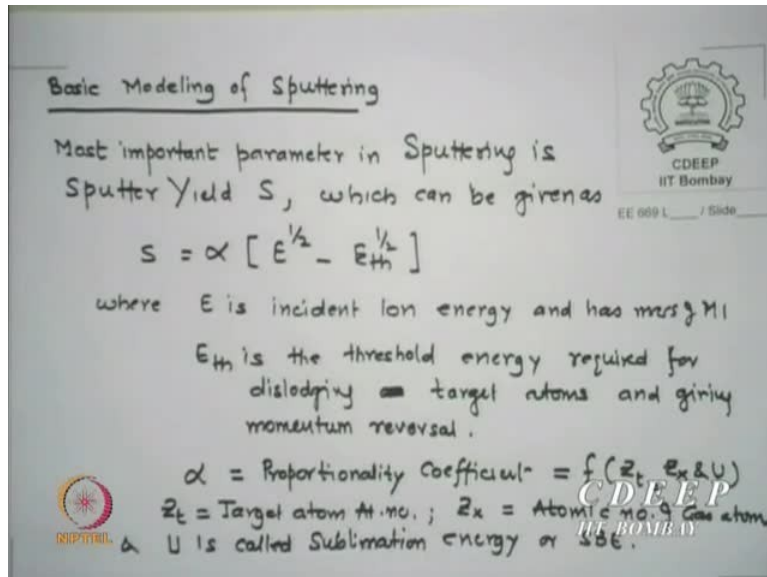
If it is stepped, it will step. It will go down, it will go down. This figure is probably available in every book, whichever book you have seen or not seen. So basically 2 things I am saying, sputtering helps you. DC sputtering can sputter metals, even high, rare earth metals like titanium, platinum, high, noble metals. They can also be sputtered. And other rare earth like molybdenum, tungsten, they also can be sputtered. Evaporation cannot (())(20:59) because there they are used as a source and basket where you heat the material.

So never use these. For other ions, sputtering is the only possibility. What is the else possibility could be? If I do not want to do sputtering, the problem what do you expect this problem is sputtering? See, there are too many electrons and ions are going and their energy they are going to adjust, there will be some damage on the wafer is going to come. Okay. And this damage has to be annealed again. So instead of trying to anneal the damage, you can reduce the damage by another process which we will now do, chemical vapour deposition. So there we will not use physical bombardments okay.

Okay so this is advantage of RF system rate is it is conformal and even dielectrics can be sputtered. But before we go to CVD, here is a model for, simple model for sputtering. This model is not the best model but you can one can use it to find the thickness of the film deposited. What is our ultimate aim in the model? I want after so much time, how much is the film thickness I got because that is the precision given by the circuit people, I want thickness of metal line to be so much because I am expecting R to be per unit length so much okay, interconnect.

So I am told by them. So I must provide them that much thickness okay. Is that clear why designers actually just say I want this? Then how much we play for it. Okay.

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A very basic model of sputtering is provided. We have already said sputter yield is the ejected atoms per incident ion and it is found that S is equal to alpha times, it is not proportional, alpha times E to the power half - E to the power TH to the power half. There is the incident ion energy and as a mass, M_1 and maybe Z , atomic number Z_1 . With, what is for this incident means what? In our case, argon. So Argon has atomic number of 18, Mass is larger, typically 30 to 38, then E_{TH} is the threshold energy required for squeezing a target atom.

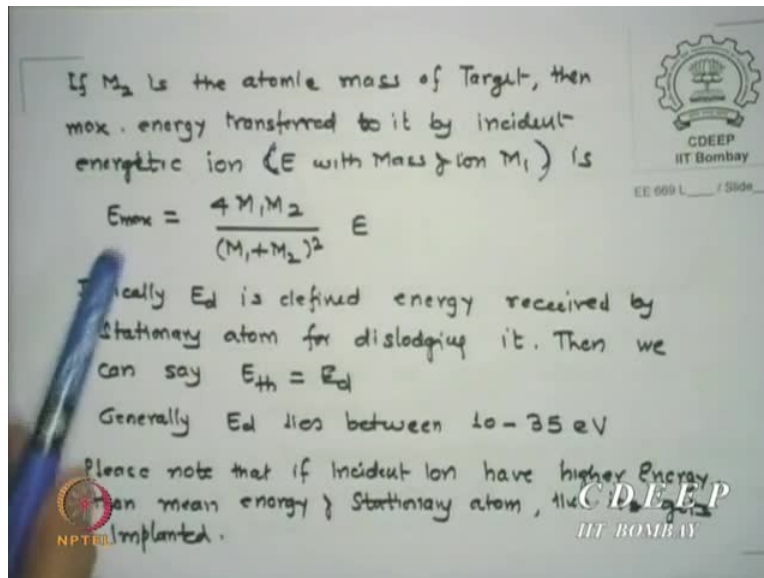
So unless E exceeds that target cannot, atom cannot be displaced and also gives the momentum reversals and alpha is the proportionality coefficient and it has been found that this is a function of target atom atomic number, the atomic number of incident ion gas atoms and also what we call as sublimation energy or it is also called binding energy, substrate binding energy, SBE. Alpha is a proportionality constant which is a function of target atom atomic number, atomic number of incident gas atoms and also it is sublimation energy which is also called the binding energy.

So we will get the formula for alpha, so I will find I will be able to find alpha. I know what E I am incidenting and if I can find E_{TH} , then what should I do? I must adjust E so that for a given species and given substrate gases, (())(24:37) be able to get some yield of your choice. What is

yield to do with it? How much ideal yield will be? 1. 1 yield should give 1 or even more if possible. Ek mara, chhe nikle. That is even game but that is very difficult to get. So we are trying to see how much number of items I can get on the substrate per unit time, per unit area flux as we call and for a given time and mass, we are using, we can find out how much film thickness we have.

So that is our ultimate purpose of , so I must 1st find what should be ETH and once I know ETH, and if I know alpha, I know for a given field which is decided by the current requirements or the sputter requirement I will be able to adjust my E. Is that correct? So how E is adjusted is adjusted what given as which decide the thickness.

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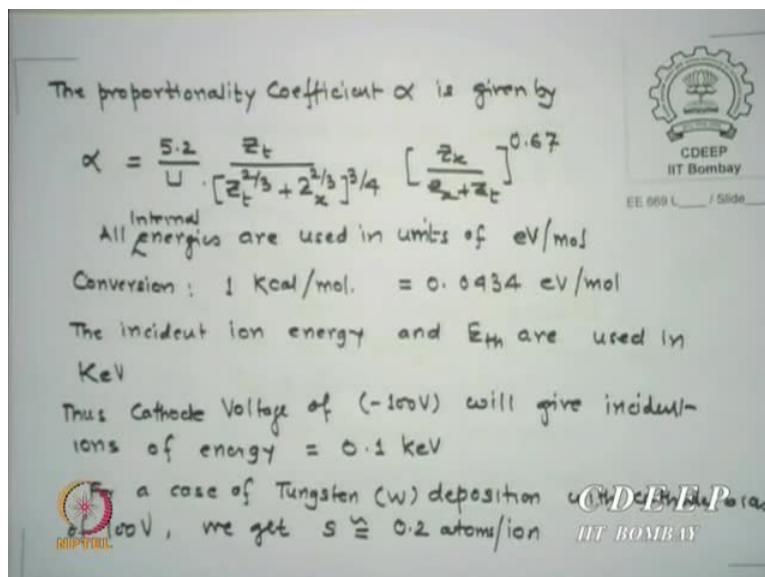
Now without going into kinetics I just wrote down final answers for it. If M_2 is the atomic mass of the target and maximum energy transfer to it by incident energetic ion E , energy is the ion and mass of that ion is M_1 , that is argon in our case. This is not C . It can be found by writing the conservation of energy momentums, one can derive this expression. E maximum which is transferred to stationary atom is $4 M_1 M_2$ upon $M_1 + M_2$ Square into E , E which is incident ion energy. The maximum E max which you can achieve is called E_d or what is called a displacement energy and that is also we can say in normal case, this E_d should be same as the threshold energy for removal of atoms.

So I must find E_d from this. I know M_1 , M_2 , I know incident energy, so I know E_d . And if that E_d , I used that as a thermal energy and if E is larger than this, only then we can say some sputtering will take place. Generally, this energy transfer is in the range of 10 to 35 eV please remember in a E_d is this is the maximum transferred energy and not E_d . E_d is the stationary atom energy which it can pick up if I hit with E max okay. After exchange, E max is available energy there and E_d is the one which is required to take the displacement of atom which essentially is threshold energy.

So E_d is typically found to be 10 to 35 eV. Incident ion will be higher energy and normally eV will be smaller and only then, sputtering can take place. Please remember, unless heated and energy is received by stationary atom, it cannot come out. So it must get transferred enough that it ejects out. So this as I say, I just write down this right now because lot of theory involved and I have no time to explain now, I just thought I will give you the expression which, this expression you should know, this energy which I may give you what is the typical threshold energy is used and why I am doing it?

I want to finally get interested in what? Thickness of the film. So I will try to delete that S some way. Is that okay?

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The proportionality coefficient α is given by

$$\alpha = \frac{5.2}{U} \cdot \frac{Z_t}{[Z_t^{2/3} + Z_x^{2/3}]^{3/4}} \left[\frac{Z_x}{Z_x + Z_t} \right]^{0.67}$$

Internal All energies are used in units of eV/mol

Conversion: 1 Kcal/mol. = 0.0434 eV/mol

The incident ion energy and E_{th} are used in KeV

Thus Cathode Voltage of (-100V) will give incident ions of energy = 0.1 keV

For a case of Tungsten (W) deposition with Cathode Voltage of 100V, we get $S \approx 0.2$ atom/ion

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Alpha can be derived as $5.2 \times U^{2/3} Z_T$ upon Z_T to the power $2/3$ Z_X to the power $2/3$ to the whole power $3/4$ Z_X upon $Z_X + Z_T$ the power 0.7 . This is some kind of a function derived for alpha incident ion hitting the stationary targets. Please remember, in this analysis, all internal energies are used in some eV per mole. So 1 kilocalories per mole is essentially 0.0434 eV per mole. Since all this formula has been derived using eV per mole, so even if your actual this is kilocalories per mole, you must 1st convert it into 0.0434 eV mole ratio.

All incident ion energies and ETH are expressed in kilo electron volts. Okay. The cathode voltage for example 100 volts is essentially saying, has a ion energy of 0.1 KeV. Is that K into e? So it is called KeV. For a case of tungsten, using the alpha value for tungsten and argon, I have figured out at 100 volts as is typically 0.2 atoms per ions. You can find out yourself. I have given all the values. You can calculate as, this is the value which I calculated. Roughly 0.19 something it came. So I adjust it, 0.2 atoms per ion.

So one incident ion, that is 5 incident ions will eject equivalent of one target atom. So what is the rate of sputtering if S is the yield? If ions, number of ions per unit area per unit time is J which you are monitoring across the circuit, which is how matching network you can actually monitor the current. So it is a current densities J ion. So what is the sputtering rate? J into S divided by Q okay, divided by Q. Because J has Q terms, so just divide by Q. Is that okay? Point clear to you? This of course is not given anywhere. This is my just calculation from the formulae which I had. Just try yourself, put some values.

I used argon and tungsten. Tungsten has a rate of 74 okay, atomic number is I do not remember, 32 or 31 something. I have taken from a table, so you can also, that data I will give you. Actually, I had to go and look for these values. So I have to ask you means I will have to 1st search that new item, uska data mujhe hi nikalna padega but I will do that. The rate of sputtering is called Rsp is S Times J ion by Q. Units of Rsp is number of atoms sputtered per unit area per unit time and Rsp is related to growth rate which is what you are looking for, is G times. G is the growth rate, rho is the density, atomic density, Avogadro number, atomic weight M.

This we did somewhere in implantation. Okay so it is similar expressions are obtained. Now the question asked by this, if your incident ion energy is much larger than threshold energy, much larger, then ions will get inside. Okay. And not be able to dis, even they displace, since the depth

is higher, they will sit inside. They will not get ejected. If I have very large incident energy, the ions will actually go deeper to lose the energy and the momentum reversal may not allow items to come from the surface or you can set there will be some, but that yield will be very small and I am looking for sufficiently of atoms to come back.

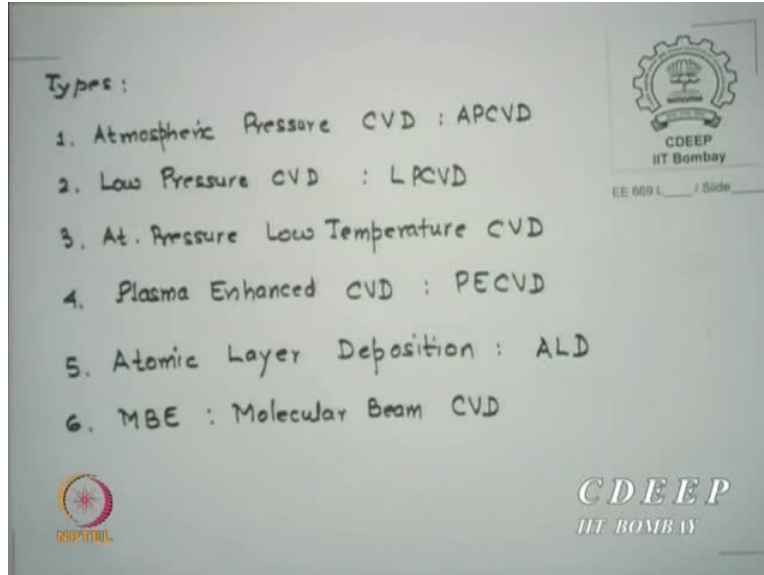
And therefore larger energies are used only in implantations, smaller energies are used in sputtering. So basic process is similar. Only thing is, if you hit too far, it will go inside and then the atoms coming out may not transfer energy enough to come out of the substrate, I mean target itself. It may sit inside. It may, what we call, damage the upper layer but nothing will come out. That is what has happened in implantation. The upper layer gets all damaged, atoms keep moving the sides. Nothing comes out. No silicon deposition takes place.

That is exactly is the difference between sputtering and implantations. Is that clear to you? So do not get too different. They are similar process and similar formulas have been used to derive both cases. So this essentially we did one of the method of deposition is physical vapour. Why it was called physical? Because I am energising and kinetic energy is provided by me and if they hit somewhere or they evaporate with another kinetic energy vapours and hit somewhere. So physical vapour depositions are evaporations using filaments, using electron beams or using sputtering.

Before we offer, we go to the etching part later, maybe next week, last class. Can you think the same sputter unit can be used as a etcher? What is being deposited is the target piece. So if we change the one upper to lower, lower to upper, it will become a RF etcher okay. Exactly what they do. Okay, so this finishes PVD. Now we start with the next possible method of deposition which is called chemical vapour depositions. Again there are many many features of CVDs which this course should have talked about but we will not be able to talk about.

So some (34:55) we will now be provided okay. And maybe actually according the rest part, some other time and we will put it into my course but for your class of 3 hours, 3, 3 and a half hours or whatever it is, I will not be able to do a lot of justice to lot of Thermo dynamics which is involved in this. I just mentioned what is the thermodynamics (35:17).

(Refer Slide Time: 35:18)



There are number of way CVDs are, number of systems and number of methods available for CVD. One is called atmospheric pressure CVD which is popularly known as AP CVD. Then there is a low pressure CVD which is LP CVD. Then there are also of course there are not, these and these are similar but not exact. There is a atmospheric pressure, low temperature CVDs okay particularly used for doped glasses. Then there is a plasma enhanced CVD. Then there is a very popular name, atomic layer deposition.

Essentially I may tell you, MBE, they are used for textured deposition and we will some other time, this word will be explained. MB, molecular beam CVD or actually it is not called CVD, it is MB, is deposition is going on. Molecular beam, epitaxy as the word. We will discuss this word, epitaxy here as well and we will see that this is the best possible deposition system, extremely costly, these days, SMU has one. It is only for one specie. If you are working on galium arsenite, you have that MBA machine is only dedicated to Galium arsenide, (36:43) another machine and 10 crore is the cost as of now okay. So it is a huge money. Unless you are really working on LEDs, do not buy any such systems okay.

Okay, so these are possible CVD techniques. We will not go into all of them but at least briefly to expose one. What things we need in VLSI? We need dielectric films of SiO₂, silicon nitride, (37:08) oxide and many such high K materials okay. (37:12) oxide, galladium oxide, many.

Polysilicon films, self aligned gate and small interconnects a, these are requirements for poly films. Of course now pure poly films are really used, are used as silicides with some material, metal, molybdenum or even titanium. Where do you think poly films other than CV MOS transistors are used? (37:43) hai na, abhi ek bola na. LCDs, LEDs.

What else? There is a driver for the small displays or LCD display, there is a circuit which is used out of thin-film transistors. All thin-film transistors are made out of poly silicon. Of course there are 25 things which polysilicon can do. A poorly planned, 200 million tonnes 2 million tonnes a year may cost you \$ 200 million. Unless that much, 2 tonnes poly is used by us, there is no point in putting a plant. Therefore in the world, there are 3 or 4 companies which manufacture silicon, poly silicon and (38:27). One is (38:29) Germany, the other is (38:31) from US, (38:33) something from Japan.

okay, so further we also need atmospheric CVD for epitaxial films. Now the word epitaxial will come back again later. EP stands for as it is. Okay, tax means texture. So if I have a silicon wafer and I want to deposit silicon, just (38:55) as it is because lower was crystalline wafer. I want to deposit a layer of crystalline silicon. Then it is called epitaxy or epitaxial layer. The process is also atmospheric pressure and maybe quickly we will talk about how they do that. How much is your thermal budget and the quality of films desired decide the choice of process.

You have seen just now the purpose which we have gone through. We have used titanium, we have used tantalum, we have used tungsten, we have used poly, we have used nitride, we have used and of course high K, we did not show but that is also replacing SiO₂ great. So everywhere we require one or the other CVD growth. And not all processes will be from one kind of CVD. At one time, I will use one kind of CVD, for other time, I will use other kind of CVD. And in some cases, I may use sputtering. Like the applied material has sputter etch. They are using etching using sputtering but they also can use it as a deposition system, metal deposition.

So they have same system. Of course there are separated so that no contamination but the system is same. Have you been any time to that lab space? Try yourself, if not force yourself to someone just for the heck of it before we start one of the process or the other. There is some comparison people do which I also did. There are 3 kinds of CVD compared, AP CVD LP CVD and PE CVD and there are other advantages, there are certain dis again we will when I come to the figure, I

will give you some more data there. But just for the heck of it (())(40:46). The AP CVDs require simpler reactor.

It is a very fast depositing system and can be operated at low temperatures. The disadvantage is poor step coverage, there is a particle contamination possible and it has a very comparatively lower throughput rate. What is lower throughput rate? Number of wafers per unit time, how many come out is the throughput rate. So it has much lower throughput rate. Of course we will show you one (())(41:21) system where throughput is increased but not so great. There the gas are, amount of gas which I pass in APCVD is in litres, tons of litres. So the growth rate is very high. If I do not do it, then what I will show you, a boundary layer cannot be formed.

That is laminar flow is not maintained. So I want a luminous glow. So I maintain my gas pressures as well I mean whatever gas amount, so they are laminar (())(41:49). I will show you this now. So it is very fast deposition. Throughput oh sorry throughput and this is not correct. Throughput is the number of wafers per unit time which susceptor can hold. So there are 16 wafers. So at best in one run, 16 will come out. It has throughput. The deposition rate only decides how thick the film cycle, how fast I can deposit a given thickness. So that is fast whereas throughput is from the system, how many wafers come out per minute per hour whatever be the rate.

So if we have if we have a susceptor which can hold 100 wafers, it has a throughput of 100 per say 30 minutes or whatever. But any flat system, you know you have a 8 inch dia wafers. So how many wafers you can really keep? 6-8 on a big susceptor. But if you start like this, you can start 200. So normally, atmosphere CVD has a flats requirements and LPCVD all have vertical requirements. And therefore they have a lower throughputs this. They can be used in doped and undoped oxides. These are called low-temperature oxides and also of course I forgot major and EP but then it is not (())(43:14) temperature.

At times very high temperature, 1100 degree. LPCVD which is low pressure CVD, it has an excellent purity, very good uniformity, very good coverage and very large throughputs. The disadvantage is it is high-temperature process relatively and low deposition rates and it can do almost everything okay. Ya, that for poly silicon, depends on what you are growing. It can grow anything. Amorphous can be grown on 300, poly will be at least 600 to 900 which is not.

Atmospheric pressure, you can do at 400. LTO, low-temperature oxides. If the application of APCVD is only deposition of doped glasses, passivation as we call it and it is 400 degrees deposition.

But EP as I said, if you are doing APCVD, epitaxial growth, then it is 1100, it is a very high-temperature because you want crystallinity. Is that okay? Poly has to be little larger temperature because you want some crystallinity to attain. Is that clear? Nothing else can create crystallinity except the thermal energy. So we will have to provide that. You know that either by furnace, by RTO, RTP, what all processes, but energy will have to (())(44:48). There are methods of doing halogen lamps, all kinds of processing can be done is but energy should be (())(44:56) for crystallisation, no other way. Atoms must settle. Okay.

Other stringent methods, it can go very thick films but their quality is so poor that they cannot make any cell. If you make a solar cell out of such sol gels, solution gel as they call, it may have less than a 0.05 percent solar cell. You may have of silk. So it depends on the application and what kind of purity you are looking, that much thickness and quality has to be attained. So process is decided (())(45:29). Is that okay? There are cheaper processes available. Now thin-film deposition which we are trying for silicon is a polysilicon film, just deposited, keep doing on a river.

So large area solar cell thin-film, you got 3 percent, 5 percent efficiency. So it depends, as I keep telling you all, processes are available. Your application and your quality of requirement should decide. Yadi mass aisa hai toh ye sab jagah same thickness chalega. Since it is a gas, it does not have to be hit by anything. It just finds the slope wherever it climbs on that. So thickness is roughly uniform even if you have steps. If it is a lar upper area is upper uske upar bada aata hai. We are showing you in a (())(46:22). We had to do a CNP just because the areas are, I mean the surface is not planar.

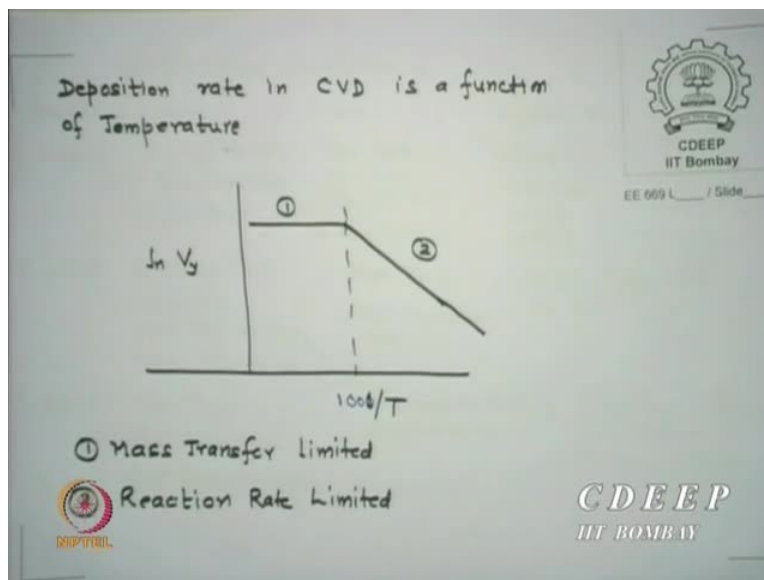
So a nonplanar surface will create a nonplanar deposition. There is nothing we can do. The last is of course the PCVD which is low-temperature fast deposition system. It has excellent safe coverage. Actually, it is doing at pressures which is slightly better than LP CVD. There may problem of chemical and particle contaminations which is like APCVD. You can do low temperature insulator depositions over metals which is many times required in interconnect.

Where this is used? There are several layers of interconnects I am creating and in between, I need a low dielectric material and these are normally deposited by plasma enhanced CVDs okay.

And I also finally receive because we do not want to disturb the wafer reliefer circuit so the passivating silicon nitride is normally done by PECVD or sometimes using low-temperature atmospheric pressure CVDs. Because 300 degree is the uppermost temperature will be given to you. Okay, this can be done at 100 to 300, this can be done up to 354. Yes, both have. APCVD does not have because it is it goes, gas goes like this. I will show you the figures. See, anything in which its a, of course the word is coming which is only temperature dependent. Then it will cover everywhere. If it is mass dependent, how much gas reaches?

Then it depends on, if you have to go, all mass cannot go in. So there is an issue of, whenever there is a mass transfer, there will be always less step coverage. If there is a temperature reaction limited then everywhere everything can go. Here is what I am saying, all that said.

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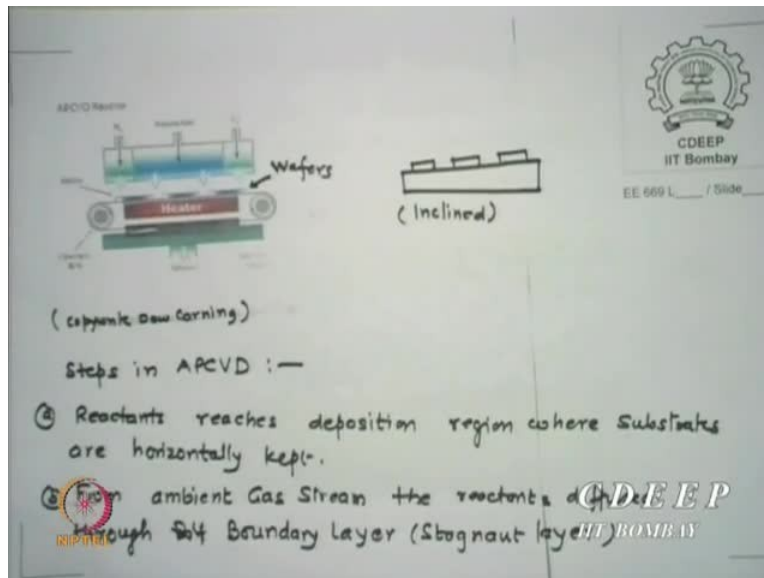


A typical deposition rate which is called VY of a CVD process and its temperature dependence is shown here, sometimes of course instead of one this, I may actually give you $1000/T$. All temperatures are measured in Kelvin, please remember unless specified. If I give you 27 degrees centigrade, make it 300 degrees Kelvin. So if I plot $1000/T$ vs $1000/T$ means T which side increasing? T increasing on this side. So if, one it is found that at higher temperatures

somewhere, the process of deposition is normally controlled by mass transfer and relatively, lower temperatures, relatively, not very low it is limited by what we call as reaction rate limited.

These names do you get somewhere from? Groro-deal model. Okay, same, deposition rate. Ln is log, okay you forget about Ln. Because it is a log scale so it is a PY. PY is the deposition rate. Okay, deposition rate. The Y word was because of X is people are using XY. So it is just a matter of, Y is not necessary because they will show you some directions. So I also used the same method. Okay so is that clear? So the point which I am trying to create is the following. So before I go to the actual APCVD and others, typical CVD reactions can be shown in this figure for APCVD in specific.

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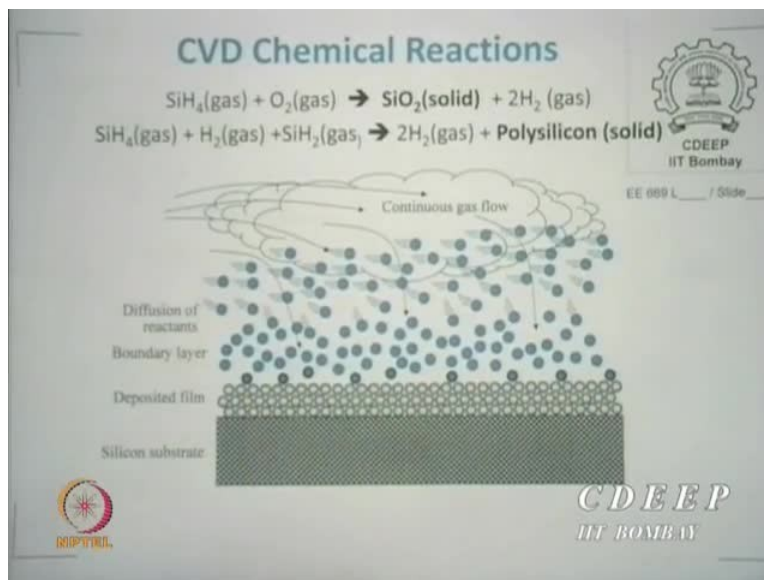


For APCVD system or maybe I will 1st show you APCVD so that you will appreciate what I am talking. This figure has been taken from Do Corning's paper. It is a copyright, this equipment is a copyright of Do Corning. Why Do Corning became very unfamous in India? Why Do chemical became so bad? Because they took over Neon Carbide which created all problems in Bhopal okay. Okay so here is a typical APCVD. We will show you some more figures on that. There is a heater here over which wafers are kept vertical. Then there is a nitrogen gas, processed gas, hydrogen gas or nitrogen gas, many gases.

There is an exhaust. And this is a little higher throughput machine. That is a standard machine. What is this circle from here? Pulleys and it is a conveyor belt. So it is in the chamber, so wafers come, they deposit, hold on, keep going through this lower side. So this is slightly higher input, this is of course required in EP and I will come back to it later. What are typical steps in APCVD? Reactance reaches deposition region where substrates are horizontally kept. Is that clear? The 1st thing is, in APCVD, wafers are kept horizontal.

From the ambient gas stream, the reactants diffuse through the boundary layer. That is something we earlier discussed in crystal layer, there is a stagnant clear which is called boundary layer which is the region which is between the gas stream and the wafer, there is a region where nothing is actually happening or we say velocity is balanced, the stream velocity with the surface velocities are balanced. Okay. Is that okay, 1st stage? They come on, the wafers are kept horizontal, the gases come and move over them. Okay. And the way it is and that is together we will draw a little later, there is a boundary layer between the gas stream and the wafer.

(Refer Slide Time: 52:55)



So any reaction has to take place and that is where that figure will be better off, okay before I come back. Here is the continuous gas flow, this is your substrate. This layer of atoms is called boundary layer. They do not move very much okay. So new species has to actually diffuse through, this gas stream molecules attempt actually then to deposit. Is that clear? There is a

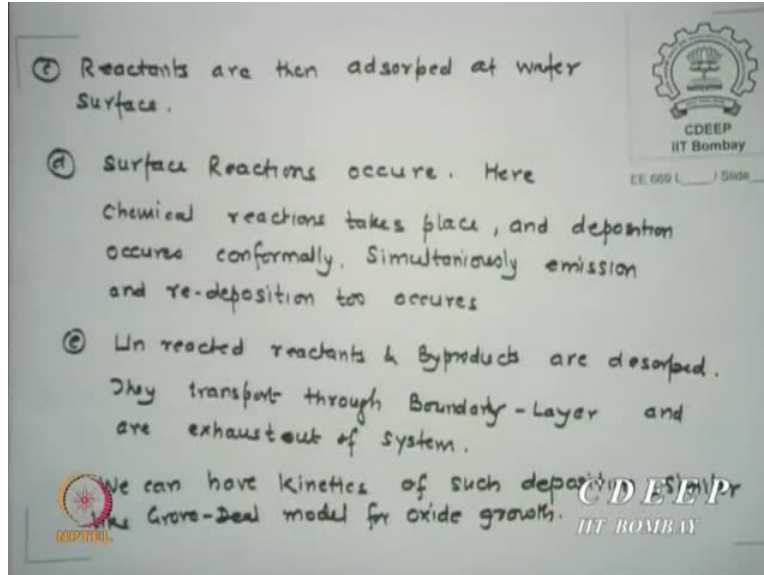
boundary layer of gas which is because of the pressure to adjust and stream velocity to adjust, there is this layer above this which is constant. Typically, this is a function of gas stream velocity but it is typically constant in its thickness generally.

So what is the reaction I am talking for this silicon depositions or poly silicon? Silane is the gas I use. Which gas? Silane. I oxidised it with oxygen, create SiO_2 and gas H_2S , exhaust it. This SiO_2 also has another this, if you want then $\text{SiH}_4 + \text{SiH}_2$ gas, this is called Disilane, H_2 gas may create H_2 and polysilicon. This is that low-temperature, that is at high temperature. This is at high temperature, this is at low temperature. Thermal dynamics is avoided. I just gave the final result. So this is continuous gas flow, there is a boundary layer, reactant atoms go through this and then start settling here. Now when they settle, they have many things.

Whenever atom sits somewhere here, it should have sticking. So what is this sticking related to? One is called surface binding energy okay. The other is, it should be able to move ahead because the next atom has to come. It is called volume energy. These 2, when it is called nucleation sites. So 1st it should create nucleation sites. So it must have enough surface binding energy so that atom can sit there. And it should move. So it should have some energy which should overcome the volume energy and then only they will move.

So there are few energies involved which thermodynamically (())(55:24) how much is available for each gas stream and each gas atoms okay.

(Refer Slide Time: 55:43)



Now this process which I was discussing just now is the reactor, the reactance have then absorbed the wafer. This word, absorption and adsorption is slightly different. What is the difference? Adsorption is also at the surface. Where is it then?

Student1. (())(55:54)

Professor1. No no, it is called inside the surface. It is still on the surface but inside the surface.

Addition and subtraction, is the word used in adsorb and absorb. Okay, the reactance the reactants have then adsorbed the wafer, surface reactions occur. Here the chemical reaction takes place, deposition cause conformally. What is conformally? Step (())(56:21). Why? Because sites are where, wherever it finds sites, only there it can deposit. So, and also it will be simultaneously something will be limited. Not all will be sticking there, some will come out and some will also redeposit.

So there is some kind of equilibrium will be attained in this system. Unreacted reactance in the in the byproducts adsorbed. Adsorbed means they leave the surface. They transport through the boundary layer and are exhausted out of the system. We can have kinetics of such depositions similar to grover-deal model. I just do this today and then maybe. I have a boundary layer, some gas stream is coming and reacting. Same thing. Only difference in grover-deal model there was a

thickness of oxide throughout oxidant was diffusing. There is nothing called such in between. Only boundary layer which is also gas.

So that is the only difference. Is that correct? There is no intermediate oxide layer. So how many fluxes will be there? 2. There was 3rd flux. There is not exist. Please note down and then I will show you the maths for the day. We will finish today for that. Unreacted reactance and byproducts, all gases are not reacting. So the some part will just go away. Some part whereas like high hydrogen, if I use strike level, if I use silicon tetrachloride, what will be the byproduct? HCL. So there will be always a byproduct of this system.

Okay, is that fine? We assume normally that the boundary layer is fixed okay but it can be a function and can be solvent. But right now I say Delta X but then I say, it is delta. But as such, delta X is not uniform. Is that okay to all of you? Is that okay? So where is that simple kinetics which we do. We have the gas stream, we have the silicon substrate.

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Gas Silicon Substrate

Here
 F_1 = Diffusion Flux of Reactant to the wafer
 This process is Mass Transfer process

F_2 = Flux of Reactant consumed by Surface reaction
 Thus this process is Reaction rate limited

We have $F_1 = h_m (C_G - C_S)$ h_m is Mass Transfer Coeff. (cm/sec)

and $F_2 = k_s C_S$

In steady state $F = F_1 = F_2$

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C_G in the gas stream concentration and C_H is the corresponding gas stream concentration gas concentration at the surface. And this delta X or delta as such I am going to use constant later is the boundary layer thickness. So anything which is coming from here has to go through the boundary and not all will reach because there will be diffusivity involved there. Okay. So C_G to

CS and from here, whatever flux available, will react with silicon or deposit on silicon to create the new atomic layer. So we have two fluxes to offer, the diffusion flux of reactant to the wafer, this process is mass transfer, why it is called transfer?

Available gas concentration is proportional to partial pressure. So how much is available is decided by the partial pressure. (())(59:45) Toh ye CG aaya, yeh F1 flux hai. Then F2 is the flux which is reacting or depositing system, okay which is surface reactions. Is that clear? This Si creation there from SiH4 or SiCl4 acts where? At the side. If you take away wafer, the reaction can take place also in the gas stream sometimes and we must avoid that. It should always occur at surface. So we have 2 fluxes to matter. We say F1 which is mass transfer limited. HG is called mass transfer coefficient, units of centimetre per second, F1 is HG times CG - CS, and F2 is reaction rate constant KS times available concentration CS and in steady-state, F1 equal to F2. Same as groro-deal model. What is the difference there? There is no oxide layer where further 3rd flux is occurring. F1 is equal to F2, these 2 are equal okay. Steady-state, both fluxes must match. Okay, maths, clear maths.

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$$\text{or } h_c (C_g - C_s) = k_s C_s$$

$$\text{or } h_c C_g = (h_c + k_s) C_s$$

$$\text{or } C_s = \frac{h_c}{h_c + k_s} C_g = \frac{1}{1 + \frac{k_s}{h_c}} C_g$$

$$\text{or } C_s = \left(1 + \frac{k_s}{h_c}\right)^{-1} C_g$$

The Growth rate $V_y = \frac{F}{N}$ N is no of atoms incorporated on surface

$\therefore V_y = k_s \left(1 + \frac{k_s}{h_c}\right)^{-1} \frac{C_g}{N}$

If C_T denotes conc. of all Molecules in Gas Phase
 then C_g is fraction of C_T or Mole fraction

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So if I equate them and collect the terms, I can write CS is equal to HG upon HG + KS into CG 1 upon 1 + KS by HG into CS, or in a 1 + KS by HG to the power - 1 into CG. So I now related CS and CG through what terms? Mass transfer coefficient and reaction rate constant. The growth

rate as we did the deox deox X ox by DT is similar here, here, thickness grown for deposition rate. Growth and deposition are slightly used in same fashion but they are different. There is no growth, that is no silicon is consumed here. But assume that deposition and growth, I am talking in same terms okay which is + divided by number of available atoms which are incorporated in the surface.

Then VY I use F from here, one of this KS, KS times CS is flux. So KS times CS is flux divided by N. Okay, and there is another term which we use in actual this. There is a CT denote the concentration of all molecules in the gas fields in total chambers okay. CG is the fraction of CT which is available for diffusion. Is that clear? Poore gas stream mein CT concentration. Usme se kuchh hi react karne neeche aati hai. That is $CT \cdot CG$. So iska pressure, how much is available and how much is going down is called mole fraction. Ideal gas law fir se padho. Thoda chemistry hai isme. C we remember, CT is in a whole system and CG is where actually reaction is going to take it.

How much is going coming in. So this is called mole fraction Y which the CG divided by CT. Why I am interested in this? CT is proportional to what? The actual pressure with which gas would be introduced. How many litres per second and what pressure, I know how much gas I am pushing in. This is measurable quantity. CT is measurable quantity okay. Is that point clear? If I know CT and I know why, how much is then reaction I can derive, how much is the mole fraction I am having. Then I will be able to correlate external gas flows $(\text{()})_{(63:48)}$. Okay. Is it okay is that okay?

(Refer Slide Time: 63:58)

$$Y = \frac{C_G}{C_T} = \frac{P_G}{P_T} = \frac{P_{SiCl_4}}{P_{SiCl_4} + P_{H_2}}$$

Reaction used here is

$$SiCl_4 + 2H_2 \xrightarrow{Temp} Si + 4HCl$$

$\Delta G = \Delta H - T \Delta S$ is Thermodynamic statement.

The growth rate V_y is therefore written as

$$V_y = \frac{k_s h_a}{k_s + h_a} \cdot \frac{C_T}{N} \cdot Y$$

Two cases :-

- ① $k_s \ll h_a$, then $V_y = \frac{k_s C_T Y}{N}$ - (A)
- ② If $h_a \ll k_s$, then $V_y = \frac{h_a C_T Y}{N}$

GDEEP IIT BOMBAY

So why is C_G by C_T ? But we know I partial pressure law (64:02) is proportional to P_G by P_T . P_G is let us say if I am using trichloro silane and the reaction which I use to show this is for an epitaxial growth. Silicon tetrachloride + 2 H₂ at high temperatures reduces to reacts to give silicon + HCL. And whether this reaction will be favoured or silicon may react back with HCL and give me Silicon tetrachloride is decided by thermodynamics. Okay, a ΔG is positive or negative, ΔS is the change in entropy at temperature T and ΔH is the enthalpy. If this is this, positive, this will be forward reaction. If it is -, it is a reverse reaction.

So you must adjust your T and the concentration such that forward reaction is (65:03). Okay. So if I have now C_Y which is proportional to P_G by P_T then I say V_Y is $K_S H_G$ upon $K_S + H_G$ C_T by N into Y okay. Now there are 2 possibilities. This is the growth rate or deposition rate. What is this? 1 of $K_S H_G$ by $K_S + H_G$ means what essentially I am talking is 1 upon $K_S + 1$ upon H_G , I am talking something like this. Is it? So now because this lower version will be much easier to understand, if I say K_S is much smaller than H_G , K_S is much smaller than H_G which means $H_G H_G$ can cancel and you get V_Y as $K_S C_T Y$ by N .

What is it limiting? K_S . K_S is related to what quantity? Temperature, E to the power - E by K . So if you can make the process and which K_S is much smaller than H , then the reaction will be governed the deposition will be governed by only temperature. Rest remaining constant, only

temperature. But if I make a case in which HG is smaller than KS, then the process will be VY HG CT Y by N. HG is decided by what we called as mass transfer. On what basis what is the equivalent it can be in a figure which I have shown you?

There is a boundary layer and reactant is diffusing through. So what will be roughly HG value? T by Δ is essentially called mass transfer coefficient HG. Diffusibility divided by Δ , the boundary layer thickness. So what are the 2 equations I am trying to say? By adjusting whichever parameters you wish, you can either make a process of deposition which is function only of temperatures or which is a function of the available mass, Mass transfer. LP CVD uses the 1st case in which HG is much larger than KS. APCVD uses the 2nd case in which HG is much smaller than KS and therefore HG, it is mass transfer limited means wafer has to be then kept flat because then only it can create a boundary layer and reactant can go.

In the case of LP CVD, it is only a function of temperature. So how wafers can be kept? Even like this. As long as they are temperature is known, I know how much growth it will (())(()) (68:14). So the is that point clear what I said in LP CVD? Their throughputs are very high because they are only temperature dependent processes. All APCVDs are mass transfer limited process, so wafers have to be kept flat and then their throughput is less because susceptor cannot have hundreds of wafers. Of course their system does improve the throughput but still it is limited by the amount we take, how much belt you can have? You cannot have of course, belt is right now 14 feet.

Normally, Intel has a process which are 14 feet belt which holds around 12 inch wafers around 12 all (())(68:53). So 12 wafers hi at a time belt pe aate hai. Woi chamber me entry hota hai (()) (69:01) bahar aa jata hai. So there is a retention time, you can see under monitor what is happening. It will say end, wafers will come out. New wafers will start coming. So if you, of course unless you join Intel Kotla and or Aregone Aregone elsewhere, you will never be able to see the real life process. Try joining TSNC but in TSNC go, I do not know how many will go. Some days you go, you will be restricted to some 100 feet by 100 feet area. You cannot go other groups. So tomorrow we will start with what tomorrow means Friday. We will discuss more about the each process and do integrates okay and then finish the, we can start etching later.