

Fabrication of Silicon VLSI Circuits using the MOS technology
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Lecture no 24
Module no 01
Thin Film Deposition

Okay here we go, till now we have seen many processes and also we have seen how to fabricate an IC and how many process steps we go through, the simplest process which I shown you last few days is 16 mask process and you can imagine now any additional features I had I will have another mask on it, another metal another mask and if it is a tungsten step and we have another mask for it so there are many mask keep adding and each mask costs a million dollar + so it is not that so trivial that I add another mask. So process wise one has to plan very carefully how many mask will be required and that is a designer's job as well as process people job so now some way now in 2012 onwards or 2010 onwards both technology and designers should sit together and actually plan what is the system to be designed okay.

So it is not arbitrary earlier, in 1970s a very famous professor Carver Breder Cartake he suggested and he successfully did that as well that a computer scientist can design a chip without knowing absolutely anything of technology okay. He himself as a professor of computer science, he was professor in electrical engineering, he was professor in applied sciences, material science and he was (())(1:43) he was in 7 department. In spite of all of that his 1st book on VLSI appeared, this is the 1st textbook in VLSI design appeared in 78 from Carver Breed. of course there is another author Lin Conway, she was with Xerox company surprisingly the 1st IC chip interest was shown by Xerox company and not by any Intel or anyone you know. 1st such chip for usefulness was shown by Xerox people and Lin Conway was the chief of design group in Xerox.

So this is some history so I just want to tell you that now technology knowledge is as much-needed for designers as is design knowledge is as much-needed by technology people and today that we also know little bit of physics, little bit of chemistry, materials science, optics and whatever you think about, little bit at least you should know, at least terminology should be known what is it talking about okay. Okay so we will start now with a new topic and we have seen in that last so many days that certain things we grow but there are very few things we can

grow mostly silicon dioxide can be grown out of silicon but rest of the time I will have to keep depositing films of different kinds.

So the process which is very dominant in all IC manufacture is deposition and anything you deposit we see we have seen other day that there will be selective etching of something so you need to etch something so the next part of this is etching so how good etching you do will be deciding the characteristics, so etching and deposition to some extent are not necessarily exactly complimentary but to some extent they are complimentary, whatever you deposit somewhere you etch okay, so somewhere you etch means somewhere you deposit so there is some theory at least some process you can say like RF deposition what we do normally RF based, they can be used by just changing the RF source priority as an HF okay so that is exactly what you we do that is why I am trying to tell you that many things are similar identical but not everything, so let us see each of them separately.

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In an Integrated Circuit Fabrication, many films of different materials are deposited.

These films are of either Metals, Metal-silicides, and Dielectrics like SiO_2 , Si_3N_4 .

Requirements of Deposition

- i Desired Composition, Low Contaminates
- ii Good Electrical properties of films (Desired)
- iii Mechanical Properties should also be good. Adhesion is one such important Property

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Today we start with little basic of thin film deposition and at least 2 of the most common methods of depositing films we will discuss and unfortunately all that I will discuss is rarely used these days in manufacturing but they are the precursors, our labs have many such operators so I think we will discuss that. In an integrated circuit many films of different materials are deposited typically films can be metals, metal silicides, it can be dielectrics like nitride, oxide, many others and so these all films you need to deposit so a typical system which allows you to deposit and the

film which you will going to get this is essentially called film deposition because normally thickness of this deposition films or thickness of deposit layers are very thin comparatively. It is not 300 microns or an microns, it maybe few thousand Armstrongs or 2000 Armstrong, (5:03) half a micron, 5000 maximum.

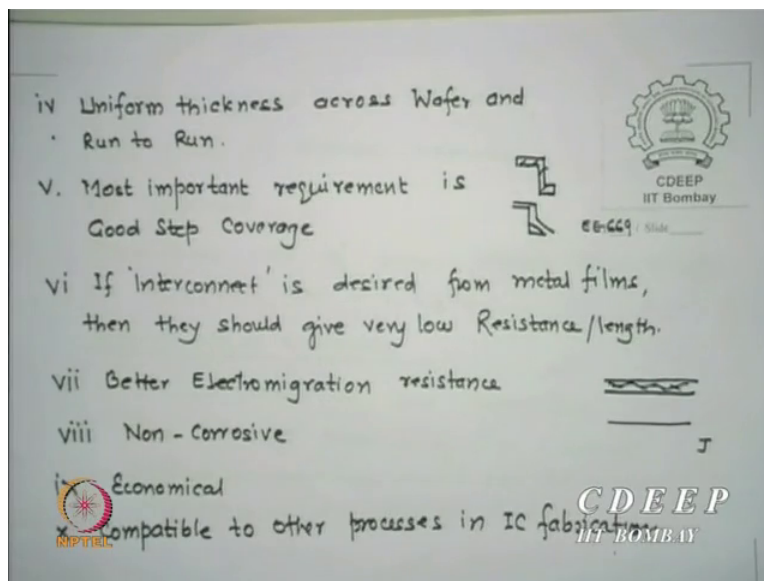
So in that case they were called films okay, films are actually we are not doing this course here but other way I may tell you there is another technology which is used in SITs is called thin film technique and thick film technique. So the idea there was thick film technique will be thicker films and thin-film technique will be thinner films, there are requirements when thin films are thicker than thicker films and thick films are thinner than thin films so all games are only namesake but let us look at the requirements of deposition. any system which I use should have should be able to give me desired composition of film which I want to deposit, it should not dissociate if I am putting silicon dioxide it should retain silicon dioxide property after depositions and it should not allow any contaminants with it because if it allows contaminate then whole process will get tarnished and we will not be able to proceed further.

And low in contaminants and any composition should be retained after the deposition process is over okay. Most cases if they are used in silicon IC manufacturers have interconnect in many other areas or even insulating films, they should actually retain their electrical properties in the best fashion. If you have a conductor it should give largest conductivity possible, it should not modify conductivity, if you have a dielectric film it should retain dielectric constant okay and also porosity. So one of the major requirements of any system is that it should remain good electrical property the film which are desired by you for the next processing. The mechanical properties should also be very good there is very important properties maybe I will show you later, the new deposited film, you have molecules or atoms coming mostly items, in some systems molecules also can come.

So if these atoms are impinging on substrate they should take other than move away, so they should be something called adhesion or sticking coefficient available, unless there is a sticking these atoms... Please remember what is the problem, this whatever this energy whatever these ions and electrons sorry the films atoms are coming they are energetic they are not the row energies so when they set they lose their static energy and they may actually move okay. So what

is asked that the energy should not be so high that they actually display something and move themselves so it should be retained as the film they want we want to okay, that is very typical so adhesion is very important. Of course we will see in CVD later, there are 2 kinds of additional properties or adhesion energies we use, one is called surface energy the other is called volume energy, so when to have what higher or lower we will decide whether film will grow or it will etch okay. So a mechanical property is very crucial for any deposition system, it should retain and give whatever property I am looking for.

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Then I want any film iron depositing on a wafer of whatever size I have, I have 4 inch, 8 inch, 12 inch, 16 inch wafers, it should be uniformly deposited or around the same thickness same compositions okay that is minimum what I am expecting. If every changes then I do not know for each chip for each area what is the film thickness okay. so that is it is wafer to wafer sorry on wafer, wafer to wafer and run their thickness should be as what you are looking for. The next important system next important requirement is as we have seen yesterday VIAs.

For example, if there is a step something like this so the metal film or whatever film you are depositing it also should follow a step okay coverage has to be full. What it can do is if this is my step I may actually get this, in some regions there may not be any sticky okay so there has to be a property of your system which will allow coverage of all steps okay conformity it is the most required property in any IC manufacture okay. so this is as I said step coverage is the most

important part which system should allow and the material should go inside that wherever we VIAs or voids are created. If the films are metal and they are used for interconnects as I just now said they should provide you very low resistance per micron for length okay because essentially if you are running an interconnect what do you mean by interconnect?

Some signal is going from one point to the other okay and the length of interconnect will be large enough compare that is why it is called interconnect, this R is larger what will it create problem, the delay RC time constant will increase and it may happen that this RC time constant equivalent frequency may be same as what your system clock or your signal frequency is going on, so you may actually have 180 degree out of phase signal going okay so it is a very typical problem, one going to 00 becoming one because of delay signal okay because most circuits are these days, there are 2 kinds of circuits as professor Desai talked about, one is Gayle okay think of it. There is something some circuit has to be locally synchronous globally asynchronous, some circuits are globally asynchronous locally synchronous, synchronous means timed without clock which you generate or you have in your system okay.

So all signals need not be there may be some asynchronous signals going and many process many such systems do use asynchronous transfer okay. It does not mean please also for the circuit people I may say asynchronous does not mean there is no clock okay it is not static logic, asynchronous essentially means it is not running at the system clock is that word clear, so asynchronous has nothing to do with non-clock okay, still the clock for example, one of the features which I keep asking the M.Tech students when they come for interview; take a latch 2 inverter back-to-back there is absolutely no clock why it should be called asynchronous system? It is a timed system when there is no clock okay so how it acts as a clock?

There is no clock given to it but a latch is essentially a time signal based system okay, similar system has to be done in the RAMs so some are asynchronous some are synchronous, some are non-looking synchronous okay latches for example, so these are issues independent of all that but this RC time constant since it affects that very much of course one method which circuit people use is buffer it, keep pumping every after certain length, you actually have a buffer stage then you pump it again so the delay is taken care through the buffer out. However, that means you need additional power every certain length because you are signal pumping every now and

then, this additional power is not good because you are reducing the power of the system and you are saying I will put buffers.

It will take area larger area because it is larger buffer so all these issues are related to interconnect, so to some extent now giving a correct interconnect is a crucial part for me but it will at the end affect the performance of the performance means speed, speed of the circuit. So somewhere do not think that interconnects are very trivial, interconnect technologies very crucial because that decides the performance at the end of the day okay. All this I just want to show you how long we think okay, same way this interconnect have a problem which is called electro migration typically electro migration can be thought like this, you have some substrate or something and you have a metal layer okay, now this metal layer this layer is getting thinner and thinner okay because of scaling.

Also we are finding it now that this film which you have this earlier our since we are not scaling voltages, the currents because the area is now reducing, current density which wire is now taking or thin interconnect is taking is increasing is that clear, the number of electrons per square centimeters are now more compared to earlier one because you have thicker this so per unit area will be smaller, now it is larger current densities. If the current density is very high which can be typically say greater than equal to 10^5 times per centimeter square, this is called critical current density or J_c , if J is greater than J_c then there are huge number of electron densities available and ions there, there are metal of ions and electrons.

But since there are huge number of electrons per unit area and you are applying a voltage that is why the current flows so it creates an electric field and large number of electrons are accelerated with this electric field and they create an effect which is called Wien effect okay they create an effect. Ions are very immobile thing, are very heavy, they stick to where they are but electrons are very light, they are acquiring energy because there are large number of carriers per cc per centimeter square and you are applying current, voltages, then actually pick up enough energy from the field okay, this is something called Wind effect and they have enough force Kinetic energy required to actually dislodge ions okay as actually dislodge ions.

So if there is a small crack in your metals film wherever it is somewhere here, so this whole metal will actually climb from here and there will be a gap between the left side to the right side,

metal will climb up okay from that crack okay so there will be a gap between interconnect and when it still happens, it may not happen in 1st day, the crack may form initially so initially circuit may work, after some day you find it did not work, everything was connected everything was fine chip was working and tomorrow we used to say in class it is electronic mood, the mood is migration okay, the metal actually climbs okay. So there is a reliability issue this is called reliability aspect and one has to worry that anytime and that is why someone was asking the other day copper inter copper has better migration compared to aluminium, aluminium has lowest migration density so even near 10 to the power 4 or little higher it may migrate okay.

So this electro migration is a major issue and probably even now in all SOC systems or all systems which are hardware so (())(16:43) design people are doing, one of the major worries is migration. Violin may not be there but area you are reducing all the time and fields you are not reducing increasing with voltage you are masking. If you scale everything exactly nothing should happen, but it is not happening, there are issues which are reliability issues which is hurting people, so one method when we actually lay the (())(17:12) there is a case there itself we should think if this is going to carry how much current in this area, we know why because I am designing chips so I should actually add additional features thicker I must announce I need thicker or at least wider okay so all this interconnect designs are becoming very-very crucial now as we are scaling down.

In 90s when I had many students and I myself used to design now I do not, those days this was all irrelevant; 5 micron, 3 microns, 1 micron, all find everything is fine, things are changing so fast now that every day one has to worry about failures and failure means money so all the problem is economics. So please remember this electro migration is not trivial, now people are looking from layout to the logic, people say look at the layout and declare how much yield it can give, there is CAD tool have been developed for layout generation issues, these are all problems of what you all think new problem for 2014.

The next problem which metal system or any other FIN system I am expecting is non-corrosion or oxidise particularly Copperfield for example, it should not become copper oxide and please remember copper oxide is not just one kind of copper, copper has 2 valences and it can be C2O or COO and both are as bad as far as corrosion is concerned, some have lesser etchebility, others

have stronger etchability so depending on how much oxygen it picks up I may have worst phases okay so this is very crucial in actual processing. Then of course this you can write whenever someone ask desire to this, this line you can without thinking economical BOHOT costly NAHI CHAHIYE that is why we do not use gold so often, gold is actually not as costly as platinum so we use platinum and keep saying gold is costly so this is something another.

If you go to a jeweller you will never buy platinum, of course nowadays I do not have enough money to buy so I do not know so otherwise platinum jewelry is also available which is costlier than gold jewelry but gold has that aura okay platinum does not have. In the lot I have a platinum target I even keep it like a normal pickup but if I have a gold target I am sure next day it will not be there if I just keep it okay so worries are terrific in economics okay. And all similarly then (()) (19:58) you can always say, it should be compatible to all other processes because suddenly you say 1200 degree no no no no we have 800, 1000 no one more than that, whatever compatible other processes are there this cannot be different from it. Okay so these are I mean these are all not bad it is not given in book but I just number you to show that what is so important for deposition system and depositing system materials.

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Two Major Deposition Techniques :

1. Physical Vapour Deposition (PVD)
 - (a) Evaporation
 - (b) Sputtering
2. Chemical Vapour Deposition (CVD)
 - a. At. Pressure CVD (APCVD)
 - b. Low Pressure CVD (LPCVD)
 - c. Plasma Enhanced CVD (PECVD)
 - d. Hot-Wire CVD (HWCVD)

The slide includes logos for CDEEP IIT Bombay (top right), NIPTIL (bottom left), and CDEEP IIT BOMBAY (bottom right). The slide number 'EE469 Slide' is also visible.

There are 2 major methods of deposition of films; one is called physical vapor deposition, the other is called chemical vapor deposition okay, 1st we will only do today possibly I am not sure but possibly PVD which is physical vapor deposition. And as I keep saying there are 2 kinds of

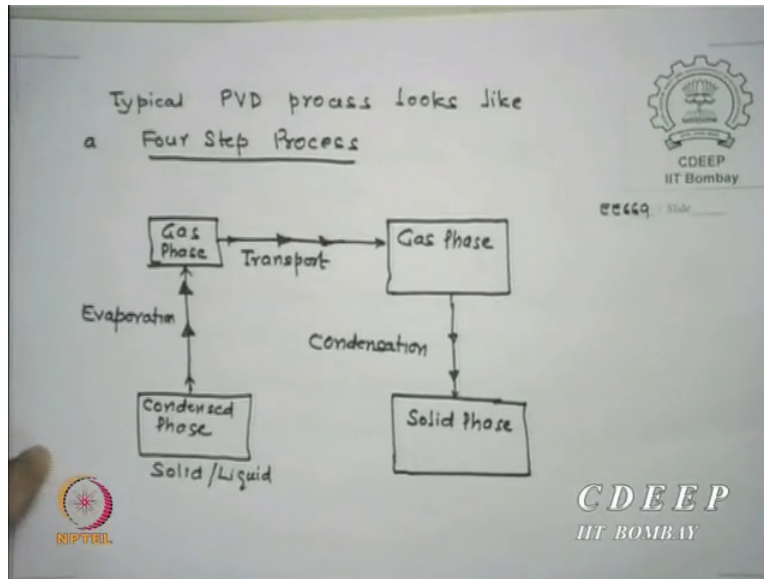
physical vapor deposition, one is called evaporation, the other is called sputtering, this not sure whether we will finish today because it needs some plasma so maybe we will do something on plasmas today. The 2nd possible mechanism is chemical vapor for you actually have a source which can be of any form, but should convert to gaseous form and those whatever material you want to deposit the gas form of that should move on the surface by some temperature, pressure adjustment it should stick to the surface and deposit okay is that clear.

The gas will come, it will some way connect to the surface of the substrate which you have kept at a given temperature and pressure there is some mathematics we can create then we say when it will stick okay so a layer of that specie can deposit it, it can be silicon it can be silicon dioxide, it can be silicon nitride or for that matter any metal. So CVD is very popular at as I said there are number of CVDs possible, one is called Atmospheric pressure CVD, low-pressure CVD, plasma enhanced CVD and Hotwire CVD. If you are working with Professor Ram Gopal Rao, he will take you some day to ground floor lab inside and see there hotwire CVD everything can be done there.

Let us do evaporation 1st, and once we do evaporation we will say that are some problems of evaporation and as I say no one is now want to work with that okay so we went for sputtering which is another PVD, (())(22:40) is still used hundred percent used but it also has some problems okay. Like for example this conformal depositions are very difficult in sputtering systems, it can deposit it is not that it cannot, you need some special gadgets to do that whereas CVD normally will always go through conformal or contours, it will get take steps okay. So in most cases and in all ICs we have seen so far every step there is different thicknesses everywhere, so any film goes it has to actually follow everywhere okay and that is our worry actually, if it does not follow then we have a worry.

If it follows also we have worry because then we have to do CMP we have to planarise so there are all issues okay. So we look into the 1st one evaporation PVD; actually both PVD and sputtering have some basic similar but only method of... This is also deposition by kind of evaporation this buttering but it is slightly different in nature so we will discuss it later on.

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Typical PVD process has 4 possible steps looks like that, you may have a source material which you want to deposit so it may be in solid phase or it may be in gaseous phase okay, we say condensed phase okay. Except gas both liquid and solid are called condensed matter, please remember this is a if you are not knowing this do not walk into the last classes of our corridor chemical, chemistry, physics, they will shout at you. Okay the condensed phase the 1st thing we do is by some method process which is calling evaporation, this condensed phase changes to gaseous phase okay.

Now this gaseous phase is then transported to someplace where we want then in the gaseous phase that means something is coming flux of gas is coming and is moving up and is also etching here so that is the gas phase position where it has reached. And at that point which is my substrate where I want to deposit something it converse into solid phase okay so this is typically the way process of evaporation or process of any deposition takes place okay. Repeat, starts with any of the solid or liquid source then it evaporates convert to gas phase, transport still in gas phase, condenses and deposits okay. These are only my figures to show how things happen, I would have set in online but now I stick to you that this is how it happens okay.

Why there is something I have to do here? Why I have to do something here? Okay my something have to be done here? Because if I just say something you will not appreciate that each places I have to do something to actually do better there okay that is why the 4 stage that is

the only thing I can add from the book which book does not know okay. I do not know Plummer anytime visited lab but hopefully okay I will show the list of them then you will not ask me. Just a minute, wait for whatever things we can deposit we are (0)(26:17) I can deposit anything okay.

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Evaporation System Requirement

1. Vacuum :
 - Need 10^{-6} torr or better vacuum for better quality films.
 - Better vacuum be Ultra High Vacuum which could be around 10^{-9} torr.
2. Heating System

Thermal Heating	} 1-10 kW Power
3. A Bell-Jar to keep vacuum.

Thickness Monitor

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So what are typical requirements of an evaporation system is it should have vacuum, the system should need metal films or any films, they can only go properly if you have a vacuum system, all around there is a vacuum okay, typical vacuum which is needed in evaporation is better than 10^{-6} torr okay 760 torr is 1 atmospheric pressure okay. Now you go and look at the Google there is a bar, there is a pascal, there are dynes, phosphor unit this centimeter square this per second, all kinds of units are there for pressure okay. Just look at how many, at least 5 or 6 units are there for pressure.

Generally because Torricelli was person who actually worked on vacuum, he was trying to show vacuum has huge potential of pressure building and because of that that credit was given to him and pressure was then called Torr and less than 1 atmospheric is normally expressed in torr otherwise it will be in the larger unit which will be either force per unit area or it may be pascals or it may be bars okay, 1335 pascals is 1 torr okay these are smaller unit. Okay I will give you some numbers, my 32 years I have gone through all kinds of units okay so this 10^{-6} torr is a very low pressure means better vacuum, this word also should go better vacuum means low-pressure okay.

I have better vacuum side does not mean 10 to the power 1 atmospheric pressure, it is not vacuum it is atmospheric pressure okay. So I need better vacuum possibly better than 10 to the power -6 means -7, 10 to the power -8, 10 to the power -9 and even if it is better than -9 it will be good for something but it may be bad for something so I do not want to go below 9, in some specific molecular need I go for -12 which I not be able to retain but I want -12. But how to generate this vacuum that itself is a problem because I need vacuum to be actually constantly placed there, wherever my vapors are there where is my source of deposition system is everything is inside a chamber which is I actually evacuate and it should maintain the pressure.

Why I am constantly telling maintain? As things will evaporate what will happen? Pressure will actually increase okay so vacuum will spoil so I should know okay if I am depositing this much time so my vacuum has to be little higher better so that even with this it should not go below -6 okay that is the word better. As I said ultrahigh vacuums are better than -9, there are different kinds of pumps may be some I list them later, which one can do to actually evacuate. Heating system; evaporation is normally a process in which the film which want to deposited, I just now showed the 4 stages for I want to convert from solid or liquid to the gaseous state so I must provide thermal energy Kinetic energy so that it operates.

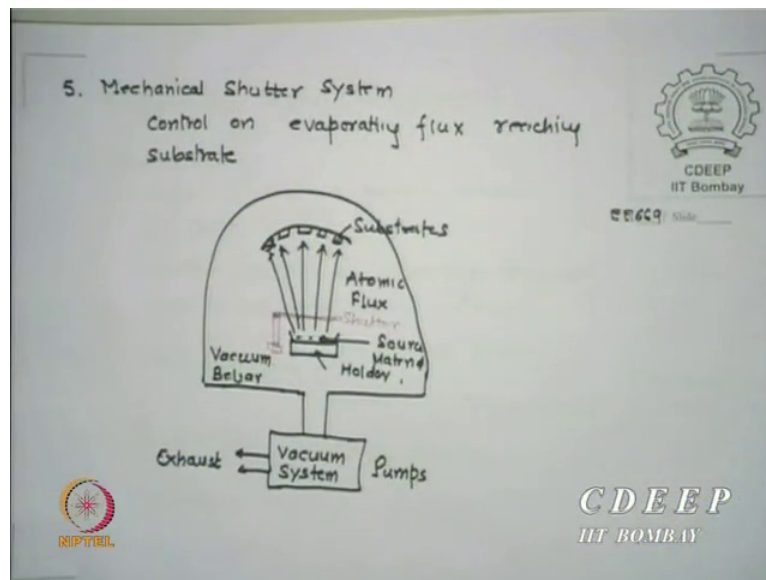
Now the question there is why vacuum? One of course I will show you some other reason, the most important reason why I am going for vacuum is, I can heat aluminum wire for example or any wire, why some other ceramic heaters; 1400, 1800, 3000, they start that way nothing wrong with it, but all oxygen around okay so it was oxidized in no time so all that I want the film to be as that is what the requirement I listed so I want that there is no oxygen content, better the vacuum the gas inside will be very very small and mostly not region okay, it is more inert okay so we will like to see that better vacuums are used because it will not oxidize the film during heating no oxygen around, of course it does have the quartz chamber which you put releases oxygen so it is not all that trivial but still.

So one method is of course you heat actually heat it okay it is called thermal heating, the other is you given an energy for heating by electron beams okay and we will show you 2 of them, Typical energy which will use is 1 to 10 KeV kilo electron volts, kilo watt is the power but the energy is KeV, but to keep a vacuum it should be covered somewhere okay so that is called Bell-

jar. And also whatever will I am growing I am depositing, I should be aware that how much film thickness I am going, I am depositing because if it is too thicker film I do not want and too thin also I do not want so I must monitor it. The monitoring system should also receive the films but should not interfere with the substrate anywhere, so thickness monitor is also a part of any such system. Then there is another problem which one sees, how do we stop the evaporation?

One method is you shut off the power do not operate but there is a still latent heat as we call, latent heat it does not go immediately so it is still I operate. Even if you switch of the power some you have already heated more than desire so by the time it goes below that temperature while it operates it will still operate that means the thickness will not be what you are looking for okay. Now this is an issue which therefore needs some kind of stopping physically so put a shutter so as soon as my operation over I bring shutter above the source, nothing can go to my substrate, it will hit to the shutter system. So therefore we need a mechanical shutter to control the flux going to the substrate.

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Typical vacuum system is shown here which is not the best drawing or either the best actually evaporating system. You have a, earlier we used to have quartz Bell jar, now we have stainless steel Bell-jars which is slightly better because why stainless steel is better? 316 in specific has a very low content of oxygen okay, 304 has okay those who are metallurgists should tell me why, 304 stainless steel are not as good as 316 these are the numbers okay TOH KABHI lab MEIN

JAO TOH DHOONDO YEH SS KAUNSA HAI, 316 HAI 304 HAI, normal steel BHI use HOTA SO stainless steel is not the only steel, unless chromium is added there is no stainless on that okay. Okay the typical Bell jar this is where it is earlier we used to have quartz now we will have stainless steel jars okay. If it was that is why we left quartz jar because quartz releases some oxygen so we wanted to get rid of that.

Then there is some holder over which the impurity I mean the film which you want to deposit species or gaseous whichever form you want to keep you can keep there okay. Then this red part I added just to make a shutter system which has a... Please remember the trick of the thread is all its operating knobs are outside the vacuum okay but if I move anything the vacuum should not change. So something has to be done some kind of Wilson Seal as we call which allows us the movement without actually, actually when I move it presses hard so it actually does not allow vacuum to go back so we need to have all kinds of Wilson Seals around so that no vacuum is released otherwise air will just get in, I move something air will go.

So all controls every control, electrode everything is controlled from outside which are mostly mechanical or electromechanical, but they should be separated from the jar they should get in but should not but anytime I do motion it should not change much vacuums. How to clear the vacuum? I have vacuum system which is connected to (())(35:15) there are 2 kinds of... If we have only one -6 or -7 torr then I say -6 means 10 to the power. -6 or -7 torr then you can have only 2 simple pumps, the 1st is called rotary pump, in market it is called mechanical pump and the 2nd pump is diffusion pump okay. So a diffusion pump can only operate if pressure below it is 10 to the power -2 I mean when it is sucking, diffusion pump cannot operate in atmosphere so it needs vacuum at least 10 to the power -2 to improve on that.

10 to the power -2 Torr I can create by rotary pumps so I have a rotary pump followed by diffusion pump, so 1st rotary pulls vacuum to -2 and then I start diffusion okay, and once diffusion starts pump starts it will start evacuating gases from above and will exhaust out. The system may be some other time I can show you 7-8 kinds of pumps each have own problems turbo, non-turbo but anyways right now this course will look into this. If you are in a lab at least that is what we have been told when we were students or we were even in engineering people in (())(36:42) that if you spoil a system you have to repair okay.

So if vacuum pump does not work during your evaporation, it is your job to open it, see what has gone wrong, read it, understand it, repair it and fix it back because other person is waiting to use that, so that is the method we learned so we almost know A to Z of system which we work simply because in so many years something will fail when I am working then I will get stuck. 4 months I spent only on designing an electron beam system, I had no idea what it is, (37:21) is not available in the market so I designed my own. Okay so please do it... If you vacuum it then there is heating something here which I can create heater which will convert this into gaseous phase, I open a shutter so these gas molecules or gas atoms depends on what you are operating will actually move upwards.

There is a target system where substrates are held, this typically this target system is some kind of spherical or cylindrical or rather spherical part of the sphere okay and the wafers are held everywhere. And very important thing which we do there is in a large sphere then maybe say 24 or 32 small wafers you can pick, so I have a mechanical motor on every wafer on the top so wafer actually rotates and this whole wafer system also rotates, what is it called? Planetary system. So in all evaporation system we have a planetary system in which whole sphere of holder is moving and each wafer is also rotating. Why we did this? Uniformity and step coverage, any angle this time when it will come I will see operation that side so step coverage as well as uniformity is possible by planetary system, what is planetary system?

Half spherical beam inside which there are wafer holders as many wafers you can hold and this whole system keeps moving and each wafer which has a small motor on that DC motors now they are degassing so USKO BHI protect KARNA they keep rotating. There is (39:20) you should rotate okay so there are all kind of electrical engineering goals in designing this planetary system okay. Now question arises few things before of course we will come back to it again, why vacuum? One of the things I said is that oxygen I do not want, or any other specie which can create some kind of impurity I do not want that but that is not the only reason I want vacuum there, vacuum has more relevant requirement is we will see this formula little later depending on atomic radius of any specie which you are operating, they mean free path of these gas molecules or this gas atoms is inversely proportional to pressure okay is that okay.

So what happens if I want let us say this distance is 1 feet or 30 centimeter, if I want the incoming atoms to reach substrate without collision, why with the collide what will happen they will split everywhere else but they will not go to the substrate area so I want them to go upward without collision. Collision will not happen if the distance I mean if the mean free path is larger than the distance you are travelling, the pressure and mean free paths are inversely proportional so larger the vacuum larger is the mean free path so more likely you will get flux which is going up okay, 2 regions vacuum is needed one is... (0)(41:07) of evaporation is a therefore since as I say I need to do all processes in the system I must provide you the growth rate okay or time or which this film thickness is achievable so I must create model okay.

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Modeling of Evaporation:

(i) We define P^* as Partial Pressure of a gas in equilibrium with its Condensed Phase at a given Temperature T .

Generally P^* is only function of Temperature (T).

(ii) p is defined as ambient hydrostatic pressure acting upon evaporant in Condensed State

According to Hertz principle, the evaporation rate is $\propto (P^* - p)$

In vacuum, p is closed to zero

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For everything which I do reality in my lab I should be able to create equivalent model and only then computer also can do same process. So where I am having for evaporation there are some definitions 1st, we define partial pressure P^* of a gas which is in equilibrium with its condensed state okay. We have a condensed state solid or liquid and what is gaseous total pressure which is exerting on it is called partial pressure at a given temperature this is fixed okay so for a specie so that is P^* . What is the total pressure which is outside, in the chamber there is a net pressure but at the vacuum it is I mean at the material to this whatever number of gases they will also exert pressure that is called partial pressure, (0)(42:19) law in chemistry lead it okay what is the difference.

Whenever there is condensed state and you are evaporating or some regions in the vapors are there, vapours are always there even at room temperature but their pressures are much lower because the amount of gas which is available in room temperature is very small, when you heat enough molecules are there, they will exert pressure on the condensed state that is called partial pressure. Whereas the chamber pressure or if it is in room that is called atmospheric pressure or room temperature which is the P capital P okay this is called P^* . And we know larger the temperature more atoms or molecules will come so pressure will be building as a heat. So it is found I will proof this and that is what the proof I want to give, P^* is only a function of temperature for a specie this I will proof by math or physics whatever it is, math is always needed for physics.

P is defined as ambient hydrostatic pressure which is normally around other than the condensed state wherever the net pressure is, is called the P . According to Hertz principal hertz law is called the evaporation rate is proportional to difference of partial pressure and the vacuum pressure outside is that clear the difference of that. In general in vacuum P is taken close to 0 it is not 0 but close to 0, compared to P^* it is always very small so one can say it is proportional to partial pressure, Hertz says that evaporation rate is proportional to partial pressure difference he said but I say okay P is normally close to 0. (44:13) we substitute that value and mathematical it will get subtracted accordingly fixed decimals bar accuracy, these days computers have 128 bits of accuracy so you can use it.

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ciii) V_g and V_c are volume of evaporant in Gas Phase and Condensed Phase respectively.

(iv) If we define ΔH_e as enthalpy-change from one phase going to the other, then according to Clausius Clapeyron Equation

$$\frac{dp^*}{dT} \propto \frac{\Delta H_e}{T(V_g - V_c)} \approx \frac{\Delta H_e}{T V_g}$$

(Normally $V_g \gg V_c$)

Ideal Gas Laws $p^* V_g = RT$ where R is Universal Gas Constant

Clausius Clapeyron Equation

Then there are 2 more terms we define V_g and V_c ; V_g is the volume of evaporant in gas phase and V_c is the volume of evaporant in the condensed phase. Condensed phase means either liquid or solid mostly solid so their volume will be very small because they are solid or liquid confined to area, gas means move away so the volume of gas phase is always larger than condensed phase. If we define ΔH_e as the enthalpy change going from one state to other.

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Modeling

(i) We define in eq at a

General

(ii) p

$p^* - p$

p is closed to zero

$p^* V_g = RT$ where R is Universal Gas Constant

$\frac{\Delta H_e}{T V_g}$

enthalpy-change from one phase to the other, then

Clausius Clapeyron Equation

Clausius Clapeyron Equation

The correct spelling is written here Clausius, Clapeyron, these are the 2 scientists and in those days scientists only used to become engineers so 1st they will do physics and then they will build a system. So according to this equation using thermodynamics dP^* by dT that is rate change of or not rate, temperature dependent change or partial pressure is proportional to enthalpy divided by T times $V_G - V_C$ differential volume. Typically as I say V_G is much larger than V_C , why I say you? Because V_C will condense state either solid or liquid very small volume, gas large enough so V_G s are much higher.

You can keep V_C also, if I give you a value, you subscribe and it will be smaller. Typically constant is proportional to unity so it is ΔH_e into T into V_G , this is typically dP^* by dT ΔH_e is enthalpy energy of formation atoms okay or regaining that atomic structure or atomic bonding that is given for a given material or at a given temperature. So for a given temperature ΔH_e is known so I know dP^* by this is this but I also know this gas which is now I created though it is not accurate to say it is ideal gas but we still believe it follows ideal gas law is, we say $PV = RT$ ideal gas law so $P^* V_G$ is RT where R is universal gas constant, is that okay PV is equal to RT 7th standard MEIN PADHA HAI ABHIBHI WAHI HAI change NAHI HUA.



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$\therefore \frac{dp^*}{p^*} = \frac{\Delta H_e}{RT^2} dT$
 or $\ln p^* = -\frac{\Delta H_e}{RT} + c^*$ let $c^* = \ln c_1$
 $\therefore p^* = c_1 e^{-\Delta H_e/RT}$
 Clearly p^* is only function of Temperature T

(v) Evaporation Rate R_{ev}

We have two Fluxes:

- Evaporant's Vapour Pressure $\rightarrow P$ dependent
- Condensed evaporative rate $\rightarrow p^*$ dependent

So dP^* USI equation KO modify KIYA TOH dP^* by P^* is $\Delta H_e / RT^2$, $PV = RT$ TOH LIKH DIYA then we organize the term so you get a term which is dP^* by P^* ,

Delta H e by R T square d T, I take integral of that, L and P star is – Delta H e by R T + some constant which I take L and C 1, constant can be in any form so I take L and C 1. Then I write P star as C 1 e to the power – Delta H e by R T, ABHI BOLA THAT NA P star is only a function of temperature (47:35) has proved that partial pressure is proportionally e to the power – hai na, so e to the power – infinity is how much? 0, e to the power 0 is sorry T is infinite, this is 0 so 1 so larger the temperature partial pressure is larger. ISKA KYA meaning HAI, ZYADA heat KAROGE ZYADA vacuum pressure BADHEGA ZYADA flux BAHAR AYEGA, as straight evaporation KA model AGAYA AAP CHAHTHE THE NA KE evaporate KAISA HOTA, AISA HOTA HAI all that we are doing is increasing the vapour pressure.

Now I am not interested in pressure, I am interested in KITNA film AYEGA, I want rate and I want to how much it will grow there okay so I 1st find evaporation rate. Now we can see from here there are 2 classes involved there okay, one of course is the one from the source the flux which is going up, but from the substrate which is not sticking there is a pressure P outside P star like this P from the top will return some flux okay return some flux okay. So this evaporants vapour pressure down is essentially P dependent external pressure or vacuum dependent, whereas this condensed pressure is dependent on the vacuum pressure at the condensed state okay just about that, how much is that. Now using this if A is the cross-sectional area through which this flux come, then there is a statement made by Hertz

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If A is cross-section area of flux coming out of evaporator, then

$$\frac{1}{A} \frac{dN_e}{dt} = \frac{1}{(2\pi m k T)^{1/2}} (P^* - p)$$

where $\frac{1}{A} \frac{dN_e}{dt}$ represents net Evaporation Rate

$$\text{or } Rev = \frac{1}{A} \frac{dN_e}{dt} = \frac{1}{(2\pi m k T)^{1/2}} (P^* - p)$$

Hertz-Knudson equation for Rev also takes care of return flux which is decided by α called Sticking Coeff for vapour molecules the surface and thus is written

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He says $\frac{1}{A} \frac{dN_e}{dt}$ where N_e is the number of atoms involved or atoms or molecules sometime, rate change of this this is the rate of number actually going with the time per unit area, what does that mean? Flux, this is essentially a flux which can be given by $\frac{1}{2\pi m k T}$ to the power half $P_{\text{star}} - P_0$, this is essentially called Hertz Knudsen equation this is called Hertz Knudsen equation but this is as I say is the rate represents the evaporation rate so evaporation rate R is $\frac{1}{A} \frac{dN_e}{dt}$, $\frac{1}{2\pi m k T}$ to the power half $P_{\text{star}} - P$. And P is how much? 0 so it is very small, it can be used or not. But just now also said that some flux may return okay so we say whatever is not sticking may come back, not necessarily because that pressure alone something which did not stick comes down okay.

The ratio of what is coming down to what is going is called Alpha V which is related to sticking coefficient. How much sticking coefficient I want? 1, everything should stick nothing should come, so Alpha V is typically maintained closed to 1 where oxidation but this is nothing this is vacuum this is ideal gas law, there was no gas law used there except the last flux, there we have 3 different fluxes except in gas phase we use gas phase, the other was solid there is no solid here, here there is only vacuum okay there the partial pressure was inside solid and insight silicon oxide and this is no partial pressure in solids okay this is partial pressure in vacuum okay on the condensed state. Okay so R_{VV} which is evaporation rate is $\frac{1}{2\pi n k T}$ to the power half $P_{\text{star}} - P$.

If we say Alpha V is close to 1 then you can neglect Alpha V otherwise I will have to give coefficient 0.9, 0.87, whatever number generally people in most cases we get Alpha V close to 1 most cases if your system is well-designed and you are a good... How do I improve the sticking coefficient? Anyone? If anything has to stick here, what how can I improve sticking, reduce then it will move around na, I want stick increase so (())(52:07) actually it will pick up now, it has an energy to bind, you need energy to bind so you provide substrate heating is that clear? So as you increase 100 degree temperature no step the material will stay, is that clear to you so there is Alpha is adjustable value.

Okay let us talk of 2 things, have you written down this? This is very as I said I am writing all these formulas for what purpose I keep saying, my process simulator has all those formulas built in then why I am learning because if the new process comes you should know how to actually

modulate okay, one of you may do maybe 1 out of 20, 124, 123 may not do but at least the availability of 1 percent I know how it is, for him only this is. There are 2 things as I said pressure P, one of course is the if we use something called Knudsen cell, when we can restrict the pressure so it can be made 0, there is nothing from outside pressure coming in so I can reduce that part number, the other of course as I said just now earlier I want to improve mean through path so this pressure is very crucial, smaller the pressure larger is the vacuum and larger is the vacuum lambda is...

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$$R_{ev} = \frac{1}{A} \frac{dN_e}{dt} = \alpha_v (2\pi mkT)^{-1/2} (P^* - P)$$


In vacuum, two things are affected

- ci) P the pressure due to return flux could be closed to $\rightarrow 0$ (Zero). Knudsen cell ensures this.
- Δ cii) The mean free path of evaporant atoms increases i.e.

$$\lambda = \frac{kT}{\sqrt{2} \pi \sigma^2 P}$$

Clearly better vacuum means higher mean free path.

Higher Mean free path means, unlikely collision between evaporant atoms. Unidirectional flow.


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So the at least how much lambda it should be? Whatever is the distance between source and the substrate, at least 3 times that you should have to increase. Typically I may say the distance may be 30 centimeter and the mean free path of 100 centimeter is necessary for having one (1) film growth film deposition. I repeat, typical distance between substrate is one foot 30 centimetres so at least 3 times that should be the mean free path. Sigma is the cross-section of atoms per unit area, P is the pressure, T is the temperature at which you are doing this, rest of the things are known so I can always calculate lambda mean free path for a given temperature for a given pressure and for a specie which cross-section is known to me, 10 to the power -4 centimeter square, whatever area atomic volume cross-section you can substitute, that number I will give in case I ask you to evaluate.

I never set the paper till last day so I cannot myself tell you what I will ask, only last day I decide I will ask with this so in that case often I cannot say what I ask, λ is $\sqrt{\frac{kT}{2\pi m}}$ upon $\sqrt{2\pi}$ σ^2 P by σ is the cross-section of the atoms which we are looking at πr^2 okay πr^2 , r is the radius. Everyone I am not sure I have not read Plummer's book but must be I mean all these are not novellas, this is not first-time it was during 18th-century to 19th-century so most of things are known to everyone. Like this I picked up from physics book, something I picked up thermodynamic book, now after I picked up many others are also picked up from the same source, they never told I have done it, everyone is doing same.

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$\therefore R_{ev} = \frac{\alpha_v P^*}{\sqrt{2\pi m k T}}$
 In Knudsen Cell, we can make $\alpha_v = 1$
 Then $R_{ev} = \frac{P^*}{\sqrt{2\pi m k T}}$
 Then the Film Growth Rate
 $F_{GR} = \frac{R_{ev} m}{\rho}$ ρ is density
 $= \frac{\sqrt{\frac{m}{2\pi k T}} P^*}{\rho} = \left(\frac{C D E E P_m}{T} \right)^{1/2}$
 $\Rightarrow \text{cm/sec.}$

A diagram of a Knudsen cell is shown, consisting of a central chamber with a small orifice and an outer chamber. Arrows indicate the flow of atoms from the inner chamber through the orifice into the outer chamber. The area of the orifice is labeled 'A'.

Logos for CDEEP IIT Bombay and NIPTR are visible on the slide.

Some of them are of course my own derivations but in our times it was not very important to tell I have derived it. I derived it I derived it, nowadays before you derive you say I have done it that is the only difference. So typically R_{ev} is $\alpha_v P^*$ upon $\sqrt{2\pi m k T}$ then there is to make $\alpha_v = 1$ the reason if you have this is the place where you are heating the material to be operated, I have to have another small chamber around whose orifice or the this 'A' you write everywhere 'A' word and now you can see if anything goes out or comes in there is very little chance of return attacking anything, it is called Knudsen cell, it is little costly so most evaporators do not have it but I just tell you that it is possible.

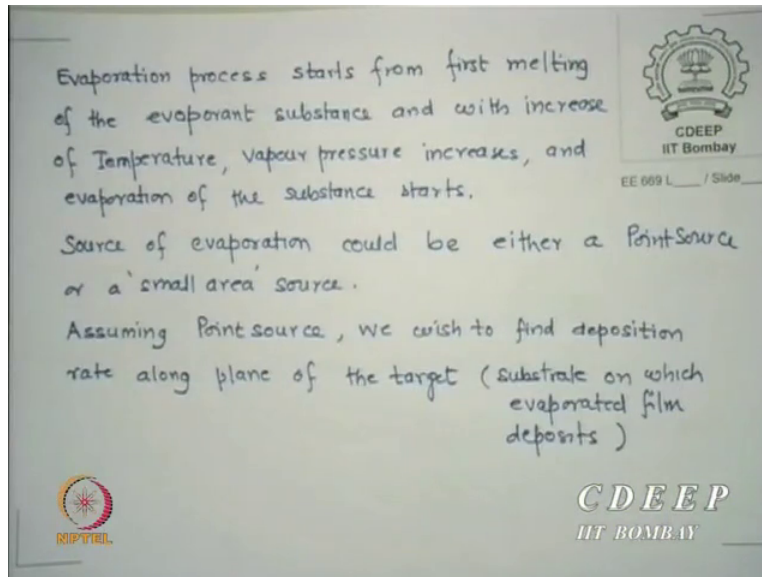
See if you are buying (56:31) or any small advert system you want to buy in few lakhs so all these features are not given Okay as straight as that. The natural cells are used you are doing

some better vacuum system like MB has... If you see MB if you see molecular beam (56:50) system has a Knudsen cell okay, and because they are putting 3 crores and above okay then they will put to you design of a chamber around the source okay it should be the degassable it should not actually release gas, it released it should be 1st cleaned out so there are many features in Knudsen cell, it should have area which is adjustable which I have fixed right now so Knudsen cell is a Knudsen cell.

Okay but our aim is not evaporation rate, our aim is to grow films, thickness, I want thick how much? So I say the growth film growth rate is decided by evaporation rate divided by... into mass by density that is the growth rate okay film growth rate, ρ is the density. So if I substitute this R_{evp} from here this can be written as $m \text{ upon } 2 \pi k T P_{star} \text{ by } \rho$ if I just for a given species $k T$ all these constants I know, for a normal way I assume that these are the metals where ρ is roughly this, this comes out for aluminium at least this $5.83 \cdot 10^{-3} A m \text{ by } T \text{ to the power half } P_{star}$, where A is the area of Knudsen cell. Or if there are no Knudsen cell whatever is the this area itself is the area.

So if I want thickness what should I do? Just multiply by the time of ρ operation so that much film thickness you have achieved, you know film centimeter per second, this is the deposition rate going on. Whatever time whatever thickness you want you decide time and what time it should do then shuttle should come, so there is a timer outside which can automatically do this, you set the time for the thickness you want. It is also connected with I have not shown but there is a film near the substrate on both sides there is a monitoring this thickness monitors okay, they also receive same films and they are mostly transducers okay they are capacitive transducers, so we actually monitor how much is the thickness of the film we are say ductile sensor okay. So pressure change HUA I figure out how much is the thickness okay.

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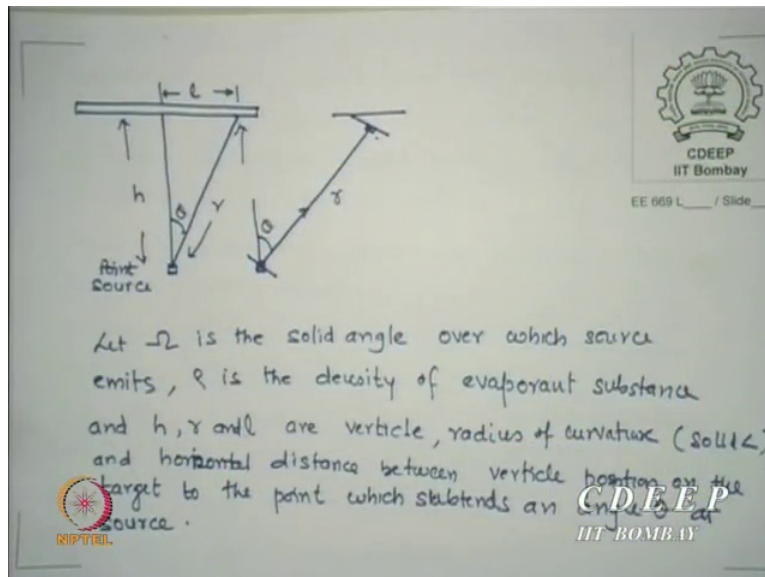


You know ductile sensors ITNA ductile ductile, where do you use? Keyboard, which has ductile sensors pressure sensors okay. So ductile sensors if VAJAN HOGA UTNA pressure BADHA DEGA WOH monitor HO JAYEGA, so I know how much, I have 1st calibrated this thickness social, just comes stops. As soon as shuttle comes power shuts off okay so it is not that in our system you do not have anything like this so your hand on the shutter your watch this is what we do. The reason is I am not interested in numbers of them okay so what is the actual evaporation process is, it starts from melting the evaporant substance, as you increase the temperature the vapour pressure increases, this is summary of what I said and evaporation of substance starts, is that clear.

Source of evaporation could be either a point source or maybe extended point source. If you have extended small area source little more mask and needed because now there are multiple points evaporations, most cases we take it point source and solve math, we wish to find now deposition slightly, what was our assumption? All molecules are travelling straight okay, but there are vapours all around so some flux will go at an angle, they may not interact but they certainly will not only travel vertical, they at an angle they will travel. So if you have a film substrate like this, the film thickness here and film thickness here will not be same, is that clear? If this is your target, some flux is coming some like this, so there is larger correct thickness but not necessarily same as this, so some angle which it is upstanding has an effect on the thickness.

Spherical reduces that but still it is a away position, the reason there is spherical because this unless the Knudsen cell design that it actually matches with that r it have the same problem okay equivalent problem. Right now I am assume only horizontal substrate and heating it, so is that clear to you why I am interested because I want on a wafer n number of wafers same thickness. It can be if you put the source up-down it will come down there is no problem, but you just look at, it will be your evaporant in liquid what will happen to it? Gravity JO HAI WOH NEECHE HAI NA so WOH solution NEECHA AJAYEGA ISLIYE UPAR SE RAKHA TOH UPAR HI JAYEGA. All possibilities are true only think of all possibilities, if you have solid so it will also fall but you can put clips, if you put a clip what material I should use is that clear?

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So there are issues, in this gravity SE WOH ANDAR RAKH SAKTA HAI, it does not bother us okay, simplicity of system, but theory wise it does not matter if it comes down or it comes in okay. If Sigma is the solid angle over which source is emitting solid angle all directions is that clear, there is a solid angle associated it is called Omega and where is the density of evaporant substance? And did are the distances I nominated, these are h vertical, this is the distance at L where I want thickness and this is the r and let us say it sub stands an angle to vertical as Theta. Then since it is this all around so I will assume here and here it will be same, here and here it will be same, where Theta is it will be same, is that point clear?

Spherical so everywhere same r , so all these positions ending an r will have the same things, is that clear what I want? I want to find thickness so roughly what I am doing is I assume vertical (0)(63:27) I measure it and put an angle to that that is what I am I did not show you exactly in formula, but the really is I actually do as vertically in one direction it come and projection of that along that axis COs Theta of that. This figure is 100 percent must be given in books so I am not saying this is because this is needed, how much thickness around. How I thought it is projection USKA example HAI WOH, YAHA DIYA USKA projection assuming that it is vertical and at an angle what is the projection okay so that is the method most people do so I thought I will show whether it is same Theta.

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vacuum is better ($< 10^{-6}$ torr), then mean free path is good no. like 100 cm. Since distance between source & target, vertically is around 30 cm (max.) [$h \sim 30$ cm], we can assume flux transport reaching target with scattering and at low pressure, return flux from target can also be treated v.v. small.

In this case $\Omega = 2\pi$

Then flux reaching in vertical case = $F = \frac{R_{\text{evp}}}{2\pi r^2}$

\therefore Growth rate = $\frac{R_{\text{evp}}}{2\pi r^2} \frac{m}{\rho}$

From geometric consideration and $\cos \theta = \frac{h}{r}$ $h^2 + l^2 = r^2$

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Is this Theta and this Thetas are same? Yes they are, only one YEH PURA AISA SAB JAGAH HAI NA, solid, if that thing is better, better than -6 torr, mean free path is as good as 100, typical distance between source and target is typically... Please do not think that HUMARE ISME TOH 50 centimetre HAI then USKO 150 CHAHIYE WO then accordingly you push it. So etch is typically 30 centimetres, we can assume flux transport reaching target with scattering at an angle at low pressure return flux target is very very small, nothing P is not effect. Then is that solid angle is how much now? 2π 360 degree, so solid angle is 2π is that okay. The flux density reaching a vertical case are evaporation by area whatever $2\pi r^2$ the growth rate is R_{evp} upon $2\pi r^2$ m by ρ from geometric considerations, what is geometry?

Triangle, $h^2 + l^2 = r^2$ and $\cos \theta$ is h by r , you want to just a minute h by r is $\cos \theta$, θ is angle from the vertical so \cos base is only vertical, base by hypotenuse is \cos so h by r and geometry says right angle triangle $h^2 + l^2 = r^2$ THOD math KARTE HAI ISKE UPAR. What is that I am looking into, film growth rate at an angle θ , evaporation R upon 2π WOH TOH HAI, AUR EK term ANA CHAHIYE JO angle PE HO. Please check it because when I solve it I do not check it okay maybe sometimes I make mistakes, do read the book and verify I am right and tell me also I am right. Why I say? At least I know you have read, you read from the book and tell me I am right and it is not that good then I will modify.

Actually I am writing it so much because I am actually doing whatever lecture I prepare I just think I am writing there so that I do not have to redo it, I should not do this method I should only say give points and you should think but the way I preparing myself I am just writing without seeing anything. So okay for your faith I have given you 3 lectures today and the earlier 3 or 4 whatever they are they will be available on moral on next maybe 3-4 days okay but I keep telling you and my undergraduate students will verify that.

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Growth rate at point 'L' from vertical point on substrate is

$$= \frac{R_{\text{evp}} m \cos \theta}{2\pi r^2}$$

since $h^2 + l^2 = r^2 \therefore r = \sqrt{h^2 + l^2}$

We have $\cos \theta = \frac{h}{r}$ and $\frac{\cos \theta}{r^2} = \frac{h}{r^3}$

$$\therefore \frac{\cos \theta}{r^2} = \frac{h}{(h^2 + l^2)^{3/2}}$$

Film Growth rate = $\frac{R_{\text{evp}} m}{2\pi r} \frac{h}{(h^2 + l^2)^{3/2}}$

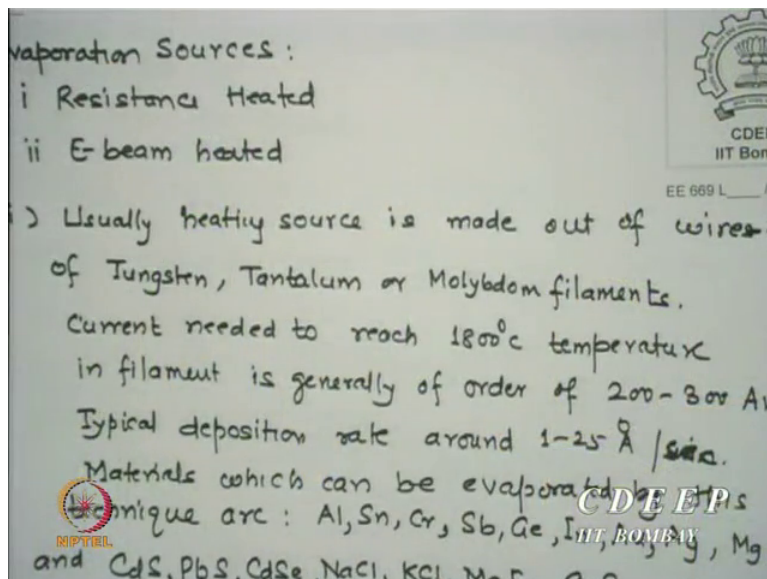
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So growth rate at any point L from the vertical point is $R \text{ evp } m \cos \theta$ and this $\cos \theta$ as I said is h by r , r is $h^2 + l^2$ under root so $\cos \theta$ is h by r , $\cos \theta$ by r^2 CHAHIYE MUJHE h by r^3 $\cos \theta$ by r^2 is this sorry r^3 , no no WOH r^2

hi hai theek hai then the film growth is $R \text{ evaporation } m \text{ upon to } \pi R \sin \theta \text{ upon } h^2 + l^2$ square to the power 3 by 2, this $r \text{ cube ARAHA HAI ISLIYE } 3 \text{ by } 2$, $r \text{ square TOH IDHAR SE ARAHA HAI EK AUR } r \text{ HAI NA}$, $\cos \theta \text{ MEIN } h \text{ by } r \text{ HAI}$, $\cos \theta \text{ JO HAI by } r \text{ square } h \text{ by } r \text{ cube okay THEEK hai } r \text{ cube KE KARAN } 3 \text{ by } 2 \text{ term aya}$, I now know how much is the film away from if h is the distance and l is the point where I am measuring thickness, I know roughly how much is will be smaller or higher? Denominator is higher larger than the numerator obviously, the maximum flux will go straight, some will go on this okay that is why that planetary are required and rotating systems are required.

So if everywhere get so every position finally will be seen equivalently on an average therefore uniform film. Last KO material POOCH RAHE THE WO DIKHATE HAI FIR we will start it next time okay. Is that formula clear? Any point the flux reaches is smaller okay so thinner oxide thinner films and uniformity how do I get? If I have planetary motion it rotates wafer rotates so everything is roughly seen here. From where that was designed is this formula, this was used to actually design the planetary system how much I okay so what rate you should move so that this actually goes uniform, so this is not just for the sake of it, it was used for design okay.

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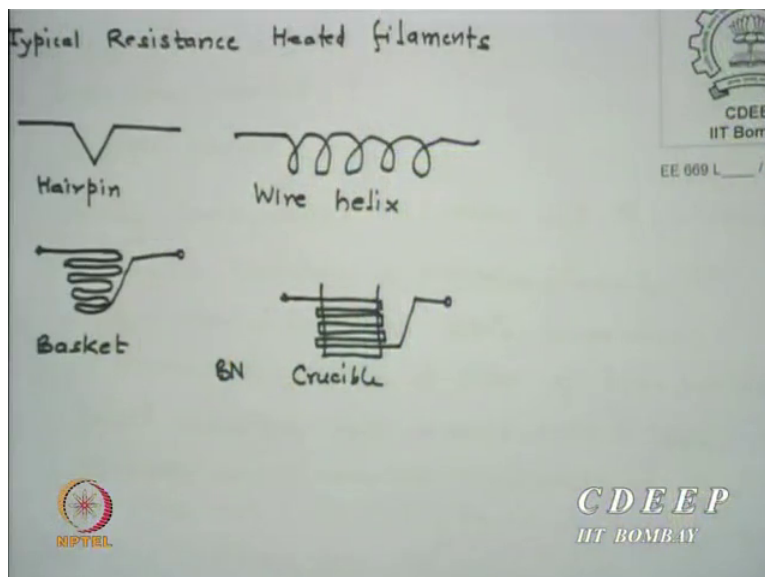


There are typically there are 2 kinds of sources we use for this, one is resistance heated, E-beam heated, e-beam we will see later but today only we will show you resistance. Usually the heating sources made of wire filaments not wires, wire elements of either tungsten, tantalum,

molybdenum, maybe others, what are these metals called? Transition metals, very unlikely for they will evaporate I mean their temperature of melt is 3000+ okay. Now if I pass current through this tungsten or tantalum or molybdenum filaments, they will heat because they are $I^2 R$, it will heat okay. The maximum temperature which most of them can give for a typical currents of the order of 200 amps to 300 amps is 1800 degree centigrade, most metals which we use can evaporate at 1800 degree.

Typical deposition rate using a resistive source is around 1 to 25 Angstrom per second. This is $I^2 R$, there is R there I current, $I^2 R$ simple wattage. The materials which can... If you do joules it is much better but it is not joules, there is no 2nd material on that okay. This is not joules, joule actually is done because it is cold heating as we called okay some other time. Okay the material which can be evaporated with this technique are aluminium, tin, chromium, antimony, germanium, indium, gold, silver, magnesium, calcium (71:18) okay any specie. It can also deposit so-called compounds cadmium sulphide, lead sulphide, cadmium silicides, and even calcium chloride. Where do these 1st 3 are used? Anyone? Solar cells, then we can deposit NaCl, KCl, magnesium fluoride calcium fluoride. Calcium fluoride is very important material for self-assembly nanostructures, THODA PADHO, calcium fluoride is one of the biggest candidate for self-assembly nanostructures okay.

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I repeat, most things can be evaporate which have melting temperature around 1800 can be evaporated, anything higher than 1800 or 2000 it cannot be evaporated. Just last slide for the day, the typical filaments shapes are something like this, there is a hair pin kind of this, then we have a wire which you want to evaporate USKE UPAR AISA loop BANA KE DAALDO, you understood EK hair pin HAI USME wire fold KARKE DAAL DO, aluminium wire USKO BEND KARKE USPE JITNA ZYADA CHAHIYE UTNA 4 pieces DAALDO okay. When it starts melting it will actually cover-up all these wires because it will 1st liquefy, the surface tension will increase so WOH AISA CHAARO TARAF flow HOJAYEGA and then it will start evaporating.

Sometimes we have a wire bigger wire and larger flux you want, you have some kind of a coil and you put wires inside, spherical coils USKE ANDAR MEIN wire DAALDO JO BHI HAI operate KARNA HAI HUMKO USKE (73:11) HONA CHAHIYE. SAMJHO AAPKE PAAS wire NAHI HAI, PC HAI TOH ISKE basket BANA SAKTE HAI WIRE KI, (73:19) MILTA HAI ISKO HEAT KARKE FORM KARTE HAI, USKE ANDAR WOH PIECE DAALDO since this is smaller than this it just fix inside like this. If you have are you want something species powder then you can use Boron nitride crucible USKE CHAARO TARAF YEH coil wind KAR SAKTE HO AUR ISKE ANDAR powder RAKH SAKTE HO so it is not necessary that what shape, you give me shape I will actually create the kind of filament it can generate.

The currents are passing through this, you need a current transformer which can give you typically 200 to 300 ions of currents, Thank you for the day.