Advanced Neural Science for Engineers
Professor Hardik J. Pandya
Department of Electronic Systems Engineering, Division of EECS
Indian Institute of Science Bangalore

Lecture – 08
Polyimide Coating on Silicon Wafer

Welcome to this lecture, this lecture is on physical vapor deposition, if you remember in the last lecture we were talking about silicon dioxide and in silicon dioxide we were talking about different ways to grow silicon dioxide one is your CVD which is chemical vapor deposition and second is your PVD which is physical vapor deposition.

In physical vapor deposition that means, you have a material which is in physical state and you have to melt it or you have to take, bombard the ions, so that the atoms would be dislodged from the material and there is a deposition of this film on the substrate. So mechanical way or electrical way of depositing the film which is physical in form from the physical form to the thin layer is called physical vapor deposition.

This is just a very easy way of teaching you, but within the physical vapor deposition there are different techniques one is called thermal evaporation, second is called Electronic Beam Evaporation or in E-Beam Evaporation and the last one is called sputtering. So let us see each one in detail.

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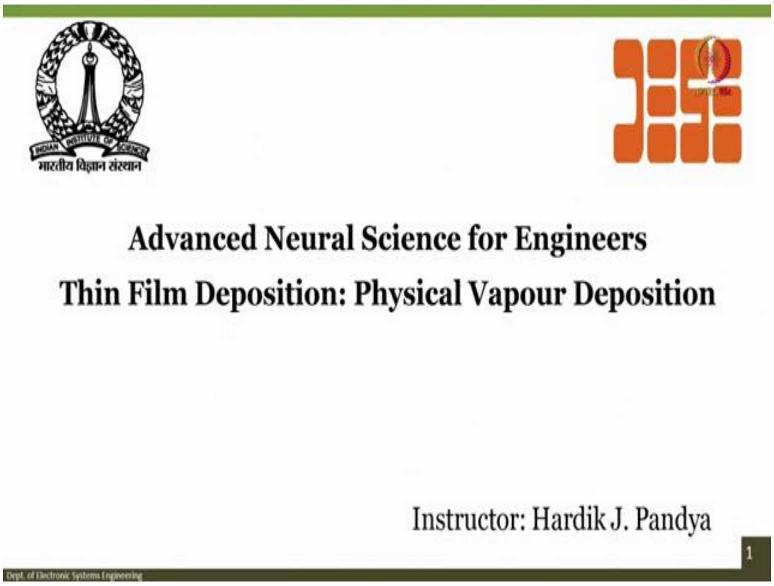

Advanced Neural Science for Engineers
Thin Film Deposition: Physical Vapour Deposition

Instructor: Hardik J. Pandya

Dept. of Electronic Systems Engineering

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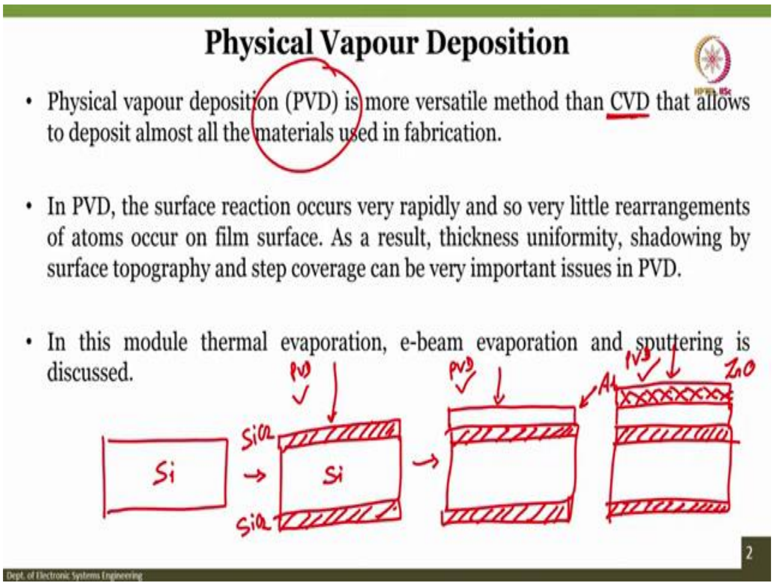
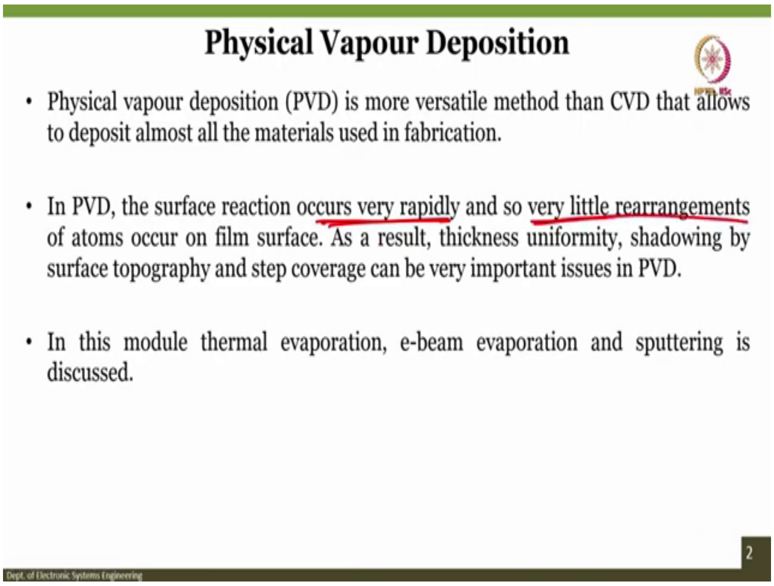


Physical Vapour Deposition

- Physical vapour deposition (PVD) is more versatile method than CVD that allows to deposit almost all the materials used in fabrication.
- In PVD, the surface reaction occurs very rapidly and so very little rearrangements of atoms occur on film surface. As a result, thickness uniformity, shadowing by surface topography and step coverage can be very important issues in PVD.
- In this module thermal evaporation, e-beam evaporation and sputtering is discussed.



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This lecture we call as a thin film deposition techniques and physical vapour deposition. So physical vapor deposition now is more versatile than CVD, how it is more versatile than CVD, once we look at the CVD, which is a chemical vapour deposition, then we will see that how we call PVD as more versatile than CVD and PVD allows us to deposit most of the materials that are used in fabrication.

So that is the advantage of PVD if you have silicon wafer and un-silicon wafer you have your oxide that means it becomes oxidized silicon wafer just for representation, I am not drawing the oxide on both sides if you want you can draw it also. So silicon dioxide on silicon wafer you start with silicon wafer and then you have silicon dioxide like this, can you deposit silicon dioxide with PVD?

Yes, now, you have a vapour once again with your oxidized silicon wafer and you want to deposit let us say metal, can you deposit a metal? Let us say you have aluminium can you deposit this metal with PVD? Yes, on this metal I want to deposit zinc oxide, can I deposit zinc oxide with PVD? Yes, this is the versatility that you can deposit insulator, you can deposit metal, you can deposit semiconductor, you can deposit semi-conducting oxides on the on the silicon wafer with help of the PVD.

And thus, PVD helps us to, or it is the technique by which we can deposit almost all the materials that are used in the fabrication. So let me just rub it around. So now in the PVD the surface reaction occurs very rapidly and so very little rearrangements of atoms occur on the film surface. Now first, you should know how this thing works.

So let me do one thing I will just get one more slide. What we are talking about in this case is that in PVD surface reaction occurs rapidly what is surface reaction what is rapidly and what are what do you mean by very little arrangements, or rearrangements of the atoms, first let us understand how the PVD works.

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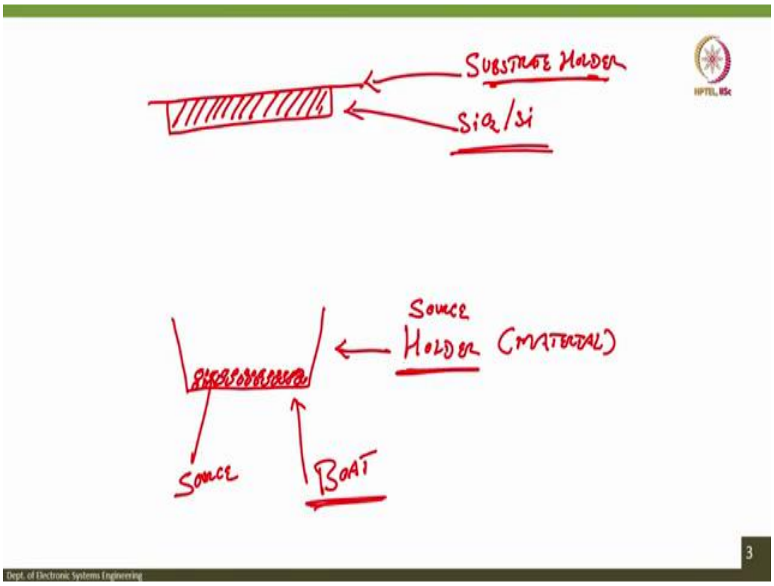

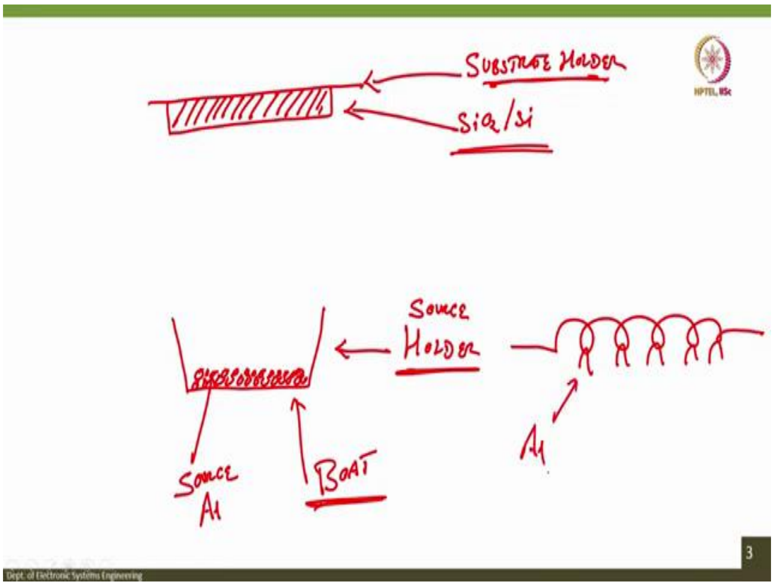

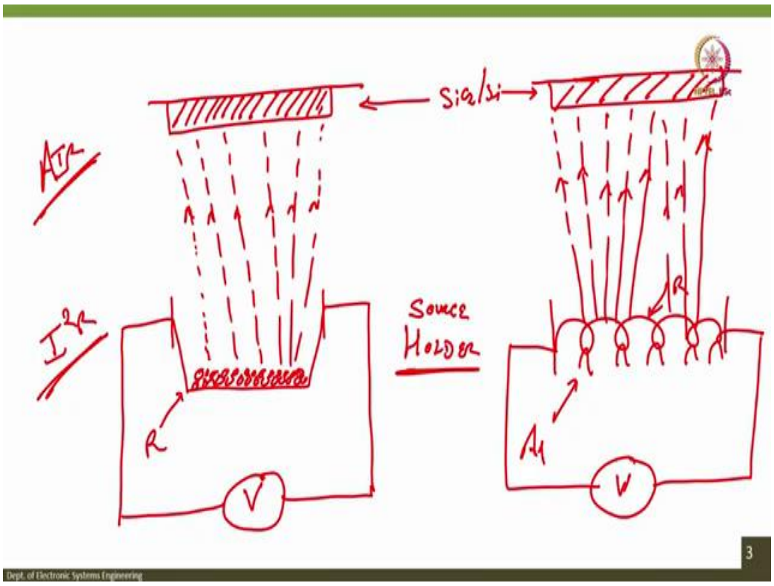

So you have a holder that holds the material and in the holder, you put the or you load the material then you have a plate to hold the substrate, a plate to hold the substrate. So this is called substrate holder. Substrate, what is a substrate? Silicon or oxidized silicon wafer. What is this? This would be your source so you can say source holder just to make it easier we call this particular holder, boat.

We call it as a boat this was easy you have oxidized silicon wafer, you have a substrate holder, you have a source holder or a boat instead of boat you can also have a coil in which you can load the wires like this, these wires are your let us say we want to have aluminium as a source material. So these wires are also aluminium.

The substrate holder and silicon wafer or oxidized silicon wafer remains as it is. Now, you apply a voltage so I will just remove you will remember the bottom is called the this one is called, source holder is called boat and what material we have aluminium. So we apply a voltage very high volt to this particular boat or to this coil.

What will happen depending on the resistance of this material, depending on the resistance of the coil the current will flow through when current passes through there is I square R heating, I square R is called Joule heating. Now, because of the joules heating because of the I square R heating the material loaded onto the boat will get will melt this will get melt and finally after melting it will start evaporating in this direction.

Same thing goes here also let me draw the substrate a little bit bigger, what is this, this is your oxidize silicon wafer and as I said the material will start melting and evaporating in this direction. But if there is air, so now let us use the logic if I have I, air is what insulator or it is a conductor, air it is an insulator, so if I hold up a power cable where there is lot of power that passes on at the end of the cable can the shock let us have a whole example let us that is good that you can see me now.

Suppose you, this is an insulator I am wearing a proper glove I am holding it to some equipment and end of this there, is very high voltage extremely high voltage, if I show it to you like this and you are standing let us say 2 feet away from me, just show you like this, would you get a shock? Most likely not. Why? Because there is air in between an air is then insulator.

So possibly when we are hitting this material, if there is a air then there is lot of collision with the particles in the air that collision will call distraction and because of that, the material that is melted may not reach uniformly to the substrate. So what is an alternative? Alternative is that we make sure that the material can travel as much as possible without colliding with any other particles.

That means the material that we want to deposit when it is melted when it is evaporated can travel at max distance before it collides with anything. If it does not collide, then we can get a better uniform material layer or thin film on this substrate. So to do that what is a solution you have a vacuum.

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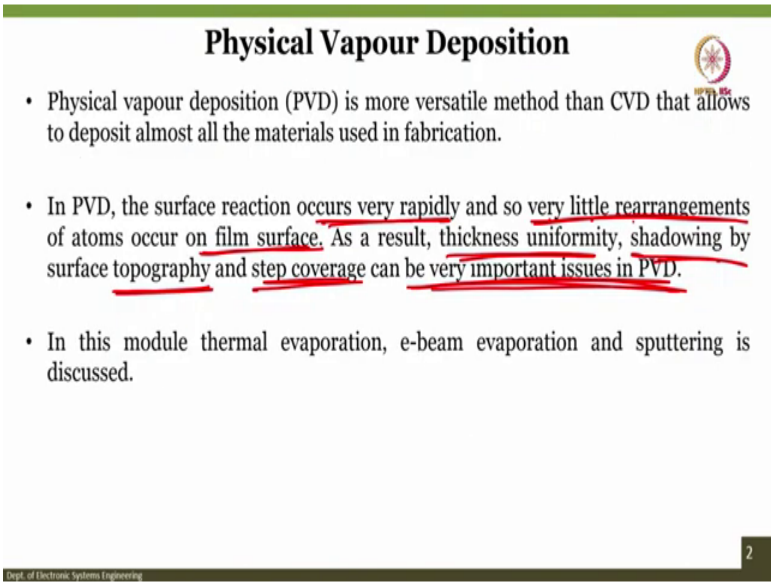

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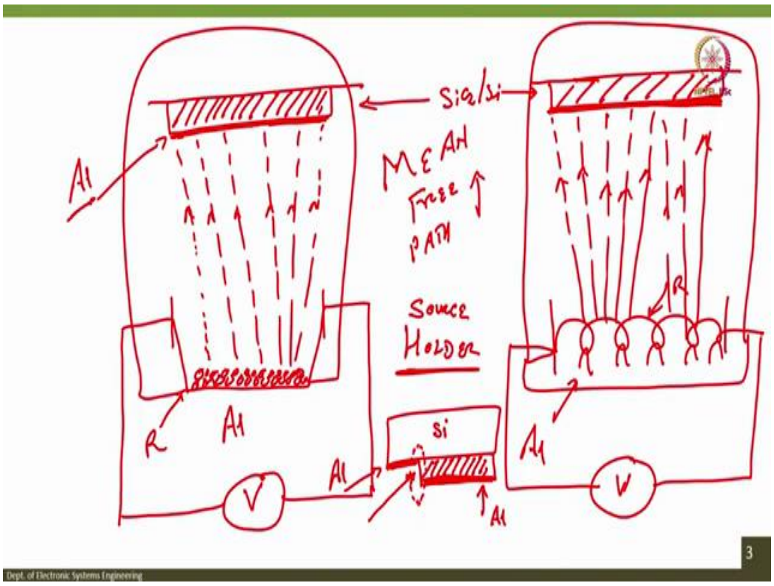

So that entire thing is kept in a vacuum chamber, this entire thing is kept in a vacuum chamber. So then there is a term that we learn called mean free path. So the mean free path will increase in presence of vacuum this much is easy. So now, what we were learning here is that because this material that is a source material in this case we have taken aluminium as a material.

So the source material when it melts and evaporates, it evaporates so rapidly that the layer that forms here, let us say this is a thin layer it forms so fast, this layers form so fast that, very little time for rearrangement of the atoms occurs, this deposition occurs so fast that very little time is there for the attempts to rearrange itself.

That is what we were learning you see this one very rapidly. So very little rearrangements of atoms occur on the film surface. As a result, the thickness uniformity shadowing by surface topography, and step coverage can be very important issues in PVD. What is step coverage we will see.

So now if you see that you have a material this is your silicon and then this silicon dioxide, in this pattern. Now, if you deposit the material, the material will get deposited here uniformly aluminium will get deposit here also uniformly, aluminium, this is aluminium, this dark one, this is aluminium, this is aluminium, but in this step, this region the deposition will not be so uniform.

That is called step coverage to cover the step uniformly, this area. This step will not be covered uniformly, and that is what is called the thickness uniformity, shadowing by surface topography and step coverage, step coverage is very important in a lot of application. And that is why that is a limitation of this particular or the issue with the PVD.

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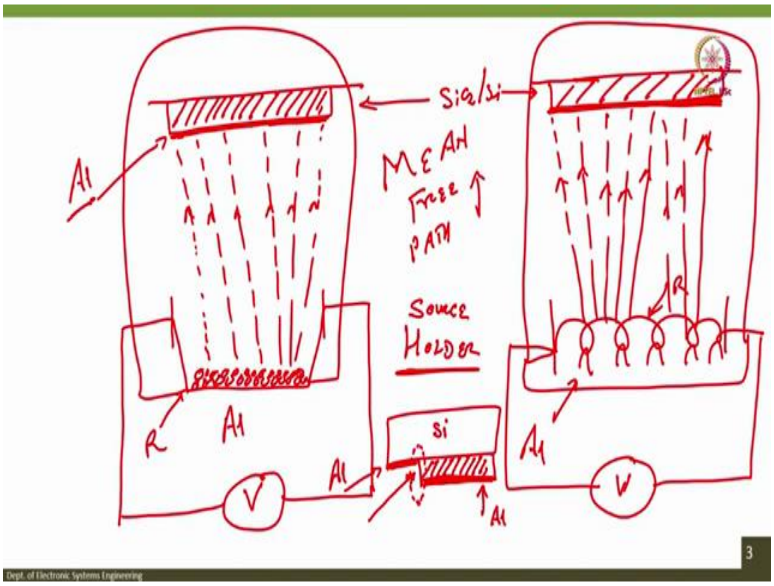

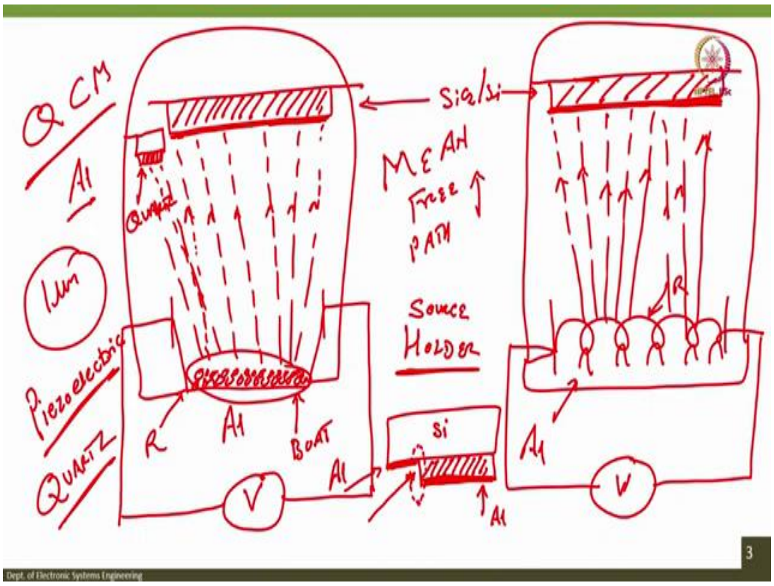

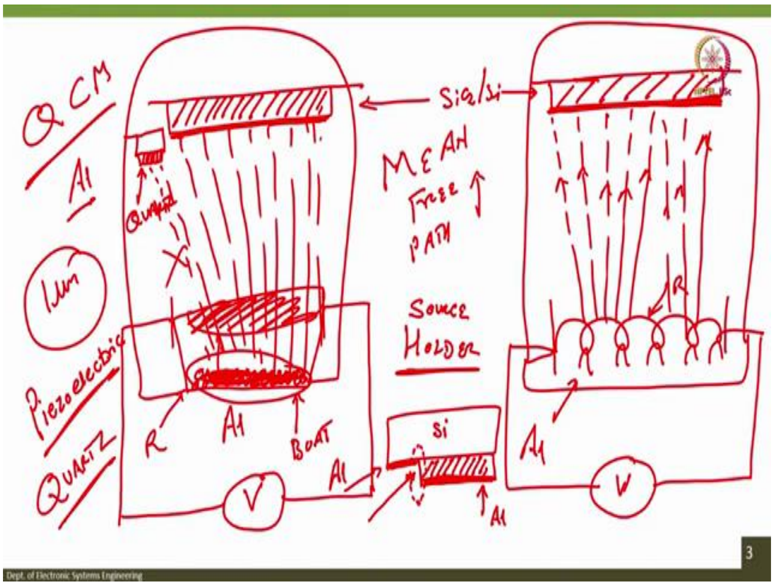

So in this module, let us understand three techniques. First one is terminal evaporation. Second one is e beam operation. And third one is sputtering. So now the question here is that, if I say that I am going to deposit one-micron aluminium, how would I know that it has reached one micron? That is my first question. Can you guess?

I will just give you 10 seconds to guess. And then we will get back, think about if I want to deposit for one-micron aluminium, how would you know it is one micron? Any idea? Even if you have I cannot hear, is not it? That is a limitation of online that interactions are less and that is why we have portal, NPTEL portal.

So you can ask us questions, doubts through the NPTEL portal, do not ask solution for the assignments, not allowed. So what we will do, we will have we will we can use the principle of piezo electricity, piezo electric, what is piezo electric? When there is a pressure there is change in the voltage. So you remember what kind of materials are used for piezo electricity or what are materials that have piezo electricity?

If you recall, there is material called quartz. So quartz crystal can be used to measure the thickness of this particular material. That means I can place a quartz in this region is a quartz. So the material that gets evaporated on to the vapour which is a substrate will also get evaporated on to a crystal which is quartz and when it gets deposited onto the quartz the there is a change in the voltage.

So we can use a quartz crystal monitor called QCM to monitor the thickness of the material that we are depositing on to the substrate that is the first point that you need to remember, QCM quartz crystal monitor can be used to monitor the deposited film. How much film is deposited, rate of the deposition, the another question is that when you heat this boat when you heat the boat the material is melted but it will take some time for the material or the material to get uniformly melted.

So should we start your evaporation as soon as we apply the voltage to the boat or we wait for certain time. So initially you have here a plate, a plate which is which will cover or mask the deposition and once these things are uniformly melted this plate is opened. So it goes in a different direction and then you can deposit your material do you understand? So you wait till the metal gets melted and then you open the masking plate.

So that when you start the deposition it will be uniformly deposited and you can always close the deposition not by just dropping the voltage but by bringing the plate back into this direction. So if you bring the plate back the material that gets deposited will not reach in this region. So that is how the things are done.

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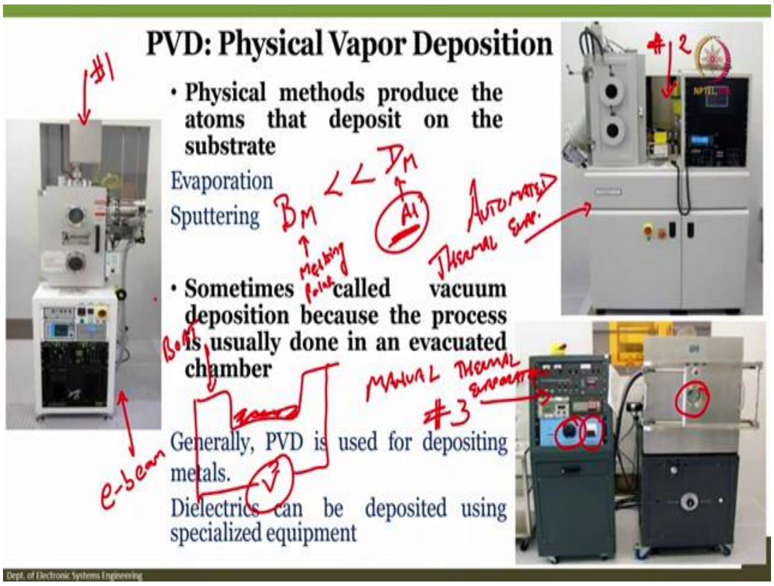

PVD: Physical Vapor Deposition

- Physical methods produce the atoms that deposit on the substrate

Evaporation

Sputtering

- Sometimes called vacuum deposition because the process is usually done in an evacuated chamber

Generally, PVD is used for depositing metals.

Dielectrics can be deposited using specialized equipment

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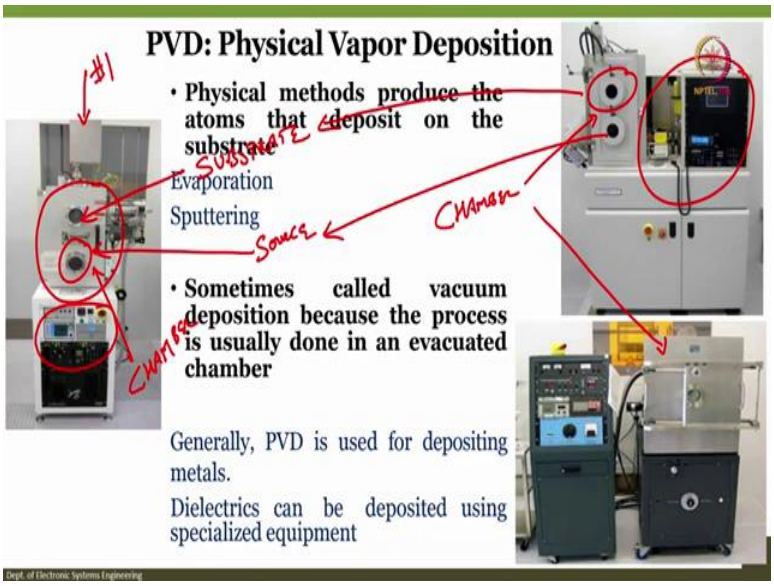

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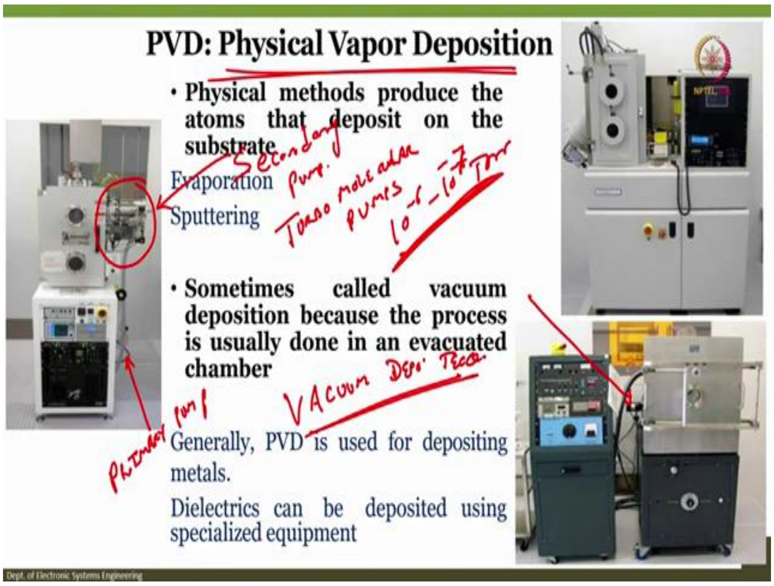

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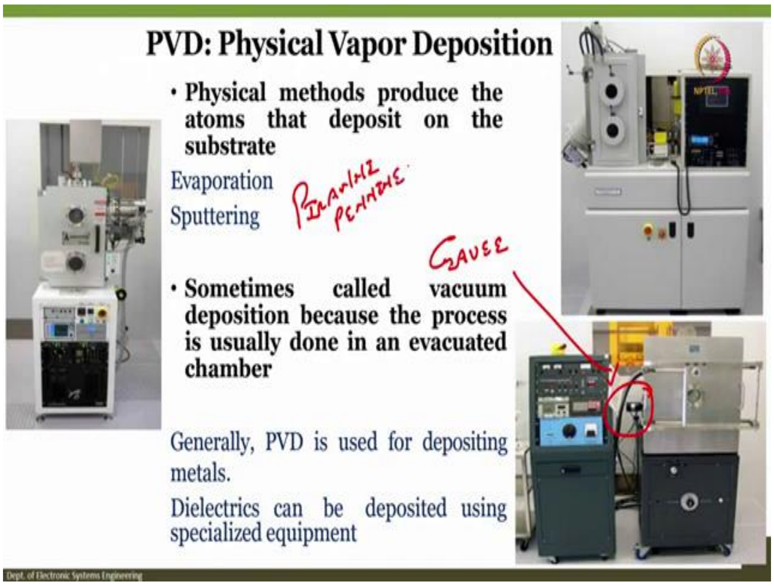

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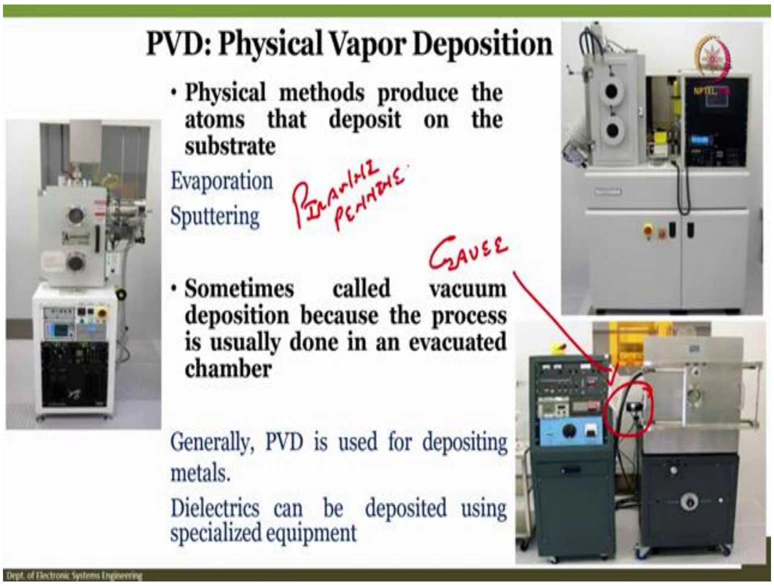

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So let us see the slide you can tell me what is this, this material or this system and this system can anybody guess? See what are the things in the system see very closely and carefully and then we will continue discussion just giving you 1 second or 2, 3 seconds to look into the photographs, we are able to see? Now, let us start with the number 3, this is number 2, this is number 1.

So this is thermal evaporation system and this is electron beam evaporation system. This is automated thermal evaporation system, this is manual thermal evaporation system, evaporator, thermal evaporator. And this one, is a knob to apply the voltage. This is the meter for understanding how much current flows through the source holder or a boat. These are the windows to see you can see whether the boat is melted or not.

The source in the boat is melted or not, if boat gets melted what will happen? All the things will fall and that is the reason why in mistake also I said that if the boat is melted what will happen? So when the boat gets melted let us say do you have this and you have material here and the apply voltage and the current becomes so high that the boat itself starts melting the material of the boats as melting what will happen this is not a good idea because then you have 2 different metals getting deposited onto the substrate forming an alloy.

So always understand that the material that is used for boat, the material that is used for boat should have a way higher melting point compared to the material that we use for the deposition. So here the material that you use for the deposition was aluminium, the materials that we use for boat should have way higher melting point compared to aluminium, has a very important point and for the material which will not, which will have the melting point similar to boat material or way greater than boat material then thermal evaporation fails.

We cannot use that thermally evaporation where the material that we had depositing its melting point is way higher than the melting point of the boat material. So you need to be careful on where to use thermal operator when not to use thermal operator. Now, what other things you can see, that is not all about thermal evaporation.

The other thing that you see is this one, this is a chamber, so is this one and so is this one, these are all chambers. Now, you say you drawn like this, but does not look like this does not have to look like this what I am saying is that a chamber in which you can create a vacuum and in this case you have only you have two windows actually you see here closely, but this is very clearly visible one is the window to look at the substrate, one is the window to look at the source, one is a window for the substrate, one is a window for the source, easy.

What we have seen there is a, and of course, here whole electronics is there to apply the voltage here it is automated you set the parameter automatically the deposition will occur and will stop. Now, the other things other things are very important to understand the equipment. So that becomes easier and just we are not just doing this for the sake of theory, I will be showing you the experimental labs in which we will show how the e beam, thermal evaporation system actually works.

So let us not worry about it too much if we do not get too much clarity from the schematic or from the photographs. The next thing that we need to see if you see the picture is this particular region in this it is not too visible in here everything is within it on the backside of it, but this is a good photo, because I want you to look at this particular gauge there are generally two gauges.

So this is by the way, secondary pump and then always there is a primary pump, primary pump. Primary pump and secondary pumps are used to create vacuum. And generally we use Turbo molecular pumps to create vacuum, vacuum can be 10 to power 6 to 10 the power 7 Torr. 10 to the power minus 6 to 10 power minus 7 Torr this will be a range in which the vacuum is created into the vacuum chamber and because a free or physical vapor deposition method.

Whether it is thermal evaporation, whether it is e beam evaporation or whether it is sputtering all the three different techniques or evaporation techniques are or requires all there evaporation technique requires vacuum and that is why these techniques are also called vacuum deposition techniques. So if in some books, if you see vacuum deposition techniques, do not worry about it, physical evaporation techniques are also called vacuum deposition techniques. Because the deposition occurs in the presence of vacuum.

So now what you are seeing primary pump, secondary pump, these pumps are used to create vacuum. Now, let us go to the next point. It is very complicated that what I am showing it to you I am just showing the easy easy part of this system, the system is way too complicated, but we do not have to worry because you have to utilize the system not make the system if you are interested in making an entire system with electronics then we can go into that particular direction.

Right now, you should be interested in what kind of systems are then and how we can use this system. So now, there is one more thing here this is called gauge. There are two gauges, one is called Piranni and Penning, Piranni and Penning gauges. So the Piranni gauge is used for measuring low vacuum about 10 to the minus 3 Torrs and greater than 10 to power minus 3 all the way 10 to the power minus 7 or minus 8 Torr can be measured with the help of penning gauge Piranni is still 10 to the power minus 3, penning is for greater than 10 to the power minus 3 onwards.

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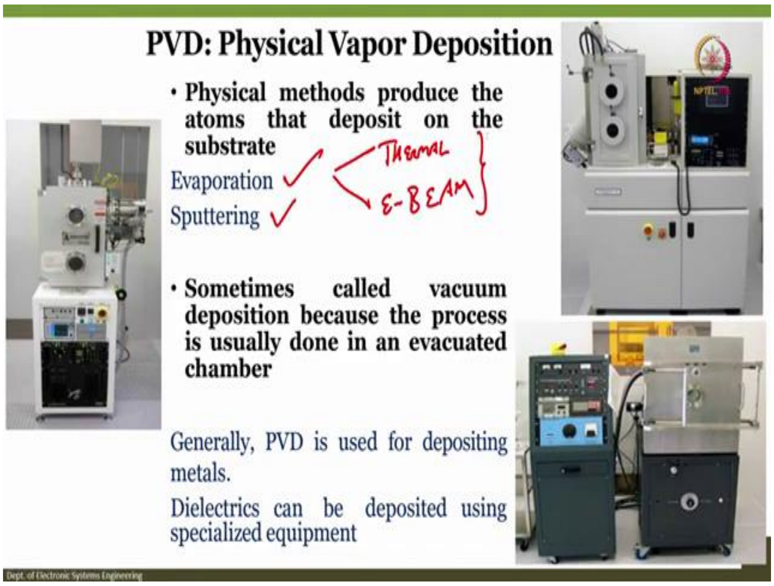

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- Physical methods produce the atoms that deposit on the substrate

Evaporation ✓ THERMAL E-BEAM

Sputtering ✓

- Sometimes called vacuum deposition because the process is usually done in an evacuated chamber

Generally, PVD is used for depositing metals.

Dielectrics can be deposited using specialized equipment

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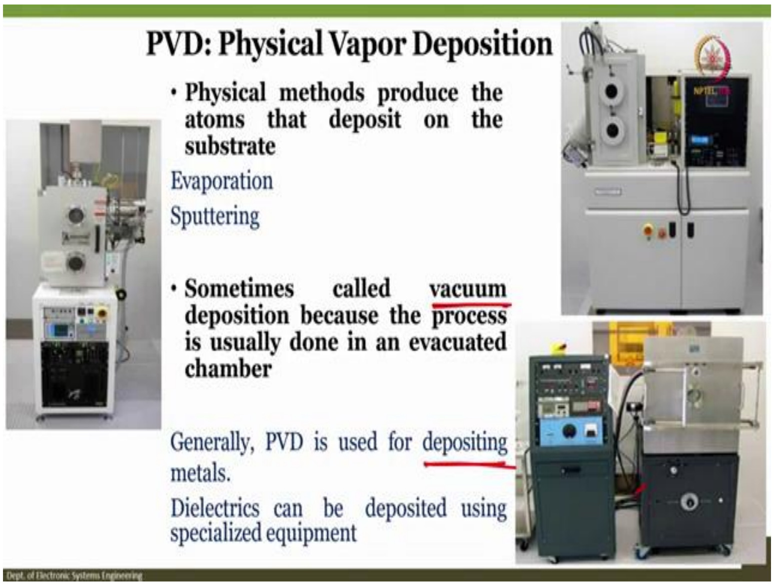

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So these are some of the some of the things that you need to understand about the evaporation system. Now as I mentioned, we can divide the physical vapor deposition, into two techniques one is evaporation, one is sputtering but within evaporation you have thermal and you have e beam, thermal and e beam.

Now, we also discussed that there are 3 deposition techniques and that is why it is a 3, but based on the way, base in the way that film is deposited thermal and e beam falls in similar zone while sputtering falls in another zone. So physical methods produced the atoms that deposit on the substrate, we can call them as evaporation or sputtering techniques and sometimes called vacuum deposition because the process is usually done in a evacuated chamber. Now, generally PVD is used for depositing metals, but dielectrics can also be deposited using specialized equipment. So let us go to the next slide.

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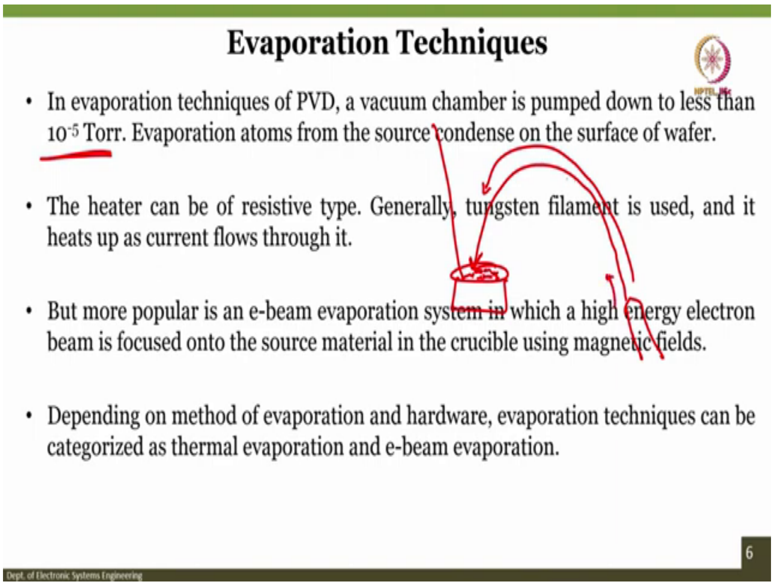
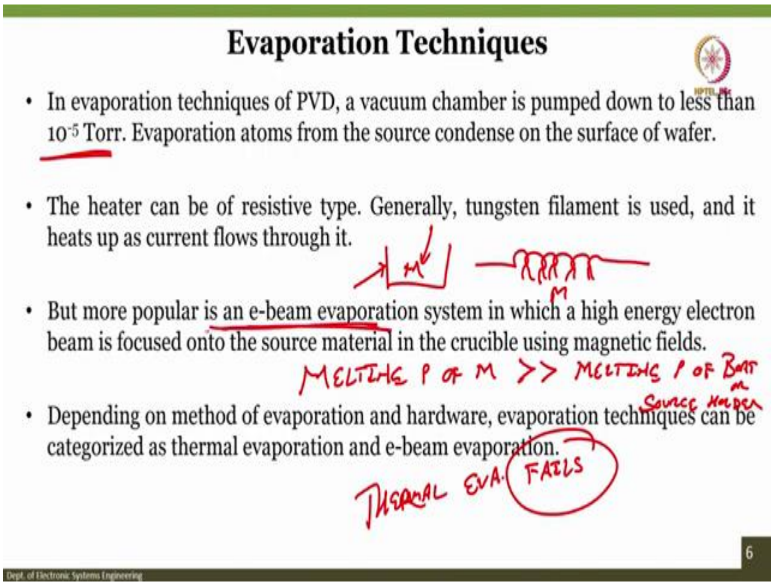


Evaporation Techniques

- In evaporation techniques of PVD, a vacuum chamber is pumped down to less than 10^{-5} Torr. Evaporation atoms from the source condense on the surface of wafer.
- The heater can be of resistive type. Generally, tungsten filament is used, and it heats up as current flows through it.
- But more popular is an e-beam evaporation system in which a high energy electron beam is focused onto the source material in the crucible using magnetic fields.
- Depending on method of evaporation and hardware, evaporation techniques can be categorized as thermal evaporation and e-beam evaporation.



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MELTING P OF M >> MELTING P OF BOAT or SOURCE HOLDER

THERMAL EVA. FAILS

So in the evaporation techniques of PVD, a vacuum chamber is pumped down less than 10 to power minus 5 Torr that is first thing we need to understand. Second is that evaporation atoms from the source condense on the surface of the vapour we have seen that that when you melt the material, it will get deposited onto the vapour the rearrangement of atoms will not happen or does not have that much, we do not have that much time, because it the depletion occurs so rapidly.

So atoms will not have time to rearrange itself. The heater can be of resistive type generally tungsten filament is used and it heats up as the current flows through it. Now, this depends on again what kind of material that you use, whether it is resistivity or some other type of heating, but more the most popular is an e beam evaporation system in which a high energy electron beam is focused on to source material in the crucible using magnetic fields.

So when the e beam comes I will tell you what is the advantage of e beam, right now just understand that e beam is you have a crucible and there is an electron beam that is created. It comes and it scans this particular material and because the heat that is created because the electron bombardment onto this material this material gets melted and gets deposited.

But the way to travel and to form an angle it all these things are not so easy we need to understand how the magnetic fields where the magnets are placed, how the accelerator works, how the electrons are accelerated further how the bending works, because of the magnetic field all these things are important you have a spot beam, you have a raster mechanism for the beam.

So there are different way of using electron beam evaporation system. Why to use e beam is very simple reason that you have substrate, source either like this or this and the materials that we use, materials that we use on this one, like this material M if the melting point, melting point of material is way greater than melting point of boat or source holder thermal evaporation fails, because this material will evaporate faster than the material that we want to deposit.

So that is why when these are the cases when such materials we want deposit, we go for the electron beam evaporation that is the reason of e beam evaporation when the materials that you want to deposit has a very high melting point then the material that you are using for the boat then we need to go for e beam evaporation system and depending on the method of evaporation and the hardware, evaporation technique can be categorized as thermal evaporation and e beam evaporation.

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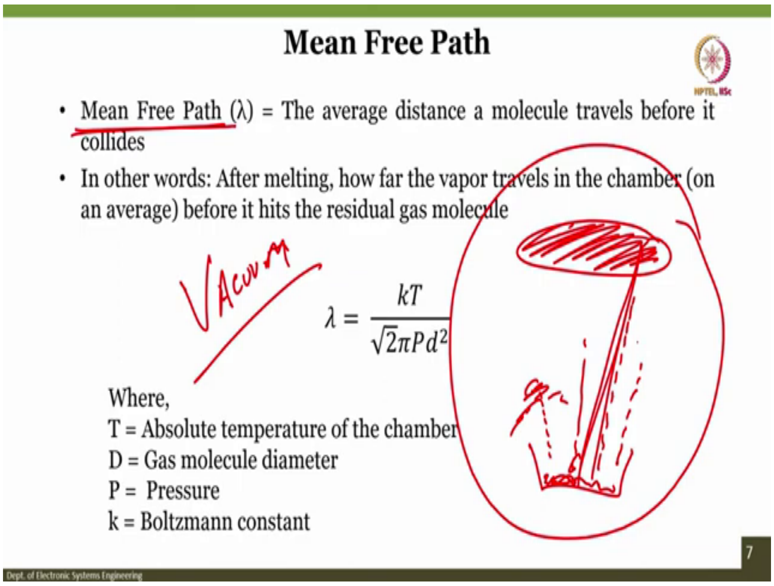


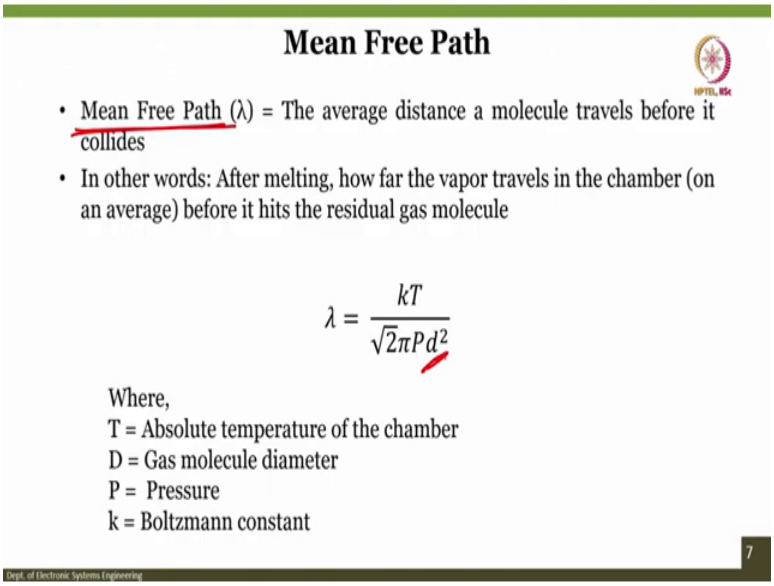
Mean Free Path

- Mean Free Path (λ) = The average distance a molecule travels before it collides
- In other words: After melting, how far the vapor travels in the chamber (on an average) before it hits the residual gas molecule

VAcuum

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

Where,
T = Absolute temperature of the chamber
D = Gas molecule diameter
P = Pressure
k = Boltzmann constant



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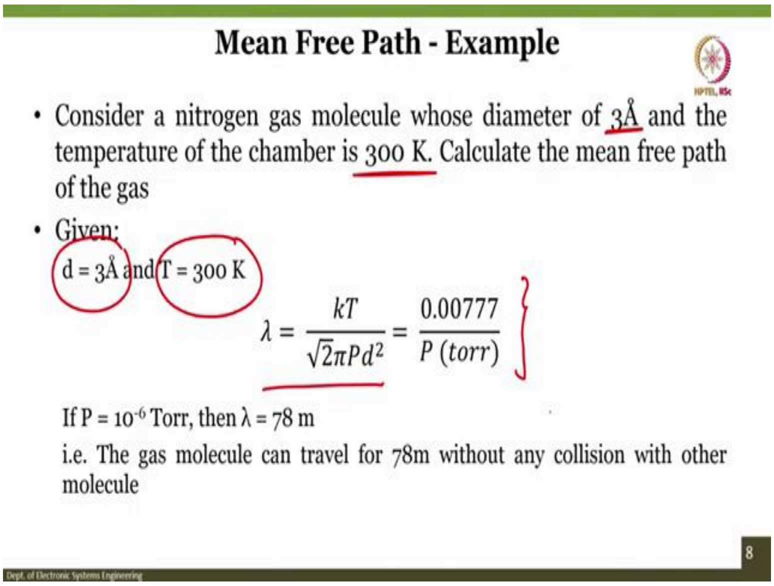
P = Pressure
k = Boltzmann constant



Mean Free Path - Example

- Consider a nitrogen gas molecule whose diameter of 3Å and the temperature of the chamber is 300 K. Calculate the mean free path of the gas
- Given:

d = 3Å and T = 300 K

$$\lambda = \frac{kT}{\sqrt{2}\pi P d^2} = \frac{0.00777}{P\,(torr)}$$

If $P = 10^{-6}$ Torr, then λ = 78 m

i.e. The gas molecule can travel for 78m without any collision with other molecule

Now, very important thing that comes when we are depositing a film using this evaporation technique and that is called mean free path. Mean free path is given by lambda and mean free path lambda is nothing but the average distance a molecule travels before it collides.

So you have this boat and you have this substrate here how much the material that is here, how much material can travel before it collides with something and gets distracted. How much it can travel. So the higher the mean free path, the better the chance of we have deposition, uniform deposition.

So, this with what it will collide, will collide it with some particles or residual gas molecules and to remove these residual gas molecules we use vacuum, to increase the mean free path the longer the path is the better the deposition. So the mean free path lambda is average distance of a molecule travels before it collides with the residual gas molecule and it is given by:

$$\lambda = (kT)/\sqrt{2}\,\pi\, Pd^2$$

Where T is absolute temperature of the chamber, D is gas molecule diameter, pressure is P, k is Boltzmann constant. And if you want to take an example, to solve it we will solve a lot of mathematical equations, some problems in the T A class, but let us take one such example here, considers nitrogen gas molecules whose diameter is 3 angstroms and the temperature of the chamber is 300 Kelvin, calculate the mean free path of the gas.

Now, if you have 3 angstroms which is d, T = 300 Kelvin, we know the formula

$$\lambda = (kT)/\sqrt{2}\,\pi\, Pd^2$$

And we put the values then we can say that for 10^{-6}, $\lambda = 78$ meters the gas molecule can travel for 78 meters without any collision with other molecule if your $P = 10^{-6}$ and if the gas molecule diameter is of 3 angstroms and if the temperature of the chamber is 300 Kelvin. So this is way the lambda is calculated like I said higher the mean free path, better chances of uniform deposition.

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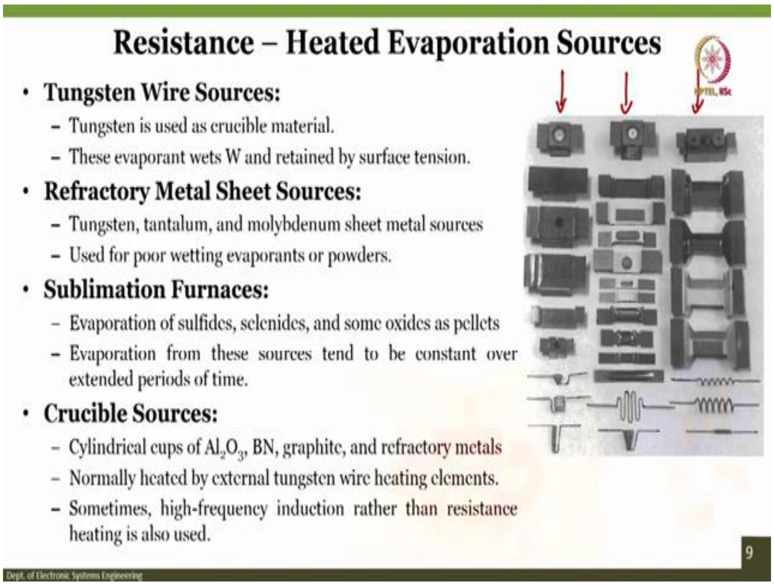

Resistance – Heated Evaporation Sources

- **Tungsten Wire Sources:**
  - Tungsten is used as crucible material.
  - These evaporant wets W and retained by surface tension.
- **Refractory Metal Sheet Sources:**
  - Tungsten, tantalum, and molybdenum sheet metal sources
  - Used for poor wetting evaporants or powders.
- **Sublimation Furnaces:**
  - Evaporation of sulfides, selenides, and some oxides as pellets
  - Evaporation from these sources tend to be constant over extended periods of time.
- **Crucible Sources:**
  - Cylindrical cups of Al_2O_3, BN, graphite, and refractory metals
  - Normally heated by external tungsten wire heating elements.
  - Sometimes, high-frequency induction rather than resistance heating is also used.

The next question that comes into our mind is the what are the different kinds of evaporation sources. Now, I have shown it to you in the drawing in the schematic but these are way more than what I have shown to you, these are all evaporation sources and you start with a tungsten wire sources, so wire sources as a tungsten is used as a crucible material, this evaporation evaporant wets tungsten and retained by surface tension.

The refractory metals sheet sources are made up of tungsten, tantalum and molybdenum sheet materials and is used for poor wetting operation, evaporants or powders. Then we have sublimation furnaces in which the evaporation of sulfides, selenides and some oxides as pellets are possible the evaporation from these sources tend to be constant over extended periods of time.

While there are crucible sources that release cylindrical cups of Al_2O_3, BN, graphites and refractory metals that are used as a crucible sources and normally heated by external tungsten wire, sometimes high frequency induction rather than resistance heating was also used for such sources.

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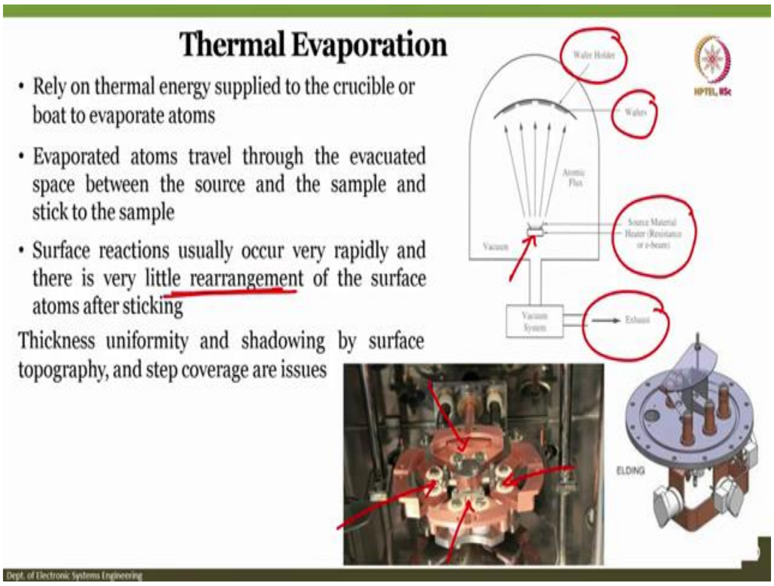

Thermal Evaporation

- Rely on thermal energy supplied to the crucible or boat to evaporate atoms
- Evaporated atoms travel through the evacuated space between the source and the sample and stick to the sample
- Surface reactions usually occur very rapidly and there is very little rearrangement of the surface atoms after sticking

Thickness uniformity and shadowing by surface topography, and step coverage are issues

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So if you use if you see the thermal evaporation then like I have shown it to you earlier there is a vacuum chamber then there is a wafer holder you can say substrate holder and then there are wafers placed here, source material or heater resistance here there is a vacuum system that will have to keep the vacuum intact and then the thermal evaporation systems relies on energy supply to the crucible.

Which is crucible is here or boat to evaporate the atoms evaporated atoms travel through the evacuated space between source and the sample, surface reaction usually occurs very rapidly and there is very little time of rearrangement you see this is again we came back to the same point that there is very little time of rearrangement of the surface atoms after sticking, and the thickness uniformity and shadowing by surface topography as well as step coverages are the issue.

So in this case, if you see, these are the substrate, these are the source holder, four source holder are there. This is the photo within the terminal operation system. And we can have four different sources at one time only one source can be used, but we can load different material and we can also form different layers of the material or the alloys. So we will go to the next slide.

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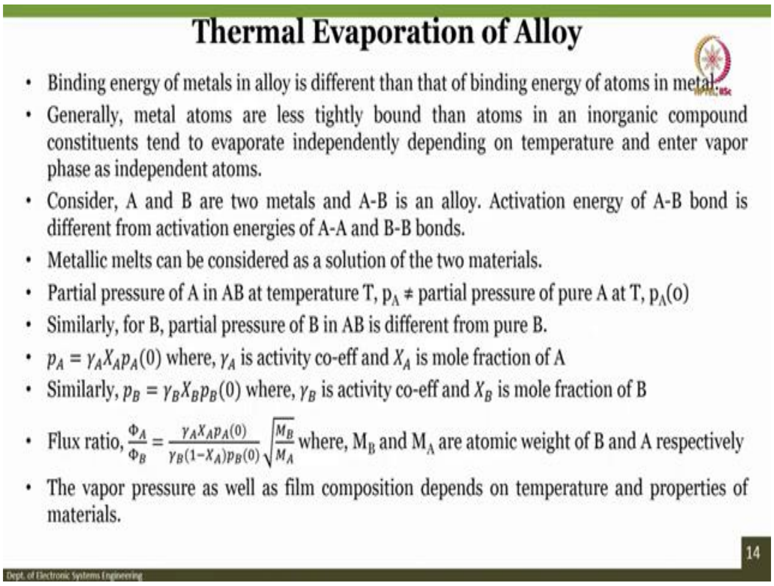
WATCH@: https://www.youtube.com/watch?v=_JfN4pHOIQk&ab_channel=NormElectronicsLtd


Thermal Evaporation of Alloy

- Binding energy of metals in alloy is different than that of binding energy of atoms in metal.
- Generally, metal atoms are less tightly bound than atoms in an inorganic compound constituents tend to evaporate independently depending on temperature and enter vapor phase as independent atoms.
- Consider, A and B are two metals and A-B is an alloy. Activation energy of A-B bond is different from activation energies of A-A and B-B bonds.
- Metallic melts can be considered as a solution of the two materials.
- Partial pressure of A in AB at temperature T, $p_A \neq$ partial pressure of pure A at T, $p_A(0)$
- Similarly, for B, partial pressure of B in AB is different from pure B.
- $p_A = \gamma_A X_A p_A(0)$ where, γ_A is activity co-eff and X_A is mole fraction of A
- Similarly, $p_B = \gamma_B X_B p_B(0)$ where, γ_B is activity co-eff and X_B is mole fraction of B
- Flux ratio, $\frac{\Phi_A}{\Phi_B} = \frac{\gamma_A X_A p_A(0)}{\gamma_B (1-X_A) p_B(0)} \sqrt{\frac{M_B}{M_A}}$ where, M_B and M_A are atomic weight of B and A respectively
- The vapor pressure as well as film composition depends on temperature and properties of materials.

And next slide is a video so I will just play the video you look into the video and see how the thermal evaporation works. Then the question that comes to our mind is what happens if you want to evaporate an alloy? So in that case, the binding energy of metals in alloy is different than the binding energy of atoms in metal that we already know.

So the metal atoms are less tightly bound than atoms in an inorganic compound constituents tend to evaporate independently depending on temperature and enter vapor phase as independent atoms. Thus, let us take an example let us say A and B are two metals and AB is an alloy it is a mixture of 2 metals I hope that you know what is alloy.

Now activation energy of AB bond is different than activation energy of AA or BB bonds. You agree with that, so, metallic melts can be considered solution of 2 materials partial pressure of A in AB at temperature T, $p_A \neq$ partial pressure of pure A at T or $p_A(0)$. Similarly, B for material B the partial pressure of B in AB is different than from pure B.

So p_A can be $\gamma_A X_A \rho_A$

Or $p_A(0)$ where the γ is the activity coefficient and X_A is a mole fraction of A. So from this what we can understand actually to cut the story short we can find out the flux ratio. And on flux ratio we can understand how the materials that are we are using for forming an alloy, has to be considered and how the vapour pressure as well as film composition depends on temperature and properties of the materials. So when you want to deposit an alloy you need to understand that what should be the temperature, what should be property of material, what should be the vapour pressure.

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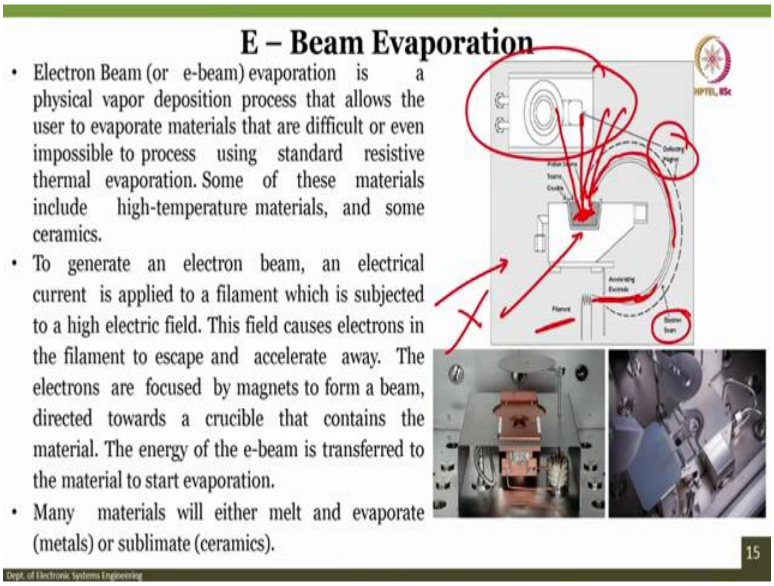
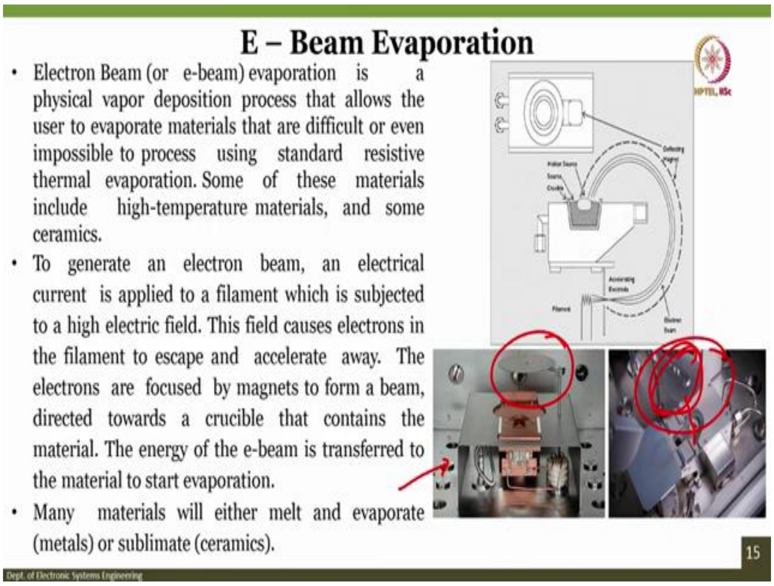


E – Beam Evaporation

- Electron Beam (or e-beam) evaporation is a physical vapor deposition process that allows the user to evaporate materials that are difficult or even impossible to process using standard resistive thermal evaporation. Some of these materials include high-temperature materials, and some ceramics.
- To generate an electron beam, an electrical current is applied to a filament which is subjected to a high electric field. This field causes electrons in the filament to escape and accelerate away. The electrons are focused by magnets to form a beam, directed towards a crucible that contains the material. The energy of the e-beam is transferred to the material to start evaporation.
- Many materials will either melt and evaporate (metals) or sublimate (ceramics).



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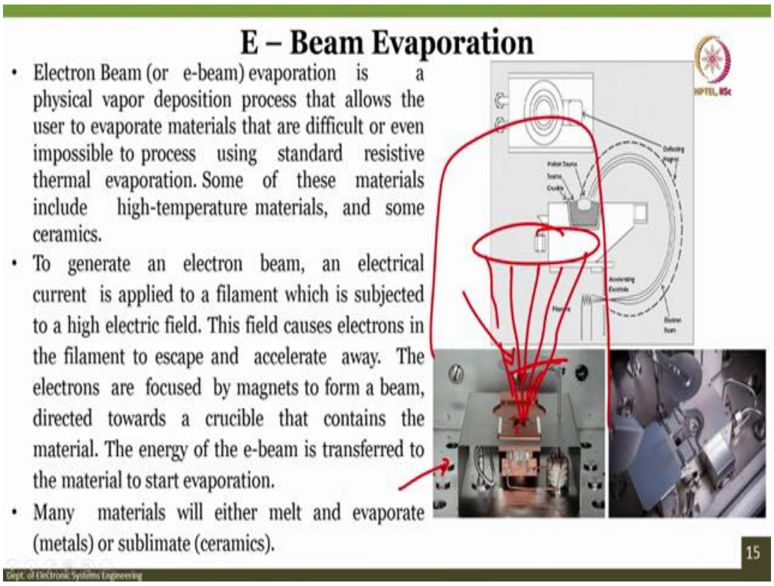

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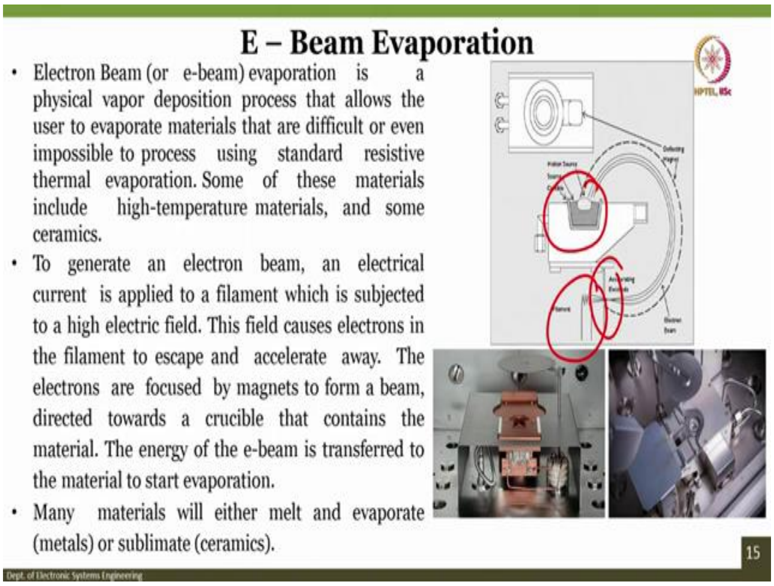

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- Many materials will either melt and evaporate (metals) or sublimate (ceramics).

Now, what we have discussed earlier is on the thermal evaporation and I told you the limitation of the thermal evaporation system that in thermal evaporation system if the metal or the material that is loaded on to the source, is melting point is higher than the source material we cannot use thermally evaporation but in that case, we can use the e beam evaporation and you can see this particular schematic you have a filament where there is a generations of the electrons.

Then there are accelerated electrodes to accelerate the electron beam, then there is an electron beam which is forming here, there is a deflecting magnet which is which looks like this and then this deflecting magnet will deflect the electron and electron will be focused or the beam ray focused on the crucible that contains the source when electron beam IZ is a point source or as a raster scanning falls on the source which is loaded into the crucible the material which is the source material will start melting and is melt molten material will start evaporating.

Thus in this case you are not hitting the crucible that means the crucible has to play, the material the crucible has to play no role except that it should withstand high temperature and there is a coolant also on the backside to keep cooling the crucible from the backside.

Now, if you see the second schematic which is here you can see how you can block the evaporation still you feel there is a uniformity of the melting material here also you can see the same thing there is a material here when it starts evaporating you can remove this thing from the evaporation site and then you can deposit the material.

So but this very important plate it is a masking plate that will not allow the material to gets deposited because the subsidy somewhere here if I just have a bigger chamber and here the material gets deposited we cannot pass through this only when you remove this plate from the path then only the material will start depositing onto the substrate.

So electron beam or e beam evaporation is a physical evaporation technique that allows the user to evaporate materials that are difficult or sometimes even impossible to process using the resistive thermal evaporation. Some of these materials would have extremely high temperature. Now, for generating the electron beam an electrical current is applied to a filament which is subjected to high electric field, it is here this field causes electrons filaments to escape and accelerate with the help of accelerating electrodes.

The electrons are focused by magnets to form a beam directed towards the crucible that contains the material here the energy of the e beam is transferred to the material to start evaporation and many materials with either melt or sublimate directly sublimate.

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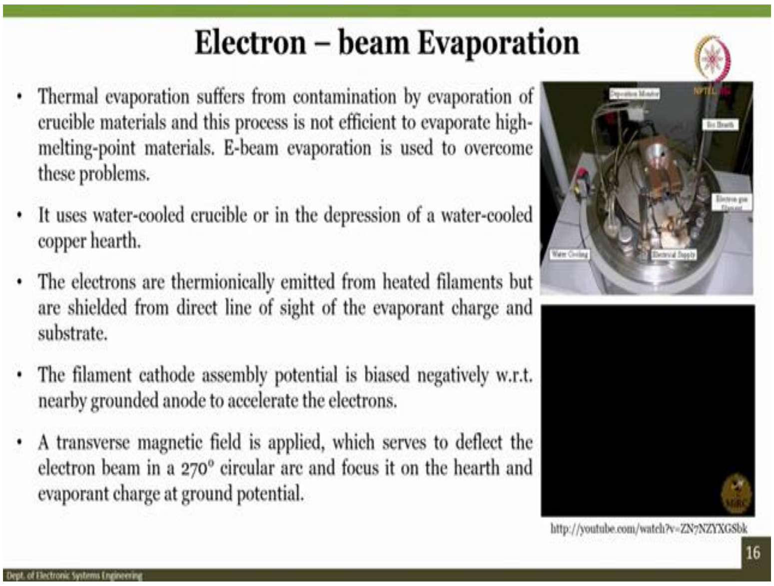
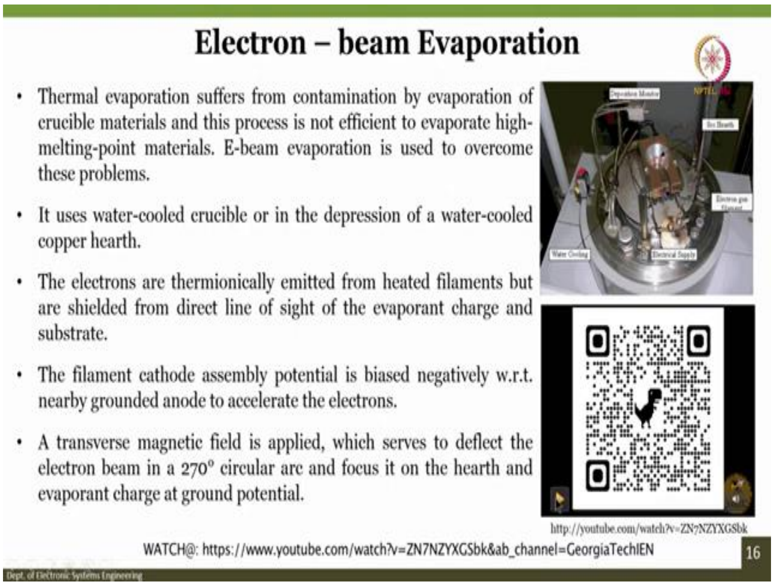


Electron – beam Evaporation

- Thermal evaporation suffers from contamination by evaporation of crucible materials and this process is not efficient to evaporate high-melting-point materials. E-beam evaporation is used to overcome these problems.
- It uses water-cooled crucible or in the depression of a water-cooled copper hearth.
- The electrons are thermionically emitted from heated filaments but are shielded from direct line of sight of the evaporant charge and substrate.
- The filament cathode assembly potential is biased negatively w.r.t. nearby grounded anode to accelerate the electrons.
- A transverse magnetic field is applied, which serves to deflect the electron beam in a 270° circular arc and focus it on the hearth and evaporant charge at ground potential.

http://youtube.com/watch?v=ZN7NZYXGSbk



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WATCH@: https://www.youtube.com/watch?v=ZN7NZYXGSbk&ab_channel=GeorgiaTechIEN

So this region where you can have your crucible, the electrical supply, electron filament gun, wafer cooling and deposition monitor, you can see quartz crystal monitor deposition monitor. So generally the QCM’s are present within the chamber, so as to measure the deposition rate.

So as we have discussed earlier the e beam evaporation is a rescue for the users who would like to use materials which have extremely high melting point the water cooled crucibles or in the depression of water cooled copper hearth, the source holder is placed which is crucible is placed and the crucible there is a source the electrons are thermo ionically emitted from the heater filaments.

But are shielded from direct line of sight of the evaporant charge and the substrate, the filament cathode assembly potential is biased negatively of course with respect to the nearby grounded anode and this will accelerate the electrons. A transverse, magnetic field is applied which serves to deflect the electron beam in a 270-degree circular arc and then the focus it on the earth and evaporation charge at the ground potential. So let us see the video for the same and we will continue from there.

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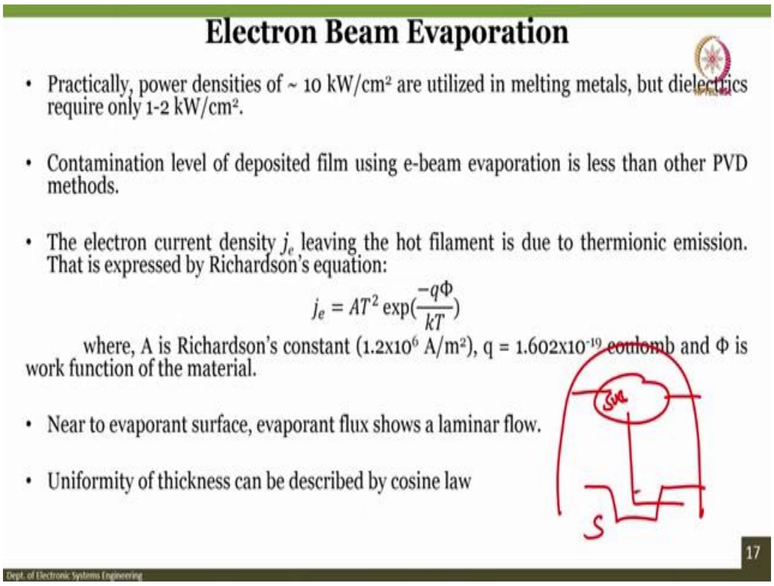

Electron Beam Evaporation

- Practically, power densities of ~ 10 kW/cm² are utilized in melting metals, but dielectrics require only 1-2 kW/cm².
- Contamination level of deposited film using e-beam evaporation is less than other PVD methods.
- The electron current density j_e leaving the hot filament is due to thermionic emission. That is expressed by Richardson's equation:

$$j_e = AT^2 \exp(\frac{-q\Phi}{kT})$$

where, A is Richardson's constant (1.2×10^6 A/m²), q = 1.602×10^{-19} coulomb and Φ is work function of the material.

- Near to evaporant surface, evaporant flux shows a laminar flow.
- Uniformity of thickness can be described by cosine law

So what is what are the power densities? Practically the power densities are approximately of 10 kilowatts per centimeter square and are utilized in melting metals but dielectric require only 1 to 2 kilo watt per centimeter square. The contamination level of deposited film using e beam evaporation is less compared to other E PVD methods the e beams current density Je leaving the hot filament is due to the thermionic emission.

That we know and is expressed by Richardson's equation which is given here and near to the evaporation surface evaporation flux, the evaporant flux shows a laminar flow while the uniformity of the thickness can be described by the cosine law, you please read why we are placing the substrate at almost 90 degree with respect to the source material. It was a reason. Just look into that and then you understand what is cosine law and you will have your answer.

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ELECTRON BEAM EVAPORATION SOURCES

Single Pocket

A water cooled copper block is bored out to have a "pocket" in the shape of an inverted, truncated, cone. Source material is placed within this pocket or within a crucible whose exterior fits squarely within the pocket. The crucible has a smaller, similar pocket within it.

A magnetic structure consisting of a permanent magnet and two pole extensions are located around the block such that its field lines run parallel to one side of the block.

On the the same side of the block (below these primary field lines) is a filament which produces electrons by thermionic emission and is formed into a beam - this is called the emitter assembly. This electron beam is "steered" by these field lines in a 270o arc to impinge on the center of the pocket. The electron beam's energy is controlled such that the magnetic field will bend it precisely into the center of the pocket.

An additional electromagnetic coil known as the "sweep coil" is employed to effectively raster the beam around the surface of the contents of the pocket to evenly heat the source material - this part of the operation is typically referred to "XY sweeping". A variety of sweep patterns are used in the control program for the electromagnetic coil. Materials with lower melting points melt readily and fill the crucible - they do not require an XY sweep. Materials with high melting points require an XY sweep to prevent the e-beam from "boring" a hole in the melt and subsequent "spitting" which creates large nodules of the source material in the growing thin film (undesirable).

Rotary Pocket

A rotary pocket electron bea[illegible]has all the same parts as a single pocket unit except that the water cooled copper block is essentially a turret of multiple pockets each of which can be indexed into position. With this design a number of different materials can be evaporated sequentially from a common magnet/emitter/sweep coil structure. Obviously this design includes additional shielding to prevent cross contamination of the source material in the pockets. The pocket in "position" is chosen via a motorized, rotary "indexer".

Linear Pocket

A linear pocket electron beam source is similar to a rotary pocket source except that its pockets are arranged in a line and are indexed into position in a linear fashion within the common magnet/emitter/sweep coil structure.


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ELECTRON BEAM EVAPORATION SOURCES

Single Pocket

A water cooled copper block is bored out to have a "pocket" in the shape of an inverted, truncated, cone. Source material is placed within this pocket or within a crucible whose exterior fits squarely within the pocket. The crucible has a smaller, similar pocket within it.

A magnetic structure consisting of a permanent magnet and two pole extensions are located around the block such that its field lines run parallel to one side of the block.

On the the same side of the block (below these primary field lines) is a filament which produces electrons by thermionic emission and is formed into a beam - this is called the emitter assembly. This electron beam is "steered" by these field lines in a 270o arc to impinge on the center of the pocket. The electron beam's energy is controlled such that the magnetic field will bend it precisely into the center of the pocket.

An additional electromagnetic coil known as the "sweep coil" is employed to effectively raster the beam around the surface of the contents of the pocket to evenly heat the source material - this part of the operation is typically referred to "XY sweeping". A variety of sweep patterns are used in the control program for the electromagnetic coil. Materials with lower melting points melt readily and fill the crucible - they do not require an XY sweep. Materials with high melting points require an XY sweep to prevent the e-beam from "boring" a hole in the melt and subsequent "spitting" which creates large nodules of the source material in the growing thin film (undesirable).

Rotary Pocket

A rotary pocket electron bea[illegible] has all the same parts as a single pocket unit except that the water cooled copper block is essentially a turret of multiple pockets each of which can be indexed into position. With this design a number of different materials can be evaporated sequentially from a common magnet/emitter/sweep coil structure. Obviously this design includes additional shielding to prevent cross contamination of the source material in the pockets. The pocket in "position" is chosen via a motorized, rotary "indexer".

Linear Pocket

A linear pocket electron beam source is similar to a rotary pocket source except that its pockets are arranged in a line and are indexed into position in a linear fashion within the common magnet/emitter/sweep coil structure.

So when you talk about e beam evaporation then there are e beam evaporation sources as well there is a single source where you can only hold one material then there are rotary pockets that means you can have 4 different rotary pockets, if the first is exposed then you can rotate it then the second will expose then you can rotate it, third will get and fourth will get like this is the rotary mechanism you can also have linear pockets where you have multiple sources but linear lead comes in the path of the electron beam.

So let us read the first one which is the single pocket, a water cooled copper block is bored out of out to us to have a pocket in the shape of inverted truncated cone source material is placed here so it is placed inside and within a crucible or whose exterior fits squarely within the pocket, so when you have this when I am drawing, this is not exact but the point is it will just fit very well in this region.

It will not come out, will not go too deep, exactly it fits well here. So there is a source holder that fits well or crucible. A magnetic structure consists of a permanent magnet and two pole extensions are located around the block such that field lines run parallel to side of the block on the same side of the block is a filament with this same thing that we they are saying but the point is it comes from here and the beam is focused here.

So electron beam energy is controlled such that the magnetic field will bend it precisely into the center of the pocket as I have drawn in the figure in additional electromagnetic coil, called as sweep coil is employed to effectively raster the beam. So one is that continuously the beam falls on this source and then this is a point so the depression is faster. Second one is it is it will go like this from here then here then here then here again like this, and is this.

So, triangular formation, raster formation all things are possible because of the electromagnetic coil, which is additional called as a sweep coil is placed in the mechanism. A variety of patterns are used in control program for electromagnetic coil materials with lower melting points melt readily and will the crucible they do not require X Y sweep. But the materials with high melting point you see there is a very important point requires the X Y sweep to prevent the electron beam from boring a hole.

Because if you just keep on using this electron beam at one particular source let us say this is the material it will start only taking out the material in this fashion for the materials that are of high melting point, this is a material and if your electron maybe is only focused on one point it will form a hole, and that is what we do not want.

So in that case you use the X Y sweep. As I mentioned a rotary pocket electron beam source as all same paths a single point unit, however, the design a number of different materials can be evaporated sequentially because what like I said this is if you say this one is the first pocket and you have four pockets, then you can have different sources that you can evaporate.

This design includes additional shielding to prevent cross contamination This is the shielding this one, this is the shielding. And the pocket n position is chosen via motorized or rotary indexer. Final one which is a linear pocket. Electron beam source is similar to rotary pocket source, except that its pocket are arranged a line and are indexed in position in a linear fashion, the common magnet emitter sweep coil structure.

So this is, these are four or three different types of electron beam evaporation sources that we need to kind of just understand that there are three different evaporation sources what for electron beam evaporation.

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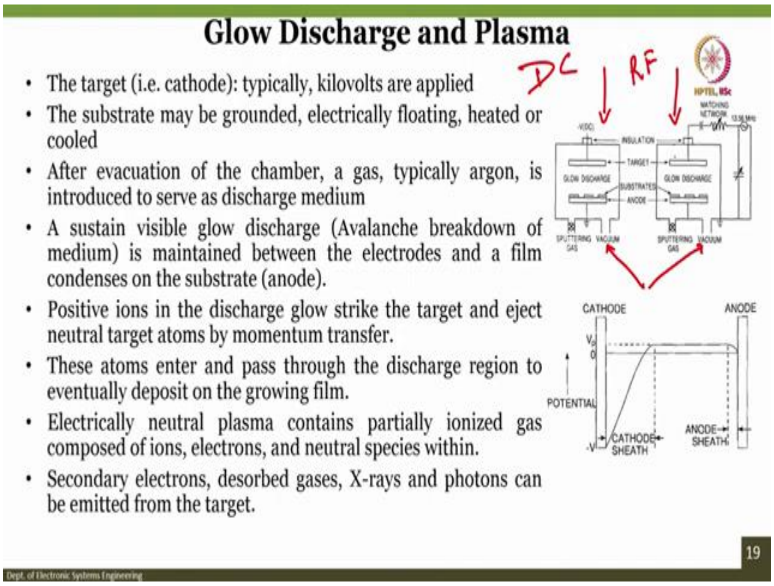

Glow Discharge and Plasma

- The target (i.e. cathode): typically, kilovolts are applied
- The substrate may be grounded, electrically floating, heated or cooled
- After evacuation of the chamber, a gas, typically argon, is introduced to serve as discharge medium
- A sustain visible glow discharge (Avalanche breakdown of medium) is maintained between the electrodes and a film condenses on the substrate (anode).
- Positive ions in the discharge glow strike the target and eject neutral target atoms by momentum transfer.
- These atoms enter and pass through the discharge region to eventually deposit on the growing film.
- Electrically neutral plasma contains partially ionized gas composed of ions, electrons, and neutral species within.
- Secondary electrons, desorbed gases, X-rays and photons can be emitted from the target.

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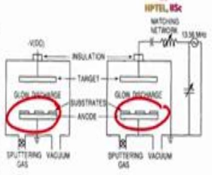

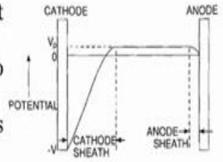

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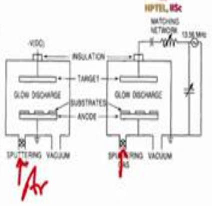

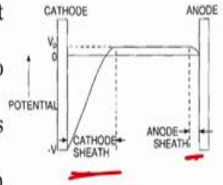

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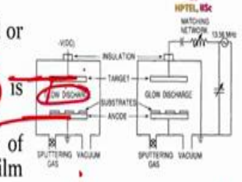

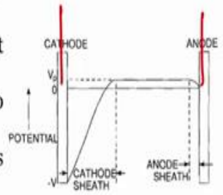

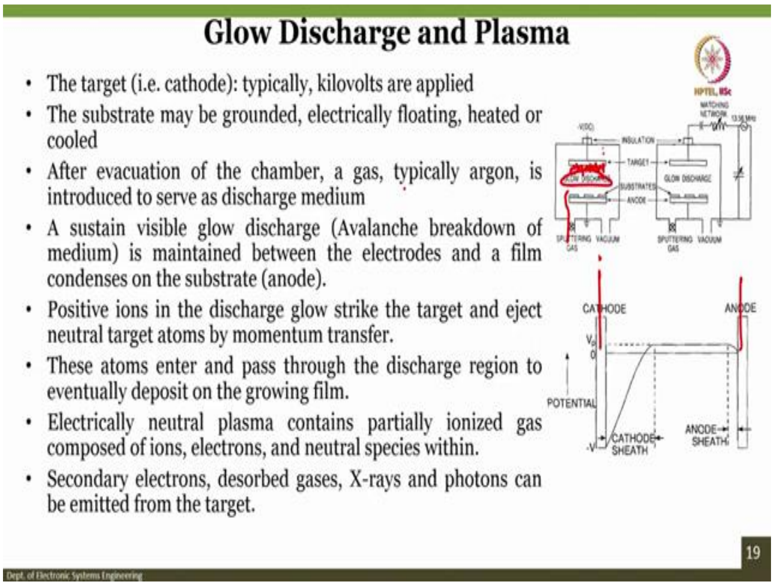

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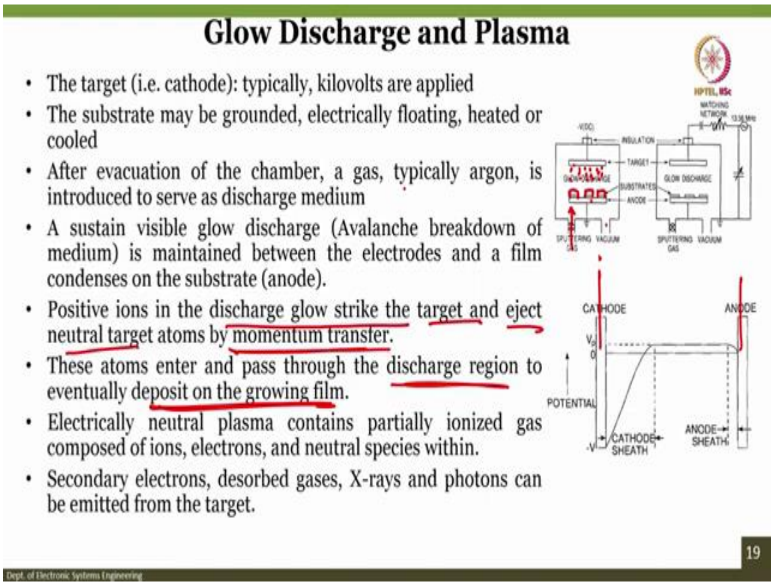
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So here we will stop and the next class will continue what is glow discharge and plasma and followed by PVD sputtering techniques. So in fact let us do this thing let us finish the glow discharge and plasma and we continue DC sputtering in sputtering in the next class, let us let me continue.

So the glow discharge and plasma, what exactly this means. So now you have but actually this glow discharge in plasma comes into play when we go for this sputtering. So let us understand first glow discharge and plasma and then we go further into the mechanism. So here you have again a chamber, you have a chamber, you have a matching network. So we have moved from the e beam and thermal evaporation to a technique called sputtering where it is a mechanical way of dislodging the atoms from the source and depositing onto a substrate.

First let us understand what exactly glow discharge and plasma is and then we will see what how this sputtering works. So in this case again we require vacuum because sputtering is also a vacuum deposition technique it requires vacuum, then we have either DC sputtering, DC sputtering or we have RF sputtering Radio Frequency sputtering.

So these two images that you see are of both DC and RF sputtering and in RF sputtering you require a matching network as well the 13.56 megahertz is the RF frequency then you have a target, you have a substrate so, you see here the substrate are placed and are in this fashion, until now, what we are doing the source was at the bottom and the substrate were at the top in this case the substrate is at the bottom and the source is at the top, source is at the top, this is the source.

So these are the plates. So the plates and the substrate are anode, source is cathode, we can apply, the sputtering gas we can flow through here, generally argon is used as a sputtering gas and from the cathode to anode, there is a cathode sheet there is a anode sheet and when you apply a potential this is how the difference between anode and cathode can be seen.

And also very important point is that the positive ions in the discharge glow strike the target and eject neutral atoms by momentum transfer and the electrical neutral plasma contains partially ionized gas composed of ions, electrons and neutral spaces the secondary electrons dissolved gases X rays and photons can be emitted from the target, now what exactly the all these things that I have read means.

So first thing to understand is that the between the cathode and anode, between the cathode and anode. So between this one and this one or this one and this one, we apply some kilo volts of kilo volts of power densities.

So kilo volts of power the substrate may be grounded electrically floating or heated or cooled after evacuation of the chamber gas typically argon as I told argon is used as a sputtering gas for this purpose, is introduced to serve as discharge medium and a sustained visible discharge called evidence breakdown of the medium is maintained between electrodes and a film condenses on the substrate which is anode.

Now, what will happen is because of this voltage that we apply between cathode and anode, the positive ions in the discharge glow strike the target. So the in the glow discharge, this will strike the target when you introduce this sputtering gas this will the positive ions will start striking the target or the glow discharge striking the target.

So when it happens, what will occur the neutral target atoms will start dislodging, start dislodging and when start dislodging what will happen it will form the layers on the substrate that is what it means, discharge glow strikes the target, eject neutral target by momentum transfer and this pass through the discharge region to deposit the film on the substrate again.

When you have vacuum and you and you allow the Argon to flow and apply very high voltage, there is a glow discharge, the Argon ions will bombard the target and the atoms from the target they need to let them sort of target they are dislodged and they form a thin film on the substrate and substrate are silicon wafer.

The next thing is, the electrically neutral plasma contains partially ionized gas composed of ions, electrons and neutral species within and also very important is, when this striking of these ions onto the target material, the secondary electrons that are dissolved gases and X rays and photons can be emitted from the target.

So this is something that is very important and that is why sometimes the sputtering is not used for fabrication of some of the electronic materials, electronic devices like transistors, because the secondary electrons and the X Ray would cause damage while fabrication, but for us to just understand the focus on that, when you when the ions are bombarding on the target, there is a secondary electron then, there are X rays and photons that can be emitted from the target.

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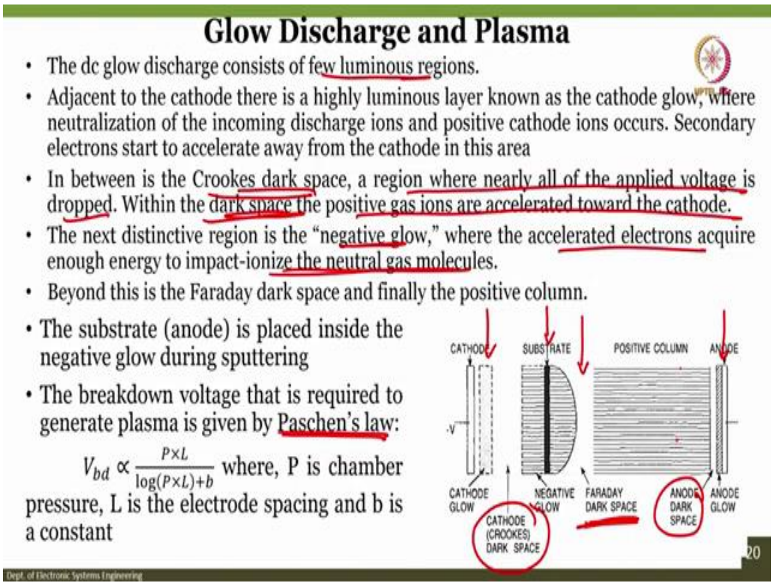

Glow Discharge and Plasma

- The dc glow discharge consists of few luminous regions.
- Adjacent to the cathode there is a highly luminous layer known as the cathode glow, where neutralization of the incoming discharge ions and positive cathode ions occurs. Secondary electrons start to accelerate away from the cathode in this area
- In between is the Crookes dark space, a region where nearly all of the applied voltage is dropped. Within the dark space the positive gas ions are accelerated toward the cathode.
- The next distinctive region is the "negative glow," where the accelerated electrons acquire enough energy to impact-ionize the neutral gas molecules.
- Beyond this is the Faraday dark space and finally the positive column.
- The substrate (anode) is placed inside the negative glow during sputtering
- The breakdown voltage that is required to generate plasma is given by Paschen's law:

$$V_{bd} \propto \frac{P \times L}{\log(P \times L) + b}$$ where, P is chamber pressure, L is the electrode spacing and b is a constant

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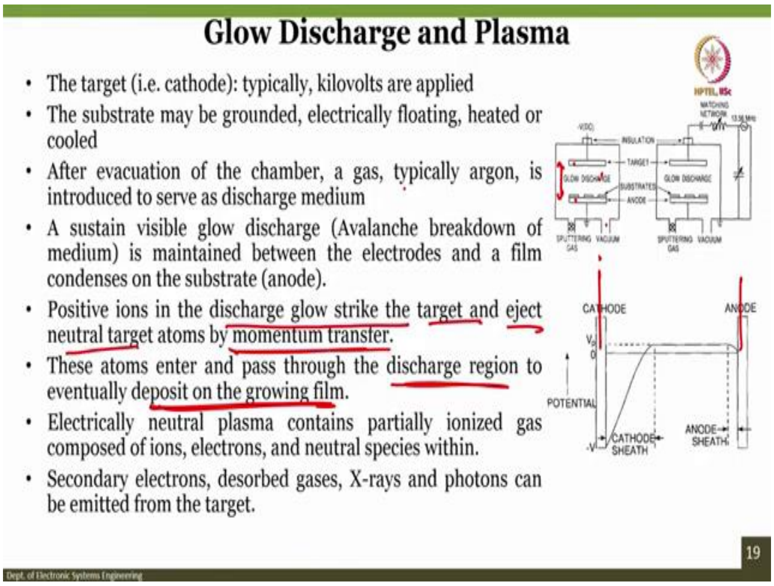

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So if you want to understand further that how the glow discharge and plasma between the cathode and anode occurs then you need to understand that when you apply a voltage between cathode and anode, the next two cathodes is always a cathode glow and the next two anode is anode glow.

So first is there is a cathode glow one is the anode glow then the substrate are placed here and you have a negative glow and then there is something called cathode Crookes or dark space. The Crookes dark space and or cathode dark space and then between the positive column and the anode here, that is called Faraday’s dark space and in between anode glow and positive column there is anode dark space, this once you understand.

Now, the DC glow discharge consists of few luminous regions adjacent to the cathode there is a highly luminous layer known as cathode glow, where neutralization of the incoming discharges ions and positive cathode ions occurs. Second electrons start to accelerate away from the cathode in this area in between the Crookes Dark space a region where nearly all the applied voltage is dropped, within the dark space the positive gas ions are accelerated towards the cathode.

So the positive ions are accelerated towards the cathode and what happens is that the next distinctive region is negative glow where the accelerated electrons acquire enough energy to impact ionized the neutral gas molecules. Now beyond the Faraday dark space which is this one and finally, these are positive column the substrate anode is placed inside the negative glow during the discharge or during the sputtering and the breakdown voltage that is required for creating the plasma is given by the Paschen’s law.

Which is right over here, where a P is the chamber pressure and L is a electron spacing and B is constant. So it is very important to again understand that what should be the distance between the electrodes that is between the anode and cathode if the distance is more than the deposition will be slower, if distance is too close the heating of the substrate will occur. So that is why sometimes you cool down to substrate and also the pressure is very important in case of the sputtering.

So this is some of the things that we need to remember when it comes to glow discharge and plasma. In the next lecture, we will continue with sputtering and the types of sputtering, just you need to understand glow and plasma discharge again, I will not be asking you questions from that because it is just understanding about how when you use sputtering what is within the chamber.

So let us not go into thin film physics. But let us understand that there is a glow there is plasma discharge and then there is a voltage between anode and cathode, what are the mechanism when you apply argon or when you insert argon gas, how the ions bombard the target or dislodginging the atom, so dislodging the atoms that means now you are not evaporating you are not melting it, you are dislodging it that means is a mechanical way of depositing the film onto a substrate other than melting the material and then evaporating.

So this is something that we need to understand in the next lecture. We will be talking quickly on the DC sputtering, RA sputtering, Magnetron sputtering and the reactive sputtering. Till then you just go through this class once again. Do not get overwhelmed with some of the terms. But just do understand that when we go for physical vapour deposition techniques that are three, one is evaporation, one is sputtering within evaporation, there is thermal evaporation and e-beam evaporation and sputtering.

There are different kinds of sputtering, where we apply DC then DC sputtering, RA then RA sputtering, Magnetron sputtering and so on so forth. And this all things falls under physical vapour deposition to deposit the different materials. There is an advantage and limitations of each of these techniques.

So we should be careful when you want to make a device when you make a transistor when you make up chip at which particular technique we need to use and what are the advantages over the other techniques. So till then you take care I will see in the next class cheers.