Fundamentals of Materials Processing-2

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Module – 02
Thin Film Deposition
Lecture – 04
Thermal Evaporation continued

Welcome to lecture 4 of Thin Film Deposition module. In this lecture we will continue our discussion on thermal evaporation. Before we move forward let us recap some of the silent features from lecture 3.

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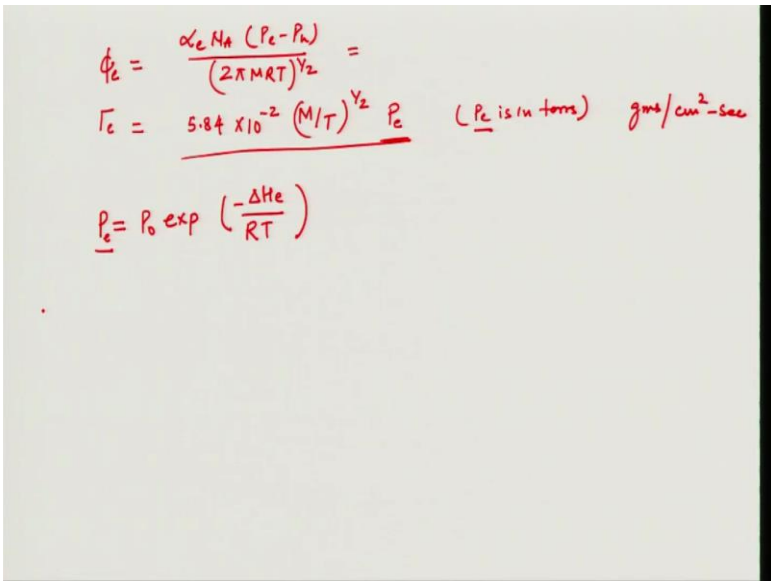

$$\phi_e = \frac{\alpha_e N_A (P_e - P_h)}{(2\pi MRT)^{1/2}} =$$

$$\Gamma_e = \underline{5.84 \times 10^{-2} \left(M/T\right)^{1/2} P_e} \quad (\underline{P_e} \text{ is in torrs}) \quad \text{gms/cm}^2\text{-sec}$$

$$\underline{P_e} = P_0 \exp\left(\frac{-\Delta H_e}{RT}\right)$$

If you remember that we had defined flux of evaporation as alpha e N A, P e minus P h over 2 pi MRT and power 1 by 2. So, this was in terms of molecules or moles and this can also be written as in terms of mass evaporation rate as 5.84 into 10 to power minus 2 M over T to the power 1 by 2 and P e and where P e is in torrs and this P e is the vapor pressure of the source being deposited or evaporated at temperature T, M is the molecular weight and this gives you an idea how much mass sorry that this is in grams per centimeter square per second. How many grams of the material per unit area of the source per second is going to vapor phase? Now from this and we also had derived an equation to know how the vapor pressure changes with temperature, which is an exponential relation and it depends on the enthalpy of a operation or molar heat of evaporation. How much heat is released or is required is absorbed one mole of material is goes from condensed phase to the vapor phase.

So, let me write this as P e because we are using P e terms here. Now so far so good and we had also discussed the vapor pressure curves with temperature how for several materials and rather several elemental materials and we have said that for thermal deposition the vapor pressure at that temperature should be around 10 to power minus 3 torr range.

We had also seen the difficulty in evaporating metal alloys because metal alloy is a solid solution of 2 components, 2 or more components and since different elements or different constituents of the solid solution would have different vapor pressure at a given temperature, there evaporation rate would be different and if the evaporation rate is different than they would the how much amount of that materials is going in the vapor phase would be different from the composition of the source material and that will give you a different composition in the form of thin film on your substrate.

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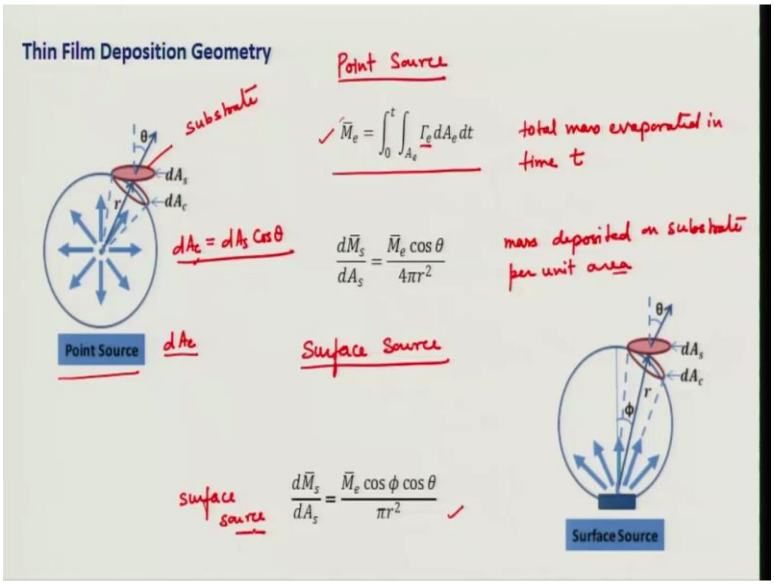

Thin Film Deposition Geometry

Point Source

✓ $\bar{M}_e = \int_0^t \int_{A_e} \Gamma_e \, dA_e \, dt$

total mass evaporated in time t

$dA_e = dA_s \cos\theta$

dA_e

$$\frac{d\bar{M}_s}{dA_s} = \frac{\bar{M}_e \cos\theta}{4\pi r^2}$$

mass deposited on substrate per unit area

Surface Source

surface source $\frac{d\bar{M}_s}{dA_s} = \frac{\bar{M}_e \cos\phi \cos\theta}{\pi r^2}$ ✓

So, these we had discussed in lecture 3 now let us move forward the dependence of thin film deposition on the geometry of source. So, let us consider first the point source, which is shown here in this geometry I am considering that my source is a point source of an elemental area d A e. So, this is an elemental area of the source. Now when this source its melts and evaporates, the vapor is going to move in all directions and the total mass evaporated in a given time t can be calculated using this expression, this is total mass evaporated in time t. So, this is integrated over the surface area of the source and integrated over time. So, this is total mass because I am using this gamma e, which is a mass per unit area per unit time.

Now, if you look at this geometry some of this will fall on my substrate which is kept here this is my substrate at an angle such that the normal to this substrate makes an angle theta with the direction of evaporation. So, keep this mind in this angle theta. So, this area d A c is nothing but d A s cos theta, this is from geometry.

Now, if I could have kept this area along the tangent of this sphere, then I would have collected the uniform dose of the material which is being evaporated, but since I have kept at an certain angle straight then I will have to use this area, this is the projected area. Now this is the rate of deposition or deposition per mass per unit area.

Now, from this expression you can see that total mass evaporated into cos theta divided by 4 pi r square. Why? Because this entire area of 4 pi r square of the sphere is going to receive what is being vaporized here. So, it is not that the whole amount or whole mass is going to my substrate, its going in all directions since its going in the all directions and I am capturing only a small area of that then I have to divide it by 4 pi r square. So, this is mass deposited on substrate per unit area. So, this is for the point source and this is angle is 0 degree then this becomes M e over 4 pi r square.

Now, usually we do not use a point source, we usually have our material in some kind of crucible which can be approximated to a surface source because now our material is evaporating from the surface. So, this was for point source, this was simplicity and this is for surface source. Now surface source has another angle called phi, which depends on how directional my flux from the source is. We will discuss this in detail later, but imagine that now the flux cannot go in all directions because it has a surface; it cannot go in the back direction it is only evaporating from the top surface. So, it is going only forward and forward also it will not spread out uniformly in all directions, but in a way that it forms an angle phi.

So, my same mass deposited on substrate per unit area, for surface source is modified according to this expression. So, this is for surface source.

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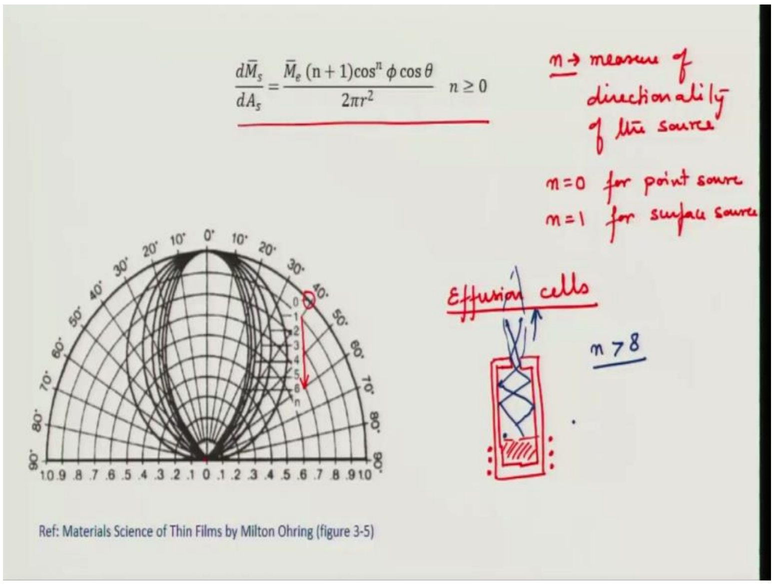

$$\frac{d\bar{M}_s}{dA_s} = \frac{\bar{M}_e\,(n+1)\cos^n\phi\cos\theta}{2\pi r^2} \qquad n \geq 0$$

n → measure of directionality of the source

n = 0 for point source
n = 1 for surface source

Effusion cells

n > 8

Ref: Materials Science of Thin Films by Milton Ohring (figure 3-5)

In general for any given source, the expression is given from this expression like this so where n is a measure of directionality and gives you a measure of directionality of the source. Now if it is a point source its non directional because point source is the material is going to vaporize in all directions and the flux will be in all direction exactly the same, but in a directional source, the flux is directed towards certain angle or certain direction and that is the measure of directionality given by n.

So, n is equal to 0 for point source and n is equal to 1 for surface source and n can be very high 5, 6, 8 or 10 and how the flux is spread out once it comes out from my source is given in this chart here and it follows a cosine law. So, this is for n is equal to 0, you see that it spreads out from this point equally in all direction from minus 90 to plus 90; however, as the directionality increases in this direction, you would see that this spread becomes narrower and narrower and the flux from the source is going only in one direction that is what is the measure of directionality.

Now, let me give you an example of a highly directional source and these sources are called effusion cells and they are specially de designed such that you get a very rational source for very specific purposes. So, effusion cell something looks like this: it is a very narrow crucible with a small opening and where this distance the material is only kept in the lower part of the crucible and with some heating elements, to adjust the temperature.

Now, when the material evaporates from this effusion cell, the atoms go and collide with these walls of the crucible and they come out in a very narrow distribution of angles. So, this material is not going in all directional its highly directional source and such a source would have n more than 8. Sometimes it would not want to waste the material and you want to direct your material towards a specific region where you have kept your substrate. So, you can adjust your n by designing the effusion cell.

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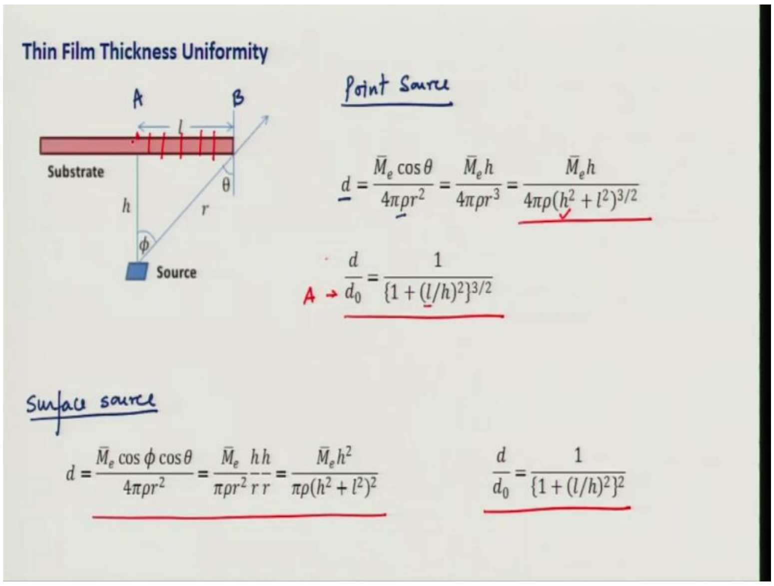

Thin Film Thickness Uniformity

Point Source

$$d = \frac{\bar{M}_e \cos\theta}{4\pi\rho r^2} = \frac{\bar{M}_e h}{4\pi\rho r^3} = \frac{\bar{M}_e h}{4\pi\rho(h^2 + l^2)^{3/2}}$$

$$A \rightarrow \frac{d}{d_0} = \frac{1}{\{1 + (l/h)^2\}^{3/2}}$$

Surface source

$$d = \frac{\bar{M}_e \cos\phi \cos\theta}{4\pi\rho r^2} = \frac{\bar{M}_e}{\pi\rho r^2}\frac{h}{r}\frac{h}{r} = \frac{\bar{M}_e h^2}{\pi\rho(h^2 + l^2)^2}$$

$$\frac{d}{d_0} = \frac{1}{\{1 + (l/h)^2\}^2}$$

So, this is about how the mass is going to deposit per unit area. Now, how does the substrate size and distance from the source affect the uniformity of the film? Let us look at this picture here, in which I have kept a substrate and a source which we can either take it as point source or surface source for simplicity, this calculation is for point source here and this is for surface source. Now have a look here I have converted the mass per unit area deposited to thickness by simply dividing by density. So, mass divided by area divided by density will give you thickness. So, this is my thickness of the thin film on the substrate.

The substrate which is kept at a distance h from the source and I am calculating the thickness as a function of l at point let me call point A and point B change the colour right. So, as a function of h and l from this geometry I can calculate what would be the thickness at any given point h is fixed, l I can vary. So, I can measure the thin film thickness at different points and it would be all different because l is changing.

Now, this will give me a non uniformity in deposition, because this distance is quite small compared to this distance right. So, this d over d 0; d 0 is at point A, thickness at point A, which is just above the source and d is at any other point along the distance l. So, you can see how is the non uniformity comes into this deposition.

Similarly, for a surface source this expression gives you the thickness along l, if the source is kept at a distance h from the substrate and how does the thickness vary and this gives you the normalized thickness distribution for a surface source and it also depends on l. So, if l is 0 which means point A then it is 1 over 1 equal to 1, as l increases this d thickness decreases.

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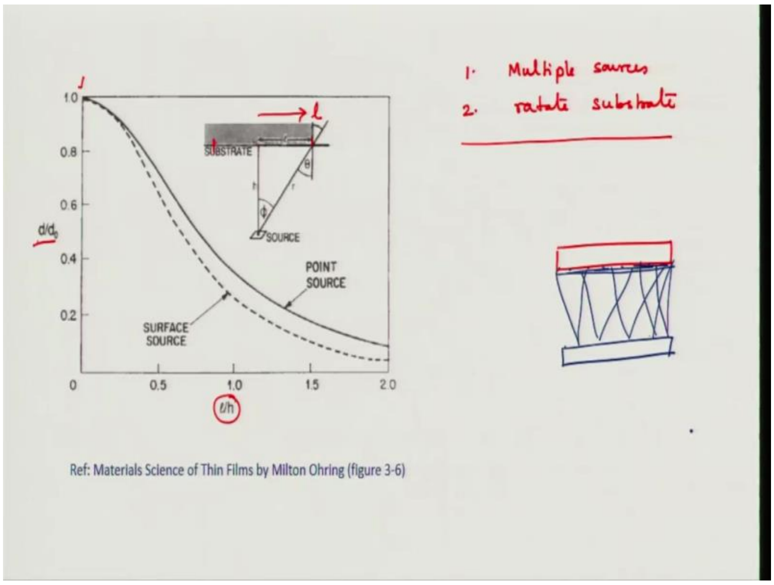

1. Multiple sources
2. rotate substrate

Ref: Materials Science of Thin Films by Milton Ohring (figure 3-6)

Let us have a look at this. So, this is a comparison between as l over h distance increases how does the 2 sources behave point source and surface source and this x y axis is normalized thickness - d 0 is 1 if l over h is 0, l over h means 0 means l is equal to 0, so we are looking at the point directly above the source. So, the thickness there is 1 and how it drops off along the distance l. So, this is the distance of l. So, you will get a quite a drastic change in thickness being deposited at a different distance from the centre of the substrate.

Now, this poses a problem because you want to deposit a uniform thickness all through the length of your substrate right. So, either you can limit the length of the substrate or the substrate size that is one option. But still it is not very practical, because your substrate size is not should not be governed by your process and or you can increase h if we go back we can see that h is in denominator. So, if we keep the source away from the substrate, we can have more uniformity, but if we do that then my deposition rate will slow down because if you see here this h is in denominator also. So, my d would be small.

So, how do we adjust this h and l parameter for a more uniform deposition? There are some practical ways of doing that, either use multiple sources, second rotate your substrate and rotate your substrate such that it is not rotating above this point otherwise of because these two points are same. So, if they keep exchanging between them by rotation, you will not get any benefit. So, you should keep the substrate of axis and then rotate. So, that a normalized area exposed to the source flux will remain same.

So, these are some of the things that we can do to improve the uniformity. Or we can increase the surface size of the source. If we use the source as large as substrate then we will not have any problem, because if this is my substrate and my source is also this then for each of these points we will have a distribution from each point, and we will get a uniform deposition on the substrate. So, we can use a very large surface area source, but large surface area source means lot of material to be heated, melted and evaporated which is also not very practical for production purposes. So, we should keep this in mind and will come back to this issue, how do we deposit on a large area.

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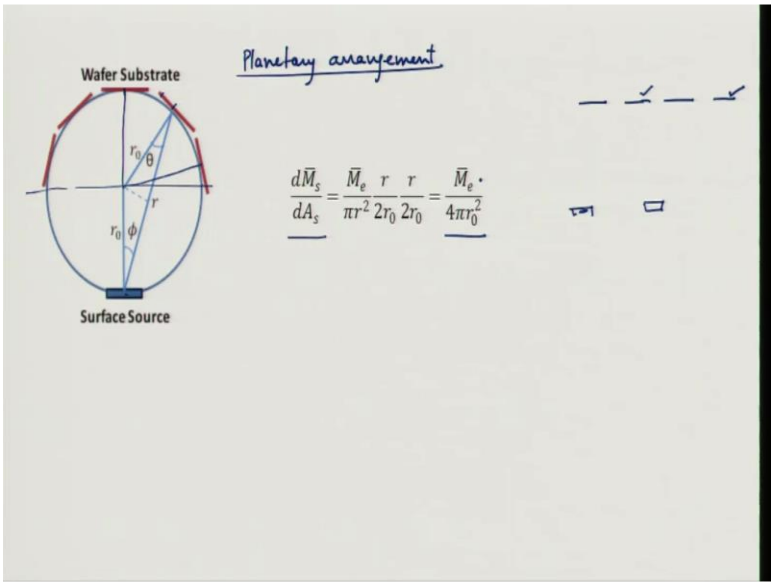

Planetary arrangement

$$\underline{\frac{d\bar{M}_s}{dA_s}} = \frac{\bar{M}_e}{\pi r^2}\frac{r}{2r_0}\frac{r}{2r_0} = \underline{\frac{\bar{M}_e}{4\pi r_0^2}}$$

Another, there is a unique way to solve this, but this is a large scale solution where we often use multiple vapors. So, if we use multiple vapors and keep them in a geometry which is called planetary arrangement, then to a large extent we can avoid this non uniformity issue how is that? In this case the substrates are kept at the periphery of a large sphere, the surface size is small enough, but you can keep large number of vapors or substrates. So, I am not going to discuss that difference in thickness on a substrate, but from substrate to substrate. If I were to use keep this substrate in a line from a surface source, either here or here then we will have difference in thickness between the substrates.

But in this case as you can see that the surface source is kept here and from geometry, the thickness per unit area deposition comes out to be M e, which is total evaporated mass. So, this is e is for vaporized mass divided by 4 pi r 0 square, r 0 is fixed for all the vapors right this distance is r 0, this distance is r 0. So, it is fixed for all the vapors. So, all the vapors would have the same deposition per unit area. So, you can solve this non uniformity issue for lab scale equipment, but still you cannot use very large substrate, you can use large number of substrates in this way, but not very large substrates. So, we will come to that issue in a while.

So, we have discussed how to control for geometry and how to control for deposition rates, now let us look at some of the sources.

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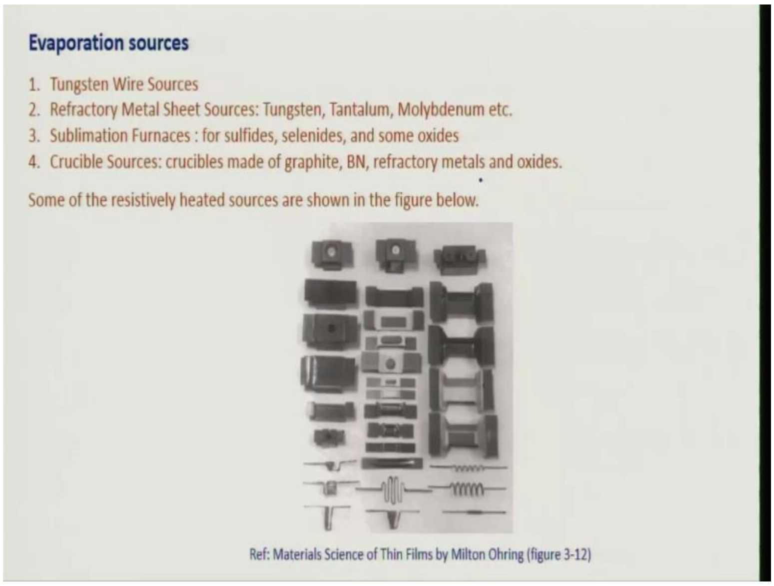

Evaporation sources

1. Tungsten Wire Sources
2. Refractory Metal Sheet Sources: Tungsten, Tantalum, Molybdenum etc.
3. Sublimation Furnaces : for sulfides, selenides, and some oxides
4. Crucible Sources: crucibles made of graphite, BN, refractory metals and oxides.

Some of the resistively heated sources are shown in the figure below.

Ref: Materials Science of Thin Films by Milton Ohring (figure 3-12)

So, most common sources are for evaporation or tungsten wire. So, you have a tungsten wire something like this or a coil, where in a tungsten wire formed in sort of a crucible in which you put your source material whatever metal you want to deposit you put in inside it and you resistively heat this tungsten wire to heat the source inside, you can also have refractory metal sheet sources or which are called bolts, where you can clamp these two in your thermal evaporator, pass a current through this and the source material kept in these melts. So, the source material is kept here in these bolts sometimes there are small opening, sometimes large, different types of bolts can be utilized. You can also use crucible sources; you can use graphite crucible or tungsten crucible and heat using heating elements.

So, with this we will stop here and in the next lecture we will discuss some more evaporation techniques and we will address the issue of how to do deposition on large area.

Thank you very much.