JUDY HOYT: All right, I think we can go ahead and get started. I'm going to put this-- is anybody here-- I think everybody who's here has already signed up. I'm going to put the clipboard in the back. And a couple of people haven't signed up, but wanted to-- everyone who signed up, I've actually approved your topics. But there's a couple people who haven't filled in their topics. So obviously, I can't approve them until they're filled in. So I'll put this back here.

There's two handouts for today, the lecture notes and the homework, your final homework. And I'm handing back some homework sets that people haven't picked up yet. They're in the back.

OK, so let's just take a look at where we are schedule wise. So today is November 9, and we're on the second lecture here on chapter 9. So hopefully you're reading chapter 9 of your textbook. And homework number 5, I'm handing out today. And that's your final homework. So I think it's an interesting problem set.

One thing I want to remind you is that there is a part B on the back, so don't miss part B on the back side of the homework. There's three problems. And particularly problem number 3, I think you'll find interesting. It's about transient enhanced diffusion. Part A, you'll be doing some hand calculations of TED and using some analytic formulas for ion implant and diffusion.

And part B, which is on the back side, again-- don't miss that-- you'll do some supreme simulations and then compare it to the hand calculation of the TED. And the other thing for me to mention about part B, this is the first homework where you're not given the supreme code. Supreme codes you've been running all along, have been given to you that have been written by the TA, and you just have to run them.

3B, you're actually asked to write the code. Now, what you can do, clearly, is you've been given a lot of codes. You can take the examples of what you've been given as your starting-- you don't have to start from scratch. You can take other files and just modify them accordingly. And it's a relatively simple process. But I just wanted to make you aware that there is a part B on the back side. And I think problem number 3 should be an interesting one for you.

And as I mentioned, that's the last homework for the course. The reason I make just the last problem set, this one is due on November 18, because I want to give you enough time between that last problem set so you can get the problems out of the way, enough time to be working on your final project. So that's either the written report or the oral presentation. So definitely, if you haven't done so, get started on your project soon.

All right, so that's the mechanics of where we are. And let's go on with today's-- I'll start with today's lecture handout. This is handout number 31. And this is the second lecture on chapter 9. Chapter 9 is about thin film deposition and epitaxy. Last time, we gave you an introduction. We developed a very simple model for atmospheric chemical vapor deposition. And remember, we had two rate-limiting regimes.

We had a regime of growth where the growth rate was determined by the surface reaction rate. And it had a certain activation energy, dependent exponentially on temperature. And we had another regime where the growth rate was determined by mass transport. That was the rate-limiting step.

We also talked about the fact that the mass transport regime gives you a very high growth rate. This tends to be at high temperatures, where the surface reaction is fast. Gives you a high growth rate. It's relatively independent of temperature in contrast to the surface reaction control regime. But it's also sensitive to reactor geometry. So the growth rate and uniformity depend quite a bit on how the gas flows through the reactor.

We also introduced this LPCVD, which is an acronym that stands for low-pressure CVD. And we introduced the use of LPCVD in a hot-wall batch reactor, which is in just about every fab that you'll ever see. And it's used to deposit very commonly-used films, such as polysilicon for the gate or other applications, oxide, deposited oxide, and deposited silicon nitride.

So in the next lecture or two, what I want to discuss are some specific examples of CVD. So I want to discuss specifically the aspects of the deposition of polycrystalline silicon, deposition of silicon dioxide, and silicon nitride. And also, what we'll talk about towards the end of today's lecture is introduction to the basics of physical vapor deposition. So we have chemical vapor deposition and physical.

OK, let's go on to page number 2, or slide number 2 on your handout. This is just a chart I took right out of your textbook in the section in chapter 9 on manufacturing methods for CVD. And what it gives you is just some common thin films that are deposited by CVD. I think these are the most common, episilicon, polysilicon, silicon nitride, and SiO2.

It talks about the type of equipment used. For example, we talked last time about epitaxial silicon can be either atmospheric or low-pressure CVD. There's actually another type of epitaxial silicon that wasn't listed here because it's not commonly used in fabs that much. But it should be listed for completeness if you want to put it down. Ultra high-vacuum CVD, UHVCVD is another method of depositing or growing epitaxial silicon. And that wasn't listed in the text.

Some typical reactions that we talked about, for instance, the use of silane to grow epitaxial silicon at high temperature. The silane decomposes into silicon and hydrogen and evolves hydrogen. Under comments here is listed some typical temperature range. Here, if you're an atmospheric pressure CVD, you typically don't grow too much below 1,000, maybe 900 degrees centigrade. Much more common these days, though, is reduced pressure deposition of epitaxial silicon. We talked about that.

Here, the deposition temperatures are lowered significantly compared to atmospheric pressure. And people can deposit epitaxial silicon typically all the way down to 750, maybe 700 even in the reduced-pressure systems.

Besides silane, we also talked about silicon tetrachloride being used, also, trichlorosilane, shown here, and dichlorosilane, probably one of the most common gases, so dichlorosilane for selective epi growth.

Polysilicon, which we mentioned last time, it's put down in a batch furnace, typically, by LPCVD. The gas reactions and the precursors are the same, typically, as used as epitaxial silicon. I would say that silane is really the precursor that people use for polycrystalline silicon.

Polysilicon is typically put down somewhere-- and it's pretty tight temperature range, 575 to 650 degrees centigrade. The morphology of the film and its grain structure-- and we'll talk about that in this lecture-- depends on the deposition conditions, the temperature and the doping quite a bit. So you adjust your temperature to achieve the type of grain structure that you need for your application.

Silicon nitride can be put down by an LPCVD process as well as we talked last time about plasma-enhanced CVD. This is becoming more and more common. For a low-pressure CVD, there are two different types of reactions that are commonly used. Silane is reacted with ammonia to create a silicon nitride.

The other one, the most common one, the one that's used here at MIT in LPCVD is to use dichlorosilane, react that with ammonia and obtain silicon nitride. This reaction typically goes or is typically deposited to get reasonable depth rates at around 800 degrees C. So LPCVD nitride is one of those things that it's at a temperature where we talked about in the last several lectures transit-enhanced diffusion can be an issue. So it's right in that intermediate temperature range.

What else do people use? Well, an alternative people sometimes use is low temperatures plasma-enhanced CVD for a passivating layer. Doesn't have as good of properties or the same properties as LPCVD nitride. And I'll talk a little bit more about that.

The last one here, probably one of the most important, silicon dioxide. Remember, earlier in the course, we talked about growing silicon dioxide. Well, now we're talking about depositing it, which is quite different. We react typically silane as a precursor with oxygen to form SiO2 so that you don't have to have silicon exposed on the wafer. You don't consume, necessarily, much silicon on the wafer.

This is listed of between 200 and 800. That's a pretty wide range. Really, the most common is between 200 and 500. In fact, LTO is a very common acronym you'll find in the fab, LTO, as we call it. Typically, LTO has put down between 350 and 450. That's really a more reasonable range. In order to get reasonable properties, so to reduce the etch rate and things, people usually have to high-temperature anneal LTO. So they have to what they call densify it because it's not a stoichiometric SiO2.

In modern fabs, you will also find a very common process called TEOS. People refer to LTO sometimes as TEOS. And TEOS refers to this particular organic compound. And you notice it's a compound that includes silicon along with an organic group, a C2H5 group. You react that with ozone at a very low temperature, say, 400 or below, you can get very high DEP rates of SiO2.

Now, the only thing about TEOS is that you need to be aware of, what's different is there's an organic element in the precursor, some of which can potentially be incorporated in the film. And so TEOS films may have more carbon incorporation or carbon contamination. And some of their properties will be a little different from LTO. But TEOS is very commonly used in fabs today.

OK, so that's just a little background on the different types of materials. Let's remind ourselves about low-pressure, here on slide 3, about low-pressure CVD. Atmospheric pressure systems have some major drawbacks.

For example, if you operate them at high temperature, the gas flow makes a really big difference. And they have to be designed just right. You typically need a horizontal configuration, as we showed last time. And you only can really do a few wafers at a time in order to get any kind of real uniformity. So atmospheric pressure systems are really not that commonly used anymore.

If you try to operate them at low T, you say, OK, I'll go to low temperature where there will be surface reaction rate-limited, but the deposition rate goes down quite a bit. So there is a solution, though, which is to operate the reactor at lower pressures. So instead of 760 torr, you might operate at 1 to 10 torr.

Now, if you go back to the mass transfer-limited regime, remember, there was a transport coefficient, H sub G. So this tells you this is the limiting step in getting from the mainstream of the gas to diffuse through the boundary layer to the surface where it can react.

So this mass transport coefficient HG was equal to a diffusivity through the boundary layer divided by the boundary layer thickness. So delta here is the boundary layer thickness. But you notice the diffusivity in the gas phase is proportional to 1 over the pressure, 1 over the total pressure. So this is the key leverage that you're going to use by reducing the pressure.

So the diffusivity will go up by about 760 times. If I go from atmospheric pressure-- remember, atmospheric pressure is 760 torr-- if I go down to one torr, this is going to go up by 760, while the boundary layer itself is also going to increase but not quite as much, only seven times. So we can get about a factor of 100 in HG if I drop the pressure from atmospheric down to one torr.

And then in the one torr regime, the transport of reactants from the gas phase through the surface boundary layer is no longer rate-limiting. So it can really speed up that process. In fact, we can show this graph-- let's look at slide number 4, and you can see this graphically.

This is a plot similar to what I showed last time. It's the growth rate on a log scale versus 1 over T. So we typically call this an Arrhenius plot. And for atmospheric pressure CVD, it's this lower line right here is the net growth rate. And at low temperatures here, your surface reaction controlled. But look what happens. You get to a certain temperature, and there's a knee in the curve. And it sort of flattens out. So at 760 torr, it flattens out. And you can only get a certain growth rate for atmospheric systems.

Now, if I drop the pressure to one torr, again, I could get about a factor of 100 increase. Remember, this is a log scale. So going from here to here doesn't look like much. But this could be a factor of 10 to 100 in growth rate at one torr because why is this happening? Because the gas phase diffusion rate through the boundary layer is increasing as I drop that pressure. So can really up the growth rate by going to low pressure.

And so that's how the two curves-- notice the two curves converge, though, pretty closely. When you get down to low enough temperatures that you really are surface reaction controlled, you can drop the pressure by a factor of 1,000. You only get a very small increase. You'll get some increase or some change, rather, in the growth rate but not so much because the surface reaction rate is rate-limiting at that temperature. So that's one of the big motivations for going to low pressure.

Let's go to slide number 5, and we talked about this last time, but I want to give more detail now on the deposition of polycrystalline silicon. We introduced this rudimentary reactor. This type of setup is found pretty much in every fab, maybe slightly different configuration. But it's essentially a hot-wall furnace. It's a hot-wall furnace and it's resistively heated. The wafers are usually put in quartz boats or quartzware. And they usually stand up together very close to each other. And it's a batch process. So you can get 25, 50, maybe 75 wafers in a batch, quite a few wafers.

You have some gas sources, consisting of silane and nitrogen and maybe dopants if you want, that flow into this quartz tube into the hot zone in there. The pressure, the low pressure is maintained by a vacuum pump. So this is not an open tube furnace. The mouth of the furnace where the wafers come in and out actually is sealed with an O-ring so you can pull a vacuum.

Typical depositions, usually, polysilicon is deposited on oxide, maybe, or on an oxide with silicon windows. It's a nonselective process. So it goes over the entire wafer on all structures. The diluent gas, so what is the usually flow? Sometimes people flow nothing. Sometimes it's just silane flowing in the tool, relatively low.

Sometimes people will use a carrier gas, such as nitrogen. Notice that hydrogen is not used, typically. And there was a question, I believe, about this in the last lecture. Hydrogen is not used because it reduces the growth rate. Again, this is the reaction from silane going to solid silicon. And it involves hydrogen. If you put hydrogen into the reactor, it tends to push the reaction backwards and slow down the growth rate.

Typical pressure for polydep is about 200 millitorr, maybe up to a torr. Torr is a little bit high. The low pressure here in the hundreds of millitorr range improves the film uniformity, the film thickness uniformity. And again, the temperature range is pretty tight, 575 to 650. And an important number to keep in your head, an important temperature for polysilicon is 580. That's right about the amorphous to crystalline phase transition.

So if you go below 580, the film is pretty much amorphous, primarily. Although, it will contain some small polycrystalline-- or crystallites, which sometimes people call seeds. So 580 is the magic number. You go down below that, you get amorphous material as deposited. You go above that, and you get polycrystalline material.

So if we go on to slide 6, in fact, there are some pictures of polycrystalline silicon. Although, this is a figure in your text in chapter 9, figure 9-32, it's actually originally taken from Ted Kamin's book on polycrystalline silicon. So I've given up here on the upper left the original reference of that work.

And these are cross-section TEM micrographs under four different conditions of polysilicon put down by low pressure CVD. And all these films were deposited at 625. So here's just an example of a cross-section TEM of undoped film. It's a little hard to see. That didn't reproduce that well. But you see the very columnar grain structure. These dark bands correspond to regions where the electron beam is diffracted by the different crystalline orientations and by grain boundaries.

So in an undoped film deposited at 625 in cross-section looks something like this, a very columnar grain structure with relatively small grain size. As deposited, if it's heavily phosphorus doped, again, at 625, so still a very low temperature but very heavily phosphorus doped, you see lots-- the grains are more equiaxed, larger grain size. So phosphorus is one of those dopants that tends to cause secondary grain growth. It causes the grains to grow quite large. So you get a very different film morphology. If you deposit it in situ doped, say, with phosphine.

The third one down is the undoped film. So if you take film A here and heat treat it, so you anneal it afterwards at 1,000 degrees, you can see the grains are still columnar. But they've grown, so the average grain size looks larger. It's a little bit hard to tell an average grain size in cross-section. But you get that impression. But look what also has happened to the surface.

As the grains grow, there's a certain amount of induced surface roughness. So the surface is much rougher than it was in the as deposited case. It's typical, of course, to anneal a polysilicon film during the source drain annealing or whatever to activate dopants. So this is more what it might look like in a gate material.

And the last one is one that was in situ doped. So it's film B, but it was also annealed up at 1,000 degrees C. So look at the big difference. Both of these films deposited 625, and both annealed at 1,000 C. The real big difference is this film is phosphorus doped, very large grains. In fact, if you take a thin film course in material science, Carl Thompson's courses or whatever, you'll study the thermodynamics of this much more carefully.

But basically, it turns out that the grains tend to grow laterally to about the same size as the thickness of the film. So the thickness of this film is about half micron, and the average grain size ends up being, in these large grain films, about half micron. And so it's phosphorus, the presence of the dopant really accelerates the grain growth. And you get a very different morphology film.

OK, so let's go on to slide 7. Why do we care about all that? Why did we go through all that? Well, the grain structure, as it turns out, is critical in determining the properties of diffusion of dopants through polycrystalline silicon and also in determining the final resistivity of the film.

Now, I don't know if anyone signed up for it, but on the clipboard, one of the topics that I had open to do a final report on is diffusion and/or dopant activation in polycrystalline silicon. I'm not going to talk about it in great detail in the course.

Diffusion through polycrystalline silicon is quite different than what we've talked about diffusion in single crystal silicon because in polysilicon the dopants can diffuse along the grain boundaries. Look at this. This is an example up here labeled B called the columnar grains. The dopants, a lot of them, like arsenic, diffuse very rapidly down grain boundaries. They can also diffuse more slowly in the grains.

So you can imagine that the diffusion of dopants in this cartoon labeled B here on the upper left is going to be quite different from the one labeled A. A you have more random grain structure. Looks more like a brick wall. So the diffusivity is going to be very different in this structure to get the dopants from the top down to the bottom. It's going to be quite different.

Why do we care about that? Well, polysilicon is the gate material in CMOS, until we get to metal gates. Of course, metal gates are coming very quickly. But for the last 30 years or 25 years, polysilicon has been the gate material. Typically, how it's doped is it's put down in undoped state, and then it's [INAUDIBLE] planted in the near-surface region. And then you do a high-temperature anneal, typically during the source drain anneal or maybe a separate one, in which you hope that you-- try to get these dopants down from the surface all the way down to the interface with the oxide to form the gate.

If don't get all the dopants down there, you're in deep trouble. You're in deep trouble because polysilicon then no longer acts metallic if it's not heavily doped. In fact, it will deplete under gate bias, and you'll end up with something called gate depletion. And it will not act as a good metallic-like electrode.

So how you put the polysilicon down is very critical because it determines how the dope is diffused through it, how well they activate. So the temperature that you use is very important. And here's just an example of-- now, this is a planar view. So in this case, you're looking down on the top of the film. Again, it's transmission electron micrograph but plan view. This is about 400 nanometers thick. And these are all phosphorus-doped films.

Again, I'm showing the enhancement in the growth rate of the grains with phosphorus. These are all annealed at 1,000. This one has an average doping of about 1 E20. Micrograph B, the sample has about 2 and 1/2 E20. And micrograph C is about 7 and 1/2 times 10 to the 20. You can see how large-- again, you have large grains on the order of half micron to a micron here in grain size. So phosphorus doping can really accelerate the grain growth.

How about on slide 8? How about film resistivity? And besides the fact that-- so I mentioned to you we need to get the dopants that are implanted at the top of the poly down to the gate oxide interface. Otherwise, we're not going to have a good polycrystal electrode. We're going to have gate depletion, and your MOSFET won't work.

But there's other requirements. We also care about the sheet resistance or the resistivity of the poly itself, particularly for some high-frequency applications. So this is a plot also took from Ted Kamin's book of resistive now in ohm's centimeter as a function of dopant concentration in polysilicon.

These films were all ion implanted with these dopants and then annealed at 1,000 degrees C. So it gives you a rough idea of what happens if you were to do a reasonable job of ion planting and annealing. And you could see the boron and the arsenic and phosphorus, they all kind of come down here. And so as you increase the doping concentration, the resistivity drops. But all of a sudden, it sort of plateaus out.

So above about 1 E20 or 2 E20, arsenic and boron-doped poly, they sort of flatten out here at a certain resistivity and a couple of hundred micron centimeter, or a couple thousand. I'm sorry. So this is around 2,000 micron centimeter, which is still pretty high resistivity.

If you use phosphorous, you're a little better shape. You can continue getting the resistive down as you-- and it plateaus somewhere above 5 10 to the 20. It plateaus around 400 microohm centimeter. So if you need to get the lowest resistivity, phosphorus is a good dopant to use. And it activates pretty well.

So the conduction mechanism, as you can imagine, if you go through Ted Kamen's book, the conduction of current in polycrystalline silicon is going to be very different from that in single crystal because one thing you're going through, if you go back, just go back one slide, you can imagine I've got a current passing through either this film or this film. There are all these grain boundaries that the carriers end up going through. The grain boundaries are regions of very imperfect crystalline quality. You can get scattering off of grain boundaries.

The scattering rate can depend on the amount of dopant that segregated to the grain boundary. So there's a whole lot of information that you really need to understand if you want to understand the resistivity and diffusion of dopants in polycrystalline silicon. We don't have time in this class, but I just wanted to make you aware. And Ted Kamin's book is a good reference. He's got a couple of chapters that topic if you're interested. OK, so that's polycrystalline silicon, and again, it's commonly deposited pretty much every fab just by simple low-pressure CVD.

On slide 9 now, I want to go on to plasma-enhanced CVD and just show you some examples of those reactors and how it works. And again, the acronym here is PECVD. The idea, why do I want to use a plasma? Why would I want to use a plasma? Well, we want to enter-- we want to give to the system some kind of nonthermal energy, which is the plasma energy in order to enhance the process. So it will go faster at lower temperatures. So we get enhanced DEP rate at low temperatures.

And this is a typical reactor, if you want a canonical plasma-- a simple plasma reactor. Actually, it's got an RF input here. So there are two electrodes, one at the top and one at the bottom. The wafers sit on one of the electrodes. There is a plasma here in between, and this plasma consists of electrons, ionized molecules. They'll have neutral species, neutral molecules, neutral and ionized fragments of broken up molecules, excited molecules and free radicals. So there's a lot of things present in the plasma that are not there if I'm just flowing silane.

If I'm flowing saline and the plasma is off, what do I have in the reactor? I have silane, OK? But if I'm flowing silane and the plasma is on, I can break up this molecule into all different subcomponents, some of which are highly reactive. And therefore, the deposition rate at the surface will be dramatically impacted by the presence of this plasma. So here's sort of a canonical plasma system, and there is a heater here that would typically-- because you need to do this at a finite temperature that would heat the wafers.

OK, so free radicals I mentioned, if you go on to slide 10, they're really critical. Free radicals are electrically-neutral species that have incomplete bonding. They're not naturally found in nature in this free state. They're created because they're in a plasma, and you have energy stripping off atoms from these molecules. And therefore, they are extremely reactive. And so the deposition rate can be dramatically enhanced.

So for example, here's an example of a free radical, SiO. Typically, to be electrically neutral this would be SiO_2 or SiH_3 instead of SiH_4. So you have an extra unsatisfied bond here on the silicon. So it's going to be very reactive. Fluorine, in and of itself, typically, fluorine is present as F_2. But you can break it up with a plasma to form a lot of free radical just free flowing, which is very reactive.

So the net result from this breaking up-- this fragmentation, the free radicals and the ion bombardment is that the surface processes occur at much lower temperatures. So for dielectrics, you can do PECVD typically between 200 and 350 and get very high deposition rates.

This is particularly important if you're doing a backend process. So backend meaning you have some metal on the wafer. You can't take it above 350, for example. Well, if you want to deposit LTO, you have to go to 400 to get any kind of reasonable DEP rate. It's going to be difficult. So people can use, in that case, can use plasma-enhanced CVD to get the DEP rate up even if you can't use high temperatures. So that's a very common application of PECVDs in the back end.

If we go to slide 11, actually, this is a picture of-- an example of a PECVD deposition tool. There's one here in the microsystems technology lab in building 39 here at MIT. It's made by a company called Novellus, and it's called the Concept One. And on the bottom of the slide, I put down the URL where you can go get more information about that particular piece of equipment and how it works.

This is a photograph of it on the left, and it's set up right now processing 6-inch wafers. Look at the interesting thing about it. Look at the DEP rate for oxide. At low temperature, 350, 300, it can put oxide down at a micron per minute. That's an absolutely phenomenal growth rate when you think about it. Yeah, question.

AUDIENCE: [INAUDIBLE].

JUDY HOYT: Well, if you need only a couple thousand angstroms, you don't want to use that. But you can slow down the DEP rate as well. But the kind of people who will be using it at this DEP rate might be somebody who wants to put down 10 microns. Maybe they're making a MEMS device, so they need 10 microns. To do that by any thermal technique, you'd be there running the reactor for days. And you'd be going through cylinder after cylinder of silane. And it would be totally ridiculous. So for people who need the thick films, this is the way to go.

You can back off on the DEP rate. This is the highest DEP rate. You can go slower than that, and people do do that. It does more than oxide. It can deposit nitride, oxynitride, and other films. It's an RF plasma. It has an interesting thing. It has a multiple-station processing sequence. It cycles each wafer through different deposition chambers or stations to get an averaging effect so that you get better uniformity.

In any given tool, you often find, if it has multiple stations, say, it has five slots, slot one and slot five never have exactly the same DEP rate, and it's always a problem. So you put five wafers. In wafer 1 and 5 come out differently. This is a very brute force obvious way to do it.

But what they do is instead you take one wafer, and you cycle it through all five slots. And so one wafer sees a little bit of all five and kind of averages out the nonuniformity. Now, with a robotic control, you can do that kind of thing.

So anyway, this is the Concept One, typically used more for backend processing. You don't see too many people using this in the frontend. And why is that? Why is that? Well, backend has to use it because typically you need very low temperatures. But if you go to slide 12, the characteristics of plasma-enhanced CVD-deposited films, like oxide or silicon nitride, they can be quite different from those that are deposited at higher temperatures by LPCVD.

For example, very different stress, very different amounts of stress in PECVD and LPCVD films. Hydrogen content, in particular-- make a note-- PECVD films tend to be loaded with hydrogen, a lot. Could be like 10% hydrogen. They're just stuffed with hydrogen. And that's because a lot of these precursors, if you go back, look at some of the precursors you might be using, silane.

Well, a lot of those hydrogens get ripped off during the plasma process, and you're growing so fast they can get buried in the film. So hydrogen incorporation, just by stuffing it in the film is kind of common in any low-temperature plasma process. Also, the temperature is low enough, hydrogen gets in the film and it just sticks. It doesn't evolve.

At higher temperatures, like LPCVD, the sticking coefficient of hydrogen on the surface is very low. So you don't get so much hydrogen. Hydrogen would be less than a percent, maybe half a percent or less in an LPCVD film, oxide film or nitride film. Whereas, in a plasma-enhanced film it could be 10%, have a dramatic effect on the properties.

And the stoichiometry of the film, it will not necessarily be-- LTO is not necessarily exactly SiO_2. It could be SiO_x. x is slightly different from 2, again, because you're not growing it thermally. You're depositing it.

So these differences between PECVD and LPCVD can affect properties like the film adhesion, the presence of pinholes. Plasma-enhanced films tend to have a little more tendency to have pinholes because, again, as was mentioned, they're going down really fast. Surface roughness can be different.

A very important thing is the dielectric constant. Again, because the presence of different impurities will be quite different for a PECVD. So the optical property-- the index of refraction can be dramatically different because of stoichiometric differences or because of hydrogen. Hydrogen can induce vibrational modes, which can absorb light. So dielectrics put down by PECVD can have much different light absorption characteristics.

And finally, the important thing is etch rate the etch rate of a PECVD-deposited film will be quite different from that of an LPCVD film, which will be quite different from that of a thermally-deposited film. So depending on how you put it down, you need to know what the etch rate of oxide is in Hf or whatever you need to test for that.

OK, so that's sort of what I wanted to say at this point about chemical vapor deposition. If we go on to slide 13, I want to move on to another topic, which is called physical vapor deposition that's discussed in your text. As the name implies, it's pretty obvious, PVD uses physical processes. It's not just chemistry to deposit films in the gas phase and to get them onto the wafer.

The most common and the most classic physical process, and maybe some of you are familiar with this, is thermal evaporation. This is pretty much totally physical process. There's not a whole lot of chemistry. You're not flowing in gases or doing any chemistry. Here's an example of a bell jar, a large vacuum chamber.

You heat the source material. There's a source material here on a heater that is then made molten, so it's liquefied. And it literally evaporates off. It has a finite vapor pressure. It evaporates into the vacuum. The vacuum pressure is low enough, less than 10 to the minus 5 torr so that the mean-free path is quite long. So it literally just is like a line-of-sight spraying paint, if you will, where the paint is some atomic species onto the surface of these wafers. And so this is a very common physical process. Not a whole lot of chemistry involved in thermal evaporation.

So what for thin-film evaporation, what are some of the properties? Well, it's mostly what we call line-of-sight deposition because the pressure is low. So there's not a whole lot of collisions. Let's say I'm evaporating aluminum. As this aluminum comes off, it has a certain flux in all directions. And pretty much, the aluminum atoms find their way straight to the wafer, depending, of course, on the pressure. If the pressure is low enough, they can get straight to the wafer with very few collisions.

The DEP rate, the deposition rate is really pretty much determined by the emitted flux and the geometry of the target. So it's much less complicated in some ways to calculate or to model it than it is in CVD. In CVD, the DEP rate-- well, we had that model as a function of temperature. But it's very hard to get an absolute DEP rate model. You always have to do fitting in CVD. This physical deposition is quite a bit simpler.

This evaporation source, what is it? Well, usually it's a little cup called a crucible that's heated, that holds the hot the molten liquid. And there's two ways of modeling it. Sometimes, if it's small enough, depending on the geometry, it can be modeled as a point source, just like you have a point in space that's emitting aluminum atoms or whatever you're trying to evaporate in all directions.

Sometimes, the cup is large enough, then you have to actually model it as a finite source, a small-area surface source. This is typically more applicable to evaporation systems. And I should mention, the heater here is just shown as this little box underneath it. There are different types of heaters. One is a very, very simple resistor. It's just a piece of wire, of tungsten wire that's wrapped up into a filament like you would have in a light bulb. And you pass a current through this wire, and it gets really hot. And that will heat the aluminum or whatever it is you're trying to evaporate.

You can only get so hot with resistive heaters, though. So there's another way of heating up the material in the crucible, and that's to take an electron beam and to shoot the electron beam and to deposit energy by the electron beam into this solid here and liquefy the aluminum or whatever. So that's called e-beam evaporation, or electron beam evaporation. Two different methods of creating-- either case, you're creating molten material that then flashes off and creates an atomic flux. And that flux hits the surface of the wafer and is deposited.

So if we go on to slide 15, this is a picture I took directly out of your text. And if you sit down with it and spend some time, you'll realize this is primarily, really, just geometry. So there are two cases, case A on the left, case B on the right. Case A is for what we call a point source, and case B is for a small planar surface source of a finite extent.

So if we just look for a minute at the point source, this is where the source is located. Imagine it's some distance away, h, some perpendicular distance. H, there is a wafer holder on which you can put wafers. And let's say you have your wafer out here on this wafer holder at a distance L from this point from the center. This makes a right triangle.

So the line H, L, and R three together make a triangle. For any of these deposition processes what really counts is the perpendicular flux. So it'd be the flux perpendicular to the surface. So you need to usually project this flux onto the surface, and that's where you end up with a cosine theta kind of dependence of the deposition rate.

So anyway, we have this point source. It has a certain flux that it's evaporating, that it's emitting. And that is the rate of evaporation, or evap, divided by the solid angle, omega times r squared, where r is the distance.

So if I take my point source and I just move it further away, the flux at that surface goes down like 1 over r squared. So you can adjust the evaporation rate by taking the wafers and moving them further or closer to the point source. You can adjust the flux, I'm sorry, with the 1 over r squared.

This omega is the solid angle over which the source emits. It's equal to 4 pi if it's emitting in all directions. And in this deposition rate term here on the left is this equation for the velocity, the deposition rate. n is the density of the material being deposited. So here's a very simple formula to calculate the deposition rate of your reactor.

It's the evaporation rate, which you'll have to calculate-- it depends on the temperature and all that-- divided by the solid angle times the density over r squared. And there's a cosine theta, theta sub k here. So theta k here is this angle right here. So as I move out, if I take a wafer and move it from right here and I move it along this line, the deposition rate is going to go down according to this cosine function.

A small planar surface source is a slightly different. There are two angles involved here. There is this angle here, theta i. That's the angle between the perpendicular of the planar source. So this planar source is like my hand. It has some angle that it's making, theta i to the point of evaporation. And there's also the cosine theta k.

So the key point is this outward flux, FK, from a point source p is independent of theta i because theta i really equals theta k in this case. So it's independent of-- it's emitting-- a point source emits the same around a sphere in all directions. But the outward flux from a small area source, like from my hand, it depends on some variable. It depends in some way cosine theta i to the n, where n is going to be a variable you end up fitting.

Let's give-- I'll maybe give you an example to make that a little bit clearer on slide 16. This is a plot of exactly that structure. Here, I have a substrate, and I'm looking at the evaporation, the evaporation rate or the flux-- yeah, the surface evaporation rate as a function of l over h. So again, l is the distance that you go out from being directly under the source, and h is the distance of the substrate holder from the source. And this r, l, and h makes this right triangle.

So as a function of l over h, you see the DEP rate can be calculated just according to these two equations. So when l equals h here, you can calculate the relative DEP rate compared to the EP rate directly perpendicular from the source. It's down by about-- it's like 30% of what it would be the DEP rate right at this point.

So you get an idea of what the uniformity will be along this surface. And there's different curves. The dashed line here is for the surface source, and the point source is the solid line. So they have slightly different dependence on those parameters.

So if we go on to slide 17, as we mentioned, the outward flux from a point source, p, is independent of this theta i. Whereas, from a small area source, it goes like cosine theta i. And in fact, if you look at this-- I think it becomes more intuitive if you just look at this diagram on slide 17.

Look at diagram A. I have a point source right at this point. And I'm assuming that source has uniform-- that it's isotropic. It's the same in all directions-- emission from a point source. So each line, the length of a line is meant to represent the flux. So the flux is the same in all directions. So this is a very spherically uniform isotropic source. That would be like a point source.

If you look at number B here, this is what they call ideal cosine emission from a small planar surface source. So imagine right here at this point in space I have a planar surface source. The flux is largest straight above because it's the longest arrow. And the flux then goes down. As you go from here to here, it goes down like a cosine theta, where n equals 1. So the flux is going down.

And they're also, in c, there are nonideal, more anisotropic emission from a different type of small planar source. This is cosine theta to the n, in general, where n is some number. And so you can see what this means is you're getting much higher flux going straight above the source than you are going as you make an angle with respect to the source. So it really depends on how the source is set up.

Why do we care about this? Well, we care because, depending on the type of source, we have to figure out how to place the wafers in the evaporator so you get the most uniform thickness across any given wafer or from wafer to wafer.

So there are two different places you can place in common-- in evaporators. So if you have a point source, something that behaves like an ideal point source, you typically put it right in the center of a sphere. So you would put the evaporation source of platinum or aluminum right here in the center. Then you get a uniform flux in all directions, and you put the wafers along the circumference facing that point source. So use a spherical wafer holder.

If you have a small surface source, you usually put the source on the inside of the sphere, right here. And you put the wafers, again, on the surface of the sphere. So putting it here tends to compensate for the cosine theta at the end because look what happens. This is my source right here. I have the highest flux, according to this diagram, I have highest flux straight in front of me. That wafer is the furthest away. So I have a high flux. It's the furthest distance. That 1 over r squared dependence will tend to compensate for that higher flux. And so you get the same DEP rate on this wafer as you do on this wafer.

This wafer has a lower flux, right? It's going down by cosine theta. But on the other hand, it's also closer. So the 1 over r squared dependence will cancel that out. So this is typically where you want to put it for a surface source in an evaporator.

OK, a little bit more on evaporation, slide 18. This is an interesting plot. This shows the vapor pressure in torr as a function of temperature for a number of different elements. Remember, if I go back to my flux equation or my deposition rate, going back to slide 15 for a minute, the flux was directly proportional to the evaporation rate over something times r squared. So I need to know what the evaporation rate is in order to calculate the DEP rate on the wafer.

So again, going back to slide 18, this tells you, here, I have a formula here that you can calculate the evaporation rate here, depending on this vapor pressure, p sub e at the evaporation temperature. So the evaporation rate is naturally proportional to the vapor pressure at the evaporation temperature.

So what you can see is you just need to-- depending on the element, depending on whether you're trying to evaporate indium-- well, indium you can do that at pretty low temperatures. Look at its vapor pressure. It skyrockets above about 550 centigrade. If you're trying to evaporate some refractory metal, for instance, molybdenum or tungsten, good luck with a resistance heater. You'd have to use an electron beam. You have to go to very high temperatures to get any kind of reasonable vapor pressure here.

But just about-- as you can design a heater, an electron beam or a resistance heater, then you can evaporate it. That's the name of the game with evaporation. You can evaporate just about any element. So in a thin films lab, you can do just about anything. The DEP rate of some elements is going to be very slow because the evaporation rate is low. Its vapor pressure may be low.

One thing-- a good point, though, is it's very difficult to evaporate alloys or compounds. As you can see that, depending on the material between aluminum and nickel or chromium and nickel or whatever, at a given temperature, their evaporation, their vapor pressures vary by orders of magnitude, orders of magnitude.

And so if you had put in your little crucible a little bit of one element, a little bit of another element, they're going to come off at very different rates. So trying to evaporate a compound is tricky. You probably need two crucibles with their temperatures controlled electronically very carefully. So that gets a little tricky.

Probably the most important reason why evaporation is not used in fabrication, in semiconductor manufacturing anymore is this DEP coverage is very poor. It's pretty much line-of-sight. So if you're trying to fill a trench, for example, in A here, and let's say you uniformly want to deposit the material all along the trench, because of shadowing effects, as this aluminum or whatever comes down, it's pretty much just going to deposit right here. It's not going to hit the sidewalls.

So if you need this conformal deposition, you're not going to be able to get it by-- you're going to need to use sputtering. You're not be able to get it by evaporation. There are other reasons it's rarely used, not just the line-of-sight, but the evaporator itself is very hot. When you have a little hot body, a hot metal body like that, any impurities on the metal body can end up being put onto your wafer. So it's a little bit tricky to control impurities.

And the electron beam itself, when it strikes things, remember, if you have a high-energetic electron striking something, you can create x-rays. You can create photons. That's how x-rays are actually created. So there is an inadvertent creation of energetic material, energetic things, like x-rays, which can then hit the wafer and interact with the wafer, potentially causing oxide damage and things like that. So evaporation is used in MEMS or maybe in research these days. But you don't find it too much in CMOS manufacturing.

What you do find in MOS manufacturing fabs today is sputter deposition. So we're going to spend more time talking about this in the PVD area. What is sputter DEP? Well, this uses a plasma. It's different from plasma-enhanced CVD. So it's not so much chemical process. You use a plasma, but this time, you're physically using the plasma to hit a target and sputter off or dislodge atoms, dislodge atoms. And they will then find their way onto the wafer to form the film. That's what sputtering is all about.

Sputtering uses higher pressures than evaporation. Evaporation, remember, I said you need to have 10 to the minus 5 at least, probably 10 to the minus 6 torr. That way, that you can evaporate and just not hit anything as that atom goes to your wafer. Higher pressures here, we're talking about 1 to 100 millitorr. So that's 1 to 10 to the minus 3 torr, something in that range.

Sputtering is typically better at depositing an alloy because the sputter rates vary a little bit with the material, with the element, but not so much-- this is an example on slide 19, a very elementary DC sputter deposition. I have some sputtering gas that I put in the inlet. And argon is very commonly used. And why do we use argon? It's inert, right? It's a noble gas. It's big. It's heavy. It's fat. Given enough kinetic energy, it can sputter off something off your target, your electrode, whatever the materials you're trying to get off. So argon is commonly used.

You create this argon glow discharge of this plasma. The argon is accelerated. It's positive, so the argon accelerated here towards this electrode. It knocks off the aluminum or whatever, which finds its way onto the wafer. So this is a common DC sputtering system, which you would use to deposit metals.

So let's look a little more carefully on slide 20 at what the plasma consists of. So this, again, now I've turned the plasma on its side. Here, the negative electrode has a voltage v sub c, the cathode, as it's called. The cathode is the target. So this material would be aluminum or platinum or whatever it is you're trying to sputter. On the other side, you have the anode, which in a DC system would be grounded. And you put your wafers on the grounded-- or on the anode.

The plasma itself contains-- pretty much, it's electrically overall neutral. So it has equal numbers of positive argon ions. So the argon ends up being positively ionized, and electrons that are in the plasma, as well as some neutral argon atoms. And if you take plasma physics class, it'll explain in more detail.

But for now, you can take this as a given that if you plot the voltage here in the plasma as a function of distance from the cathode, most of the voltage drop from here to here-- the plasma has a positive bias here-- most of it occurs over the cathode sheath. So most of it occurs right here right near the cathode.

So that means that the argon then can be accelerated in this voltage drop going from the center of the plasma. Here, it'll be accelerated towards the cathode, towards the aluminum target or whatever it is. And then it'll gain enough kinetic energy that it can knock off the aluminum.

So on slide 21, these positive argon ions are accelerated by this voltage, this voltage drop across this cathode sheath. And they hit the target, and they sputter off, say, aluminum. These aluminums now then travel through the plasma, and they deposit on the wafers that are sitting on the anode.

So what rate limits you here is the sputtering rate, and it depends on the sputtering yield, which we call y as the number of atoms of aluminum or the number of atoms of a target that come off per incident argon ion. So that's the definition of the sputter yield. So if you have a very high sputter yield, for every argon ion that comes in you'll get an aluminum off. That would be a high sputter yield.

Looking at slide 22, the sputter yield y is a function of the energy. So that'll be the dependent on the bias in the plasma, right, the voltage drop. And it'll be also dependent on the mass of the ion-- argon is very commonly used. It's very massive-- and on the target material. It'll also be a function of the incident angle of the argon coming in.

Why the sputter yield doesn't vary that much, not nearly as much as the vapor pressure. Vapor pressure varies by 5 or 10 orders of magnitude among the elements. That's not the case with sputter yield. So sputtering is pretty good for depositing alloys. This is just a schematic on slide 22 of what's going on.

Let's say I have an aluminum target here, and here's my wafer on the surface. And this is the cathode sheath of the dark space. The aluminum ions that are in the plasma are accelerated towards this negative electrode. They have enough energy that they can knock in a little-- I'm sorry, the argon accelerate it. They knock an aluminum off. It finds its way down to the wafer, where it may move around a little bit if the wafer is hot. But it pretty much will stick and deposit.

There are other species, of course, around. There are electrons in the glow discharge. And depending on what's going on, there may be some other impurities as well, depending on the cleanliness of the vacuum.

We'll go to slide 23. This just gives you a schematic, which is supposed to point out that a sputtering target itself is generally quite large. If you go to buy a target for aluminum, it can be big, a couple of feet on a side. It will be much larger than the wafer. And so because it's so large compared to the wafer, it gives you a wide range of arrival angles in contrast to a point source.

So on the left, you can imagine if I had a point source, the arrival angle here is somewhat limited. But if I have a source that's really much bigger than the wafer, I get a range of arrival angles. And at any given point, I can get pretty good uniformity, reasonably low shadowing effects.

In the evaporator, there were a lot of-- when we talked about thermal evaporation, if you have a step that you're evaporating into or a hole, you can get shadowing effects. Sputtering doesn't suffer nearly from those kind of shadowing effects. It's not really considered line of sight.

OK, so let's look at slide 24. I just to copied this page from this text or this book called *The User's Guide to Vacuum Technology* by O'Hanlon. I just wanted to remind people of an important concept where you're talking about these vacuum processes, like evaporation and sputtering.

The concept of a mean-free path, just to remind you what this is if you haven't seen it before. This mean-free path here, a lambda, of a particle from the kinetic gas theory, it depends on temperature, directly proportional to the temperature. And it's inversely proportional to the pressure.

So for example, in just a typical sputtering system, the pressure, let's say, maybe is 5 millitorr. So this gives us a mean-free path on the order of a centimeter. So you can think of these argon atoms or ions moving around or the aluminum moving around in that five militorr system with about every centimeter it has a collision.

So that's a lot less than the physical path length because a sputtering system might be this big. So you have your target up here, your wafers down here. It has to go a lot of centimeters. So that atom sort of jiggles around, and it has a lot of collisions as it finally gets to come to rest on the surface.

Contrast to an evaporation, could be just as long or a longer distance. But evaporation is line-of-sight. Bingo. Goes right from here to here. I'm at 10 to the minus 6 torr there with no collisions. So this mean-free path is also what determines the conformality of the deposition in sputtering and how it's different from evaporation.

Looking at slide number 25 here, contrasting two different cases. On the left, case A is for isotropic flux arrival. Now, I'm considering-- I have my surface of a wafer, and I've got a flux of things coming in from the sputtering. That's not from evaporation, but it's coming in at a certain angular distribution in the sputtering tool.

And so if n equals 1, I'll get a cosine theta arrival angle distribution depending on the angle of this source with respect to the normal. If have an anisotropic flux, a rival flux, n will go up. n can be much greater than 1, maybe 10 or something like that. And if n is very large, it means most of the flux is coming straight down. Not much but it's coming from wide angles.

So typically, for sputtering, we also use a cosine theta at the end. And it's the normal component of the flux. So it's the component in the normal direction that strikes the surface and determines the DEP rate. So the size and the type of source, the geometry of the overall sputtering system, the pressure and, therefore, the collisions and the gas phase, all of those are important in determining the arrival angle distribution, in determining what this flux looks like as a function of theta.

So that says a little bit about DC sputtering. Now, you might say, well, that's fine if the target electrode is a conductor, like platinum or aluminum or whatever. What if I want to sputter a dielectric material? It doesn't conduct DC current. You're going to have some problems. Well, what people do is then you use an RF power source because you can transmit power through insulators in an AC sense by using RF.

So it looks very much or somewhat similar to a DC system, except now you have an RF generator and a matching network. And you put your target or your electrode up here. And you notice, we'll talk about why this is, but it's a smaller area than the electrode that holds the wafers. Again, you still bring in argon, and it's accelerated towards this target. And you can sputter dielectrics. SiO2 can be sputtered in this way.

Slide 27 shows an example of the steady state-- now, this is steady state voltage distribution in an RF sputtering system. And so it's a plot on the y-axis here is voltage as a function of distance. And here on the left is meant to be the target. This could be SiO2 if you're sputtering that. And on the right is the electrode where you put the wafer.

And there are two different plots here. Well, first of all, because there's slower mobility of the ions, the ions are more massive than the electrons, the plasma always tends to bias positively with respect to the two electrodes. So the plasma tends to be positively biased. The question is, what does the voltage drop look like as a function of the area in these two electrodes?

So it turns out, when the area of the electrodes is not equal, the field has to be higher at the smaller electrode. So this is my small-- let's say, if this is the smaller electrode, the field is higher because there's a higher current density. So to maintain overall current continuity, it turns out that this voltage drop here, v1, will be related to v2 inversely to the areas.

So if I have equal area electrodes, I have the solid line. So there's sort of a drop. The voltage drop on the left, and the right is about the same. If I make the area-- this electrode where the wafer sits much larger, so by making the target electrode smaller, in other words, there's a larger voltage drop near the target. And so all the sputtering tends to occur near the target, not during your wafer, not to your wafer.

So just by imbalancing the size of the electrode where you put the wafer and the electrode where you do the sputtering, you can cause most of the voltage drop to be on this side with a smaller electrode. And then that way you ensure that you get sputtering, not of your wafer, but sputtering of the target material.

And going on to slide 28, the other thing you can do, you can have a separate RF bias, which allows you to control the voltage drop on this side. So you can do a cleaning step. So at the very beginning of sputtering, you often want to sputter a little bit off the wafer surface. Let's say you have a little bit of deposition, or you can also do a bias sputter deposition.

So you can actually have the wafer be at some finite bias, and this ends up giving you more conformal deposition because you can get a more highly directional sputtering flux. So there are a couple different methods in using sputtering where you can control the arrival angle with bias sputter deposition.

OK, so the final technique that I want to talk about today for PVD is this ionized sputter deposition or high-density plasma sputtering. So far, let's just make it clear, what we've been talking about is the argon has been ionized. It's been accelerated towards the target. But the atoms coming off are pretty much neutral, the aluminum coming off or the platinum or whatever.

But in some systems, you can arrange it, that the depositing atoms themselves are ionized, so not just the sputtering material. And so what you do is you place-- in addition to the target and the substrate that are biased with some kind of RF, you can put an RF coil. So now we have two RF sources. And you can put an RF coil around the plasma, and that's going to induce collisions in the plasma, which is going to tend to ionize the aluminum. So the aluminum comes off neutral, but you can ionize it with this inductively-coupled antenna, essentially?

So now I have a different situation. I'm using the argon ions to be accelerated towards the target, get the aluminum off. And then I ionize the aluminum as it comes down. Why would I want to do that? Well, if I have now ions coming down, and if I bias the substrate, I can get a much narrower arrival angle distribution because they're being accelerated towards the substrate. Before, they were just sort of coming down and sort of collisions, mean-free path. And the aluminum was just hitting the surface.

But now you can actually accelerate them towards the substrate. Maybe you can use this to fill a deep contact hole. Here's an example. On slide 29, you have a deep hole. And look at the-- schematically, on the right, in B, the arrival angle distribution is very narrow. They're pretty much all coming straight down, compared to here where they're coming in at different directions. So you can then adjust in this high-density plasma or inductively-coupled-- people sometimes call this ICP sputtering-- you have another knob that you can turn, literally.

So what are some common PVD films, and how are they put down? That's listed on this chart took from your text, here on slide 30. Aluminum put down in a number of different ways, but sputter deposition is really the most common. The standard deposition of aluminum is to hold the wafers near to room temperature, pretty close to room temperature.

There are some special sputter deposition systems where we'll put it down in about 400 to 500, so in other words, hot aluminum. And this is if you need to reflow the aluminum for better step coverage. You don't see aluminum deposited by chemical vapor deposition. That's extremely rare. It's usually sputtered. Another very common material you'll find in fabs is Ti or Ti-tungsten. This is also sputter deposited. Again, CVD can be very difficult. So people will use sputtering.

Tungsten, tungsten is used to fill plugs. It's often put down by low-pressure CVD using tungsten WF 6, tungsten hexafluoride. Ti-silicide can be put down in a couple of different ways. It's usually sputtered. The titanium is usually sputtered initially, and then it's reacted. And we'll talk a little bit more in I think one of the last couple lectures on how silicides are formed.

Ti-nitride is also sputtered but usually in a nitrogen plasma. Instead of using an inert gas like argon, they use nitrogen, which then can, not only knock the titanium off, but then react with it and then go down as Ti-nitride. So those are some common films you'll find in the fabs.

So let me just summarize that the LPCVD uses low pressures. And why do we do that? We want to increase the diffusion rate through the boundary layer so you can get more uniform depth across the wafer, even when the wafers are very closely packed. So the nice thing about LPCVD tubes is you don't have to worry about how the gas flows. You just have to get a very uniform temperature.

Polysilicon is the most commonly deposited material by LPCVD. It's the gate in CMOS. We've barely scratched the surface of poly. I think it's a reasonably good topic to do if you want to do on one of your reports. You need to optimize the temperature and the pressure and the exact conditions to get the right grain structure so you can get diffusion of dopants properly and good electrical activation in the grains.

This plasma enhancement can be used to enhance the DEP rate at low temperatures, especially for dielectrics. We talked about the Novellus Concept One, which is an example. There are many, many examples of PECVD systems that are used in fabs. Typically, use plasmas when you have a limited thermal budget or if you happen to be doing MEMS or you have something where you really need thick layers and doing it thermally just is not practical.

The most commonly used PVD technique is sputtering, either DC for metals or RF for dielectrics. In contrast, to DEP evaporation, you can get very good step coverage and filling of high aspect ratio holes. So far, we've talked very qualitatively. What I want to go through next time is some actual models that people have developed, methodologies for modeling these processes, both CVD and particularly sputtering of PVD.

So that's all I have. If you came in late, remind you, the homework number five went out. And there is a problem on the back, so don't miss part 3B. And if you haven't signed up, make sure-- today is the last day to sign up for a topic. So I've got the clipboard there in the back.