JUDY HOYT: Go ahead and get started. We want to start with looking at the schedule, get ourselves reoriented. This is November 16. And we'll have our final lecture today on chapter 9. Chapter 9 has three lectures. We'll talk about modeling the topography of deposition. And you're working on-- hopefully everybody's working on homework number five. That homework is due next lecture on the 18th.

And does anybody have any questions on the homework? Or if you do, make sure you see me after class or send me an email. In addition to the homework, everyone has now-- except one person on the clipboard-- has a topic. And I had my assistant type it up. I'll put it on the web. Everybody's signed up for a final report topic. And you can verify that she got it right.

And then if you're doing an oral presentation, this week I'll start making up a schedule so you know which day you're going to speak. OK. So hopefully everybody recovered from the snowstorm we had over the weekend. And we'll go ahead and start this lecture with handout number 32. As I mentioned, this is the final lecture on chapter 9.

So far we've by way of thin film deposition and epitaxy we've talked at least a little bit about silicon epitaxial growth. We discussed the low pressure chemical vapor deposition of the three most important films in front end processing. That's polysilicon, oxide, low temperature oxide, and silicon nitride. And we introduced some PVD techniques such as sputtering. We talked about systems for DC and RF sputtering, which is the most commonly used PVD technique in modern fabs.

The nice thing about it is it can be adjusted to give reasonably good step coverage. This is in contrast to evaporation. And thermal evaporation is typically not used in CMOS processing. Today, what I want to talk about, though, is modeling of these processes. And you'll see how these models are a little bit different. They're much more quasi-empirical than the models we had for ion implantation.

But there are methods to do modeling of these processes. And we'll give a couple of specific examples. OK, let's go on to slide number 2. Within the last 10 to 15 years ago or so, there have been a number of simulation tools have been developed for topography simulation. Now, I want to make clear, topography simulation is not what SUPREM-IV does. You've all been using SUPREM-IV to model ion implantation, oxidation, diffusion, a lot of the front end processing.

SUPREM-IV doesn't have any topography simulation of any sort. If you tell it to make an etch, it assumes it's etched at a certain angle. You tell it the angle. It doesn't make any effort to calculate those angles. Or if you tell it that something is deposited, it assumes conformable deposition unless you say otherwise. So it's not a simulator for topography.

There are other simulators. And one of the ones that also came out of Stanford is called SPEEDIE. And there are some examples in this lecture from the SPEEDIE simulator and from in your textbook. OK, so what is it that we need to think about if we want to do topography simulation? Let's say we are trying to model the topography of deposition of some film.

This particular example on slide 2 is shown assuming we're doing deposition of aluminum, say, in a sputtering chamber. And this is the surface that we're depositing the aluminum, for instance, onto. That surface has some starting initial topography. Well, this is a generalized picture of what's involved in the deposition. And you'll see that modeling topography ends up being a lot of bookkeeping of the different fluxes involved.

In general, we are not going to consider gas phase boundary layer in these simple models. So this picture will not be accurate, for example, atmospheric pressure CVD where diffusion through a boundary layer is very important. We're not taking that into account. But it will be reasonably useful for modeling low pressure CVD or for modeling sputtering, which also takes place at reasonably low pressures.

So these are the fluxes involved. For example, if we're depositing aluminum on this surface, we have a direct flux to the surface of neutral aluminum atoms. We also have a direct flux of ions that we need to keep track of. Aluminum can come down and it can actually-- we can have a desorb. It can desorb aluminum that had already been deposited at a point. And then we have a desorbed or emitted flux that can be redeposited elsewhere on the surface.

So that's a flux we need to take account of. Argon ions, because again this is in the sputtering system, argon is nominally supposed to be directed towards the target, not towards the wafer. But it's possible that it would be directed towards the wafer, argon ion, some of them, and that they would sputter off aluminum that had already been deposited. And then that can redeposit elsewhere.

And there's a surface diffusion flux. Aluminum can diffuse along the surface a certain distance and then deposit at a different point. So we end up just doing a lot of bookkeeping on all the different fluxes. And it'd be good if you think about this picture because we're going to use the exact same picture when we talk about etching.

When you think about it in this terminology, etching is sort of just the opposite. Instead of depositing, we're talking about fluxes coming down and reacting and removing films. But it's not that much difference. It's mathematically the inverse of deposition.

So in order to simulate that process that I just showed on slide 3 here, we need some kind of mathematical description of all of these fluxes. And then we need to add them all up and see what we get at any given point. So what we write is this equation shown at the top of slide 3 that we say the net flux at any point I.

So point I, point I is just-- if I go back one, point I is just at some point on the surface. It could be at this point right here. It could be at that point right there. It's just at some point on the surface. The net flux is, well, it's the flux deposited at that point minus everything that was emitted, right? And that gives you the total atoms per square centimeter per unit time.

So you add up the direct flux of neutrals, the direct flux of ions, any flux that's redeposited that's coming off from another area, any flux that's due to surface diffusion. All of those are positive terms. You subtract off any flux that's emitted from that point, any flux that diffuses out or that sputter from that point by virtue of argon ions coming down or something.

So you can see, this is going to amount to basically a lot of bookkeeping. And this is something that computers are very good at doing. And you can and you can model those fluxes across the surface. So usually, what we need to do for a specific system-- let' say you're doing LPCVD or something-- we have to figure out which one of these fluxes is important and ignore all the others so we can simplify the models to a certain extent.

And this picture gives you a rough idea of how we do the modeling. What we consider is we draw this dashed line here right above the surface of the wafer. And so it's a plane just above the surface. And the first thing we need to look at is what's the arrival angle distribution of atoms and ions that are coming down on that plane? And then later on, the next step will take into account topography.

So first, you do it assuming you have a plane just above the surface. And now what we need to take into account are these direct flux of neutrals and the direct flux of ions. These we generally model with some kind of arrival angle distribution just above the wafer. And I've noted here what it says is it doesn't model the equipment.

What that means is you have to put in the arrival angle distribution. You can't say to the simulator, oh, yes, I have an applied materials sputtering tool in the endura, and now tell me what it's going to look like. It doesn't have that level of knowledge of the individual tools. What you do is you put in flux, the direct flux, as a function of the angle theta and that's measured with respect to the normal.

And you give it usually-- it's some normal flux times a cosine theta to the n power. So that's a variable that you need to put into the simulator. But there are some guidelines for different systems, different types of systems, what kind of arrival angle distribution for neutrals and ions you might use.

So let's look at a couple different types of flux distributions. The first one here shown on the slide number 4 is what we call isotropic flux arrival. As the name suggests, the flux is essentially isotropic. And in this we use an n equals 1 in the formula of cosine theta to the n.

So what we get is that the direct flux f as a function of angle theta. So if theta is measured with respect to the normal, is whatever the flux is in the normal direction f0. So it's this flux number here times cosine of theta to the n. So what's happening is I'm moving from normal. I have a certain flux in. And as I go this direction, as I coming in at shallower and shallower angles, the flux goes down according to this cosine theta.

And this little derivation that I've shown mathematically, the second half of slide 4 kind of explains where that comes from. What we're interested in when we're looking at deposition, we're interested in the normal component of the flux, OK? So let's say this is my wafer down here. This solid line here represents the wafer or the surface that I'm depositing on.

And if we look at this little red region, that represents a certain normal flux coming. And that would be my f super 0. And this, I'm drawing this for the n equals 1 case. So I have a certain flux coming in normal in normal. Now, at some other angle theta I have that same flux. You notice I drew those same number of arrows.

So it's coming in this direction normal to this plane here, normal to this plane. I have the same number of atoms per square centimeter per unit time. But I need to project that now onto this surface. So when I project this distance here of length l onto the surface, I have this sort of distance-- it's spread out over a lateral dimension h.

Now, we have right triangles here with angle theta here and theta here. And you can write-- it's very simply that the cosine of the angle theta is just this distance l divided by the distance h, where h represents how far that unit flux is spread across the wafer.

OK, so now it's just bookkeeping. If I want to know what is the flux here in this region, it's just a number per unit area per unit time that's going to be proportional to the number per unit time divided by h, right, because it's spread out over the distance h. But you can substitute in for h is cosine theta over l or l over cosine theta, Right so you can substitute that in.

So you get the fact that for isotropic, so assuming you have just as much intensity in this red bar as I had in this direction theta in the black bar, assuming that, then I get this simple formula, which shows that the flux as a function of theta is just the normal flux times the cosine of theta. And that's assuming that the source is isotropic like this.

If for some reason your source varies, and you have much greater intensity over here and over here or whatever, this cosine theta term will be modified. But again, this is assuming isotropic, an isotropic source. And the cosine theta just comes from the geometry factor.

OK, you can sit down and stare at that for a little while. Hopefully, it'll make sense to you. Go to slide 5. So in contrast to that, on the left side I show what I just derived, which is the isotropic flux arrival distribution. On the right side, for some systems you may have very anisotropic flux. Most of the atoms or ions coming down may be directed mostly normal to the surface.

There may be very few coming out at shallow angles depending on the particular machine that you're using. So here in the cosine theta to the n, we make n greater than 1. And you can see just based on the way these arrows are distributed most of them are coming in normal. The flux coming in at angles, higher angles theta, is much smaller. You can see that from the length of the arrow.

So the length of these arrows here is supposed to represent the flux at any given angle. So generally, we have this arrival angle distribution at a plane just above the wafer. It has some cosine theta to the n type of dependence. And again, it's the normal component, normal to the surface, that strikes the surface that determines the deposition rate.

So let's take a look at examples of distribution of flux arrival distribution functions. Here's that formula I just mentioned. And for example, if you have a high pressure system, reasonably high pressure, you're going to have a lot of gas phase collisions, which means you have a short mean free path. And you're going to tend to get isotropic arrival because those atoms are all bouncing around. And regardless of where they're coming from, it's just sort of the flux is equally distributed for all angles.

If you're in a very low pressure system where you have very fewer gas phase collisions, a long the mean free path, and is going to be closer to 1, you're going to get more like line of sight from the source, whatever that source happens to be. It could be a point source. It could be a plane if it's sputtering. But you're going to have n greater than 1. That's all assuming neutrals.

If you have ionic species and the wafer is biased, imagine the wafer has some bias and you have an ion, the ion can be attracted to it by the electric field, OK, that's set up. In that case, for ionized species, it tends to be very anisotropic because, again, there's a force driving it towards the wafer so it doesn't tend to bounce around. The species tend to go right to the wafer.

So these are just some examples of flux distribution so you can see what it looks like for different values of n So this is the relative flux. So it's the flux at any given angle theta divided by the normal flux, divided by f0. And this is what it looks like. So it starts here at theta equals 0. So that's normal is one. And you can see for n equals 1 it drops down and the flux finally goes to 0. At 90 degrees, you're just skimming along the surface. Obviously, the normal component is 0.

n equals 3, which is slight anisotropy. It looks something like this. It's starting to flux really dies down dramatically after 60 degrees. n equals 15, which could be appropriate for some ionized deposition systems, you can see really the flux goes to 0 by the time you get to about 30 degrees. So it's very anisotropic arrival at that plane. And again, in most models, these are inputs that-- parameters that you can vary.

OK, so that gives us an idea of the direct fluxes and their angular dependence. The next thing we have to do is to take into account the surface topography. And just to give you an example of that, I'm showing here-- imagine your surface is not flat, but that you have a wafer and you are sputtering aluminum into it and you have a via or you have a hole, contact hole. So it's like this, and then you have this hole right here.

Well if you have imagined each one of these little regions corresponds to an emitter with a certain flux, depending at any point i on this vertical surface, it's going to have a certain viewing angle. And if you're beyond that viewing angle, you're going to be shadowed. So this is a shadowing effect on the sidewall of the trench. It's not that uncommon depending on the depth and the aspect ratio of the trench.

So we have to take into account the orientation of the surface, what its angle is, this viewing angle, and shadowing. And typically, in the near certain way for surface region we will neglect the gas phase collisions on that. So if you will, you can think of this-- imagine my reference plane. Remember that reference plane is sort of a plane just above the wafer surface. And each small area on this reference plane can be treated as an emission source.

So if you have a emission coming down, you have all these little emission sources. And each source is emitting to the topography below it. And then the total direct flux at any point i can be calculated by just adding up the flux from each one of these little miniature emission sources, which each one of which has its certain angular distribution depending on the type of system that you're modeling.

So you can now begin to see how in a computer model you can build equations and you can build structures that would be able to model this type of deposition. Let's go on to slide 8. And I'd wanted to give you a practical example. We're talking about all these mathematical things. But a practical example, which should be somewhat intuitive, here on slide 8 is the impact of having a finite target size compared to the wafer and if you're doing sputter deposition on asymmetry across a wafer.

So if you look at this illustration, imagine I have a target that I'm doing sputtering. And this could be aluminum. And it's up here. It has this dimension. It's relatively small compared to, say, I'm doing a 6 or 8 inch wafer. So what's going to happen? And you have the wafer sitting there, and you're sputtering into a trench on the left side of the wafer, and you have a dye over here on the right side of the wafer. And let's say for now you're not rotating the wafers or anything.

So you can imagine what's going to happen here on this trench. This white region indicates the region that you've sputtered, the material you've sputtered. You get an asymmetry on the sidewall because you've got here at this point in the wafer you have more flux coming from this direction. And so you're going to get-- because of shadowing you're going to not get much deposition on this wall. You'll get more on this wall.

On the right side of the wafer, we have just the opposite type of shadowing. So you will tend to get asymmetric deposition on the left side of the wafer as opposed to the right side of the wafer with this particular geometry. So what do people do in a real system? Because obviously this is not desirable. We want to have it-- each side of the wafer should look the same.

Well you can widen the target size. So I can take this target and make it much bigger, make it larger than the wafer. Or you can take the same size target and move it further from the wafer. So in either case, you're going to get an arrival angle distribution that is more symmetric across the wafer. Another thing people sometimes do is to rotate the wafers. So you can put the wafers on a plate and that rotates with respect to the source, which is essentially similar to widening, increasing the effective size of your target.

This is why sputtering systems are very large because they tend to have huge targets. Imagine today people were processing 6 inch wafers-- not 6 inch. Here at MTL we're processing 6 inch, 12 inch wafers in industry. That target has to be huge basically. And then you would be rotating the wafers. And so this is why the equipment in the fabs is getting larger and larger. You're fundamentally limited by some of these processes to obtain uniformity.

And on slide 9, in fact, there's just an example of how we would ameliorate this asymmetry from the left and the right side of the wafer. Here's an example where the target's been made as large as the wafer. In fact, most targets today are much bigger than the size of the wafer. And this is also why they cost a lot of money. If you have a target of platinum, if you're sputtering platinum, it has to be 2 feet by 10 inches or something like. That's a lot of platinum. That's a very large sheet of platinum. So it costs quite a bit of money.

Or if you want, instead of making a target so big you can move it further away and you'll get a little better symmetry between the left and the right side of the wafer. But that makes the machine really big. And you can only have so much size in your clean room. So they kind of trade offs here. So in practice, people use larger targets at some reasonable distance, and scale the tool size, and rotate the wafers to help. There's a practical example.

OK, so we talked about how to calculate the direct flux. Basically, you're just taking-- it's like a geometry problem essentially. And you have to have a cosine theta to the end dependence. How about the indirect flux? First of all, on slide 10, what do I mean by indirect? Well, I mean all those processes that occur on the surface or near the surface of the wafer during the deposition. So these indirect fluxes include surface diffusion.

So I could have an aluminum atom that's that started here. But it can diffuse along the surface and end up somewhere else. So that represents a flux to that point. Emission, species come down, but they don't always stick. They don't always stick where they land. They might actually go there and then be re-emitted. So that's an indirect flux called re-emission.

Sputtering, incoming atoms can knock off-- you could have a film of aluminum already on the wafer, but incoming atoms could knock them off. And redeposition, sputtered atoms can be redeposited elsewhere. Here's an example. Aluminum comes down. It hits an aluminum atom that was already deposited on the surface. It's then desorbed or emitted and redeposited down here. So there's a number of processes.

We call these indirect because they're not directly coming from the source. They're coming from other regions on the surface, but that need to be taken into account in the topography. So let's go through each one of these surface processes, the diffusion, and the redeposition, and things, and talk about how we might model them.

If we go on to slide 11, to surface diffusion, well, surface diffusion-- and I'll refer to your text. I'm not going to derive this equation. But it turns out diffusion along a surface is different from diffusion in the bulk. We spent a lot of time talking about diffusion in the bulk of single crystal silicon. Surface diffusion has slightly different driving forces. Not always just driven by a gradient, but it can actually be driven by the shape of the surface.

It can actually be-- diffusion can be driven by the local curvature of the surface, if you're depositing a film, in order to minimize surface free energy. So we have a different type of equation from what you're used to seeing perhaps for diffusion. We see that if there's a flux into a point on the surface, minus the diffusion flux out, so that's the net diffusion flux to a point, it actually depends on a surface diffusion coefficient d sub s, diffusivity. But it also depends on this curvature, this derivative, which has to do with the curvature of the surface.

And what I would do-- I don't want to go through it in detail in class. But if you look at equation 11.37 in the associated texts, in chapter 11, they talk a little bit more about surface diffusion and where this equation comes from. But the main point is because it increases with curvature during deposition, filling in of corners may be enhanced. And you can sometimes get more smoother, more conformal deposition.

Of course, you have to be at a high enough temperature that these species can diffuse. And depending on the material and the temperature, it may not be diffusing. You may have to raise the wafer temperature slightly if you want to get more surface diffusion. So you can think of it this way. If I raise the temperature of the wafer, I can smooth out and get a little more conformal deposition by virtue of surface diffusion processes.

So that's something that can be modeled in topography simulators. Page 12, a little bit simpler, this is very much a bookkeeping thing. There's something called surface sticking and emission and a sticking coefficient. So there's this flux at any given point i that's emitted that arises because not all molecules stick when they arrive at the surface. And so in fact, we write the emitted flux from any point as being equal to 1 minus s sub c.

So the fraction emitted is 1 minus s sub c, where s sub c is called a sticking coefficient, times the flux going in. So what is s sub c. Well, it's a very simple thing. It's the fraction that stick basically. So sticking coefficient here, s sub c, it's the flux that react and stay put divided by the total incident flux. So to give yourself an idea, if you have a high s sub c-- s sub c is a number between 0 and 1 really because it's a fraction.

If you have a high s sub c, like s sub c equals 1, basically you have line of sight deposition. Everything that comes down just stops and sticks on the surface. If you have a type of deposition with a low sticking coefficient, what happens is atoms come down. They may touch the surface, but they don't stick. They don't react. They're kind of inert, in which case they'll be re-emitted. They touch somewhere else, and then they don't react. And then finally they might be emitted and stuck at this point.

So when you have a low sticking coefficient, much, much less than 1-- and sticking coefficients can be 0.001-- it means that things bounce around a lot before they actually stick on the surface. So you're going to have more conformal type deposition. So this depends a lot on the deposition system, on the temperature, on the chemistry.

Again, we don't model all that. We don't say, oh, I'm putting a wafer into an LPCVD system. The sticking coefficient must be 0.01 or 0.1. We don't know that for any given tool. You can put it in as a variable in the model and then you can compare that to what you get. You can compare the modeled deposition to the profile of what you get. And then you get an idea of what your sticking coefficient is.

It's not a number you can calculate from a first principles point of view. But people have derived sticking coefficients for various types of deposition. OK, so slide 13, so this is the formula we said. The flux emitted is just 1 minus the sticking coefficient. It's those that don't stick times the flux incident at the point.

We make some assumptions. Generally, we assume that ions stick. So if we have an ion coming down, we assume sticking coefficient is 1. Why is that? ions tend to be very reactive and they often come down with a certain amount of energy. So we usually say that they have sticking coefficient of 1. Neutrals can have any number one or less. And they're often assumed to be emitted with some kind of a cosine theta angle distribution.

So that is they may have no memory of their arrival angle. So don't think of this, for example, in here, don't think of this as a little trough like a pool that we've taken all the water out, and you have a ping pong ball and it's bouncing around with billiard ball kind of collisions. It's not supposed to be thought like that.

This atom is supposed to come down. And then atoms are coming down continuously, say at this point, and then it's readmitting at with some angular distribution, but it's not necessarily a billiard ball kind of collision type of thing happening. So you need to put in a re-emission flux distribution. So at any point i we get a flux of redeposited material because the emitted flux can land somewhere else on the surface.

So we have this sort of, again, this ends up being bookkeeping. We have this something we express as f super ik redeposited. And what this is you take the flux, the direct flux, f sub k, that's coming into a point k on the surface-- let's say it's right here-- and we're looking at then point i. It's desorbed from point k and it's redeposited at point i. So this redeposited flux depends on some geometry factor, gik. So it has to do with the geometry between point i and point k times f sub k that's emitted, so times this emitted flux from this point k.

Well, the emitted flux from point k just depends on the incoming flux to point k times the 1 minus the sticking coefficient. So the nice thing is here for point i can take any point k and figure out if I know the geometry factor between the two. How much is deposited at this point i resulting from having come from being emitted from point k?

And then what you do is you take all of these at this point i you take redeposited fluxes from all points of the surface so that all points of a surface could be redepositing at this point. So you sum up for all i and k and you figure out what's deposited. So gik then accounts for the geometry between any point i and k.

Because, obviously, if you're over here, let's say I'm over here, my point k. We're up at the surface, and it's re-emitting. Well, chances of it coming back down over to this point are dramatically lower than if it's re-emitting from the walls just based on geometry. OK, so let's take a look at some examples on slide 14. And hopefully this will become intuitive.

But if you have a low sticking coefficient, s sub c much less than 1, you can end up with more conformal deposition or conformal coverage of the step because of the redeposition process. Redeposition and this low sticking coefficient is usually more important than surface diffusion because most of the time in these processes the wafer temperature is low enough that the surface diffusion is not all that high, especially if you're doing PVD.

But let's just take a look here at the case A where I have a high sticking coefficient. So it's sticking coefficient is 1. Everything comes down and sticks. So what do I get if I'm depositing in this trench? Well, I get very non-conformal deposition. I get a film deposited at the bottom of the trench. There'd probably be a film up here too. It should have been shown. But we're only looking at what's happening in the trench. But nothing on the side walls. Why? Because I really don't have any opportunity for redeposition.

Whereas, I can have that same angular arrival distribution. So with the exact same angle of arrival distribution, if I have a low sticking coefficient, things can move around a lot and hit the side walls. And then you can end up with more conformal deposition. And again, you would use this type of equation in the computer to be able to model that. You just vary the sticking coefficient. And you need to calculate the geometry factor as part of that.

So low sticking coefficient is good if you want to coat a trench. Now, that may not be what you want. You may want to just deposit at the bottom. But again, it depends on the process that you're trying to do. OK, so that has to do with sticking coefficient. That's an important concept in basic surface physics. And we talked about surface diffusion.

The third concept is sputtering, what happens on the surface. And that we talk about here on slide 15. There's a sputtered flux at any point i is caused by energetic usually incoming ions. Why do we care about ions? Well, the neutrals usually come down with low enough energy. They do a little bit of sputtering but not much.

But an incoming ion can come in and it might have a couple hundred electron volts of energy. With enough energy, it can then hit something at the surface and cause it to be sputtered or emitted. So what we typically say is any point i the sputtered flux depends on the sputtering yield, y. y is just the number sputtered divided by the number incident.

And this plot tells you how the sputtering yield varies with angle, depends on y times the flux of incident argon ions, flux of argon, and the direct flux of ions. So the total ionic flux is what we add up. So you might be curious to say, all right, well, how does the sputtering yield depend on the angle? Because that's going to tell you if you have a trench with a certain angle, and the atoms are coming in, and the ions are coming in, how is the sputtering yield going to vary.

Well, this is a typical plot of yield versus angle. So again, a yield of 1 means it's 1 to 1. For every one that's incident on that point, one comes off. And you can see. And this is all measured with respect to the surface normal. So theta equals 0 means normal sputtering. So it's coming straight down.

So at theta equals 0 for this particular example, the sputtering yield is one. And look what happens. As you increase theta-- so you're coming in a little more grazing, I'm increasing theta-- it peaks somewhere here around 50 or 60, 65 degrees. Gets up to about 2, 2 and 1/2, and then eventually at your very glancing incidence there's really no sputtering at all. It really drops dramatically.

So this angular sensitive and you can use this to achieve more planar surfaces during a deposition. In fact, we'll show some examples where we use ionized species during deposition to give you a little better planarity. But so this angular dependence is something that we want to keep in mind.

OK, and now on slide 16, so what happens? So let's say you do sputter that off, then you have redeposition of the sputtered molecules, how do you model that? The exact same way you modeled reemission when you were just coming off due to low sticking coefficient. You just say the redeposited flux between i at point i due to whatever is sputtering off from point k is just a geometry factor gik, which you which end up summing over the surface, times the sputter flux from point k.

And that sputter flux from point k depends on the flux incident of ions times the sputtering yield y to see how the sputtering yield comes into it. And finally, if you want to substitute in the sticking coefficients, what you say is the redeposited at point i depends on the emitted from k, which depends on 1 minus the sticking coefficient. So we have this redeposited due to emission is very, very similar to the redeposited due to the sputtering.

And there's a final term in a lot of these. And this is the biggest fudge factor I would say in the whole model, which is that ions coming down on the surface can sometimes enhance the deposition rate in a way that's not completely obvious. The ions may come down. They may supply enough energy to drive a chemical reaction that might take place at the surface. So we have a deposition flux. So we can have a deposition rate that is called ion enhanced or ion induced chemical reaction.

So it's kind of a fudge factor. We have an additional flux and a term with a k sub i, where k sub i is a fitting parameter, times the flux of ions coming in at any given point. So you can have this extra ion induced deposition rate. Obviously, that's only important in systems with ionized type of deposition.

OK, so those are all the different processes at the surface and the direct flux. And now, starting on slide 17, I want to give a couple of examples because it seems like there's a lot of different equations. But it turns out a lot of them simplify for most systems. So let's do an example of low pressure CVD. Remember, LPCVD is probably the most common deposition process in a fab, typically takes place in a furnace that's pumped down to low pressure, say 10 to 100 millitorr.

Now, the wafers are usually stacked in a batch. People do 25 to 50 wafers at a time. It's in a resistively heated furnace. There are no ions. This is not a plasma system. So we can get rid of all ionized processes. So we can ignore sputtering because, again, we're going to say that only in the presence of ions do you have enough energy to sputter something off. So we get rid of the sputtering.

Usually, long range surface diffusion is not that important. So we can also ignore the surface diffusion. So if in my bookkeeping I have all these different fluxes, most of them are all not present. There's only two that dominate at any point i. It's the emitted flux. Yes, because we have a finite sticking coefficient, and the redeposited flux. Yes, we need to take that into account, and the neutral direct flux.

So really in this example I really only going to have three fluxes I need to worry. About all the rest of these we don't have to take into account in the simulation. So then we can write down those fluxes pretty simply, and the net flux here on slide 18. So at any point i on the surface, f super i, the net flux is again the flux coming in minus the flux going out.

So it's the flux of directs, neutral species, the redeposited flux that comes from other areas of the surface, minus the flux that goes out. Well, those that don't stick, that's 1 minus the sticking coefficient times the direct flux of neutrals and the redeposited direct flux. OK? So these are the ones that come in, and these are the ones that go out. And there's a negative sign in between the two.

So you can rearrange this a little bit and you can write it then as shown here, the net flux at any point i is the sticking coefficient s sub c times the direct flux at that point of neutrals plus a term that relates-- a geometric term, this gik times 1 minus s sub c. That's those that don't stick times the flux into some other point on the surface k.

And then we just need to sum this up over all points k on the surface. Now, what you can do to simplify this a little bit, you can define f sub d to be the deposition flux at each point to be equal to the direct flux of neutrals plus the redeposited flux if you want to do that. And then you can write the deposition rate more simply as the sticking coefficient.

So this is the dep rate, then sticking coefficient times the flux at any given point i divided by n. So we can then calculate the deposition rate at any point i on the surface. And we use a cosine theta to the n distribution for the incoming molecules. So it's a relatively simple formula can be used for LPCVD.

And in fact, on slide 19, I just wanted to go through an example. This took directly from your text. What we're asked to do is calculate the dep rate using this LPCVD expression that we just derived, sticking coefficient times a flux divided by density, for silicon dioxide. So this is low temperature oxide. And we have a flat surface. So this is nice. There's no topography.

We are told that the sticking coefficient is 0.3 and that the maximum unobstructed flux, so that's the maximum flux that's coming straight down, is equal to 3 times 10 to the 15th molecules per square centimeter per second. So that's a molecular flux. And we're given the density of the film that's deposited, 2.27 grams per cubic centimeter.

So this is a relatively simple calculation. We want to get the deposition rate on a flat surface, therefore there is no shadowing effect. There's no redeposited flux because we're not coming off of a side wall of a trench. And each surface position is in a horizontal orientation. So we're only concerned about the direct flux. So f sub d, the deposited flux, is just equal everywhere to the maximum value, which is this 3 times 10 to the 15th molecules per square centimeter per second.

And you can look up this equation 9.53. In fact, that's exactly what I just was showing down here for the dep rate. So we have that equation. The rate is just the sticking coefficient times the flux divided by n. We need to do a little bit of conversion here to get ourselves from grams per cubic centimeter into molecules. The way we do that is we take the density of SiO2 being 2.27 grams per cubic centimeter. And we multiply that by Avogadro's number divided by the number of grams per mole of SiO2.

So we need to do a little conversion to convert this density of grams per cubic centimeter into a number of molecules per cubic centimeter for SiO2. So you get 2 times 10 to the 22 molecules of SiO2, those units per cubic centimeter. And then you just use the simple formula. The rate is just a sticking coefficient times the flux, the maximum flux over n. You plug-in the numbers you were given. And you get about something like 0.023 microns per minute.

But now, if you had a deposition on a non-flat surface, if you had a trench or something like that on the side wall, for example, the local dep rate would be less. So this gives you a maximum, a rough idea of the maximum. So it just gives you-- we'll talk later about SPEEDIE simulations, more complex topographies. But it gives you a rough idea of how you can model this simple type of process.

OK, let's go on to slide 20. And we'll give some more examples. Now we're going to do PVD. So we've already talked about physical vapor deposition systems. We said there could be DC or RF sputtering or evaporation. Typically, ions do not play a significant role in these kind of PVD systems most of the time.

So the modeling of simple PVD is very much analogous to LPCVD. The parameters are very different though. So here's an example of a simple DC sputtering system, which we talked about a couple of lectures ago. And these are the processes that go on. So just like LPCVD, we can say a rate at any point on the surface is a sticking coefficient times the flux, the total deposited flux divided by the density.

However, the key difference is that the sticking coefficient and the arrival angle distribution, cosine theta to the n, will be very different between LPCVD and PVD systems. And that's where the real differences tend to come about. There is one other type of system for PVD, though, where you do have to pay attention to a little more complex processes than you would in LPCVD. And that's shown on slide 21 when you have ionized PVD.

We did talk about the case where we have systems that are more complex. This because ions and neutrals both play a role. Here's an example of an ionized PVD system. So you have sputtering of aluminum coming off this target. But then you have an additional-- in addition to that, you have a coil that goes around that ionizes the aluminum as it comes off. Now you have a large density of ions that are being created. And then these can be accelerated towards the substrate.

So this is not that uncommon for metal deposition. So you have aluminum or maybe titanium ions that'll be present. Therefore, when you have ions, you do have to take into account sputtering and other processes that will not be present in LPCVD or the simpler PVD systems. So ionized PVD, inductively coupled ionized PVD, is a little bit more complicated to model, just more bookkeeping in the equations.

Here's an example, in fact, on slide 22, if we do ionize PVD, of all the different fluxes that really do need to be taken into account. And you see we have yes on all of them, the direct neutrals, the direct ions. The only one we're not taking into account in this case because we're assuming the wafer is low enough temperature that we can ignore surface diffusion. But all these fluxes would need to be taken into account.

And if you do that, shown here on slide 22, this is the example of the possible terms that could be included in your computer model. So you would say that the rate at any point i depends on the sticking coefficient times the direct maximum deposited flux, where fd includes the direct and the redeposited neutral fluxes. Plus f sub i includes the direct redeposit and ion induced flux. So there's an f sub i.

And again, f sub i doesn't have a sticking coefficient associated. We say for ions, we include all of them, we say they just come down and stick. And then you have a minus those that are sputtered off. You have a sputter term plus a redeposited term. So this frd models the redeposition due to sputtering. So you have extra terms here divided by the density n.

And so you have a positive term and a negative term, some of which depending on the point i and the surface and the angles involved may cancel each other out. OK so those are some basic bookkeeping models. I want to actually do some examples of the values of these parameters that are useful for specific systems. And so far, we've talked about two parameters that are most important, the n value, which is the exponent in the cosine theta to the n arrival angle distribution, and the sticking coefficient s sub c.

Those are the two most critical in modeling simple systems. And there are a couple of different model systems shown here. On the top we're talking about sputter deposition, either standard or ionized, and evaporation. So these are PVD systems. In the bottom, we have the CVD systems. So let's look at PVD.

Well, physical vapor deposition, it tends to have much more vertical arrival angle distribution. So the n value is big, right? Almost everything in PVD is coming straight down. Certainly in evaporation you have very low pressure, so you have line of sight. Even in sputtering you tend to have close very anisotropic. So for sputter deposition, depending, you can have n equals up to five maybe. If you're ionized you can get up into the range of 50 or so.

But in any case, n is usually greater than 1 for PVD. In contrast, CVD systems tend to have pretty much isotropic arrival angle. PVD, again, takes place you're sputtering in 10 to the minus 5 torr, or 1 times 10 to the minus 3 torr, or something like that. CVD usually much higher, hundreds of millitorr, 0.1 torr or something like that.

So you usually have higher pressure. You have a lot of gas phase collisions that randomize things and mostly neutrals. Usually, in CVD, you don't have many ions. So n is usually 1 in CVD. So the cosine theta to the n is usually fairly isotropic. What about PVD? Well, the sticking coefficient in PVD tends to be close to 1. There really isn't much surface chemistry involved.

The aluminum or whatever it is that's being evaporated or sputtered usually comes down and pretty close to sticks. There isn't a whole lot. There can be. But most of the time the atoms arrive and stick. Very, very different, though, in the case of LPCVD-- look at LPCVD, the sticking coefficients, depending on what your chemistry using, if you're using a silicon source of silane, you might have a sticking coefficient of 0.5 or 0.3.

For TEOS, we mentioned there's other ways of doing low temperature oxide, not just with silane, but there's this other silicon sources. Sticking coefficient can be much lower. LPCVD tungsten or polysilicon you have much lower sticking coefficients, so very different from PVD. That same chart is reproduced here again on slide 23. It's the exact same chart. I just wanted to reproduce it and talk a little bit more about the CVD thing.

Because they have surface chemistry, sticking coefficient much, much less than 1, and things often evaporate before they react. What does this mean? Well, just by looking at these numbers, you know that CVD systems with their small sticking coefficients are going to tend to have more conformal deposition. If you want to cover a step and you want to cover it very conformally, what does that mean? That means the thickness along the flat part of the wafer is exactly equal to the thickness of the film along the trench wall is exactly equal in the bottom. It's just completely conformal.

In that case, you probably want to use CVD. Now, that may not be what you want, but this is what we mean by conformal deposition, that equal thickness. And CVD tends to give you more conformality just because of this sticking coefficient argument. OK, now I want to show some actual examples of simulations to convince you of some of these things that we've been talking about. And we're going to vary the parameters n and s sub c in the model.

So on slide 25, these are topography simulations that are taken from the simulator that I mentioned called SPEEDIE. Again, that's a topography simulator. You cannot simulate this type of topography in SUPREM-IV. SUPREM-IV doesn't do topography. So this is an example of you're doing a deposition using LPCVD of SiO2 and you originally have a trench that you have etched that looks like this.

And each contour line-- it's a little bit hard to see. But each contour line represents the deposited topography at different time intervals. So each one might be after a 1 minute interval. So you get an idea of how the topography develops over time. In this particular example, we did a SPEEDIE simulation with a sticking coefficient of 1.

Actually, the sticking coefficient of 1 is probably more typical of PVD. So this really should be PVD in your mind. And all we did mathematically is vary the arrival angle distribution, the n value. So this is for n equals 1, that's isotropic. Here's for n equals 3, somewhat anisotropic, n equals 10. So let's look at this. Even for isotropic arrival distribution, because of shadowing effects and things, conformal coverage is not achieved with the sticking coefficient of 1.

That is, what do I mean by conformal coverage is not achieved? Well, the thickness of the film here at the surface on the flat portions is not equal to the thickness along the side wall. The side wall is thinner even for n equals 1. And so what this implies that if you have a sticking coefficient s sub c equal to 1, the geometry and line of sight issues are going to be very important.

So for example, for PVD, you really need to take into account the geometry of what you're depositing into. Look at this one for n equals 10. You almost get no deposition on the side wall. You get quite a bit on the bottom. And notice this is for an aspect ratio that's pretty gentle, I mean, pretty not that sophisticated. This aspect ratio of 0.3, what does that mean?

That means the trench is 3 times wider than it is tall. So it's only 1 micron tall, but it's 3 microns wide. And you're already seeing these nonconformallity types of issues. So this is what you'd expect from PVD with these parameters. Just to remind you, on page 26 what we're talking about, the n equals 1 the flux as a function of angle looks like this. N equals 3 looks something-- it cuts out after about 60 degrees. And the n equals 15 cuts out after about 30 degrees.

So this is close to n equals 15. So when I was getting more than about 30 degrees, so from a normal you can imagine going on to this surface, there is not a whole lot of flux. And that's the problem. That's why we're getting such low-- with the sticking coefficient of 1, you're getting such low deposition along those vertical walls.

Let's make it a little more difficult even let's take an aspect ratio. We're going to take those same parameters, so the same parameters that we just saw. Sticking coefficient equals 1 here on slide 27, but now I've increased the aspect ratio from 0.3 up to 1.3 or 1.25. So now the trench is 1.25 times tall compared to what it is wide. So it's much taller than it is wide, just the opposite of what I had before.

Now, what you do see again is less deposition on the side walls. Here, this is A here on the left is for isotropic arrival, n equals 1. And b is for anisotropic, n equals 10. So let's look at the n equals 1. Well, what's happening? You see if for isotropic arrival angle, you're not getting much material down at the bottom of that narrow trench.

Because, again, it's reasonably isotropic arrival, you're getting material coming deposited along here and you're sort of developing these lobes up at the top, which if you had a narrow enough trench, you can imagine these might cut off and you end up with a big void. If you're more anisotropic, you're coming down straight. So you do get quite a bit at the bottom of the trench. You get quite a bit on the flats. But you get nothing or very little on the side walls.

So as you go to narrower and narrower trenches, you can imagine you might end up not being able to fill them at all. You might end up with voiding if you have a sticking coefficient of 1 is really what this boils down to for high aspect ratio trenches. So if you want to avoid that, let's say the purpose of your deposition is to fill this trench. You haven't done a very good job in this case. And you're not going to do a good job in this case at all. You're going to pinch it off.

What do we need to do? Well, we need to lower the sticking coefficient. We need to have not such a line of sight distribution. We need for atoms to come down, come in here, and not stick, and move around so they can eventually cover these side walls. And that's exactly what is shown on slide 28 in the SPEEDIE simulations.

Here's an example of now I've got that same trench, that same high aspect ratio, 1.25. But on the left here, A, I have the sticking coefficient of 0.1. So only 1 in 10 atoms sticks. The other 9, when they hit a point, they go somewhere else and they continue to bounce around until they finally stick. Here's 1 in 100 sticking.

so, again, this is with n equals 1. So it's isotropic arrival, but with different values of the sticking coefficient. So sticking coefficient is the knob you want to turn if you want to fill a trench. Changing the n value helped, but not a whole lot. It was really lowering the sticking coefficient. You get much more conformal coverage. So you get on the sidewall just about what you had.

So this is typical on A, this view of things, the parameter values. n equals 1 and sticking coefficient of 0.1 is very typical of LTL, so low temperature oxide or CVD SiO_2. b with a sticking coefficient of 1 and 100 is more typical of tungsten CVD. So we need to reduce the sticking coefficient if you need more conformal deposition.

How about the sidewall angle? So if I even go back here, I look at this, I didn't do a perfect job in this case of filling this trench. It look like it's going to pinch off and form a void before I get the whole thing filled. Even here it doesn't look all necessarily that perfect. So what can we do? You only have so much latitude, you're sticking coefficient. You can change the pressure and do things in your reactor. But you only have so much latitude.

Well, what you do is you change the topography that you're starting with. So these examples are results of SPEEDIE simulations where you're doing LPCVD into a trench. And we've changed the sidewall angle. Here, the trench has a 90 degree angle, so the side walls go straight down. Here, it's opened up slightly by 5 degrees. So this is an 85 degree angle. And here you open up a little bit more, 80 degree angle.

This has a sticking coefficient of 0.2 and an n of 1. So this is very typical of low temperature oxide deposition, for example, into a trench. So if you decrease the angle from 90 to 80 degrees, you greatly improve the filling. See at 90 degrees you're going to pinch off and you're going to get a void. At 80 degrees you're not going to.

So it's very common in etching, when you go to etch, to try to etch a contact hole in a via, you never want to etch it straight down. You always want to have a slight angle, say make it 80 degrees to slope this so that you can get much better filling of the hole. Or if you're trying to make-- you want metal lines to go over a step on your wafer, you never want to make the step look like this. You usually want to have it more sloped.

So you somehow slope the step when you etch it, or you put in side wall spacers, or do something. So the general idea, if you want good step coverage, don't make such abrupt steps. If you're doing vias, you can just decrease your angle from 90 to 80 and you get much better filling of the trench.

OK, how about there are a little bit more complicated cases? I've just shown very simple cases, PVD without ions or LPCVD without ions. How about the case where you do have an ion flux? And there are a couple of cases like that. There is what's called HDP, high density plasma CVD. This has a very high ion flux, could be three or four orders of magnitude higher than what you have in ordinary CVD.

So how does this work? Well, think we mentioned this at one point. This particular one has a microwave source. What we have is we have a plasma up here. And there's a microwave supply that's creating those ions. But then it's created remotely. So this ionized plasma has a very high density, but it's created remotely, not directly over the wafer.

And then you have an RF bias and you extract those ions towards the wafer. So the nice thing about this is that you can get a very high density without having huge energies, huge voltages, to extract them to the wafer so you don't get so much damage. And this high density plasma can give you a very high CVD dep rate, even down to a room temperature with relatively low pressures.

So the key is you have a separate RF bias applied to the substrate. That controls the angular dependence of what comes down and of ion sputtering during deposition. So we have a direct ion flux coming down like this on the surface. And we have ions that come down and sputter off. And now here's where our resputter flux becomes important for these high density plasma systems.

And the thing that we need to realize is because of the angular dependence of sputtering, sputtering occurs preferentially on a slope surface rather than a surface that's either vertical or horizontal. Because, remember, that sputtering rate sort of peaked at around 60 degrees. So if you have a sloped surface, you get preferential sputtering. So you can actually use these high density plasma systems to do planarization.

Now, all along I've been talking about conformal deposition. You may not want to get conformal deposition. You may want planarized. So what do I mean by a planarized deposition? Well, if you start out-- let's say your surface topography looks like this. You have a metal line or something and you want to cover it with oxide, but you want it to be planar when you're done. You'd like the surface to look like that after deposition, completely flat.

That's just the opposite of conformal. If it were conformal, right, it would have looked like this. It would reproduce that big hump. But if you're trying to do planarization during deposition without using CMP, you'd love a process that would deposit like this. Well, how can you do that? Well, there are some processes that are self planarizing during deposition.

And here's an here's an example of such a process. You need these ionized techniques, which in addition to depositing, are doing sputtering preferentially. So here's an example on slide 31 of two SPEEDIE simulations. On the left, I have low pressure CVD, regular low pressure CVD. So I have a line like this and I'm trying to cover it with oxide. And you see you started out with a bump and you end up with a bump. There is no planarization. It's perfectly conforming.

In b, we've simulated this high density plasma CVD deposition, and it has a directed ion flux. And the key is it has this angle dependent sputtering, which you end up with a little bump but much more planarized topography after deposition. So if you had to do CMP to planarize, on this one you'd have to CMP quite a bit. On this one, you'd probably have to CMP only a little bit, just a small amount.

And that's very desirable because CMP is a tricky process. It introduces non-uniformity and it's fairly expensive. So if you can do self planarizing deposition with these fancy ionized deposition systems, you're much better off. And I'll actually show some real examples of that. So besides depositing over a line, you can also use this high density plasma CVD. It's very good at filling open spaces and reducing void formation.

So here's an example here, again, a SPEEDIE simulation on the left. I had a trench with a relatively high aspect ratio. This was that 1.25 aspect ratio. By LPCVD, you see it pinches off and you end up with a void. And in order to do this, we used a sticking coefficient of 0.2 and an isotropic arrival angle. On the one on the left-- on the right, I'm sorry-- is high density plasma deposition in the trench. And you get much better filling. You don't see the void.

Well, why does it do this? Well, high density plasma gives you better filling because you combine this highly directed ion flux. So a lot of the ions are coming straight down, and that helps. They get into the trench. So they're towards the surface with this angle dependent sputtering. So the angular dependent sputtering tends to etch off any of these overhangs. As they form they get etched off by the sputtering preferentially.

So overhangs that develop get sputtered away, and you end up being able to fill the trench pretty well without a void. Often, you do not want voids in the film. You don't want air spaces in your chips. So this is a way to do it is that high density plasma. Here's an example on slide 33 just to show you-- instead of just showing SPEEDIE simulations, actual data. These are scanning electron micrograph images of HDP oxide deposition.

And on the left, this was a metal line you can see. And we we're trying to deposit oxide over that. And again, if it had been conformal, you'd have a big hump in your oxide. But with high density plasma CVD, which is not conformal, all you end up with pretty planar oxide. You still have a little bit of a bump there, a very small little bump, that you would have to planarize away. But the amount of CMP you'd have to do on that would be very minimal.

And again, so that's the case of depositing over a line. If you're depositing oxide in a trench, so here's an example of a trench. You have two metal lines, one on the right, one on the left. They're separated by half a micron or so. You want to completely fill this without voids. You can see you've gotten excellent filling. You did get some of these strange, you know, topographies because of the ion effects. But that would have to be CMPed off. But the key is you were able to fill a very small space without inducing voids. And that would be a problem if you're trying to use, say, an LPCVD system.

So you can imagine looking at these topographies, simulating, and then going back in SPEEDIE and varying your models to try to get something that looks like what you actually got from SCM. And that's what exactly what people do in topography simulation. Again, it's not first principles. You vary all these different parameters. The sputtering yield is a function of angle, the n value, which is the cosine theta to the n distribution, the sticking coefficient. You vary all those until you get something in your simulation that looks somewhat close to what you actually deposited.

Slide 34 shows the case-- we haven't had much chance to talk about it, but this whole idea of surface diffusion. And this becomes important only when you're usually doing high temperature PVD, say for aluminum. That's a practical example that people sometimes do. Again, all of these issues tend to arise when you have high aspect ratios on the wafer. So you have a very high aspect ratio trench like this and you're trying to fill that with aluminum.

And so on A on the left is a high aspect ratio trench using PVD. So we have a sticking coefficient of 1, n equals 4. So this could be a sputtered situation. And you have very poor filling. In fact, you don't have much at all aluminum on the side walls if you weren't able to fill the trench well at all. In B, this is again, now this is way of high temperature PVD where we've raised the surface of the wafer up to about 400 degrees, much better filling, not completely, but much better.

And finally, if you do to a deposition temperature of 550, and you can't go to hot. Aluminum melts at six something. You'd be in trouble. But at 550, you get a lot of surface diffusion. And you get a lot of reflow of the aluminum, essentially, and you completely filled the trench, so much better much smoother topography. So that's an example. When you get to very high aspect ratios, you cannot rely just simply on sputtering.

And so you need to add something to the system. You add the surface diffusion component by raising the wafer temperature. So then you need a special system where the sputtering system is designed so it can heat the wafer up to reasonably high temperatures at which the species will surface diffuse. OK, so on slide 35 I just want to summarize. As I mentioned, this is the last lecture on chapter 9.

We talked about important issues for thin film deposition. We said there are two different properties, the physical properties and the chemical properties of the film. The coverage of topography, for example, this conformal deposition and step coverage we said were very important. There are two main techniques you need to keep in mind, chemical vapor and physical vapor deposition.

If you have simple models, the dep rate is limited by either the surface reaction rate-- that's usually at low temperatures-- or the mass transfer through the gas phase boundary layer. That's usually at high temperatures. But you do have to take into account shadowing and surface features to model the actual coverage.

For PVD, these processes, again, their names-- it's very physical rather than chemical. The arrival angle distribution at the wafer surface is important, that cosine theta to the n term. In a lot of these techniques, the species arrive more vertical to the wafer surface, and the sticking coefficient tends to be one for PVD. So PVD has a lot of shadowing issues that you need to keep in mind.

We model this by having a sticking coefficient s sub c. And if you have a low sticking coefficient, say much less than 0.01 or something like that or 0.001, and you have an isotropic arrival distribution, you'll get much better filling of holes. But there are new techniques. But this only works to a certain extent this filling.

So the latest techniques use these high density plasma and these ionized sputtering techniques, which have simultaneously sputtering going on at the same time as deposition. And this can be used to get good gap filling and planarization. So these are the most modern techniques people use today. There's a lot of things we didn't get to talk about in chapter 9 in this course.

6774 is about front end processing, but we give the lion's share of the time to oxidation diffusion and ion implantation. Most of the lectures are on that. If you really want to know a lot more, if your thesis research is going to be on thin films, for example, we didn't cover a lot of things. We didn't talk at all about the grain structure, the density, the stress in the film. None of these things did we have time to cover and how to model these properties.

There are courses that are more thin film oriented courses, like in the material science department. And if you really want to know about thin films beyond what's in chapter 9, I would recommend you look towards some of those classes. But I just wanted to make it clear that this is sort of the minimum amount of information you need to know for front end processing as far as thin film dep and epi goes.

OK, I think that's about all I have in this for today's lecture. As I mentioned at the beginning, if you came in late, hopefully you're working on homework number 5. It's due Thursday. And I did bring the clipboard. My assistant has typed up her version of what she thinks you're going to be either talking about or writing up. You can check. That I've approved all of them. There's only one person who doesn't have anything listed there.

And if you're giving an oral report, what I'm going to do this week is start scheduling for the last week of classes so you know which day you have to give your oral report. OK, good, well, I'll look forward to seeing you on Thursday then.