Fundamentals of Micro and Nanofabrication
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Lecture - 18
Chemical Vapor Deposition: Types of CVD Equipment

This is a continuation of a lecture on chemical vapor deposition in the module of additive processing. In the last lecture, we discussed some basic mechanisms of CVD, the mass transport limited regime, and the reaction rate limited regime. Here, we look at the various practical implementations of CVD equipment, various terminologies used, for example, hot wall, cold wall, low-pressure CVD (LPCVD), atmospheric pressure CVD (APCVD) etcetera. We apply the basics that we learned in the previous lecture to these systems and understand their advantages and disadvantages.

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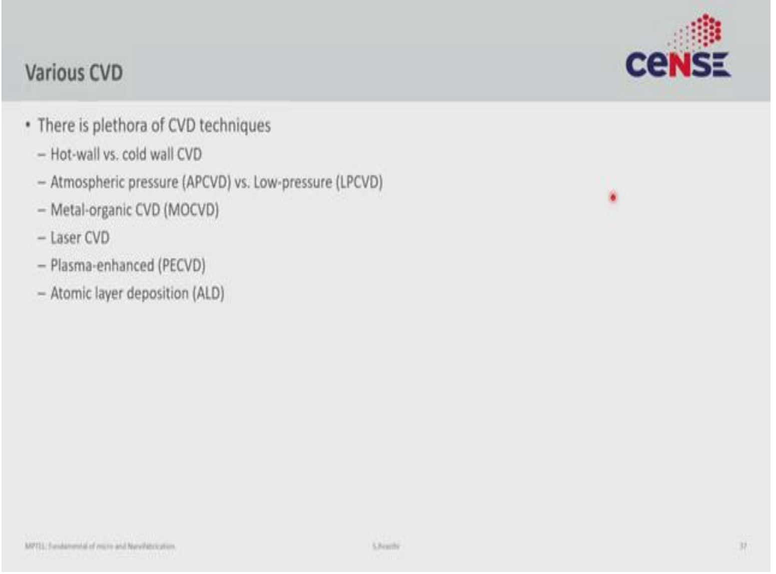

In the last slide of the previous lecture, we saw various types of CVDs that people have designed over the years. Let us take each one by one.

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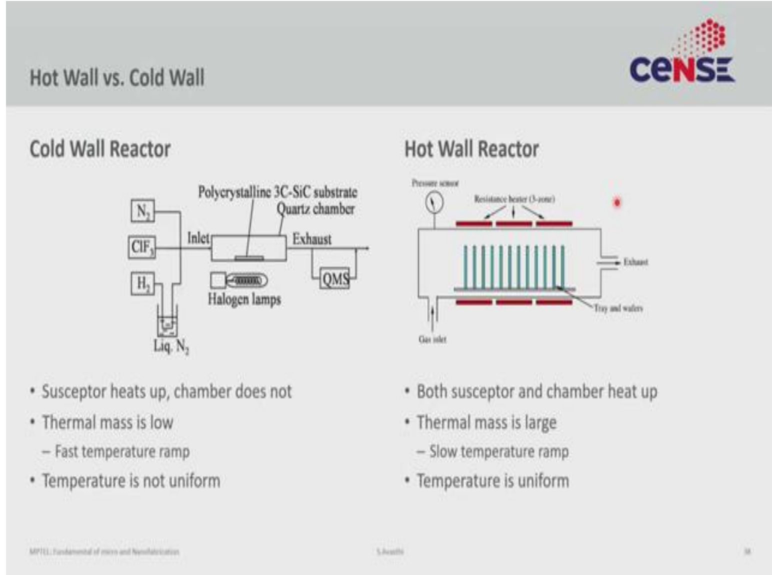

The first one is a hot walled versus a cold walled CVD. The basic difference is the chamber temperature. The distinguishing factor between a cold wall and a hot wall is this quartz chamber. On the left, we have a quartz chamber that is heated by a halogen lamp. The halogen lamp emits in the visible region, and the quartz is transparent to the visible radiation. The radiation coming from the lamp goes through the quartz without heating it up and directly heats the polycrystalline wafer. Some amount of heat might come from this polycrystalline silicon carbide substrate to the chamber, but primarily the chamber is not heated on its own. As long as you can keep the substrate insulated from the chamber, the chamber always remains cold. Compare that to the case of a hot water reactor like on the right where the whole thing is enclosed in a furnace with the resistance heaters in contact with this quartz tube. The quartz tube also heats up, which in turn heats up the gases and the wafers inside. In this case, the chamber remains hot.

What is the advantage of the cold walled system? The system with thermal mass is fairly low, and only the wafer heats up. If you want to change the temperature during your recipes, it is fairly easy to do so, and it does not take too much time. You can change the temperature of the wafer in a matter of seconds. However, the disadvantage is that the temperature is not uniform. The only way to guarantee that the temperature T of the wafer is to keep it in an environment where all the walls of that chamber are also at the same temperature T. This is what a hot-wall reactor or a typical furnace accomplishes. As all the walls of this chamber are hot, you can be sure that the wafer inside is also hot.

But in this case all the walls of the chamber are cold and only the wafer heats and this wafer will then radiate the heat out. That radiation will be non-uniform and hence, the temperature of the wafer would also be non-uniform.

The problem with the hot wall reactor is that it has a very large thermal mass. Not just the wafers are hot, but the quartz chamber and the resistance heaters are hot. So, in order to change the temperature, you now need to change the temperature for all of this. So, temperature ramps are very slow, often you cannot cool down a reactor faster than around 5°C/min or something on that order. The advantage, however, in the hot wall reactor is that the temperature is uniform. The advantage of the cold wall temperature is that the temperature can be changed very fast. It depends on what type of growth you need; the ability to change the temperature or temperature uniformity.

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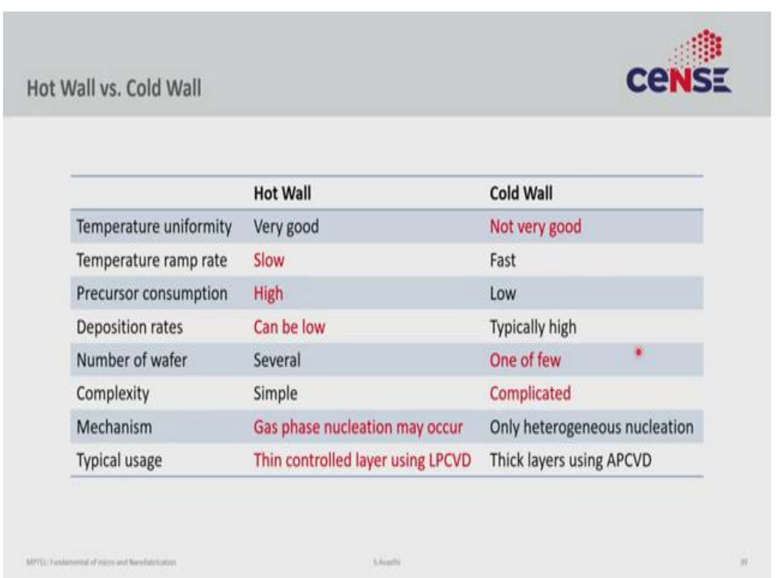

	Hot Wall	Cold Wall
Temperature uniformity	Very good	Not very good
Temperature ramp rate	Slow	Fast
Precursor consumption	High	Low
Deposition rates	Can be low	Typically high
Number of wafer	Several	One of few
Complexity	Simple	Complicated
Mechanism	Gas phase nucleation may occur	Only heterogeneous nucleation
Typical usage	Thin controlled layer using LPCVD	Thick layers using APCVD

The precursor consumption is another aspect. The precursor consumption in a cold wall reactor is typically very low because the only thing that is hot is the wafer. While the precursor consumption in the hot wall reactor is high because even the chamber is hot right. The chemistry/deposition will happen wherever the temperatures are high; in the gas phase, on the surface, on the wafer, and on the quartz chamber. The hot wall deposition rates are sometimes low depending upon the chamber design. For the cold wall reactors, typically they are very high.

In cold wall reactors, we will have fewer wafers. It is just a matter of putting them in. You typically have to put the wafers laterally which means they take a lot of space and you can only put so many wafers in a practical length of a tube. While in a hot-wall reactor, you can just keep your wafers vertically and that allows you to stack a lot of wafers in one shot which means the batch is larger.

Cold wall reactors tend to be a little more complex, partly because the temperature is a little more complex to measure and control. Hot wall reactors are simple furnaces which are very easy to get. We will discuss this later, but hot wall reaction can have gaseous nucleation; cold water reactors only have heterogeneous nucleation. When we discuss nucleation, we shall see that the heterogeneous nucleation is preferable, especially if you are trying to deposit a thin film. Typically, hot wall reactors are used in low-pressure CVD system and cold wall reactors are used in atmospheric pressure CVD systems.

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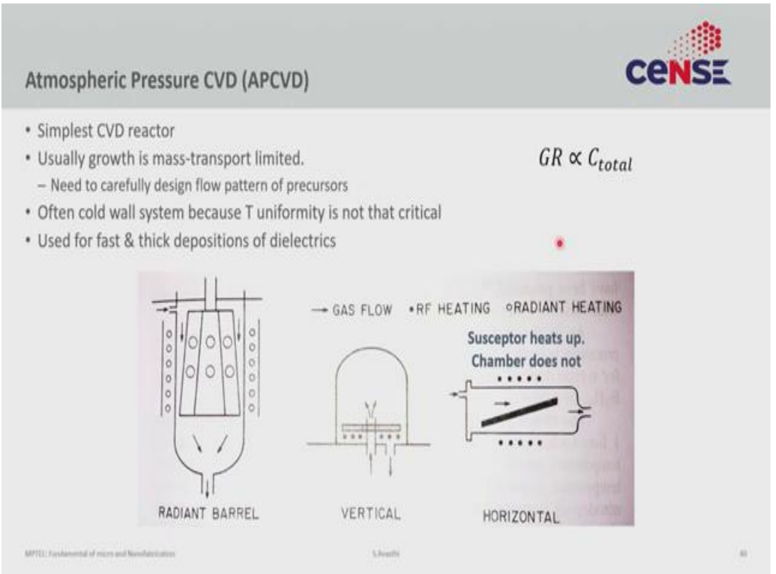

Atmospheric pressure reactors, as the name suggests, work at very high pressures. This can be at atmospheric pressure or slightly higher than the atmospheric pressure, but or at least a few hundred torr types of pressures. This is the simplest reactor we know how to design because it does not have any extensive vacuum equipment seals. The furnaces used for diffusion and oxidation are similar to the APCVD reactors. The growth is mass transport limited in these reactors; partly because the pressure is so high. Pressure increases your growth rate, no matter what type of reactor you have. Since this is an

APCVD reactor (which has high pressure), the growth rates tend to be high. Because these are mass transport limited high growth rate systems, you also need to be very careful in the flow of the precursor and the boundary layer is a problem because you are mass transport limited. Often this is a cold wall system because T uniformity is not that critical as the temperature dependence of the growth rate is polynomial or weak. All you have to ensure is that the boundary layer is consistent and the flow uniform. Usually, we use these for fast and thick depositions. You do APCVD for a quick, simple and cheap deposition.

Reactors look something like this. This, for example, is called a radiant barrel reactor. There are some radiant heaters that emit IR or halogen radiation. The radiation heats up the susceptor and the wafer. If you notice, each facet that holds a wafer is at an angle, which ensures that the boundary layer is consistent from top to bottom and gives you a uniform deposition. Some of these are vertical reactors where the precursor gases come from the bottom and then flow laterally. Sometimes it is a simple slanted susceptor on which you mount the wafers and do the deposition. Here, you may have RF heating, where the susceptor is made of something conductive such as graphite. You put induction coils that induce a current in graphite which heats it up. In this case, also, the chamber does not heat up.

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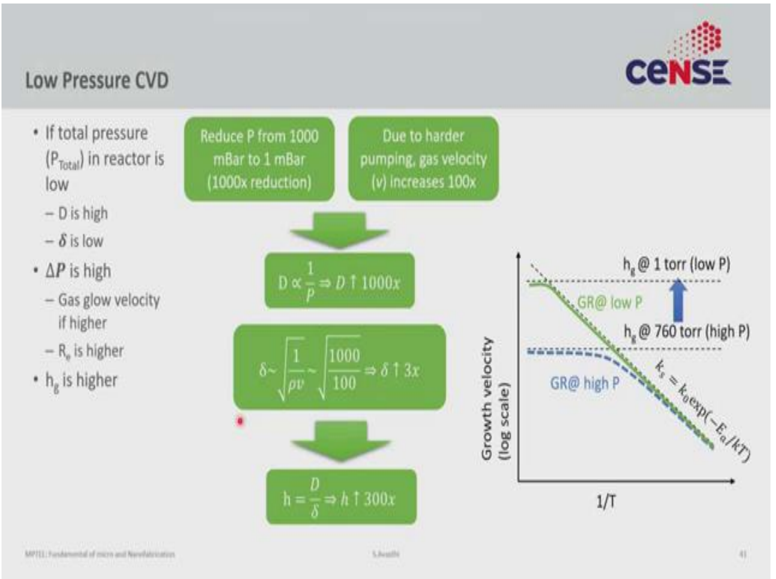

The other extreme is low-pressure CVD systems. These systems are often used for semiconductor depositions or high-quality film depositions. Prima facie, you would think that because we are cutting down on pressure, we must be cutting down on growth rate. To some extent it is true, but the impact on growth rate is less than what you think.

If the pressure is reduced from 1000 mbar to 1 mbar, it is a 1000x reduction in pressure. In order to achieve that, we need to put a stronger pump to increase the vacuum in the system to increase the gas velocity. Let's assume, in the laminar flow regime, you increase the velocity by 100x for a 1000x reduction in the pressure. That counteracts the effect on growth rate and that is why the effect on growth rate is small. The diffusion coefficient $D \propto 1/P$ would also increase by 1000x. The boundary layer thickness inversely depends upon the density as well as the velocity. The velocity increases 100x, but the density falls by 1000x because the pressure has fallen 1000x. Overall, the boundary layer thickness increases 3 times. Hence, Henry's coefficient increases 300x.

Higher Henry's coefficient means that compared to the case of 760 torr, which is a high-pressure regime or APCVD (indicated by the blue curve) if you go to 1 torr (green curve), the edge of the reaction rate limited regime gets pushed to a higher temperature and you get a longer range where you are surface reaction rate-limited and at very higher temperature, you then become mass transport limited.

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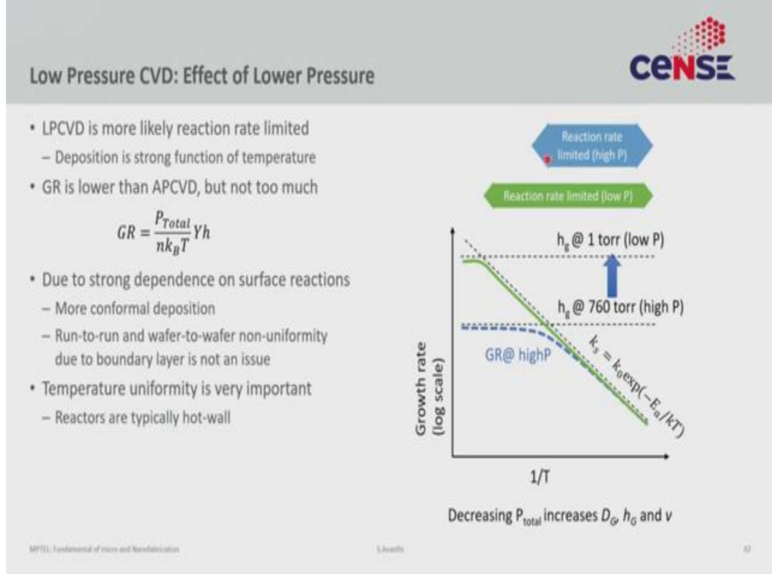

Now you have a higher probability of being in a reaction rate limited regime than previously. And in the reaction rate limited regime, your growth rate depends on the total pressure which has reduced 1000x and also depends on Henry's coefficient that has increased 300x. Overall, the growth rate reduces 3x. Even though the pressure fell 1000x, the growth rate only changed by an order of 3. It is not a very strong reduction. Compared to APCVD, you do have lower growth rates, but not orders of magnitude lower growth rate. The other consequence is that it is dependent on the surface reaction rate and the rate constant k, which is exponentially dependent on temperature.

You are not very sensitive to the boundary layer and flow non-uniformity, but you are very sensitive to temperature non-uniformity. That is why LPCVD reactors typically are hot walled because hot walled reactors tend to give more uniform temperatures.

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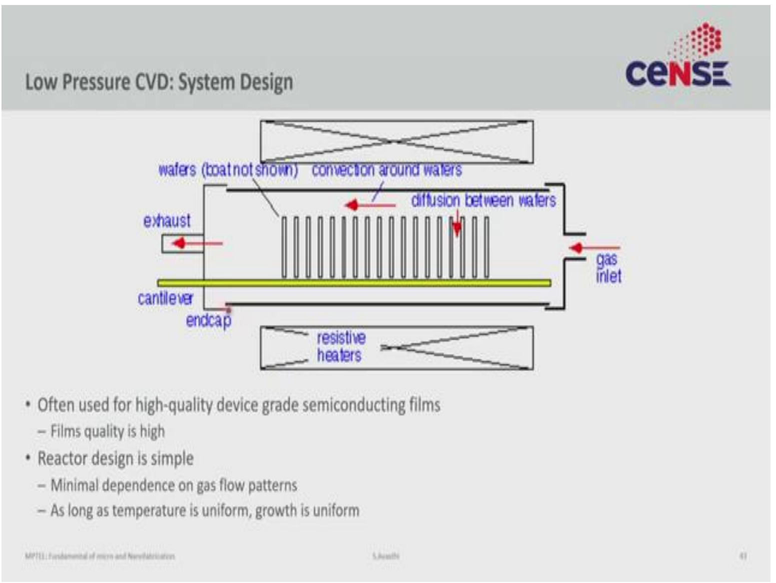

This is what a typical LPCVD reactor looks like. The chamber is often made of quartz and has these resistive heaters that heat up both the chamber as well as the wafer. The wafers are vertically stacked. This is possible because even though the gas flows from right to left, it does not matter how the gas flows and how the boundary layer is. As long as the wafers are at the same temperature, they get the same deposition rate. That is a great advantage of an LPCVD.

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LPCVD vs. APCVD

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	APCVD	LPCVD
Temperature uniformity	Not very important	Very Important
Mechanism	Mass-transport limited	Reaction-rate limited
Gas flow uniformity	Very important	Not very important
Wafer placement	Parallel to gas flow	Stacked axially
Precursor consumption	High	Low
Precursor concentration	Low	High
Deposition rates	High	Low
Complexity	Simple	Complicated
Usage	Cold wall reactor for thick dielectrics	Hot wall reactor for thin semiconductor layers

If you were to compare APCVD and LPCVD, in APCVD gas flow uniformity is very important, while in LPCVD the temperature uniformity is very important. In APCVD we are often mass transport limited; in LPCVD we are often reaction rate limited. The wafer placement in APCVD is often parallel to the flow of the gas; in LPCVD, it is stacked vertically. The precursor consumption in APCVD can be high because the growth rates are high and low in LPCVD as the growth rates are lower. The precursor concentration in LPCVD is often higher, as people just bump up the partial pressures a little bit to compensate for the lower growth rates. In APCVD, they do not need to do that.

APCVD reactors are much easier to construct because of the lower vacuum and non-critical temperature uniformity. The LPCVD becomes a little more challenging to make. Often LPCVD id used for semiconductors and APCVD for dielectric depositions.

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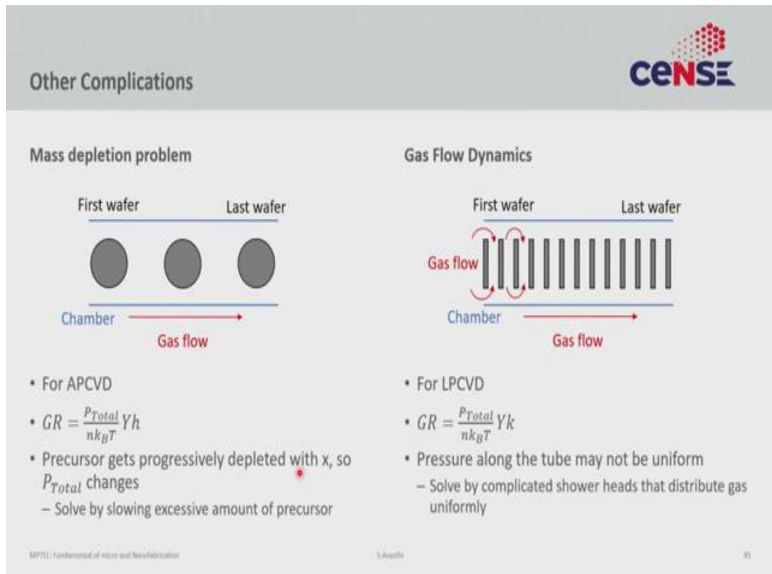

In this slide, I will highlight some complications not included or yet understood in the simple model that we have discussed until now, without going into any more details. One problem is of mass depletion. Imagine you have mounted 3 wafers in a cold walled APCVD chamber. The gas flows from left to right. The growth rate will depend upon the total pressure and Henry's coefficient which you hopefully have designed correctly. It also depends upon this Y or the ratio of the partial pressure of the precursor. As the gas flows from left to right and as the precursor keeps getting consumed, the concentrations of precursor will change. The concentration might be slightly higher on the left than on the right. So, even though you have fixed the boundary layer and the gas flow dynamics, you do not have control over the exact partial pressure of a component simply because it is getting used up.

Unless your usage is a very small percentage of the total concentration, you will have a concentration gradient and non-uniformity issues. If you are flowing 100 moles of silane and are using 1 mole, then that mass depletion is very minimal (1 %) but if you are flowing 100 moles of silane consuming 90 moles as you go from left to right, the gradient can be fairly large (90% consumption) and that can cause non-uniformity. Even if your reactor is very well-designed from a gas flow perspective, because of the depletion of the precursor, you might still see some non-uniformity. This can be avoided by flowing a lot of excess precursors and use a very small percentage of that. Of course, this causes a lot of wastage which increases the cost.

The second is non-uniformity in LPCVD. You stack your wafers vertically. We have repeatedly said that the gas flow pattern in LPCVD does not matter and it is all about the temperature. However, the growth rate does depend upon the total pressure, the concentration of precursors and the reaction rate. The pressure along the tube itself may not be uniform. We ignored this effect by saying that the pressures in gas typically are uniform. But if you stack these wafers very close to each other, then it is possible that you create a non-uniformity in the partial pressure because the only way the area between the wafers get fresh precursors and get rid of its byproducts is by diffusion as there is no active flow between the wafers. If the wafers are placed very close to each other, there is essentially a stagnant layer. So, even in an LPCVD reactor, there is a component of diffusion in the axial direction, because, in reality, this is a 2D problem, not 1D. All these issues complicate the design of the LPCVD reactor.

In the real-world, reactor design is a complex art that requires a lot of fluid dynamics, a lot of experience and a lot of institutional knowledge because the details are complicated. With that, we come to the end of the flow dynamics part of the CVD reaction. Next, we shall look at how do the adsorption and the surface reaction occur and how do the nuclei on the substrate coalesce together to form a thin film.