Fundamentals of Micro and Nanofabrication

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Lecture - 15
Methods and Some Definitions

This lecture starts the module on chemical vapor deposition, but before we get into the nitty-gritty of the technique itself, I like to take a little detour and explain some of the definitions and terminology that we will use in the rest of this module.

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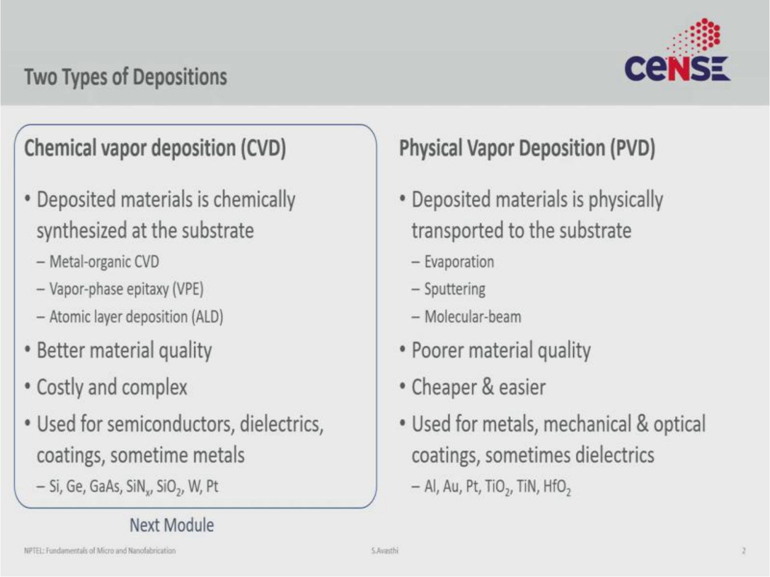

Two Types of Depositions

Chemical vapor deposition (CVD)

- Deposited materials is chemically synthesized at the substrate
  - Metal-organic CVD
  - Vapor-phase epitaxy (VPE)
  - Atomic layer deposition (ALD)
- Better material quality
- Costly and complex
- Used for semiconductors, dielectrics, coatings, sometime metals
  - Si, Ge, GaAs, SiN_x, SiO_2, W, Pt

Next Module

Physical Vapor Deposition (PVD)

- Deposited materials is physically transported to the substrate
  - Evaporation
  - Sputtering
  - Molecular-beam
- Poorer material quality
- Cheaper & easier
- Used for metals, mechanical & optical coatings, sometimes dielectrics
  - Al, Au, Pt, TiO_2, TiN, HfO_2

There are two types of depositions that you can theoretically do, one using chemical vapors and one using physical vapors. In chemical vapor deposition, you do not have the material that you are depositing in the intended form yet. What you have is just the precursor. If you want to deposit silicon dioxide, you flow precursors of silicon and oxygen, and they react at the substrate to form silicon dioxide. In physical vapor deposition, you already have the silicon dioxide pre-made either in a solid-state, pellet or in a powder form, and then you transport this already formed silicon dioxide from your source to your substrate.

In general chemical vapor deposition gives slightly better film quality which is why it is used for semiconductor deposition. Physical vapor deposition tends to be cheaper and simpler and so it is often used for non-critical depositions like metals and dielectrics.

This is module is on chemical vapor deposition. We will discuss physical vapor deposition in the next module.

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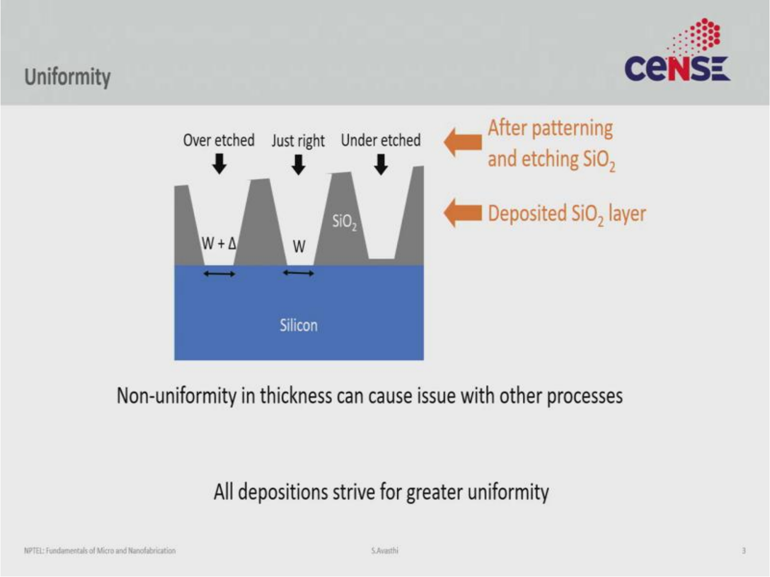

Uniformity

Non-uniformity in thickness can cause issue with other processes

All depositions strive for greater uniformity

Before that, let’s get some terminology right. Let us standardize the definition of uniformity a little bit more carefully. In a deposition, uniformity refers to the fact that how does your thickness change over your substrate. It is important because, after deposition, you often have an etching step. In this example, you have deposited silicon dioxide of some thickness. But because of some problem, your silicon dioxide is not uniform, so it is thinner on the left, thicker on the right.

The etching recipe that you have will work if the silicon dioxide thickness is just right. It assumes a uniform film of nominal thickness. After etching with that kind of recipe, you over-etch in places where the thickness is lower, so the opening is larger than expected, while under-etch in places where the thickness is higher than the nominal thickness, in which case you would do not have the opening at all. These kinds of problems can only be avoided by having a uniform silicon dioxide film. You should aim to have a uniform deposition everywhere.

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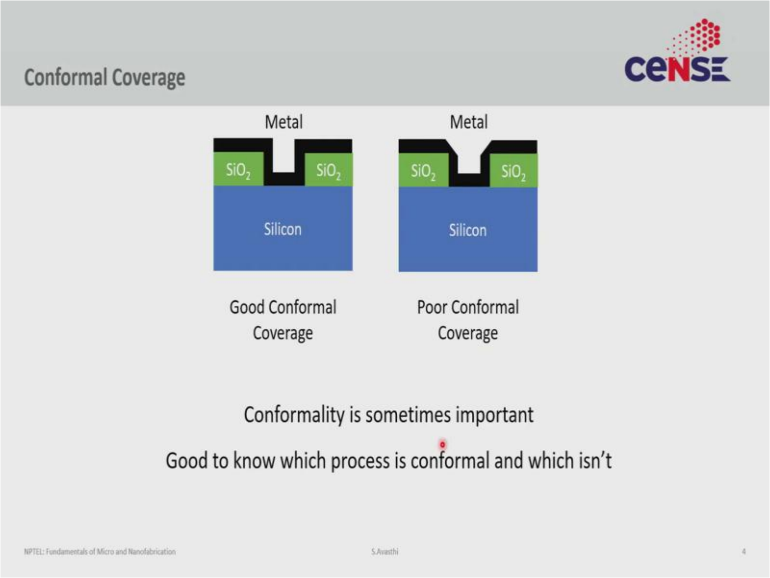

Conformal Coverage

Good Conformal Coverage

Poor Conformal Coverage

Conformality is sometimes important

Good to know which process is conformal and which isn't

Next is conformality that means the film follows the underlying topology. It is best explained by this figure. You have a patterned silicon dioxide on top of silicon and now you deposit metal on top. If the metal has a conformal coverage, it maintains a consistent thickness irrespective of the underlying topology. Practically you may not get this. Over sharp corners, deposition is a little thin. Metal film on the left has a good or a perfect conformal coverage while the conformality is suboptimal/poor on the right. Depending on the application, conformality may or may not be important but it is good to know in advance whether the process will lead to a conformal deposition or not.

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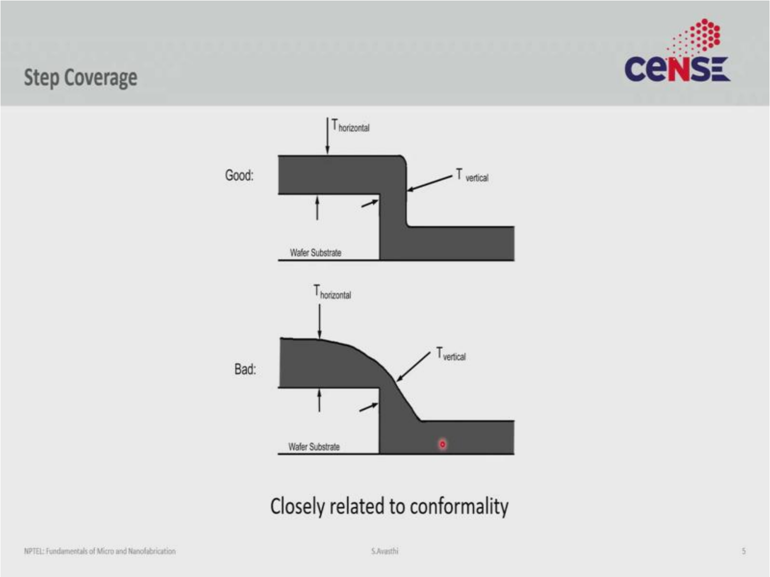

Step Coverage

Closely related to conformality

A related concept is step coverage, which you will hear in the papers or proceedings. In good step coverage, the film deposited on the step is conformal with it. Here, you have a step patterned on a film deposited on the substrate. Is this black layer that you deposit on top following this step exactly or not? If it is, you have good step coverage; if it is not, you may have a thinner deposition at the edge and poor or bad step coverage.

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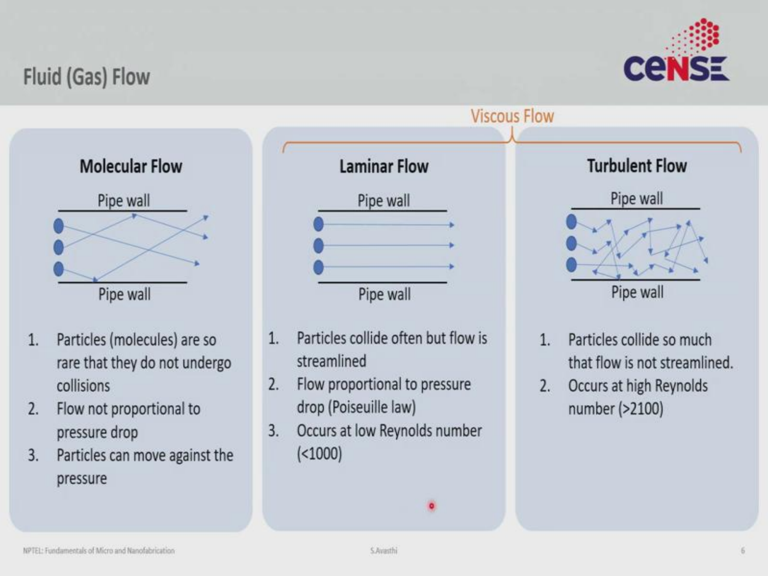

Fluid (Gas) Flow

Molecular Flow

1. Particles (molecules) are so rare that they do not undergo collisions
2. Flow not proportional to pressure drop
3. Particles can move against the pressure

Laminar Flow

1. Particles collide often but flow is streamlined
2. Flow proportional to pressure drop (Poiseuille law)
3. Occurs at low Reynolds number (<1000)

Turbulent Flow

1. Particles collide so much that flow is not streamlined.
2. Occurs at high Reynolds number (>2100)

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An introduction to gas or fluid flow would also be important to understand chemical vapor deposition. Whenever a fluid is traveling in a constrained medium say a tube, a pipe or a reactor, it follows the laws of fluid dynamics. The fluid can be liquid or gas. In chemical vapor deposition, we are primarily looking at gas. The actual physics of fluid flow is fairly complicated. To simplify things, we will look at three classes of flow – molecular, laminar and turbulent.

A molecular flow happens when the molecules are so rare that they do not collide with each other. They do not know of each other’s presence and interact only with the container itself; with a pipe, a wall or chambers, etc... In this case, the flow conductance is not proportional to the pressure drop across the pipe. This is the case with vacuum chambers, where you have very low pressure, and you are in a molecular flow regime. A more familiar case is the laminar flow regime, often discussed in introductory physics courses. You must have seen Bernoulli’s principle and Navier-Stokes equations etc…

In laminar flow, the particles collide with each other, but the flow is streamlined. The particles tend to maintain these streams. The particles will flow parallel to one another and along with the shape of the tube. This occurs at lower Reynolds numbers and the flow conductance is proportional to the mean pressure. The mass transfer from left to right will depend upon how much pressure you apply.

The third and the most complicated case is the turbulent flow, where the flow velocity becomes so high that the particles collide with each other so much that they are not streamlined anymore. It typically occurs at high Reynolds numbers. The last two regimes are called viscous flow regimes, and they are typically present in a CVD reactor. By and large, practical CVD reactors maintain laminar flow.

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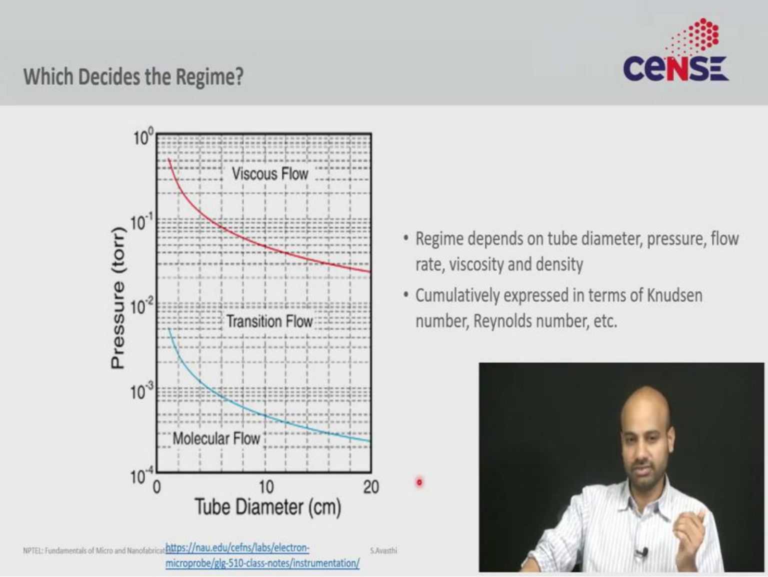

Which Decides the Regime?

- Regime depends on tube diameter, pressure, flow rate, viscosity and density
- Cumulatively expressed in terms of Knudsen number, Reynolds number, etc.

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The flow regime depends upon the pressure of the tube, as it is proportional to the density of the gas. It also depends upon the reactor diameter, the pressure difference, the flow rate, and viscosity. Cumulatively, this is captured in two numbers: Knudsen number and Reynolds number. Depending upon what those numbers are, you are either in the viscous flow regime which is laminar or turbulent or in the molecular flow regime or you are somewhere in the middle. For CVD, you tend to be in this region above this red curve in the viscous flow regime.

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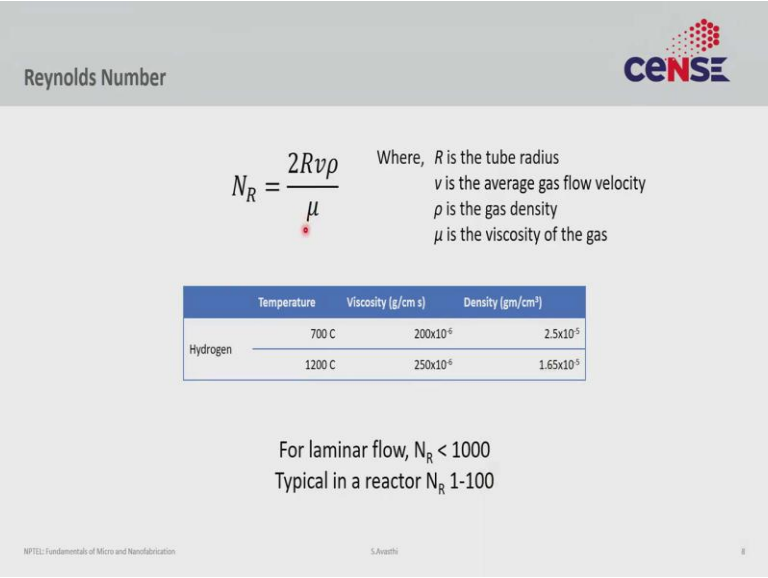

Reynolds Number

$$N_R = \frac{2Rv\rho}{\mu}$$

Where, R is the tube radius
v is the average gas flow velocity
ρ is the gas density
μ is the viscosity of the gas

	Temperature	Viscosity (g/cm s)	Density (gm/cm³)
Hydrogen	700 C	200×10^{-6}	2.5×10^{-5}
	1200 C	250×10^{-6}	1.65×10^{-5}

For laminar flow, $N_R < 1000$
Typical in a reactor N_R 1-100

For laminar flow, the Reynolds number must be < 2000. what is the Reynolds number? This is just for your information and will not be quizzed upon. Reynolds number is a unit-less quantity that tells you how fast the fluid flows through the tube. If it flows too fast, the flow becomes turbulent. You typically get a laminar flow for $N_R < 1000$ and turbulence for $N_R > 2000$ or so. Here are some numbers for hydrogen at various temperatures. Note - for a large range of temperatures, fluid dynamic properties like the viscosity and the density do not change much. If the flow in your designed CVD reactor is laminar at 700°C, there is a good chance that it is also laminar ~1200°C.

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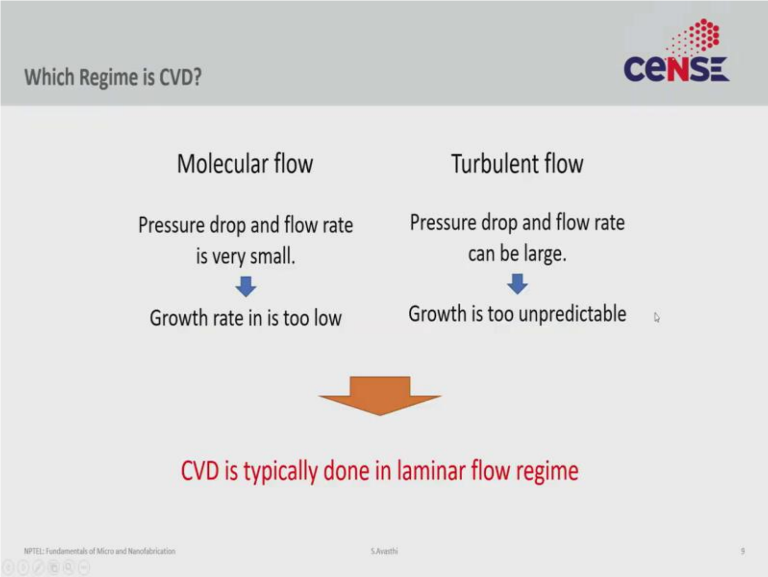

Which Regime is CVD?

Molecular flow

Pressure drop and flow rate is very small.

Growth rate in is too low

Turbulent flow

Pressure drop and flow rate can be large.

Growth is too unpredictable

CVD is typically done in laminar flow regime

The reason we try to maintain the flow in the CVD system in the laminar regime is highlighted here. In the molecular flow regime, density is very low, and so are the pressure drop and flow rates which make the growth rates impractically small. However, in the turbulent flow regime, because you have a large pressure drop and a lot of material flow, the growth is very unpredictable. If it is too unrepeatable, it is not a good microfabrication process. So, by and large, most CVD reactors try to operate in the laminar flow regime where the growth is both predictable and reasonably fast.

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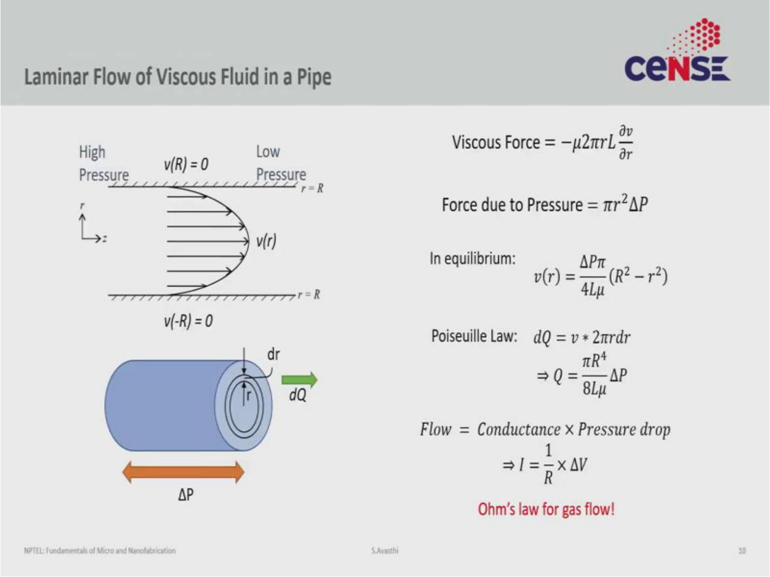

Laminar Flow of Viscous Fluid in a Pipe

Viscous Force $= -\mu 2\pi r L \frac{\partial v}{\partial r}$

Force due to Pressure $= \pi r^2 \Delta P$

In equilibrium: $v(r) = \frac{\Delta P \pi}{4L\mu}(R^2 - r^2)$

Poiseuille Law: $dQ = v * 2\pi r dr$

$\Rightarrow Q = \frac{\pi R^4}{8L\mu}\Delta P$

$Flow = Conductance \times Pressure\ drop$

$\Rightarrow I = \frac{1}{R} \times \Delta V$

Ohm's law for gas flow!

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Let's look at laminar flow inside a pipe. If you have some liquid flowing through a pipe, you must have a pressure difference. You must have a region of high pressure and a region of low pressure, and this gradient pushes the fluid from left to right. As this fluid goes through this pipe, it will have a certain velocity profile (if this is a viscous liquid). Under no-slip conditions, you assume the velocity at the interface to be 0. The velocity increase towards the center and then it again falls as it reaches the other interface. Here is a cross-section of a tube with a radius R. This kind of profile happens because of the friction between two layers of the viscous fluid. The viscous force and the force due to the pressure difference are equal under equilibrium. This gives you the velocity profile as a function of the radial position.

Poiseuille law says that the flow rate is velocity times the area. Since this velocity is non-uniform, you need to use calculus to calculate the integral as a function of radius and pressure. The total flow in this pipe is the pressure drop multiplied by a constant that consists of geometric factors and viscous force. This equation is very similar to the equation of current flowing in a resistor. The flow or current I must be equal to conductance (1/R, where R is resistance) into pressure drop (ΔP) which is analogous to the voltage drop. This is simply ohm’s law, but for the gas flow. Instead of current, you are looking at mass flow; instead of voltage, you are looking at pressure drop, and the conductance here is not electrical conductance, but conductance of the fluid flow.

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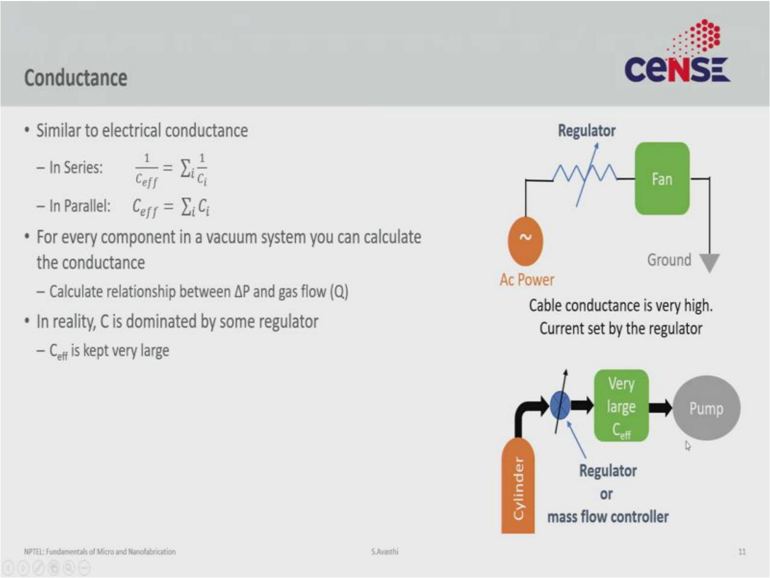

Conductance

- Similar to electrical conductance
  - In Series: $\frac{1}{C_{eff}} = \sum_i \frac{1}{C_i}$
  - In Parallel: $C_{eff} = \sum_i C_i$
- For every component in a vacuum system you can calculate the conductance
  - Calculate relationship between ΔP and gas flow (Q)
- In reality, C is dominated by some regulator
  - C_{eff} is kept very large

Cable conductance is very high.
Current set by the regulator

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This is an important insight because it allows you to understand design or analyze the working of a CVD reactor in terms of a simple electrical network problem where every component has a certain conductance, mass flow controllers as current sources, pumps as grounds, etc… The design of any vacuum system, not just CVD equipment, can often be thought of as a network of conductances either in series or parallel. The gas flow can be estimated from the pressure drop across the system and the effective conductance that follows the same rules as series and parallel combinations of electrical resistances. In series, the conductances are inversely added; in parallel, the conductances are simply added.

A real system that you build is not necessarily conductance limited. Take the example of a fan in your house. In order to control the amount of current that flows through that fan, you do not calculate effective resistance and then use a wire of precisely that resistance.

It is too unpredictable and cumbersome. A much simpler way is to connect the fan through a regulator that controls the current through the tuning knob. So, you do not take a wire with a precise value of conductance but take a wire with a very large conductance, and in series, add a regulator that can tune the conductance. In practical vacuum systems, you do the same thing. You use very thick pipes that can conduct a lot of fluid, but somewhere in the middle, you put a regulator that regulates either the pressure or mass flow. That is what actually controls the gas flow through this system. On the other end, you have a pump that creates zero pressure, which is equivalent to the ground. In this manner, you can analyze any complicated reactor to understand how the gas flows.

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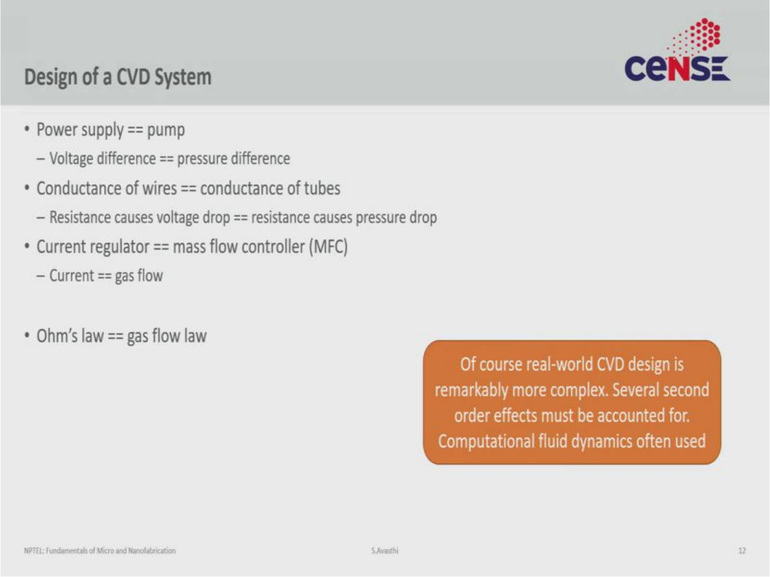

Design of a CVD System

- Power supply == pump
  - Voltage difference == pressure difference
- Conductance of wires == conductance of tubes
  - Resistance causes voltage drop == resistance causes pressure drop
- Current regulator == mass flow controller (MFC)
  - Current == gas flow
- Ohm's law == gas flow law

Of course real-world CVD design is remarkably more complex. Several second order effects must be accounted for. Computational fluid dynamics often used

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Of course, the reality is a little more complicated, CVD design is a fairly challenging problem, and there are a lot of second-order effects to consider, a lot of computational fluid dynamics to be used. Those details are far too advanced for this course. I will just leave you with this generic idea that when you are analyzing fluid flow in a vacuum system, it is often useful to think of gas cylinders and pumps as something that creates high voltage and a low voltage. The gas conductance of the tubes is analogous to the electrical conductance of wires, mass flow or pressure regulators to current regulators and like Ohm's law for electrical circuits, there is a similar law for gas flow in a fluid medium under laminar flow regime.

In the next lecture, we will get into more details of how CVD works.