Fundamentals of Micro and Nanofabrication
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Lecture – 01
Introduction

Hello. This is the Fundamentals of Micro and Nanofabrication. I am Sushobhan Avasthi from the Center for Nano Science, IISc Bangalore, and this is the start of a course on micro and nanofabrication where we go into the details of unit processes, the physics behind them, what are the engineering details and look at some basic characterizations.

In this first lecture, I will try to briefly introduce what is microfabrication, what are the various jargon that we use in microfabrication and also give you a very quick overview of the various things that we shall cover in detail in this course. So, from each module, I will pick a couple of slides, and very generally explain to you what are we trying to do in that step. The details, of course, shall wait for future lectures.

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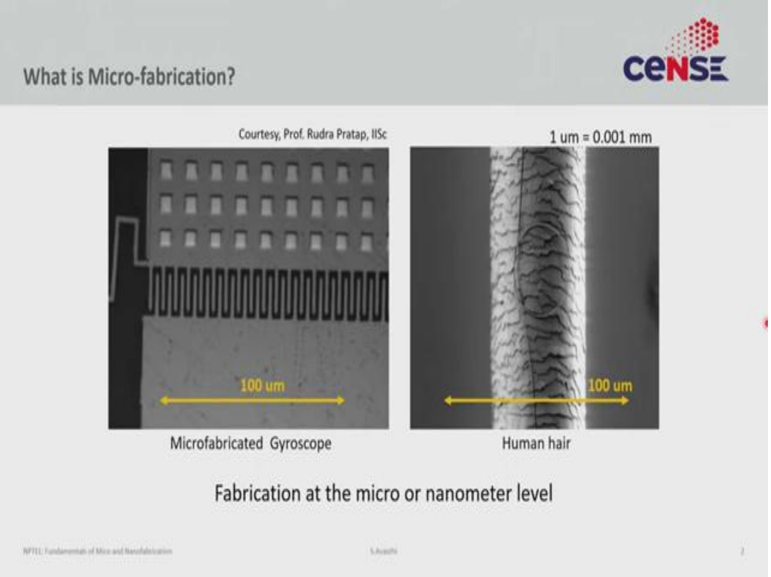
What is Micro-fabrication?

Courtesy, Prof. Rudra Pratap, IISc

1 um = 0.001 mm

Microfabricated Gyroscope

Human hair

Fabrication at the micro or nanometer level

What is microfabrication? Microfabrication is trying to make things at a very small scale, typically micro or sometimes even on the nanoscale. Here (in the slide) is an example of a gyroscope (courtesy: Professor Rudra Pratap) that has been fabricated at IISc, Bangalore. What you are seeing (in the animation) is a moving mass that provides the gyroscopic functionality. The details of the device are not important, but the scale bar is.

You are looking at a 100 µm scale bar! The features that you see on the left are actually much smaller; something on the order of 1 to 10 microns.

Such gyroscopes are significantly smaller than the macro gyroscopes. An example of where this microfabricated gyroscope is used is in your cell phones. This is the device that actually detects when your cell phone tilts right from portrait mode to landscape mode. This is the device that actually detects that motion.

To give you a fair comparison: on roughly the same scale bar is the width of a human hair. As you can imagine, these are amazingly small features and this is an amazing feat of engineering that we can actually make reliably such small features and mass-produce them. How we do that is what micro fabrication all about.

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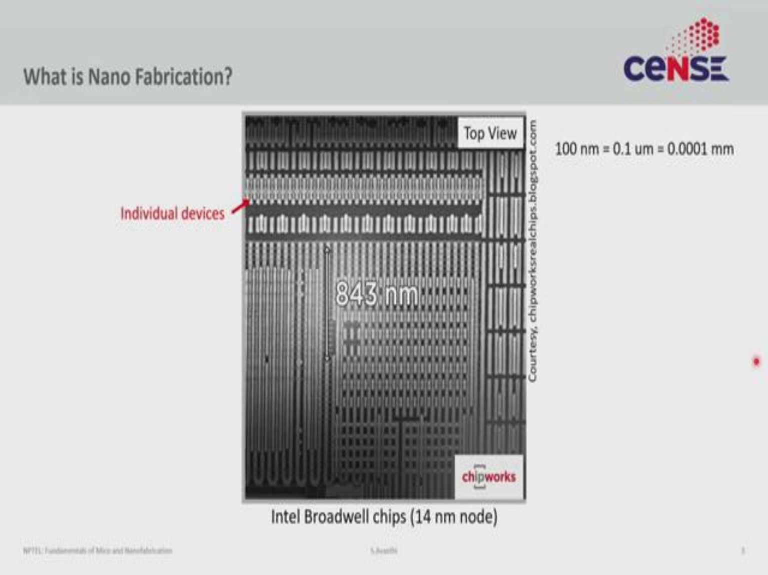

What is Nano Fabrication?

100 nm = 0.1 um = 0.0001 mm

Intel Broadwell chips (14 nm node)

Here (in the slide) is another example of something that has been fabricated at the nano-scale. So, 100 nm is essentially a tenth of a micron. So, this is 0.0001 mm for scale and this is the top view of an IC that is fabricated by Intel. This is an IC that was made at a 14 nm node. What this essentially means is the smallest feature is on the order of 14 nm.

If you look into detail in this picture you can actually see that several other features are much larger, but the smallest features are ≤ 100 nm. Individual devices can be even smaller, that are not even visible on this scale. We can fabricate millions, sometimes billions of these transistors in a single die reliably and in a mass manufacturing facility.

And the ability to do that a low cost has essentially led to the computer revolution and the electronics revolution that you see all around us.

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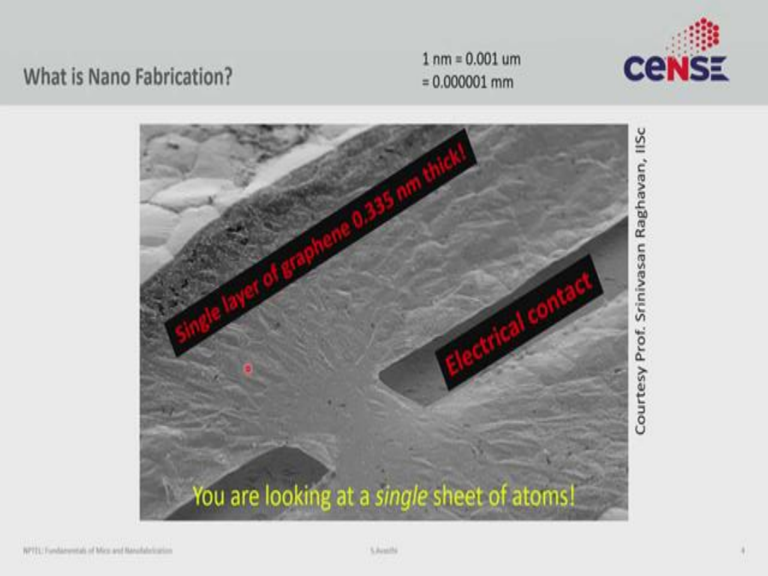

What is Nano Fabrication?

1 nm = 0.001 um
= 0.000001 mm

And, if you take this system to the extreme and start looking at below the nanoscale? You start getting into the regime of a few atoms. Here is an example of graphene - a very popular 2D material. You are looking here at a single sheet of graphene, that is 1 atom thick. A membrane that is literally 1 atom thick! Of course, the lateral sizes are a lot bigger, but it is amazing that we are able to get this amount of control, and how we do that is through the tools of microfabrication.

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WHY SHOULD I CARE?

Why should you care, both as a student, but more interestingly as a consumer or a taxpayer who funds research into micro and nanofabrication? Well, partly because there are a lot of benefits to be gained. If you take any system, it has a typical cost-performance trade-off. That means, is in order to get high performance you need a higher cost.

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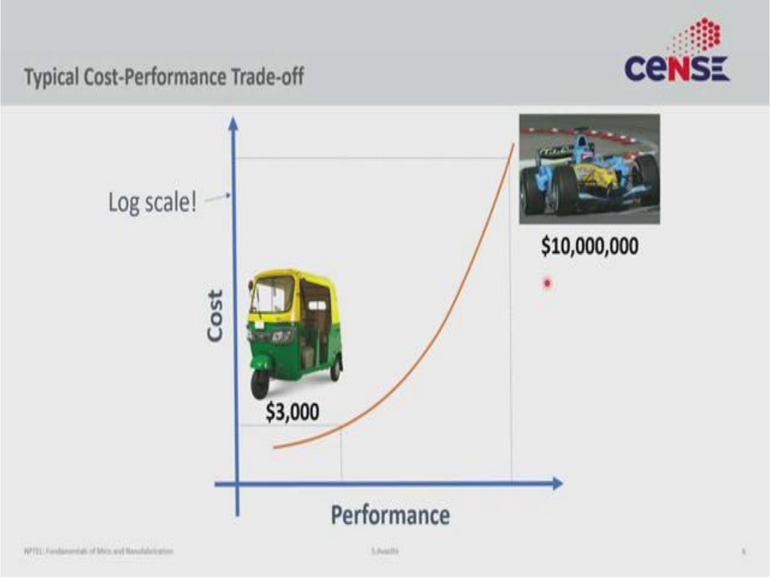

Typical Cost-Performance Trade-off

This is what a typical cost-performance curve looks like. This curve is often not linear. If you want low cost, you get low performance and if you want to now upgrade the performance, the cost typically scales much faster than performance does. Here is an example: an auto is only worth ~ $3000, but an F1 car which is probably the most engineered locomotive car that we have is upwards of $10 million. So, the performance has not scaled by orders of magnitude, but the cost has. The cost is on a log scale, not linear. This is true for virtually most technologies that we have seen.

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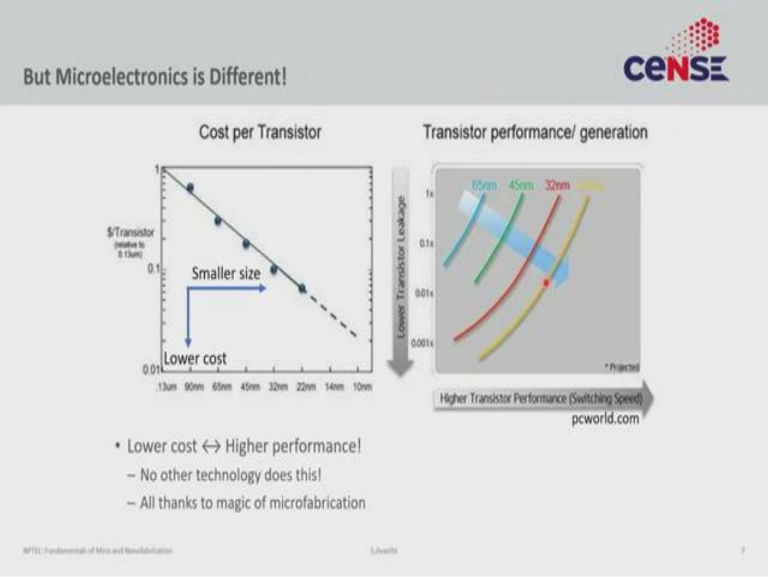

But Microelectronics is Different!

- Lower cost ↔ Higher performance!
  - No other technology does this!
  - All thanks to magic of microfabrication

Electronics is a notable exception to this. There are several ways to measure performance in electronics, but two ways in which you can measure performance are energy consumption and the transistor speed, which is how fast you can do computation.

Let’s look at both aspects. The thermal consumption typically is a function of transistor leakage current. Farther you go down, the lower the transistor leakage and the lower your energy consumption hopefully. The other metric is, of course, the speed of the transistor. So, as you go towards the right the speed of the transistor increases.

Superior technology is one where you are lower in the leakage and higher in speed. With successive technologies, as the transistor has become smaller from 65 nm to 45 to 32 and down to 22 nm, it has always improved performance. It has reduced leakages, power consumption and has increased the speed. But, at the same time, the cost of the transistor has continuously fallen. The cost of the transistor has not increased as the cost performance curve would suggest, but rather reduced and in my knowledge, there is really no other technology that does this. The reason this happens in electronics is because of scaling and because of the ability to make things continuously smaller. That, in my opinion, is the primary reason why the electronics revolution has taken place.

Every year computers get better, but they also get cheaper; every year cell phones get better, but they also get cheaper and that has allowed the percolation of electronics in every facet of our life. So, that is why you should care.

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HOW DO WE MAKE SMALL FEATURES?

How do we make the features small? With a library of unit processes. There is no one process that gets it, but a library of processes and an intelligent engineer to select which is the right process, and in which sequence, to enable the final product. Very generally, the library of processes can probably be broken down into four categories.

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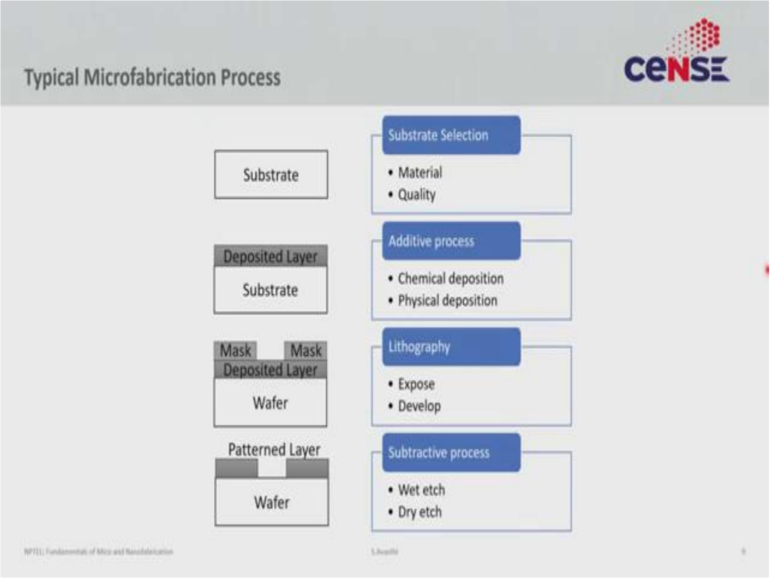

Typical Microfabrication Process

Substrate Selection

- Material
- Quality

Additive process

- Chemical deposition
- Physical deposition

Lithography

- Expose
- Develop

Subtractive process

- Wet etch
- Dry etch

The first is **substrate selection**. What substrate should I use, why? The second is some **additive process**; some process in which we deposit something, that deposition could be a deposition of a layer of films: a thin film deposition. It could also be a deposition or interpenetration of some atoms, for example, diffusion. Then there needs to be some **patterning** step; by and large blanket layers are not engineeringly useful. If you want to make a complex structure you need some way of patterning it and if you want to make nano and micro-scale structures, then that patterning must be at the nano or the micro-scale.

And the fourth thing you need is some sort of a **subtractive step**. Some step that actually selectively removes material and if you have all of these, then a combination of these can lead to any pattern or design that you want to make for your microfabrication process.

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Substrate

SUBSTRATE SELECTION

So, let us take each of these steps one by one. Once again here the idea is to give you a very general feel of things and introduce you to the jargon a little bit, but the detail shall come in later modules and lectures.

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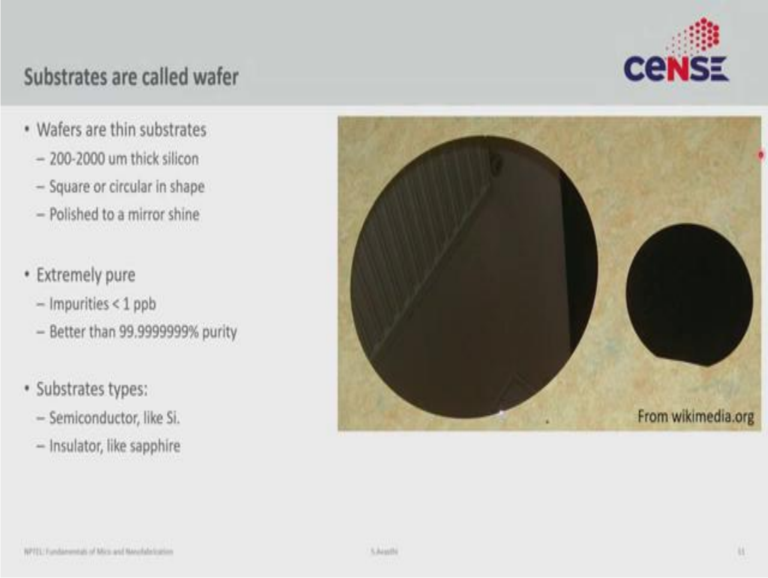

Substrates are called wafer

- Wafers are thin substrates
  - 200-2000 um thick silicon
  - Square or circular in shape
  - Polished to a mirror shine
- Extremely pure
  - Impurities < 1 ppb
  - Better than 99.9999999% purity
- Substrates types:
  - Semiconductor, like Si.
  - Insulator, like sapphire

From wikimedia.org

So, substrate: In the world of micro and nanofabrication the substrate on which we do all our work is typically called a wafer. The reasoning behind this is easy to understand. Here is a picture of a typical silicon wafer. You can see it is very thin and it is relatively large. So, the aspect ratio suggests a wafer (potato chip). Typically, these substrates are

200 to 2000 μm thick. The workhorse is silicon. By and large, 95 % of the work out there is done on silicon. It is square or circular in shape and it is polished to a mirror shine.

The singular distinguishing feature of this substrate is its extreme purity. It is arguably one of the purest materials we know how to make. In a best-case in the state of the art, it can be 99.99999999% pure, which is an amazing level of purity that in my knowledge only helium can reach. However, there are other substrates than silicon. Silicon is a semiconductor, but there are also insulating substrates like sapphire, some oxide substrates etcetera.

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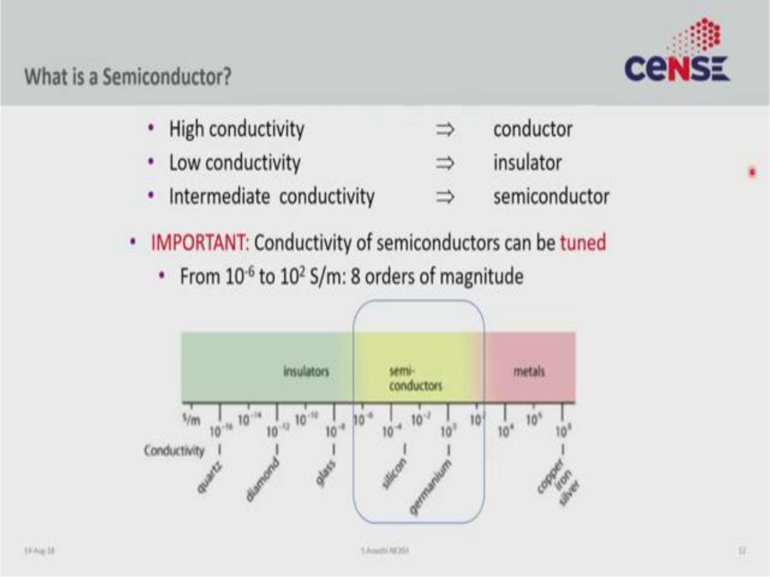

What is a Semiconductor?

- High conductivity ⇒ conductor
- Low conductivity ⇒ insulator
- Intermediate conductivity ⇒ semiconductor

- IMPORTANT: Conductivity of semiconductors can be tuned
  - From 10^{-6} to 10^{2} S/m: 8 orders of magnitude

Before going further, let us first get the jargon out of the way. What is a semiconductor? A semiconductor is a material whose electrical conductivity is somewhere between a metal and an insulator, but that is a very large range. Often, a better way to explain is to talk in terms of numbers. If you look at a typical conductor, its conductivity would be around 10^{4} to 10^{8} S/m. At the same time, if you compare an insulator like glass, its conductivity will be about 10^{-16} to 10^{-14} S/m. That is a very large change in orders of magnitude: those are two properties that are separated by 10^{16} to 10^{18} orders of magnitude. The semiconductors sit somewhere in the middle.

More interesting, however, is the claim that semiconductors can actually tune their conductivity. If you take a piece of copper and you want to change its conductivity, it is really hard to change it by more than an order of magnitude. You can introduce some impurities which will reduce it, but it is very hard to change by orders of magnitude.

Similarly, if you take an insulator and you try to change its conductivity, maybe you can make it 10 times worse or 10 times lower, but very hard to make it orders of magnitude different. Semiconductors are different in the sense that you can actually change the conductivity over orders of magnitude by introducing things called dopants.

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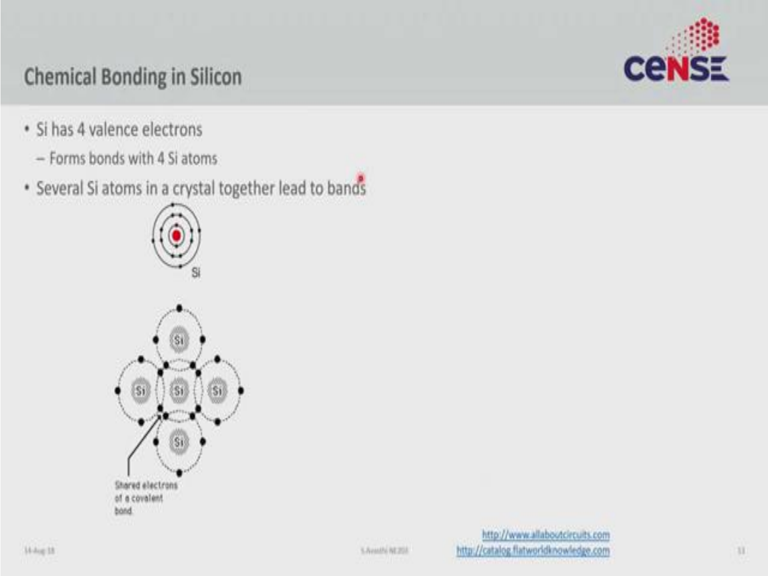

Chemical Bonding in Silicon

- Si has 4 valence electrons
  - Forms bonds with 4 Si atoms
- Several Si atoms in a crystal together lead to bands

http://www.allaboutcircuits.com
http://catalog.flatworldknowledge.com

So, what are dopants? In order to understand dopants, we have to do a little bit of chemistry. Let us take silicon. It has 4 valence band because it is in group 4 of the periodic table. In a pure crystal, it bonds to 4 other silicon atoms. This is what the picture looks like and this is a covalent bond (the electrons are shared equally).

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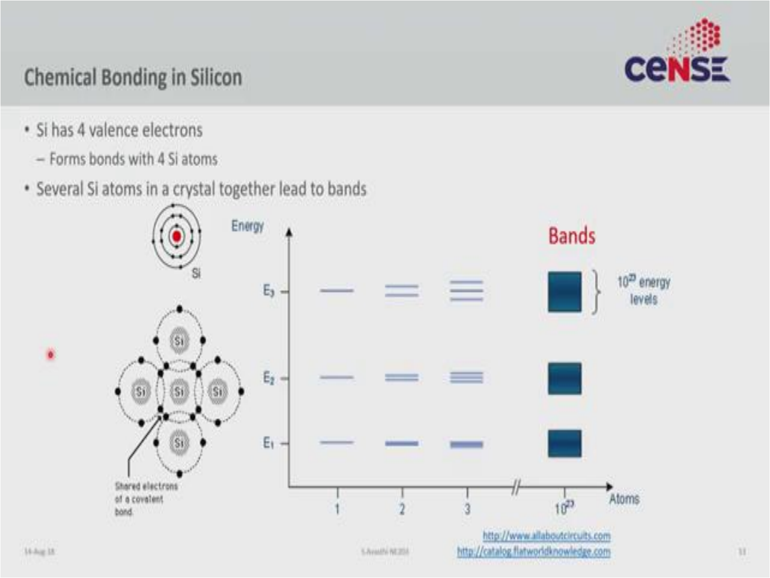

Chemical Bonding in Silicon

- Si has 4 valence electrons
  - Forms bonds with 4 Si atoms
- Several Si atoms in a crystal together lead to bands

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Look at the energy diagram on the right. Single silicon will have certain atomic levels or orbitals. If you take one silicon and bond it to another silicon, the energy levels (say E_1) will split. You will have two energy levels which will be slightly different from each other and then, of course, they will be again a couple of energy levels are little higher and a couple of energy levels even higher (E_2 and E_3).

If you bond 3 silicon atoms, this degeneracy will split again and now there will be 3 sub-levels in each level and if you take this to its logical conclusion and actually have a lattice with the 10^{23} or more silicon atoms, these levels are no more levels. They sort of morph into a band of energy where there is an almost continuous presence of energy levels.

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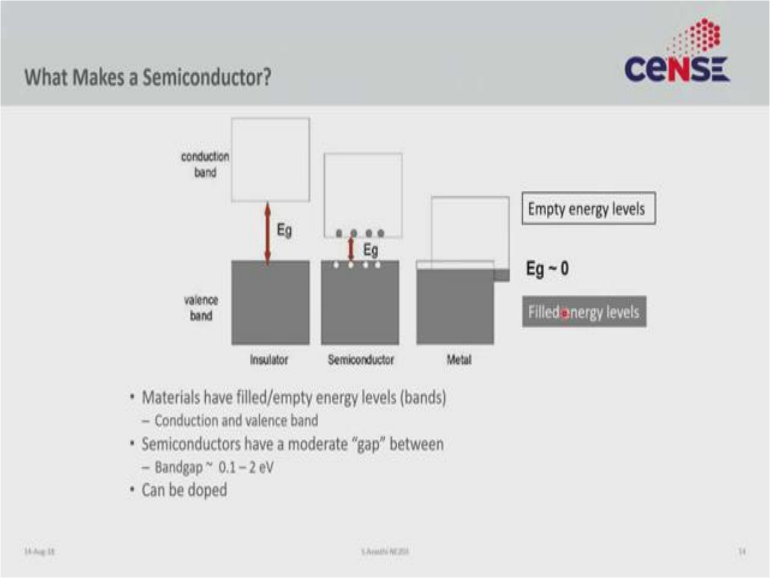

What Makes a Semiconductor?

- Materials have filled/empty energy levels (bands)
  - Conduction and valence band
- Semiconductors have a moderate "gap" between
  - Bandgap ~ 0.1 – 2 eV
- Can be doped

If you start filling electrons in these bands, at some point you will get a filled band and an empty band. The distance between the filled and the empty band is called the bandgap. The empty band is often called the conduction band and the filled band is often called valence band.

If this bandgap is small, then even at room temperature there is enough thermal energy in the system that the electron can jump (at least a few electrons) from the filled level to the empty level. When that happens, there are some free electrons in the conduction band and some positive charges in the valence band which can move, which is what gives this material some conductivity. And in the extreme case when the bandgap becomes 0 or negative then the valence and the conduction band overlap in which case, you have metal. There is an insulator on the left, metal on right and semiconductor in the middle of the figure.

However, this still does not answer the question: how are we tuning the conductivity? This seems like a thermodynamic effect which will be fixed at a certain given temperature; in order to understand that we have to go one step further. Till now what we have looked at this is an intrinsic semiconductor, it does not really have any dopants. So, it has a fixed conductivity.

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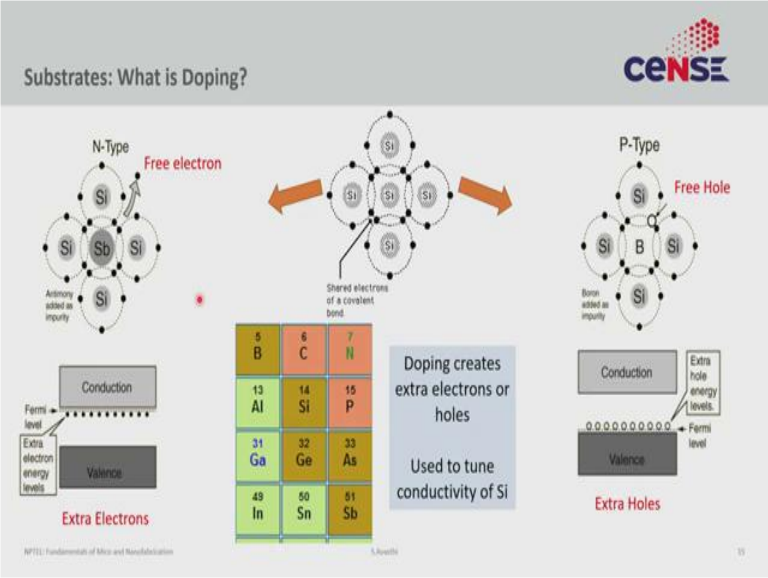

Substrates: What is Doping?

5 B	6 C	7 N
13 Al	14 Si	15 P
31 Ga	32 Ge	33 As
49 In	50 Sn	51 Sb

Doping creates extra electrons or holes

Used to tune conductivity of Si

However, if you now take this silicon lattice which is group 4 and substitute it with some element from group 5 (say antimony): Remember group 5 element has 5 valance electrons, so, it can only form 5 bonds. That means, it has an extra electron and that extra electron is now not bonded to any of the silicon atoms, is free to move.

In a band diagram picture, this is often represented as follows: just below the conduction band, there are certain extra states and these states are providing the electrons which then go into the conduction band to increase the conductivity. Because of this, the concentration of these free electrons is directly proportional to how much antimony we have in the crystal. We have now a way to tune the number of free electrons. If we can tune the number of free electrons we can tune the conductivity.

So, just by deciding how much dopants to put we can actually tune the conductivity and that is one of the singular features of semiconductors. The material would be called an insulator if you do not have a dopant that can do this. Now, you can do this with electrons, but if you substitute the silicon atom with group 3, you get positive charges or holes. The arguments are similar: you have boron which has only 3 bonds, so, there is one bond missing which means there is one positive charge that can move.

So, by adding N-type or P-type dopants you can actually tune the conductivity of a semiconductor. Elements that can do that are called dopants and they are unique to a type of semiconductor. Antimony and boron are the dopants for silicon. For gallium arsenide or some other semiconductor, there would be different dopants.

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To Maintain Purity Need Cleanrooms

1000 to 10000 times cleaner than this room!

Cleanroom suit

This leads us to another interesting fact that all of the semiconductor processing must be done in the cleanroom and the reason for that is we are starting with an amazingly pure material and that purity is required to maintain the exceptional electronic properties that we have in the semiconductor. But, in order to keep that silicon clean while we are doing the processing, the processing must also be done in an ultra-clean environment.

Typically, these are done in clean rooms. These cleanrooms are around 1000 to 10000 times cleaner than your average room sometimes even more. And in order to keep the cleanroom clean, you are typically inside a bunny suit so that you do not contaminate the cleanroom.

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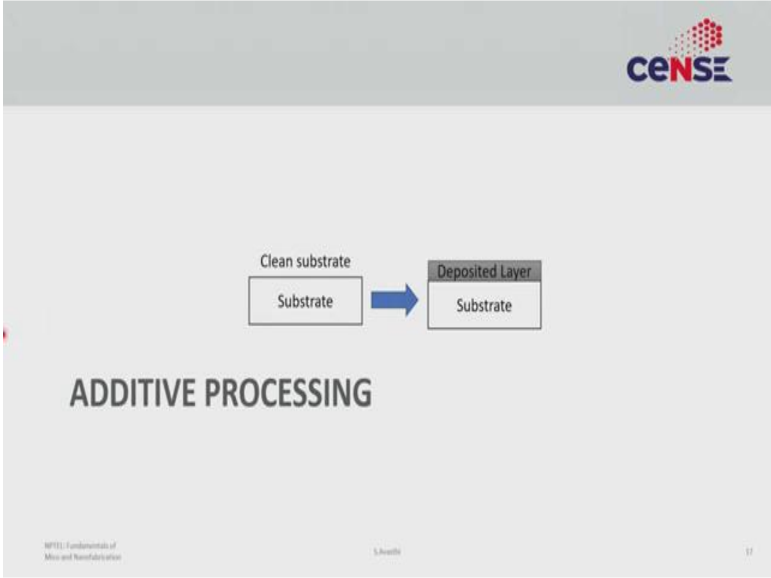

Clean substrate

Substrate

Deposited Layer

Substrate

ADDITIVE PROCESSING

With that let us move from the substrate to some additive processing examples.

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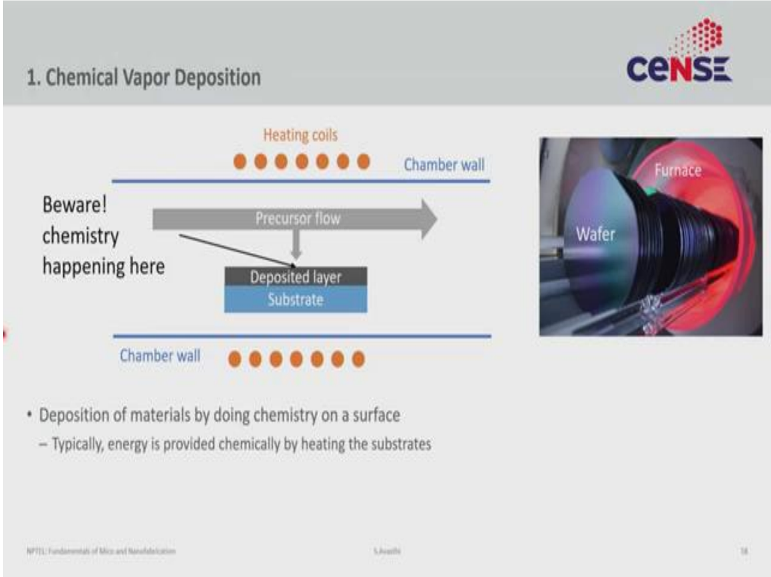

1. Chemical Vapor Deposition

Beware! chemistry happening here

- Deposition of materials by doing chemistry on a surface
  - Typically, energy is provided chemically by heating the substrates

The easiest way to do additive processing is to do chemistry. Take some substrate and flow what we call a precursor. A precursor is a chemical that at a given temperature would react either with itself or with some other chemical to form the material that we want to deposit. So, if you flow that precursor inside a furnace that would heat up the substrate, the substrate goes up to the right temperature and then when the precursor sees that temperature it would react and form this deposited layer. All of this can be done in a container that we call a chamber.

This is what a real system looks like. Here you see some wafers being loaded inside a furnace. On one side of this furnace would be some inlet which will give you the precursor and some outlet where the byproducts can get out on the other side. This is typically called chemical vapor deposition. The name sort of explains itself: we are doing the chemistry in the vapor phase. These precursors typically are gases or vapors of liquids.

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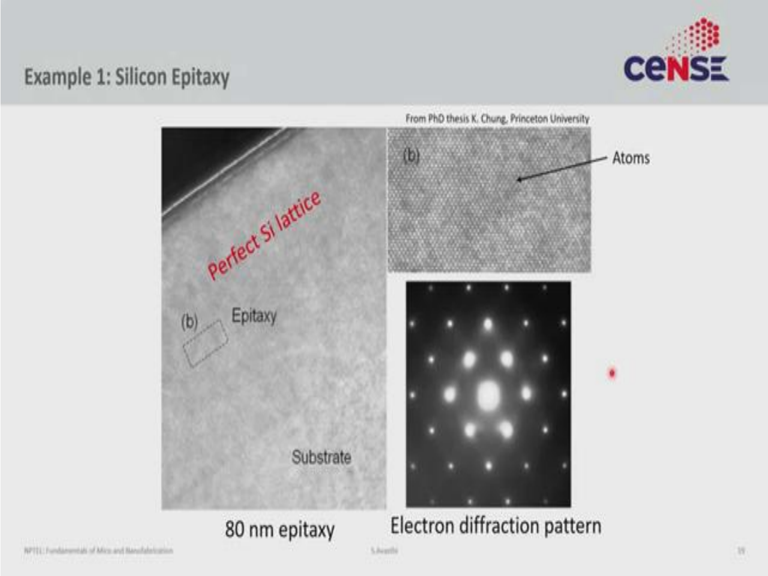

Example 1: Silicon Epitaxy

From PhD thesis K. Chung, Princeton University

80 nm epitaxy

Electron diffraction pattern

CVD has come a long way. These days we can do CVD with near-perfect lattice match. Here is an example of a silicon epitaxy which is done by CVD. Here is a silicon substrate on top of which certain silicon has been deposited using CVD and that and if you look in the detail of that silicon lattice that you have grown, the atoms are perfectly arranged! You can look at its electron diffraction pattern and that also confirms that it is near perfect epitaxy.

You can see a line between the substrate and the film. This is the interface. While you can make out the interface, the interface is remarkably smooth. There are no impurities, no islands, visible defects which shows you how far the CVD process has come. How do we do that? We will look into that in detail when we look at CVD.

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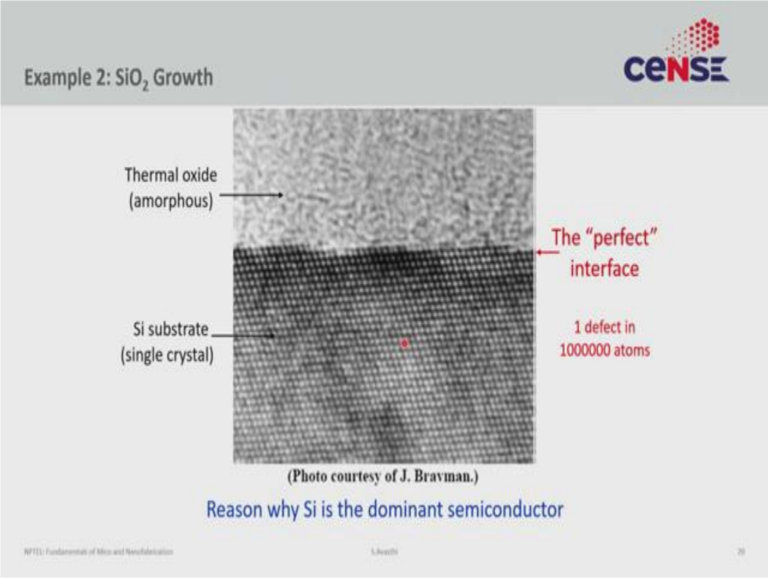

Example 2: SiO_2 Growth

(Photo courtesy of J. Bravman.)

Reason why Si is the dominant semiconductor

Another common example of deposition is to grow silicon dioxide on silicon. This is a slightly more interesting case because silicon dioxide tends to be amorphous. You are depositing it on a material like silicon which is crystalline. So, you would expect that the interface would be bad, but it turns out it is not! (Through some process maturity as well as dumb luck). The silicon dioxide interface that we can grow today is nearly perfect and that has actually enabled the whole technology of CMOS.

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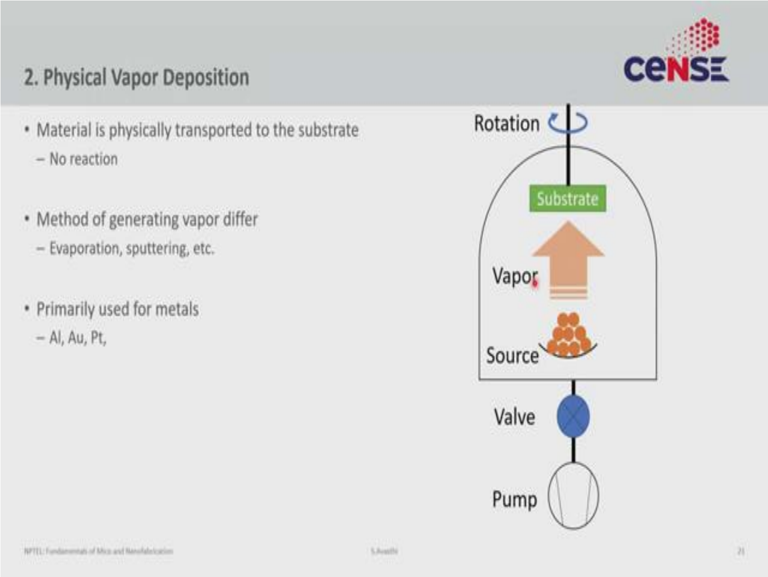

2. Physical Vapor Deposition

- Material is physically transported to the substrate
  - No reaction
- Method of generating vapor differ
  - Evaporation, sputtering, etc.
- Primarily used for metals
  - Al, Au, Pt,

The second way in which we can deposit things is through physical vapor. The insight here is that instead of chemical vapors or sort of gas or liquid-based precursors, you can start with something solid. For example, you can start with aluminum pellet, heat it till it grows red hot or melts and starts giving out aluminum vapors at a significant rate. That vapor can go and get deposited somewhere else.

What you need in this case is a chamber such that the source remains pure and does not react, some sort of pump to take the oxygen and other unwanted gases out of the vacuum chamber. And then some substrate on which the vapors can condense and deposit a film of the material.

It is very similar to how if you put a lid on top of boiling water and the water will condense on the lid. Primarily, this method is used to deposit metals and if I were to ask you where have you seen something like this before, a good example would be in bulbs.

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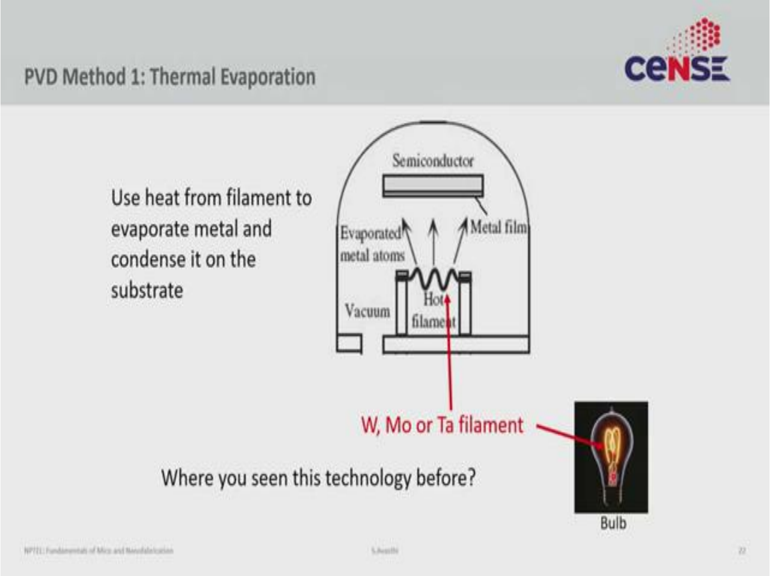
PVD Method 1: Thermal Evaporation

Use heat from filament to evaporate metal and condense it on the substrate

W, Mo or Ta filament

Where you seen this technology before?

So, what is a bulb? It is basically a vacuum chamber, inside which there is a filament, that filament grows red hot and the difference, in that case, is that the filament that you are using is kept at a very high temperature. So, it is not evaporating, but if you were to put something like aluminum inside the bulb the aluminum would evaporate and coat the glass of the bulb.

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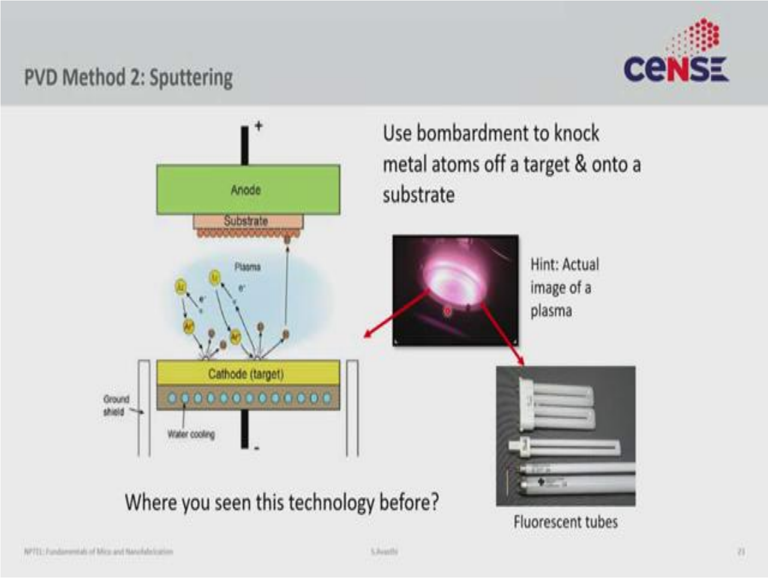

PVD Method 2: Sputtering

Use bombardment to knock metal atoms off a target & onto a substrate

Hint: Actual image of a plasma

Fluorescent tubes

Where you seen this technology before?

Another method to do physical vapor deposition is to create the physical vapor not thermally but through plasma. Again, the same system but the notable difference is now you are not heating the target that you want to deposit, instead, you are applying voltage bias to it. And if you apply large enough bias, you can actually ionize the gas inside.

In sputtering typically that gas tends to be argon which is very heavy, so that the plasma formed tends to bombard the surface and because of the bombardment of the plasma on top of the target, it creates the vapor that gets goes and then deposits on the substrate. This is called sputtering. The only difference here is instead of thermal energy now you are using mechanical energy.

The question I have for you is where have you seen this before? To give you a hint let me show you a picture of what this actually looks like. Where have you seen this glow before? This is what happens inside a CFL or compact fluorescent tube or a tube light. This is how you create light. Instead of creating light, we are using this glow to deposit things.

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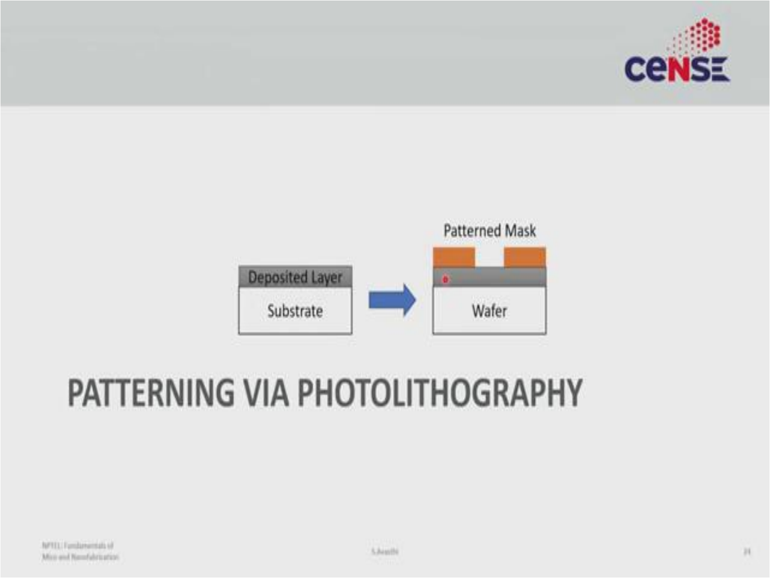

PATTERNING VIA PHOTOLITHOGRAPHY

After doing some additive processes, you may want to do some patterning which is done using lithography.

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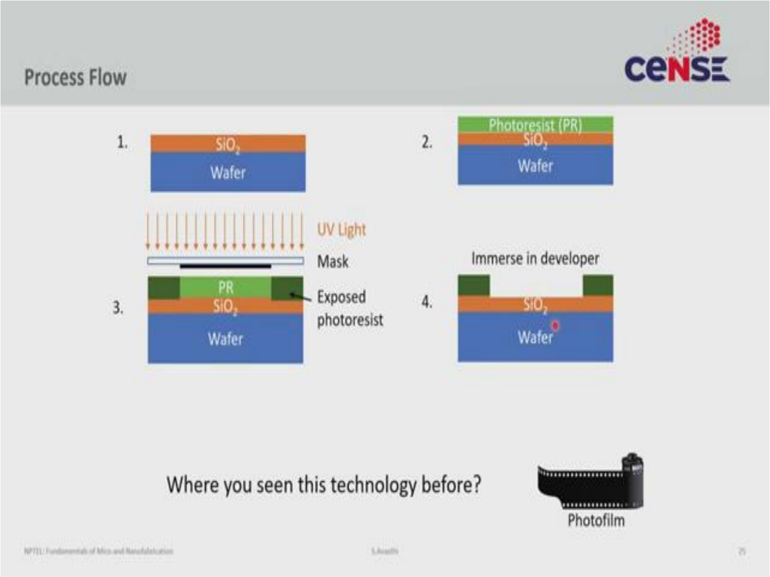
Process Flow

Where you seen this technology before?

A simple lithography process looks something like this. You start with a substrate with SiO_2 deposited on top. Then, you coat something called photoresist, that (as the name suggests) is some material that is light sensitive and resists the attack of some chemicals. It is a protective layer depending upon whether it has been exposed to light or not.

Take this photoresist and shine light through some mask. Mask is nothing, but a transparent glass on which you have created some pattern that is opaque. When you shine the light, the light goes through certain areas but does not go through certain regions where it is opaque. So, whatever pattern you have on the mask, now gets transferred on to the photoresist and the properties of the photoresist change depending upon the exposure.

Take this exposed photoresist and put it in some developer solution that is selective. In this case, wherever the light falls, that portion becomes insoluble and the remaining portion gets dissolved away. So, what you have now done is you have taken the pattern that was on the mask and transferred it on to your wafer. This process is lithography.

Where have you seen this before? Some of you may be too young to know this, but there was a time before digital cameras where there were film-based cameras and film-based cameras were doing the same thing. You had to develop the film in order to get the image and that development was often done using the technology very similar to what I am describing here. Of course, this is a little more complicated.

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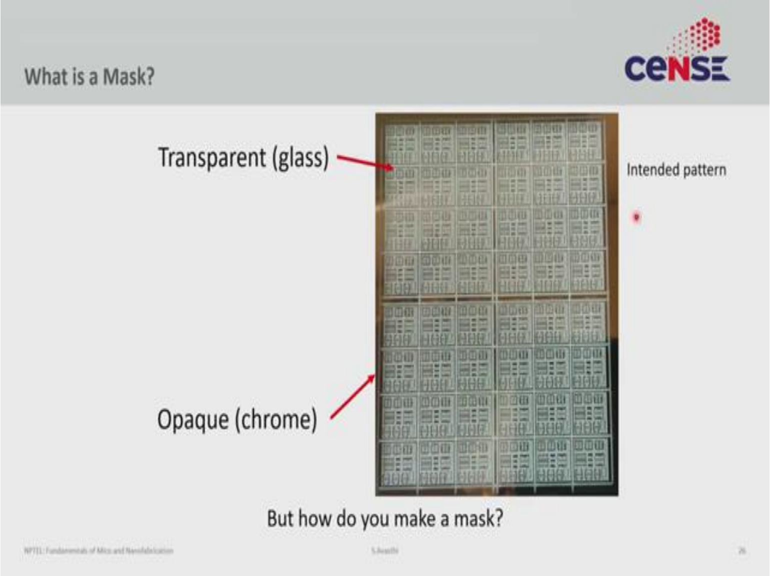

What is a Mask?

But how do you make a mask?

So, this is what a typical mask looks like. It has some opaque area and some transparent areas. The opaque areas typically tend to be metals, in this case, chrome. The more interesting question now is how do you actually make this pattern in the first place? This sounds like a chicken and an egg problem.

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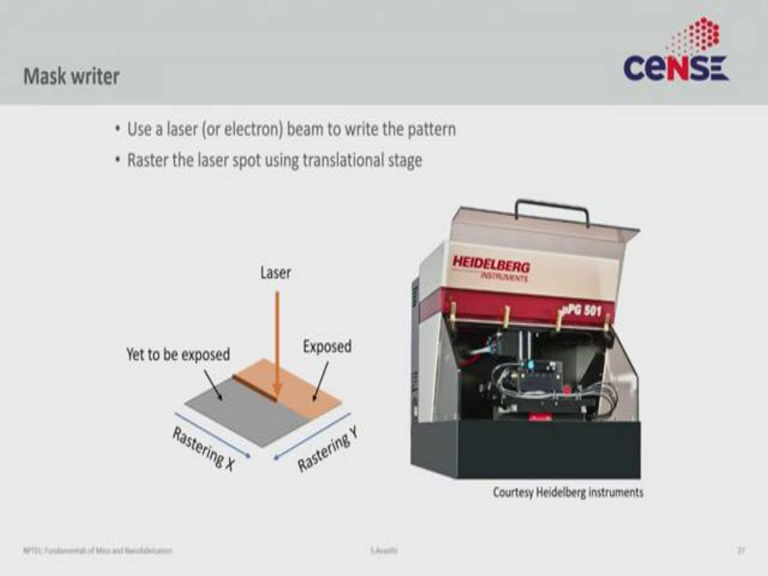

Mask writer

- Use a laser (or electron) beam to write the pattern
- Raster the laser spot using translational stage

Courtesy Heidelberg instruments

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Well, you make this using what is called a mask writer. A mask writer is simply speaking a laser; a focused laser that is mounted on a head that can be moved (in a computer-controlled way) in the x and y-direction. The laser can be turned on and off: whatever pattern you have on the computer can then be written on top of the mask. You can use this mask to write this pattern several times on top of the silicon wafers, which is what lithography is.

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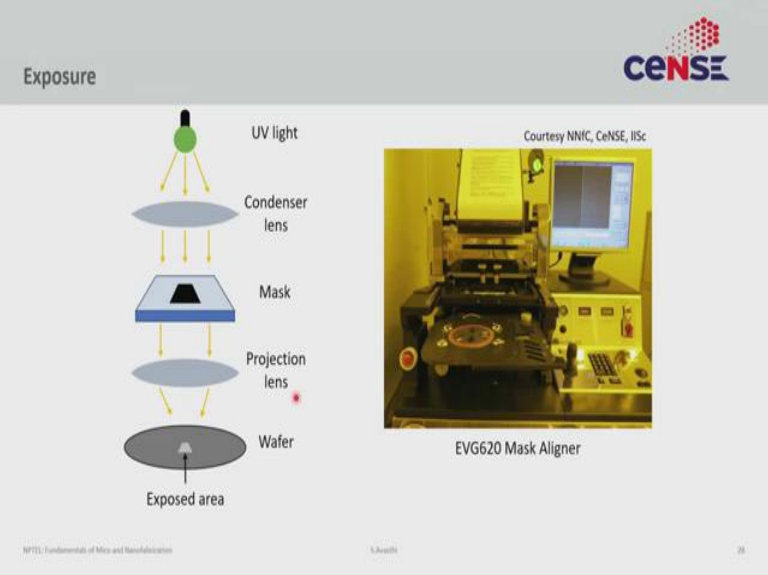

Exposure

Courtesy NNfC, CeNSE, IISc

EVG620 Mask Aligner

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Typically, pattern transfer from the mask to wafer is done in machines called exposure tools. They have UV light which does the reaction on the photoresist and there is certain optics to make sure that the light is managed well. Somewhere in the middle is the mask that casts a shadow on the wafer. This light/shadow from the mask creates the desired pattern on the photoresist coated on the wafer.

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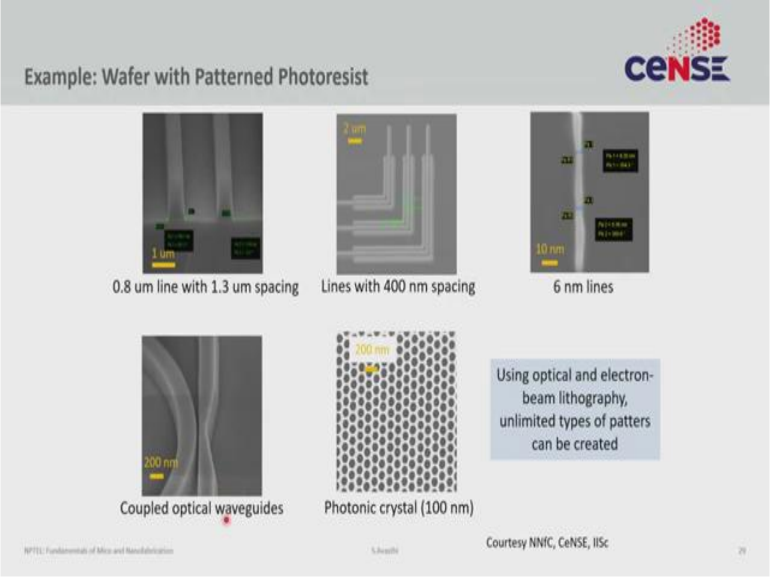

Example: Wafer with Patterned Photoresist

0.8 um line with 1.3 um spacing

Lines with 400 nm spacing

6 nm lines

Coupled optical waveguides

Photonic crystal (100 nm)

Using optical and electron-beam lithography, unlimited types of patters can be created

Courtesy NNfC, CeNSE, IISc

Here are some examples of various things you can do using optical lithography. We can go down to up to 2-300 nm; in extreme cases at Intel people have gone down all the way to 22 nm. In our facility at IISc using optical light, we go down to up to 1 μm. For smaller features, we use electrons. Using electrons, you get better resolution, down to 6 nm. Commercial fabs can do even better.

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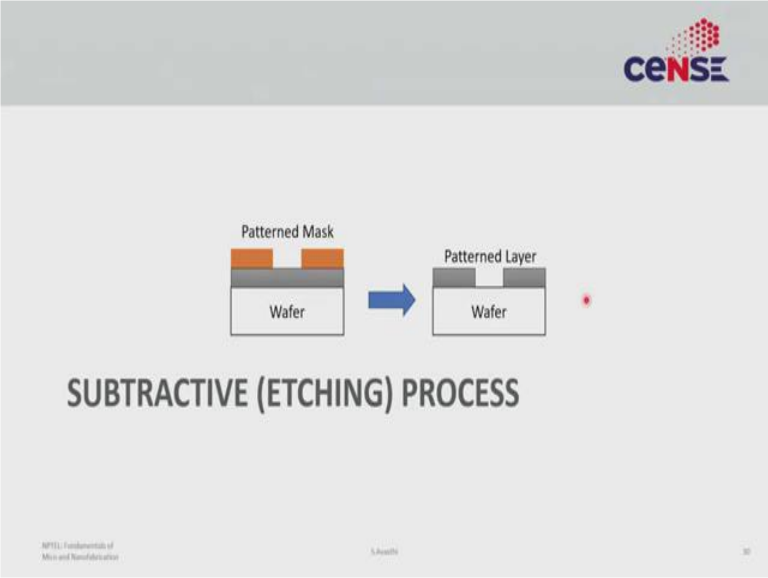

SUBTRACTIVE (ETCHING) PROCESS

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S.Avasthi

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So, we have talked about the substrate, additive manufacturing, and patterning. Now let's talk subtractive processes. How do we remove the material selectively? Supposing you have a substrate on which there is a pattern created using lithography that you want to etch (the exposed gray area below the photoresist).

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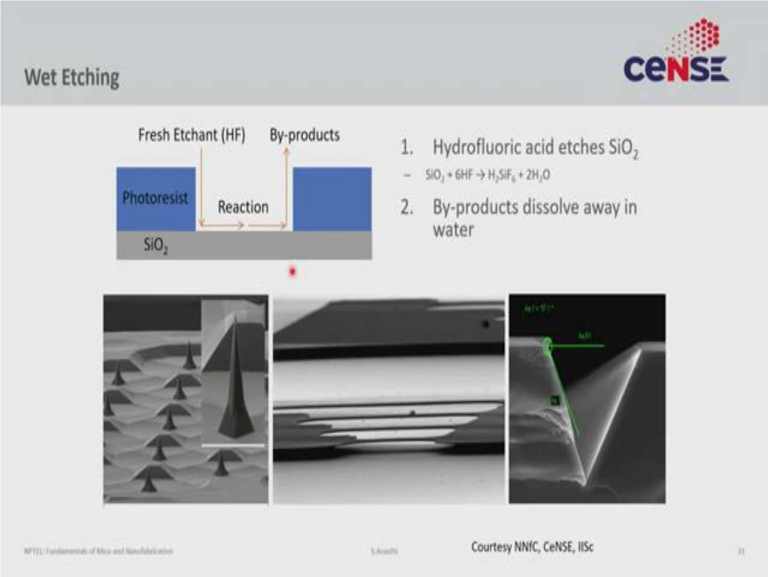

Wet Etching

1. Hydrofluoric acid etches SiO_2
   - $SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$
2. By-products dissolve away in water

Courtesy NNfC, CeNSE, IISc

The simplest thing to do is to just keep it in a solution that etches it. For example, if you want to pattern metal you can just keep this in an acid that will attack it and take it away.

In this case, we are using hydrofluoric acid to etch silicon dioxide. You can get various shapes depending upon what etchant and chemistry you use.

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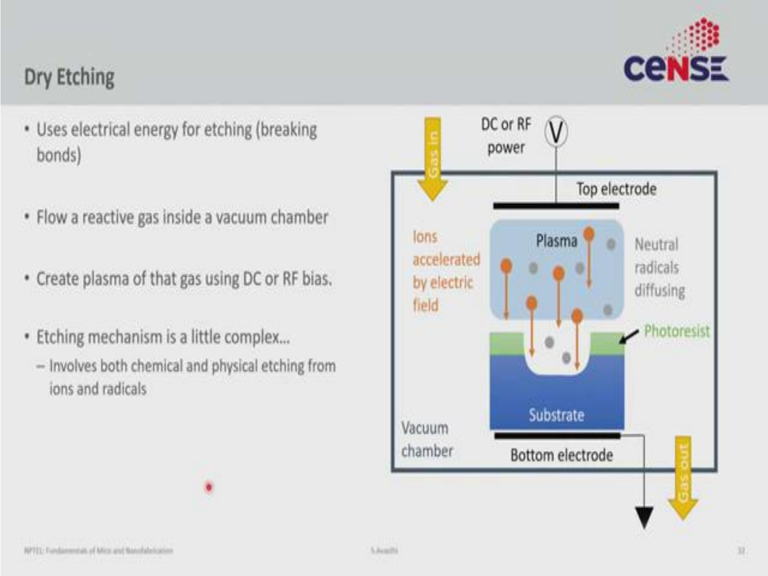

Dry Etching

- Uses electrical energy for etching (breaking bonds)
- Flow a reactive gas inside a vacuum chamber
- Create plasma of that gas using DC or RF bias.
- Etching mechanism is a little complex…
  - Involves both chemical and physical etching from ions and radicals

Etching technique that is becoming more popular and advanced is something called dry etching where you use the same plasma that we talked about before, but the mechanical energy of the plasma is now used to create patterns or rather etch patterns instead of doing the deposition. Put the substrate such that the ions bombard the surface and etch it away. The mechanism is a little more complex: it actually is both chemical and physical etching. We shall look into the details when we go into that module.

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Example: Etched Si

Courtesy NNfC, CeNSE, IISc

Here are some features that we have made at IISC using our dry etch tools. You can make very thin fins, microneedles that are painless for injections or very high aspect ratio trenches. Some of these are very hard to do using wet etching so, that is where dry etch really shines.

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PROCESS INTEGRATION

Finally, a few points about process integration. Once you have all these unit processes somebody has to figure out a way how to chain these unit processes together to actually make the final device. That is the job of a process integration engineer and the and that technique is called process integration.

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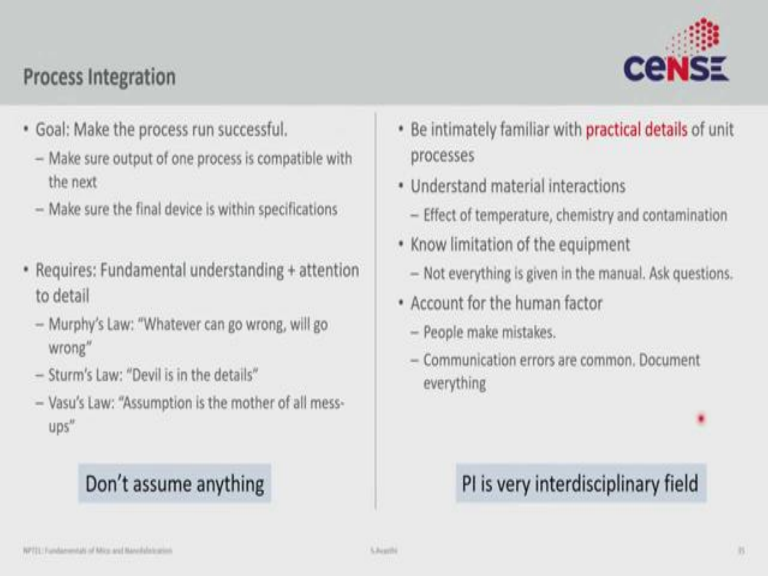

Process Integration

- Goal: Make the process run successful.
  - Make sure output of one process is compatible with the next
  - Make sure the final device is within specifications
- Requires: Fundamental understanding + attention to detail
  - Murphy's Law: "Whatever can go wrong, will go wrong"
  - Sturm's Law: "Devil is in the details"
  - Vasu's Law: "Assumption is the mother of all mess-ups"

Don't assume anything

- Be intimately familiar with practical details of unit processes
- Understand material interactions
  - Effect of temperature, chemistry and contamination
- Know limitation of the equipment
  - Not everything is given in the manual. Ask questions.
- Account for the human factor
  - People make mistakes.
  - Communication errors are common. Document everything

PI is very interdisciplinary field

Arguably, process integration is one of the more important parts of microfabrication. The goal is to make the run successful. Microfabrication tends to be fairly expensive. So, a failed run is a lot of time and money wasted. The goal of a process integration person is to make sure that does not happen.

It requires a very fundamental, detailed understanding of every step. You have to be a master of all the techniques that are being used. In microfabrication, we very strongly believe that Murphy's law applies: everything that you have missed or overlooked or assumed without thinking will go wrong. You have to be intimately familiar with practical details, not just with theoretical details. That requires certain expertise, experience, and practice.

You also have to account for the human factor in a lot of these advanced fabs. A sample is not processed by one person. It is handed over from person A to person B to person C. So, documentation is extremely important; everybody in the chain should know what they have to do and the overall device should still work.

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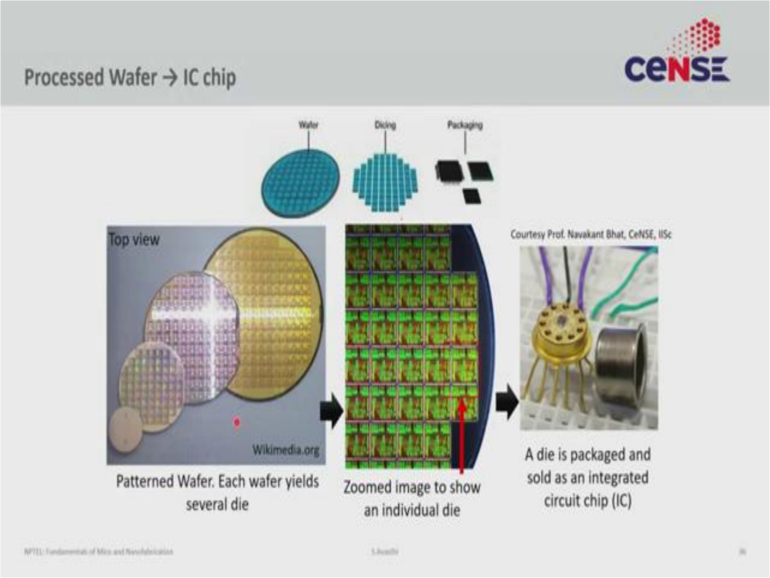

Processed Wafer → IC chip

Patterned Wafer. Each wafer yields several die

Zoomed image to show an individual die

Courtesy Prof. Navakant Bhat, CeNSE, IISc

A die is packaged and sold as an integrated circuit chip (IC)

Hopefully, you get to a processed wafer. That processed wafer does not have just one chip but is a grid of small chips. So, you take that wafer and you dice it into small individual dies and each of these dies is a functional device that you can sell in the market. They are then packaged so that they are protected from the environment and damaged and then sold.

Now, the fact that you take one wafer and you create several devices out of it is important because this is one of the ways we reduce cost. As we make things smaller and smaller we are able to cram more and more dies on top of a wafer and that has allowed us to make more devices in the same processing run, reducing cost.

With that, we come to the end of the introduction to micro nanofabrication. I hope you got a feel for what we shall discuss in this course. What I also hope is this will give you a background for the jargon that we shall use: wafer, semiconductors, doping, lithography etcetera. For details, I shall meet you again in future lectures.