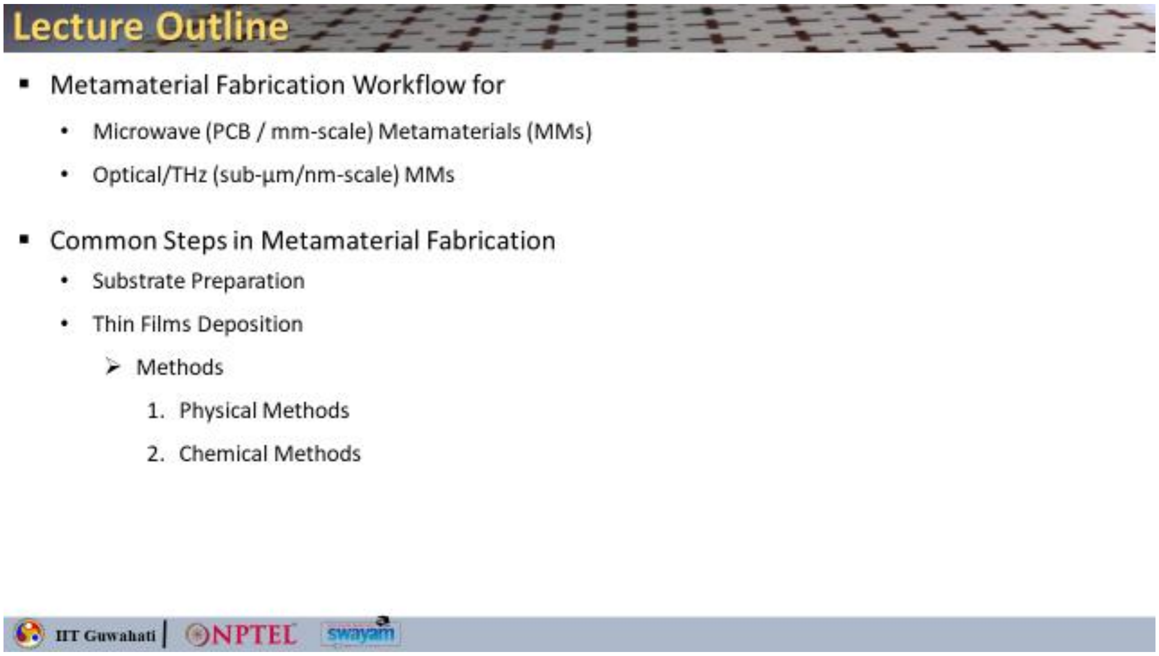
Course Name: Introduction to Microwave and Optical Metamaterials
Professor Name: Dr. Debabrata Sikdar
Department Name: Electronics and Electrical Department
Institute Name: Indian Institute of Technology, Guwahati
Week-12
Lecture-57

Lec 57: Metamaterial Fabrication Techniques

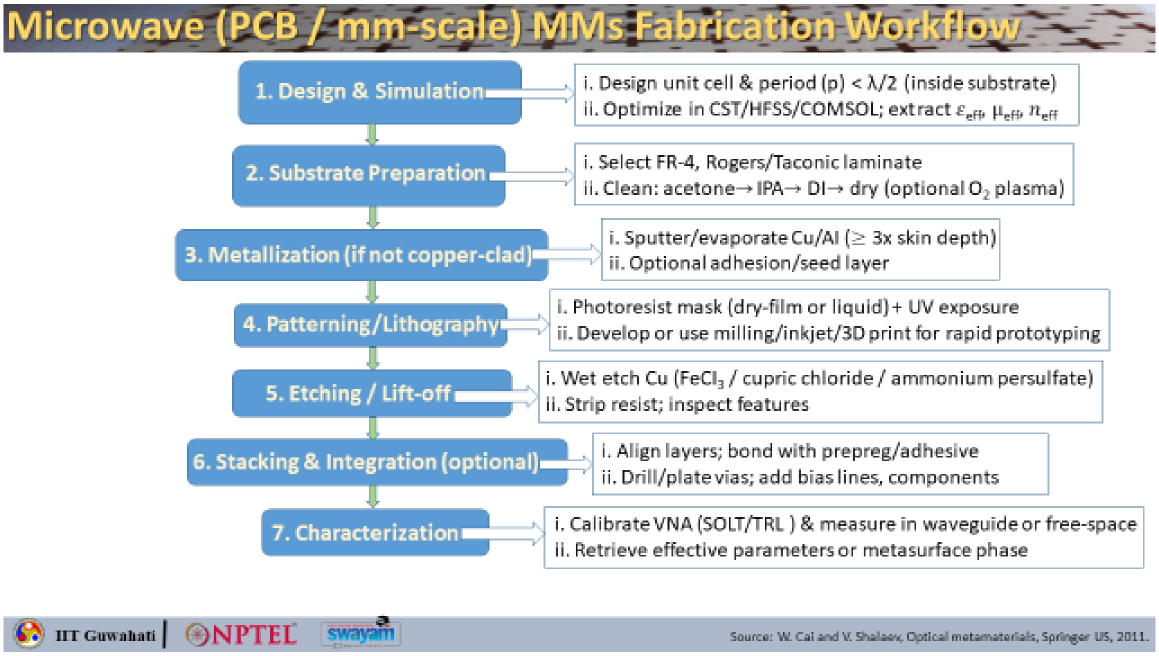
Hello everyone, welcome to lecture 57 of the online course on the introduction to microwave and optical metamaterials. Today's lecture will be on metamaterial fabrication techniques.



So, in this lecture, we will first have a look at the metamaterial fabrication workflow. For microwave metamaterials, which are typically made in printed circuit board (PCB) form, the length scale is usually on the millimeter scale. And then we will look into the optical metamaterials, which are basically sub-micron or nanometer scale. Then we will discuss some common steps in metamaterial fabrication, such as substrate preparation and thin film deposition, including methods.

Such as physical methods and chemical methods.

So, first let us look into the fabrication workflow of microwave metamaterials.



So, it starts with design and simulation. So, you design a unit cell and set the period p, which is typically less than lambda by 2, okay.

For an array structure, you can then simulate this design in CST, which is Computer Simulation Technology. These are commercial tools, such as HFSS or ComSol Multiphysics. So, these are basically commercial solvers based on FIT, FDTD, and FEM; different methods could be utilized. So, you can basically use them to solve Maxwell's equations and finally optimize your design and obtain the parameters. such as effective permittivity, effective permeability, and effective refractive index.

Okay, after that, once the design is finalized, you can go for the substrate preparation, so you can select FR-4; it's flame retardant. 4, okay, Rogers, Taconic, okay. Laminate this could be used as a substrate, and then you have to clean the substrate using acetone and then IPA, which is isopropyl alcohol. And then deionized water, and then dry it. Okay, you can also use oxygen plasma for that, and then clean it.

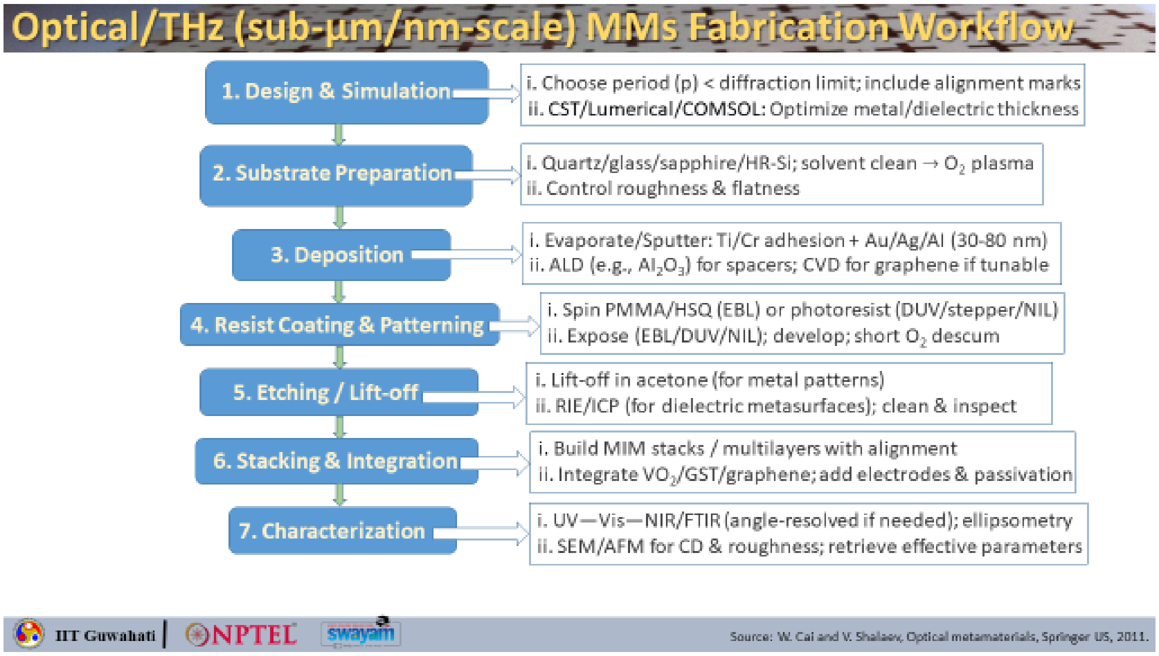
So this is the cleaning part of the substrate. Now you've got to do the metallization if your substrate is not already copper clad. So in that case, you have to deposit the copper or aluminum. So, typically, the thickness of the layer should be more than three times the skin depth. So, that can be done by the sputtering or evaporation method, and you also need a thin adhesion layer made of titanium or chromium if needed.

Now, when I say "copper clad," it basically means that the substrate already comes with a copper foil laminated on it. Either on one side or on both sides. So, you can take an example of standard PCB laminates like Rogers 5880 or FR-4, okay? Now, if your board is copper clad, you do not need to do the metal deposition, and if your substrate of the board is not copper clad, Means it is a bare, say, quartz or silicon or Rogers film or PET, etc. Then you need to first create the metallic layer, and after that is done, you do the patterning or lithography. So, there you apply the photoresist, which can be in the form of dry film or liquid, using spin coating, and then expose it to UV light for developing.

Okay. So, you can also use milling, inkjet, or 3D printing to form the patterns on the surface of the substrate. And after the patterning is done, the next step is etching or lift-off, okay. So, you can do the pattern transfer using wet etching, okay? So, you can basically use copper, or you can do the weight aging of the copper using ferric chloride and copper chloride. Or aluminum per sulfate is okay, or you can dry it and then strip the resist and inspect for any undercut or overcut done on the wafer substrate. And next, you can do, if required in your design, say stacking or integration.

So this is required if you have opted for any multi-layer structure. So you need to align the layers first and bond them with some prepreg or adhesive. Okay, so these are basically pre-impregnated laminates, and then you need to drill or plate wires, add bias lines, and components into the structure. And finally, once the structure fabrication is complete, you can go for the characterization. where you can measure with VNA that is a vector network analyzer using SOLT that is short open load through or TRL that is through a reflect line kind of calibration using a waveguide or in free space.

And finally, you can analyze the S-parameters, which are scattering parameters, to retrieve the effective parameters or the metasurface transmission or reflection phase.



Now let us look into a similar kind of step, but slightly different. That is in the fabrication workflow for optical and even terahertz metamaterials. So they are typically submicron or nanometer-sized. The optical ones are basically at the nanometer scale.

So here, the design and the simulation step are basically the first step. So here you've got to set a subwavelength period. that is your period is much lesser than the diffraction limit. Design the structure and optimize the metal dielectric thickness using numerical simulation software. Such as CST, Lumerical is based on FDTD, as I was telling you.

Comsol is based on FEM (finite element method) ok, CST is FIT (finite integration time). These are different commercially available solvers for Maxwell's equation; you can use them to optimize your design. Once the design is finalized, you can proceed with substrate preparation. So, for fabrication, take quartz, glass, or sapphire. Or highly resistive silicon is okay as a substrate, and perform the solvent clean, okay.

You can use O2 plasma, oxygen plasma, and polish it to control the roughness and flatness of the substrate. And then you can go for once the substrate is ready you can go for the deposition. So, you can deposit thin layers that are about 30 to 80 nanometers of metal, such as gold, silver, and aluminum, using evaporation or sputtering techniques. A thin adhesion layer, typically made of titanium or chromium, is placed underneath so that the metal sticks well. Atomic layer deposition can also be used for aluminum-type spacers.

And you can use CVD, which stands for chemical vapor deposition, for depositing graphene in case you have tunable structures. Next, you can think of resistant patterning. Okay, so for that, you have to first apply resistant materials like PMMA, which is polymethyl methacrylate. Which is a positive resistor, or you can think of HSQ as hydrogen silsesquioxane. OK, that is typically used in EBL as a negative resist.

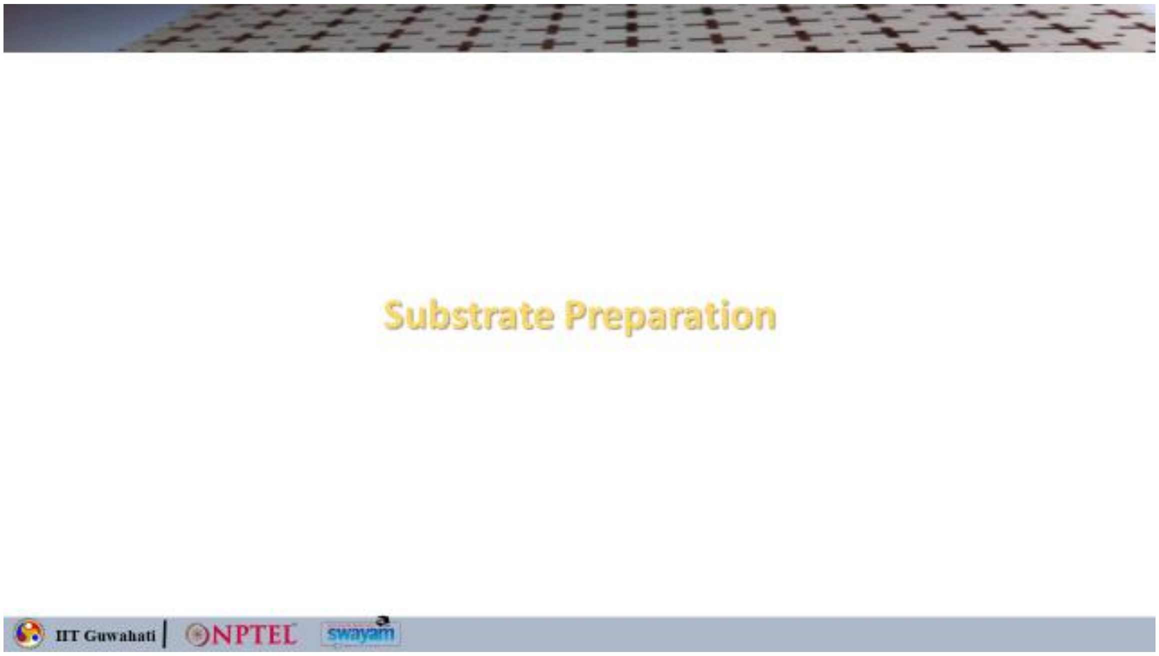
OK, so you can actually use both for electron-beam lithography. OK, and you can also use the photoresist for spin coating methods. OK, so using the spin coating method, you can use it for deep UV or a stepper. Nano imprint lithography is okay, and for patterning, what you do mainly involves resist coating, which we have seen until now for patterning. You can expose the resist using EBL, deep UV, or nanoimprint lithography.

And then develop the patterns in the chemicals to reveal the features. So in that case, you have to perform a short oxygen descamp to remove the thin residue. Next is the method for etching and lift-off. So, if using metal patterns, you should dissolve the resist in acetone. Only the patterned metals will remain, and this method is called the lift-off.

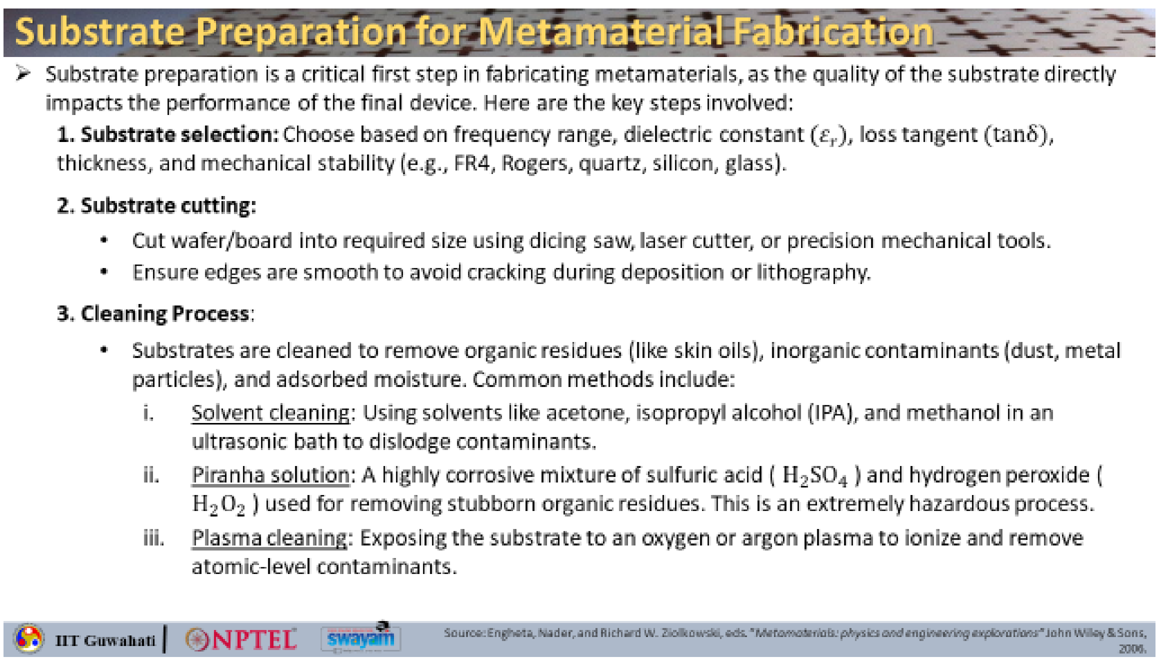
And after etching, for dielectric metal surfaces, you can use reactive ion etching (RIE). Or for sculpting structures, you can use inductively coupled plasma. So, that is typically used for dielectric metasurfaces. And then in the final step, you clean and inspect to confirm the fidelity of these structures. So, stacking and integration become the next steps if you have a multi-layer structure, as discussed before.

so if you build a metal insulator metal kind of a stack or any other multi-layer design so the alignment between the layers become very critical So, here the functional integration requires that you add phase change materials like VO2, GST, or graphene, okay And apply passivation layers for protection; you also have to add electrodes for external contact. And once the device design and fabrication are complete, you go to the characterization step. There you can use UV-visible NIR and FTIR, which is basically Fourier transform infrared spectroscopy. Sometimes you also go for angle-resolved ones to measure the transmittance, reflectance, and absorption. You also perform ellipsometry that can extract the film thickness and the refractive index.

You also perform structural tests using scanning electron microscopy or AFM to measure the critical dimensions and surface roughness And also that allows you to extract the effective parameters such as permittivity, permeability, and refractive index from the measured data.



So now let us look into substrate preparation in detail, which is basically a common step for both microwave and optical metamaterials fabrication.



So, substrate preparation for metamaterial fabrication, as I mentioned, is a critical step. This is the first step toward fabricating metamaterials, as the quality of the substrate directly impacts the performance of the final device.

And here are the key steps involved. First is the selection of the substrate. So, based on the frequency range, you'll be working on. And the dielectric constant epsilon r, the loss tangent of the material, thickness, and the mechanical stability, you have to choose. Which one of these is basically your suitable substrate? Typically, you have FR-4, Rogers, quartz, silicon, and glass, and on them, you choose.

next you do the substrate cutting so you basically cut the wafer or poured into the required size using dicing saw laser cutter For precision mechanical tools, you have to ensure that the edges are smooth to avoid cracking during deposition. or lithography and then you got to clean your substrate so substrates are basically clean to remove the organic residues such as skin oils, inorganic contaminants such as dust, metal particles, and the absorbed moisture So the common methods include something like solvent cleaning. So, you can use solvents like acetone, isopropyl alcohol, and methanol in an ultrasonic bath to dislodge the contaminants. You can also go for a piranha solution, which is a highly corrosive mixture of sulfuric acid and hydrogen peroxide. That can be used for removing stubborn organic residues, and this is an extremely hazardous process.

You can also think of plasma cleaning as exposing the substrate to an oxygen or argon plasma to ionize and remove atomic-level contaminants.

Substrate Preparation for Metamaterial Fabrication

➢ Substrate preparation steps:

4. Rinsing & Drying: After cleaning, the substrate must be rinse with DI water and thoroughly dried to prevent water spots and ensure good adhesion of subsequent layers. This is done using nitrogen/air gun.

5. Surface treatment:

- Oxygen plasma or UV-ozone cleaning for organic removal and surface activation.
- Adhesion promoter (e.g., HMDS) may be applied if photoresist is used later.

6. Polishing / planarization (if needed):

- For high-quality nanofabrication (optical/THz), ensure surface roughness < few nm RMS.
- Chemical–mechanical polishing (CMP) may be applied for silicon/glass wafers.

7. Drying : Bake substrate (e.g., 100–150 °C for 5–10 min) to remove moisture.

8. Final inspection: Check under microscope for particles, scratches, or cracks before moving to next steps.

9. Storage: Once prepared, the substrate is typically stored in a clean, dust-free container (such as a nitrogen-purged desiccator or a cleanroom storage cabinet) to prevent re-contamination before fabrication begins.

IIT Guwahati | NPTEL swayam Source: Engheta, Nader, and Richard W. Ziolkowski, eds. "*Metamaterials: physics and engineering explorations*" John Wiley & Sons, 2006.

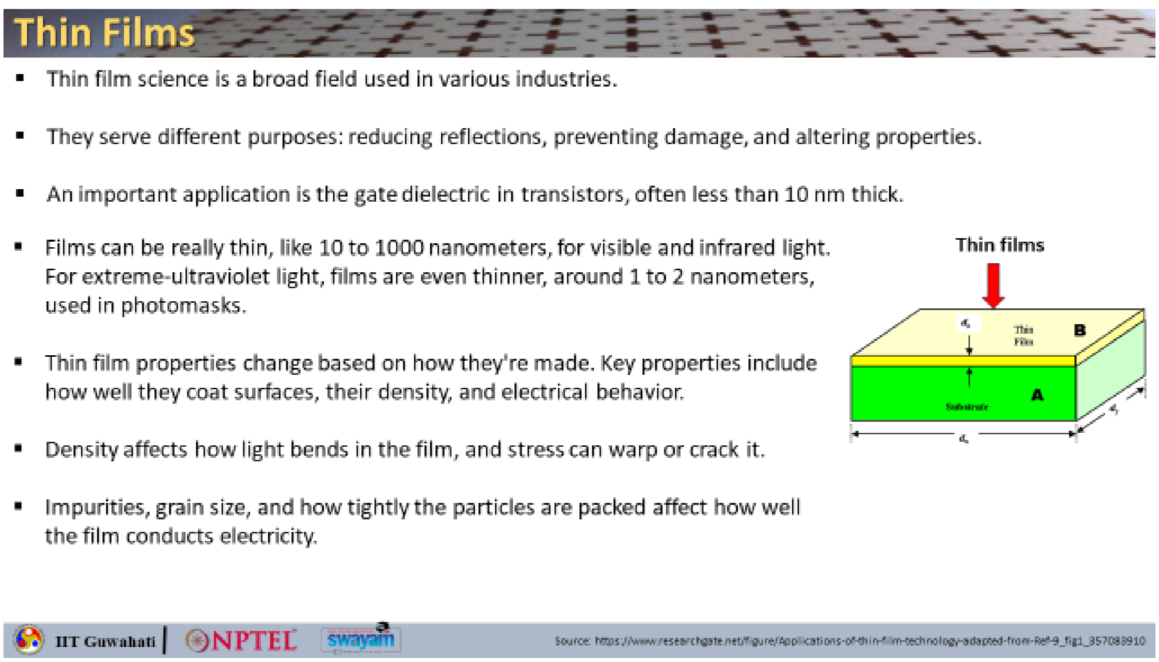
Now, in the substrate preparation steps, the fourth one is rinsing and drying. So after you are done with the cleaning, the substrate must be rinsed with deionized water and thoroughly dried to prevent water spots. Ensure good adhesion to the subsequent layers. And this is basically done using a nitrogen or air gun.

Substrate treatment is then performed using oxygen plasma or UV ozone cleaning. For organic removal and surface activation, you can apply additional promoters such as

HMDS, which is hexamethyldisilazane. This may be applied if the photoregist is going to be used later, and then finally, you do polishing or planarization based on your requirements. So, if you want to go for high-quality nanofabrication that is in the optical and terahertz regimes. So, you need to ensure that the surface roughness is below a few nanometers of the root mean square value.

So, chemical mechanical polishing may then be applied to silicon glass wafers. And finally, you can do the drying, which means baking the substrate at a temperature of 100 to 150 degrees Celsius for 5 to 10 minutes. That will help you remove the moisture content, and finally, you can inspect your substrate under a microscope. For particles, scratches, and cracks before you move on to the next step. So, once prepared, the substrates are also typically stored in a clean, dust-free container, such as a nitrogen-purged desiccator.

A clean room storage cabinet is needed to prevent recontamination before you can actually begin your fabrication steps.

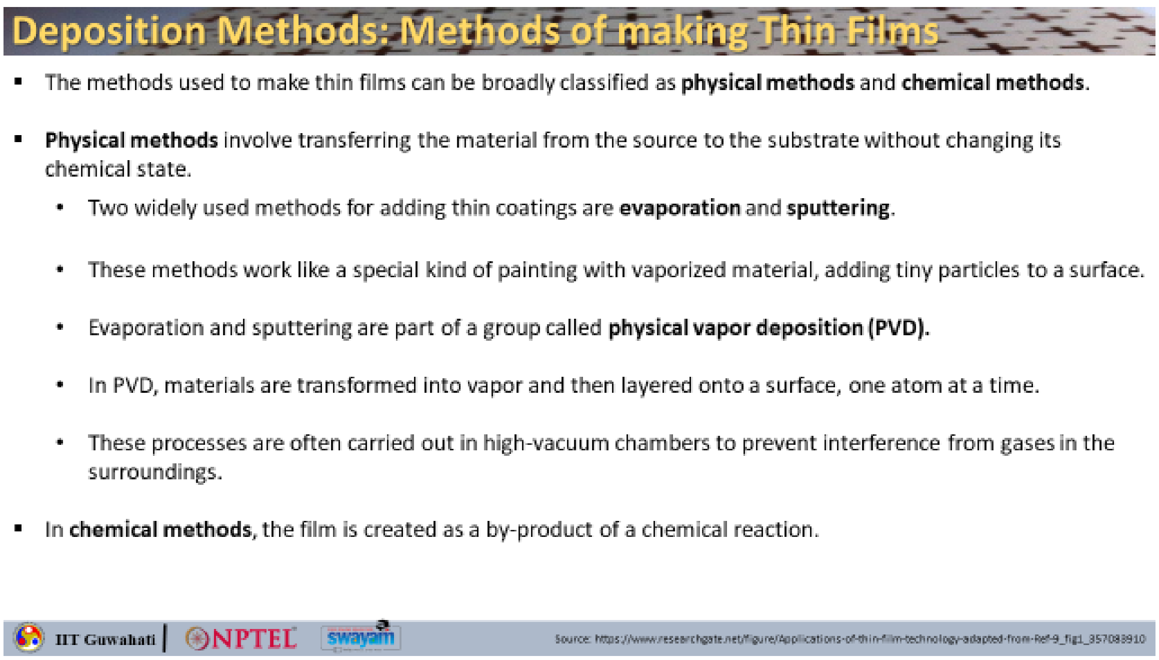


So, now let us look into the first method of depositing the thin films, okay. So, thin film science is a broad field used in various industries. They serve basically different purposes. They can be used to reduce reflections, prevent damage, or alter properties, right? So an important application is a gate dielectric in transistors that are often less than 10 nanometers thick.

So, as you can understand, these films can be really thin, ranging from 10 to 1000 nanometers for visible and infrared light. And if you go for extreme UV light, the films will be even thinner, so they will be only one to two nanometers. Which are typically used in photo masks, okay, so thin film properties. Change based on how they are made. So the key properties basically include how well they coat the surface, their density, and their electrical behavior.

So here you can see one example of a thin film. So here is the substrate, and this is the thin film B that is deposited on substrate A. Now the density is important. Because it affects how light bands in the film, and stress can wrap or crack your film, okay. Impurities, grain size, and how tightly the particles are packed all affect how well the film is going to conduct electricity.

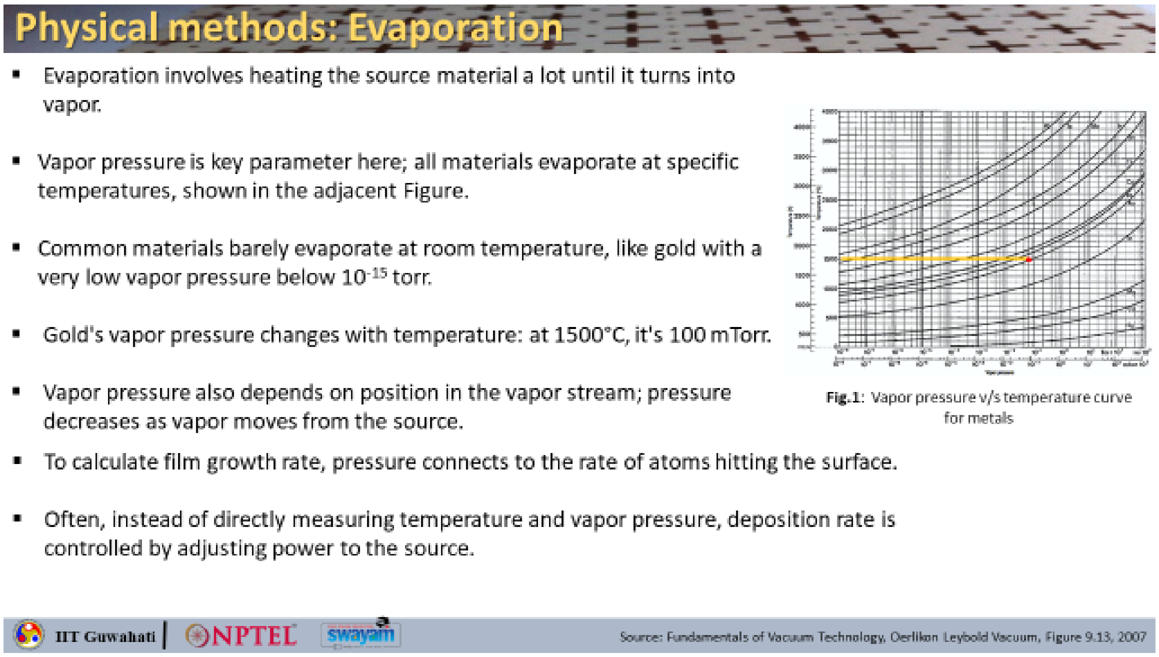
So its electrical behavior, you know, the density also tells about the stability of the film.



Now let us look into the deposition methods for making these thin films. So thin films can be made using two methods, which you can think of as physical methods and chemical methods. Now, physical methods basically involve transferring the material from the source to the substrate without changing its chemical state. So, two commonly used methods for making thin films or adding thin coatings are basically evaporation and sputtering.

So these methods basically work like a special kind of painting with vaporized materials by adding tiny particles to a substrate. Evaporation and sputtering are part of a group called physical vapor deposition. So in PVD, which is a popular name for physical vapor deposition, the materials are basically transformed into vapor. And then layered onto a substrate one atom at a time. These processes are often carried out in high vacuum chambers that could prevent interference from gases in the surroundings.

Whereas in the chemical methods, you will see that the film is essentially created as a byproduct of some chemical reaction.



Now evaporation will involve heating the source material a lot until that converts into vapor right so vapor pressure becomes a key parameter here and all materials evaporate at a specific temperature, as you can see here: mercury, gold, and all these different platinum. I'll not read out all of them. But this is the vapor pressure axis, and this is the temperature axis. So it tells you that common materials will barely evaporate at room temperature because the temperature here is very high, okay? And for something like gold, you can see that if you have vapor pressure or the temperature.

If we change the temperature to 1500, then the vapor pressure is something around 100 milli Torr, ok. So, vapor pressure also depends on the position in the vapor stream. So, the pressure basically decreases as the vapor moves away from the source. So, to calculate the film growth rate, the pressure is connected to the rate of atoms hitting the surface. So often, instead of directly measuring the temperature and the vapor pressure, the deposition rate is controlled by adjusting the power to the source.

So here we'll see one example of the resistively heated evaporation method.

Physical methods: Evaporation

- There are **two main types of evaporation** methods based on how power is given to the source.
- In **one type**, pellets of the source material are put in a metal container (boat) and heated using a strong electric current, around 100 A.
- This is called resistively heated evaporation.
- It's simple, needing only a low-voltage DC source, but has drawbacks like inefficiency and potential contamination due to other parts heating up and evaporating along with the source.

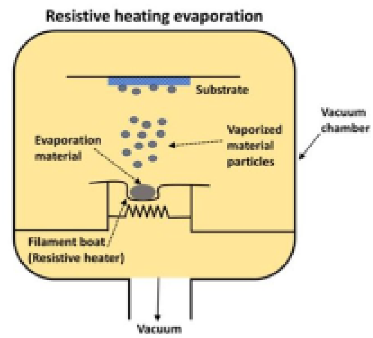


Fig.2: Resistively heating evaporation process

So there are basically two types of evaporation methods based on how power is given to the source. So, in one case, you can see that the pellets of the source material are basically put in a metallic container or something like a boat. And that is heated using a strong electric current of around 100 amperes. It will heat up, and you are basically getting resistively heated evaporation.

So, it is simple, and these vaporized molecules will go and deposit on the substrate in this vacuum chamber. So it's simple; it only needs a low voltage DC source, but it has some drawbacks, like inefficiency and potential contamination. Due to other parts also heating up and evaporating along with the source, right.

The second method is called electron beam heating. So you can see there is an electron gun that is supplying these heated electrons, which are accelerated through this high voltage. That is around 10 kV, and they are focused only on the source pallet.

Physical methods: Evaporation#2

- The **second method** is electron-beam heating, where heated electrons are accelerated by high voltage (around 10 kV) and focused onto the source pellet.

- This happens in a vacuum, so electrons can be controlled by magnetic fields without hitting gas molecules.
- Electron-beam is efficient, accurately heating the source and minimizing contamination, but it requires a complex high-voltage power source.
- Safety is also important due to the potential danger of high voltage.
- Despite this, electron-beam evaporation is widely used in thin film research and development.

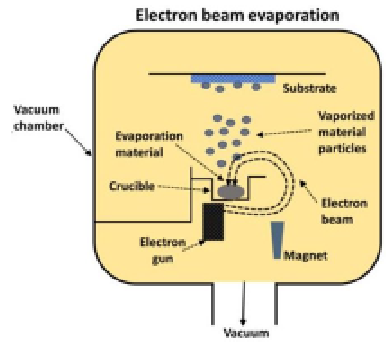


Fig.3: Electron beam evaporation process

So you basically use a magnet to redirect the beam so that it can go and heat the pellets. So, this also happens in a vacuum. So, the electrons can be controlled using a magnetic field without hitting the gas molecules, as you can see here. So, the electron beam is basically efficient at accurately heating the source and minimizing contamination. But, as you can see, it requires a complex high-voltage power source.

And the safety issue becomes important because you are using a very high voltage source. So, despite this, it is called electron beam evaporation. This is a widely used method in thin film R&D, right.

Physical methods: Sputtering

- Sputter deposition uses a vacuum system with an excited gas plasma.
- Plasma ions are directed at the cathode, knocking neutral atoms off its surface.
- These atoms collect on all surfaces, including the substrate; forms a thin film.
- Unlike evaporation, sputtering doesn't rely on heat; atoms are ejected by momentum → leads to denser films.

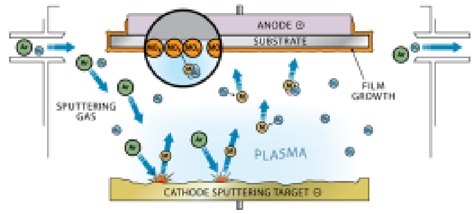


Fig.4: A generic configuration of Sputter deposition

- In sputtering, the target material is bombarded by energetic ions (usually Ar^+), ejecting atoms that deposit onto the substrate.
- The target temperature rise is much lower compared to evaporation because sputtering is a momentum-transfer process, not thermal vaporization.
- Sputtering can happen upward, downward, or sideways, while evaporation is usually only upward.

The other method is called sputtering. Now, sputtering deposition basically uses a vacuum system with excited gas plasma. So, plasma ions are basically directed at the cathode, as you can see, knocking the neutral atoms off the surface.

And all these atoms will collect on the substrate here. And it will form a thin film. So, unlike evaporation, sputtering basically does not rely on heat. Here, the atoms are basically ejected by momentum. So that leads to denser films. So, in sputtering, the target material is basically bombarded by energized iron, which is typically argon, as you can see.

And they are ejecting the materials that will essentially be deposited onto the substrate. So, you will see the film growth here. So, the target temperature rise is much lower compared to the evaporation. Because sputtering is basically a momentum transfer process, not a thermal evaporation. Sputtering can happen upward, downward, or sideways, while evaporation can only happen upward.

Physical methods: Sputtering

- Targets and plasma sources in sputtering can be made in different shapes for various coating setups, like circles, rectangles, or even unusual shapes.
- Plasma power in sputtering comes from a DC or RF source.
  - For metal targets, DC works.
  - For insulating targets use RF, where the target acts like a capacitor for the plasma.

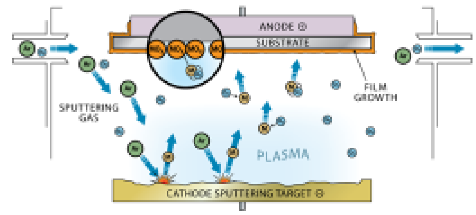


Fig.4: A generic configuration of Sputter deposition

- Thus; sputtering is better suited for thermally sensitive compounds such as oxides (e.g., TiO_2, ZnO, Al_2O_3) and nitrides (e.g., TiN, AlN), because the target remains at relatively low temperature compared to evaporation, reducing the risk of thermal decomposition or stoichiometric imbalance.
- In sputtering, atoms might collide before reaching the substrate due to plasma gas, making it less directional than evaporation.

Now, the targets and the plasma sources in the sputtering can be made in different shapes for various coating setups, such as circles and rectangles. Or even unusual shapes, and the plasma power in the sputtering comes from either a DC or an RF source. So, if you work with metal targets, DC works well. And if you are going for insulating targets, you have to choose the RF source where the target acts like a capacitor for the plasma. So, you can see that sputtering is better suited for thermally sensitive compounds such as TiO2, zinc oxide, or Al2O3 (alumina).

And nitrides, aluminum nitrate, and titanium nitrate, okay. Because the targets basically remain at a relatively low temperature compared to the evaporation. And that basically reduces the risk of thermal decomposition, or you can say a stoichiometric imbalance. Now in sputtering, you can see that the atoms might collide with one another before reaching the substrate. Due to the plasma gas, it is less directional than evaporation.

Physical methods: Reactive Sputtering

- Reactive sputtering is a variation where a bit of reactive gas (like oxygen or nitrogen) mixes with argon to create compounds from ejected target material.
- During the process, atoms are ejected from the target by energized ions to form a plasma that is directed to the substrate under a high vacuum.
- Argon is the commonly used sputtering gas, and the sputtering is carried out with a DC power source, radio frequency alternating current, or ion-assisted deposition.
- In reactive sputtering, a reactive gas such as oxygen for oxides and nitrogen for nitrides is also passed to the reaction chamber along with argon. These reactive gases react with the target atoms in the plasma to form the desired composition.

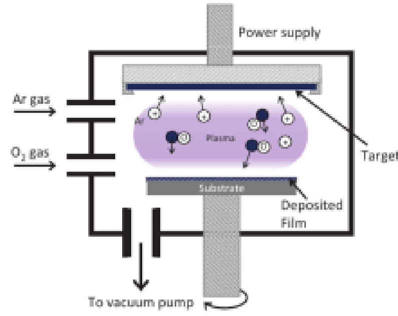


Fig.5: Reactive sputtering process

Now, reactive sputtering is a variation that involves a bit of reactive gas, like oxygen or nitrogen mixes with argon to create compounds from ejected target material right. So, during this process, atoms are ejected from the target by energized ions to form a plasma. That is basically directed to the substrate under very high vacuum. So, this is your vacuum chamber, this is the target, this is the substrate and here you have these different gases coming in. So, normally argon is the commonly used sputtering gas, and the sputtering is carried out with a DC power source, or you can also use RF alternating current.

or ion-assisted deposition. In the case of reactive sputtering, a reactive gas such as oxygen can be used if you want oxides, or nitrogen can be used if you want nitrides. That is also passed to the reaction chamber along with the argon. So, these reactive gases basically react with the target atoms in the plasma to form the desired composition, and then they get deposited, Right.

Physical methods: Reactive Sputtering

- While forming perovskite oxides films, multiple targets with different elements are simultaneously sputtered, which are reacted with oxygen and deposited as the desired film.
- Since the target elements and oxygen exhibit a large electronegativity difference, the formed ions can be negatively charged and accelerated towards the substrate due to the difference in the potential of the negatively charged target and the grounded substrate.
- These ionic fluxes possibly act as sputtering ions to re-sputter the growing thin film on the substrate or modify the composition of the films or etching the substrate.

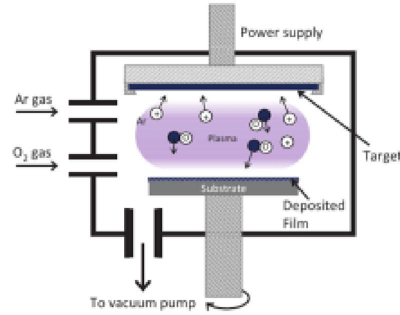


Fig.5: Reactive sputtering process

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Source: https://ebrary.net/191961/engineering/reactive_sputtering

So, while forming perovskite films, multiple targets with different elements are simultaneously spattered.

So, they basically reacted with oxygen and were deposited as a desired film. So, since the target elements and oxygen exhibit a large electronegativity difference, the formed ions you will see can basically have negatively charged and they are accelerated towards the substrate Due to the difference in the potential of the negatively charged target and the grounded substrate. Right. So, here is the target, and this is the substrate, right? These ionic fluxes possibly act as sputtering ions to re-sputter the growing thin film. On the substrate, or modify the composition of the films, or basically etch the substrate.

Physical methods: Pulsed Laser Deposition

- Pulsed laser deposition (PLD) employs brief, powerful laser pulses (a few nanoseconds) to remove the target material.

- Laser energy is focused on the target surface, causing rapid material evaporation and atom ejection (plasma plume). these atoms then gather on the substrate.

- A key advantage is that PLD can be performed in ultra-high vacuum or with various pressures and gases due to the laser source being external to the vacuum chamber.

- The main advantage of PLD is its non-discriminatory & ability to remove target material in a stoichiometric manner, treating all atoms equally due to high laser fluence and rapid ablation.

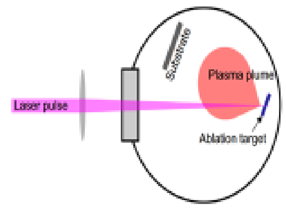


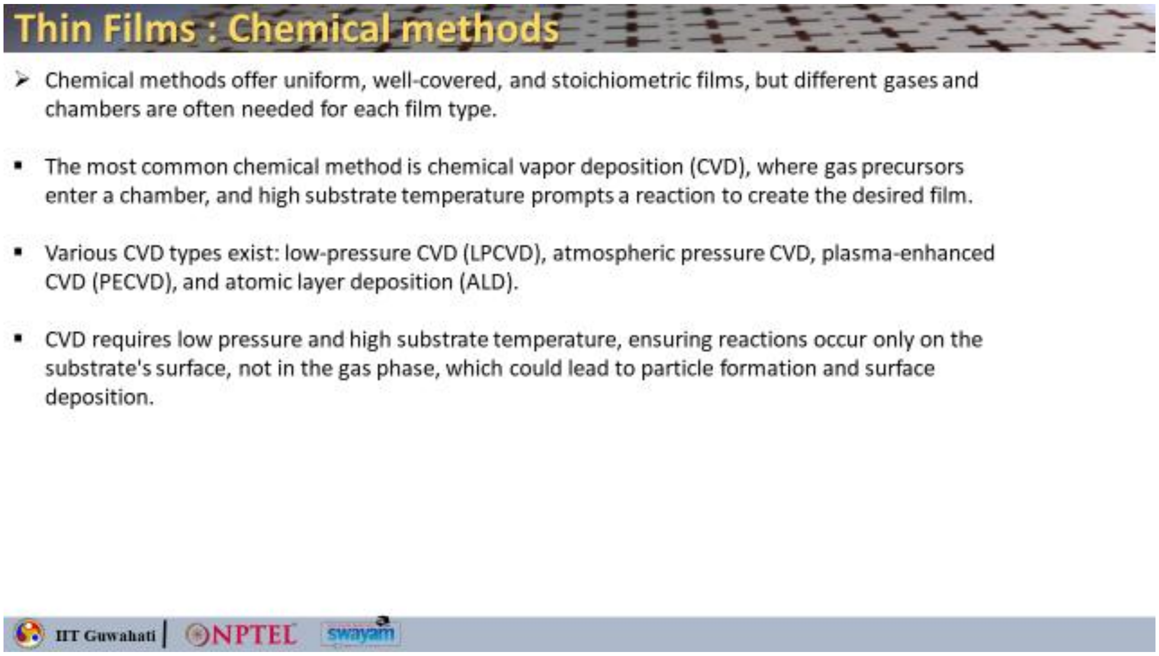
Fig.6: Pulsed laser deposition

- PLD is particularly suited for complex ceramic films like Yttrium barium copper oxide (YBCO), Lead zirconate titanate (PZT), and various carbides, oxides, and nitrides that are challenging to deposit using other methods.

Another method is pulsed laser deposition. So PLD basically employs brief, powerful laser pulses, typically a few nanoseconds long, to remove the target material. So here you can see that laser energy is basically focused on the target substrate, which causes rapid material evaporation and atom ejection. So, you can see a plasma plume here, and these atoms are basically gathered on the substrate. So, a key advantage of this pulsed layer deposition is that you can perform it under ultra high vacuum or with various pressures.

or gases due to the laser source being external to the vacuum chamber. And the main advantage of PLD is its non-discriminatory nature and its ability to remove target material in a stoichiometric manner. Treating all atoms equally due to high laser fluence and rapid ablation. So, PLD is basically particularly suited for complex ceramic films like YBCO, yttrium barium copper oxide, and lead zirconate titanate (PZT). and various kinds of carbides, oxides, and nitrides.

They are typically challenging to deposit using other methods.



So now let us look at the chemical methods, Ok, so the chemical methods offer uniform, well-covered, and stoichiometric films. But different gases and chambers are often needed for each type of film. So the most common chemical method is chemical vapor deposition (CVD), where gas precursors physically enter the chamber.

A high substrate temperature prompts the reaction to create the desired film. There are different types of CVDs: one is called low pressure CVD, LP-CVD, atmospheric pressure CVD, plasma enhanced CVD, and atomic layer deposition. So, CVD basically requires low pressure and high substrate temperature, which ensures that the reaction occurs only on the substrate surface, not in the gas phase, which could lead to particle formation and surface deposition.

So, here is the setup for low-pressure CVD.

Chemical methods: Low-pressure CVD (LPCVD)

- A low-pressure CVD reactor consists of a quartz tube connected to a pump. The gas inlet is used to introduce the reactant gases as well as gases used to purge the system, such as nitrogen.
- The wafers are loaded through the door on the left.
- In a low-pressure system, the wafers can be placed closer, as is shown here. A furnace encompasses the quartz tube. This heats the chamber, driving the reaction rate faster.
- The advantages of LPCVD include a relatively simple design, excellent economy, high throughput, and good uniformity.
- The disadvantages of these systems include susceptibility to particle contamination, which necessitates frequent cleaning, and the need to compensate for gas depletion effects.

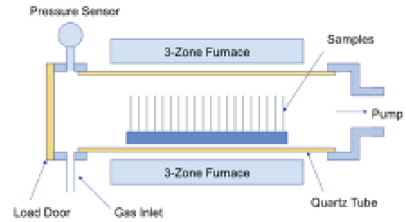


Fig.7: Low-pressure CVD

So, this reactor consists of a quartz tube connected to a pump. Okay, the gas inlet is basically used to introduce the reactant gases as well as the gases used to purge the system, such as nitrogen. Now, the wafers are loaded through the door on the left. So, this is the loading door. In a low-pressure system, the wafers are placed closer, as you can see here.

Okay, the furnace basically encompasses your quartz tube. This is the quartz tube that is enclosed by a furnace. So this basically heats the chamber, driving the reaction rate faster. And the advantages of low pressure CVD include a relatively simple design, excellent economy, high throughput, and good uniformity. However, the disadvantages of the systems will include some susceptibility to particle contamination This associates frequent cleaning with the need to compensate for the gas depletion effects.

Chemical methods: Plasma enhanced CVD

- Single wafer process chambers for Plasma-enhanced CVD (PECVD) look somewhat similar to those for LPCVD.
- Adjacent figure shows a schematic that illustrates the characteristics of a single-wafer plasma chamber.
- As with single wafer LPCVD chambers, the precursor gas is fed to the chamber using a showerhead arrangement to ensure uniformity of precursor concentration over the wafer face.
- Direct exposure RF (radio frequency) PECVD systems typically employ the showerhead as an electrode for the introduction of RF energy to create the plasma.
- Precursor entering the plasma undergoes electron-molecule collisions, producing high energy excited molecules and molecular fragments that adsorb on the substrate surface and deposit the film.

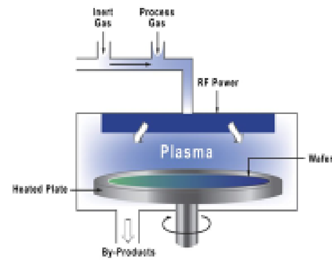


Fig.8: Plasma-enhanced CVD

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Now, this is plasma enhanced CVD. So, single wafer process chambers for plasma-enhanced CVD look somewhat similar to those of the low-pressure CVD. Here you have the inert gas and the process gas inlet; you have the RF power. Okay, this is the wafer, and then it is on a heated plate. Okay. So it basically tells you about the single wafer plasma chamber, and these are the byproducts coming out, okay? So, as with the single wafer LPCVD chamber, you can see that the precursor gas is basically.

Fed to the chamber using the showerhead arrangement. To ensure uniformity of the precursor concentration over the wafer surface. So, this is where the wafer will lie. Now, direct exposure radio frequency PECVD systems typically employ the showerhead as an electrode. For introducing the RF power or the RF energy to create plasma. Now the precursor entering the plasma undergoes this electron molecule collisions producing high energy excited molecules and molecular fragments that absorb the substrate surface that basically absorb on the substrate surface and deposit the film.

So, here you can see that, like LPCVD, the wafer basically sits on a heated plate, okay, and the byproduct gases are Basically exhausted through the ports below the wafer level, and this is a rotating system like before.

Chemical methods: Atomic Layer Deposition (ALD)

- The ALD process starts by a pulse of metal-organic precursor gas into the deposition chamber.
- Under certain conditions, the gas reacts with the surface species of substrate in a self-limiting reaction that is terminated when the surface runs out of reactants.
- The excess gas is purged in the second step with a neutral gas such as N_2 or Ar depending on the process requirements.
- The second reactant is introduced into the chamber in the third step, again reacting with the surface species.

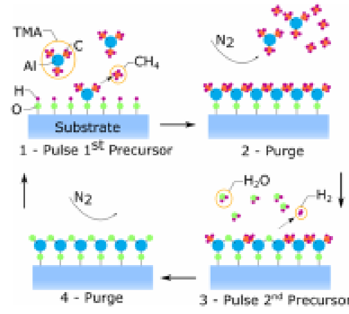

Fig.9: ALD cycle for the deposition of Al_2O_3

- The excess of reactant and products are purged in the fourth step, concluding one cycle.
- In an ideal ALD process one atomic layer of material is deposited in each cycle.
- The number of cycles determines the thickness of deposited film.

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The final method we will be discussing today is atomic layer deposition. So, this ALD process basically starts with a pulse of metal organic precursor gas into the deposition chamber. Under certain conditions, the gas reacts with the surface species of the substrate in a self-limiting reaction. That is terminated when the surface runs out of reactants, right? And the excess gas is then parsed in the second stage with a neutral gas, such as nitrogen or argon, based on the process requirements.

Then the second reactant is introduced into the chamber in the third step. So, here again it reacts with the surface species. The excess reactant and the products are again purged in the fourth step, concluding one particular cycle, and this goes on. So, in an ideal atomic layer deposition process, one atomic layer of material is basically deposited in every cycle. The number of cycles basically determines the thickness of the deposited film, and you are doing it atomically, layer by layer.

So, with that, we conclude our lecture. So, if you have any queries regarding this lecture, you can drop an email to this email address. Thank you.