# Advanced Neural Science for Engineers
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## Lecture 12
## Sputtering

Hello everyone, welcome to this lecture where we will be talking on sputtering. Now, in the last lecture what we have seen, we have seen physical vapor deposition in that we have discussed about thermal evaporation and e-beam evaporation.

In sputtering as I told you last time, there are four types where the first one is DC sputtering followed by RS sputtering followed by magnetron sputtering and the last one is the reactive sputtering.

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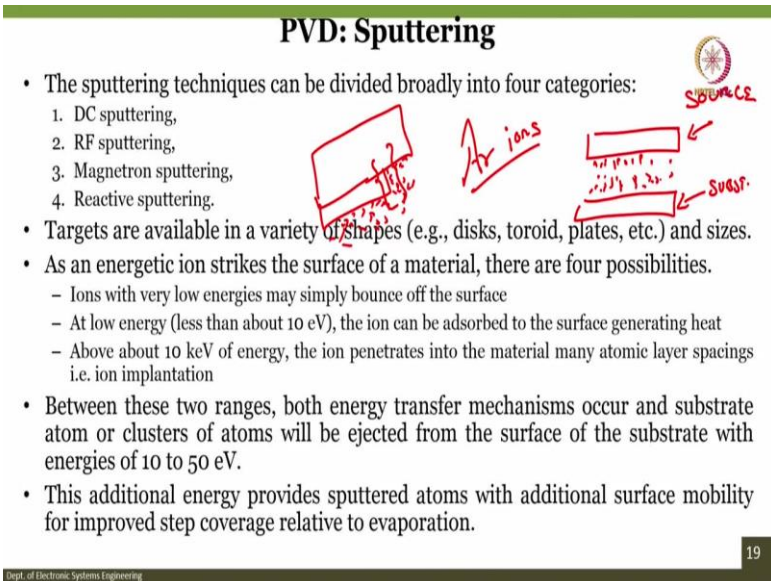

**PVD: Sputtering**

- The sputtering techniques can be divided broadly into four categories:
  1. DC sputtering,
  2. RF sputtering,
  3. Magnetron sputtering,
  4. Reactive sputtering.
- Targets are available in a variety of shapes (e.g., disks, toroid, plates, etc.) and sizes.
- As an energetic ion strikes the surface of a material, there are four possibilities.
  - Ions with very low energies may simply bounce off the surface
  - At low energy (less than about 10 eV), the ion can be adsorbed to the surface generating heat
  - Above about 10 keV of energy, the ion penetrates into the material many atomic layer spacings i.e. ion implantation
- Between these two ranges, both energy transfer mechanisms occur and substrate atom or clusters of atoms will be ejected from the surface of the substrate with energies of 10 to 50 eV.
- This additional energy provides sputtered atoms with additional surface mobility for improved step coverage relative to evaporation.

So, let us see, if you see the slide the sputtering techniques as I told you are broadly divided into four categories, the targets are available in various shapes, example, disks, toroid, plates etc. unlike the thermal evaporation where we will talk about the boat and the spiral coils or basket in sputtering generally targets are of disks, toroid, oil plates.

Now, how this sputtering works that an energetic ion strikes and generally we want to use we use argon right? So, strikes the surface of material there are four possibilities, the first one would be that ions with very low energies may simply bounce back of the surface doing nothing. The second would be that at low energy that is less than 10 electron volts the ion can be absorbed at the surface generating heat.

The third possibility is about 10 kilo electron volts of energy ion penetrates in a material and many atomic layers spacings and that is ion implantation, but between these two ranges both energy transfer mechanism occurs and the substrate atom or cluster of atoms will be ejected and when that is ejected from the surface of these surface of the material then it will get deposited on to the substrate.

So, this additional energy that is provided sputtered atoms with additional surface mobility for improved step coverage related to the evaporation. So, the again the point is that if I use argon ions, argon ions will bombard get bombarded on to the material that is your source material and the atoms from the source material gets dislodged when it gets dislodged it will get deposited onto a substrate.

Now, the advantage of this because it is like dislodging of atoms right and not really evaporation if I have a step coverage let us say if I have a step like this, this here the bombardment will occur uniformly everywhere. So, compared to the thermal evaporation where the step was not covered uniformly, the chances of better step coverage are higher when we go for the sputtering.

So, the sputtering has advantage over thermal evaporation like we can have a better step coverage.

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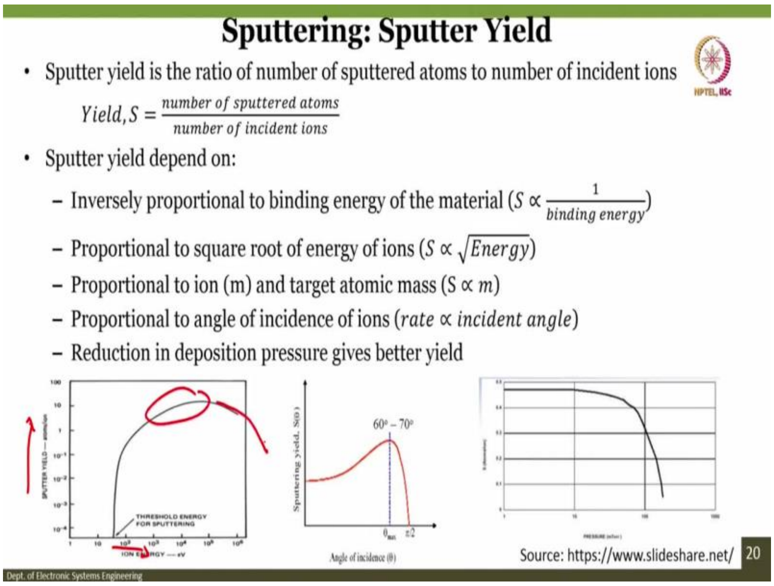

## Sputtering: Sputter Yield

- Sputter yield is the ratio of number of sputtered atoms to number of incident ions

$$Yield, S = \frac{number\ of\ sputtered\ atoms}{number\ of\ incident\ ions}$$

- Sputter yield depend on:
  - Inversely proportional to binding energy of the material ($S \propto \frac{1}{binding\ energy}$)
  - Proportional to square root of energy of ions ($S \propto \sqrt{Energy}$)
  - Proportional to ion (m) and target atomic mass ($S \propto m$)
  - Proportional to angle of incidence of ions ($rate \propto incident\ angle$)
  - Reduction in deposition pressure gives better yield

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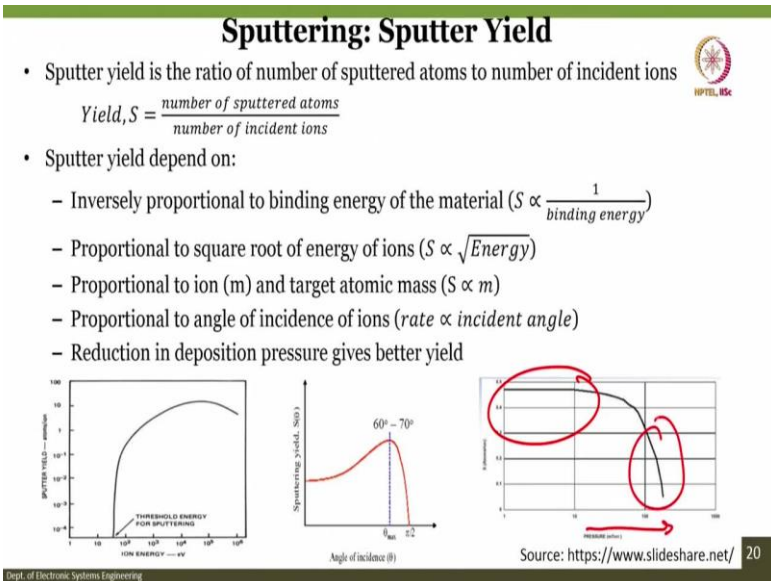

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So, let us go to the next slide. So, what is sputtering yield right? This is sputtering yield or given by:

S = (number of sputtered atoms)/(number of incident ions)

;how many atoms from the surface gets dislodged, from the source gets dislodged on bombardment of the incident ions. So, that ratio is called the yield and sputtering yield in particular, and it depends on several things, the first one is that is inversely proportional to the binding energy of the material that is one thing.

Second thing is that it is proportional to the square root of energy of ions, third one is proportional to ion m if we say target atomic mass is, then we can say S is proportional to m and proportional to angle of incidence rate is proportional to incident angle. Finally, reduction and deposition pressure gives a better yield. So, you can see sputter yield versus ion energy as you keep on increasing energy at certain point it increases then it reaches the saturation and then starts kind of degrading.

Generally, the angle of incidence is between the 60 in between 60 and 70 degree sputtering yield and angle of incidence, while the pressure versus this sputtering yield if you see, then at lower pressure, the sputtering is better as you increase the pressure the sputtering yield comes down. So, these are the some of the important points that you need to remember, while we talk about this sputtering system.

What are those, that S is proportional, inversely proportional to binary binding energy, S is proportional to the square root of energy of ions, S is proportional to the ion m or there is m target atomic mass and finally, the rate is proportional to the incident angle and reduction in deposition pressure gives a better yield.

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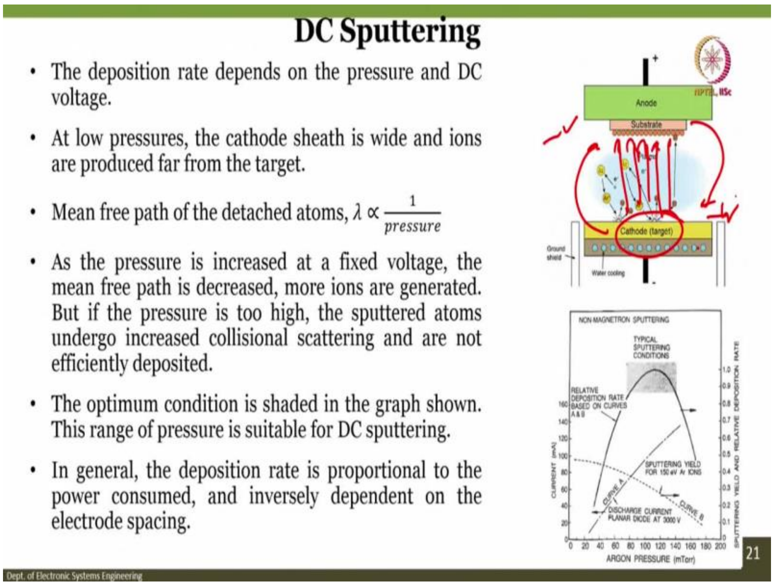
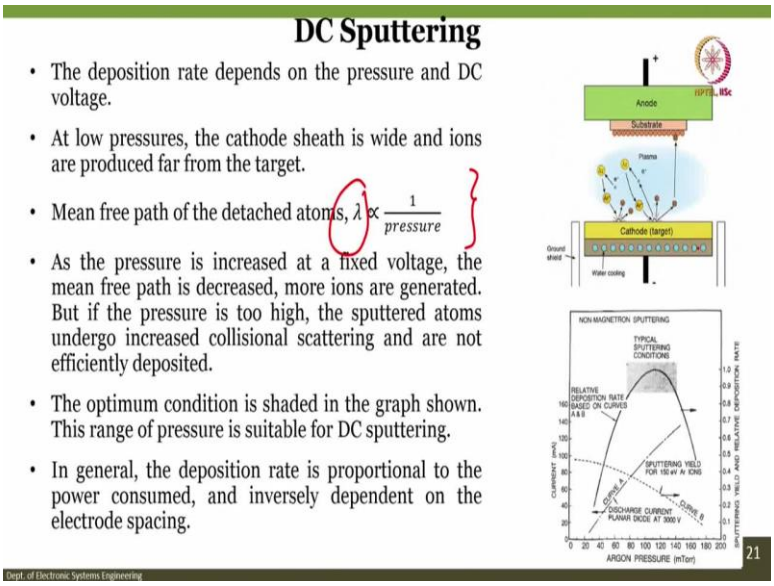


## DC Sputtering

- The deposition rate depends on the pressure and DC voltage.
- At low pressures, the cathode sheath is wide and ions are produced far from the target.
- Mean free path of the detached atoms, $\lambda \propto \frac{1}{pressure}$
- As the pressure is increased at a fixed voltage, the mean free path is decreased, more ions are generated. But if the pressure is too high, the sputtered atoms undergo increased collisional scattering and are not efficiently deposited.
- The optimum condition is shaded in the graph shown. This range of pressure is suitable for DC sputtering.
- In general, the deposition rate is proportional to the power consumed, and inversely dependent on the electrode spacing.



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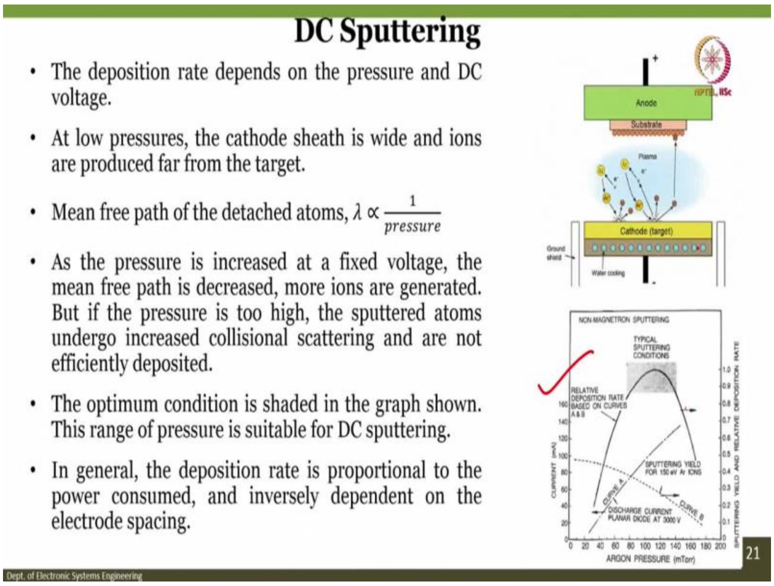

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Now, let us start with the first one out of the four categories. The first one is a DC sputtering and the depositions rates depends on the pressure and DC voltage. And we can see here there is a cathode there is a anode. Apply a DC between two and then there is a ground shield. There is a water cooling mechanism so the targets gets cooled down and when there is a bombardment of the ions onto this target, the atoms has dislodged and start depositing on the substrate, you can either use this you can also put substrate here and cathode here in that case that will be negative substrate will be positive that you already know.

The point is that, at lower pressure, the cathode sheet is wide and ions are produced far from the target and mean free path of the detached atoms, so, this lambda is inversely proportional to pressure that means, that the pressure decreases lambda would increase, as the pressure increases at a fixed voltage, the mean free path is decreased, more ions are generated, but if the pressure is too high this sputtered atoms undergo increased collisional scattering and are not efficiently deposited.

So it is too much high pressure that the mean free path would be less and instead of depositing onto the substrate, it will just collide with each other and forms the scattering. If there is a lot of scattering, that means, that the deposition would not be in uniform and also efficient. So, the optimum condition is stated in a graph which is this graph where how to have, what should be the pressure range, what should be the current range and at what pressure you will have a typical sputtering conditions where you have an optimum parameter, so, that you have efficient deposition.

In general deposition rate is proportional to the power consumed and inversely dependent on the electrode spacing. So, if the electro spacing is reduced, right the deposition rate is higher, if electrode spacing is increased, the deposition rate is lower, if the power is increased, the deposition rate is higher power is decreased, the deposition rate is lower. So, that is how the combinations are there.

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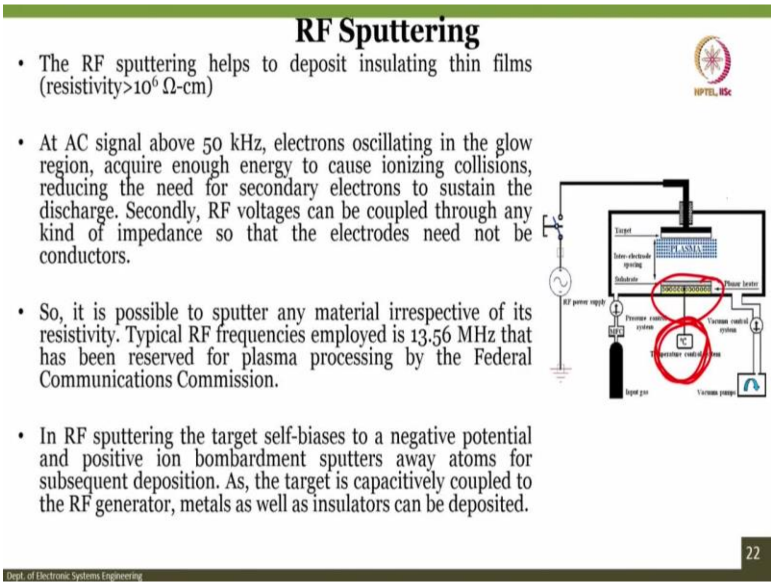
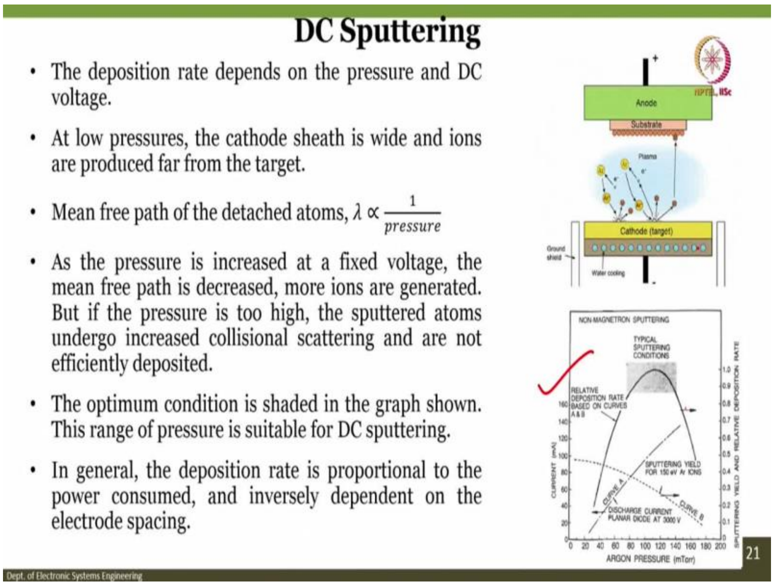


## RF Sputtering

- The RF sputtering helps to deposit insulating thin films (resistivity>$10^6$ Ω-cm)
- At AC signal above 50 kHz, electrons oscillating in the glow region, acquire enough energy to cause ionizing collisions, reducing the need for secondary electrons to sustain the discharge. Secondly, RF voltages can be coupled through any kind of impedance so that the electrodes need not be conductors.
- So, it is possible to sputter any material irrespective of its resistivity. Typical RF frequencies employed is 13.56 MHz that has been reserved for plasma processing by the Federal Communications Commission.
- In RF sputtering the target self-biases to a negative potential and positive ion bombardment sputters away atoms for subsequent deposition. As, the target is capacitively coupled to the RF generator, metals as well as insulators can be deposited.



## DC Sputtering

- The deposition rate depends on the pressure and DC voltage.
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- Mean free path of the detached atoms, $\lambda \propto \frac{1}{pressure}$
- As the pressure is increased at a fixed voltage, the mean free path is decreased, more ions are generated. But if the pressure is too high, the sputtered atoms undergo increased collisional scattering and are not efficiently deposited.
- The optimum condition is shaded in the graph shown. This range of pressure is suitable for DC sputtering.
- In general, the deposition rate is proportional to the power consumed, and inversely dependent on the electrode spacing.

Now, from DC sputtering if I want to go to RF sputtering, then the RF sputtering helps to deposit insulating thin films, in DC sputtering there is a difficulty of depositing the insulators but in RF you can very easily do that. So, films like silicon nitride, silicon dioxide you can use RF sputtering.

In RF sputtering the so there, what kind of insulating film? The insulating film where the resistivity is greater than $10^6$ ohms centimeter that you already know how resistivity is calculated:

$R = (\rho l)/A$

$\rho = (RA)/l$

;and you put the units you have rho equals to ohms centimeter right that is the unit of the resistivity which is given here.

So, now, RF frequency that means, an AC signal above 50 kilo hertz electron oscillating in the glow region acquired enough energy to cause ionizing collisions reducing the need for secondary electrons to sustain the discharge. Secondly, the RF voltage can be coupled through any kind of impedance the electrodes need not to be their conductors. So, this is advantage because, as you know this that the RF voltages can coupled through any kind of the impedance.

So, it is possible to sputter any material irrespective of its resistivity if you want to do sputter metals, you can go for DC sputtering, if you want to go for insulators, it is better to have RF because the RF voltages can be coupled through any kind of insulating material particularly any kind of impedance. So, typical RF frequency employed is about 13.56 MHz, that has been reserved for plasma processing by FCC and in RF sputtering the targets self-biases to negative potential and positive ion bombardment sputters away atoms for subsequent deposition.

As you can see, here is a substrate and substrate is generally the temperature cooled, there is the effect of temperature cooling and temperature heating, okay, heating the substrate as advantage cooling as an advantage. So, depending again on what kind of application you are looking at, because certain times you heat the substrate at certain temperature, you will have a better polycrystalline films.

But for now, just understand that this target is cooled at a certain temperature, it is kept cold is a certain temperature and as a target is capacitively coupled to the RF generator, metal as well as insulators can be easily deposited. So, that is the advantage of using RF frequencies sputtering or RF sputtering.

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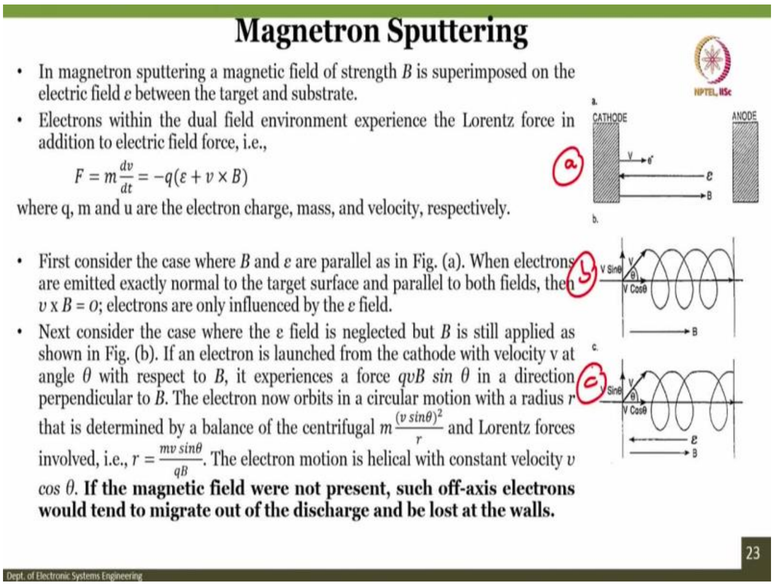


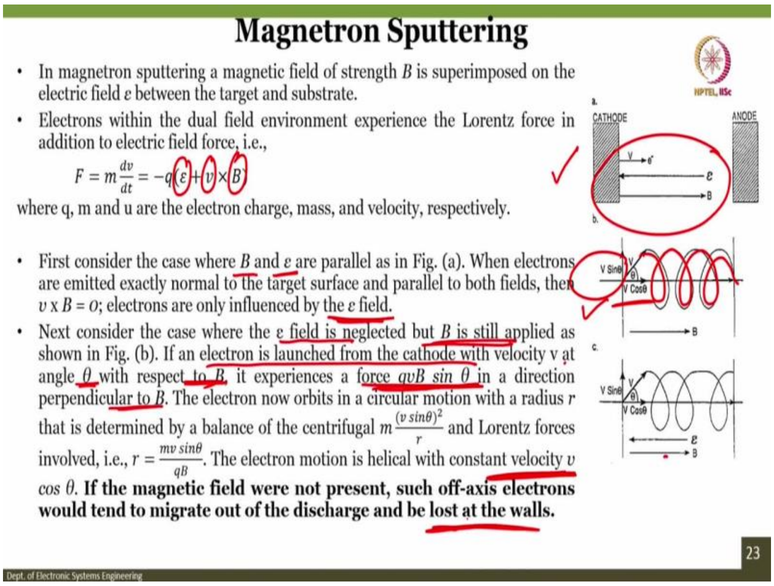
## Magnetron Sputtering

- In magnetron sputtering a magnetic field of strength $B$ is superimposed on the electric field $\varepsilon$ between the target and substrate.
- Electrons within the dual field environment experience the Lorentz force in addition to electric field force, i.e.,

$$F = m\frac{dv}{dt} = -q(\varepsilon + v \times B)$$

where q, m and u are the electron charge, mass, and velocity, respectively.

- First consider the case where $B$ and $\varepsilon$ are parallel as in Fig. (a). When electrons are emitted exactly normal to the target surface and parallel to both fields, then $v \times B = 0$; electrons are only influenced by the $\varepsilon$ field.
- Next consider the case where the $\varepsilon$ field is neglected but $B$ is still applied as shown in Fig. (b). If an electron is launched from the cathode with velocity v at angle $\theta$ with respect to $B$, it experiences a force $qvB \sin \theta$ in a direction perpendicular to $B$. The electron now orbits in a circular motion with a radius $r$ that is determined by a balance of the centrifugal $m\frac{(v \sin\theta)^2}{r}$ and Lorentz forces involved, i.e., $r = \frac{mv \sin\theta}{qB}$. The electron motion is helical with constant velocity $v \cos \theta$. **If the magnetic field were not present, such off-axis electrons would tend to migrate out of the discharge and be lost at the walls.**



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Now, what happens if you want to improve the rate of deposition and also the if we add the magnet what will happen. So there is something called magnetron sputtering and in magnetron sputtering a magnetic field of strength B is superimposed on the electric field E between target and substrate right between anode and cathode that magnetic field B is superimposed on the electric field E.

So if that happens, what will occur? The electrons with a dual field environment experiences Lorentz force and we all know how the Lorentz force is given right in addition to the equal electric field force. So, when we say that:

$F = m. (dv/dt) = -q \varepsilon + v \times B$

;where q, m and v are the electron charge mass and velocity respectively. So, this is how the effect of a super imposing the magnetic or electric field will be there on the electrons, but let us take an example so, it is becomes more easier.

You have three cases a, here, b, and c first we will talk about a followed by b and c. So, you see here let us consider the case where B and electric field so, magnetic field and electric field are parallel as in figure a like here. Now, what will happen? When the electrons are emitted exactly normal to the target, exactly normal to the target and parallel to both the fields like in this case then

$v \times B$

So, electric field here electric field velocity magnetic field right.

So, we have v into B is 0, electrons are only influenced by the electric field correct, when this this is the case, but, if you consider the next case, which is figure B where the electric field is neglected, but magnetic field is still applied as shown in figure b in that case what will happen the electron is launched from the cathode with a velocity v to the velocity v at an angle of θ with respect to B and in the experiences force q v B sine θ, in a direction perpendicular to B, is not it correct?

So, we will have this force that is experienced by the electron and the electron orbits in a circular motion with the radius r, that is determined by balance of centrifugal

$[m \times (v \text{ sine } \theta)^2]/r$

and Lorentz forces involved:

$r = (mv \text{ sine } \theta)/(qB)$.

The electron motion is helical with a constant velocity v. So, instead of going straight now, it will be like in this form the electron will move further.

So, if the then that will be constant with what, with the velocity v cos theta, is not it? So, the when the electron motion is helical with the constant velocity v cos theta because now we are considering only magnetic field to be present and electric field to be absent. So, if the magnetic field were not present such off axis electrons would tend to migrate out of the discharge and will be lost at the walls right so, that is a reason of having this.

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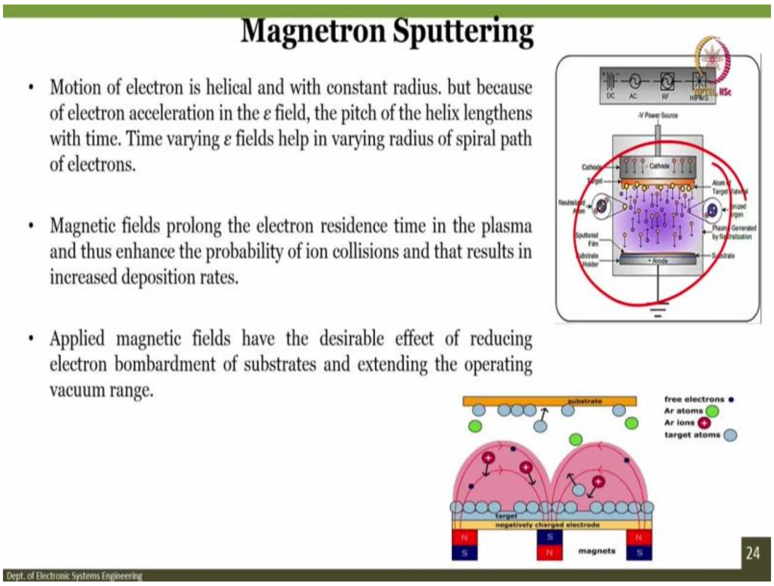
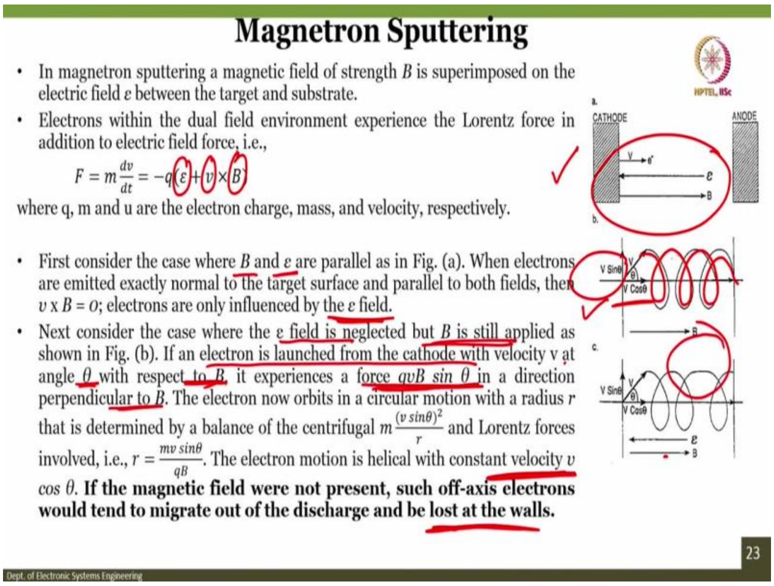


## Magnetron Sputtering

- Motion of electron is helical and with constant radius. but because of electron acceleration in the $\varepsilon$ field, the pitch of the helix lengthens with time. Time varying $\varepsilon$ fields help in varying radius of spiral path of electrons.
- Magnetic fields prolong the electron residence time in the plasma and thus enhance the probability of ion collisions and that results in increased deposition rates.
- Applied magnetic fields have the desirable effect of reducing electron bombardment of substrates and extending the operating vacuum range.



## Magnetron Sputtering

- In magnetron sputtering a magnetic field of strength $B$ is superimposed on the electric field $\varepsilon$ between the target and substrate.
- Electrons within the dual field environment experience the Lorentz force in addition to electric field force, i.e.,

$$F = m\frac{dv}{dt} = -q(\varepsilon + v \times B)$$

where q, m and u are the electron charge, mass, and velocity, respectively.

- First consider the case where $B$ and $\varepsilon$ are parallel as in Fig. (a). When electrons are emitted exactly normal to the target surface and parallel to both fields, then $v \times B = 0$; electrons are only influenced by the $\varepsilon$ field.
- Next consider the case where the $\varepsilon$ field is neglected but $B$ is still applied as shown in Fig. (b). If an electron is launched from the cathode with velocity v at angle $\theta$ with respect to $B$, it experiences a force $qvB \sin\theta$ in a direction perpendicular to $B$. The electron now orbits in a circular motion with a radius $r$ that is determined by a balance of the centrifugal $m\frac{(v \sin\theta)^2}{r}$ and Lorentz forces involved, i.e., $r = \frac{mv \sin\theta}{qB}$. The electron motion is helical with constant velocity $v \cos\theta$. **If the magnetic field were not present, such off-axis electrons would tend to migrate out of the discharge and be lost at the walls.**

Now, going further the motion of electrons is helical with a constant radius, but because of electron acceleration in the E field that is electric field the pitch of helix lengthens with time, so, time varying electric fields helps in varying the radius of spiral electrons. So, if you have time varying electric field, then you can change the radius of the helix and the length and the length of the helix can also be changed. If you have the time varying electric field.

So the magnetic fields prolong the electron residence time in plasma. So, there is a advantage one is that you can increase the pitch of the helix lengths by what we call vth time right the expression of electric field, but you can also kind of control it by time varying electric fields but the advantage of magnet here is that the electron residence time would increase in the plasma if that occurs that means, the probability of ion collisions will increase and in that results in increased deposition rate, that is advantage.

So, if the electron presents more time in this plasma, then more collisions would occur and collisions to the target which will result in born bombardment resulting in a higher deposition rate. So, applying in a magnetic field have the desirable effect of reducing electron bombardment of the substrate and extending the operating vacuum range thus when you want to increase the rate of deposition you can go for magnetron sputtering.

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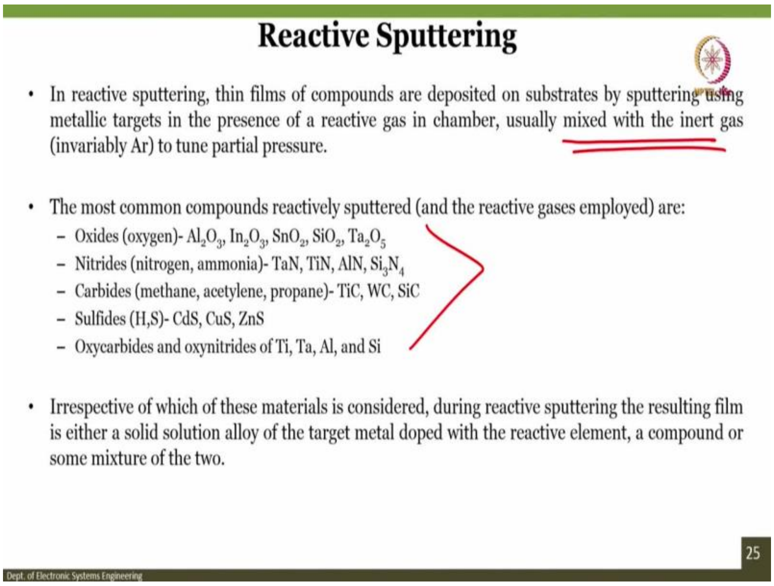

## Reactive Sputtering

- In reactive sputtering, thin films of compounds are deposited on substrates by sputtering using metallic targets in the presence of a reactive gas in chamber, usually mixed with the inert gas (invariably Ar) to tune partial pressure.
- The most common compounds reactively sputtered (and the reactive gases employed) are:
  - Oxides (oxygen)- $Al_2O_3$, $In_2O_3$, $SnO_2$, $SiO_2$, $Ta_2O_5$
  - Nitrides (nitrogen, ammonia)- TaN, TiN, AlN, $Si_3N_4$
  - Carbides (methane, acetylene, propane)- TiC, WC, SiC
  - Sulfides ($H_2S$)- CdS, CuS, ZnS
  - Oxycarbides and oxynitrides of Ti, Ta, Al, and Si
- Irrespective of which of these materials is considered, during reactive sputtering the resulting film is either a solid solution alloy of the target metal doped with the reactive element, a compound or some mixture of the two.

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Now, let us come to the last one which is that reactive sputtering and in reactive sputtering thin films of compounds are deposited on the substrate by sputtering using metallic targets in the presence of reactive gas in chamber. Usually mixed with the inert gas invariably the Argon to tune the partial pressure.

So, the most common compounds reactively sputtered are oxides in presence of oxygen, nitrides, nitrogen and ammonia, carbides, methane, acetylene, propane, sulfides, oxycarbides and oxynitrides. So, there are several materials which we can deposit which can we can deposit with the help of reactive sputtering.

Irrespective of which of these materials is considered during reactive sputtering the resulting film is either solid solution alloy of the target metal doped with reactive element a compound or some mixture of two. So, that is how the reactive sputtering is used.

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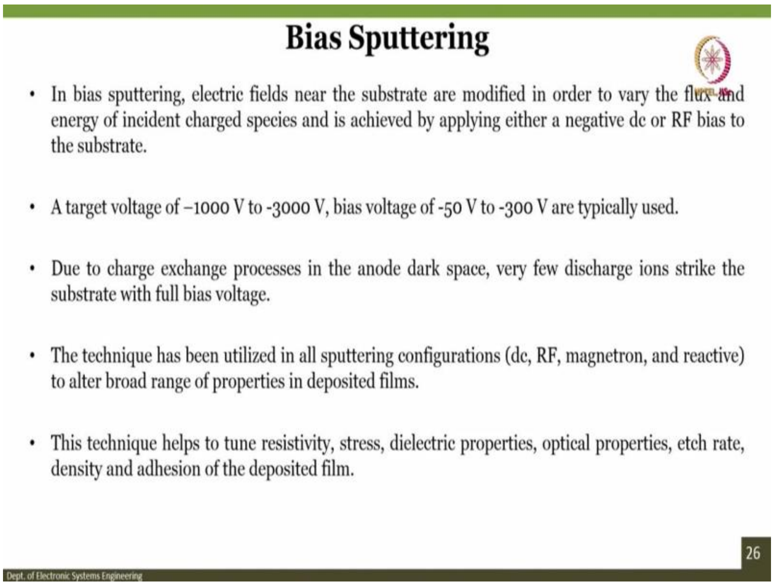

## Bias Sputtering

- In bias sputtering, electric fields near the substrate are modified in order to vary the flux and energy of incident charged species and is achieved by applying either a negative dc or RF bias to the substrate.
- A target voltage of –1000 V to -3000 V, bias voltage of -50 V to -300 V are typically used.
- Due to charge exchange processes in the anode dark space, very few discharge ions strike the substrate with full bias voltage.
- The technique has been utilized in all sputtering configurations (dc, RF, magnetron, and reactive) to alter broad range of properties in deposited films.
- This technique helps to tune resistivity, stress, dielectric properties, optical properties, etch rate, density and adhesion of the deposited film.

Now, we if we apply a bias, in the bias sputtering the electric field near the substrates are modified in order to vary the flux and energy of incident charged species and this is achieved by applying either negative DC or RF bias to the substrate. So, if you keep the target voltage around minus 1000 to -3000 volts and bias voltage about -50 to -100 volts then you can have a better sputtering and due the exchange, charge exchange processes in anode dark space, very few discharge ions strike the substrate with full bias voltage the technique has been utilized in all sputtering configuration whether it is DC, RF, magnetron and reactive to alter broad range of properties in the deposited film.

By changing this bias voltage you can have properties of the film changed and again when we go for the material characterization, the material science you need to change the properties of the film and that could be changed by the effect of the bias that technique further helps to tune resistivity, stress, dielectric properties, optical properties, etch rate, density adhesion of the deposited film, so, just not only the deposition, but also how to change the properties of the material whether it is a dielectric property or is an optical property or whether it is improving the etch rate or increasing the resistivity all these can be tuned with the help of these parameters. So, there is an advantage of bias sputtering.

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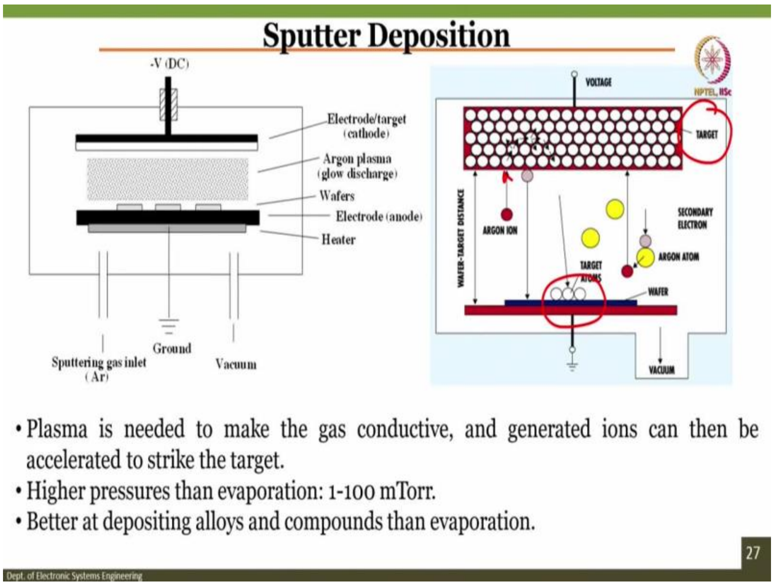

## Sputter Deposition

- Plasma is needed to make the gas conductive, and generated ions can then be accelerated to strike the target.
- Higher pressures than evaporation: 1-100 mTorr.
- Better at depositing alloys and compounds than evaporation.

As you see in the slide, this is more clear image of how the plasma is there to make the gas conductive and generated ions can then be accelerated to strike the target you can see here the target is here and the Argon ions are bombarding and the target terms are dislodging and then forming the film on the substrate.

So, higher pressures than evaporation about one 1 to 100 milli Torr, better at depositing alloys and compounds than evaporation, in evaporation you can still deposit the alloy, but sputtering is better compared to the evaporation techniques.

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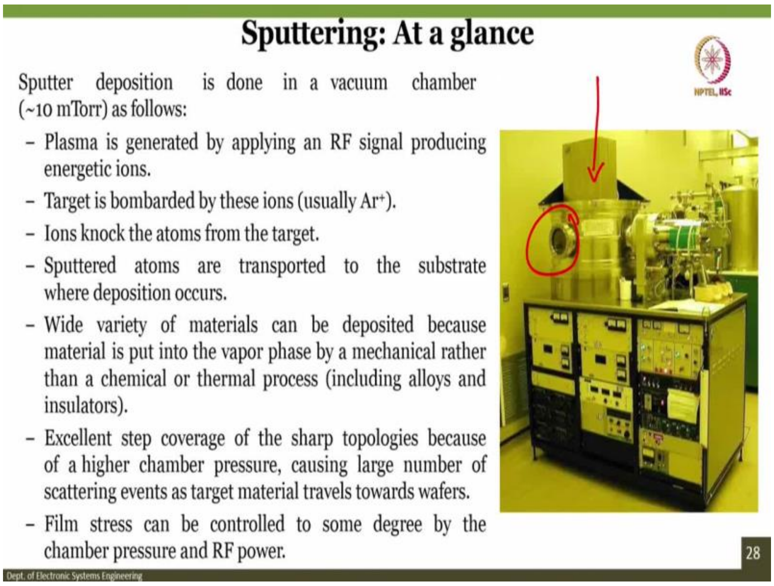
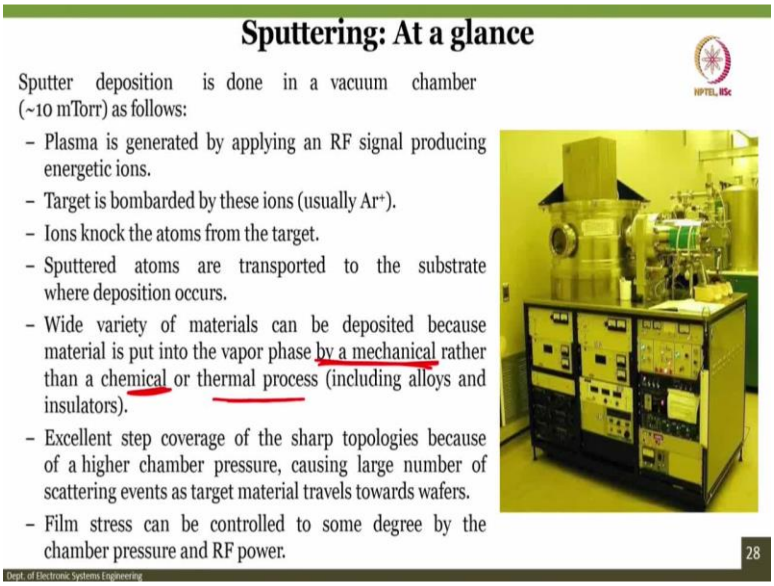


## Sputtering: At a glance

Sputter deposition is done in a vacuum chamber (~10 mTorr) as follows:

- Plasma is generated by applying an RF signal producing energetic ions.
- Target is bombarded by these ions (usually $Ar^+$).
- Ions knock the atoms from the target.
- Sputtered atoms are transported to the substrate where deposition occurs.
- Wide variety of materials can be deposited because material is put into the vapor phase by a mechanical rather than a chemical or thermal process (including alloys and insulators).
- Excellent step coverage of the sharp topologies because of a higher chamber pressure, causing large number of scattering events as target material travels towards wafers.
- Film stress can be controlled to some degree by the chamber pressure and RF power.



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Now, if you see the schematic sputtering system looks much more complicated. We will show you the actual spring system that we have in the lab and how you can sputter the material. Again you have window to look at this sputtering source and target board you can see through same window depending again on the type of sputtering unit that you buy. And this is done generally in the vacuum chamber about 10 mili Torr. The plasma is generated by applying RF signal producing energy energetic ions, if it is RF sputtering and usually the target is bombarded by this ion that is with argon ions, argon is a gas that is used in sputtering the ion knocks the atom from the target and sputtered atoms are transported to the substrate.

We were talking these things many many times right so that we do not forget that this is the mechanism by which the sputtering can be used, wide variety of materials can be deposited, because the material is put into vapor phase by mechanical rather than this is extremely important. Sputtering is a mechanical way of depositing film rather than chemical or thermal, it is not part of chemical vapor deposition, neither it is part of thermal evaporation because in thermal evaporation, we were melting it and then we were depositing it, in sputtering we are not doing that same. So that is the reason then it is called a mechanical way of depositing the film.

Excellent step coverage is an advantage of the sharp topologies because of a higher chamber pressure, causing larger number of scattering events, film stress can be controlled to some degree by chamber pressure and RF power. So the stress can be also controlled by using these parameters.

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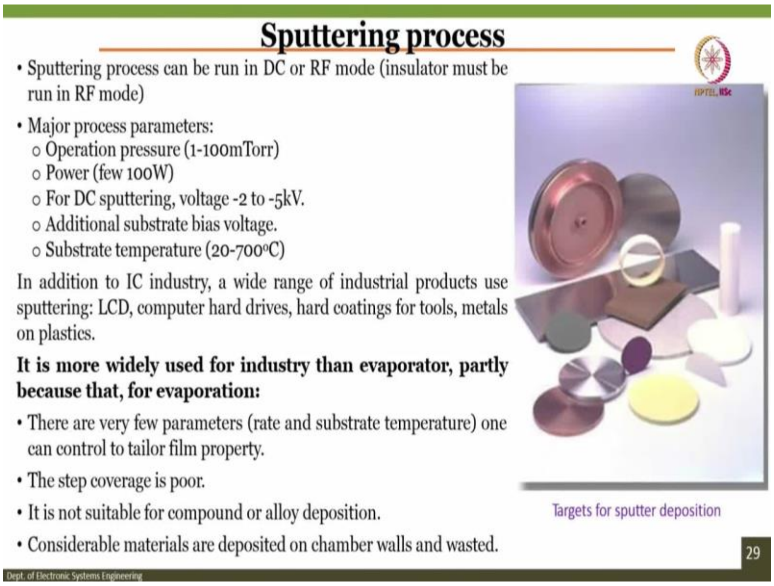

## Sputtering process

- Sputtering process can be run in DC or RF mode (insulator must be run in RF mode)
- Major process parameters:
  - Operation pressure (1-100mTorr)
  - Power (few 100W)
  - For DC sputtering, voltage -2 to -5kV.
  - Additional substrate bias voltage.
  - Substrate temperature (20-700$^0$C)

In addition to IC industry, a wide range of industrial products use sputtering: LCD, computer hard drives, hard coatings for tools, metals on plastics.

**It is more widely used for industry than evaporator, partly because that, for evaporation:**

- There are very few parameters (rate and substrate temperature) one can control to tailor film property.
- The step coverage is poor.
- It is not suitable for compound or alloy deposition.
- Considerable materials are deposited on chamber walls and wasted.

Targets for sputter deposition

So, if you want to see in a glance by this sputtering process, then sputtering process can be run in DC or RF mode, the insulator must be done in RF mode is important. Then what is the second thing the major parameter process or process parameters are one operational pressure 1 to 100 milli Torr. Second the power it should be fewer than 100 Watts, we can also change the power actually in sputtering from 100 to 200 to 300 watts.

And again depending on the power right the rate of deposition would change. As I told earlier, if you increase the power, the rate of deposition increases, if you increase the distance between source and target, the rate of deposition decreases, if you decrease the power rate of deposition decreases, if you decrease that source and target rate of deposition increases.

For DC sputtering the voltage is between -2 to -5 kilo volts additional substrate, bias voltage now, we can apply substrate temperature is about 20 to 700 degrees centigrade. That is why sometimes you have to cool this substrate. In addition to ice industry a wide range of industrial products use sputtering. For example, for LCD, it give a display computer hard drives, hard coatings for tools, metals and plastics. All this uses the sputter films. It is more widely used by industry than evaporator partially because that for evaporation, there are very few parameters rate and substrate temperature, one can control to tailor film properties.

Sputtering has the advantage that we can tailor the film properties as I have, as we have seen in the previous slide, the step coverage is poor for the thermal evaporation, it is better for sputtering, it is not suitable for compound or alloy, thermal evaporation is not suitable while sputtering is just thermal not only thermal, but e-beam also thermal when we say evaporation thermal and e-beam both are considered as an evaporation techniques.

Considerable materials are deposited on chamber walls and wasted in case of e-beam and thermal or in case of sputtering the wastage is comparatively lower.

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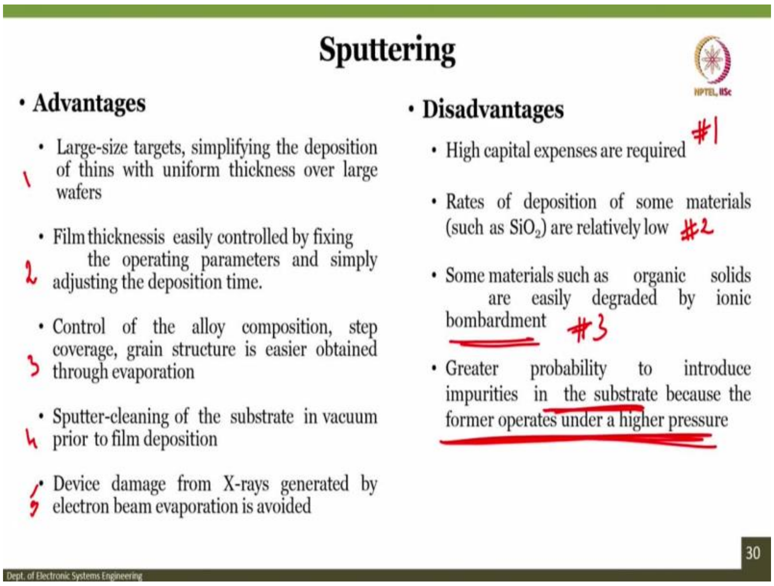

## Sputtering

- **Advantages**
  - 1 Large-size targets, simplifying the deposition of thins with uniform thickness over large wafers
  - 2 Film thicknessis easily controlled by fixing the operating parameters and simply adjusting the deposition time.
  - 3 Control of the alloy composition, step coverage, grain structure is easier obtained through evaporation
  - 4 Sputter-cleaning of the substrate in vacuum prior to film deposition
  - 5 Device damage from X-rays generated by electron beam evaporation is avoided
- **Disadvantages**
  - High capital expenses are required #1
  - Rates of deposition of some materials (such as $SiO_2$) are relatively low #2
  - Some materials such as organic solids are easily degraded by ionic bombardment #3
  - Greater probability to introduce impurities in the substrate because the former operates under a higher pressure

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So, now if you want to compare sputtering itself, by advantages and disadvantages or advantages and limitations, what are advantages? First let us go to advantages larger size targets, simplifying the deposition of thins with uniform thickness over large wafers that is first advantage, advantage 1.

Then second is film thickness can be easily controlled by fixing the operating parameters and simply adjusting the deposition rate. So, parameter advantage number 2, control of the alloy composition, step coverage, gain structure is easier so, that is step number 3. Sputter cleaning of the substrate in vacuum prior to film deposition is possible that is a very big advantage because then none of the materials that was present earlier, will still be there, we can just clean the chamber and before we start a new deposition.

So, the advantage number 4 finally the device damaged from X ray generated by electron beam evaporation is avoided. This is very important again because e-beam will cause the X rays to generate which will actually deteriorate the film. So, compared to e-beam, sputtering is better in this area, but then what are the disadvantages.

The first one is the high capital expense. So, first one is high capital expense, second rate of deposition some material is extremely low like silicon dioxide where we use RF for insulating materials. Some materials such as organic solids are easily degraded by ionic bombardment is important parameters.

Parameter number 3 right that there is a disadvantage and the last will be the greater probability to introduce impurities in the substrate because former operates under high pressure this is also very important thing that when we are using sputtering compared to the e-beam or thermal evaporation.

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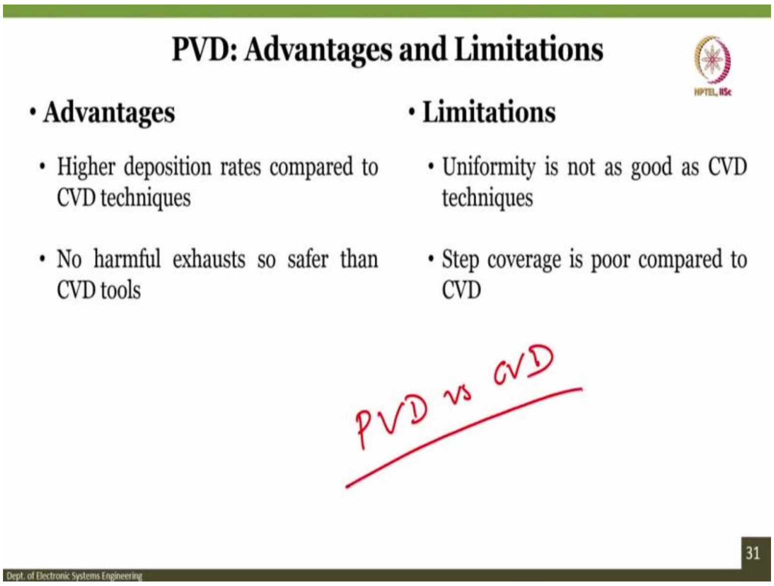

PVD: Advantages and Limitations

- Advantages
  - Higher deposition rates compared to CVD techniques
  - No harmful exhausts so safer than CVD tools
- Limitations
  - Uniformity is not as good as CVD techniques
  - Step coverage is poor compared to CVD

PVD vs CVD

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So, let us see the next slide so, if you want to have the PVD advantages and limitations, then the first advantage over CVD we are talking about PVD versus CVD now of course we are not seeing the CVD in detail we will see it in the next lecture for now, if you just quickly want to want to just you know understand advantages and limitation than higher deposition rates compared to CVD techniques, no harmful exhaust so safer than CVD tools.

In CVD the byproducts are some harmful gases which has to be treated before you send to the exhaust. When the limitation is that uniformity is not good as CVD, CVD has an excellent uniformity, a beautiful step coverage. But the step coverage is poor compared to CVD. CVD has a better step coverage compared to the PVD that is what I said that uniformity is better and step coverage is better in case of CVD.

However, the higher deposition rates is advantage of PVD and no harmful gases advantage of the PVD techniques.

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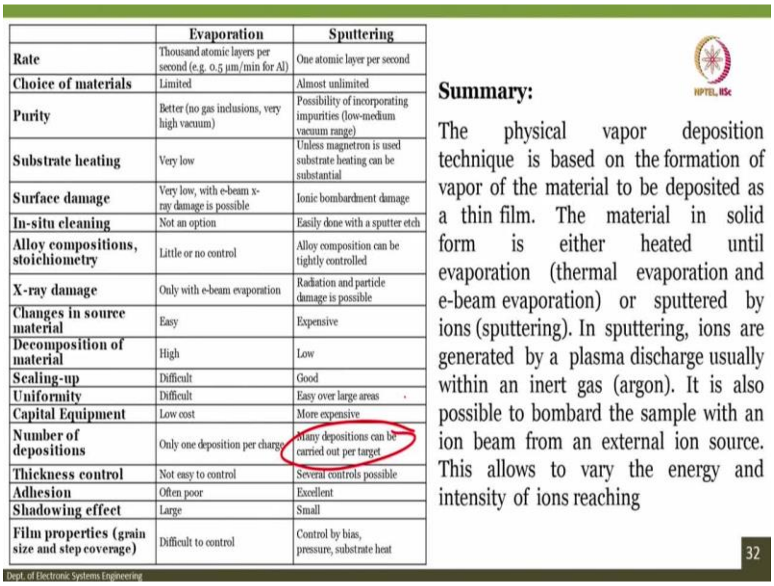
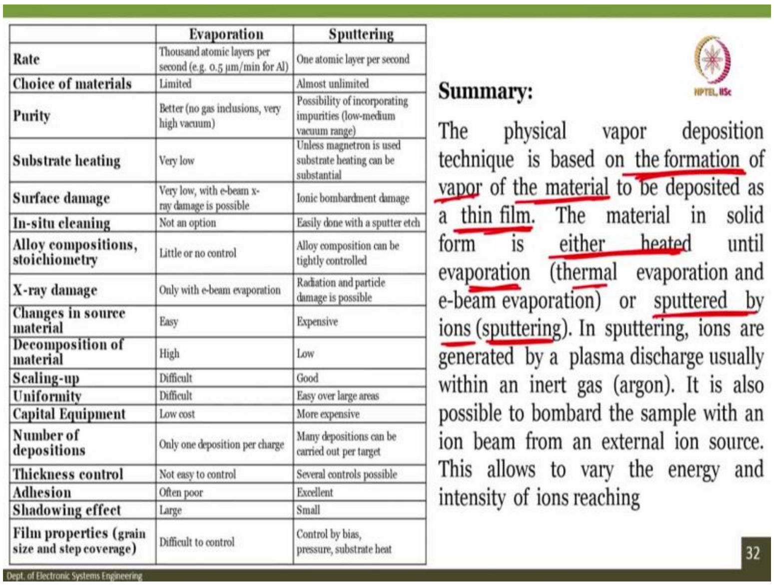


| | Evaporation | Sputtering |
|---|---|---|
| **Rate** | Thousand atomic layers per second (e.g. 0.5 μm/min for Al) | One atomic layer per second |
| **Choice of materials** | Limited | Almost unlimited |
| **Purity** | Better (no gas inclusions, very high vacuum) | Possibility of incorporating impurities (low-medium vacuum range) |
| **Substrate heating** | Very low | Unless magnetron is used substrate heating can be substantial |
| **Surface damage** | Very low, with e-beam x-ray damage is possible | Ionic bombardment damage |
| **In-situ cleaning** | Not an option | Easily done with a sputter etch |
| **Alloy compositions, stoichiometry** | Little or no control | Alloy composition can be tightly controlled |
| **X-ray damage** | Only with e-beam evaporation | Radiation and particle damage is possible |
| **Changes in source material** | Easy | Expensive |
| **Decomposition of material** | High | Low |
| **Scaling-up** | Difficult | Good |
| **Uniformity** | Difficult | Easy over large areas |
| **Capital Equipment** | Low cost | More expensive |
| **Number of depositions** | Only one deposition per charge | Many depositions can be carried out per target |
| **Thickness control** | Not easy to control | Several controls possible |
| **Adhesion** | Often poor | Excellent |
| **Shadowing effect** | Large | Small |
| **Film properties (grain size and step coverage)** | Difficult to control | Control by bias, pressure, substrate heat |

**Summary:**

The physical vapor deposition technique is based on the formation of vapor of the material to be deposited as a thin film. The material in solid form is either heated until evaporation (thermal evaporation and e-beam evaporation) or sputtered by ions (sputtering). In sputtering, ions are generated by a plasma discharge usually within an inert gas (argon). It is also possible to bombard the sample with an ion beam from an external ion source. This allows to vary the energy and intensity of ions reaching



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So, in a way if you want to see the last slide and understand how we can compare two different techniques, evaporation and sputtering and then we will see the summary of it. So first is if you want to compare the rate, rate at which the film is deposited or film is formed. So the atomic, thousands atomic layers per second 0.5 micron per minute it is super fast right? And it is one atomic layer per second, the quality is better this is faster. Second one is choice of materials. So, in evaporation we have limited but in sputtering almost unlimited we can sputter almost every material, thermal is a purity, right there is a better because no gas inclusions very high vacuum. But in the case of sputtering the vacuum is low or medium range and that is why the purity may not be as good as the evaporation.

Substrate heating, it is very low unless magnetron is used substrate heating can be substantial if magnetron is used substrate heating will be comparatively lower. Surface damage, there is a surface damage in the case of e-beam because of the generation of X ray here the ion bombardment may damage the surface otherwise, there is no generation of X ray.

In situ cleaning it is not possible in case of evaporation, but in case of sputtering you can clean the chamber by sputtering with the sputtering itself. So, that can be done. Next one is a alloy compositions and stoichiometry. So, there is little or no control because it is so fast the atoms will not have time to rearrange itself. While in case of sputtering alloy composition can be tightly controlled.

The next one is X ray damage like I said only with e-beam evaporation X rays are generated, but radiation and particle damage is possible. However, X ray is not really an issue, because it is not generated in sputtering. Also, the radiation and particle damage may be one of the issues but really not from the X ray that is generated in case of E Beam.

Changes in source material it is easy for evaporation you just had a load under material in case of sputtering it is a disk say to change the disk with a new disk of that particular source, the scaling up of the system the operation is very difficult, now is comparatively easier. While for sputtering it is low. I am sorry. So, when we talk about scaling up means to have bigger substrate and other things right for sputtering it is really good, but in case of the evaporation it is very difficult okay to scale up the system.

When it comes to uniformity, again the evaporation system is difficult, while the uniformity of the film in case of sputtering will be better, because this sputtering is a mechanical way of depositing the atoms on to the target by dislodging the atoms using the ions and these ions are from the argon.

So, the capital uniformity we talked about capital equipment cost is a cost of evaporation is lower compared to sputtering, number of depositions, you can have only one depositions per charge, you can have many depositions can be carried out per target. There is another thing that you need to understand because once you use the material, you have to use an X material in case of evaporation only one depositions is used here there is a disk. So, you can use multiple depositions whatever material you use, you can keep on using the same disk for a longer time.

Thickness control is not so easy several controls are possible in case of sputtering not so easy in case of evaporation, adhesion is often poor while in sputtering it is really good, the shadowing effect is large while it in this case, of sputtering is small, but if you compare CVD compared to the PVD, then the shadowing effect is also comparatively poor and the uniformity is larger. The step coverage is better in CVD compared to PVD but the step coverage of this sputtering system is better than the evaporation system.

Finally, when comes to film properties like grain size and step coverage, difficult to control you can control by bias pressure and substrate heat in case of the sputtering. So, if you want to summarize about the physical vapor deposition, then we can summarize in this particular paragraph that the physical vapor deposition technique is based on the formation of vapor of the material to be deposited as a thin film. The material in solid form is either heated until evaporation thermal evaporation or e-beam or sputtered by ions, which is called we call sputtering.

In sputtering seems to be like a raindrop on the metal roof. If you ever heard the raindrops falling on the metal roof, that is how this sputtering sounds like that is called sputter. In sputtering we have the ions are generated by the plasma discharges usually with an inert gas that is argon. And it is also possible to bombard the sample with an ion beam from an external ion source. This allows to vary the energy and intensity of ions reaching that particular material.

So, the advantages of the sputtering are there over thermal evaporation and e-beam evaporation. However, when we talk in general about PVD versus CVD, the CVD has a better step coverage compared to sputtering, CVD is more uniform compared to sputtering, sputtering and e-beam evaporation and thermal evaporation are faster, right there are no residual gasses. In CVD there are residual gases.

So, the next part of what we need to understand is how and when we can use chemical vapor deposition and why we should use it. So, the next set of lectures will consist of chemical vapor deposition, whether it is LPCVD or it is atmospheric pressure CVD or it is plasma enhanced chemical evaporation and where exactly we can use, so, there is a P CVD where we can grow or we can deposit with the chemicals, silicon dioxide, but the quality of that silicon dioxide is it as good as the thermal oxidation and where exactly if the quality is not good, we can use P CVD instead of thermal oxidation was an advantage of P CVD or thermal oxidation.

So, these all things are very important, why it is important, because when we are going to fabricate a device, you should insulate certain material you know for example, there is a metal layer you to insulate with some silicon dioxide, silicon nitride insulator then you had to use low temperature method to deposit this kind of insulating film, but thermal oxidation as we know is about 900 to 1100 degrees centigrade so, we cannot use it.

In case in that particular case what alternative methods are available. So, CVD will help us, will rescue us when we go for such kind of application we will see when we look at the device fabrication in detail. So, till then look into this particular lecture and understand this sputtering, a little bit about sputtering right again we are not going into depth because our idea is to understand the equipment, understand the techniques and then use it for fabrication and that also we are not there right fabrication and use it for implantation, but implantation in the brain and you collect the signals and you understand and you apply electrical stimulation and you further understand how the signals are generating and how it can be useful.

So, these are all the steps to go once one objective you can say among several interrelated objectives right to achieve our final goal of understanding how to acquire the signals from the brain, how to apply electrical stimulation to the brain. So, till then I will see you in the next class. Have a nice day, nice time from wherever you are attending this NPTEL course. Cheers.