Fundamentals of Micro and Nanofabrication

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Lecture - 47
Dry etch: Plasma etching basics

In this lecture on dry etch, we will look at plasma characteristics. So, in the earlier lecture, we discussed the nature of the plasma, its constituents, and how we generate and sustain the plasma. In this lecture, we look at the configuration that we normally use and how we supply energy to the plasma. Also, we look at how we use this plasma for etching, why we are interested in using the plasma process instead of the wet chemical process to define patterns.

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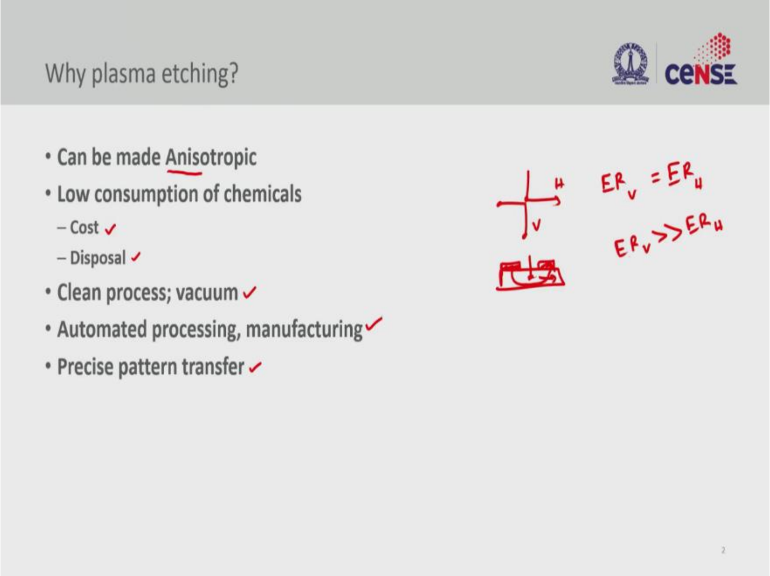

Why plasma etching?

- Can be made Anisotropic
- Low consumption of chemicals
  - – Cost ✓
  - – Disposal ✓
- Clean process; vacuum ✓
- Automated processing, manufacturing ✓
- Precise pattern transfer ✓

$ER_V = ER_H$

$ER_V >> ER_H$

So, let us look at why we need plasma etching. First of all, plasma etching can be anisotropic. We know that isotropic etch means equal etch in all the direction. i.e., both the horizontal and the vertical etch rates are the same. So, if a material covered with a photoresist is exposed to any wet chemical, we will get a profile like shown in the above slide. We will not get very smooth or very sharp sidewalls. In order to achieve sharp sidewalls, we need an anisotropic; directional etch. In an anisotropic etch, the vertical etch rate will be much larger than the horizontal etch rate and is achievable in a plasma etch process.

Secondly, the process happens in a closed chamber, so the consumption of chemicals can be controlled, resulting in cost reduction. Some of the chemicals are toxic. Using a closed chamber, we can prevent exposure to human beings. Also, controlled disposal of all these chemicals could be done.

It is a clean process because it happens inside the vacuum, and we can be assured of no contamination. It is also possible to automate the whole process, and hence, we can employ this in manufacturing. Other advantage is we can make anisotropic pattern, the pattern can have a very precise transfer as well.

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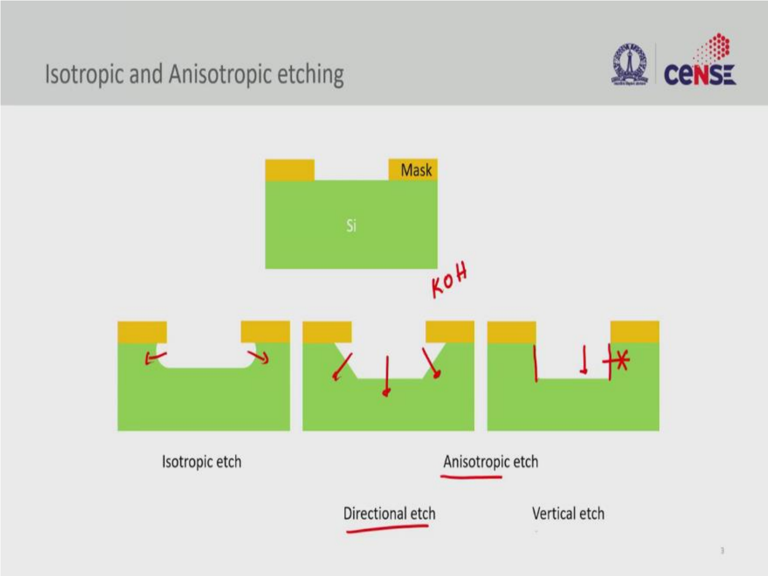

Isotropic and Anisotropic etching

So, we shall further look into isotropic and anisotropic etch. Let’s say, we have a mask and silicon underneath to be etched. In isotropic etch, there is an etch in the lateral direction in addition to the vertical direction. This is a result of equal etch in the vertical and horizontal direction. However, in an anisotropic etch, we have only the vertical etch. So, if we use chemical, such as potassium hydroxide, it etches silicon based on the crystal orientation. It is still a directional etch though we use wet chemical method. Because it etches more in some crystal plane, it is an anisotropic etch. Note that an anisotropic etch may not be vertical only.

So, when we talk about anisotropic etch, we have to be very clear about whether it is directional or vertical etch because directional may not be vertical only.

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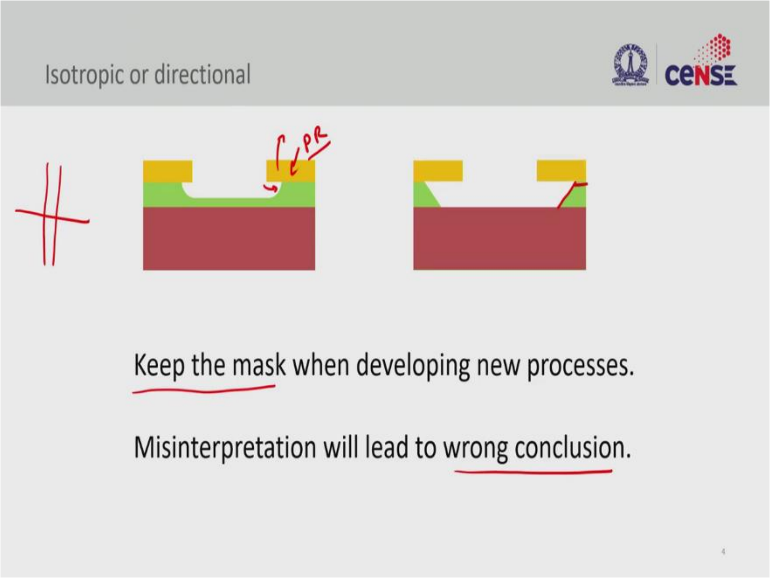

Isotropic or directional

Keep the mask when developing new processes.

Misinterpretation will lead to wrong conclusion.

We can know if the process is isotropic or directional. It can be done by retaining the photoresist during the process development and studying the cross-section. So, we have such a cross-section above in the slide. If the photoresist is removed, we will see an undercut, as shown by the red curve in the second diagram. This might seem like a directional etch. In fact, it is the isotropic etch, and the undercut is due to the material being over etched. It is clearly visible when we keep the photoresist intact. Any misinterpretation could lead to the wrong conclusion. So, when we are doing process development, we must extract maximum information from our experiments.

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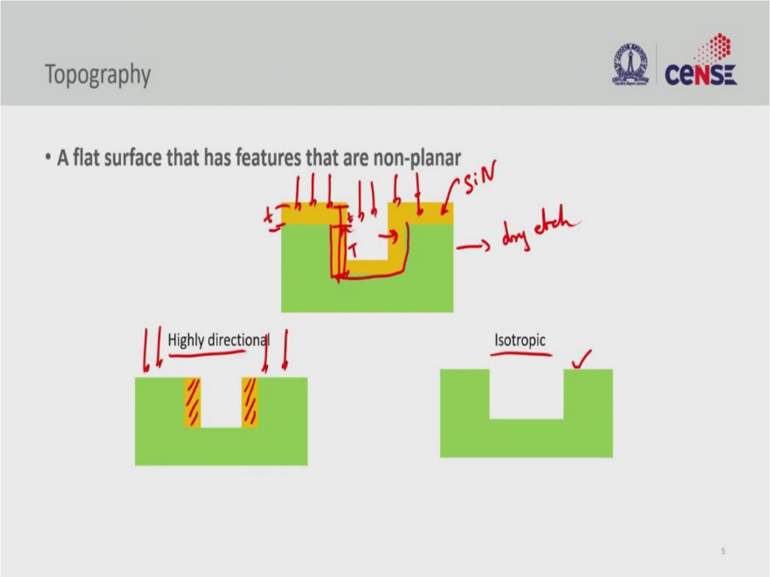

Topography

- A flat surface that has features that are non-planar

The next thing is about directionality again on a topography wafer. Topography is a surface with corrugation which is a non-planer. So, let's say we have a topography, above which we have filled some material. Let us say silicon nitride. When we perform dry etching on this, either directional etch or isotropic etch will be observed. So, if we etch isotropically on this wafer, we will remove all the nitride that is present vertically and laterally.

If we etch directionally, in this case vertically, we end up seeing the side walls assuming the ideal case that lateral etch is zero. So, we can fill or coat these sidewalls by using a highly directional etch. This process is used in spacer definition used in optical lithography for multi-layer patterning. Let us say we have a uniformly coated film of thickness t. The height of the trench would be $t + T$. While we etch the thickness t vertically and land on the substrate, we still have the remaining height left on the sidewall. So, this is how we have a sidewall coated film.

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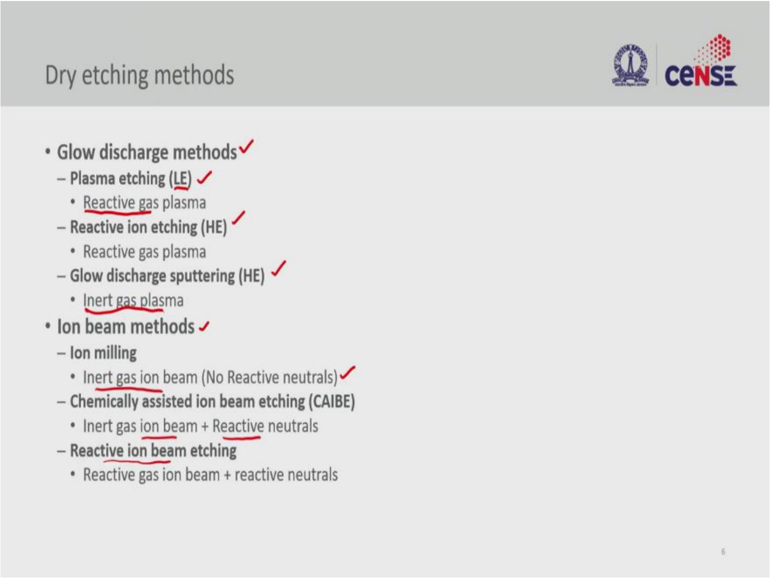

Dry etching methods

- Glow discharge methods ✓
  - Plasma etching (LE) ✓
    - Reactive gas plasma
  - Reactive ion etching (HE) ✓
    - Reactive gas plasma
  - Glow discharge sputtering (HE) ✓
    - Inert gas plasma
- Ion beam methods ✓
  - Ion milling
    - Inert gas ion beam (No Reactive neutrals) ✓
  - Chemically assisted ion beam etching (CAIBE)
    - Inert gas ion beam + Reactive neutrals
  - Reactive ion beam etching
    - Reactive gas ion beam + reactive neutrals

Various dry etching methods are broadly classified as glow discharge methods and ion beam methods. In glow discharge methods, we have plasma etching, a low energy process, while reactive ion etching, glow discharge sputtering are high energy processes.

So, in case of plasma etching and reactive ion etching, we use reactive gases, but sputtering uses inert gas. So, similar to the sputtering process used in the deposition technique, in glow discharge sputtering, inert gas is accelerated onto the substrate to sputter the material away, involving no chemical reaction. In the first two cases, the conversion of solid into gas happens through chemical reactions.

In ion beam methods, instead of having a discharge, we are using ion beams. So, an inert gas ion beam is focused towards the substrate resulting in the material removal. It is a physical process. It is going to kick out the material with force and no chemical reaction involved.

In chemically assisted ion beam etch, we have reactive neutrals in addition to the ion beam. So, physical etch uses only forces to remove the material, while chemical etch involves chemical reaction that gives out volatile products.

And in reactive ion beam etching, we create reactive ions and then direct those beams. This is another way of etching; instead of creating inert gas ions, the ions are reactive in this case. They can react and we also create reactive neutrals added to this to do the etching. These are all the broad classification of dry etching methods.

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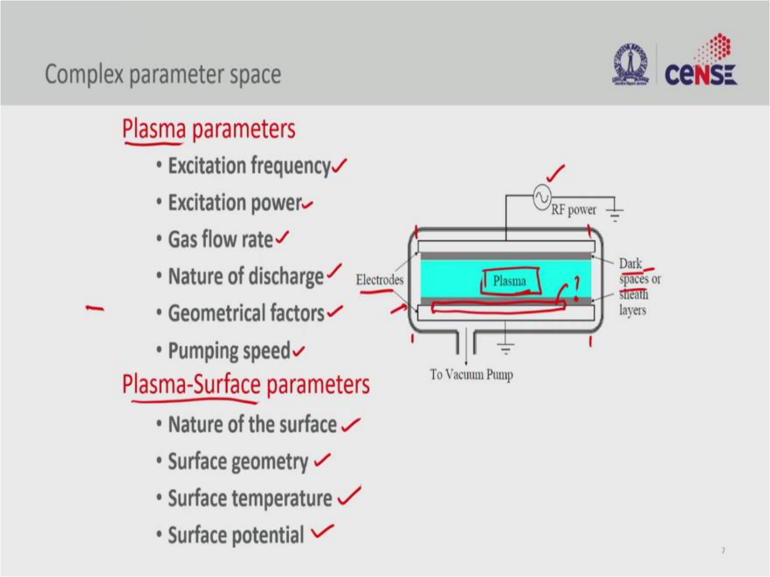

Complex parameter space

Plasma parameters

- Excitation frequency
- Excitation power
- Gas flow rate
- Nature of discharge
- Geometrical factors
- Pumping speed

Plasma-Surface parameters

- Nature of the surface
- Surface geometry
- Surface temperature
- Surface potential

In the above slide, there is a list of plasma parameters. On the right side, we see a parallel plate reactor having two electrodes, separated by a gap where plasma is created. There is a dark space on the top electrode and the bottom electrode, which we will see shortly why those things are coming in. Now, if we look at the plasma parameters, there is excitation frequency, which can be DC or RF. Then the excitation power; power that we are supplying. Gas flow rate is another important parameter because the plasma can only be generated if we have a sufficient number of molecules. The nature of discharge; the chemical and the electronic property of this gas are also important. Also, the geometrical factor like the size of the electrodes, the chamber wall all really matter. Finally, we have the pumping speed, which contributes to the determination of the pressure along with gas flow rate. These are the bulk plasma properties.

Along with bulk properties, the plasma to surface interactions are also important. The surface here is the wafer. Because when we keep a wafer in the chamber, it is not the bulk interaction that matters. The plasma should interact with this surface. It depends on the nature of the surface, whether the surface is conducting or insulating. It also depends on the surface geometry, whether it is a tiny piece or a very large wafer. Surface temperature is also a decisive factor. It is crucial to know whether the temperature is constant, whether the process is done at a lower temperature or a higher temperature because the surface reactions are affected by the temperature as well.

Lastly, we have the surface potential because we generate all the radicals in the plasma; we have ions, neutrals, and electrons. So, what is the potential at the wafer surface? It is essential because, based on the potential of the surface, we either attract or repel the species. Hence the surface potential affects the plasma surface interaction.

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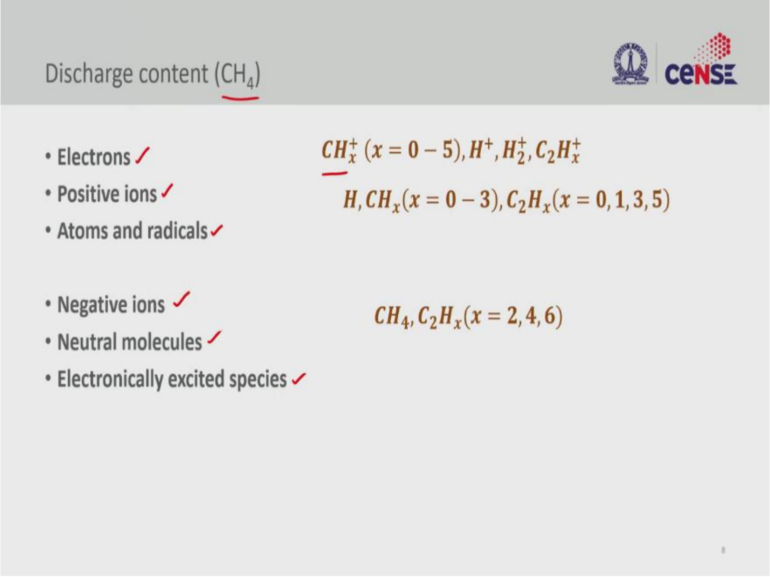

Discharge content (CH_4)

- Electrons ✓
- Positive ions ✓
- Atoms and radicals ✓

$CH_x^+ \ (x = 0 - 5), H^+, H_2^+, C_2H_x^+$

$H, CH_x (x = 0 - 3), C_2H_x (x = 0, 1, 3, 5)$

- Negative ions ✓
- Neutral molecules ✓
- Electronically excited species ✓

$CH_4, C_2H_x (x = 2, 4, 6)$

Let us look at the contents in the plasma discharge, both on the bulk and on the surface. We shall consider the example of methane, CH_4, plasma. So, we will generate positive ions, atoms and radicals, and lots of electrons. Since we are dissociating the precursor gas, we can have various combinations of CHx. We also have electro-negative ions, neutral molecules, and also excited states. So, as the molecule becomes complex, we will get all possible constituents in the plasma, which makes the plasma very rich and very complex to study as well.

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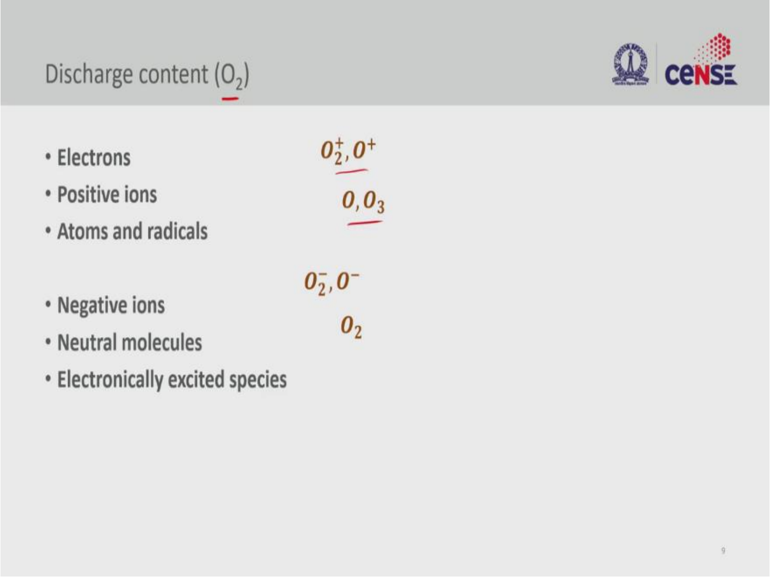

Discharge content (O_2)

- Electrons
- Positive ions O_2^+, O^+
- Atoms and radicals O, O_3
- Negative ions O_2^-, O^-
- Neutral molecules O_2
- Electronically excited species

Let us look at another type of gas here. We are taking a very simple molecule, oxygen, which has a limited number of combinations. So, this also gives us a better understanding of how we can study the discharge, and also in terms of controlling the chemistry. If the material as the molecule is very complex, it will have multiple dissociation components and hence, very hard to actually control. In this case, we are working with oxygen, it is pretty straightforward.

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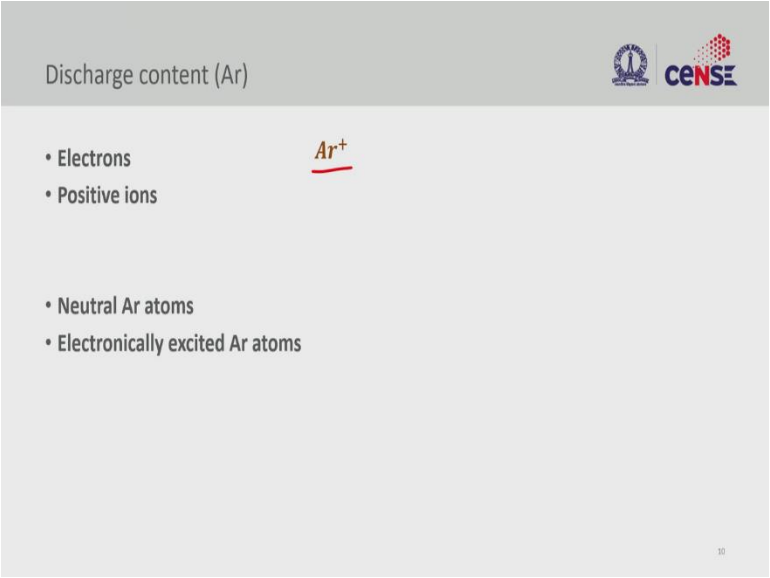

Discharge content (Ar)

- Electrons
- Positive ions

Ar^+

- Neutral Ar atoms
- Electronically excited Ar atoms

In case of argon, an inert gas, we get positive ions, electrons, and neutral argon atoms. So, that is the only possible constituents that we can generate using argon.

So, the idea here is that when the gas is very simple, it is easy to understand its plasma phase, but when the gas becomes more complex, then the chemistry also becomes very interesting. So, in some cases, we want the chemistry to be a little bit complex so that we have a handle on which paths to control and a possibility of controlling the different types of species.

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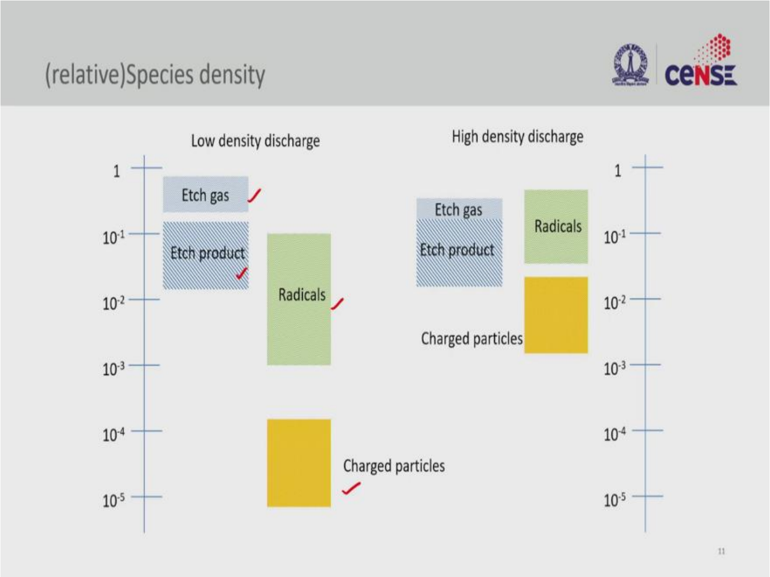

(relative)Species density

Now we look at the relative density of different species in both high and low-density discharge. We know that we have etch gases, etch products, radicals, and charged particles in the plasma discharge. In low-density discharge, the amount of charged particles is pretty low, while the radicals are high. However, in a high-density plasma discharge, all the compositions are pretty high. So, if we look at both the cases, we naturally gravitate towards high density because of the efficient conversion of etch gases in to radicals and charged particles. But in a low-density plasma, charged particle numbers are small. Because charged particles also include electrons that becomes very essential to create dissociation and participate in plasma sustenance. So, one can choose high density or low density based on the requirement of the process.

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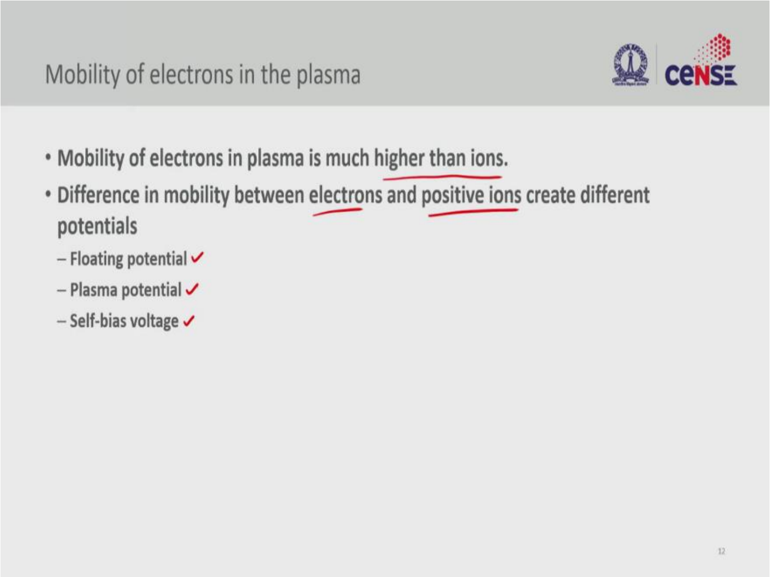

Mobility of electrons in the plasma

- Mobility of electrons in plasma is much higher than ions.
- Difference in mobility between electrons and positive ions create different potentials
  - Floating potential ✓
  - Plasma potential ✓
  - Self-bias voltage ✓

As we saw in the previous lecture, electrons are an important part of plasma, and electron mobility inside the plasma is crucial in plasma sustenance. Due to the difference in the mass between ions and electrons, electrons more quickly respond to the electric field than the ions. The difference in the mobility of electrons and ions gives rise to various potentials; to name them, we have floating potential, plasma potential, and self-bias voltage.

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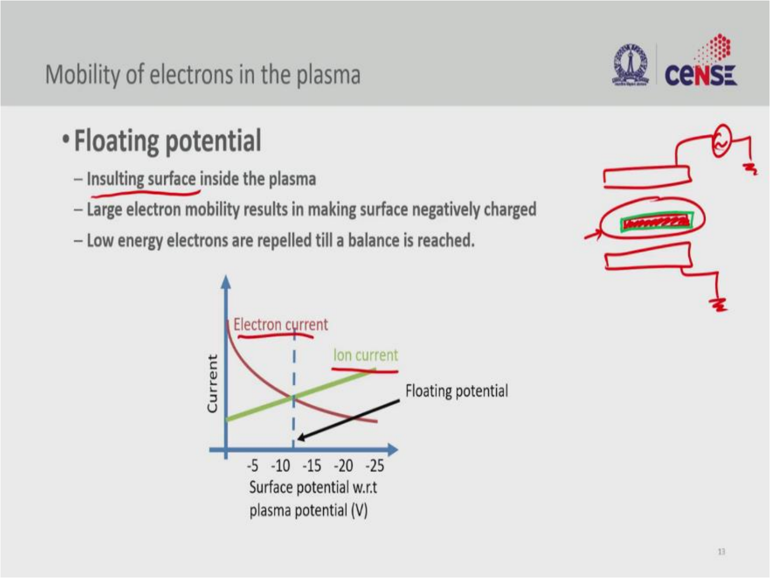

Mobility of electrons in the plasma

- Floating potential
  - Insulting surface inside the plasma
  - Large electron mobility results in making surface negatively charged
  - Low energy electrons are repelled till a balance is reached.

So, the first thing is floating potential. A floating potential is measured by inserting a highly insulating surface, like glass, inside the plasma. Note that the insulating surface is not grounded. Initially, a large number of electrons hit the surface, creating a negatively charged layer. If we monitor the current that is developed in the sheet, we will see the contribution from electrons. The negatively charged layer now attracts positive ions. So, now, we start to see ion current. Now, these ions are also going to neutralize electrons and contribute to the potential there. So, at some point both these electron current and ion current will sort of neutralize each other and that is what we call floating potential.

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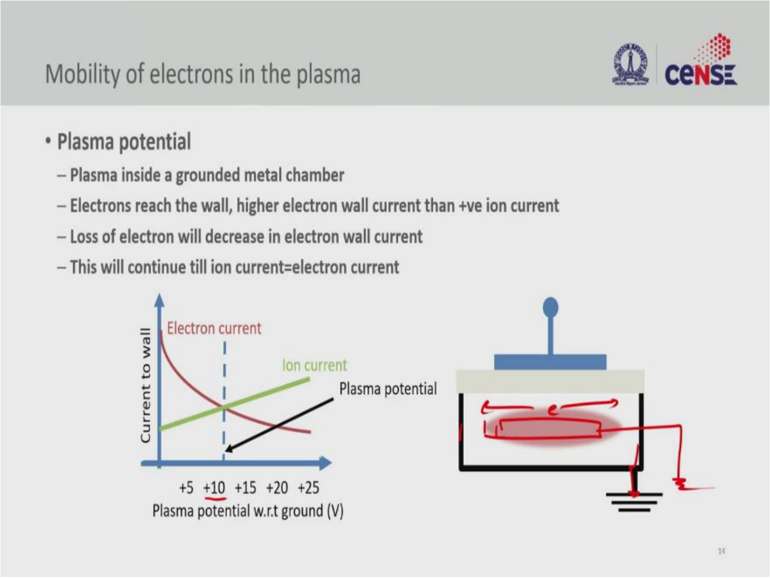

Mobility of electrons in the plasma

- Plasma potential
  - Plasma inside a grounded metal chamber
  - Electrons reach the wall, higher electron wall current than +ve ion current
  - Loss of electron will decrease in electron wall current
  - This will continue till ion current=electron current

Next is a plasma potential. It is similar to what we saw earlier, but the only difference is that the insulating surface is ground. Once we insert the insulating surface, we will have electrons coming in, and after a certain accumulation of electrons, we see ion current. So, both of these currents will neutralize each other trying to arrive at a certain potential called the plasma potential. Note that the polarity of voltage here is positive, while the floating potential is negative. The reason is that here we measure with re the electron current, . So, we start with very large electron current and in this case it is grounded as well, . So, that is the reason why wer plasma potential will be always be slightly positive, .

Also, the electron in the plasma can scatter and reach the chamber wall, which is grounded. So, the electron is lost from plasma, which makes the plasma slightly positive though plasma should be neutral in principle. Why not the ion loss? The reason for that is the mobility of electrons. The electrons are much faster, and also they scatter a lot annihilating themselves in the chamber walls. This is all about plasma potential. So, there are two ways to look at it: either we put the layer inside or measure from the chamber wall itself. The potential between the plasma and chamber wall is also the plasma potential because the chamber walls are also grounded.

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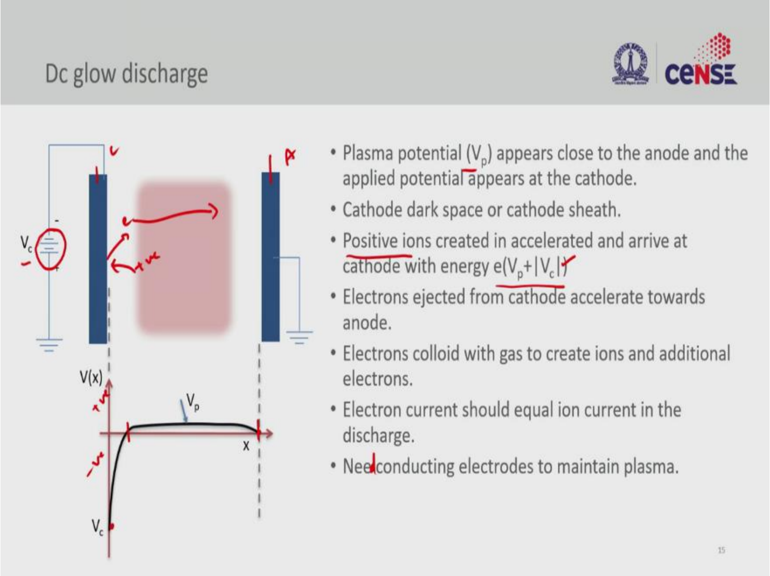

Dc glow discharge

- Plasma potential (V_p) appears close to the anode and the applied potential appears at the cathode.
- Cathode dark space or cathode sheath.
- Positive ions created in accelerated and arrive at cathode with energy $e(V_p+|V_c|)$
- Electrons ejected from cathode accelerate towards anode.
- Electrons colloid with gas to create ions and additional electrons.
- Electron current should equal ion current in the discharge.
- Need conducting electrodes to maintain plasma.

Now we look at the effect of the nature of the energy that we supply on plasma. So, let us look at two cases: DC glowed discharge, another one is RF. Let’s consider a parallel plate capacitive reactor with DC source, V_c. The energized plate is the cathode plate, and the counter electrode is the anode plate which is grounded.

So, when we apply a negative voltage to the cathode, we are going to attract some positive ions. Ofcourse, when we are switching on the whole system, we will not have anything, but we will have some charged particles anyway. These charged particles will be accelerated. So, when the positive ion hits the surface, we expect some electrons to come out. These electrons are accelerated towards the anode. On the way, they collide with gas molecules and create dissociation, ionization, and also additional electrons. So, to make this happen, we need both electrodes to be conducting.

Let us look at the energy of these ions and electrons. So, a positive ion that is accelerated towards the cathode will have the energy equivalent to $e(V_p + V_c)$ where, V_p is the plasma potential and V_c is the drive potential that we apply. So, this is the accelerating voltage we can apply which can be varied based on applied voltage.

If we look at the voltage across the two plates, we will have negative potential that we apply, near the cathode. As we move inside the plasma, it will become slightly positive. We already saw that the plasma potential is slightly positive because of the electron loss due to scattering. But once it reaches the anode, it will go to zero. Also, there are zero crossings which we will see later on we will see how this affects the way the glow discharge actually looks.

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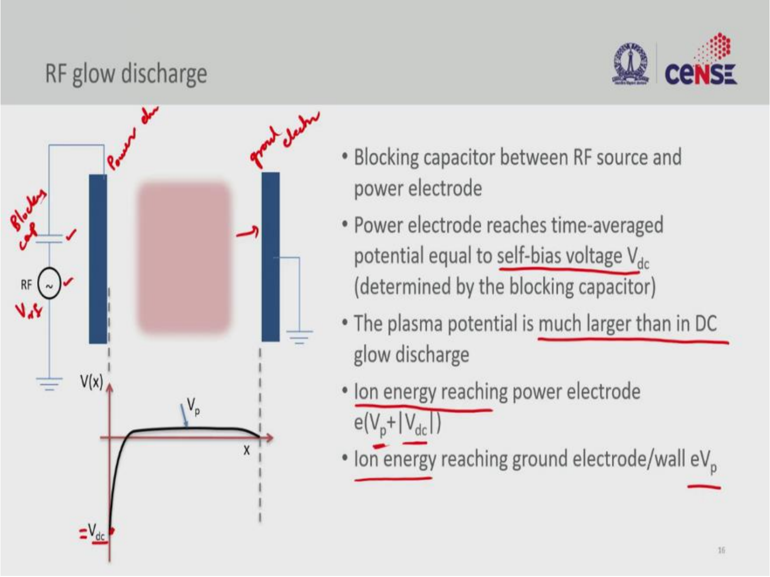

RF glow discharge

- Blocking capacitor between RF source and power electrode
- Power electrode reaches time-averaged potential equal to self-bias voltage V_{dc} (determined by the blocking capacitor)
- The plasma potential is much larger than in DC glow discharge
- Ion energy reaching power electrode $e(V_p+|V_{dc}|)$
- Ion energy reaching ground electrode/wall eV_p

In the RF glow discharge, we have an RF source and a blocking capacitor. The blocking capacitor is between the power electrode and RF source and the other electrode is grounded.

So, now, when I do when I pump RF power through this blocking capacitor, I can push energy into it and then in the same explanation wholes through here as well, but one interesting thing that we should note is the potential here. In the previous case, we have seen that the supply voltage, V_c, was the potential on the power plate. Since we are using the blocking capacitor here, the potential we see at the power electrode depends on the charge the blocking capacitor can hold. Hence, the voltage at the power electrode is V_{dc}, the self-bias voltage, instead of V_{rf}. So, the energy of ions reaching the power electrode is $e(V_p + V_{dc})$ which depends on self-bias voltage and that reaching the wall has energy depending only on plasma potential. Also, the plasma potential in an RF discharge is larger than in DC. This is due to efficient power transfer which we will see in the next slide.

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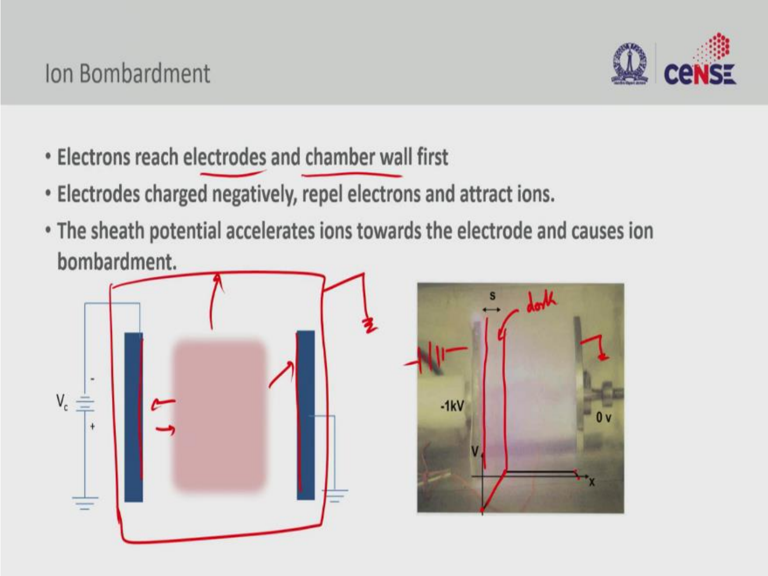

Ion Bombardment

- Electrons reach electrodes and chamber wall first
- Electrodes charged negatively, repel electrons and attract ions.
- The sheath potential accelerates ions towards the electrode and causes ion bombardment.

We know that electrons primarily handle plasma sustenance. Electrons are scattered towards the chamber wall, which includes electrodes as well. But on reaching the walls, they are repelled from the negatively charged electrode, while the ions are attracted there. Normally, the ions are accelerated towards electrodes due to the potential drop between the plasma and electrode. The reason for the potential drop is the accumulation of charges at the electrode. We can see in the second image that the right-hand side electrode is grounded, and DC is supplied to left-hand side electrode. Near the power electrode, we see a bright line followed by a dark region. This is the region where voltage transition happens, and ions are accelerated. We know that the excitation process is the reason behind optical emission. So, we have huge interaction of electrons and ions, resulting in large excitation near the electrode. The same is true in the plasma as well. Between these two regions, there is minimum collision because of the reduction in the acceleration of electrons.

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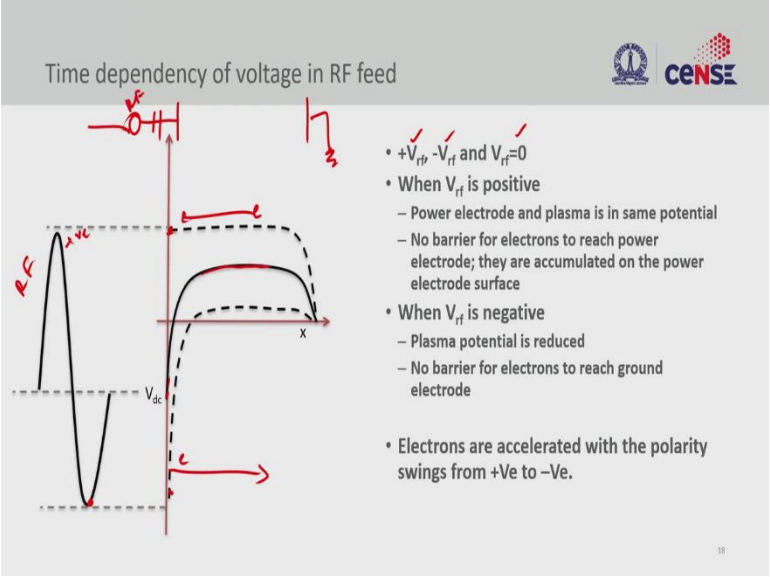

Time dependency of voltage in RF feed

- $+V_{rf}$, $-V_{rf}$ and $V_{rf}=0$
- When V_{rf} is positive
  - Power electrode and plasma is in same potential
  - No barrier for electrons to reach power electrode; they are accumulated on the power electrode surface
- When V_{rf} is negative
  - Plasma potential is reduced
  - No barrier for electrons to reach ground electrode
- Electrons are accelerated with the polarity swings from +Ve to –Ve.

Here we look at the time dependency of voltage in RF feed. So, we feed in an RF source along with the blocking capacitor at the power electrode and look at the potential across the two electrodes.

And here we are going to swing between positive, negative and then 0. When RF is positive, the plasma potential and electrode potential are identical. So, the electrons will be attracted to the electrode surface and get accumulated. When the negative cycle is fed, polarity at the power electrode reverses, and electrons are repelled away from the power electrode. Due to the repulsion, the electrons are accelerated into the plasma and create collisions.

The black solid curve shows the time-averaged potential across the electrodes. In reality, we will swing between positive and negative potential at the power electrode. The potential is stabilized inside the plasma.

And that brings us to end of understanding the plasma characteristics. And in the next session we will look at what are all the tools that we can use to exploit the plasma here for various purposes.