Fundamentals of Micro and Nanofabrication
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Lecture – 48
Dry etch: Plasma tool configuration

In this lecture on dry etching, we look at tool configurations used in dry etching of various material, the advantages and disadvantages of these configurations, and the evolution of this configuration over the years.

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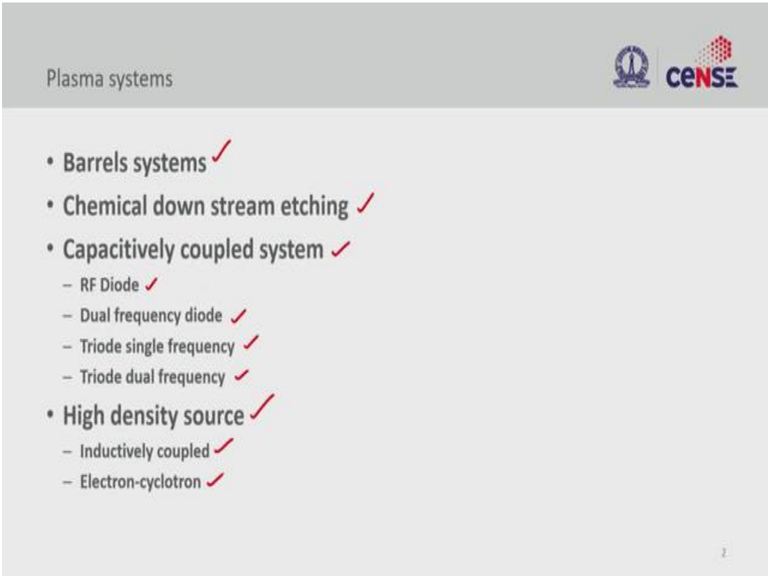

The barrel system was the first of its kind that came into the industry; we will see that in the next slide. The chemical downstream etching is a very different type of system where all the radicals are created, and then it is fed downstream. The next type is a capacitively coupled system. So, this is one of the popular configurations. We can have systems like RF diode, dual-frequency diode, triode single frequency, or triode dual-frequency. These configurations have been introduced to test, and some of these configurations are not used in industries. However, we shall go through them to understand the nature of these configurations to get a better idea about how we control the plasma.

Third is the high-density sourced systems under which we have inductively coupled plasma and electron cyclotron configuration, creating high-density plasma. In capacitively coupled systems, the plasma density is limited. We shall know the reasons for that and justify the configuration change.

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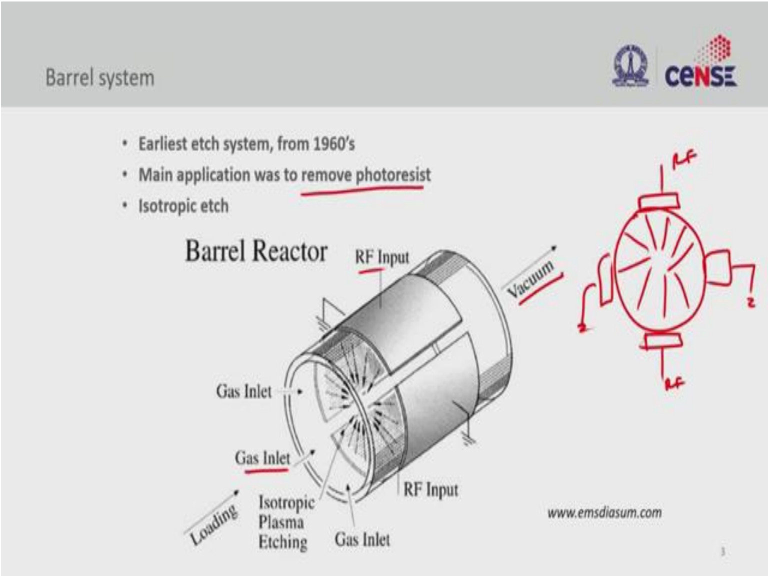

The barrel reactor is a legacy system consisting of a barrel surrounded by electrodes. Two of them are fed with RF, while the other two are grounded. Also, we have a gas inlet, and the gas is sucked out from the other side through the vacuum. In the presence of gas and the field, we generate plasma.

Here, the electrode configuration is such that isotropic plasma is created. If two RF feed electrodes are on the outer wall of the barrel placed at the top and bottom, the two ground electrodes are placed in the horizontal direction, as shown in the schematic. So, in this case, we uniformly create plasma. Because of the isotropic nature, these systems were primarily used for cleaning and photoresist removal after etch. It is the best way to remove the photoresist or any polymer sitting on the wafer as the plasma attacks all the sides.

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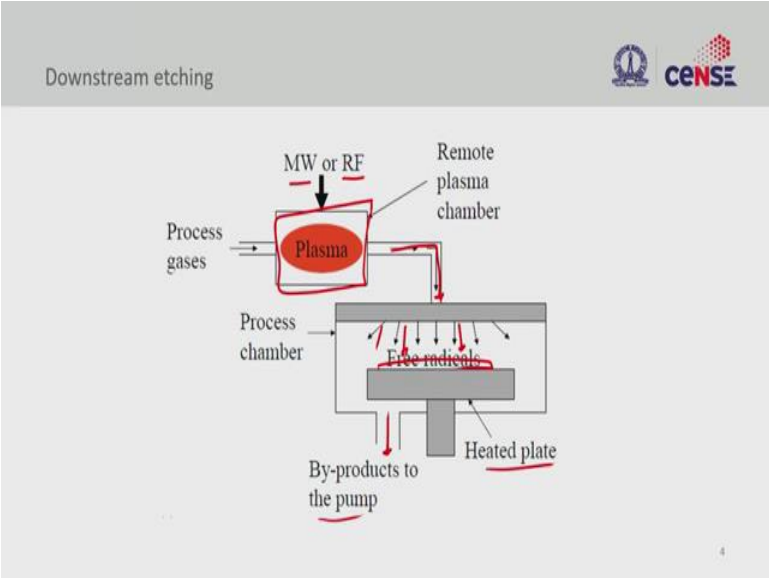

The second system in the list is the downstream etching system. Here, the plasma is created in a different chamber and the wafer is situated in a different chamber. Either an RF or microwave feed is used to create plasma. The free radicals are pushed through a duct and react with the substrate placed on heatable holder. There is an outlet to pump out the by-product and also create the differential in pressure to downstream the plasma.

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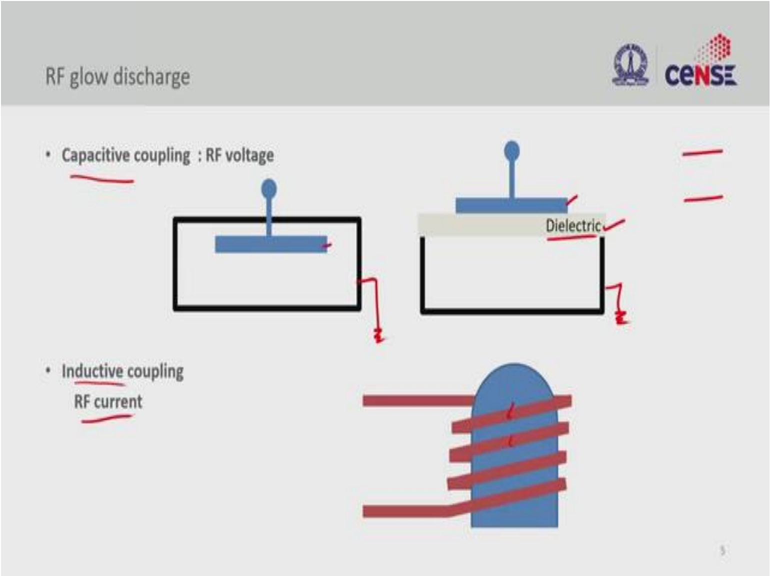

Now we shall look at conventional glow discharges, primarily the RF discharge. It can be either capacitive type or inductive type. In capacitive coupling, there are two plates. These two plates could be either the source electrode and the chamber which is grounded or the source electrode with a dielectric and the grounded chamber. We shall see the reason behind the usage of dielectric in the next slide. In inductive coupling, a magnetic field is generated by passing a current through the coil. This magnetic field, in turn, produces a current inside the chamber, which creates the plasma.

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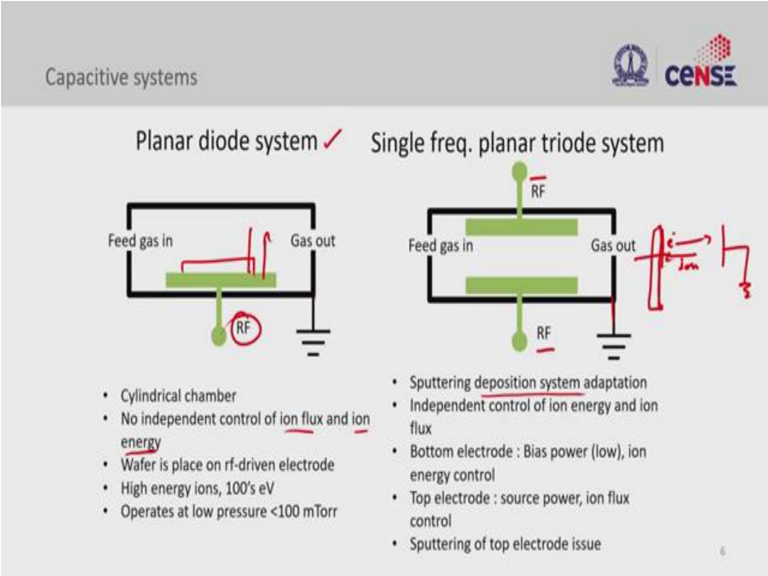

One of the different types of capacitively coupled systems is planar diode geometry. Here, we have an electrode, grounded chamber, gas inlet, and outlet. The wafer is kept on the RF feed electrode. Since both are on the same platform, it is not possible to independently control the number of ions or the ion flux and the energy of those ions. The energy supplied through the system also affects the wafer. So, this will end up sputtering the electrode as well.

Then, the single frequency planar triode system came into existence. In the previous case, we had the problem of controlling ion energy. So, here, people used two RF electrodes having the same frequencies, and the third electrode is the grounded chamber.

It was introduced so that you can give feed from both the side and in this case, we have two alternate frequency from the top electrode and bottom electrode so that we could transfer the energy to the system at the same time protect the wafer from getting sputtered. We know that when an electrode is energized, the electrons get accelerated out, but ions are coming towards the electrode. So, when the high-energy ions hit the electrode, it will get sputtered. i.e., there will be physical etching that has no selectivity and removes all the material from the electrode. This configuration is later adapted as a deposition system because the ion energy is large enough. So, when a target is placed on the electrode, the material is going to be sputtered. For etching, we need selectivity, and therefore, this configuration did not find its way into the mainstream etching system.

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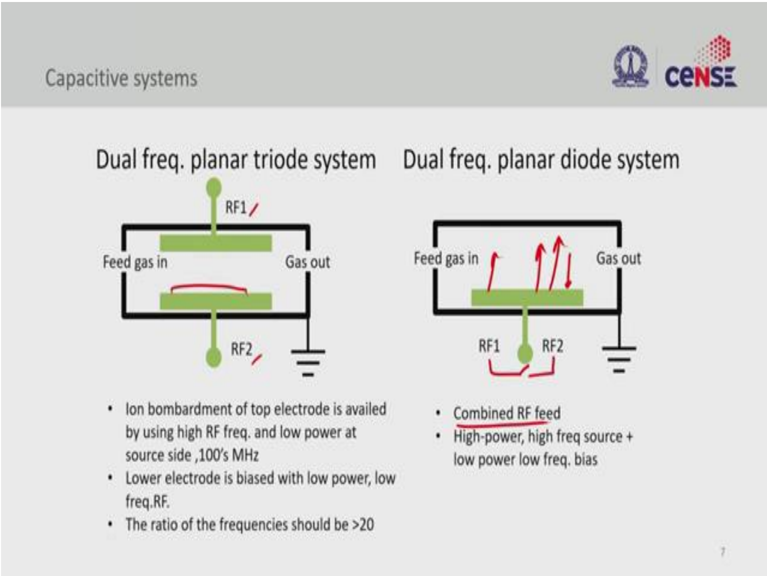

Next is the dual-frequency triode system. Here, the two RF electrodes are fed with different frequencies. In this configuration, the ion bombardment on top electrode is avoided by using higher frequency and lower power. The bottom electrode is at a lower frequency and the wafer is placed on it. So, by using dual-frequency, sputtering of one of the electrodes is avoided.

Instead of using two frequencies on two different electrodes, the configuration is modified to have two frequencies on one electrode. Thus, this is a dual-frequency planar diode system.

So, by switching between high and low frequency, we can feed electrons efficiently into the system, energize the plasma, and at the same time reduce ion bombardment. In one cycle energy is fed and in the next cycle ion energy is reduced. So, we only have the radicals into the system for etching. It is a combination of RF feed which was also popular that can avoid all the sputtering issues as well and now we have single electrode with two frequencies.

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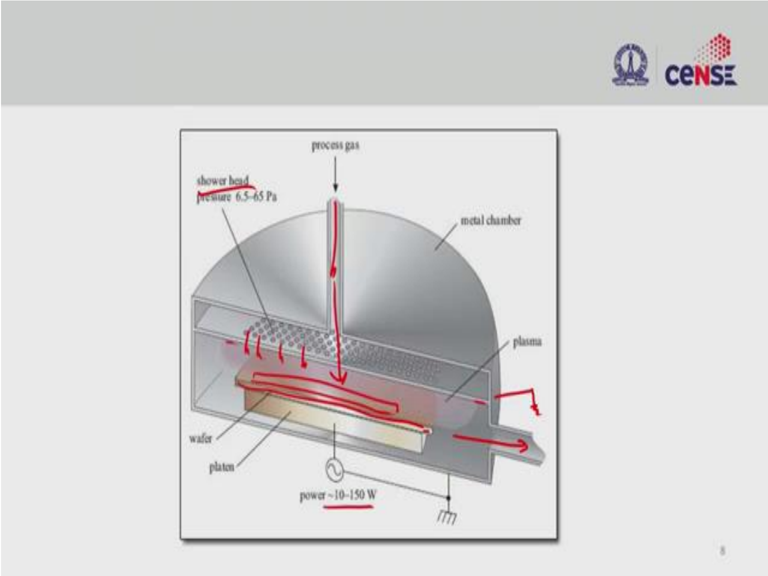

Here, we look at a cross-section of the tool configuration of a reactive ion etching chamber. The gas passed through a gas feed enters the system through the showerhead. The gas is confined by the bottom plate, which is fed with RF, and the chamber, which is grounded. The plasma is created between the top shower head plate and the bottom power plate while the wafer is kept on the bottom plate. The unreacted gases and the by-products will exit through the outlet.

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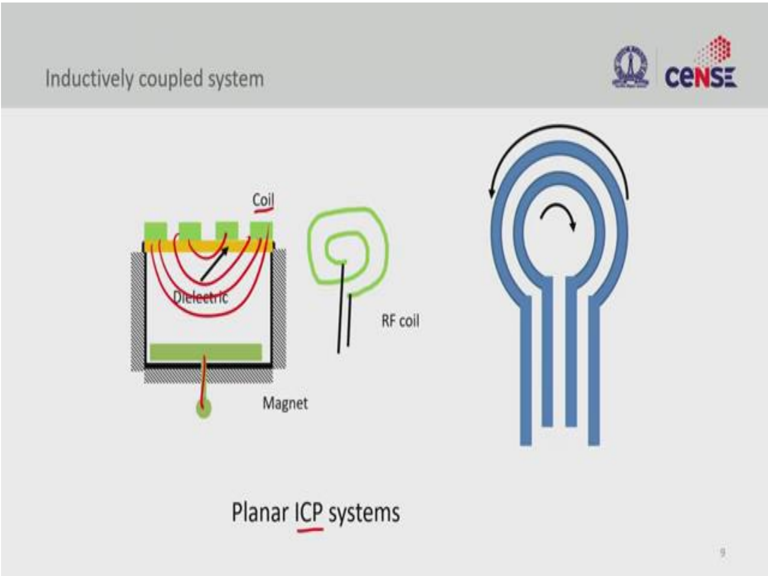

The next configuration is an inductively coupled system. As we know, such a system has a coil. In the slide, we see the cross-section of such a coil. So, we have one electrode at the bottom and a coil at the top, creating the field as shown in the slide. Here the coil is confined to one plane, and hence it is a planar inductively coupled plasma system.

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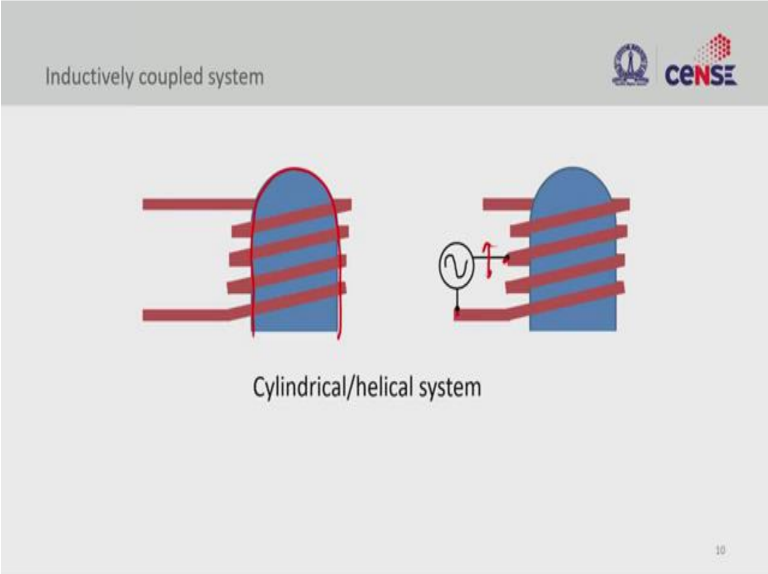

There is also a helical or cylindrical system. Instead of planar geometry, we have a doom-shaped chamber surrounded by this coil. So, when current is passed through the coil, plasma is generated inside the doom. By varying the current, and also the number of turns in the coil, we can control the plasma generated.

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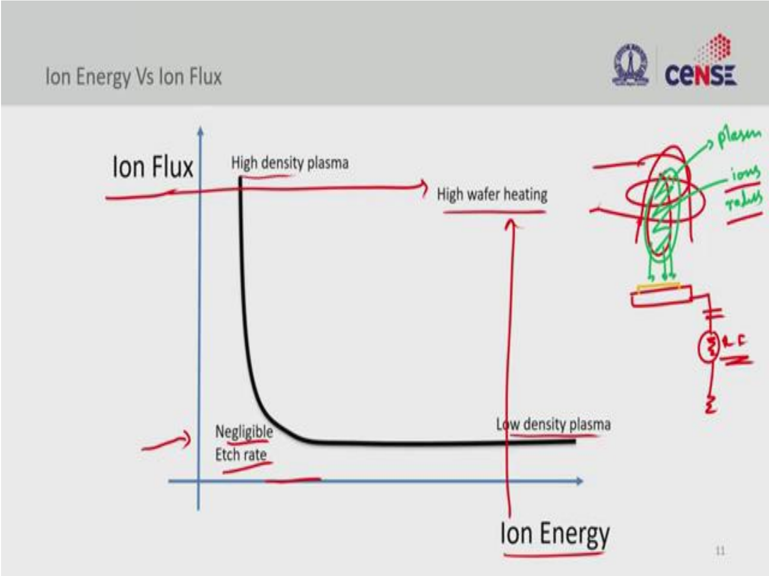

One of the important process relations we should understand is between ion energy and ion flux. We need to control both of them. Let us take an ICP as an example. So, as we know, plasma is created inside the doom by passing RF. The wafer is kept on the bottom electrode, which is energized by an RF through a blocking capacitor.

The plasma contains all the ions, radicals. They should be attracted towards the wafer surface to create a chemical reaction. By applying the RF to the bottom electrode, the attractive force for these radicals and ions is generated. The radicals being neutrals cannot be affected by applying a field, but the ions can be brought in by using electric field right.

Let us look at how this ion flux and ion energy are affected. When the ion energy is very large, the wafer gets heated up. When the ion energy is very low, the etching is negligible. So, we should be careful while reducing the ion energy to reduce the heat and impact.

When we have low ion flux and large ion energy, it is called low-density plasma. When the ion energy is moderate or low, and ion flux is high, then the plasma is called high-density plasma. Large ion flux and high ion energy will result in heating, while small ion flux and low energy result in no etch at all.

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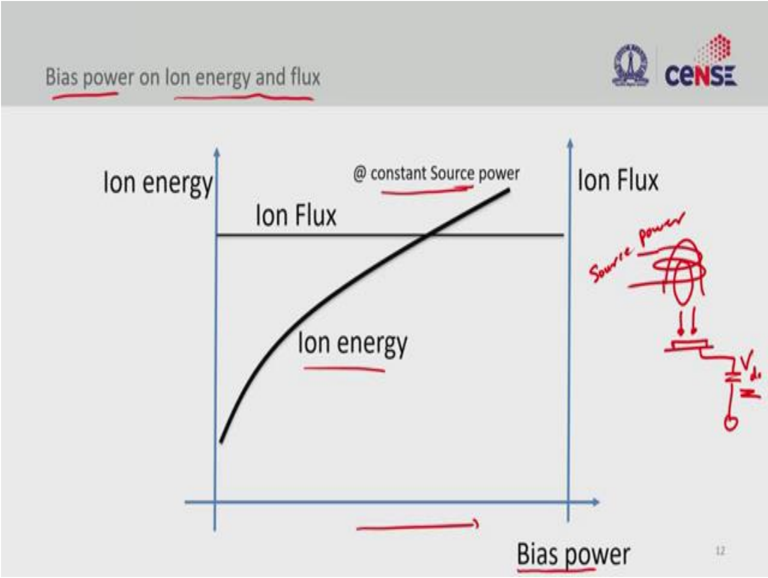

So, we need to find a sweet spot between ion energy and ion flux. Let us see how this can be controlled. There are two things here. We have seen that in the doom configuration, we supply a bias power V_{dc} to the bottom electrode. So, now, let us look at the effect of bias power on ion flux and ion energy at constant source power. Here, the source power is the power supplied to the coil which creates plasma.

With the increase in bias power, the ion energy increases, because ions are accelerated towards the bottom electrode. We are trying to push all the ions from the plasma onto the substrate. So, naturally, the ion energy increases.

But, the ion flux will not see any difference on changing the bias power. The ion flux depends on the source power. We cannot create more ions by changing the bias power. Since the source power is constant in this case, ion flux will remain constant.

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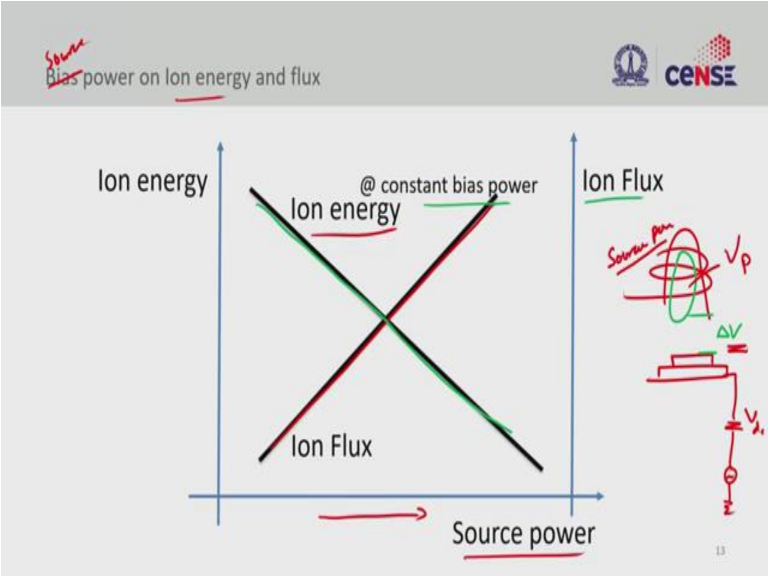

Now we shall look at how the source power affects the ion flux and ion energy at constant bias power. As the source power is increased, the number of collisions and hence plasma density increases. Hence, ion flux increases.

However, the ion energy decreases even though the bias power is constant. The reason for the reduction in ion energy is to do with the potential difference between plasma and wafer. Initially, the plasma is at a slightly lower potential. As the source power is increased, the plasma potential also increases. Hence the potential difference between plasma and the bottom electrode reduces resulting in reduction in ion energy. By understanding this relation, we can control the etch process. We can tweak the bias power and source power to have the required ion energy and ion flux.

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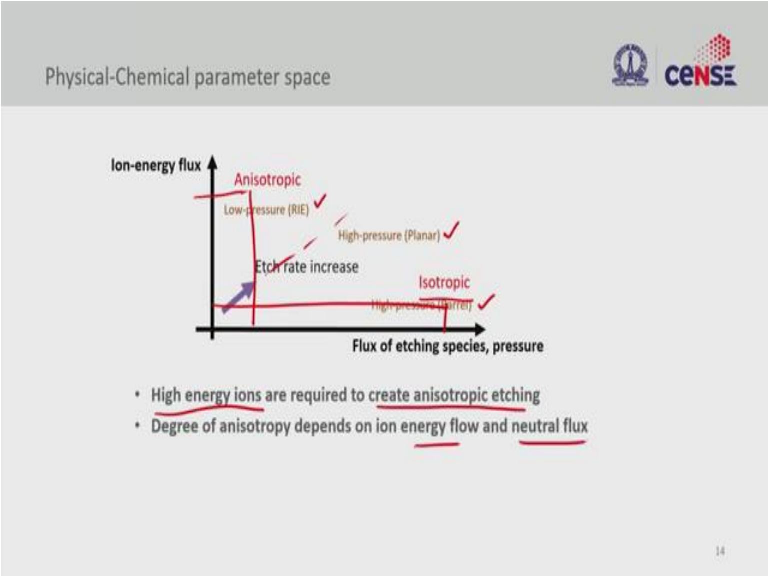

The ion energy flux decides the process regimes. High energy ions are required to create anisotropic etching. The degree of anisotropy depends on ion energy flow and the neutral flux. as well right; so, both flux and the energy. So, in this case the neutral fluxes is the important one, you have ion energy and neutral flux are important in creating this anisotropic etch.

High flux of etching species with very low ion energy results in isotropic etch. But, high energy ions with reasonable flux of etchant are required for anisotropic etch. Also, the etch rate increases as the flux of etchant and the ion energy increases.

So, based on ion energy and flux configuration, different tools can be assigned to different regimes discussed above. This is just to understand which tool to use if we want isotropic etch or anisotropic etch.

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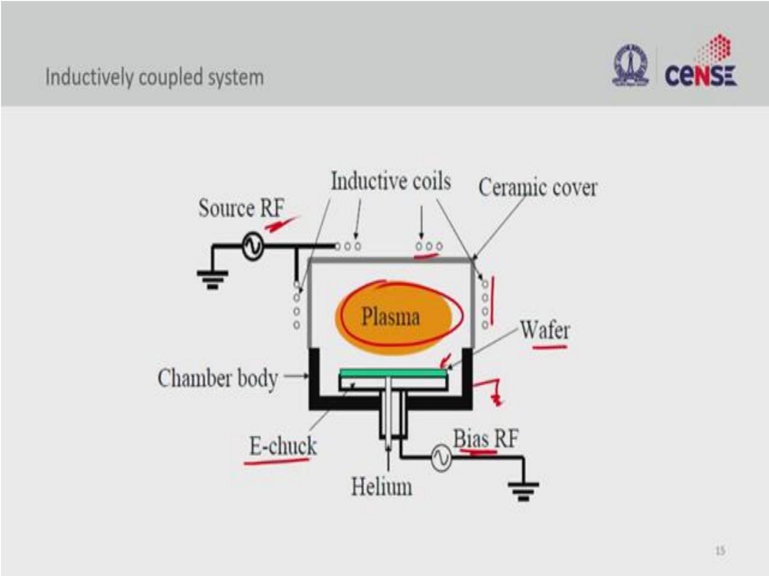

This is again an inductively coupled plasma system that is a combination of the planar and the doom system. So, the plasma is created inside the dome by the RF source. The bias RF is fed through the capacitor to the bottom electrode. And, the wafer is usually kept on an electrostatic chuck; it pulls the wafer inside. The chamber body is grounded and also acts as another electrode.

This configuration looks like parallel plate triode system. The only difference is that the source here is inductively coupled.

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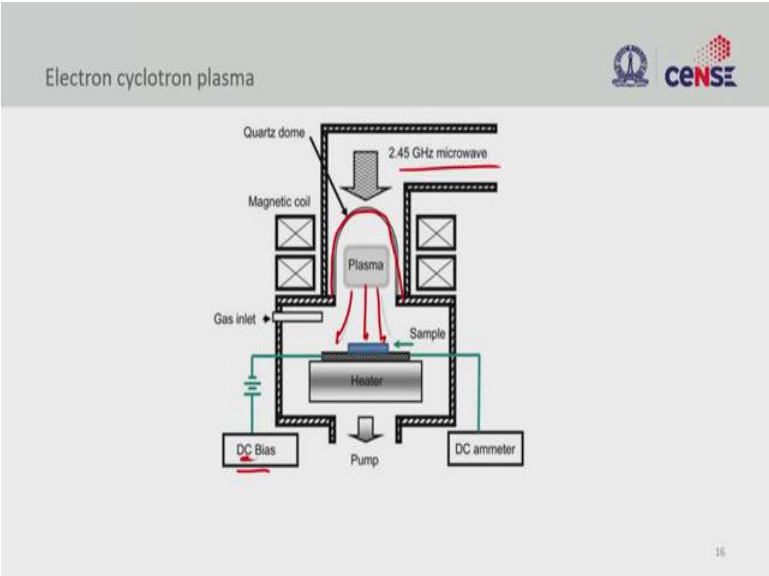

And, the other configuration is electron cyclotron plasma. It is a doom-type system with magnets to create that magnetic field, but we need to have a current to energize it. The microwave creates the required energy here to create the plasma. The etchants are pulled through the pressure difference and that the DC bias that we apply.

Unlike ICP, here we use a DC instead of an RF feed. This configuration is used in some of the research and developments and some industrial processes.

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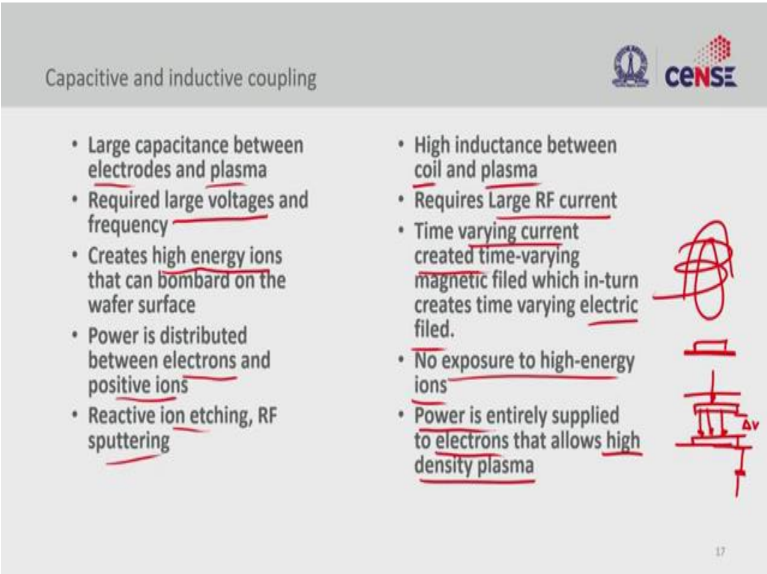

Here we see, the difference between the capacitively coupled system and the inductively coupled system. In capacitively coupled systems, a large capacitance is created between the electrode and the plasma. However, in an inductive coupling, a high inductance is created between the coil and the plasma. A very large voltage is required in the capacitive coupling, but we need a large current in inductive coupling. There is a voltage source in capacitive coupling systems and a current source in inductively coupled system.

In a capacitively coupled system, high-energy ions are created that can bombard onto the surface. However, then the source power is distributed between electrons and positive ions which is a drawback in a capacitive system. We want to efficiently transfer all the energy only to electrons, not to positive ions. The reactive ion etching and RF sputtering fall under capacitively coupled system.

On the other hand, in an inductively coupled system, a time-varying current will create an electric field and transfers most of the energy to electrons, as ions respond weekly to time-varying fields. Also, we are not exposing to very high-energy ions here. Because all the ions are restricted to the doom region as the wafer is kept far away. But in a parallel plate reactor, the voltage drop between the source and the wafer results in energetic ions hitting the wafer.

Since the energy transfer is efficient in inductively coupled systems, high-density plasma can be generated. Without supplying high energy to electrons, it is impossible to generate a very efficient and high-density plasma without affecting the wafer.

That brings us to the end of this lecture on the tools. We have seen the importance of ion energy and ion flux in controlling the etching. In the following lecture, we will see the importance of ions and neutral radicals in the etch process when we look at the etching mechanism.