Course material

Course:

Micro and Nanofabrication (MEMS)

Video:

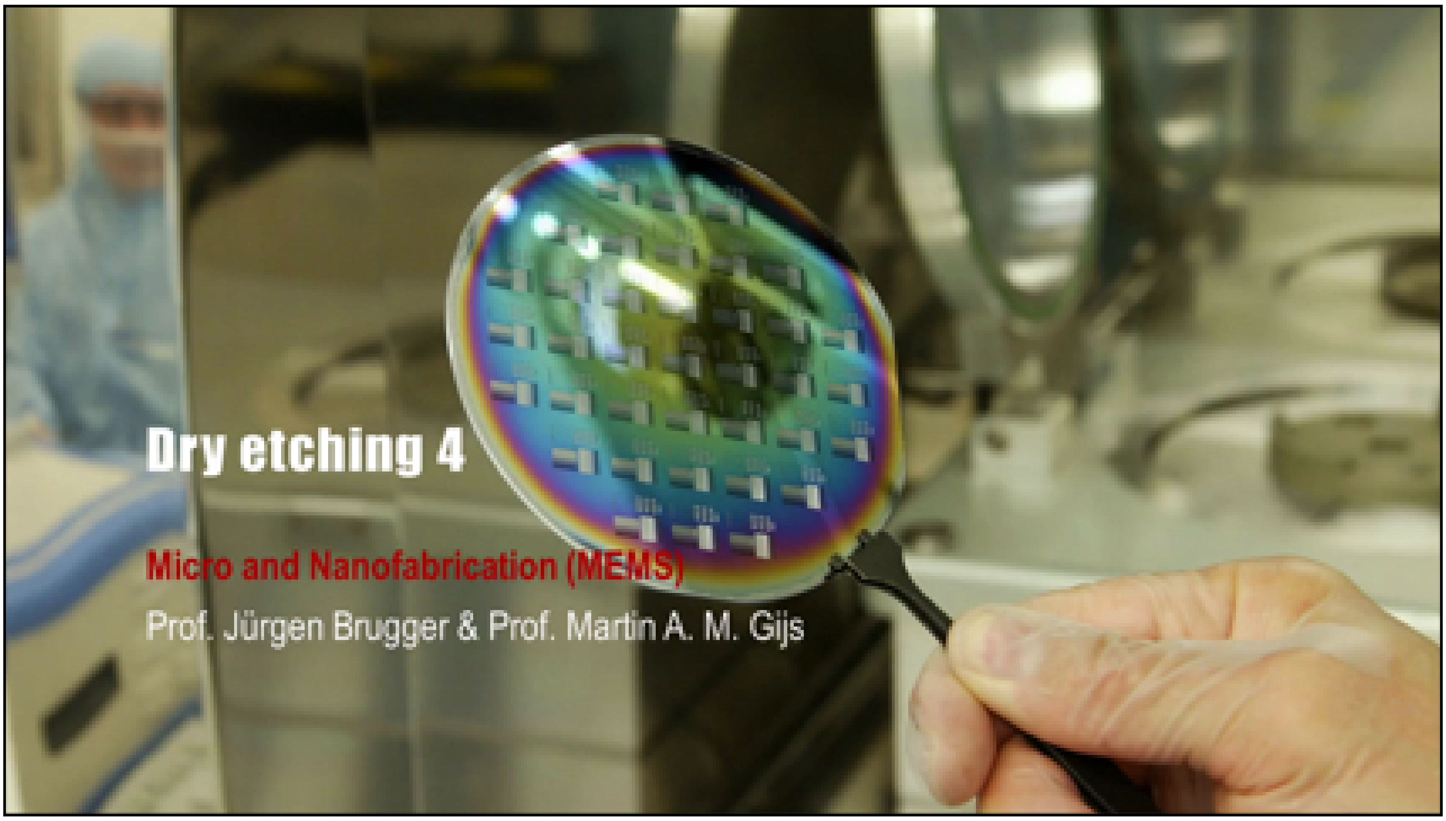
5.4 Dry etching 4

Concepts (extracted from automatically generated subtitles):

Plasma sources. Modern dry etching reactors. Chemical oxygen plasma. Electrical impedance of a capacitive plasma source. Aluminium oxide. Use of oxygen. Low voltage. Ion bombardment. Barrel reactor. Diode reactor. Schematic diagram. Electron cyclotron resonance. Rf plasma. Rf power supply. Icp source.

to video sequence search
(within Micro and Nanofabrication (MEMS).)

to video

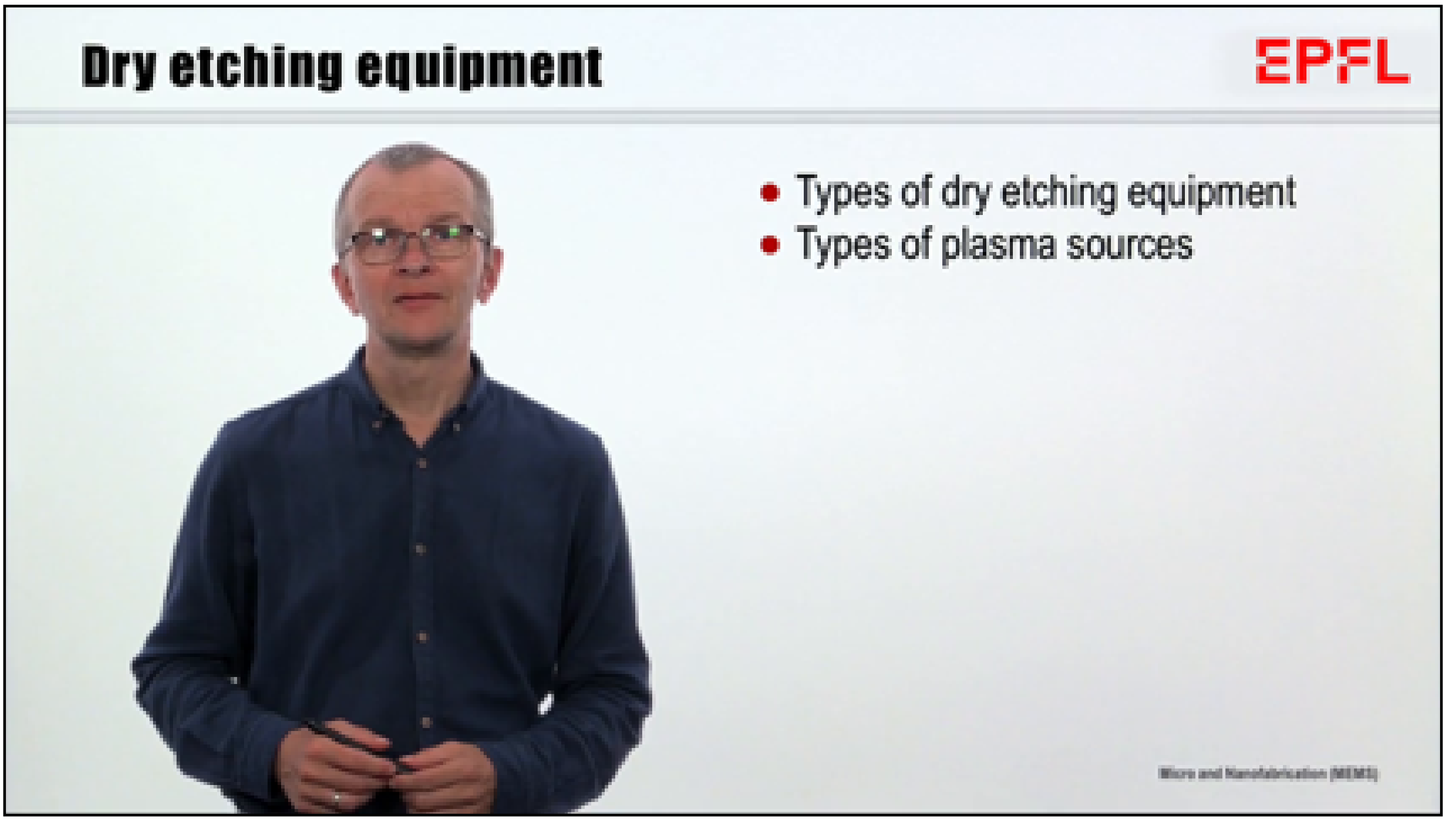


...

notes

summary

0m 0s

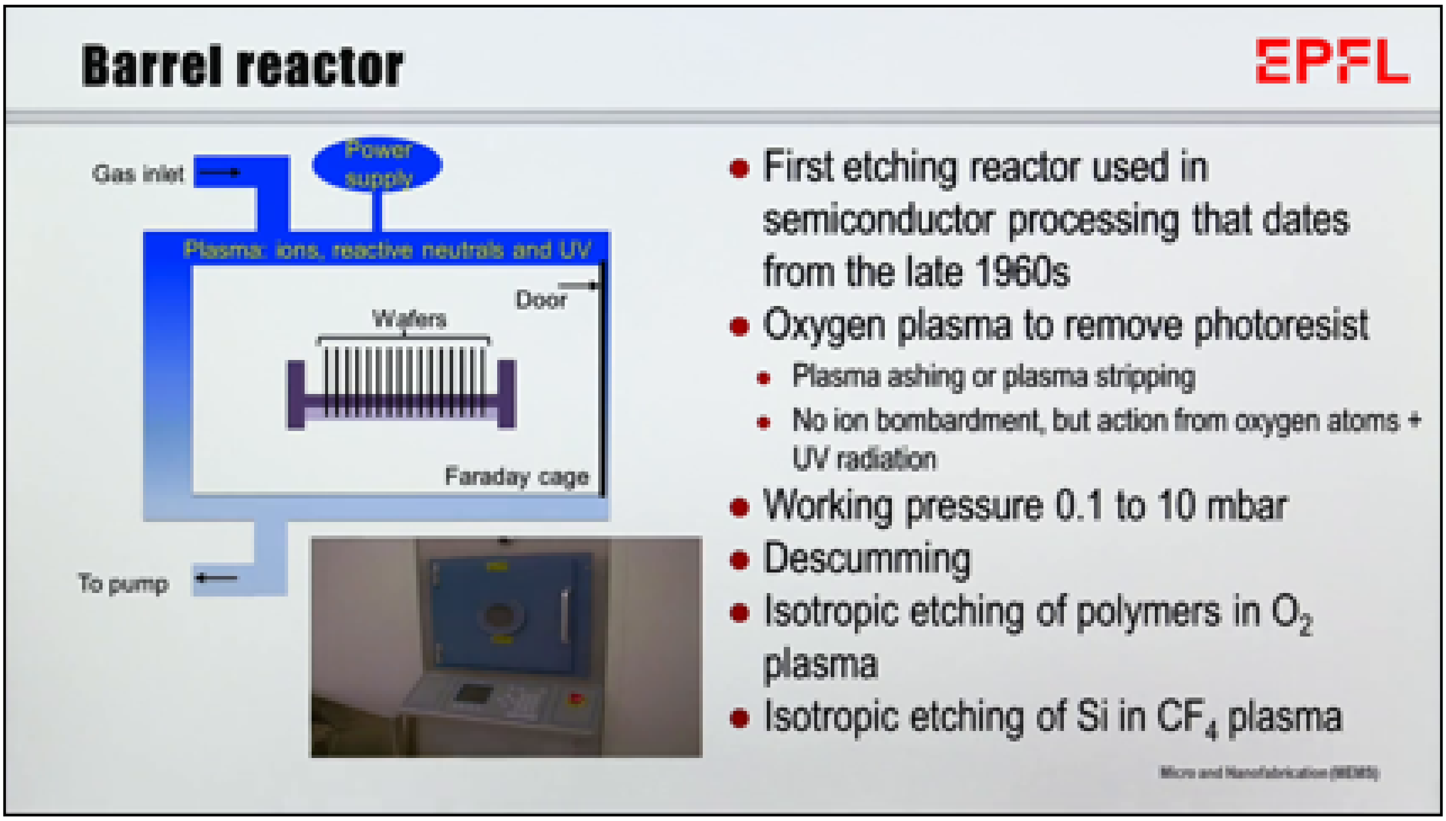


In this lesson, we will present main dry etching equipment.

notes

summary

0m 1s

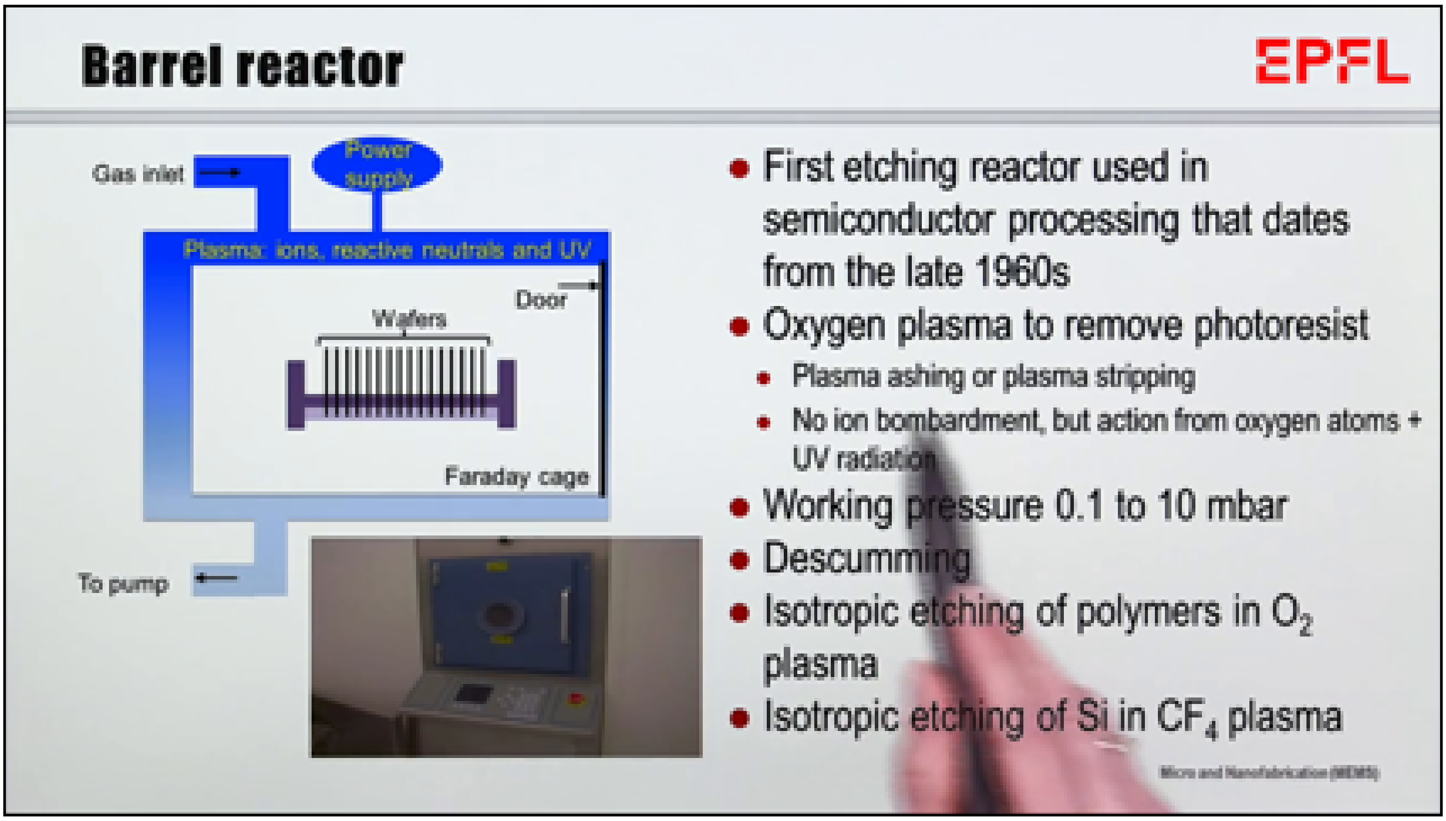


Also we will introduce some of the plasma sources that are used in modern dry etching reactors.

notes

summary

0m 5s

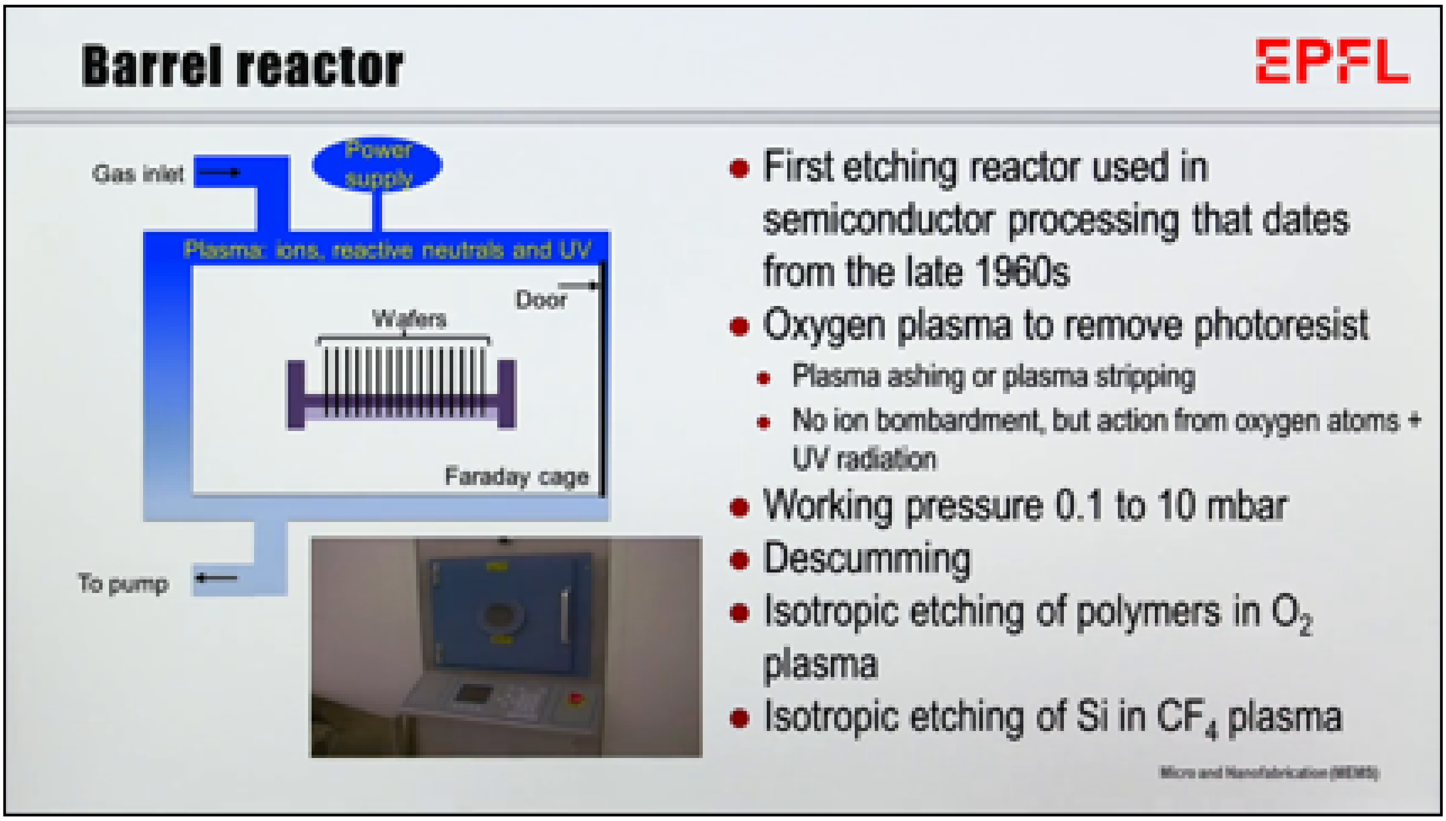


This is a schematic diagram of a so-called *barrel reactor*. It is one of the first etching reactors used in semiconductor microfabrication. It exploits a chemical oxygen plasma to remove polymers or photoresist from wafers. Such a reactor is also used for *descumming.* And descumming is removal of thin polymer residues after development of a photoresist, for example. The technique is also called *plasma ashing* or *plasma stripping*

notes

summary

0m 18s

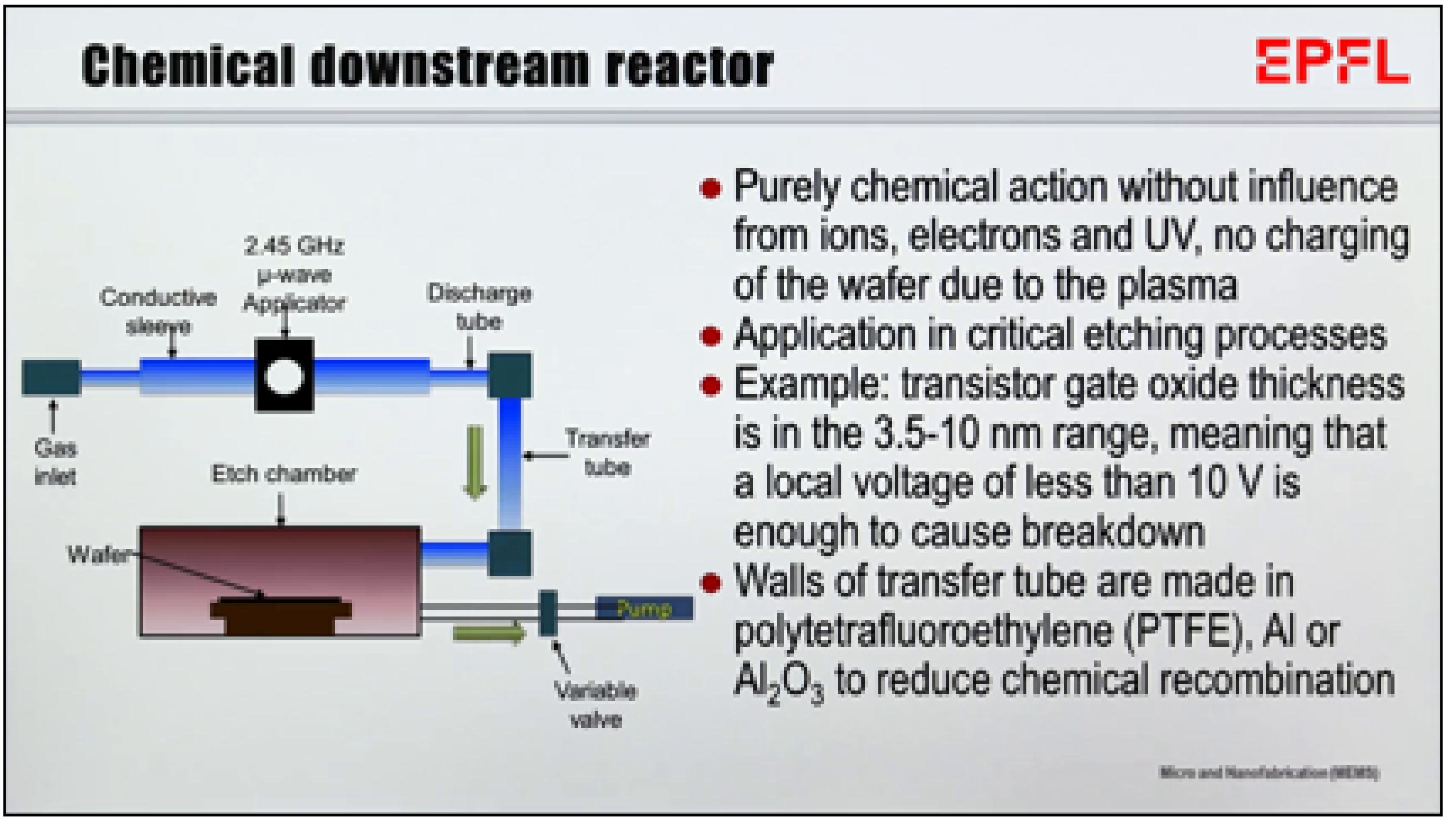


because it removes the organic molecules.

notes

summary

0m 59s

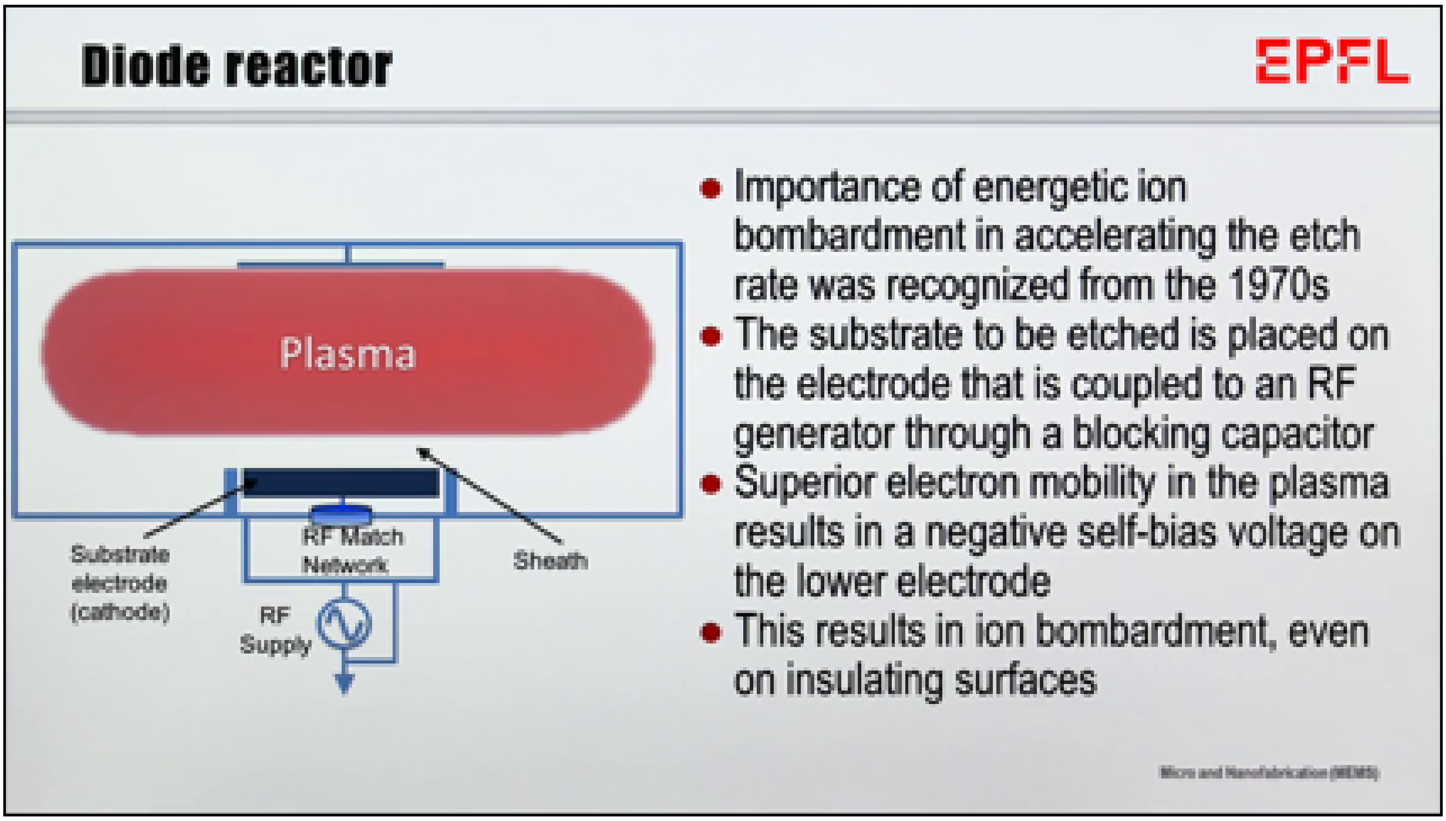


There is no ion bombardment in this technique, and chemical action from the oxygen atoms and UV radiation is solely responsible for the etching. The typical working pressure is in between 0.1 and 10 millibar. Besides the use of oxygen for removal of organic layers, one can also use a CF4 plasma in this reactor for silicon etching without bombardment. The picture below shows the entrance door of such a barrel reactor and its command panel. This is a schematic diagram of a so-called *chemical downstream reactor.*

notes

summary

1m 2s



A microwave plasma is generated remotely from the etching chamber and then transferred to the etching chamber. The wafer which is positioned here, is hence not influenced by accelerated ions, electrons, or by ultraviolet irradiation and the etching is purely chemical. The technique is used in critical etching processes. For example, for the etching of transitor gate oxides which are extremely thin, so that even a low voltage can cause dielectric breakdown of the transistor. The walls of this transfer tube are covered with inert materials like polytetrafluoroethylene, or Teflon, or can even be made of that material. Also, aluminium or aluminium oxide is used for this transfer tube to reduce chemical interactions with the plasma during transfer. This schematic diagram is that of a so-called *diode reactor* due to the presence of two electrodes, and we have already introduced this reactor before in our discussion of dry etching. We explained how the substrate electrode can acquire a negative voltage bias by incorporating a blocking capacitor in the circuit. Also of importance for this high negative voltage bias was the superior electron mobility over the ion mobility in the RF plasma. The developed negative voltage bias results after a while in strong ion bombardment, even on insulating surfaces on the wafer.

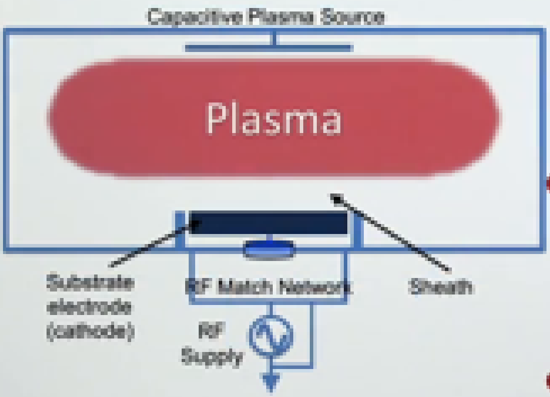
notes

summary

2m 1s

RF match network

EPFL



- Electrical impedance of a capacitive plasma source behaves like a capacitor in series with a resistor
  - $Z_{plasma} = R\text{-}j/\omega C$ with $|Z_{plasma}| > 50\ \Omega$ and $R < |1/\omega C|$
  - C ~ 100 pF due to the capacitance of the driven electrode sheath
- A match network is required to make the plasma impedance, in series with the match impedance, look like a 50 Ω impedance for the RF power supply
- The match network has variable series and shunt capacitors to minimize recirculating power losses

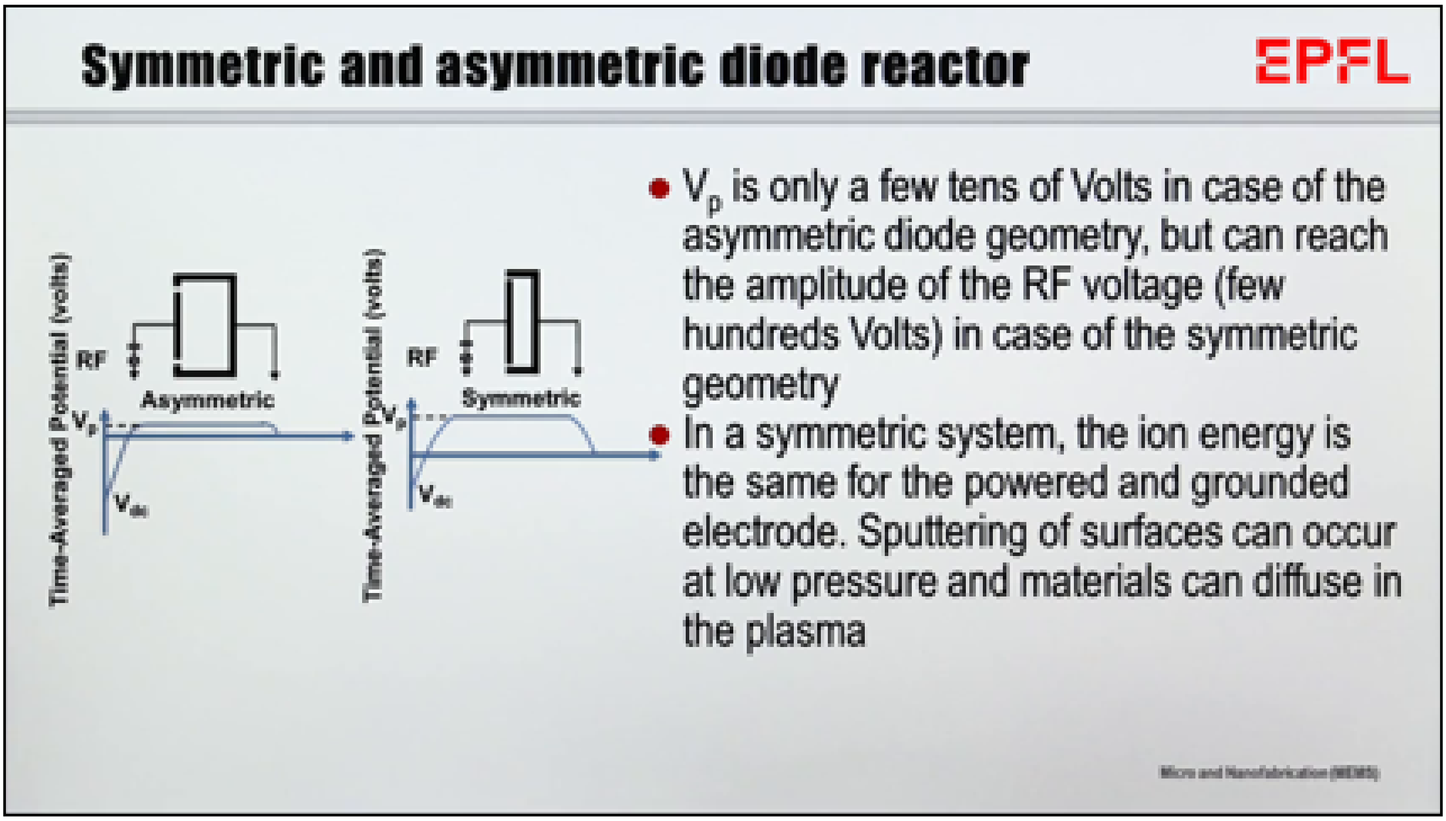
Micro and Nanofabrication (MEMS)

The electrical impedance of a capacitive plasma source

notes

summary

4m 13s



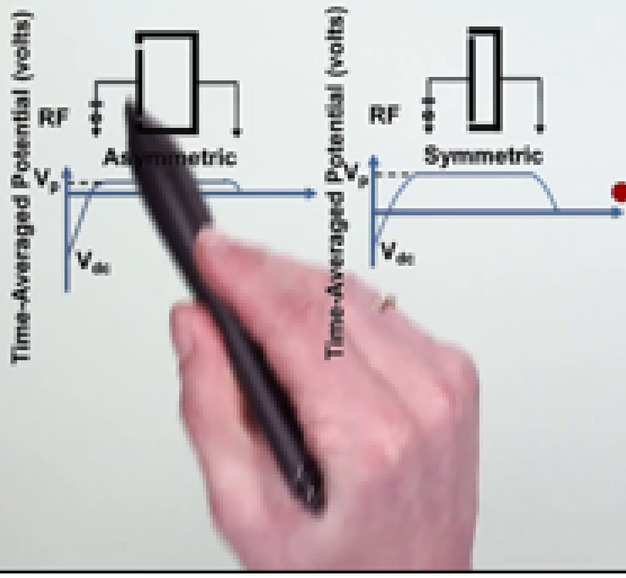
is that of a capacitor in series with a resistor. A match network is required to couple the impedance of this plasma to the RF power supply. Such a match network has variable series and shunt capacitors to minimize power reflection and recirculating power losses.

notes

summary

4m 15s

Symmetric and asymmetric diode reactor



- V_p is only a few tens of Volts in case of the asymmetric diode geometry, but can reach the amplitude of the RF voltage (few hundreds Volts) in case of the symmetric geometry
- In a symmetric system, the ion energy is the same for the powered and grounded electrode. Sputtering of surfaces can occur at low pressure and materials can diffuse in the plasma

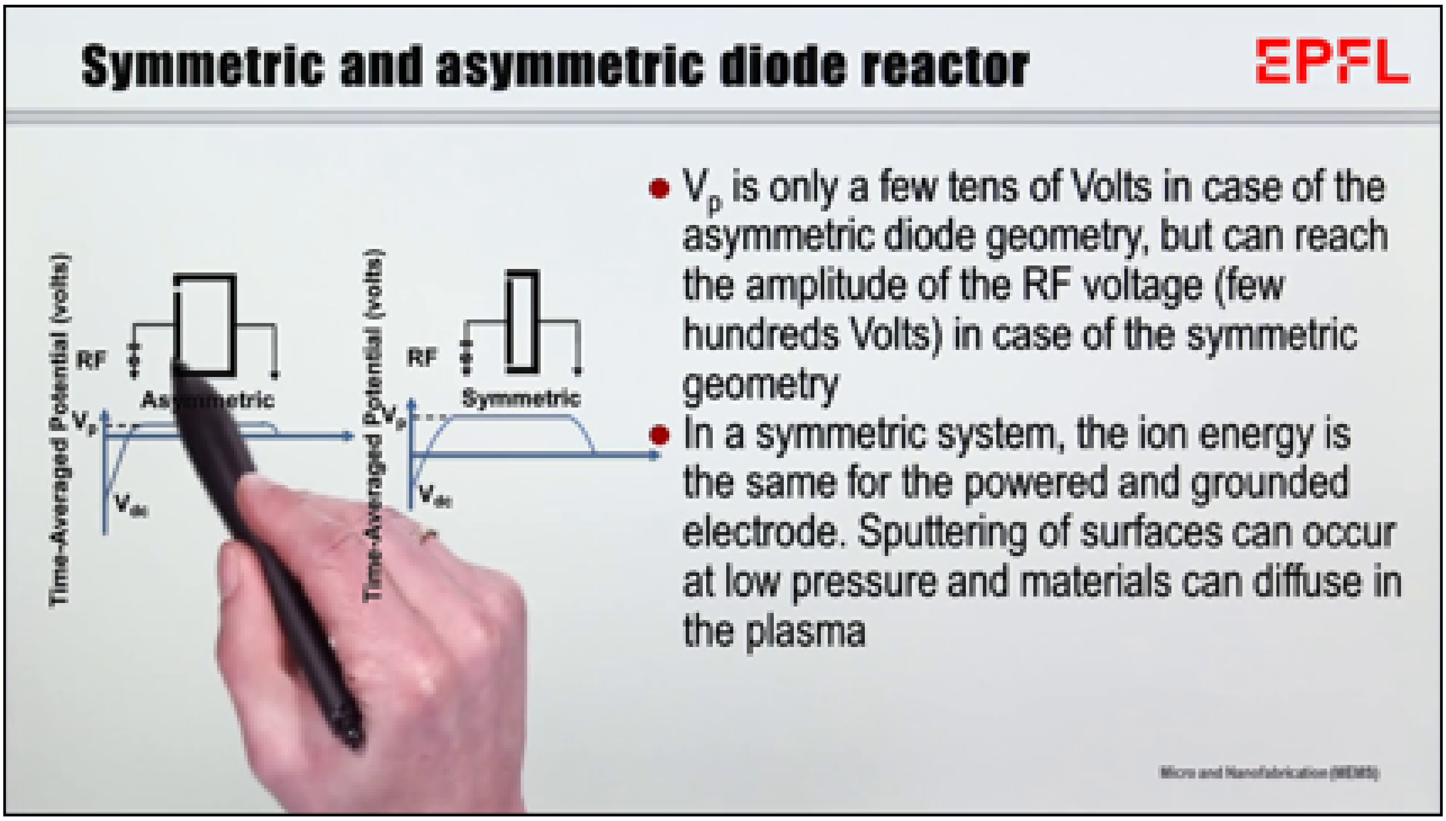
Micro and Nanofabrication (MEMS)

The difference between a symmetric and an asymmetric configuration is shown here.

notes

summary

4m 47s

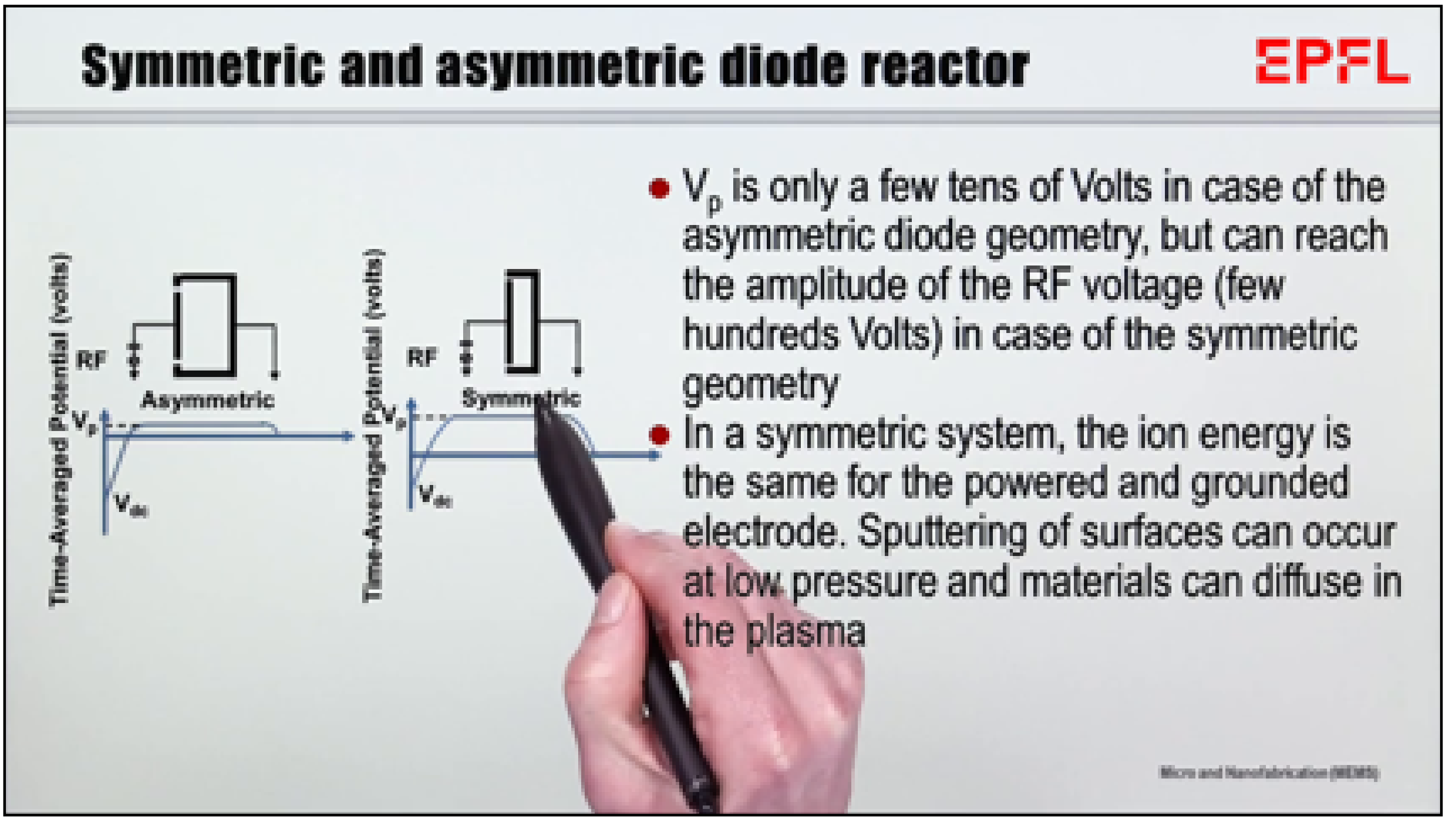


In the asymmetric reactor, the electrode on which the wafer

notes

summary

4m 59s

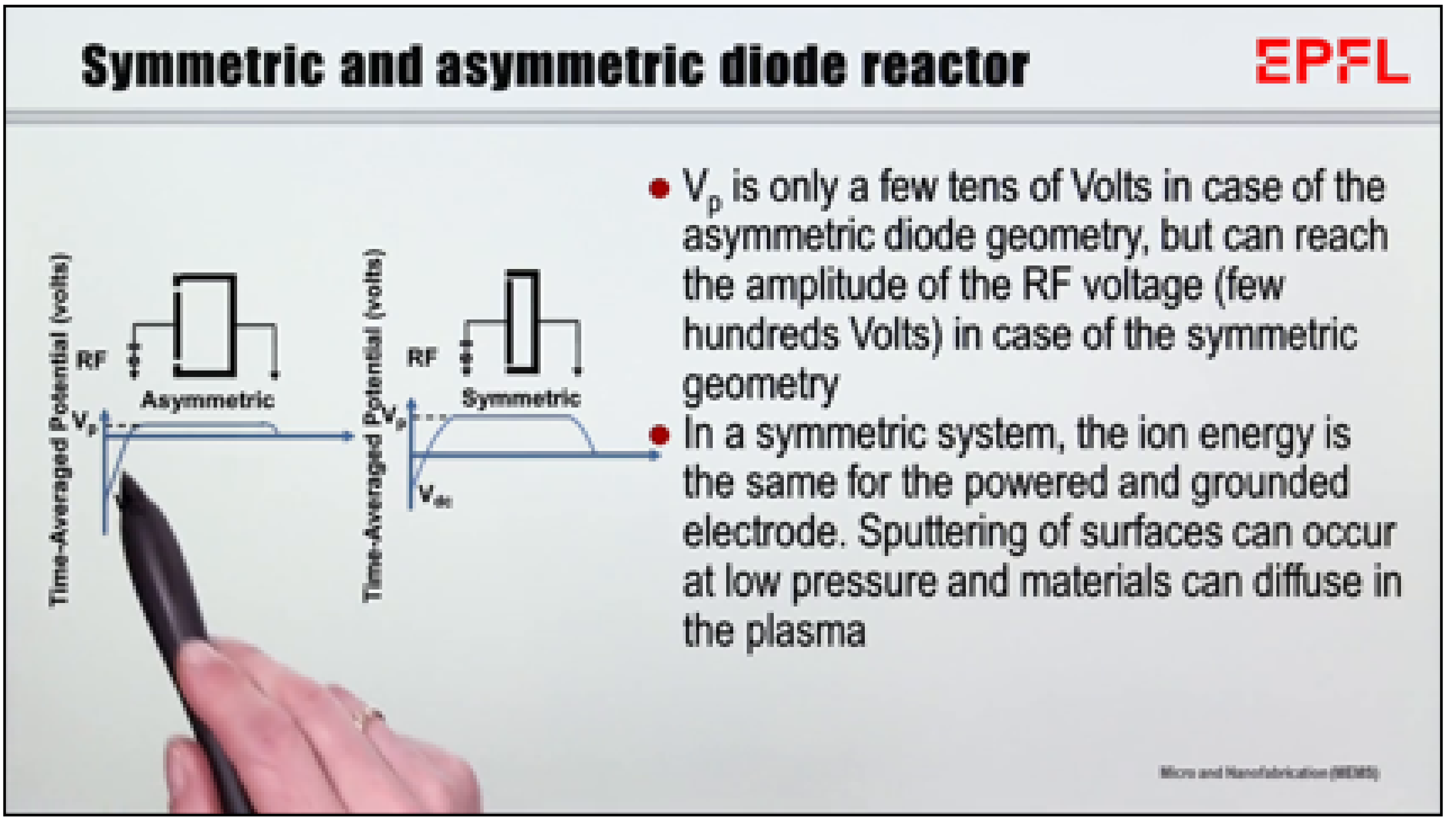


is to be positioned is smaller than the counter electrode. It's much bigger. While in the symmetric configuration, both electrodes are nearly the same.

notes

summary

5m 2s

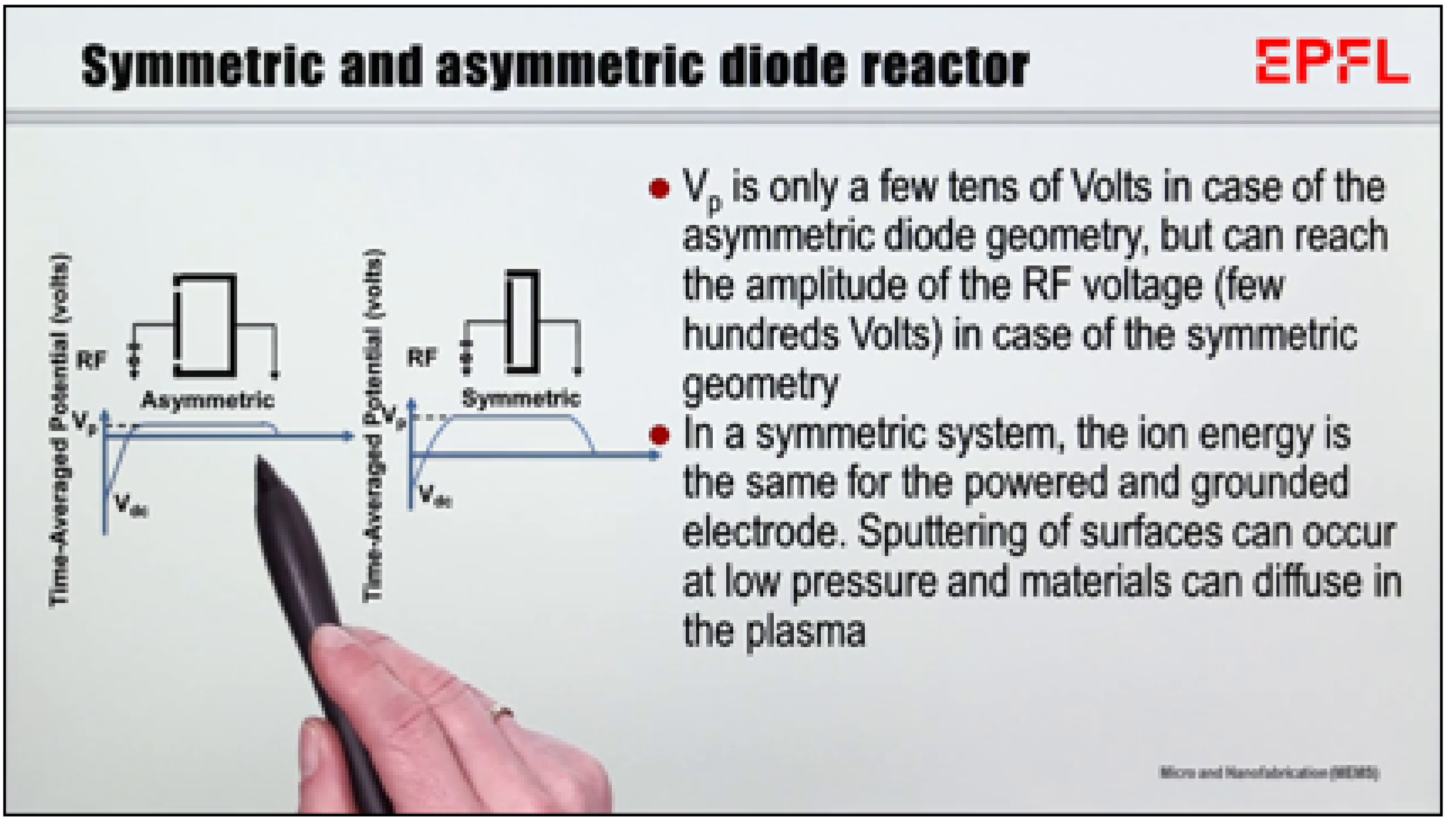


In the asymmetric reactor, the electrode on which the wafer is to be mounted was smaller than the counter electrode, and we have seen before that this leads to a strong voltage bias on the small electrode, hence, heavy ion bombardment.

notes

summary

5m 14s

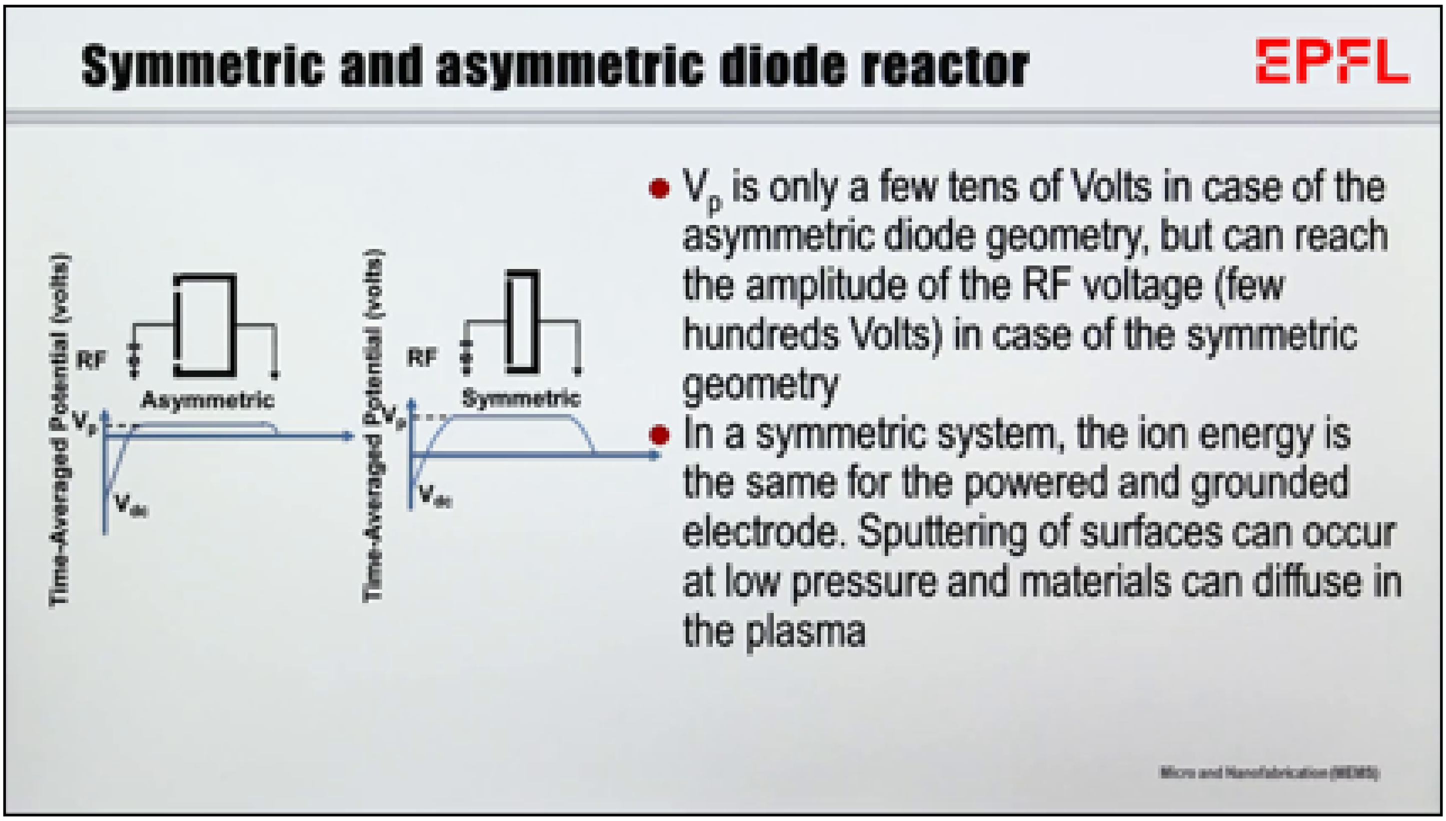


The voltage *Vp* in that case was very small so that there is little or no impact

notes

summary

5m 36s

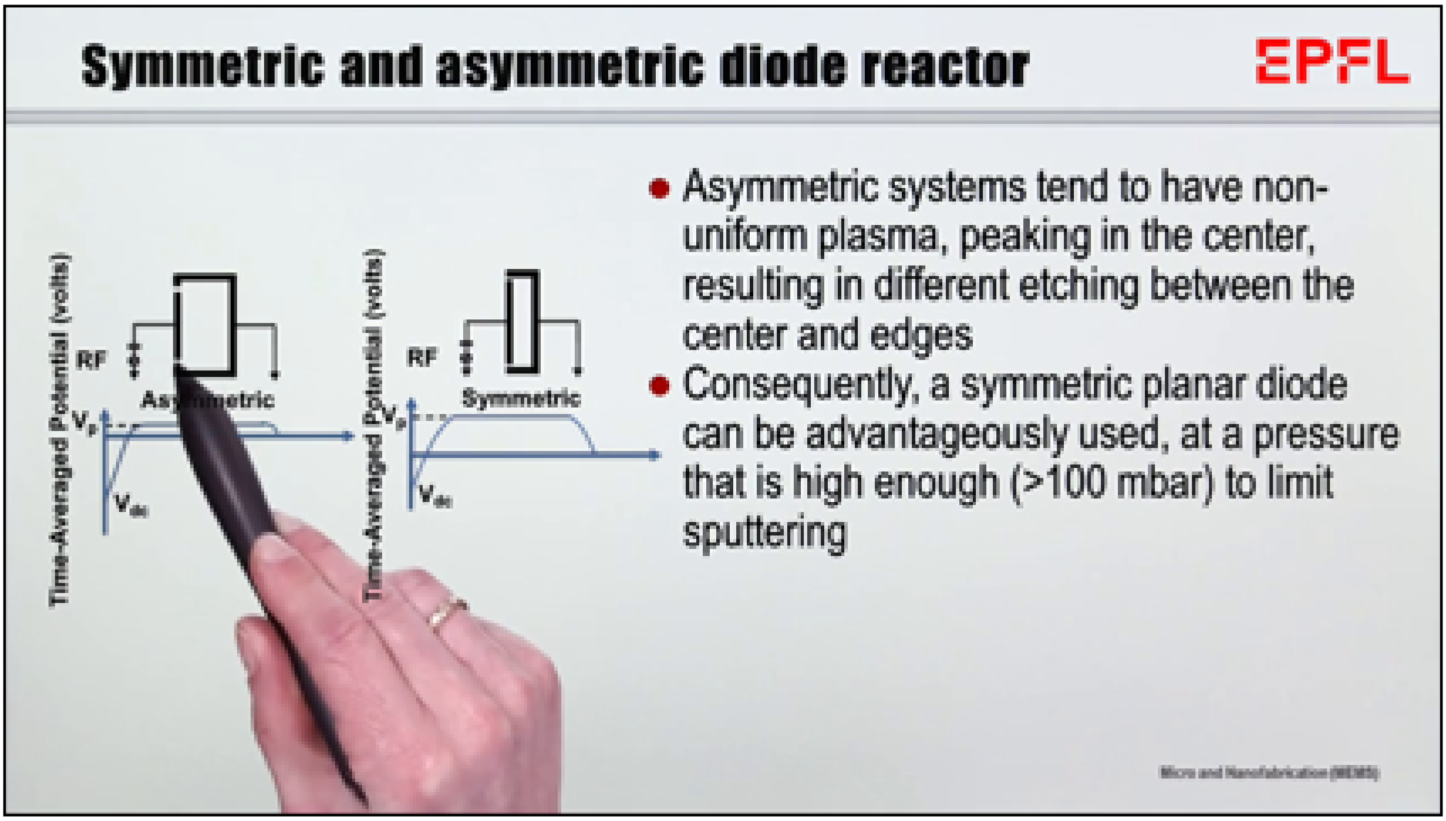


on the counter electrode, so there is no degradation of the reactor. In the symmetric diode reactor, both electrodes have about the same surface area and in this case, all electrode surfaces can be bombarded and thus sputter materials can eventually diffuse into the plasma when the gas pressure is too low.

notes

summary

5m 41s

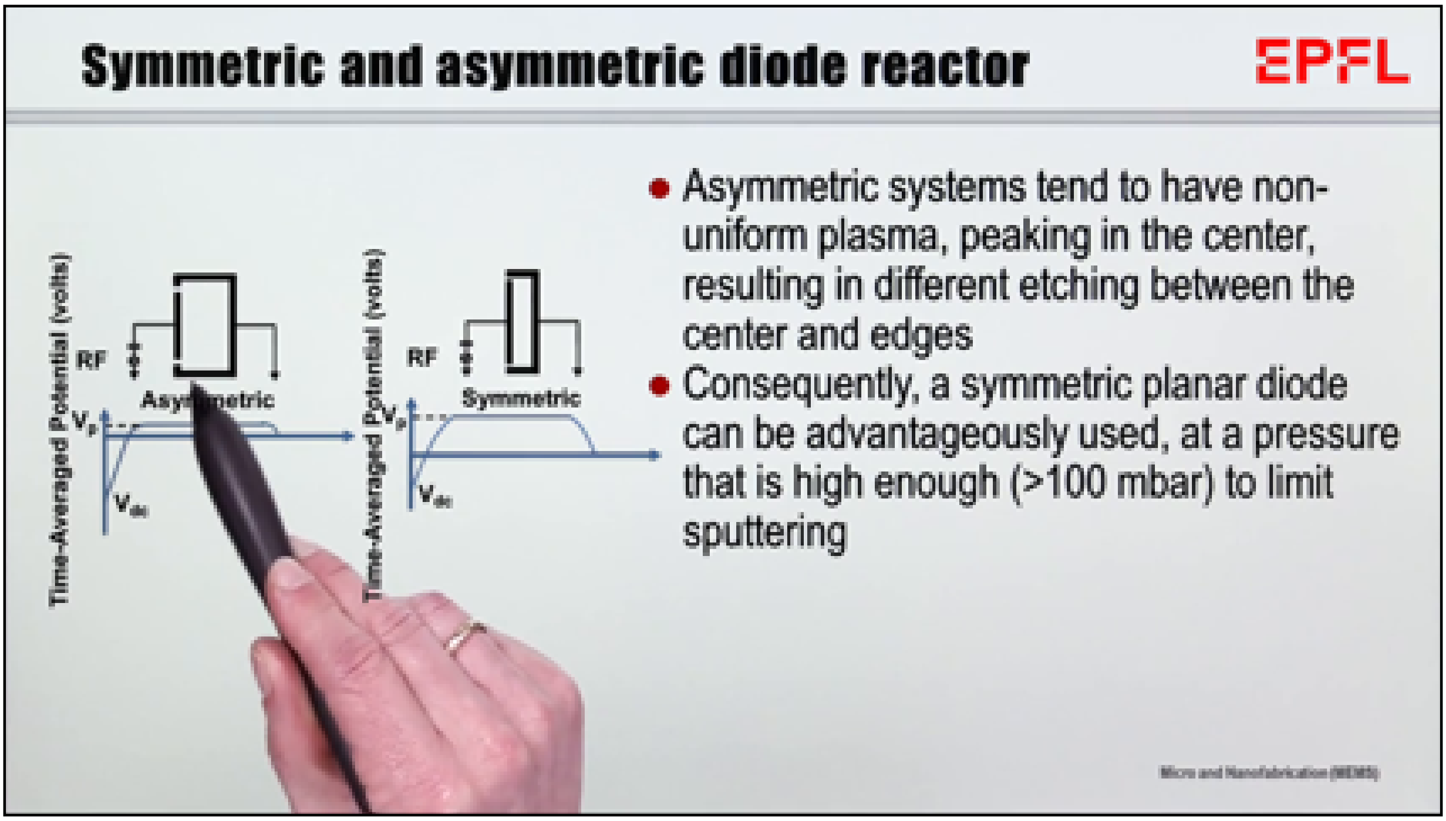


To avoid this diffusion into the plasma, one chooses typically the gas pressure not too low. At first sight, a diode reactor

notes

summary

6m 13s

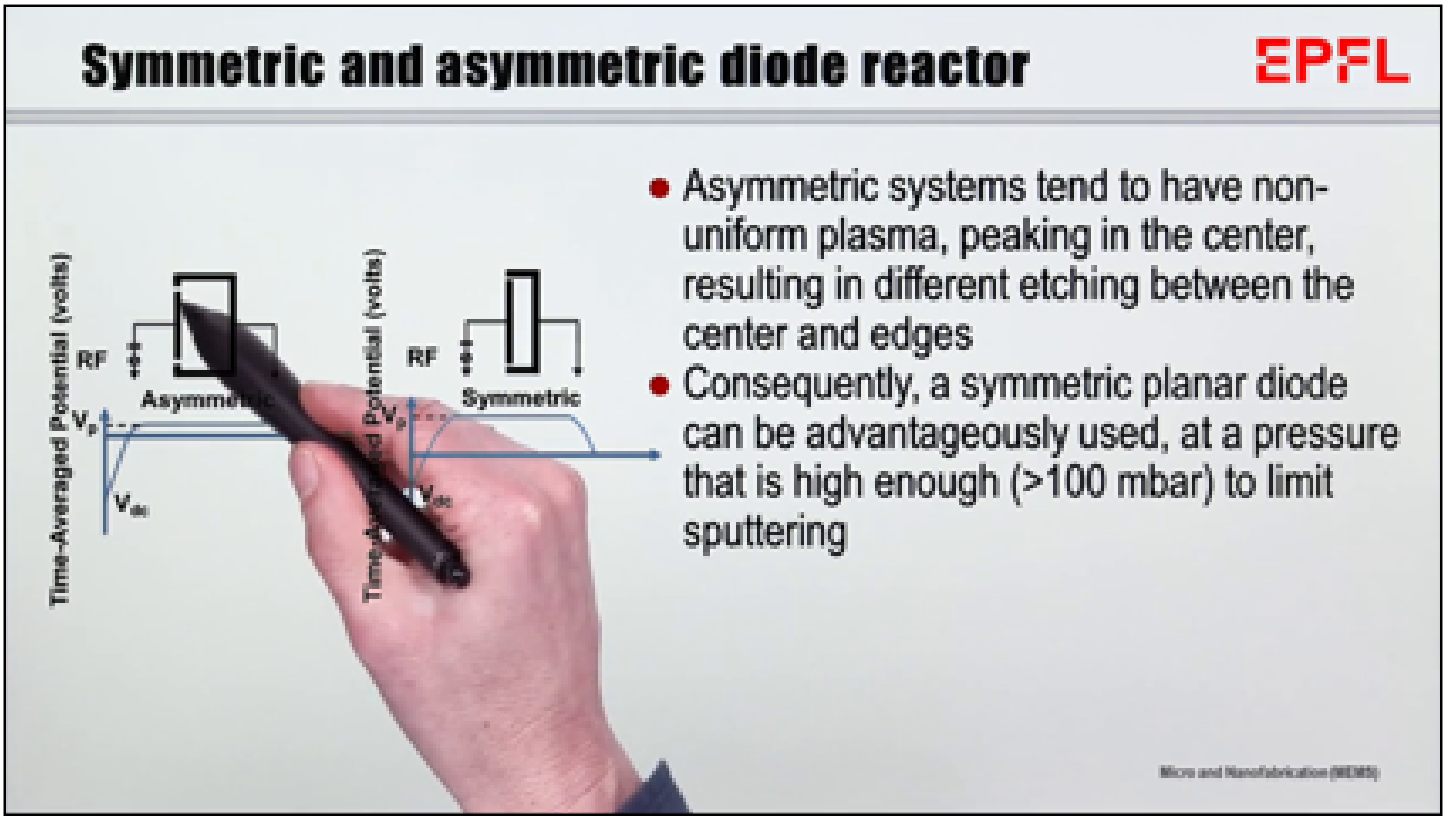


with a smaller size working electrode is advantageous

notes

summary

6m 23s

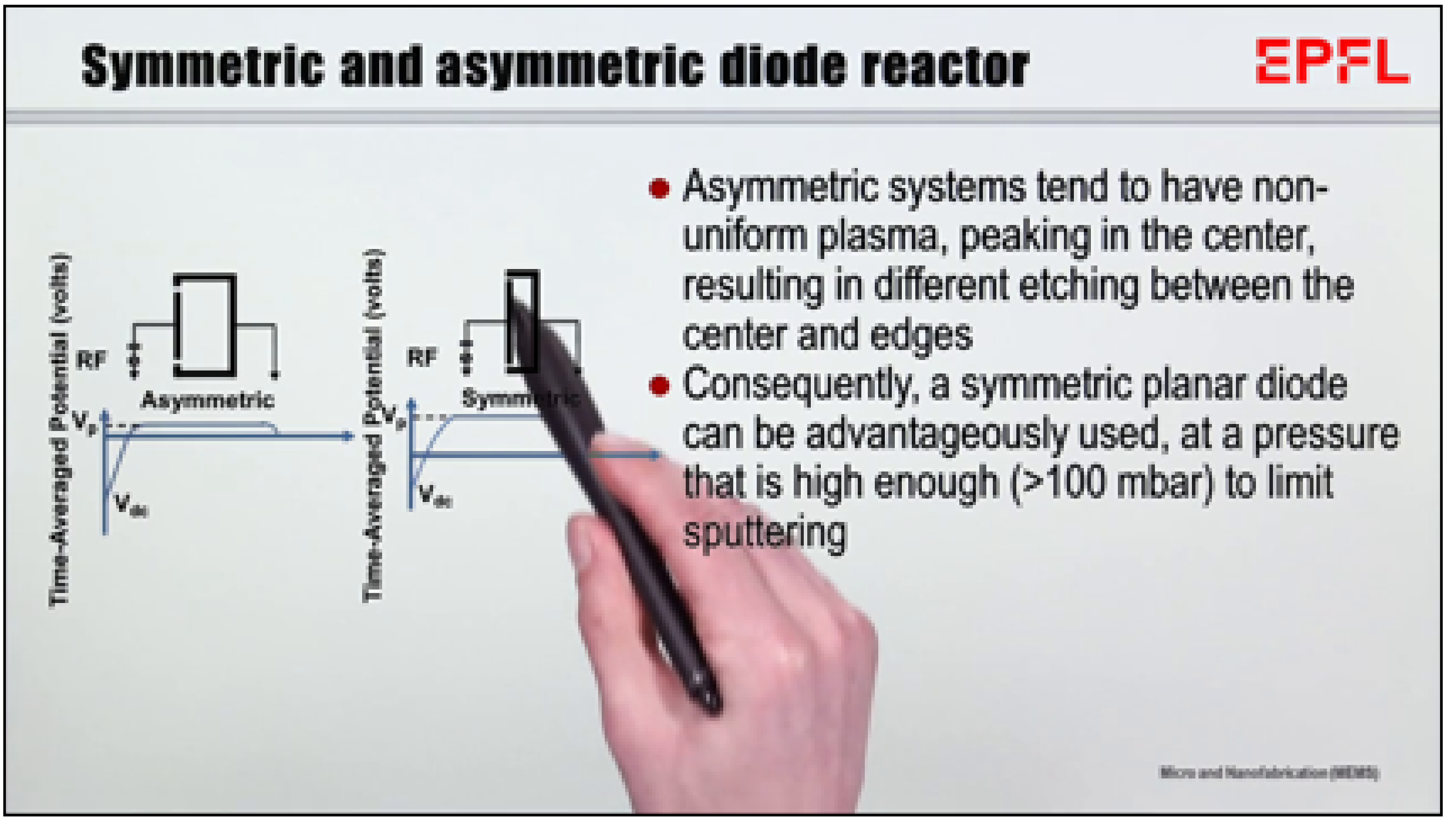


but the RF power will be peaked in the center so that there is different etching, whether one is in the center or at the edge,

notes

summary

6m 26s



and this can be problematic for some applications. If that is the case, one uses a symmetric diode reactor where the field is uniform over the wafer.

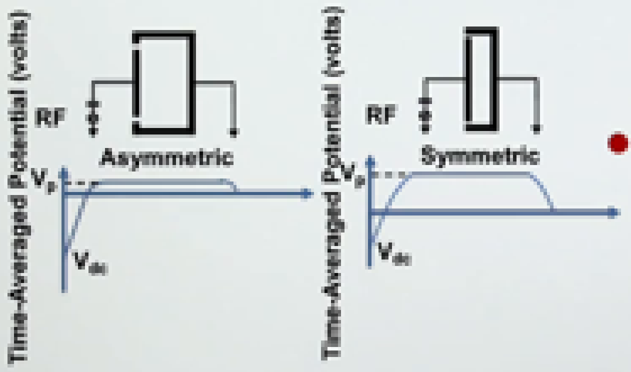
notes

summary

6m 38s

Symmetric and asymmetric diode reactor

EPFL



- Asymmetric systems tend to have non-uniform plasma, peaking in the center, resulting in different etching between the center and edges
- Consequently, a symmetric planar diode can be advantageously used, at a pressure that is high enough (>100 mbar) to limit sputtering

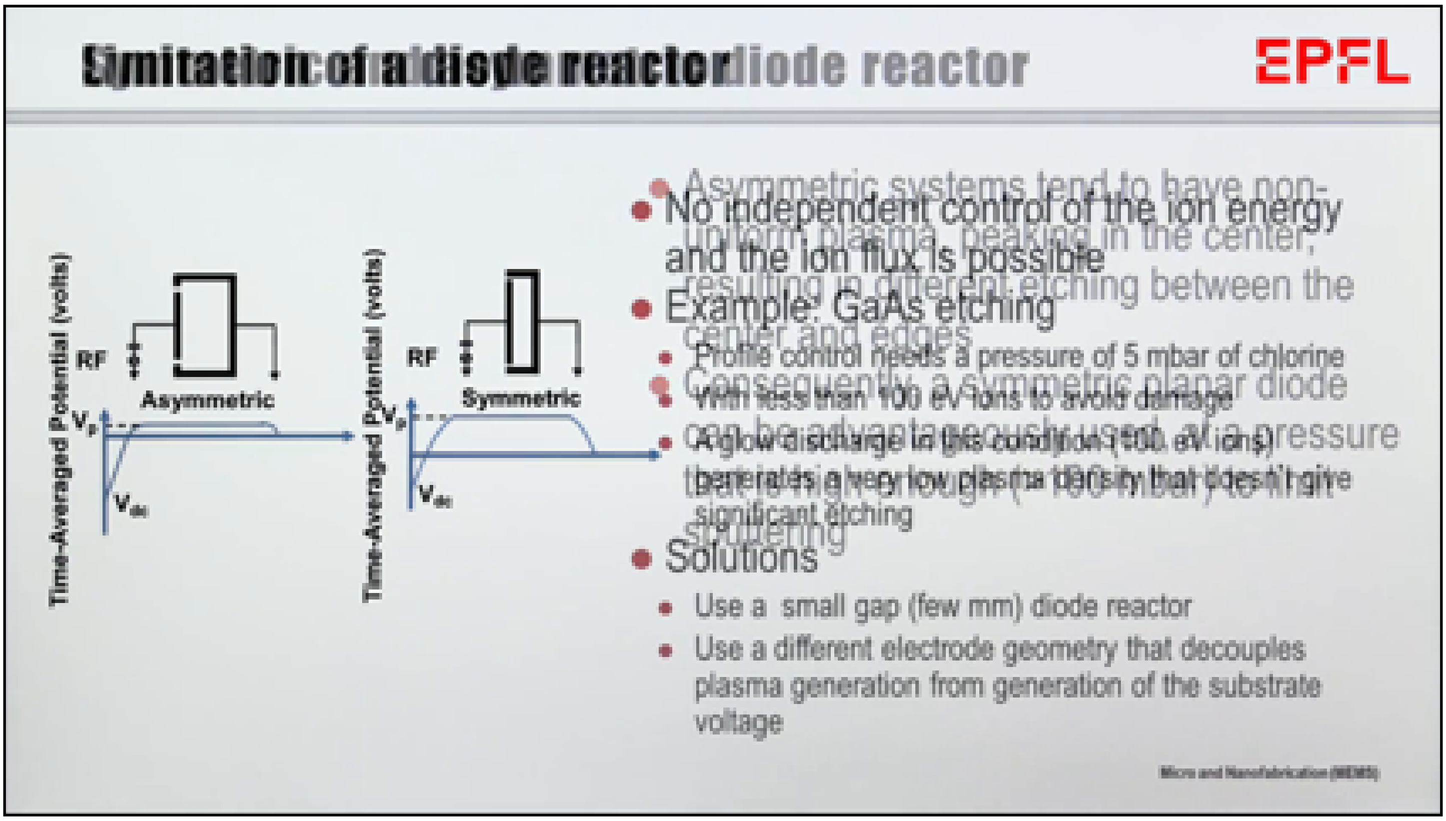
Micro and Nanofabrication (MEMS)

To reduce the effect of bombardment of the counter electrode

notes

summary

6m 59s

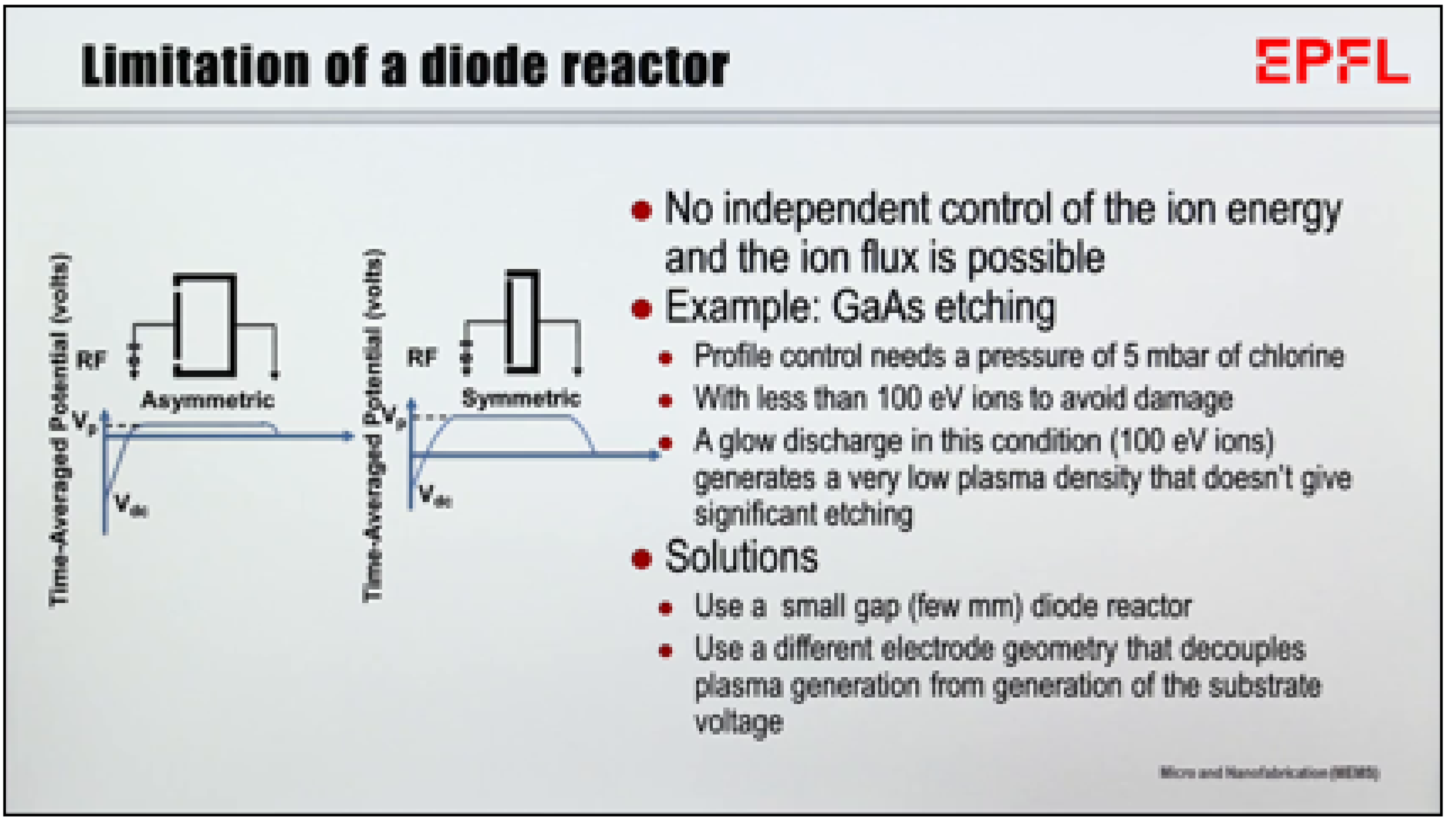


one chooses the pressure of the gas sufficiently high, so that spluttering from that counter electrode can be reduced. And as high pressure, we mention here pressures of the order of 100 millibar.

notes

summary

7m 3s

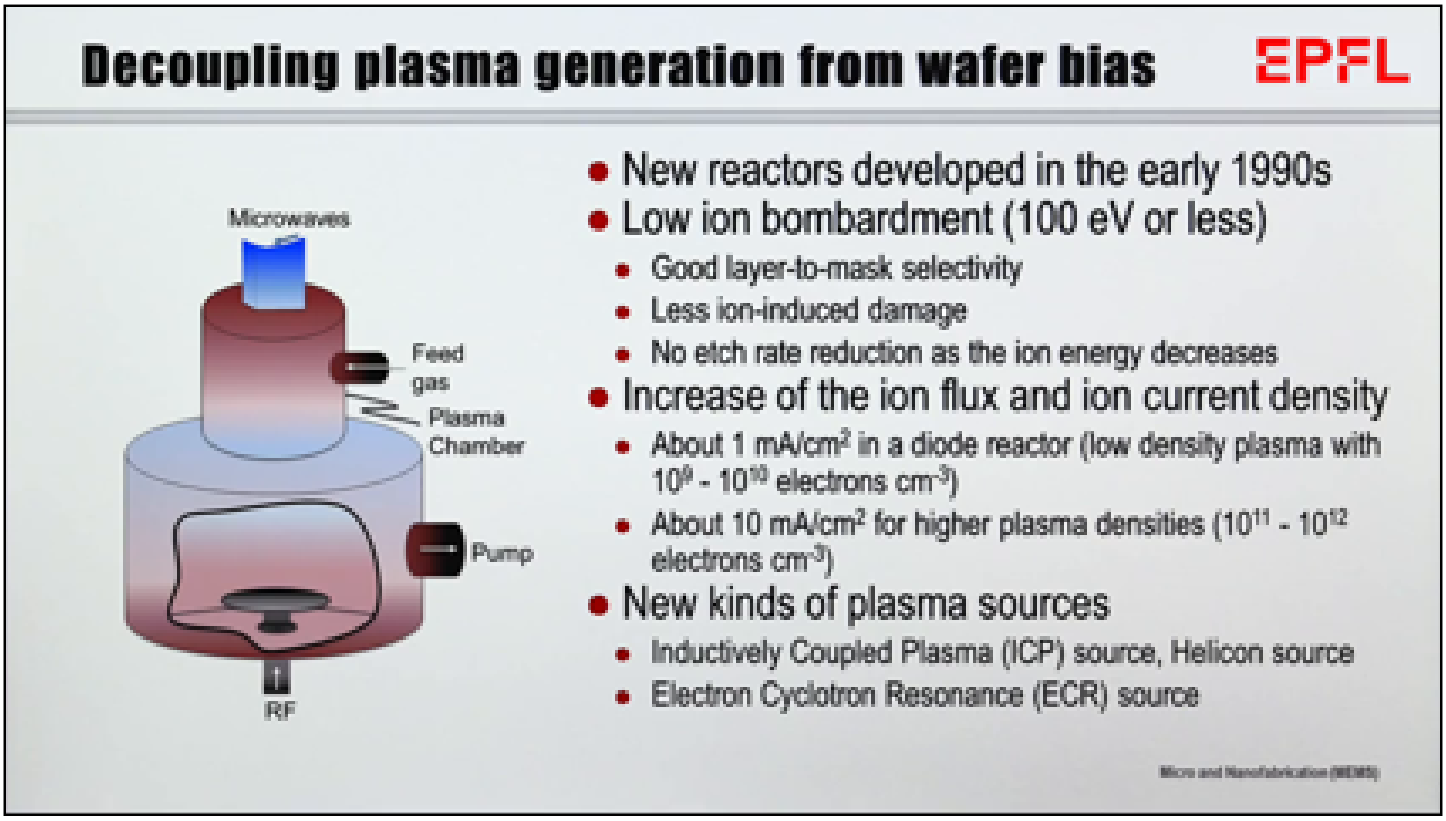


A diode reactor, like we have now discussed, has as limitation that there is no independent control of the ion energy and the ion flux. Both increase with increasing RF power. As an example where this can be problematic, we mention here the etching of gallium arsenide. We need here a chlorine plasma at a considerable pressure but we want to avoid a large voltage bias to the wafer to avoid damage of the material by the ion bombardment. However, this obliges to have very low plasma density that does not give significant etching. Two solutions exist to the problem. One can use a small gap diode reactor where the electrical fields and voltages are lower, or one can exploit a different electrode geometry than a diode

notes

summary

7m 18s

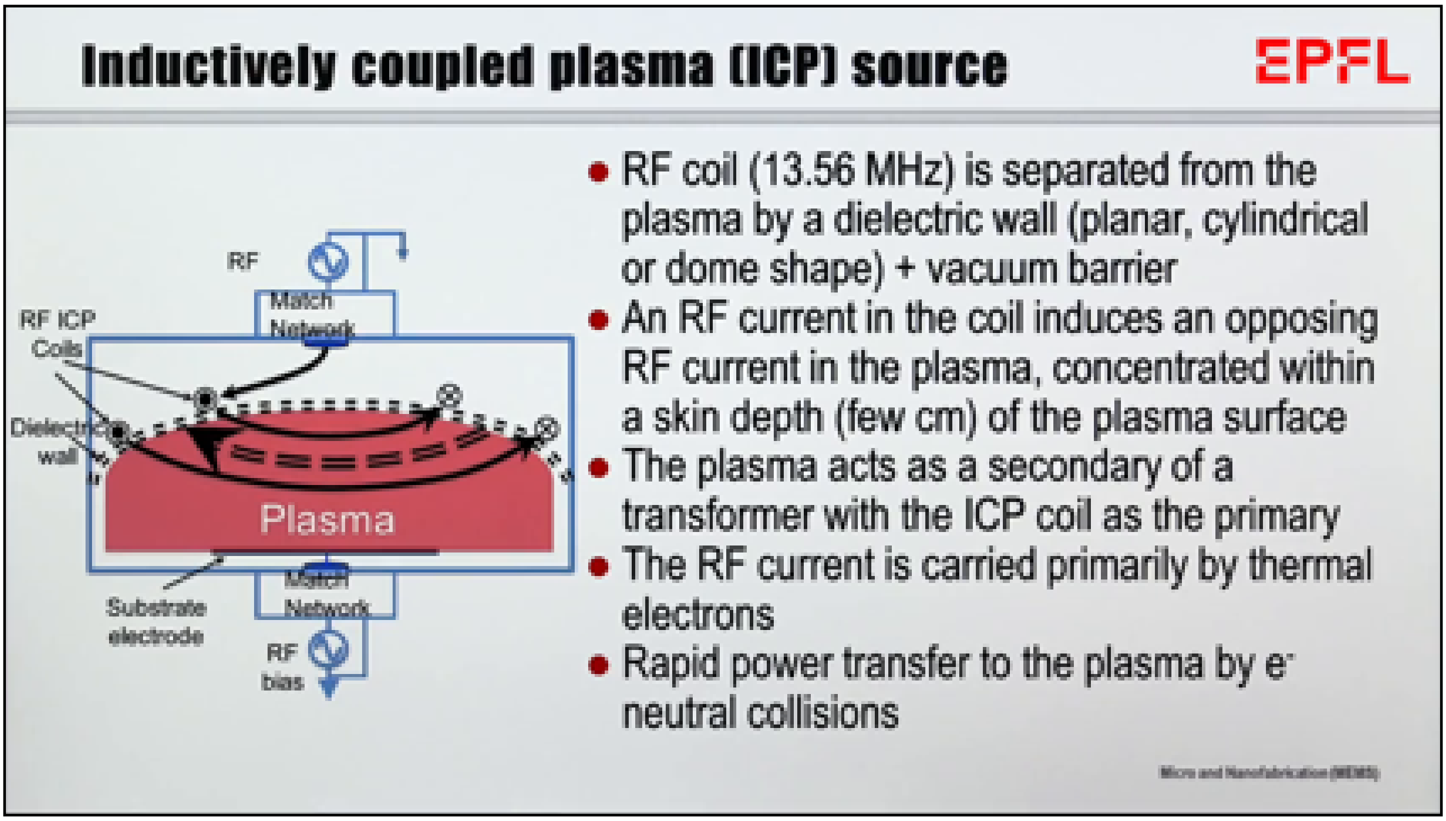


to decouple plasma generation from the generation of the negative substrate voltage bias.

notes

summary

8m 25s

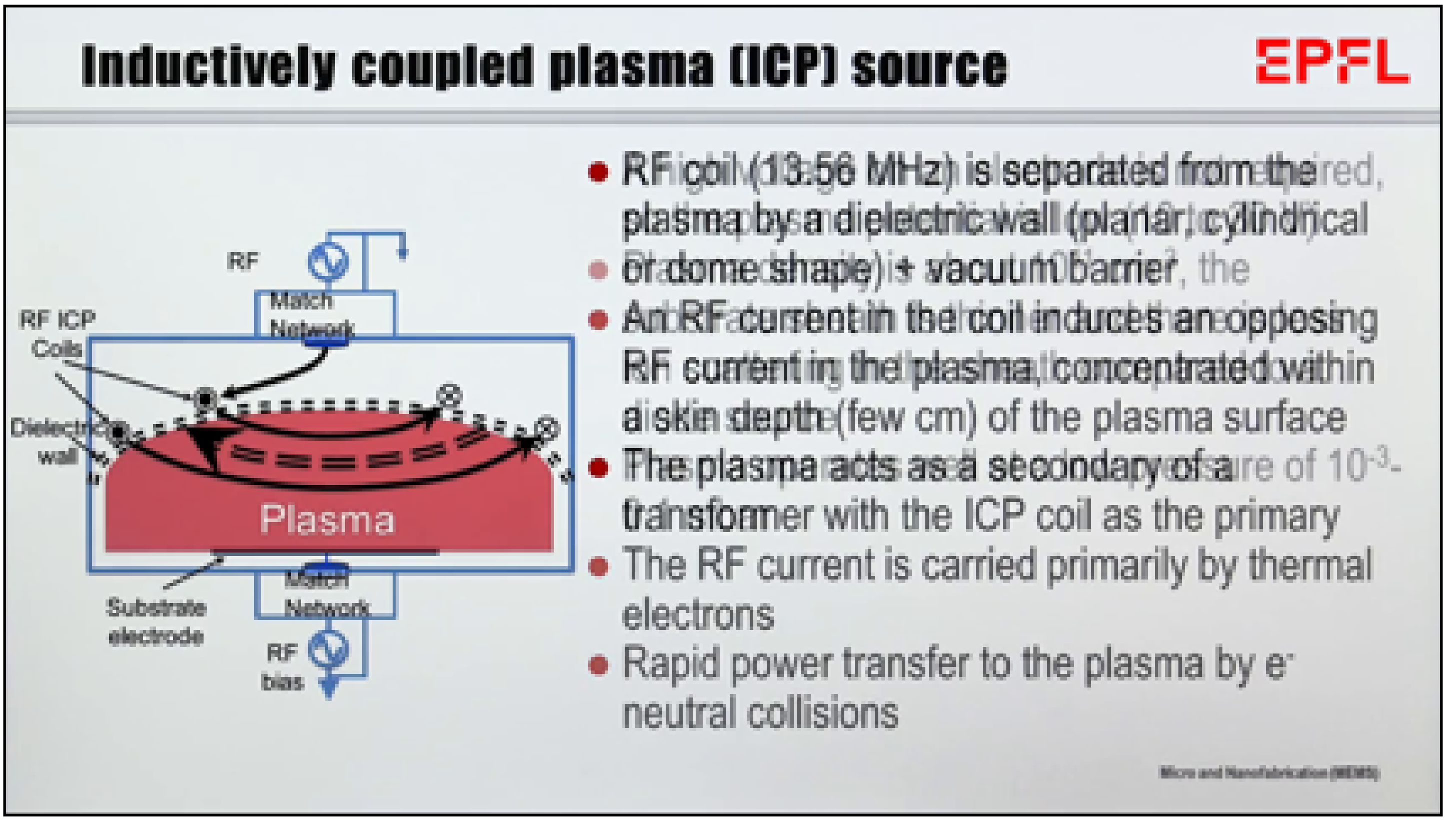


Such decoupling of the plasma generation from the generation of the bias was exploited in the newer etching reactors that were developed from the early 1990s on. These reactors are characterized by a low energy ion bombardment on the wafer, which results in a good layer-to-mask selectivity, less ion induced damage of the etched materials, and no etch-rate reduction when the ion energy decreases. In these new reactors, the ion flux and ion current density were significantly increased, typically by an order of magnitude. As examples of these new plasma sources, we will explain now briefly, the so called *inductively coupled plasma source* or *ICP source,* the *helicon source,* and the *electron cyclotron resonance* or *ECR source.*

notes

summary

8m 34s



In an ICP source, an RF coil operated at 13.5 megahertz is separated from the plasma by a dielectric wall which can have cylindrical, or in this case, a dome shape. An RF current which passes in this coil will induce a counter current in the plasma, within the skin depth of the plasma, which is a few centimeters. The plasma acts like a kind of secondary transformer with the ICP coil, the primary. The RF current is primarily carried by thermal electrons that rapidly transfer their energy to neutral atoms in the plasma.

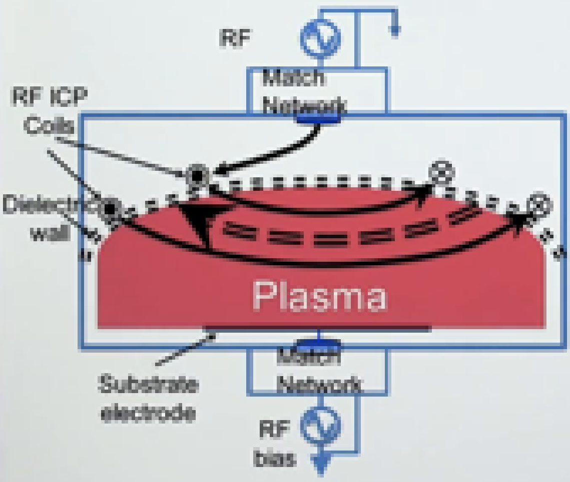
notes

summary

9m 42s

Inductively coupled plasma (ICP) source

EPFL



- A high voltage on an electrode is not required, so the plasma potential is low (10 to 30 V)
- Plasma density is about 10^{11} cm^{-3}, the substrate sheath is thinner and there is less ion scattering in the sheath compared to a diode source
- Plasma operates well at a low pressure of 10^{-3}-0.1 mbar

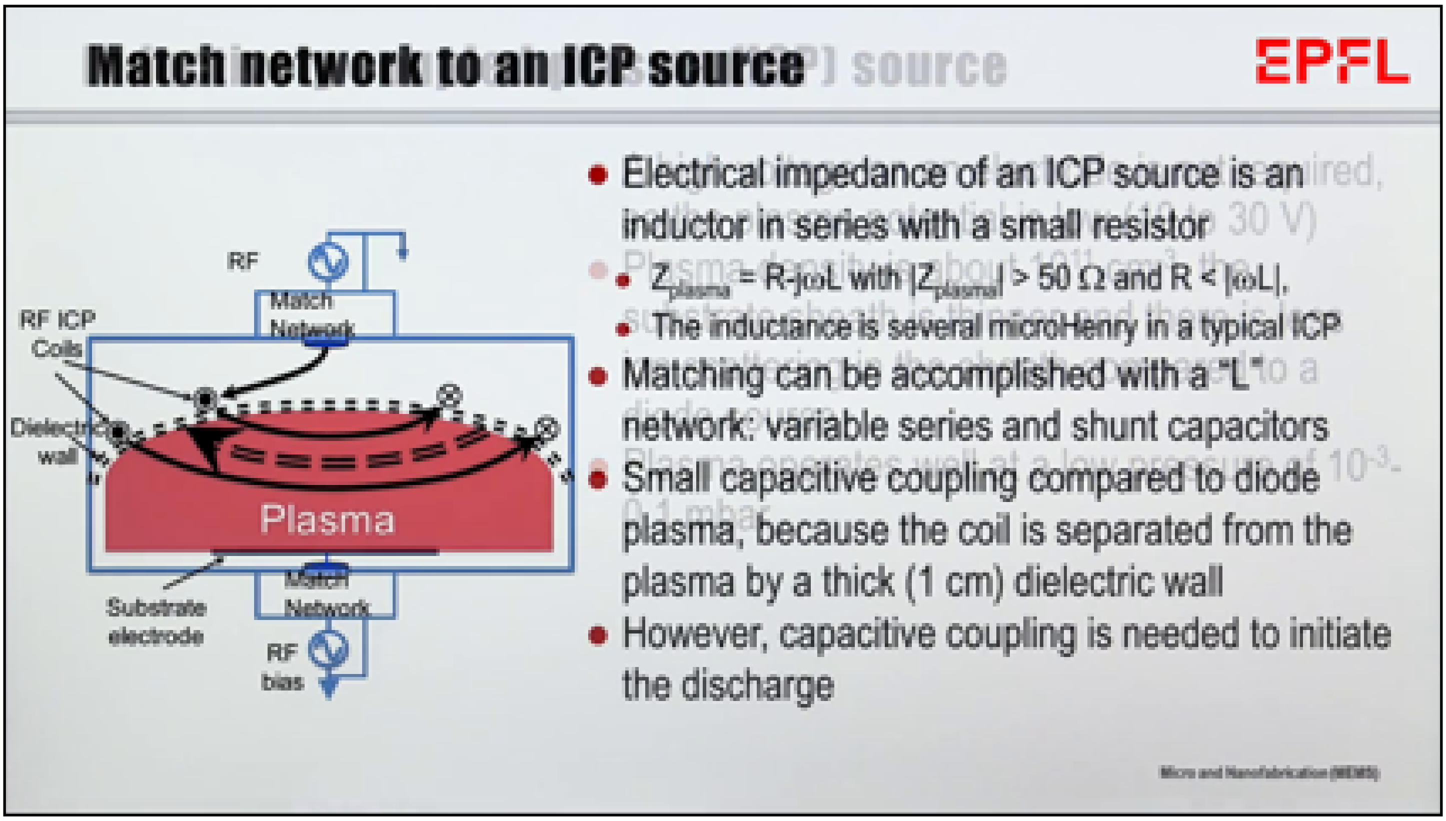
Micro and Nanofabrication (MEMS)

For an ICP reactor, a high voltage on the lower electrode

notes

summary

10m 37s

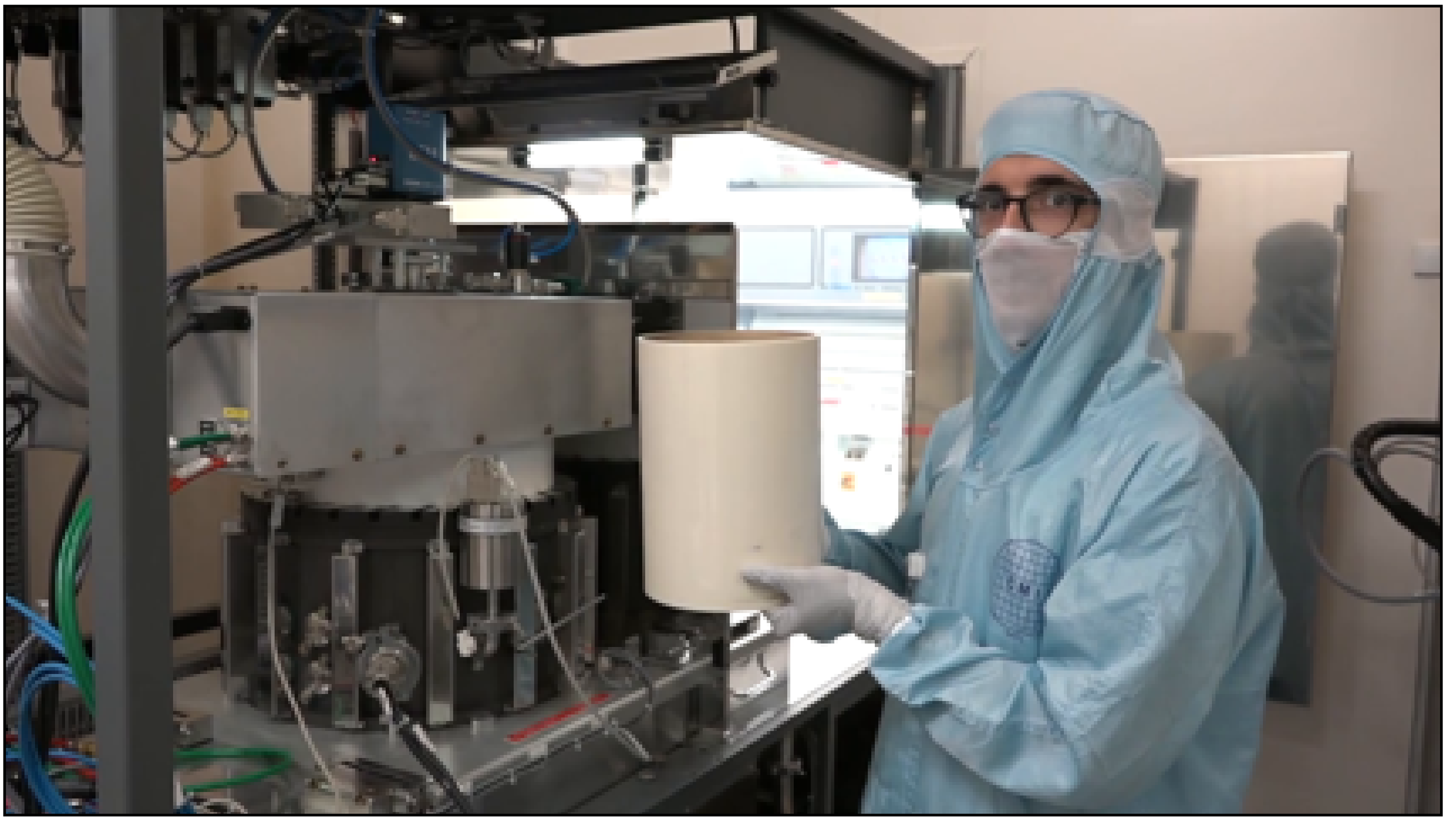


is not required, so the plasma potential can be low. Still, the plasma density can be high, as it is generated by the other RF source. The substrate sheet layer is thinner and there is less ion scattering in the sheet, compared to a diode source. The plasma operates well at low pressures of 10^-3 to 0.1 millibar.

notes

summary

10m 38s



An ICP source needs to be properly interfaced with an RF power generator. The electrical impedance of an ICP source is that of an inductor in series with a small resistor. The match network, to avoid or reduce reflection of power back to the source, can be accomplished with the so-called *L* network which consists of a number of variable series and shunt capacitors that are adjusted here. This type of plasma has a small capacitive coupling compared to the plasma generated in a diode reactor, because the coil is separated from the plasma by a rather thick, dielectric wall. However, the plasma needs to be initiated in the beginning via capacitive coupling. Note that besides the RF power for generation of the plasma, there is an extra RF power source for generating the surface voltage points. We are here in the cleanroom and show the outside of an ICP reactor. Inside of the plasma source is a coil

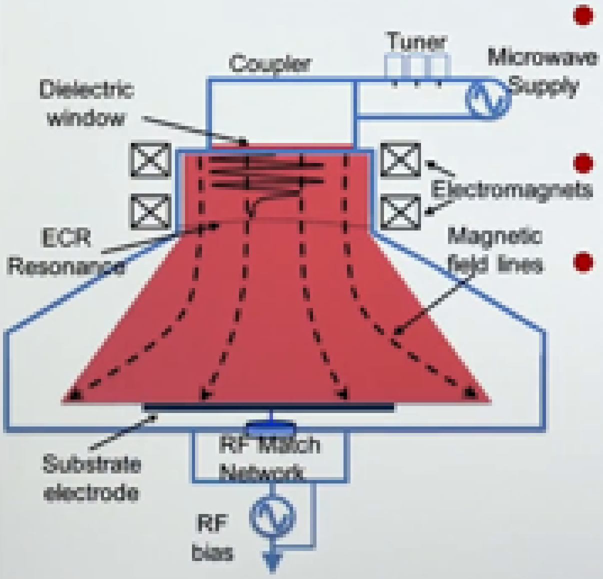
notes

summary

11m 15s

Electron Cyclotron Resonance (ECR) source

EPFL



- Microwave power at a frequency 2.45 GHz is carried by a waveguide and coupled to the plasma through a dielectric wall
- Matching is usually accomplished by a three-stub tuner
- Power absorption occurs at the location where the ECR resonance condition is satisfied, i.e. where $\omega = \omega_{ce}$, i.e. where the cyclotron motion of the electrons is in phase with the rotating electric field of the ECR wave

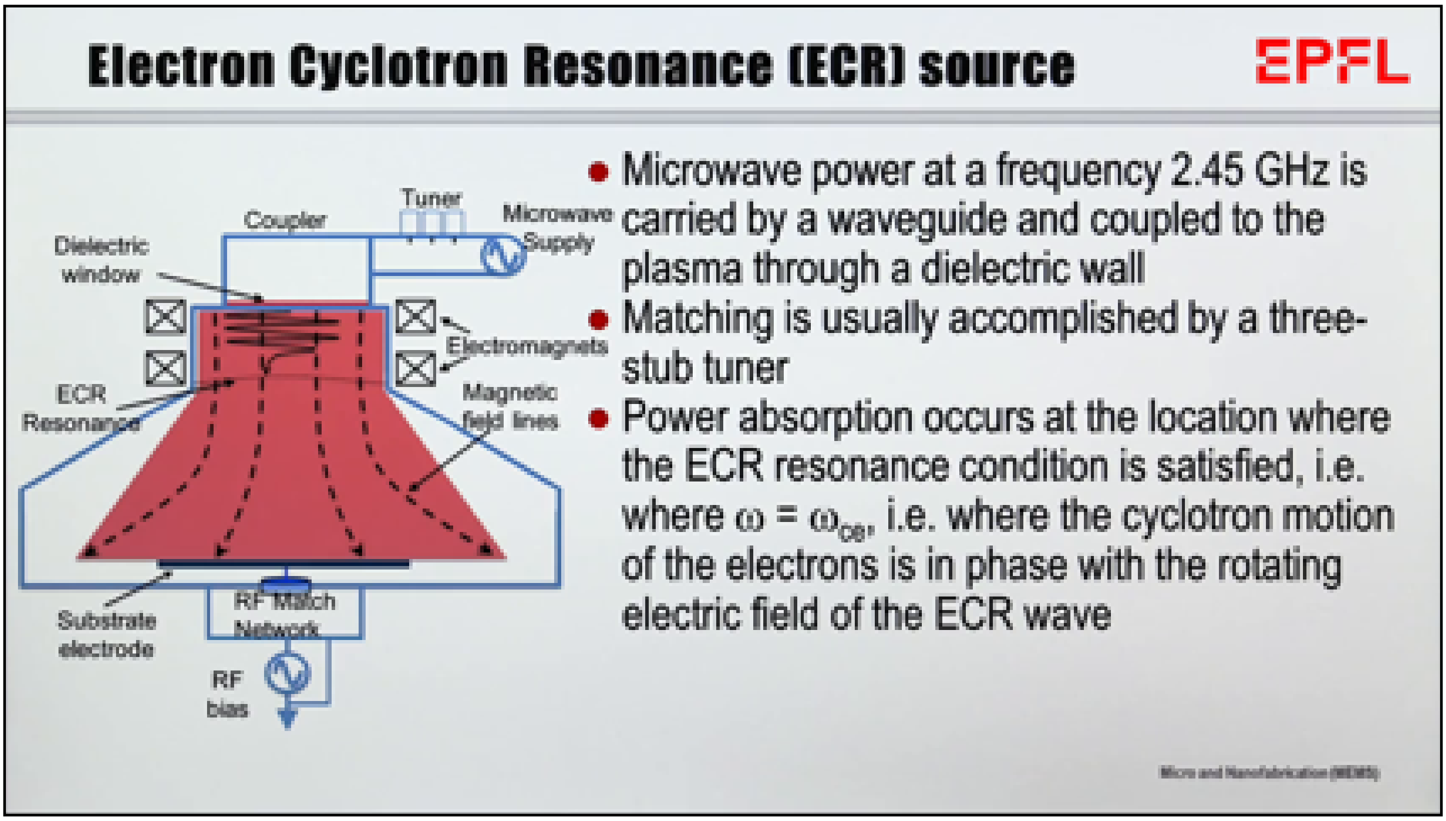
Micro and Nanofabrication (MEMS)

that surrounds a ceramic cylinder. Here we show such a cylinder that has been used and removed after a certain time of operation. At the inside of the cylinder, we see some degradation effects of the material due to the plasma, which is the reason why the cylinder has to be exchanged regularly to a new one during maintenance of the ICP etching system.

notes

summary

12m 37s



Another type of new plasma source is the *electron cyclotron resonance*

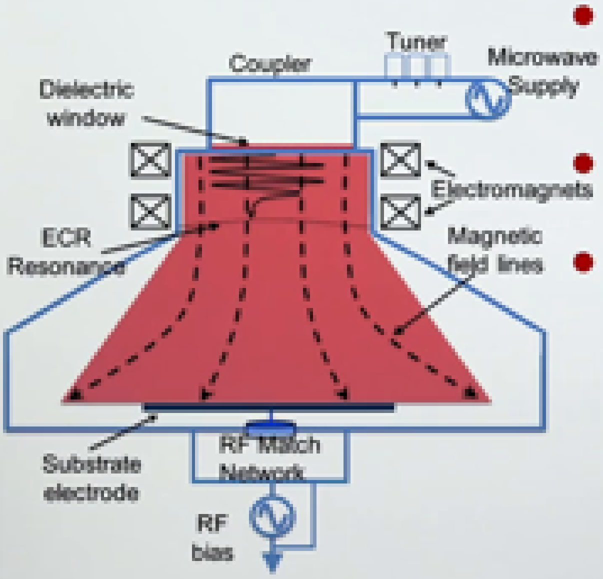
notes

summary

13m 12s

Electron Cyclotron Resonance (ECR) source

EPFL



- Microwave power at a frequency 2.45 GHz is carried by a waveguide and coupled to the plasma through a dielectric wall
- Matching is usually accomplished by a three-stub tuner
- Power absorption occurs at the location where the ECR resonance condition is satisfied, i.e. where $\omega = \omega_{ce}$, i.e. where the cyclotron motion of the electrons is in phase with the rotating electric field of the ECR wave

Micro and Nanofabrication (MEMS)

or *ECR source.* In this design, microwave power at a frequency of 2.45 gigahertz is carried by a wave guide and coupled to the plasma through a dielectric window. The source has built-in magnetic field lines

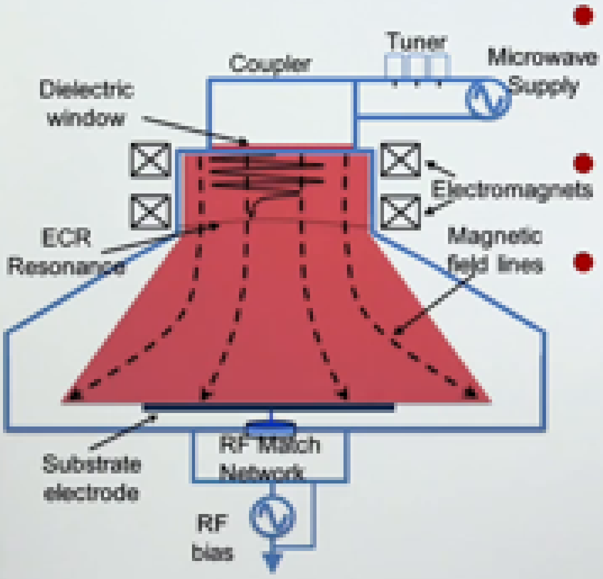
notes

summary

13m 17s

Electron Cyclotron Resonance (ECR) source

EPFL



- Microwave power at a frequency 2.45 GHz is carried by a waveguide and coupled to the plasma through a dielectric wall
- Matching is usually accomplished by a three-stub tuner
- Power absorption occurs at the location where the ECR resonance condition is satisfied, i.e. where $\omega = \omega_{ce}$, i.e. where the cyclotron motion of the electrons is in phase with the rotating electric field of the ECR wave

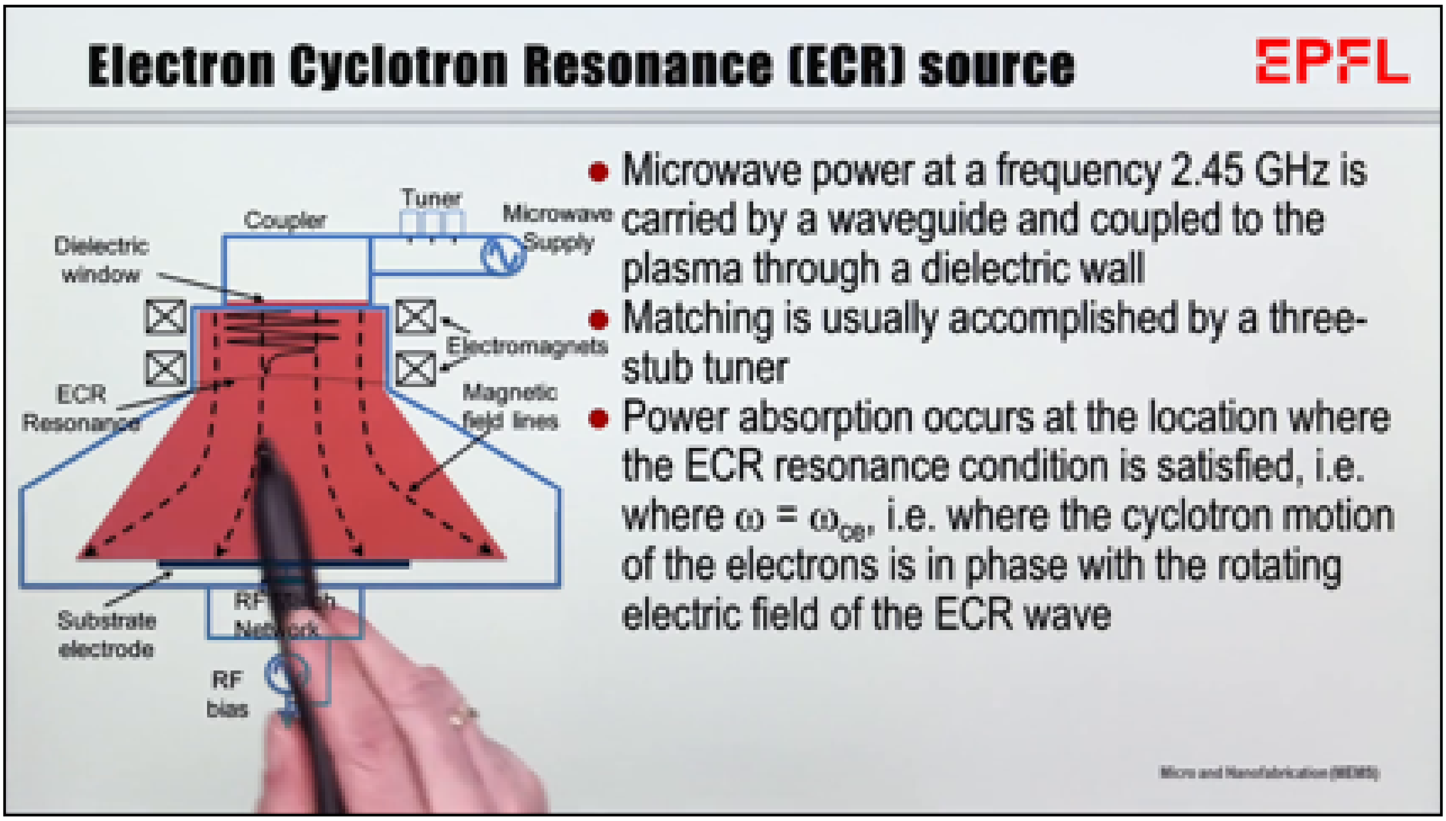
Micro and Nanofabrication (MEMS)

generated by these electromagnets around which electrons can circulate.

notes

summary

13m 37s



The plasma absorbs power at a location where the electron cyclotron resonance condition is satisfied,

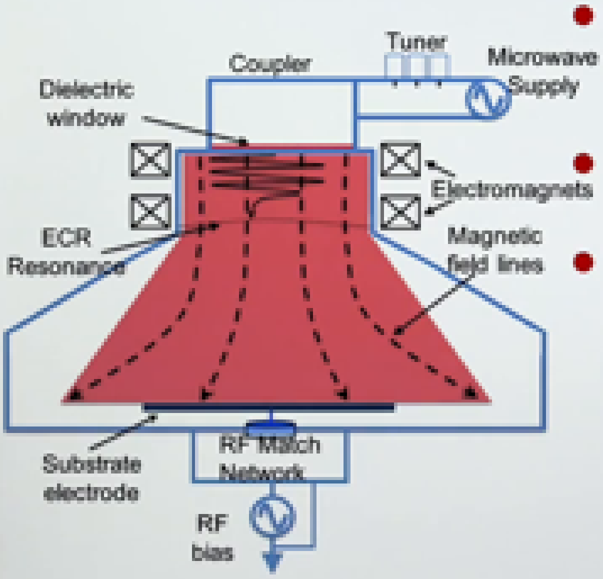
notes

summary

13m 45s

Electron Cyclotron Resonance (ECR) source

EPFL



- Microwave power at a frequency 2.45 GHz is carried by a waveguide and coupled to the plasma through a dielectric wall
- Matching is usually accomplished by a three-stub tuner
- Power absorption occurs at the location where the ECR resonance condition is satisfied, i.e. where $\omega = \omega_{ce}$, i.e. where the cyclotron motion of the electrons is in phase with the rotating electric field of the ECR wave

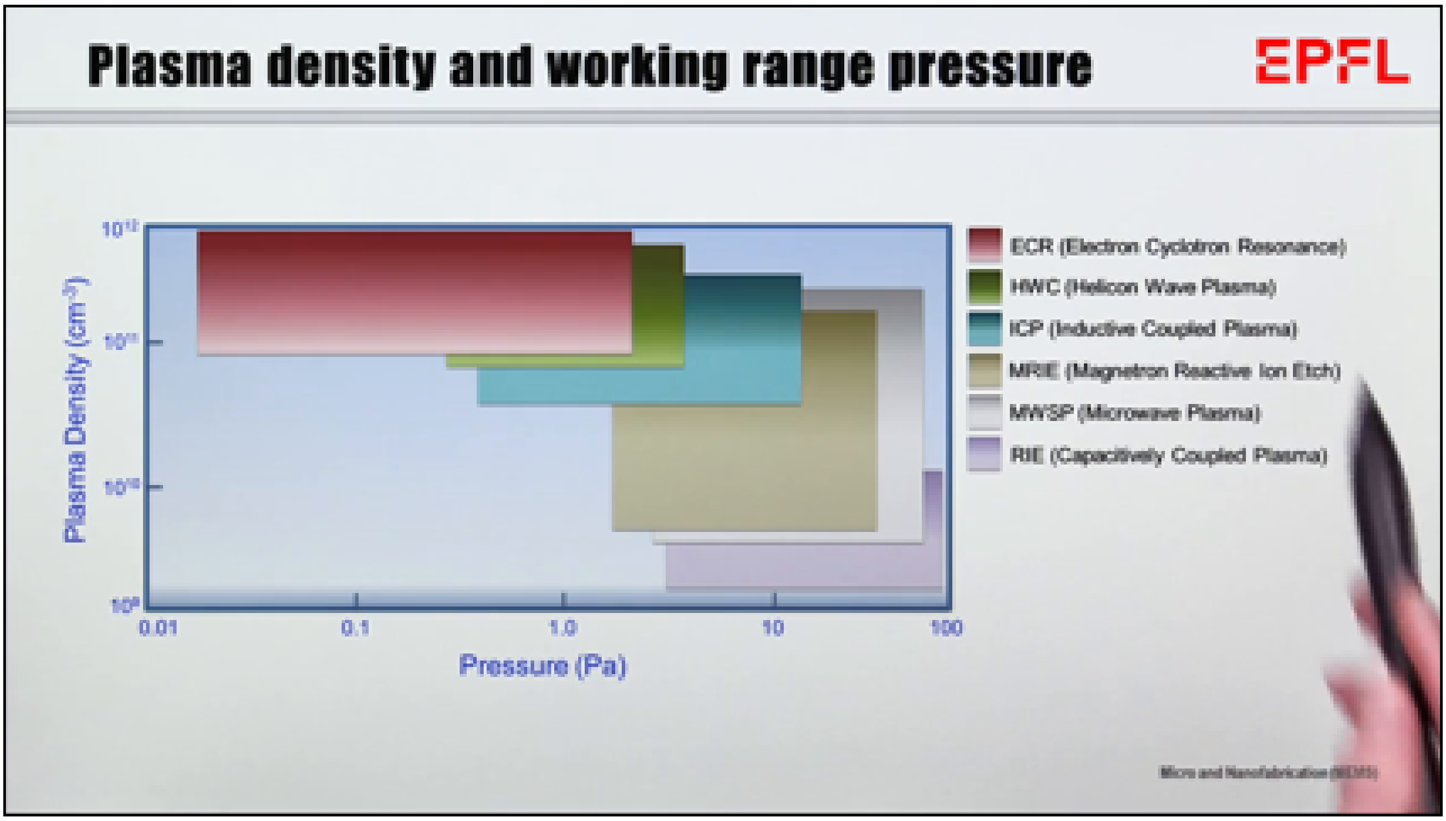
Micro and Nanofabrication (MEMS)

that is, where the natural cyclotron motion of the electron around the field line is in phase

notes

summary

13m 58s

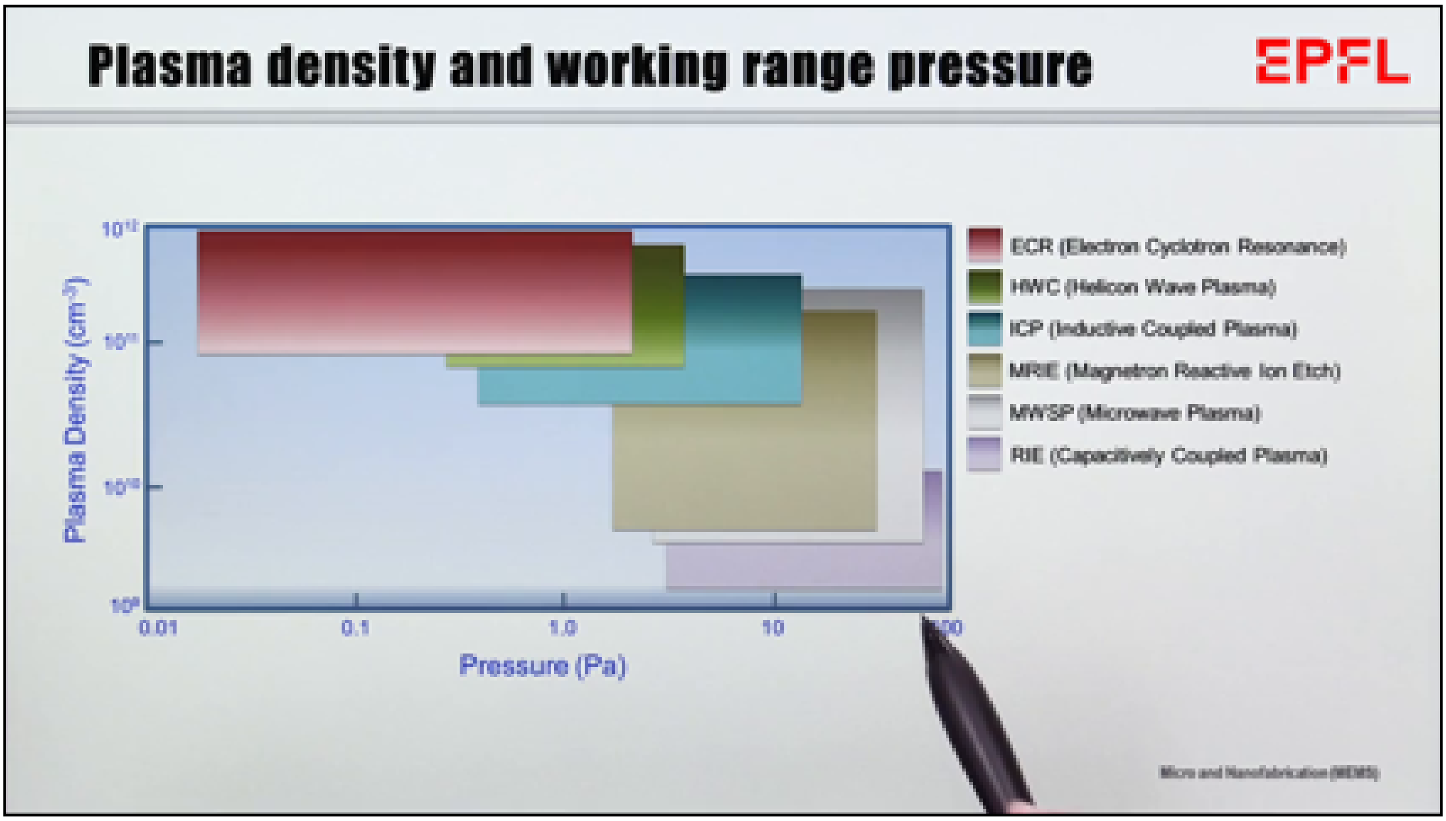


with the rotating electrical field of the ECR wave. Finally, we mentioned as one of the new plasma sources, the helicon source, in which an antenna coil with a special shape is wound around the plasma. The helicon wave source works at 13.5 megahertz, also in presence of a magnetic field. Plasma parameters of the helicon source are comparable to that of ICP and ECR sources. This slide summarizes the plasma densities that are obtained

notes

summary

14m 4s

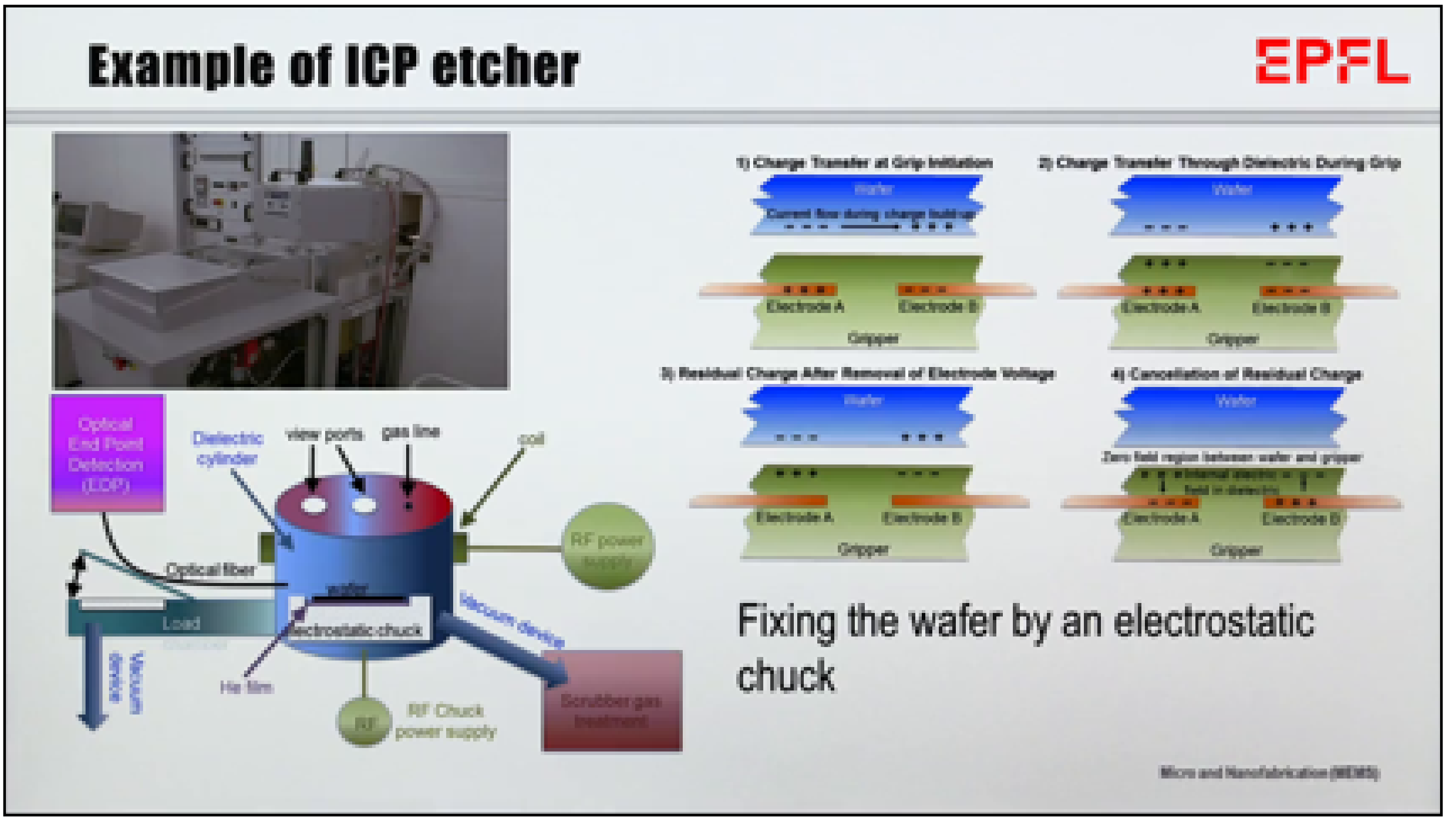


with the various plasma sources as indicated here, as well as the gas operation pressure regimes.

notes

summary

14m 49s

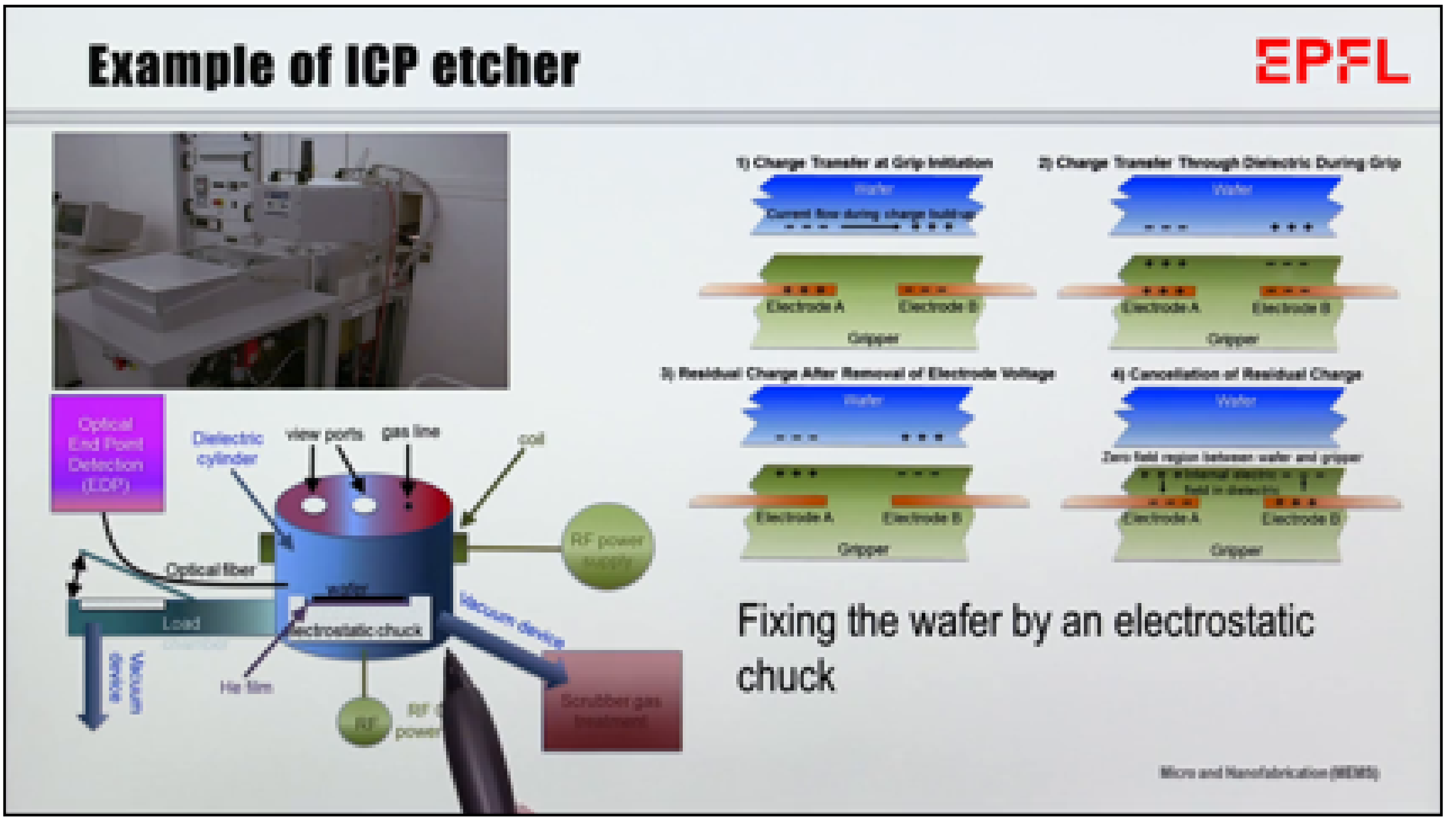


What we see on this slide is that going through more modern equipment, we go to lower working pressures and higher plasma densities.

notes

summary

15m 1s

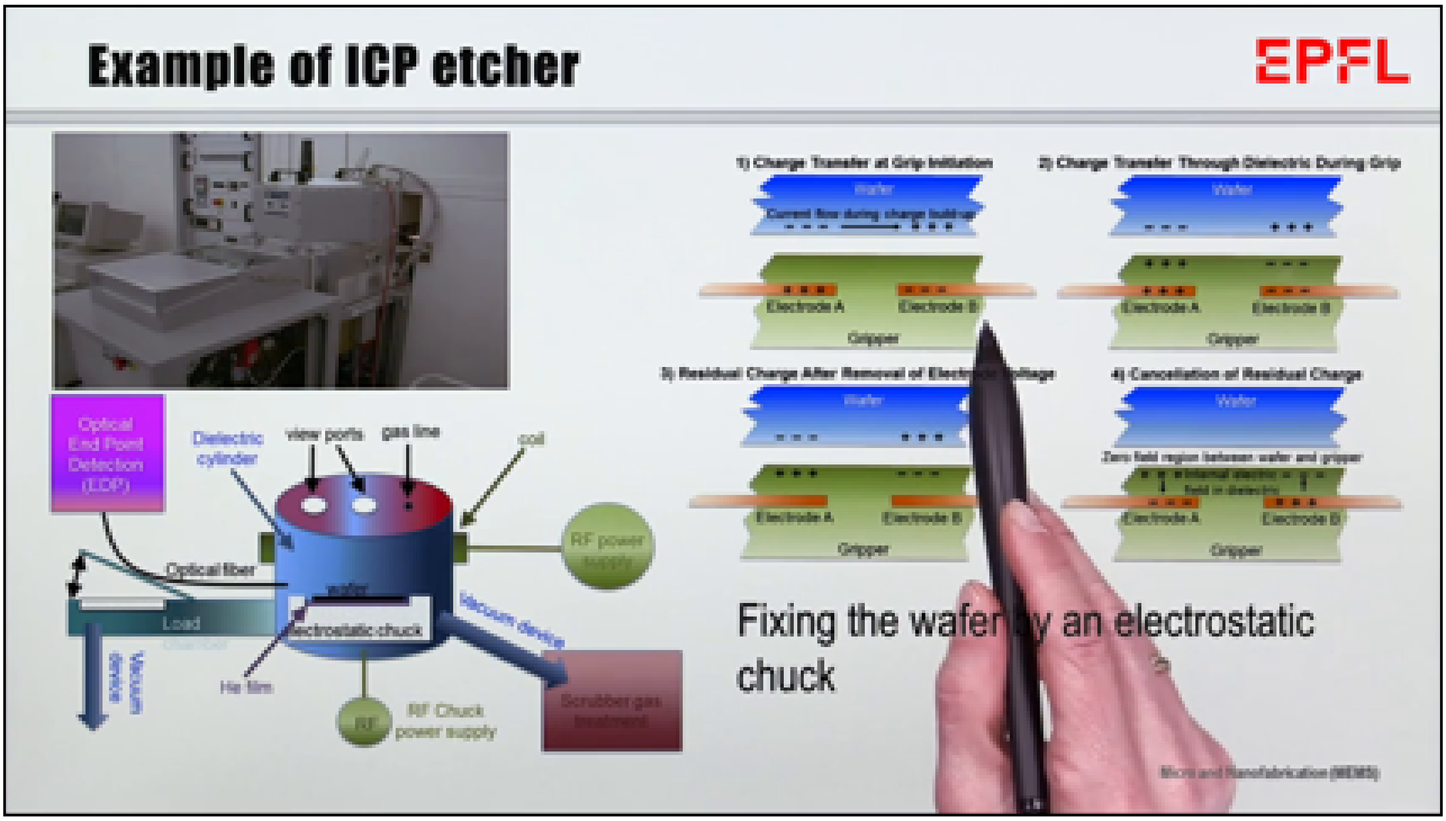


Here we show a picture and a schematic diagram of an ICP etcher which we have already introduced before. We want now to explain the mechanism of the electrostatic chuck

notes

summary

15m 11s

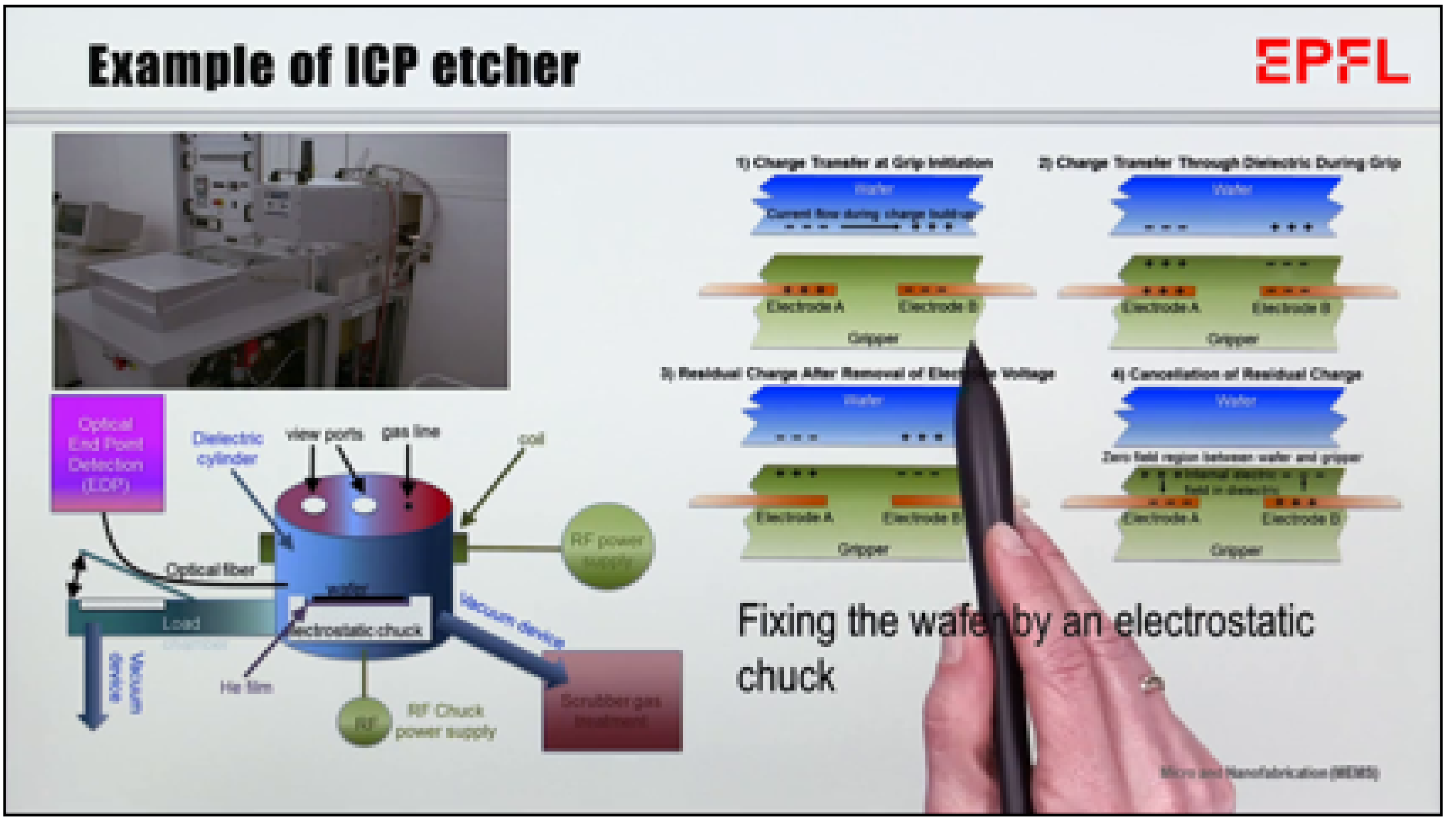


for clamping of the wafer into the reactor. The wafer was introduced via a load mechanism to the chuck and in the chuck, there is a part which is called *gripper*,

notes

summary

15m 27s

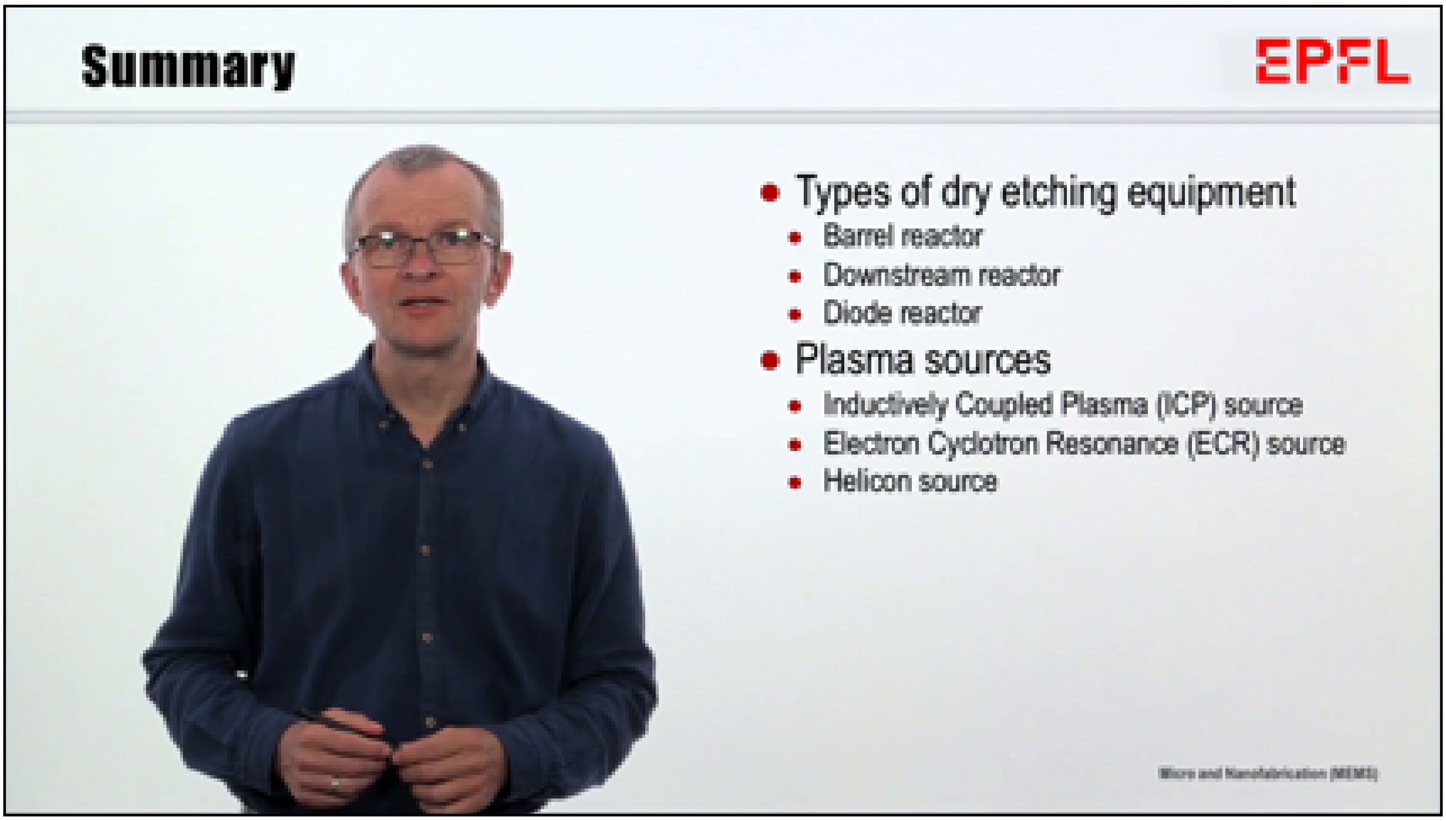


which contains two electrodes to which one can apply a voltage. Here, a positive voltage, here a negative voltage

notes

summary

15m 43s



and this induces an opposite voltage in the wafer which is then clamped to the gripper. For removal of this electrostatically bound wafer, one needs to apply opposite voltages to the electrodes. In this lesson, we have discussed three types of dry etching equipment, like a barrel reactor, a chemical downstream reactor and a diode reactor. We pointed out the limitations of a conventional diode reactor where one cannot vary independently the negative substrate voltage bias, and the flux of the reactive species towards the wafer. We then introduced three of the newer plasma sources in which one has decoupled the generation of substrate bias from the reactive species flux. These were the inductively coupled plasma source, the electron cyclotron resonance source, and the helicon source.

notes

summary

15m 51s