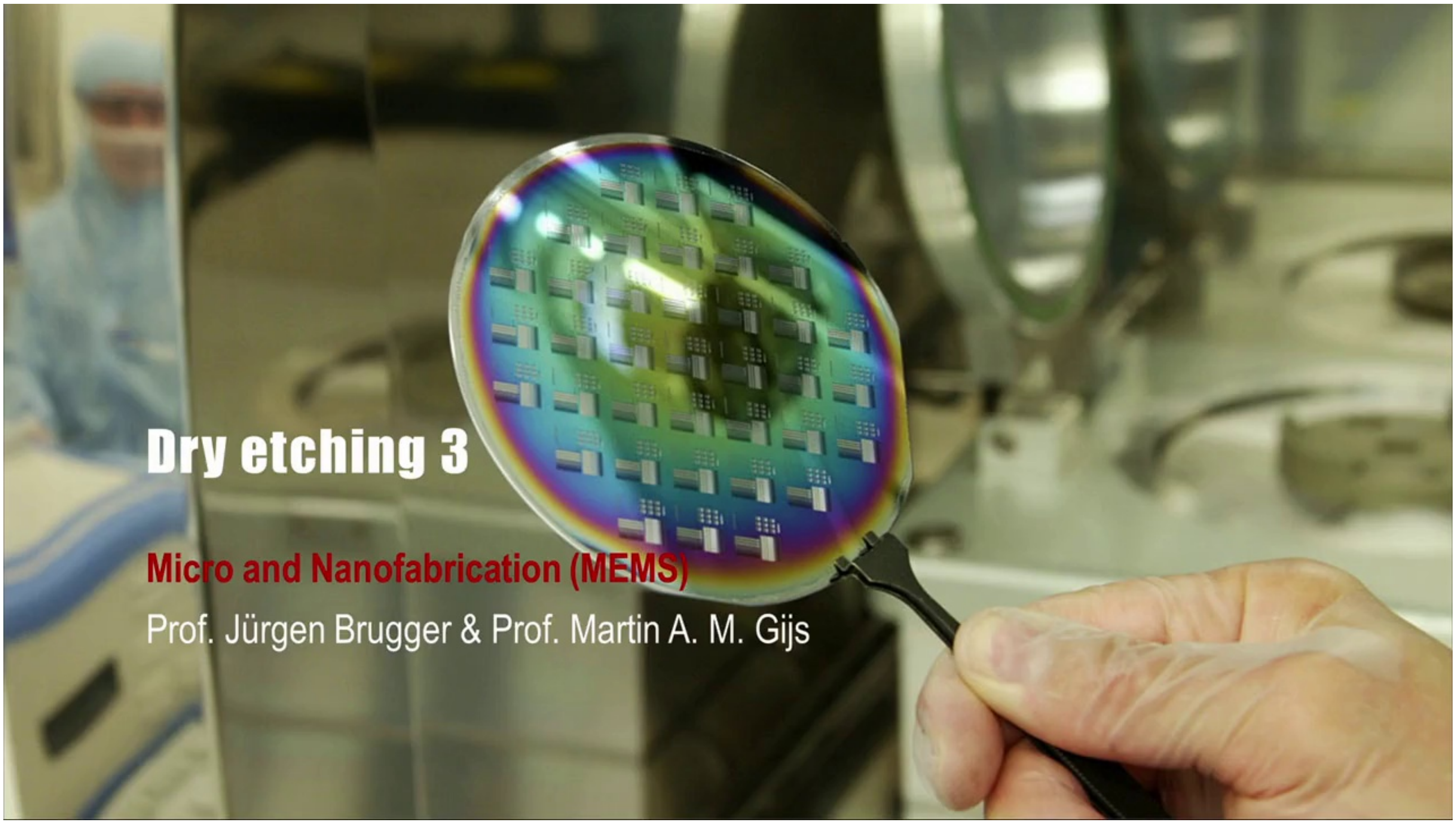


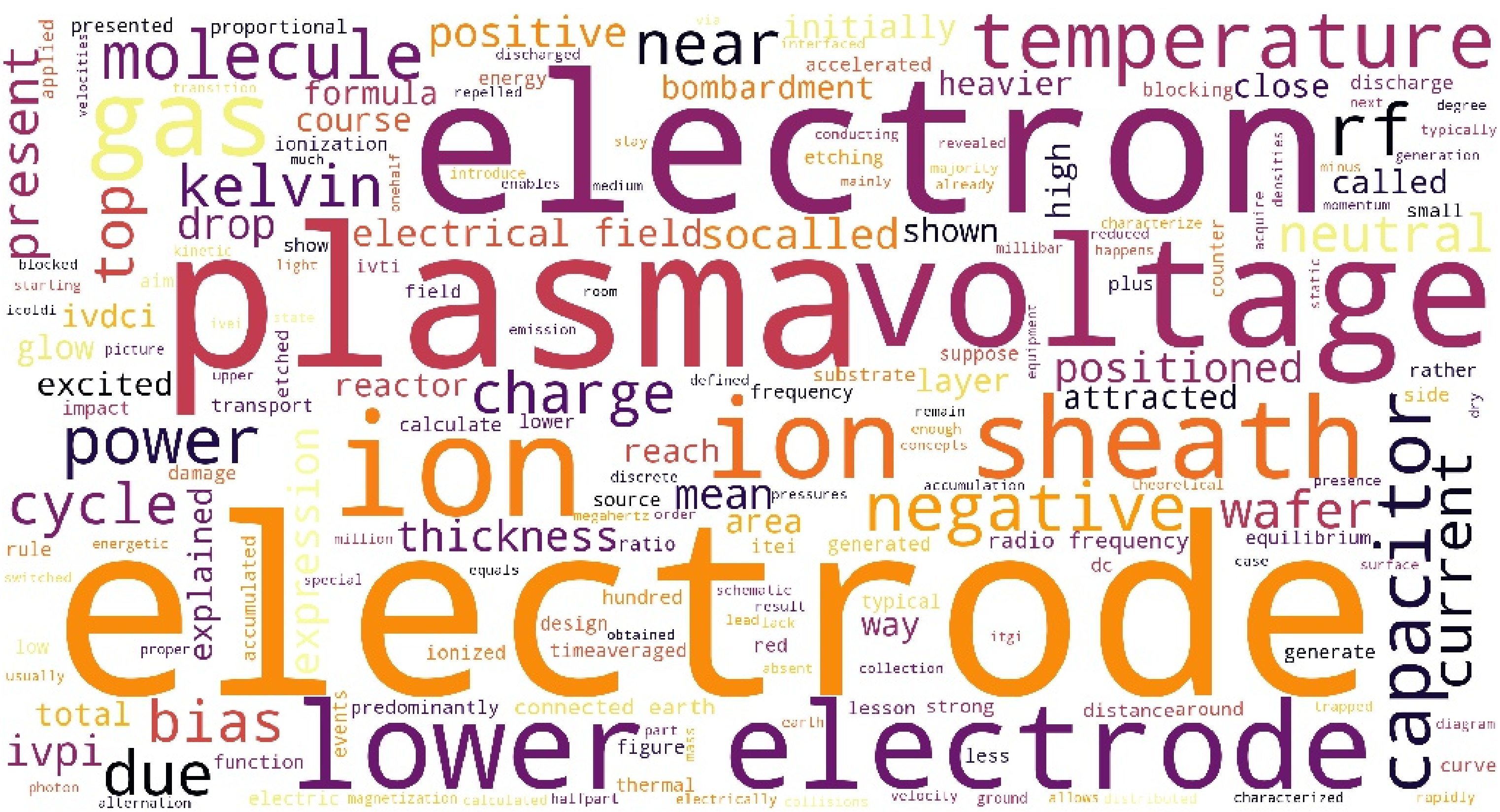


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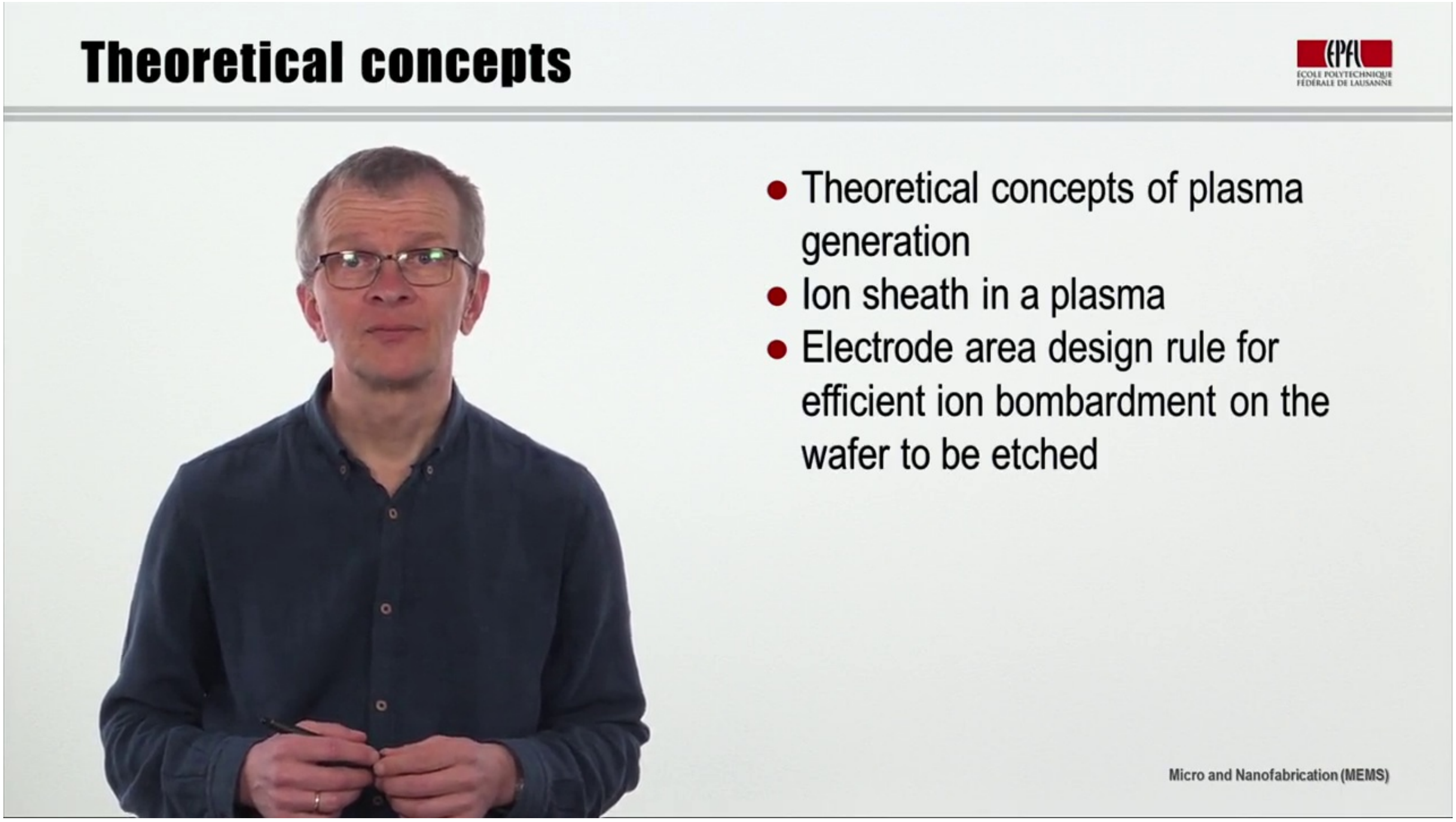
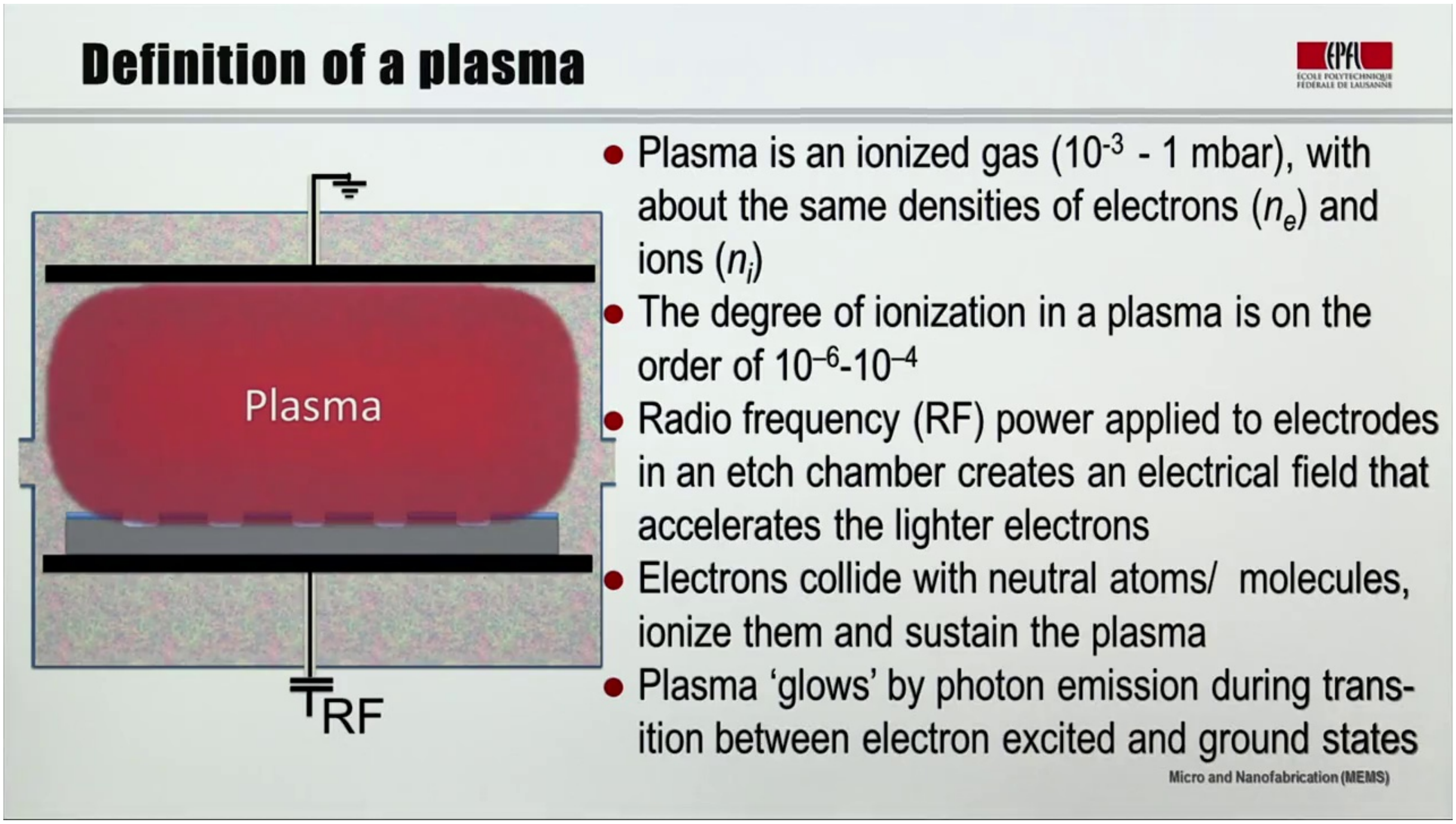
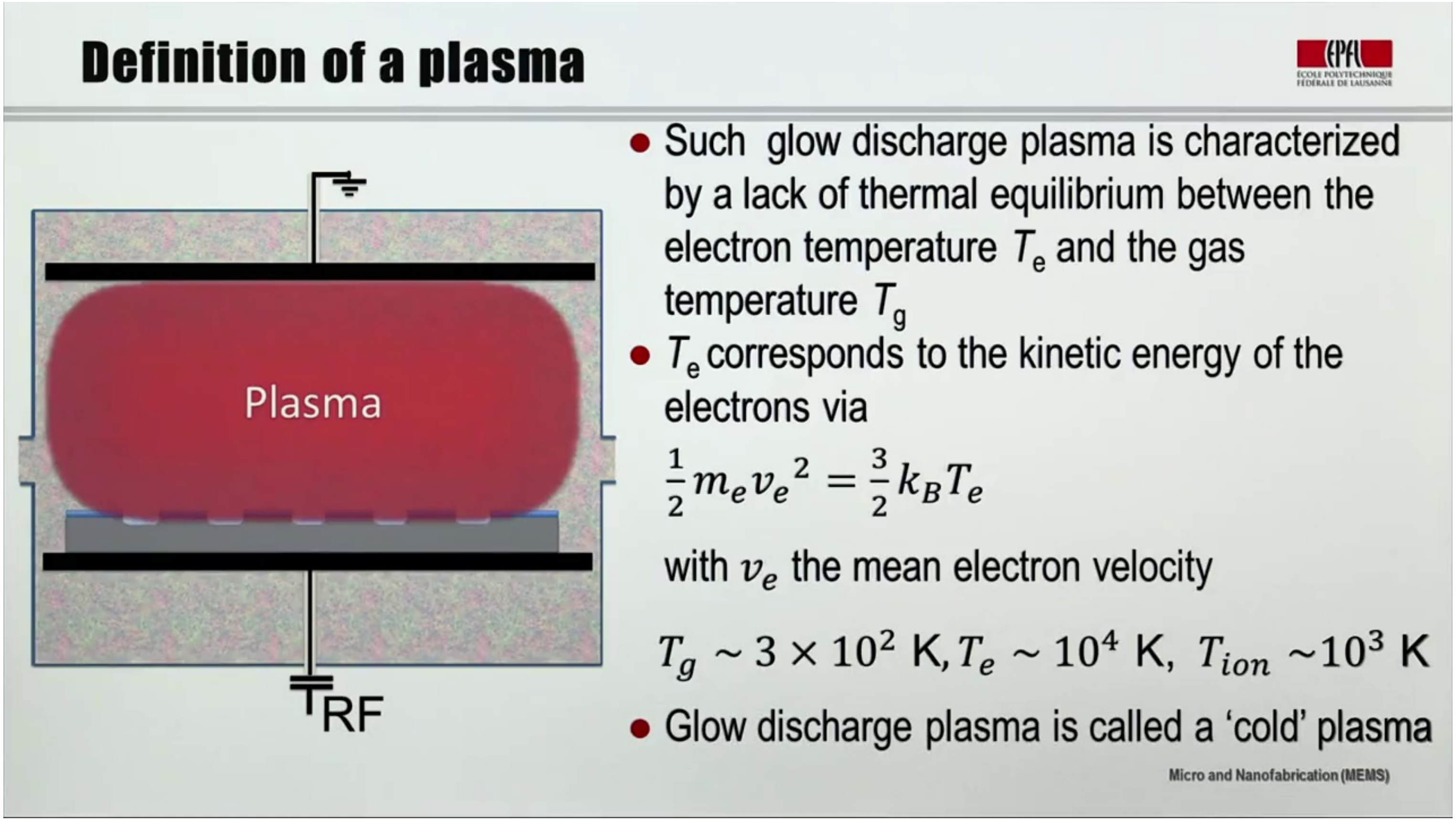


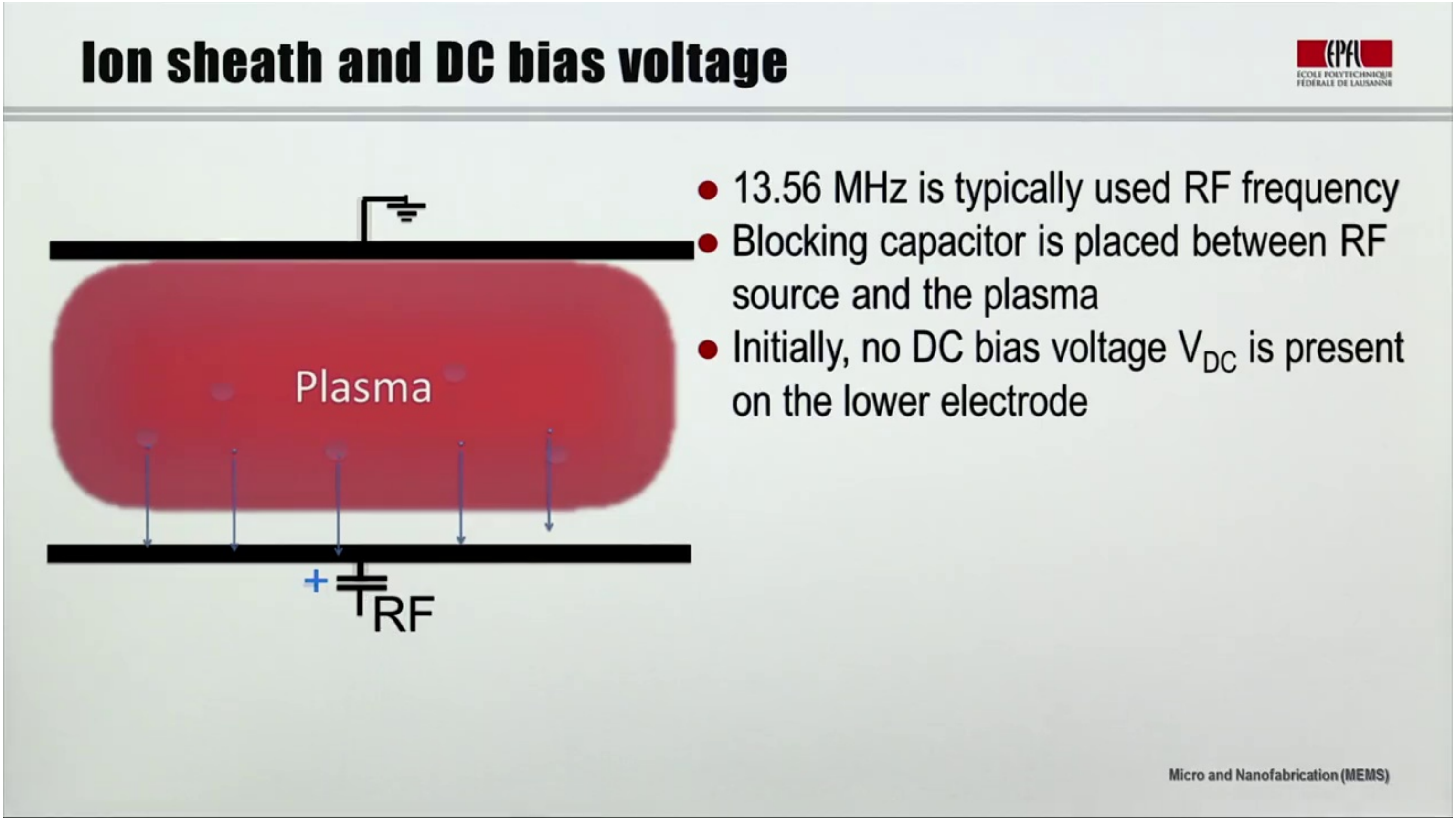

In this lesson, we will introduce some theoretical concepts that characterize a plasma in dry etching equipment. A plasma is a collection of excited neutral molecules, of ions and of electrons. Close to an electrode in the plasma, electrons are repelled so that mainly ions and, of course, neutral molecules remain there. Such a layer close to an electrode is therefore called an ion sheath. As a plasma is a special electrically conducting medium, it has to be interfaced in a proper way with a radio frequency power source. We then present a design rule for the RF electrodes that enables magnetization of ion bombardment to the electrode on which the wafer to be etched is positioned. An ion impact on the counter electrode, which would lead to reactor damage, is reduced or absent.



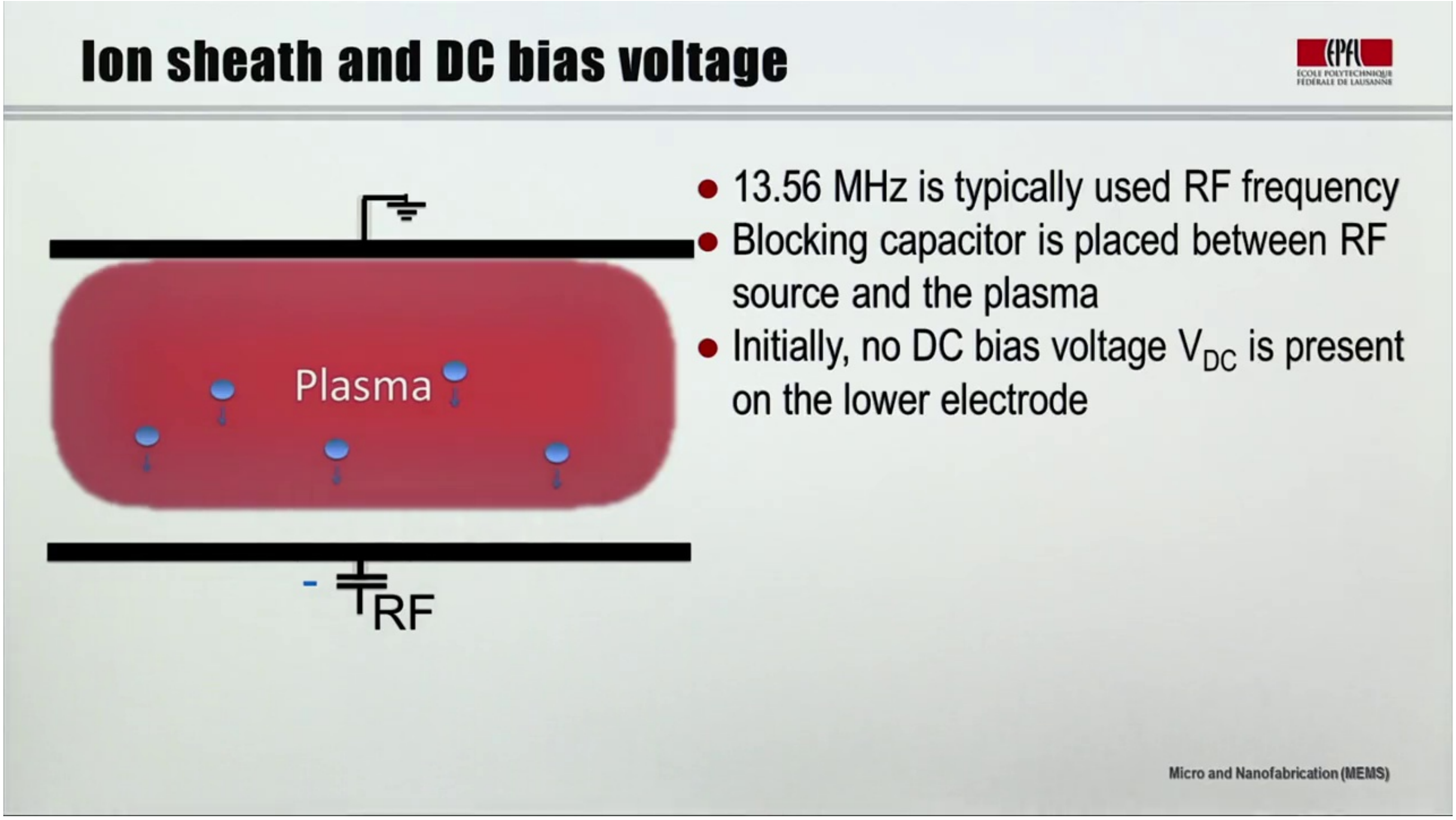

A plasma is defined as an ionized gas, and has about the same densities of electrons and of ions. A plasma is usually generated starting from a gas of pressures of 10^-3 to 1 millibar. The degree of ionization in a plasma is rather low, of the order to 10^-6 to 10^-4. That means that one of a million, or one of 10,000 molecules is ionized. This means, also, that the majority of molecules in the plasma are neutral. In the picture, we show how radio frequency power is applied via two electrodes. Initially, there is a discharge in the gas when a high electric field is applied due to discrete molecule ionization events, but rapidly, the RF power is distributed over all gas molecules due to collisions when energetic electrons that are accelerated in the electric field. The presence of a plasma is revealed by a glow of the excited gas, which is due to photon emission events during transition of an electron between an excited and a ground state.



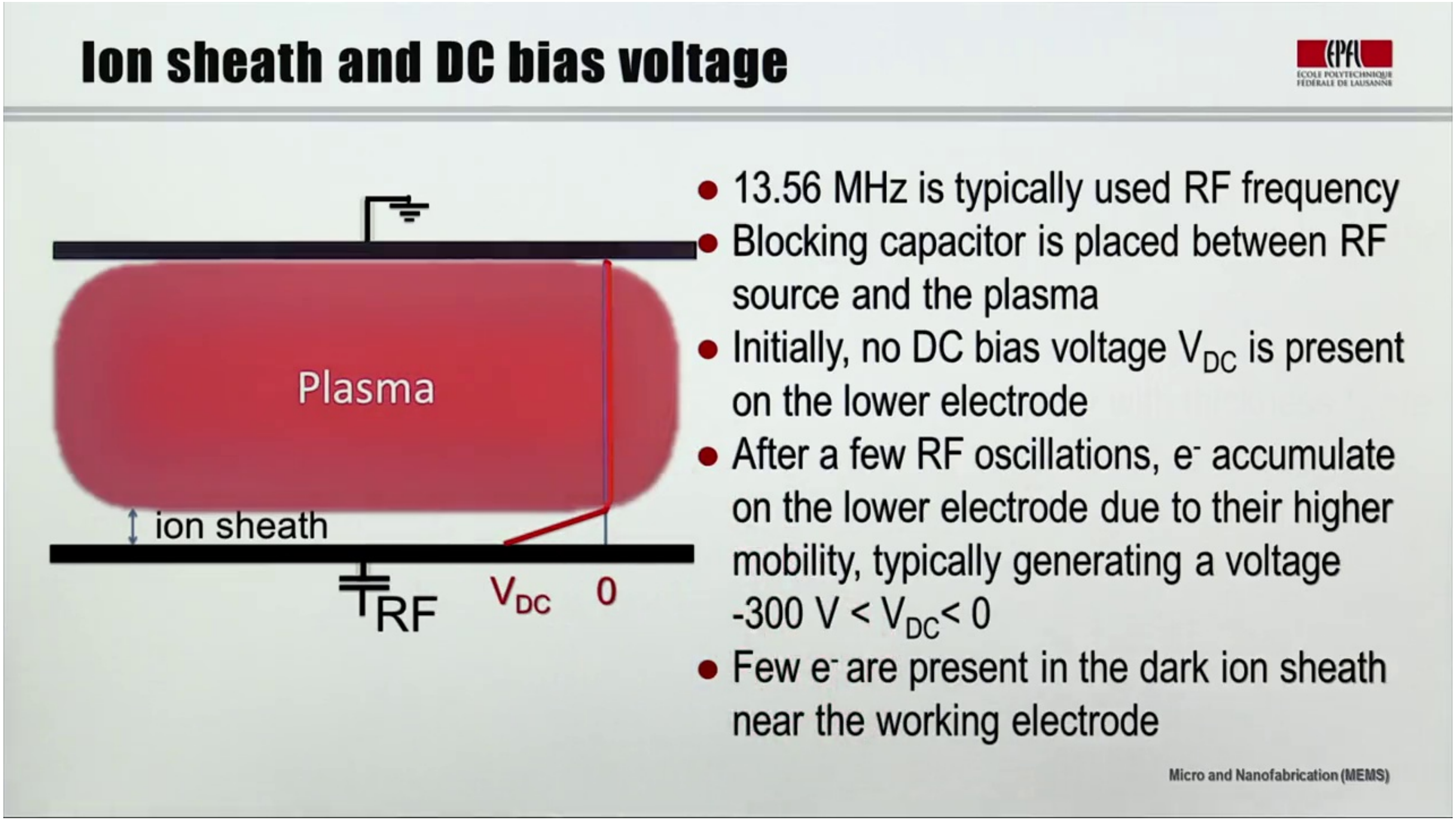

This so-called glow, discharged plasma, is characterized by a lack of thermal equilibrium between the electron temperature, <i>Te</i>, and the gas temperature, <i>Tg</i>. The electron temperature, <i>Te</i>, can be obtained if one equals the thermal energy to the kinetic energy of the electron with <i>ve</i>, the typical electron velocity in the electrical field. While the gas temperature is typically at room temperature in the plasma, that means a few hundred Kelvin, the calculated electron temperature can reach 10,000 Kelvin this way. The ion temperature, due to the heavier ion mass and lower velocities, is around 1,000 Kelvin. Due to the low gas temperature, a glow discharge plasma is therefore called a <i>cold</i> plasma.



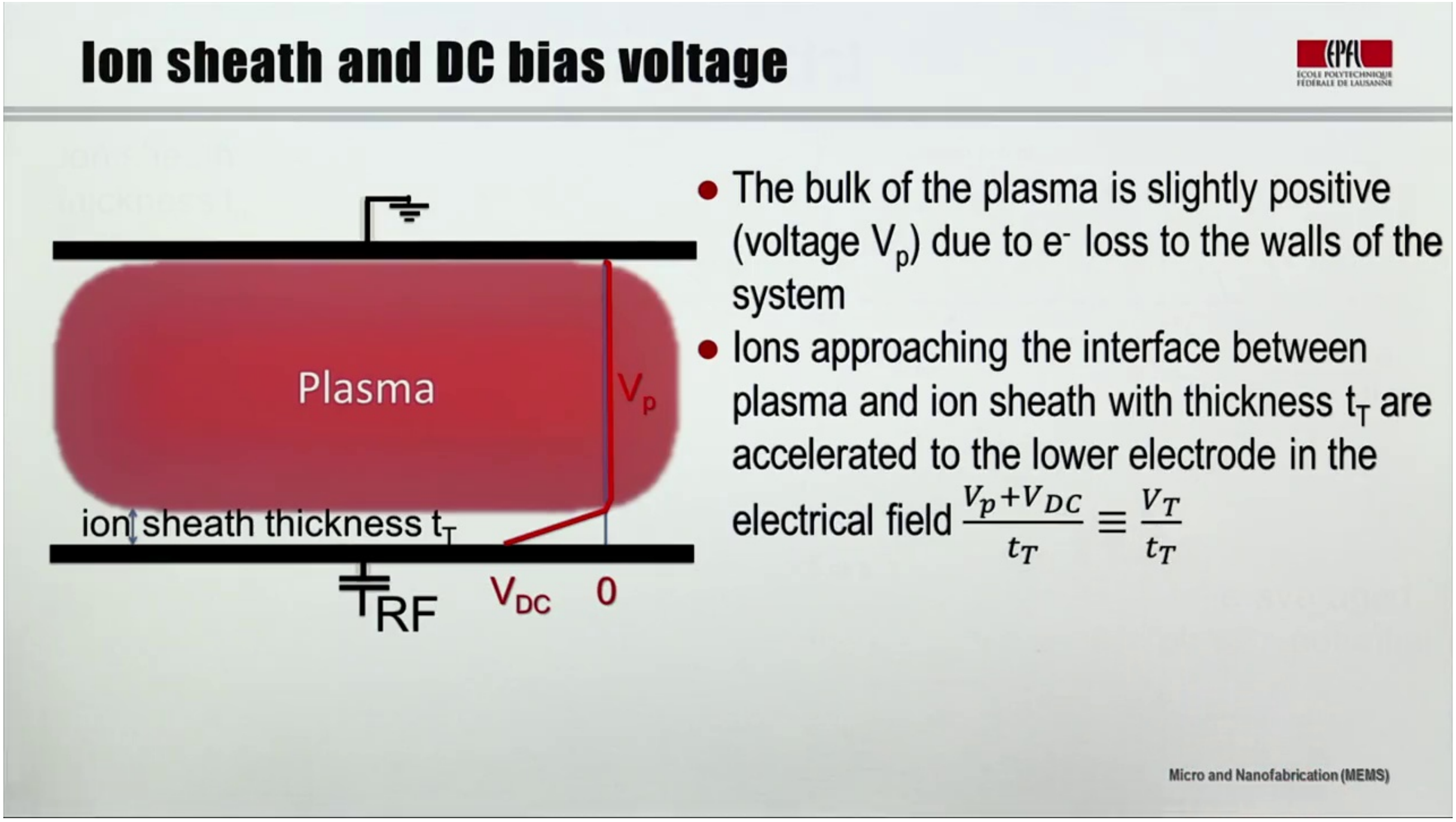

A typical frequency that is used for the generation of a plasma is 13.5 megahertz. In the schematic diagram, the upper electrode is connected to earth, while the lower electrode, on which the substrate will be positioned, has a so-called blocking capacitor in between the electrode and the RF power source. This capacitor allows accumulation of charges on the lower electrode, and, if this happens, one generates a so-called voltage bias, <i>VDC</i>, on that electrode. Initially, no such voltage bias is present on the lower electrode. When the radio frequency power is switched on, there is an alternation of positive and negative voltages on the lower electrode. Suppose one is in part of the cycle where the voltage on the lower electrode is positive. The RF frequency is very high, but electrons are so light that in one-half cycle they can reach the lower electrode, and they will charge this electrode, so they stay trapped on the electrode because they are blocked by this capacitor.



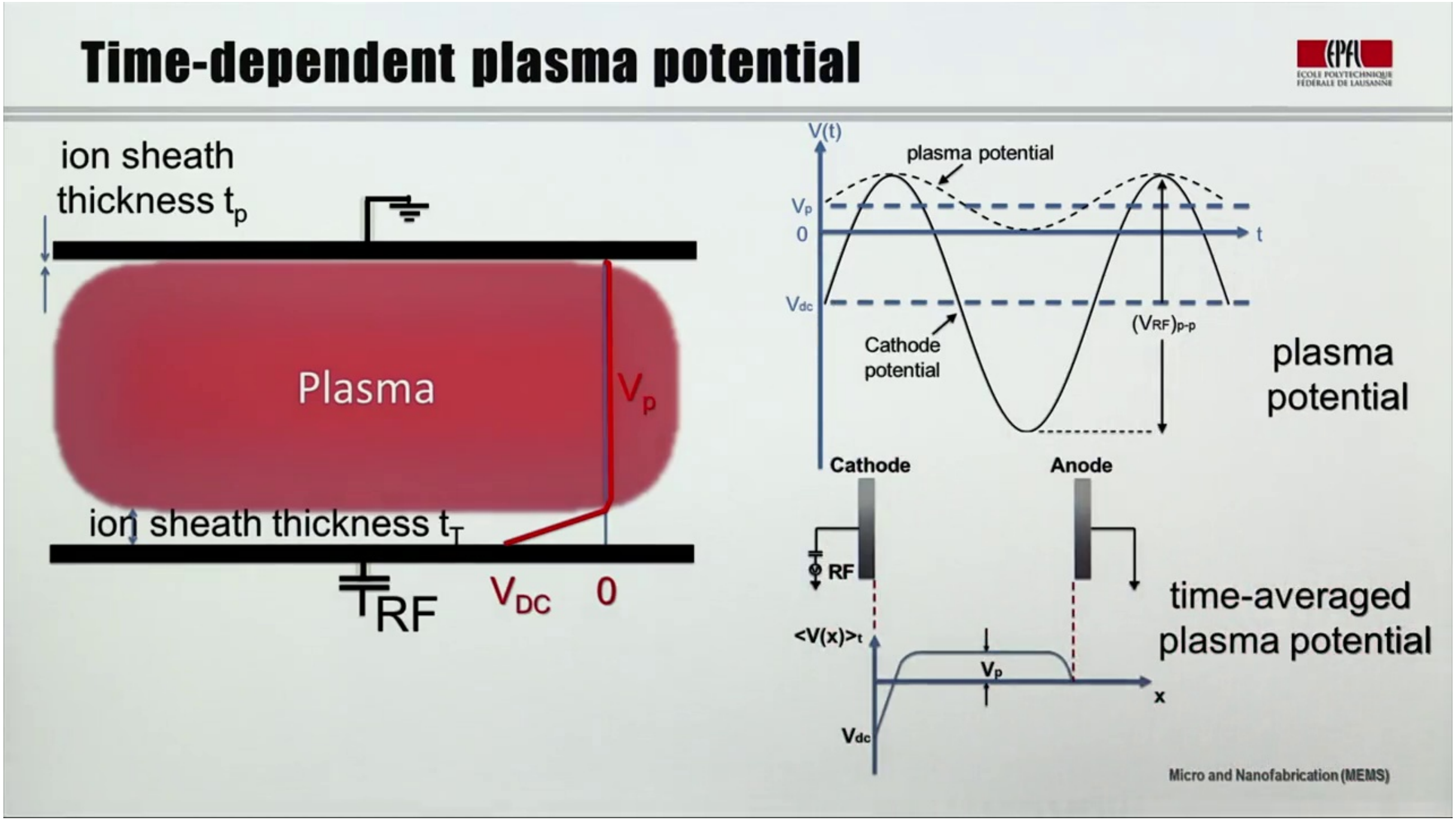

Suppose one is in the next half-part of the cycle where the voltage on the lower electrode is negative. In this case, the ions, which are positive, get attracted, but they are much heavier, and they do not acquire enough momentum to reach, initially, the lower electrode. So, as a result, after one cycle, one has accumulated here negative charge due to the electrons, and, after a few RF cycles already, a static negative surface bias is here on the electrode and on the substrate that is positioned on it.




The generated DC voltage bias can be minus a few hundredfold. Once this negative voltage is developed, one reaches an equilibrium electron ion transport regime with strong ion impacts to the lower electrode and on the wafer, as attracted by this negative charge. Once this negative charge is accumulated, also electrons are more and more pushed away from this electrode, and this leaves a zone near the electrode where there are predominantly ions, and, of course, also the neutral gas molecules. That's why this layer, where there are little or no electrons, is called the ion sheath. Also, on the other side, we have the electrode, which is connected to earth. The electrons will be evacuated to earth, so, very close to that electrode, there is also a thin ion sheath.




The top electrode is always at zero volts because it's connected to earth. The average voltage within the plasma itself is slightly positive, as some electrons from the plasma can get lost to the walls of the reactor. So, the time-averaged voltage, is shown by the red curve here. We can now calculate the electrical field that is present near the lower electrode. So, the electrical field is determined by the drop of voltage, that is <i>VDC</i>, plus <i>Vp</i>, over this distance, <i>tT</i>. Now we define the sum of <i>Vp</i> plus <i>VDC</i> as <i>VT</i>, the total.

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In a similar way, one can calculate the electrical field near the top electrode, which is given by the voltage drop, <i>Vp</i>, over this small distance, <i>tp</i>. One should keep in mind that all these are time-averaged voltages in the plasma, as shown in the figure below. In fact, this is the same graph as we have shown before in the red curve. The time dependence is presented in the figure above, so it shows the RF oscillations, which are centered around these mean voltages.

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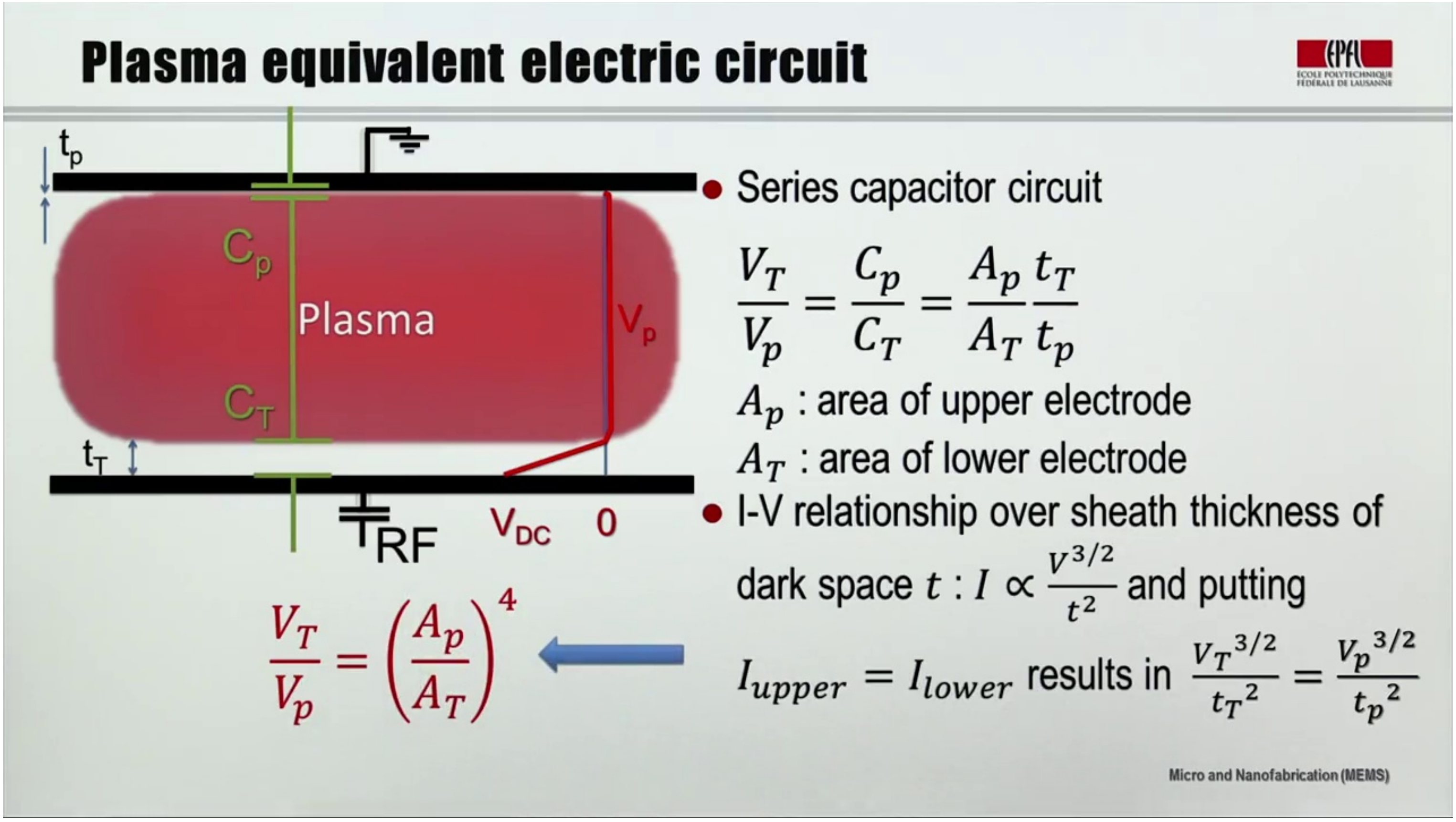
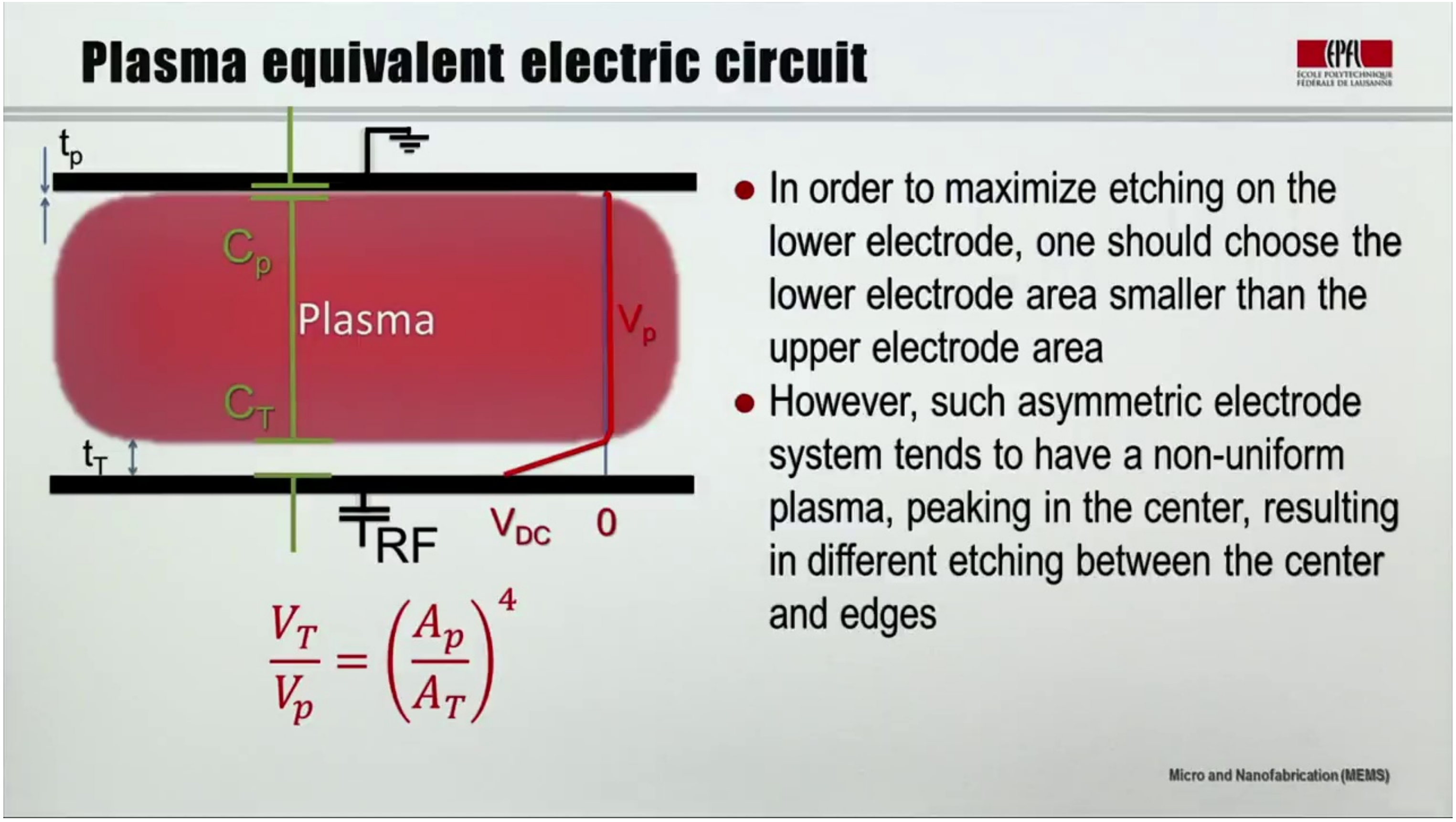
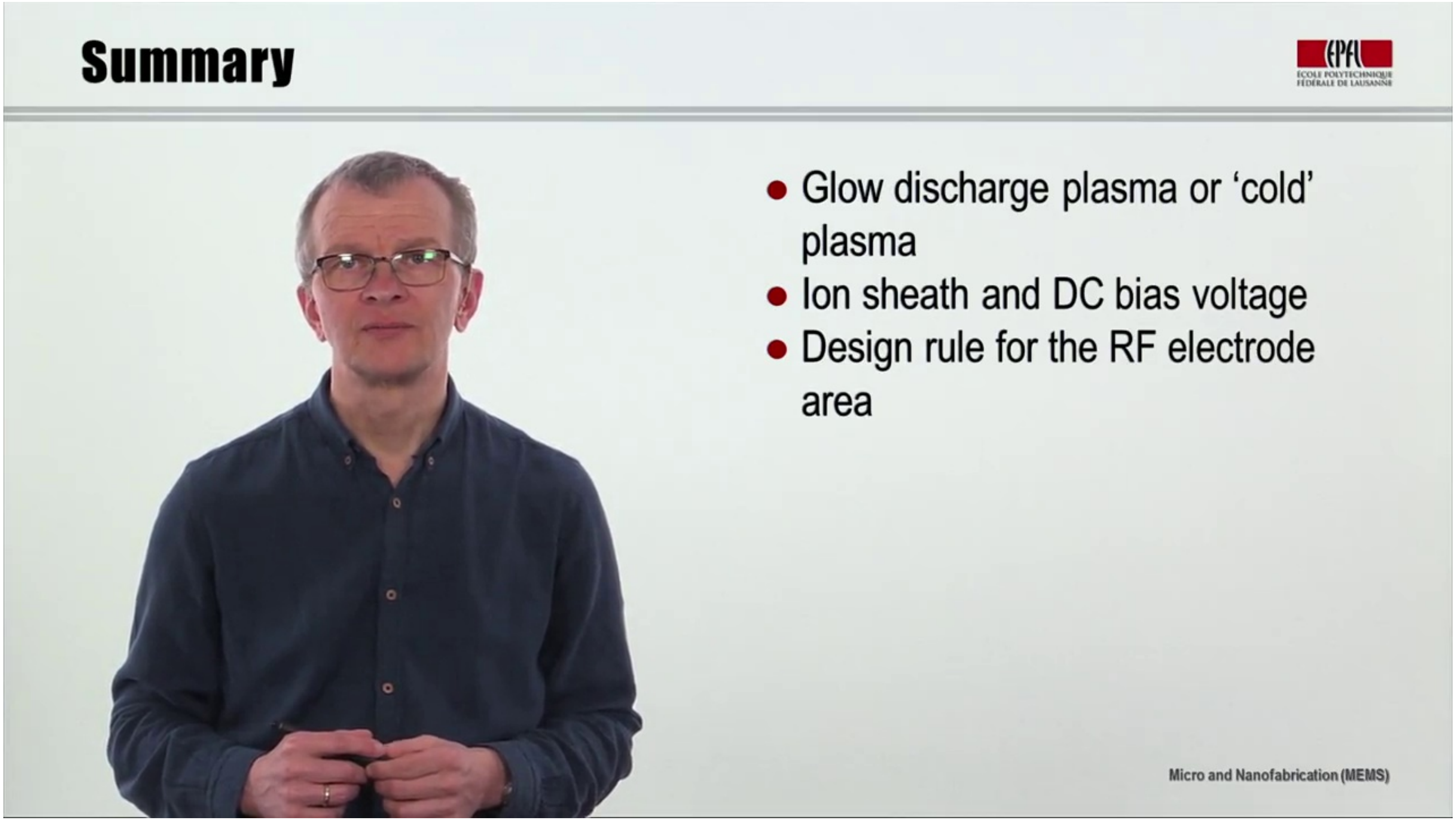



As the two ion sheaths near both electrodes contain very few electrons, but rather the heavier and less mobile ions, we can represent them to good approximation by a series circuit of a capacitor, <i>CT</i>, and a capacitor, <i>Cp</i>, and the plasma, with a lot of electrons, is then considered to be a conductor. We can now write the ratio of the total voltage drop, <i>VT</i>, over the voltage drop, <i>Vp</i>, as the ratio of the capacitors. Then we rewrite each capacitor in function of the area of the electrode and of the thickness of the ion sheath. It is not necessary, a priori, that the areas are equal between the two electrodes, and also the thickness of both ion sheaths doesn't have to be equal. Of course, an ion sheath is not a simple dielectric as in a normal capacitor, but it is a high resistance layer over which current transport from the plasma to the electrode is still possible. We present here the expression for the current voltage relationship over such an ion sheath as a function of the thickness of the ion sheath. The current is proportional to the power 1.5 of the voltage, and inversely proportional to the square of the thickness of the ion sheath. Now we simply assume that the current, which is flowing on the lower and on the top electrode are equal, so we can equalize these two current expressions; once for the lower electrode and for the top electrode. We can now combine this expression with this expression to obtain this formula. What does this learn us now?




We should remember now that what we aim for in etching is that ions are predominantly accelerated by the large total voltage, which is near the lower electrode. While we do not aim to create a strong ion bombardment on this side, as you would cause damage to the reactor electrode. This formula says that we can achieve this by choosing the lower electrode, smaller than the top electrode because there is a power of four in the formula. An inconvenience (disadvantage) of such so-called asymmetric electrode systems is however, that the plasma on this electrode is less uniform, and has more intensity in the center of the small electrode than at the edges of that electrode.




In this lesson, we have explained the basic properties of a cold plasma, which has a gas temperature of a few hundred Kelvin, and an electron temperature of 10,000 Kelvin. We then explained the phenomenon of formation of an ion sheath near an RF electrode, and explained how placement of a blocking capacitor allowed to generate a DC voltage bias, by which ions are attracted towards the electrode that carries the wafer that needs to be etched. Also, we presented a design rule for the areas of RF electrodes, which resulted in a major bombardment of ions on the electrode where the wafer is positioned, and not on the counter electrode.