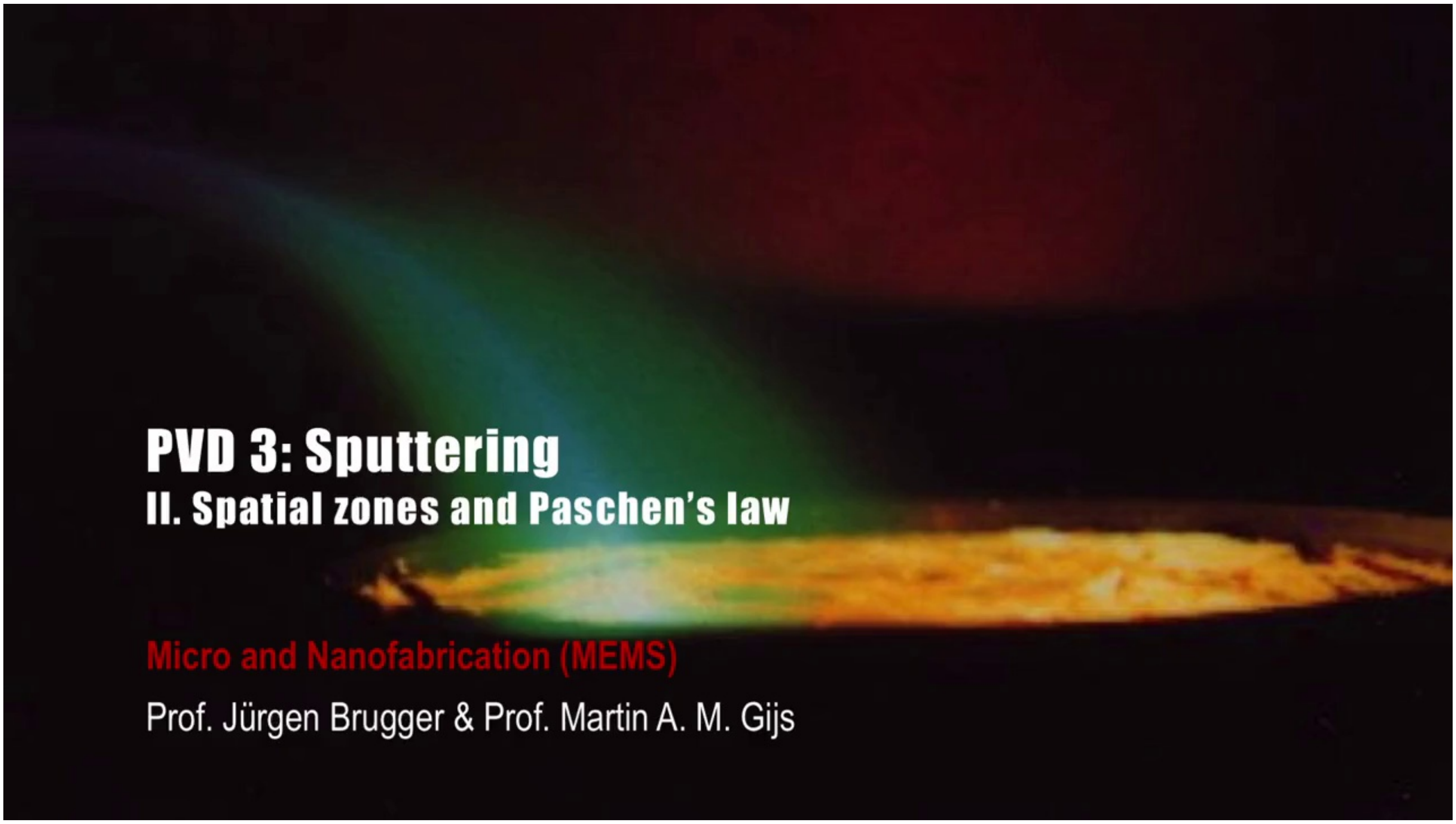

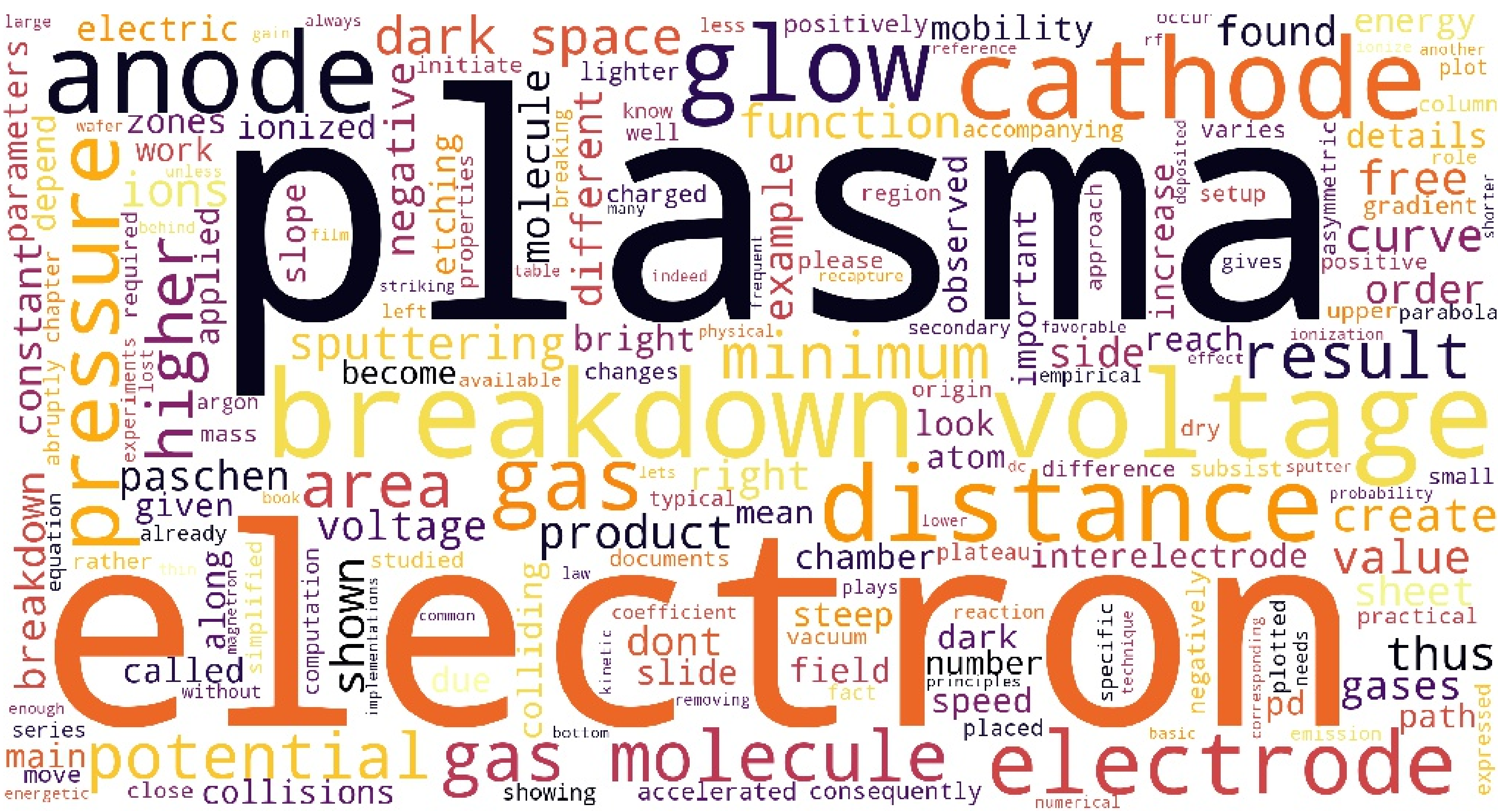

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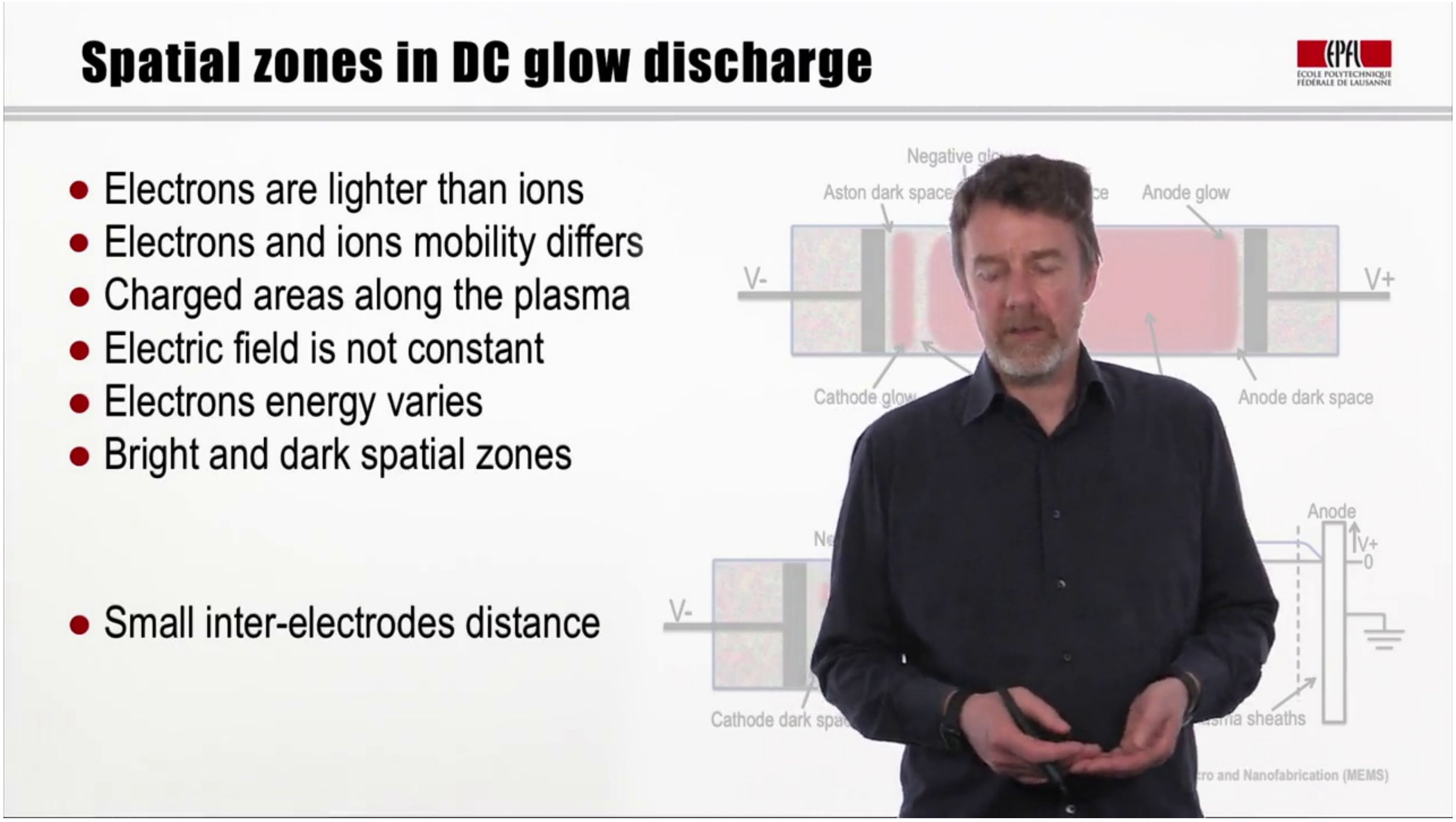
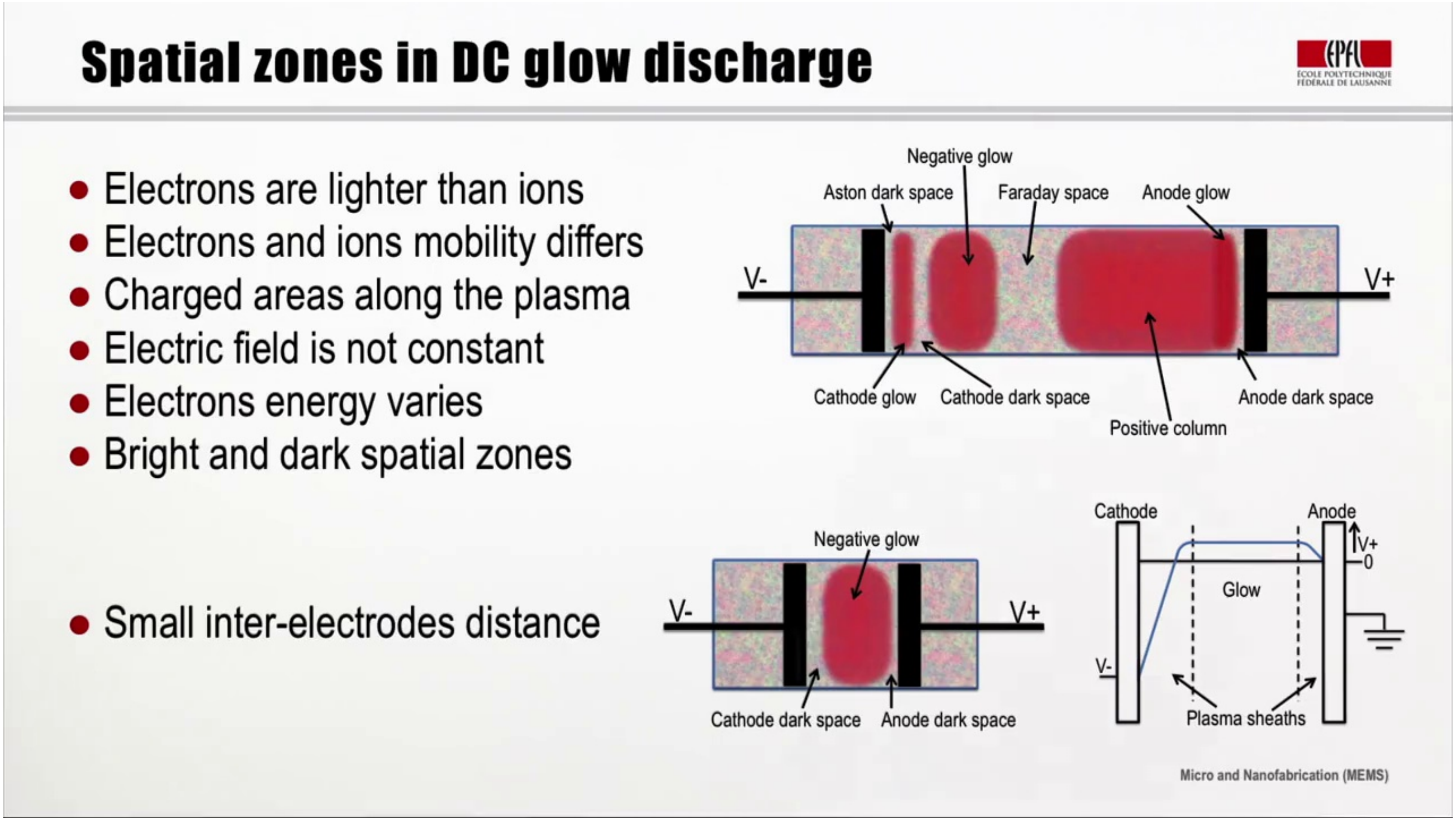
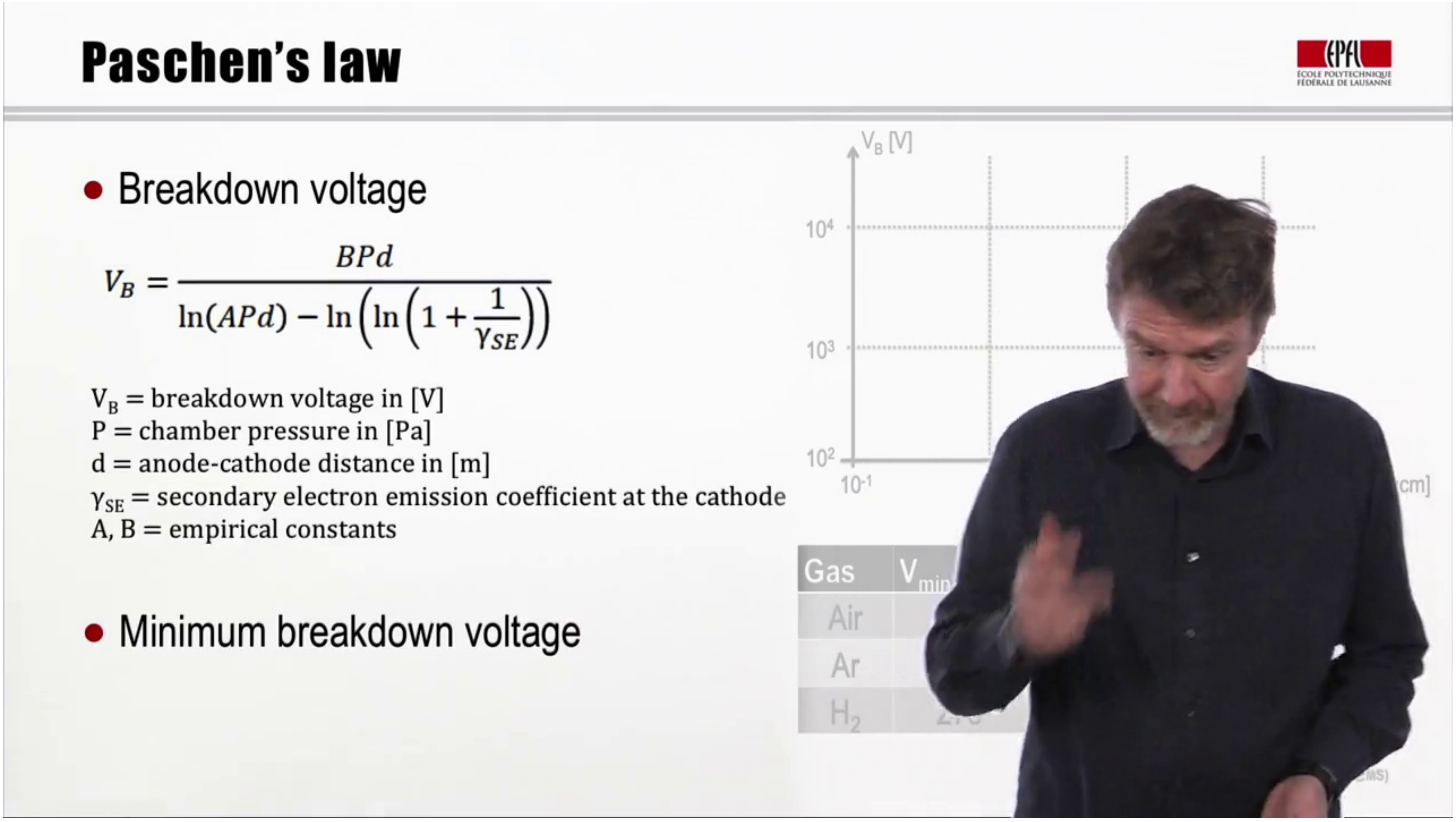


Electrons and ions don't have the same mass. Electrons are lighter and thus have a higher mobility when accelerated in an electric field gradient. As a result, in a plasma, ions and electrons don't move at the same speed which creates positively and negatively charged areas. Consequently, the electric field is not constant along the plasma and the electron energy varies and creates thus bright



and dark areas, as shown here in this slide on the upper right side. And we have the plasma chamber with the cathode and the anode and different zones in the plasma due to the different mobility of ions and electrons. For more details about plasma zones, please have a look at the accompanying documents. Bright areas are called glow, and dark areas are called dark space. In the practical setup for sputtering or etching, the distance between the two electrodes is rather small. In the order of 15cm, as we have seen before. This is showing a chamber with the cathode and the anode and the plasma in between. As a result, the anode, which is the positive electrode, is placed in the negative glow. Therefore, the plasma column can be simplified from here to here and only the cathode dark space, the negative glow and the anode dark space subsist. Negative glow, cathode dark space, and the anode dark space. The potential changes very abruptly close to the electrodes in the plasma sheets and it is constant in the glow region of the plasma. As shown here. There is a very steep slope of the potential difference of the cathode into the plasma vacuum, then the plateau where the glow area is and here again a steep slope, and we approach the anode. And these are the two plasma sheets. The origin of this plasma sheet, as well as the computation of the potential along the plasma, is studied in more details in the chapter about dry etching.



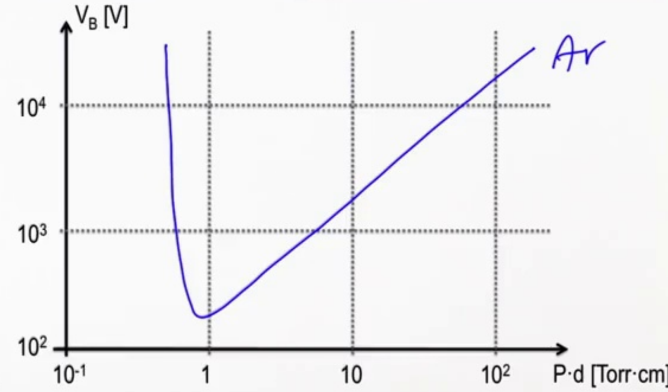
The required voltage to initiate the breakdown of the gas and create the plasma, depends on three main parameters which are the pressure, the inter-electrode distance and some gas properties. This was first observed by Paschen who found out that the breakdown voltage could be plotted as a function of the product between the pressure and the inter-electrode distance. It results in an asymmetric parabola with a minimum at a specific Pd product, like shown here.

Paschen's law

- Breakdown voltage

$$V_B = \frac{BPd}{\ln(APd) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{SE}}\right)\right)}$$

V_B = breakdown voltage in [V]
P = chamber pressure in [Pa]
d = anode-cathode distance in [m]
γ_{SE} = secondary electron emission coefficient at the cathode
A, B = empirical constants

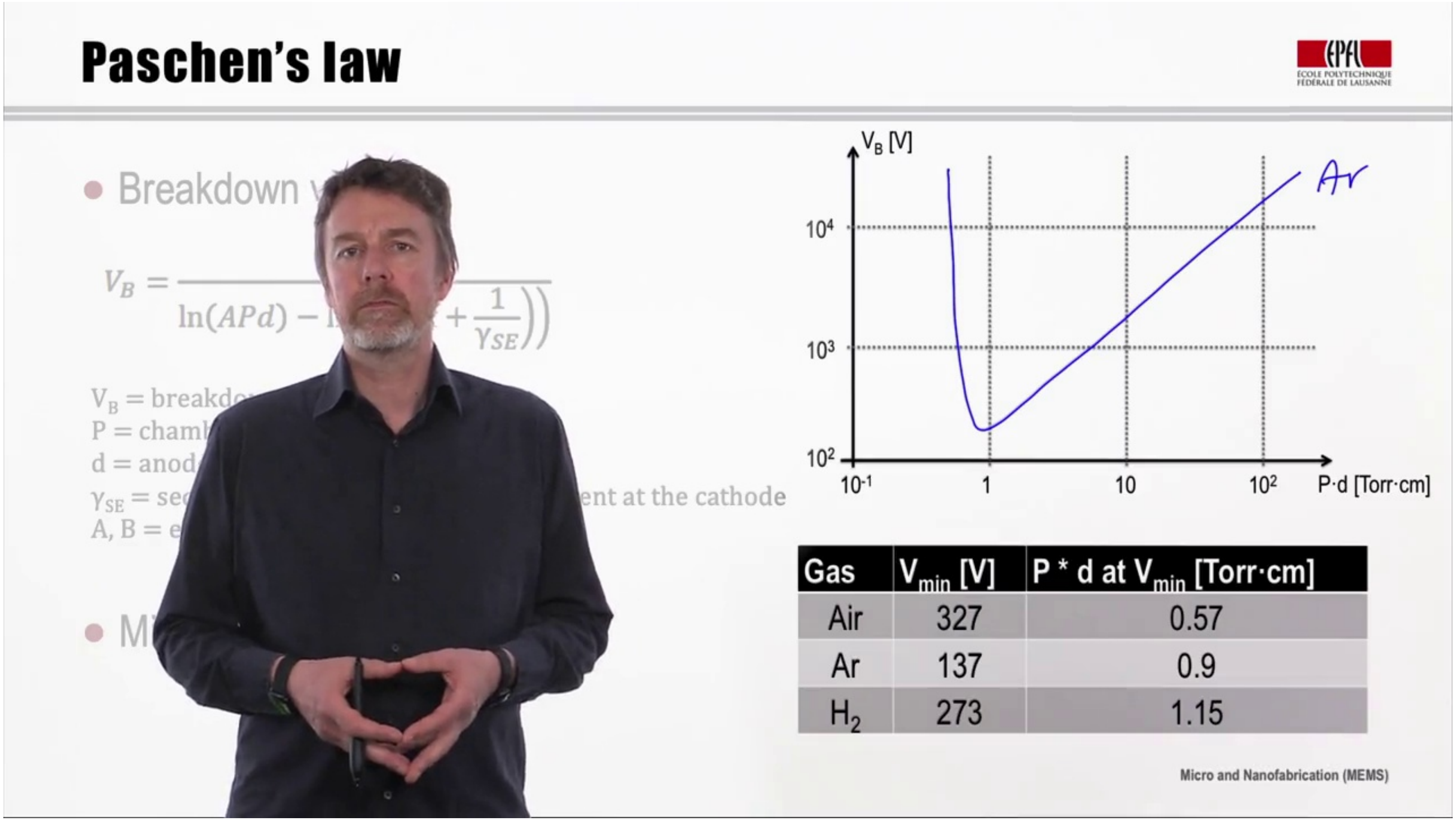


- Minimum breakdown voltage

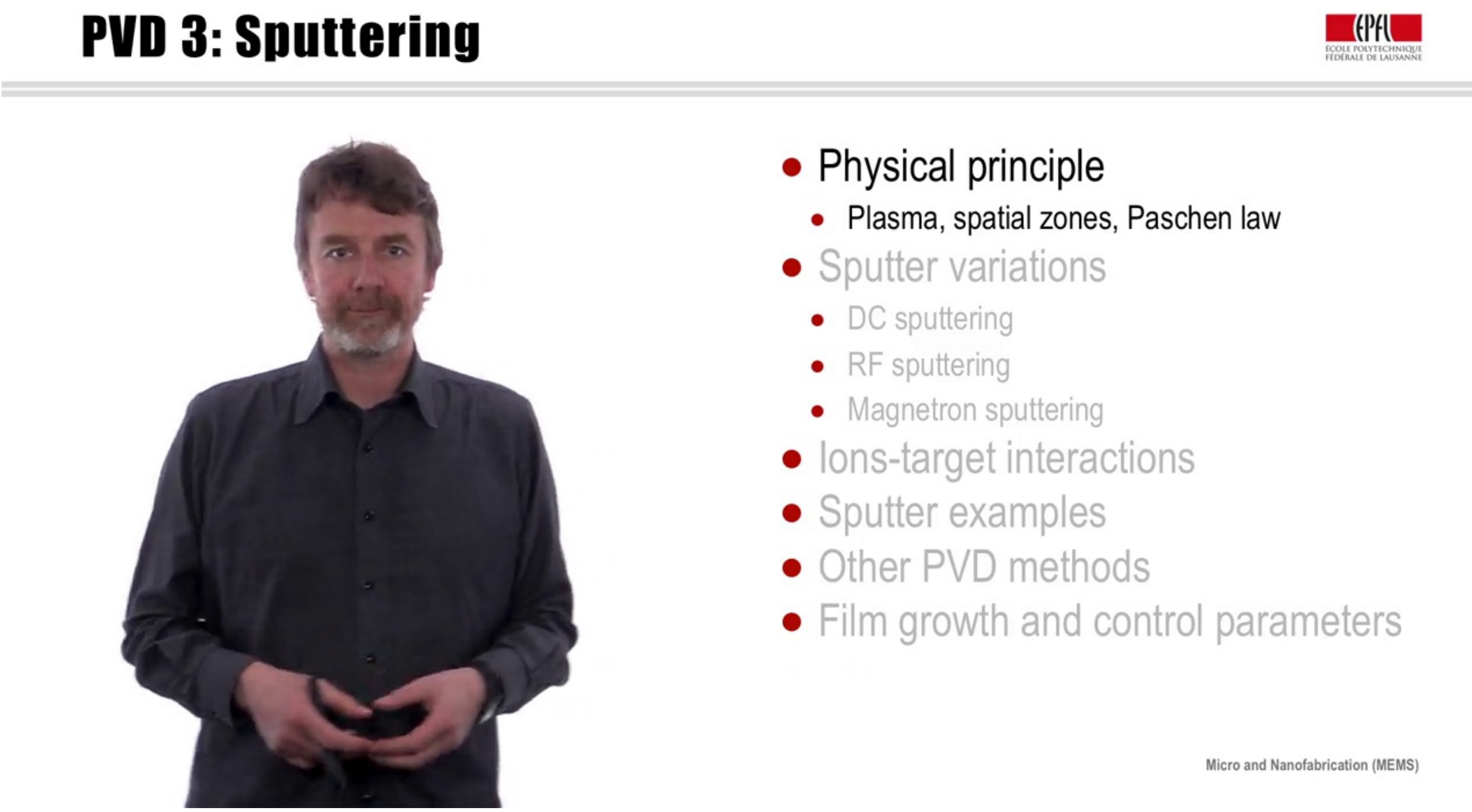
Gas	V_{min} [V]	P * d at V_{min} [Torr·cm]
Air	327	0.57
Ar	137	0.9
H_2	273	1.15

Micro and Nanofabrication (MEMS)

Here we have the typical curve, for example a gas like argon. And we plot the breakdown voltage and the plasma is breaking down as a function of the product, the pressure and the distance. Paschen has found that this curve in fact can be expressed by an equation that is shown here which gives the breakdown voltage as a function of this series of parameters like for example the pressure and the electrode distance as we already know, times an empirical constant which is observed in experiments, and then as a function of the secondary electron emission coefficient at the cathode which plays an important role. Here, three example gases with the breakdown voltage for a given value of pressure and distance.



On the left side of the curve minimum, one needs a higher voltage to reach breakdown because there are less molecules between the electrodes available for the reaction. As a result, when the gas, atom, or a gas molecule is ionized free electrons reach the anode without colliding with other gas molecules, and they are lost. For the breakdown of the gas to occur, higher voltages have to be applied in order to increase the number of free electrons and thus the probability of collisions with other molecules. However, on the right side of the minimum of this curve we have another effect for the breakdown voltage to increase again. Now, due to the large number of gas molecules between the electrodes, electron molecule collisions become more frequent and the electron's mean free path becomes shorter. As a result, electrons don't gain enough kinetic energy to ionize other gas molecules when colliding with them, unless a higher potential is applied. For each gas, the minimum breakdown voltage and the corresponding Pd product is different. These values depend on the gas molecules, mean free path, the ionization potential and the speed at which the gas molecules can recapture electrons after they have been ionized. Numerical values for the most common gases are given in the table here at the bottom right of the slide but values for many other gases can be found in the reference book. For sputtering, it is not always favorable to work at the minimum breakdown voltage. Indeed, it is more important to work with lower pressures and thus with a higher breakdown voltage in order to have energetic ions striking the cathode and removing atoms that can be deposited as a thin film on the wafer.



So now we have seen some basic physical principles behind sputtering, about how to create a plasma and the Paschen law. So now, let's have a look at the three main implementations of the sputter technique, that is the DC, the RF, and the Magnetron sputtering.