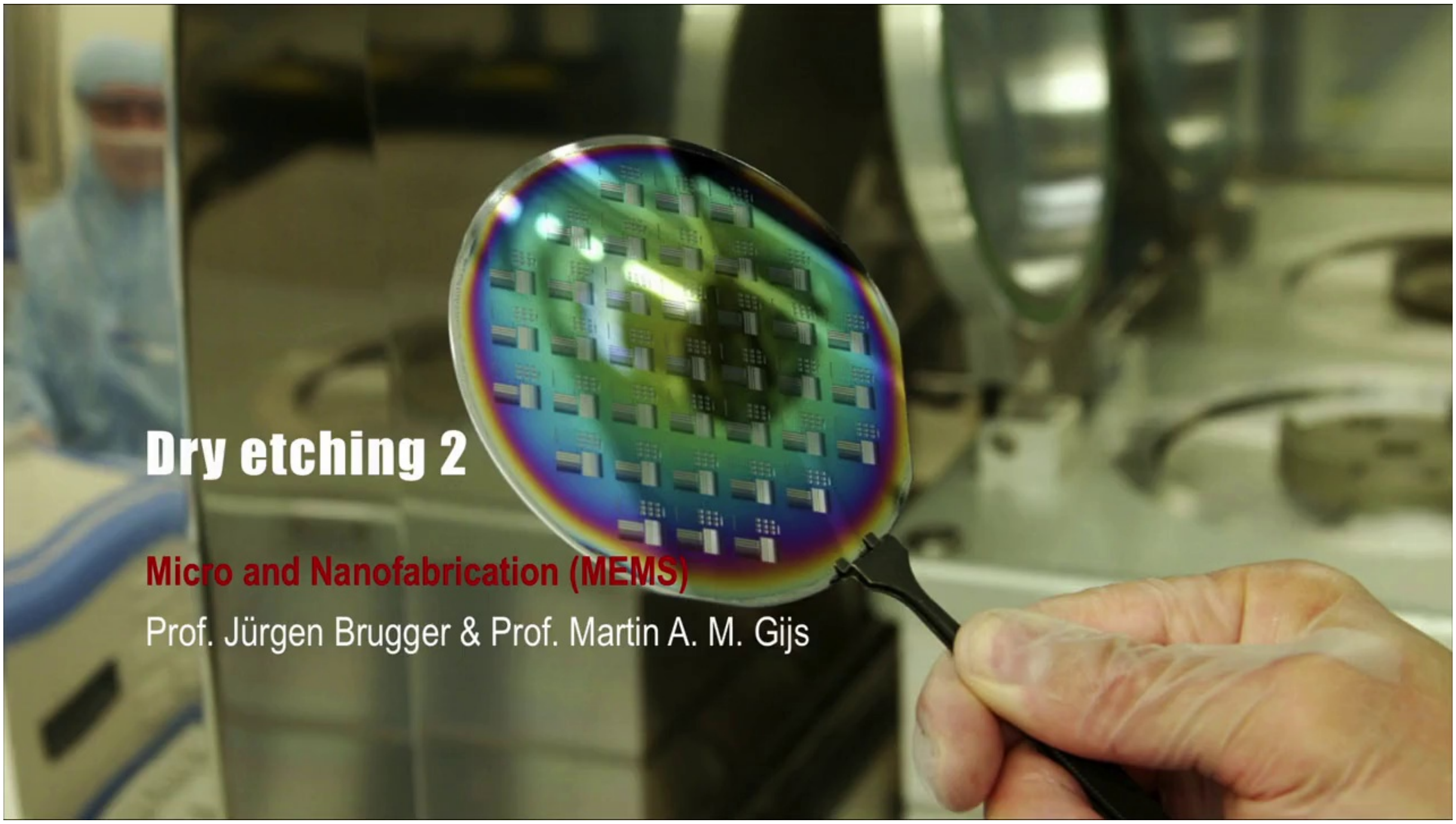

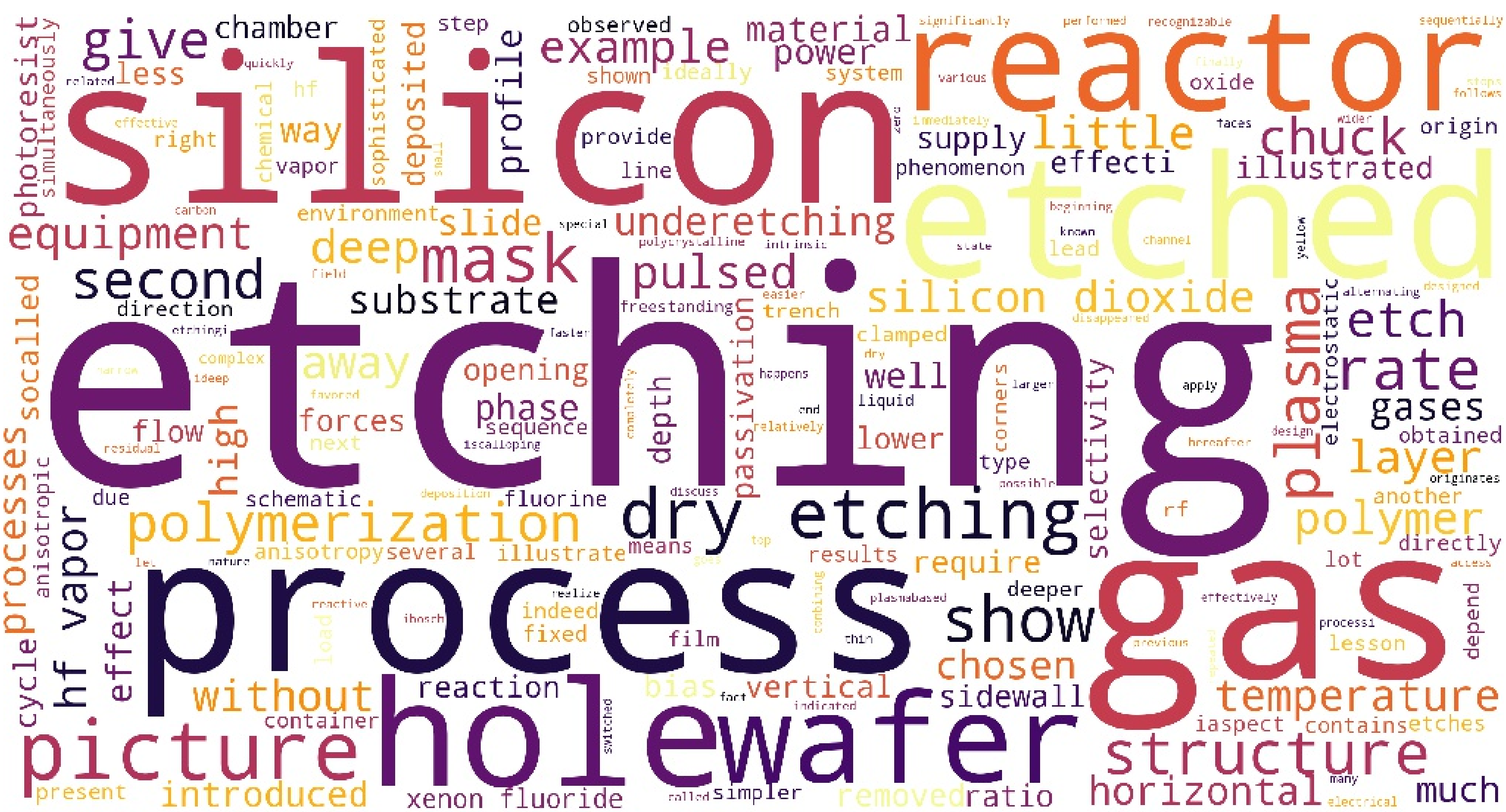

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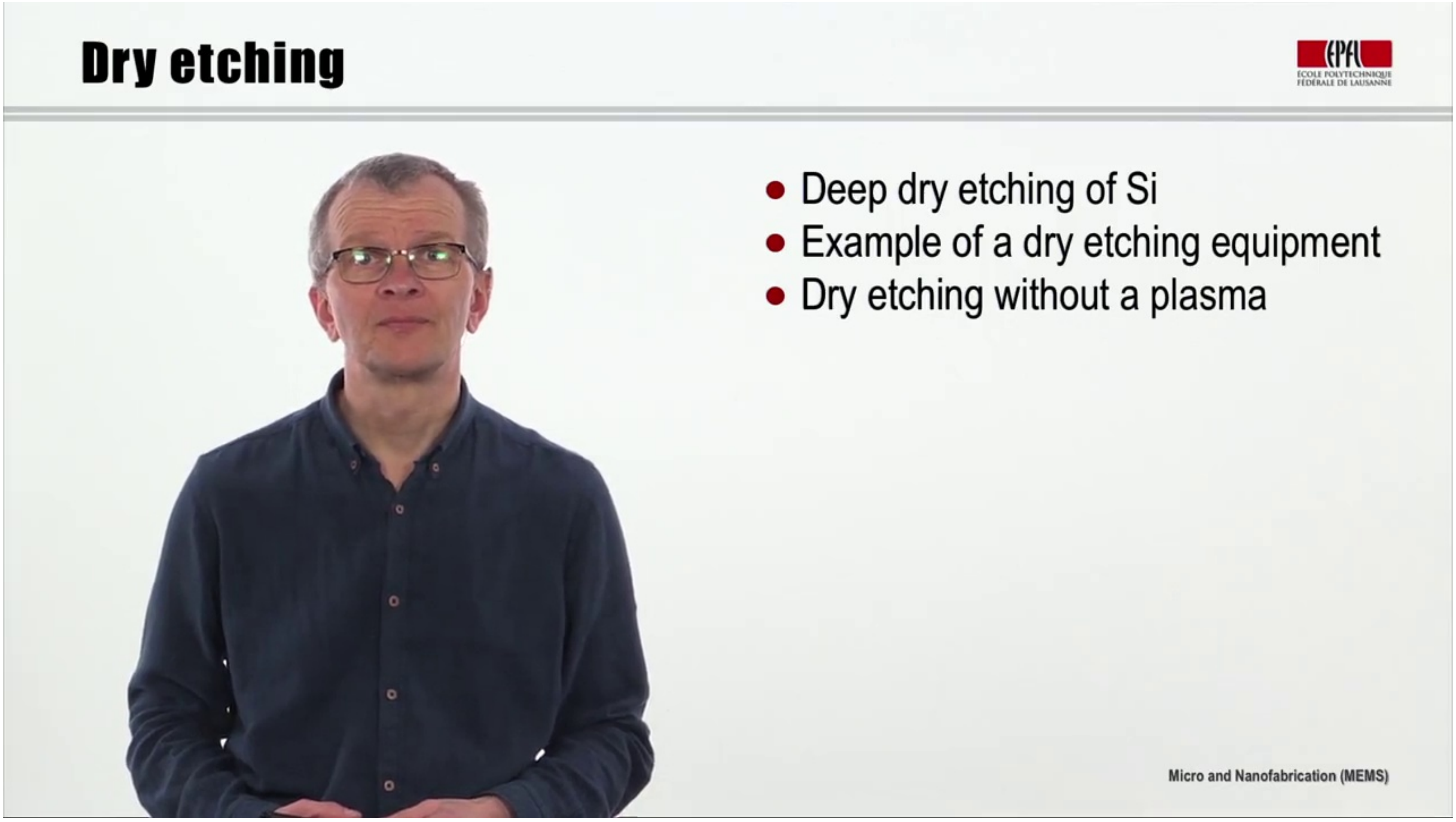
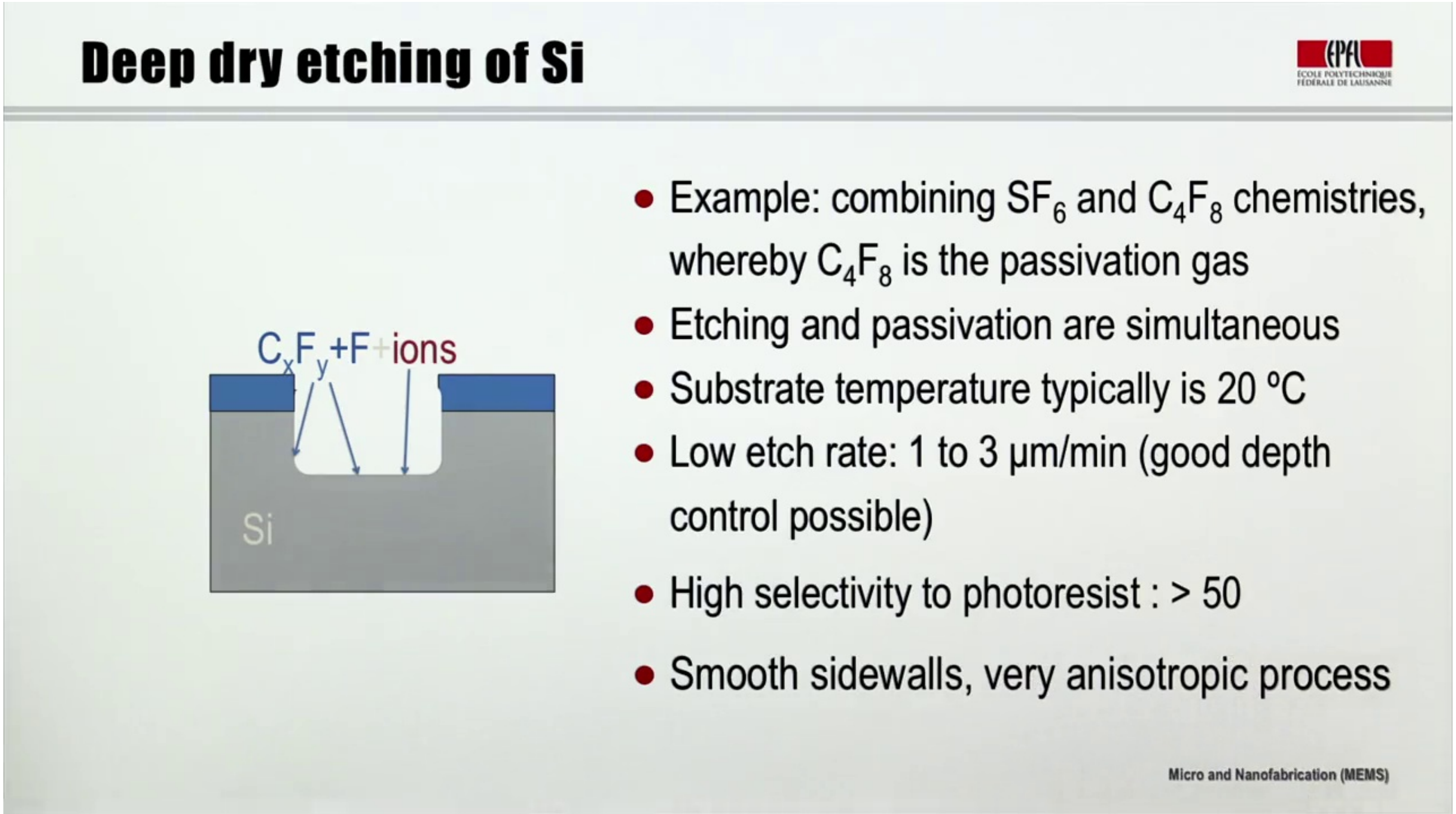
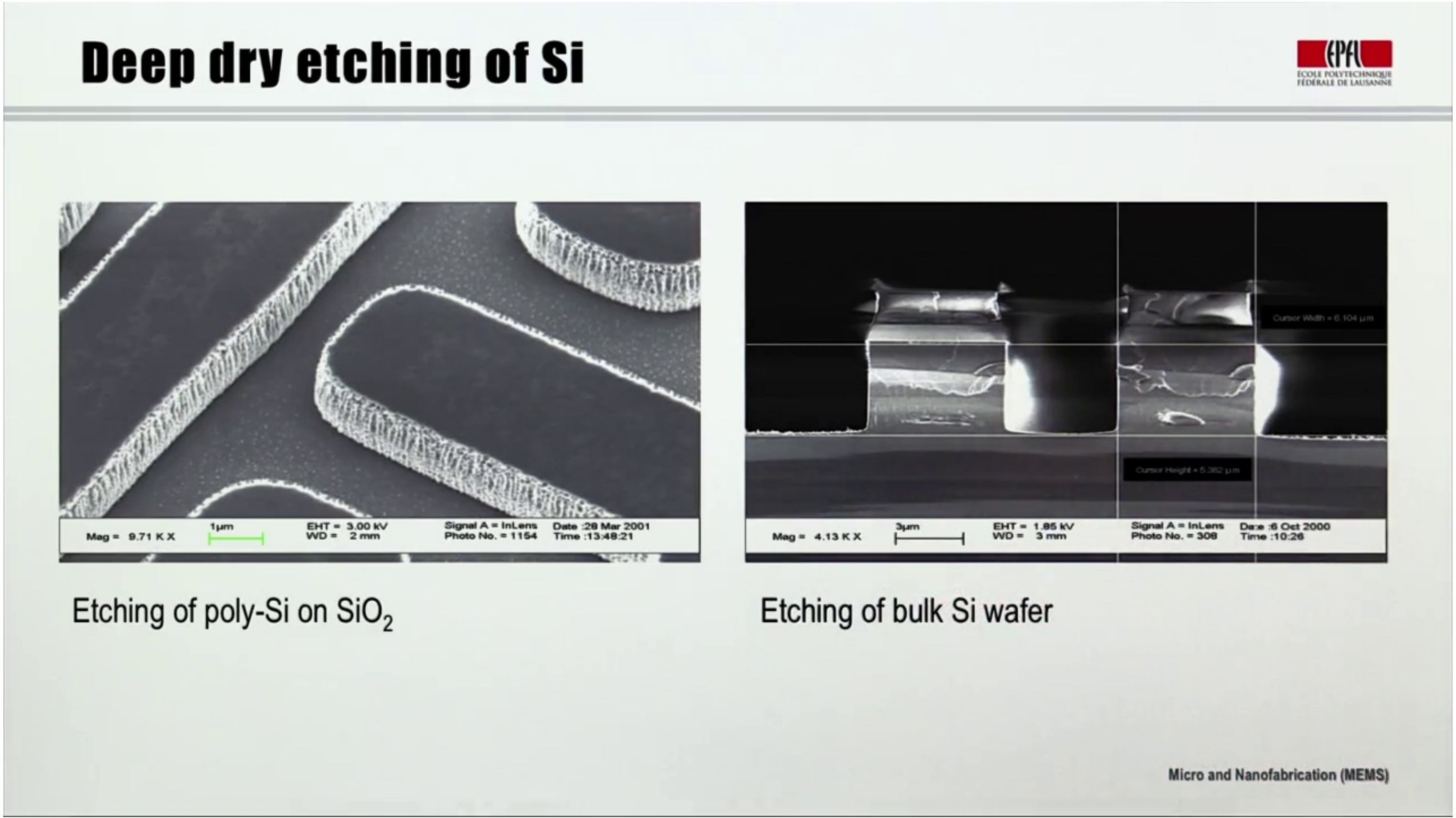


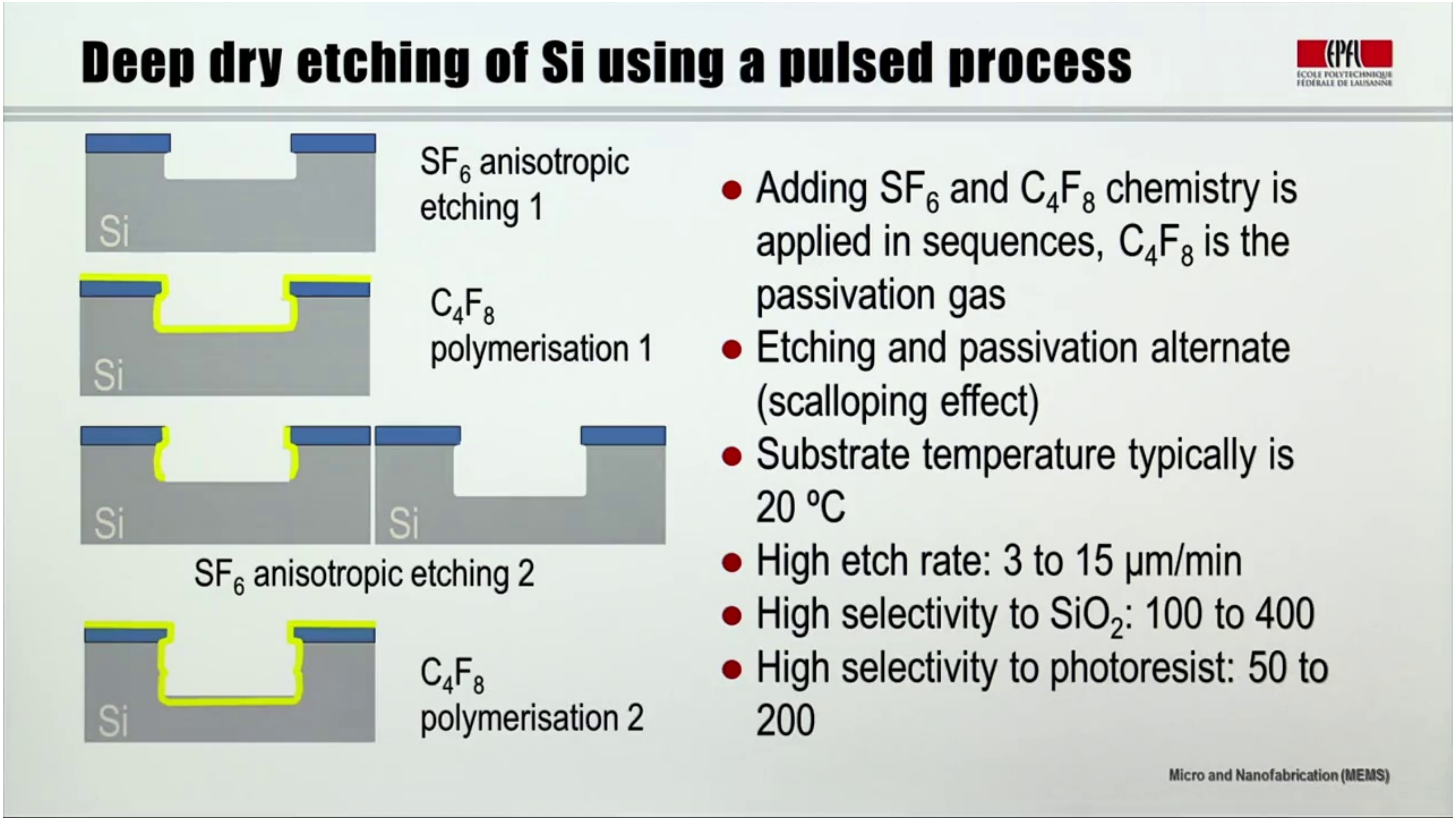
In this lesson we will discuss various so-called <i>deep dry etching</i> processes for silicon, which are processes with a high anisotropy so that one can etch deep vertical holes with little or no mask underetching. We will also give an example of dry etching equipment. Finally, we will present a few special dry etching processes that use intrinsic reactive gases and that do not require to have the gas in the plasma state, which leads to a significantly simpler etching system.



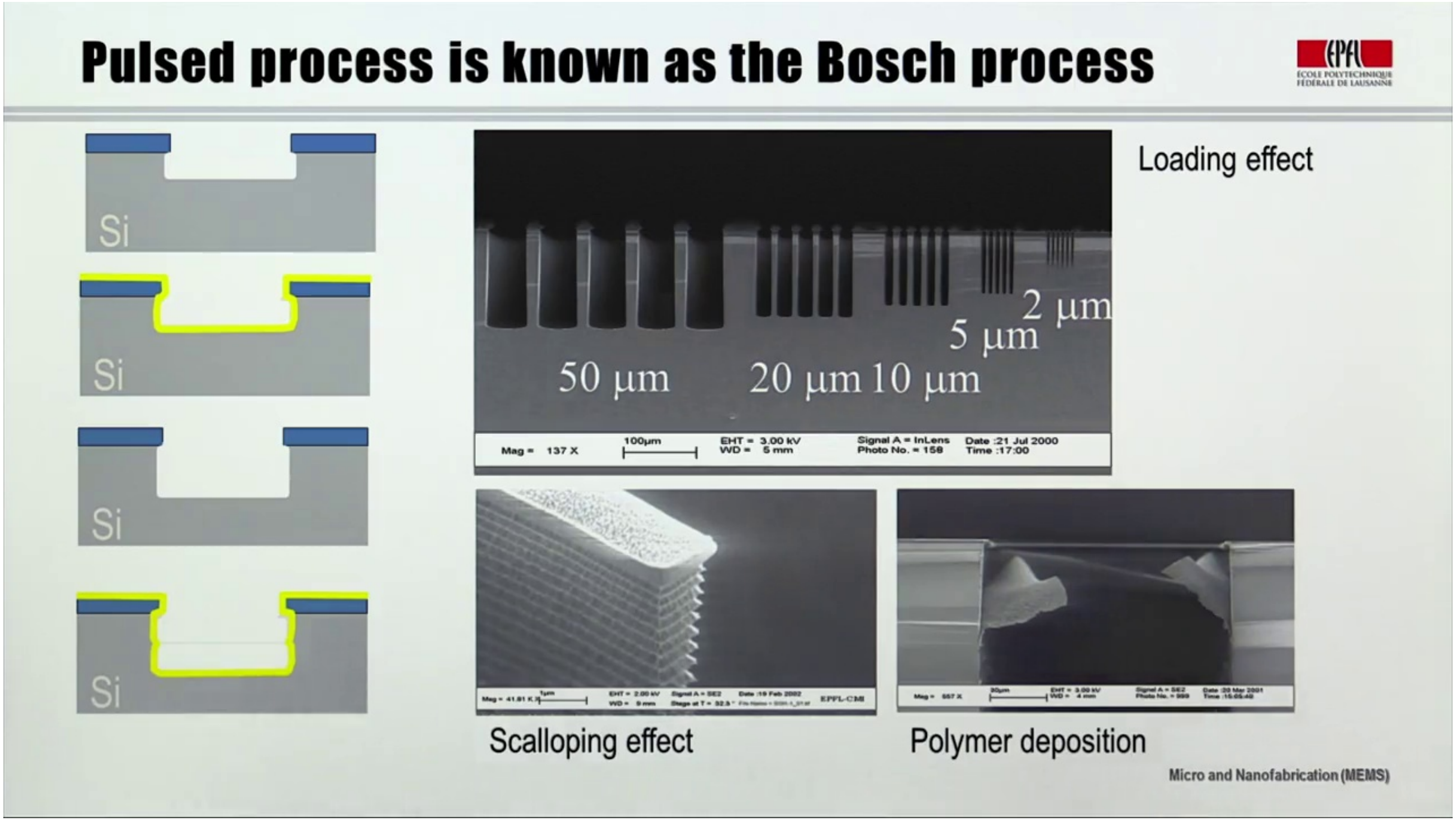
For deep dry etching of silicon, one can design a plasma-based etching process by combining the gases SF6 and C4F8 in the etching reactor. The first gas is an etching gas, as it contains a lot of fluorine, while the second is a passivation gas while it contains relatively a lot of carbon. The substrate bias has to be chosen such that there is an effective vertical etching rate while the horizontal etching rate should be zero, due to the hole sidewall passivation by the deposition of the polymer. The process can be designed to have a high selectivity to photoresist. Silicon can be etched 50 times faster than the photoresist.



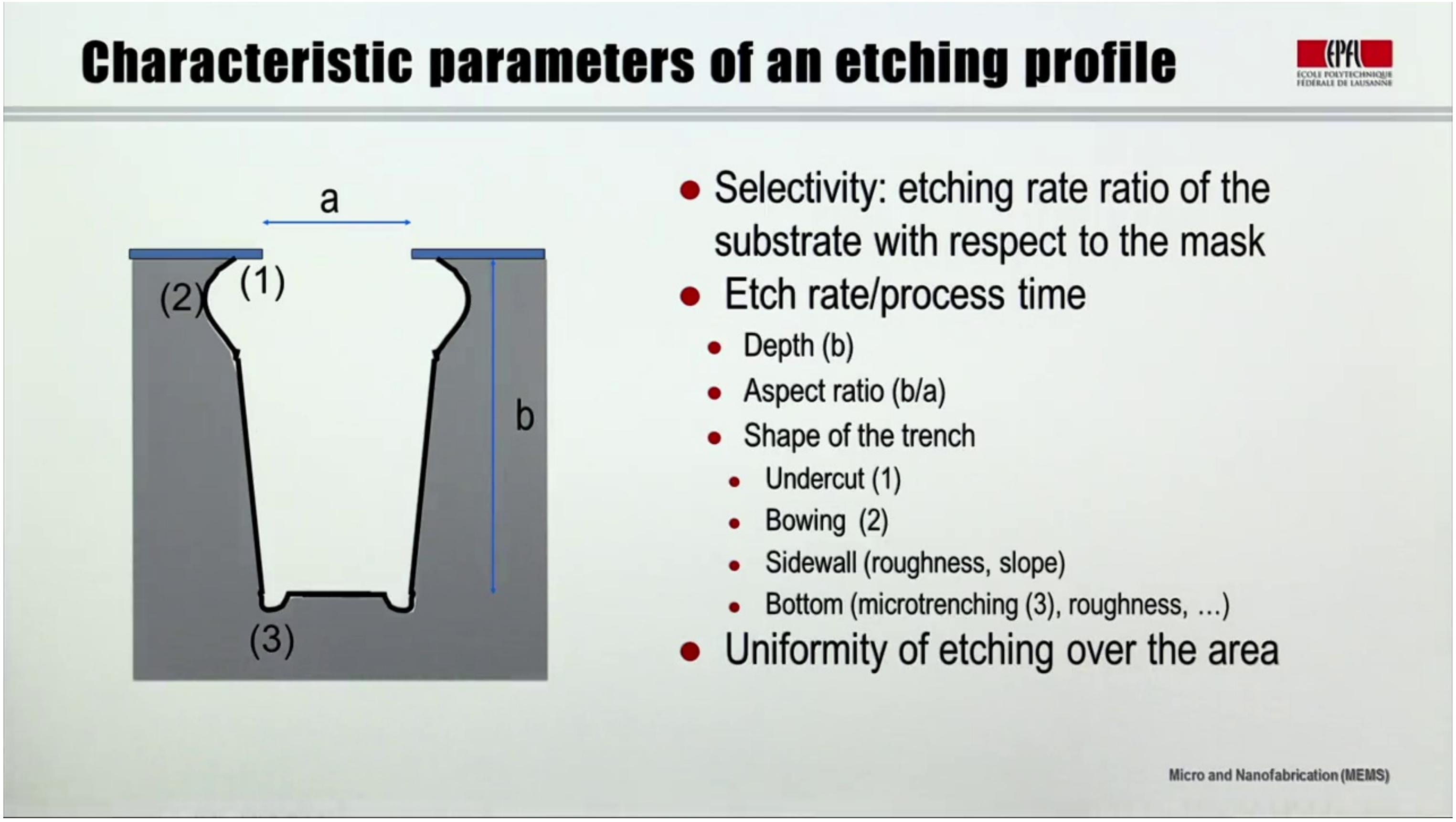
These pictures illustrate some results of this type of etching process. The first picture shows the etching of a polycrystalline silicon film which was deposited on a silicon dioxide layer. The second picture shows profiles of etched channel structures which were etched in a silicon wafer.



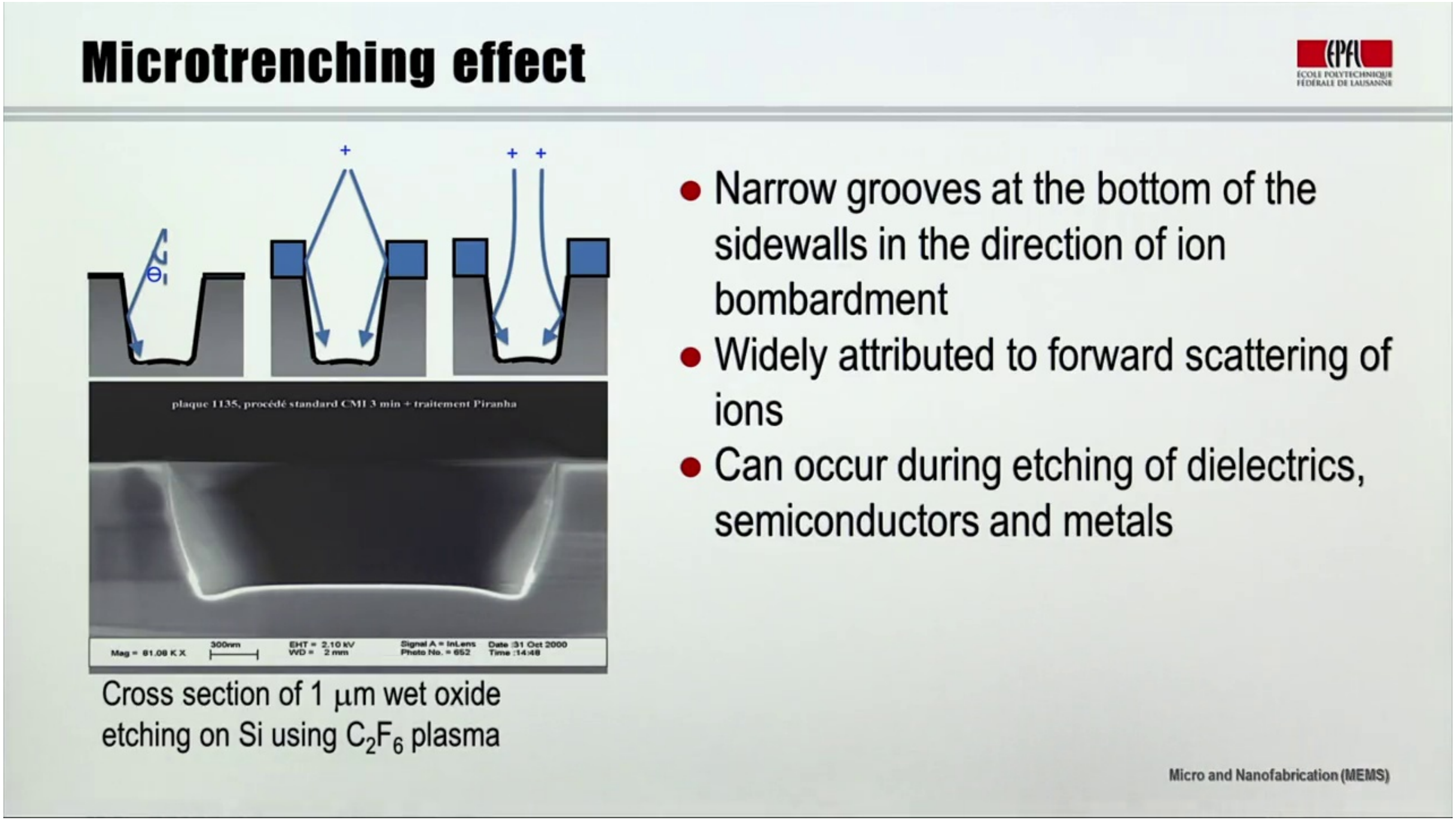
On the previous slides, both the etching and the passivation gas were simultaneously let into the reactor. It is also possible to apply the etching and polymerization gas sequentially in a pulsed process. The pictures show what happens. In the beginning, during a few seconds, chemical etching is performed in an SF6 plasma, which gives a little underetching of the mask. Then the etching gas supply is switched off and C4F8 gas is introduced, which is known to lead to polymerization. During a few seconds, a thin polymer layer is deposited, as indicated by the yellow line here. The next step in the process is again an etching sequence. Due to the substrate bias, the polymer film that is deposited on the horizontal faces of the structure is quickly removed in the etching, and hereafter, silicon is etched in that direction. Because there is no electrical field in the horizontal direction, there is little or no etching, but polymerization is chosen such that at the end of this second etching cycle, all polymer has disappeared, and then one stops this second SF6 etching cycle. One has effectively etched, now, a hole with little or no mask underetching. Next follows a second polymerization step, as illustrated in the lower picture. These pulsed etching and polymerization sequences can be repeated many times to realize very deep and anisotropic holes in the silicon. A high etching rate is obtained this way and a high selectivity of the silicon etching to silicon dioxide and photoresist masks can be obtained.



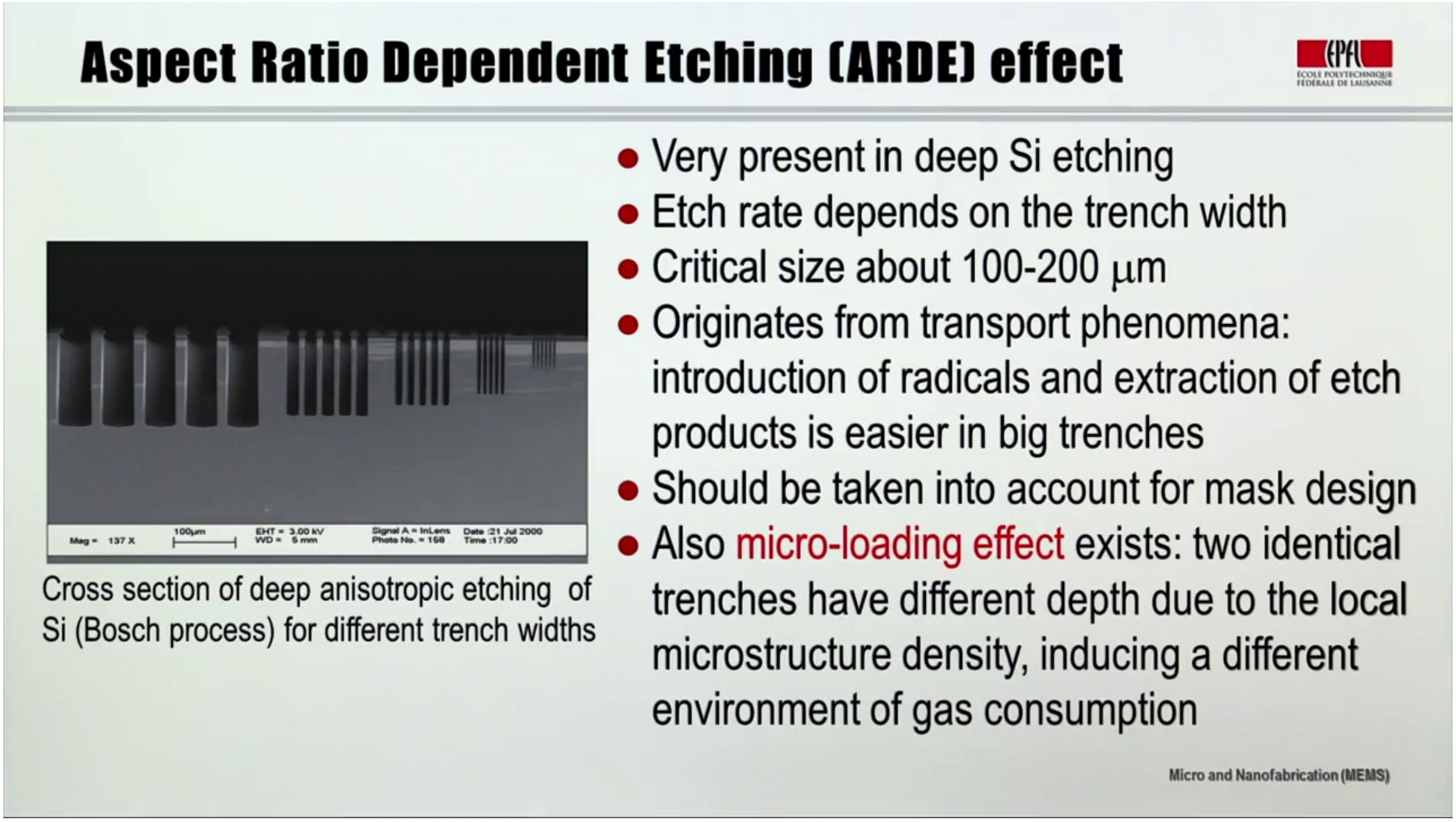
These pictures show some results of a deep dry etching process for silicon. The pulsed nature of the process is immediately recognizable by this so-called <i>scalloping effect</i> which originates from the alternating etching and polymerization cycles. The picture on the lower right shows a residual polymer layer, which was not completely removed from the sidewalls of the etched hole. The top picture shows that one can indeed etch vertical, anisotropic structures. It also shows that if there is a wider mask opening, the etching goes deeper than if there is a narrow mask opening, and this is related to the fact that the gas has easier access into a larger hole than in a small hole, and etching is more favored in that way. This pulsed process of etching in silicon is also called the <i>Bosch process</i>, after the origin of the researchers who first developed this process.



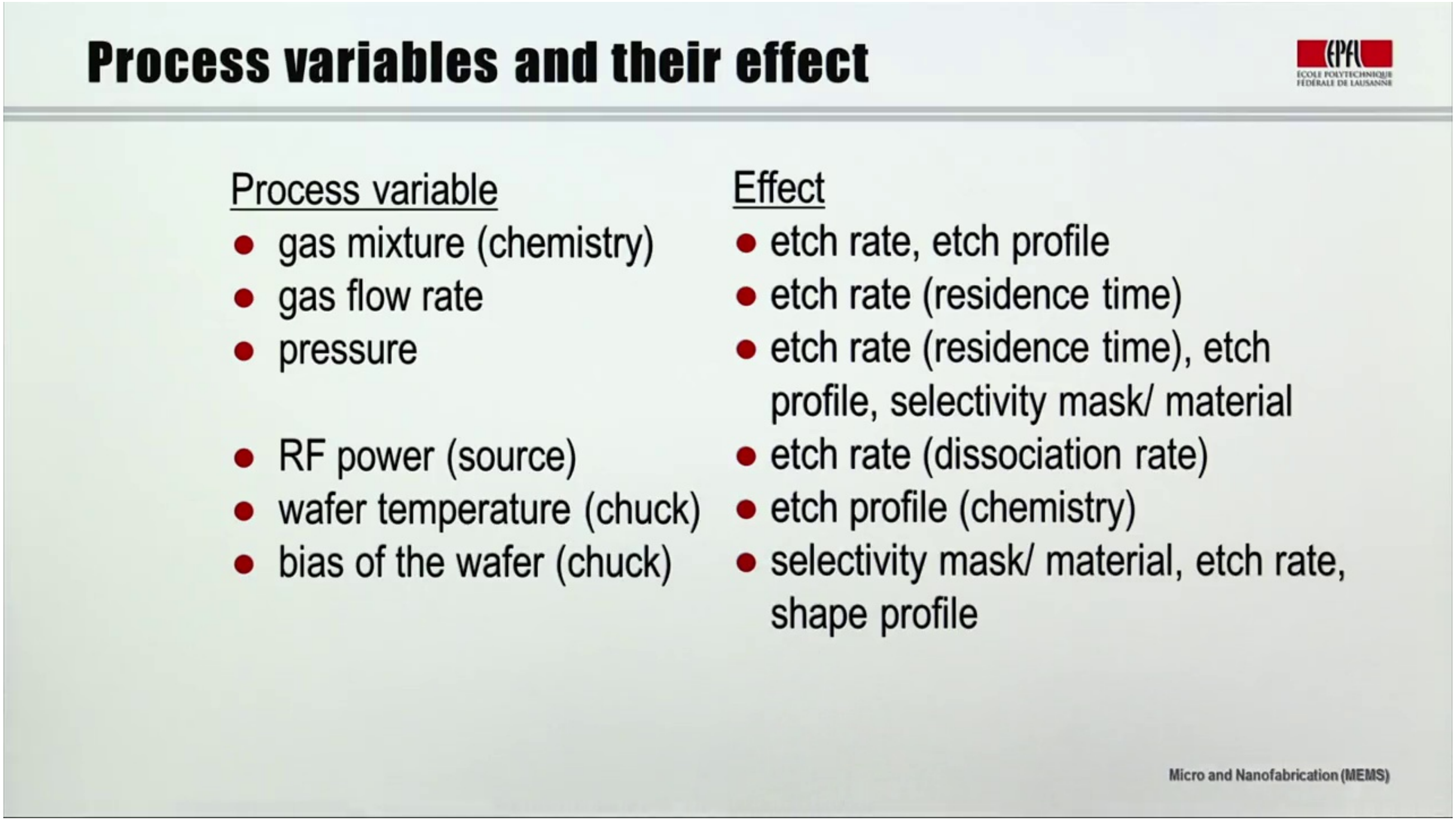
This picture shows, in general, the features that can be observed for an etched hole structure. The selectivity is defined as the ratio of the substrate etching to the mask etching, and ideally there should be little or no mask etching when the mask material is well chosen. For a hole opening <i>a,</i> one can etch a depth <i>b,</i> and this defines the <i>aspect ratio b/a.</i> Also illustrated here are some phenomena that are observed when doing dry etching of silicon. There is first the phenomenon of undercut, so there is some horizontal etching, which gives you mask underetching. There is also bowing, this kind of rounded shape, and there is drenching, at the bottom of the hole one sees some deeper recesses in the corners. Another important parameter of the etching process is the uniformity of the etching over the whole wafer. Ideally the etched profile should not depend on the position of the hole on the wafer.



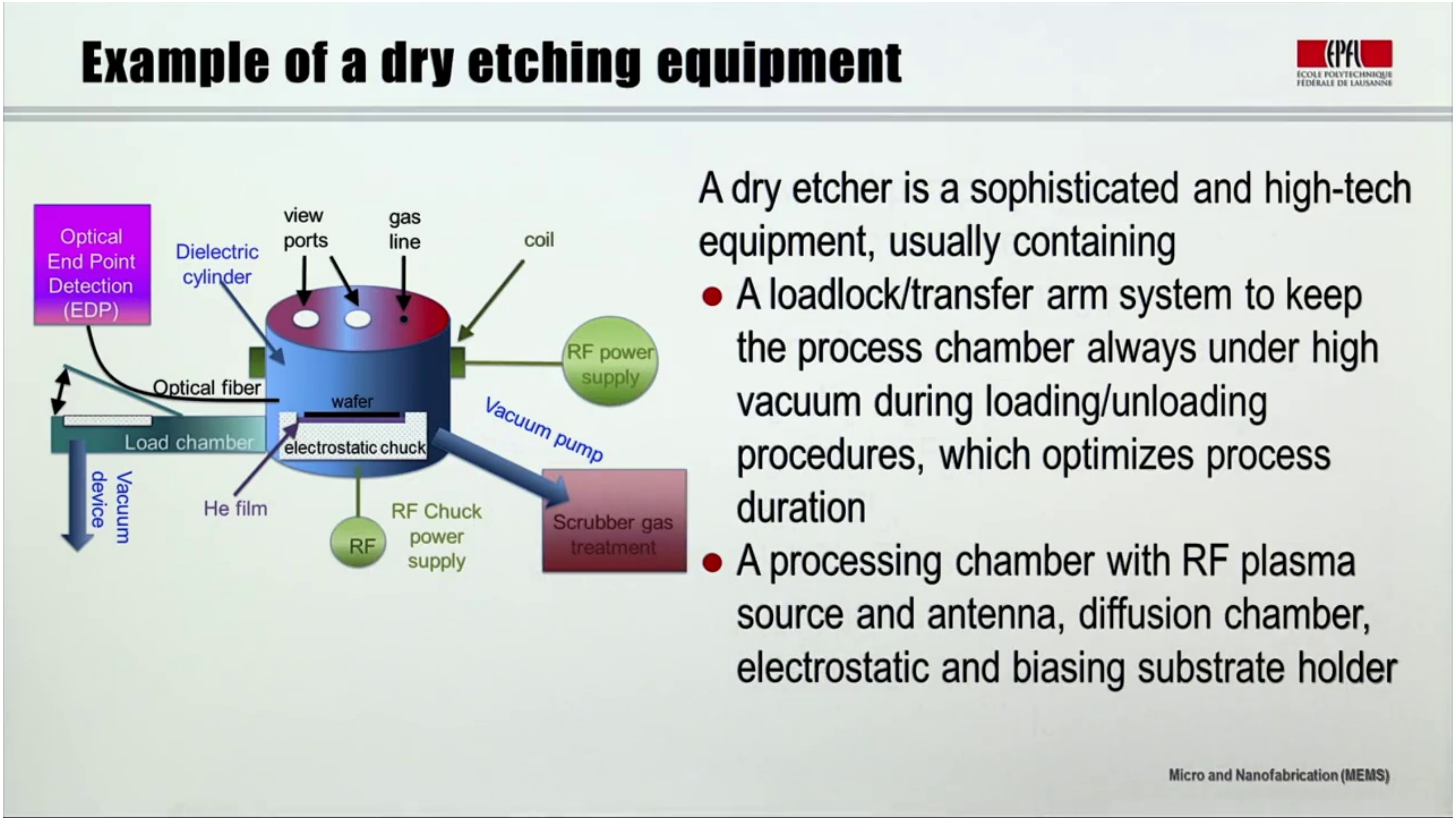
The origin of the microtrenching effect is illustrated here. It is caused by the forward scattering of ions to the sidewalls of the etched structure. And this gives extra etching near the lower corners of the hole structure. This phenomenon can occur during etching of dielectric materials, semiconductors and metals.



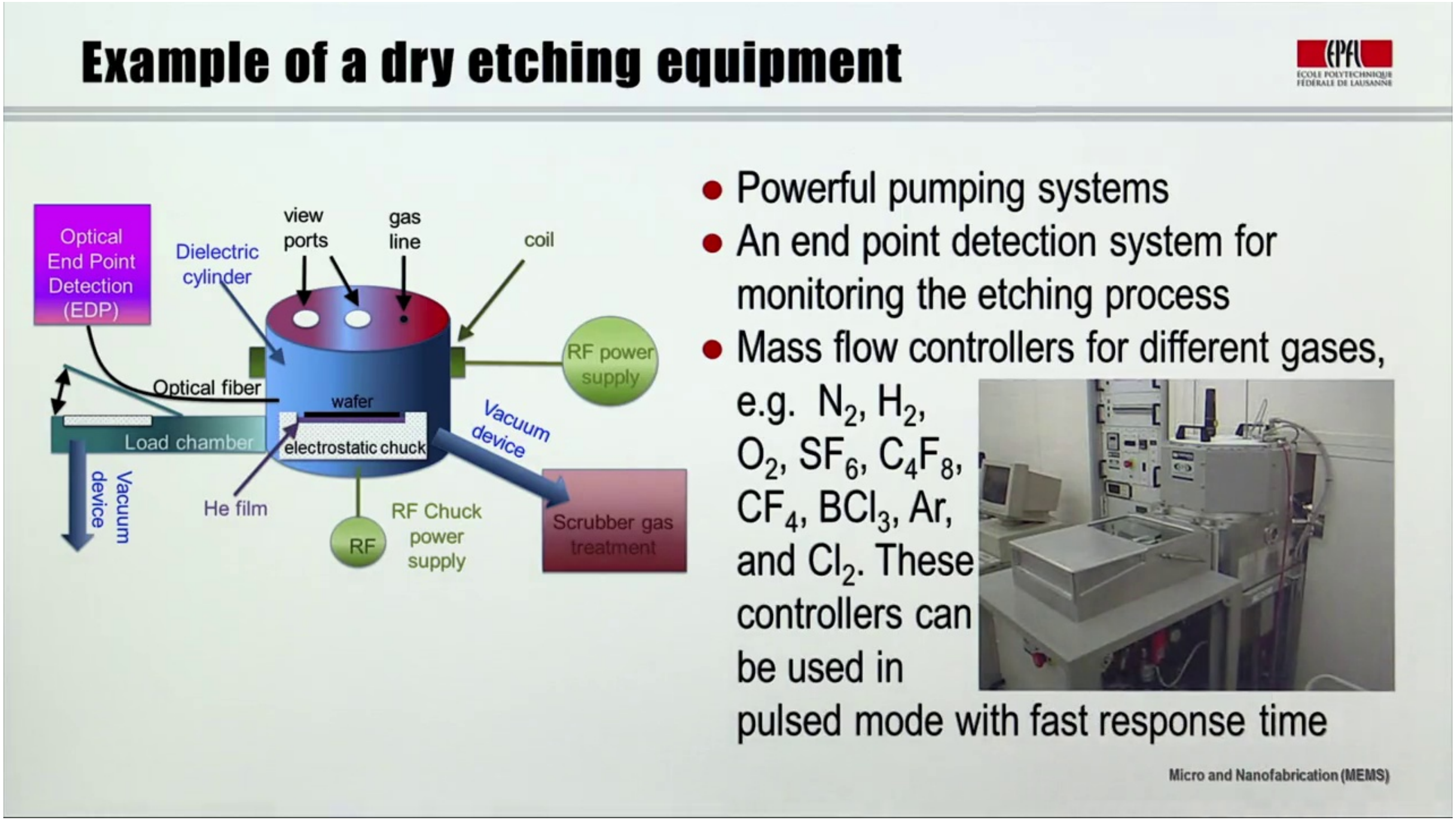
We take back, here, one of the pictures shown before, to illustrate the so-called <i>aspect ratio dependent etching effect,</i> <i>ARDE effect,</i> by which the etch rate depends on the hole or trench width, as shown in this picture. Also, micro-loading effects exist in dry etching, which means that two identical trenches can have a different depth depending on if they were in a local environment on the wafer where there was more material to be etched away. That means where there was more competition for the gas to be consumed. If more silicon is to be etched away locally, the depth of a trench or hole in such micro-environment will be smaller.



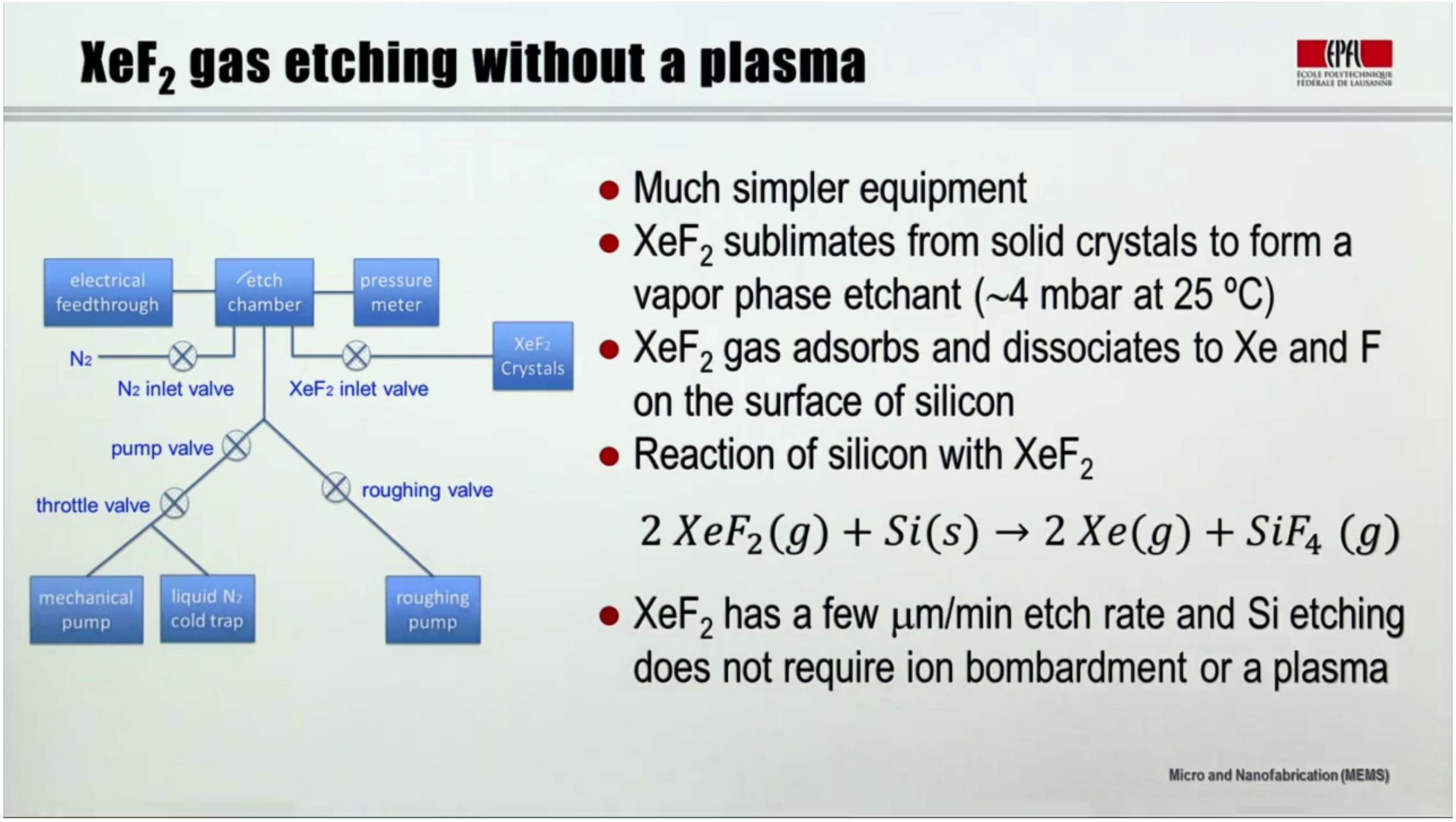
On this slide, we summarize experimental process variables that can be varied in a dry etching process, and we mention, also, the way they effect the dry etching. The gas mixture, or gas chemistry, directly effects etch rate and etch profile, as well as variations in the gas flow rate and pressure. The RF power affects the etching rate, as for a higher power, more and more gas molecules get dissocciated and the etching rate increases. The wafer temperature, or the temperature of the chuck on which the wafer is fixed, as well as the bias voltage on that chuck, directly influence the etching profile and the anisotropy.



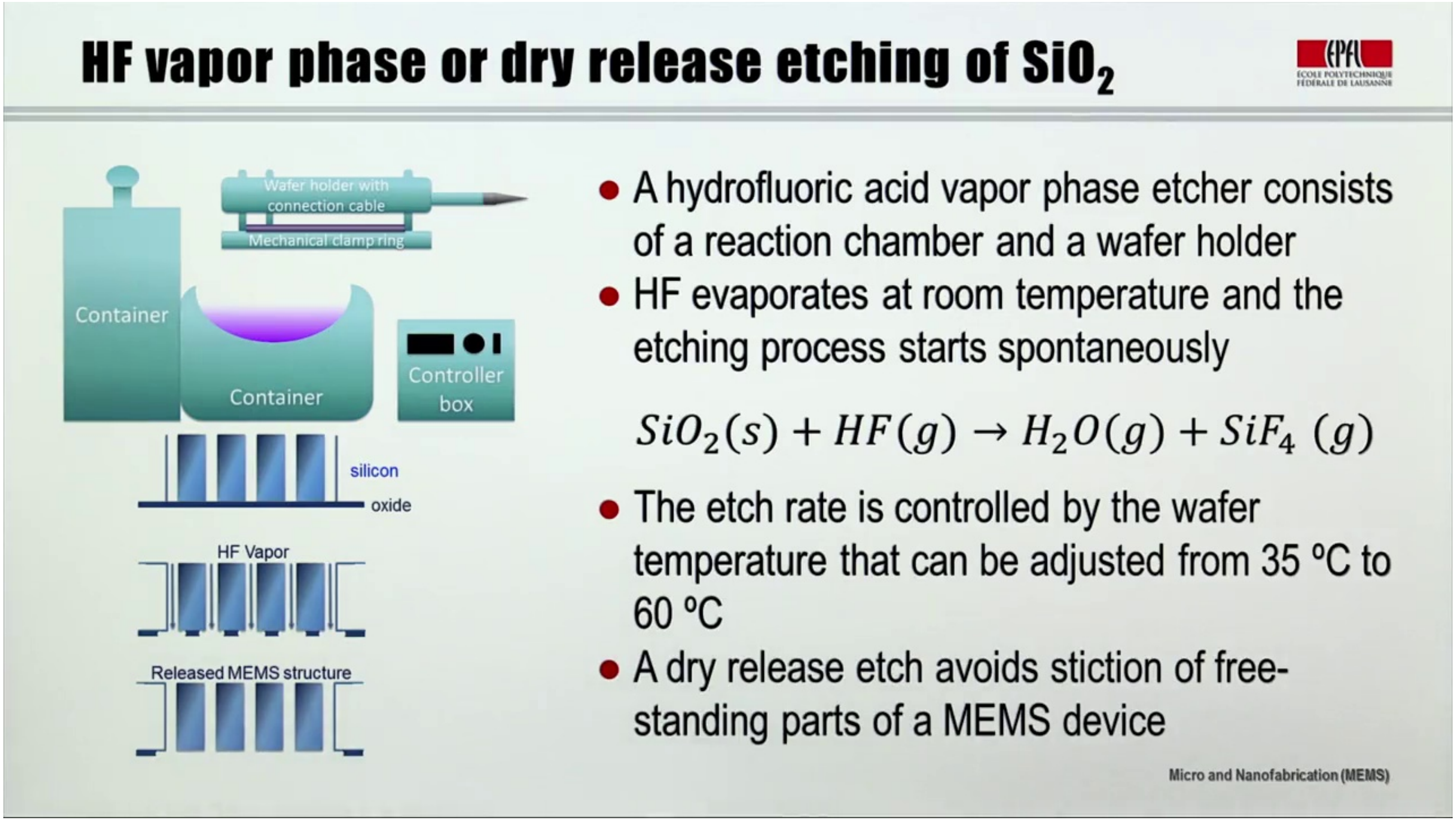
On this slide we give a schematic example of a dry etching reactor. It is a very sophisticated system which has a load chamber in which one puts the wafer to be etched. This wafer is then translated into the reactor without breaking the vacuum present in the reactor. The wafer in the reactor is clamped then to a chuck, it can be by electrostatic forces as we will explain later, and the chuck is kept at a fixed temperature and the etching can start. The reactor is equipped with a radio frequency power supply for generating the plasma, and in case an electrostatic chuck is chosen, there is an RF chuck power supply to generate these electric forces. There is also a scrubber that eliminates toxic side products of the etching reaction before leading the reactor output gases away into the environment.



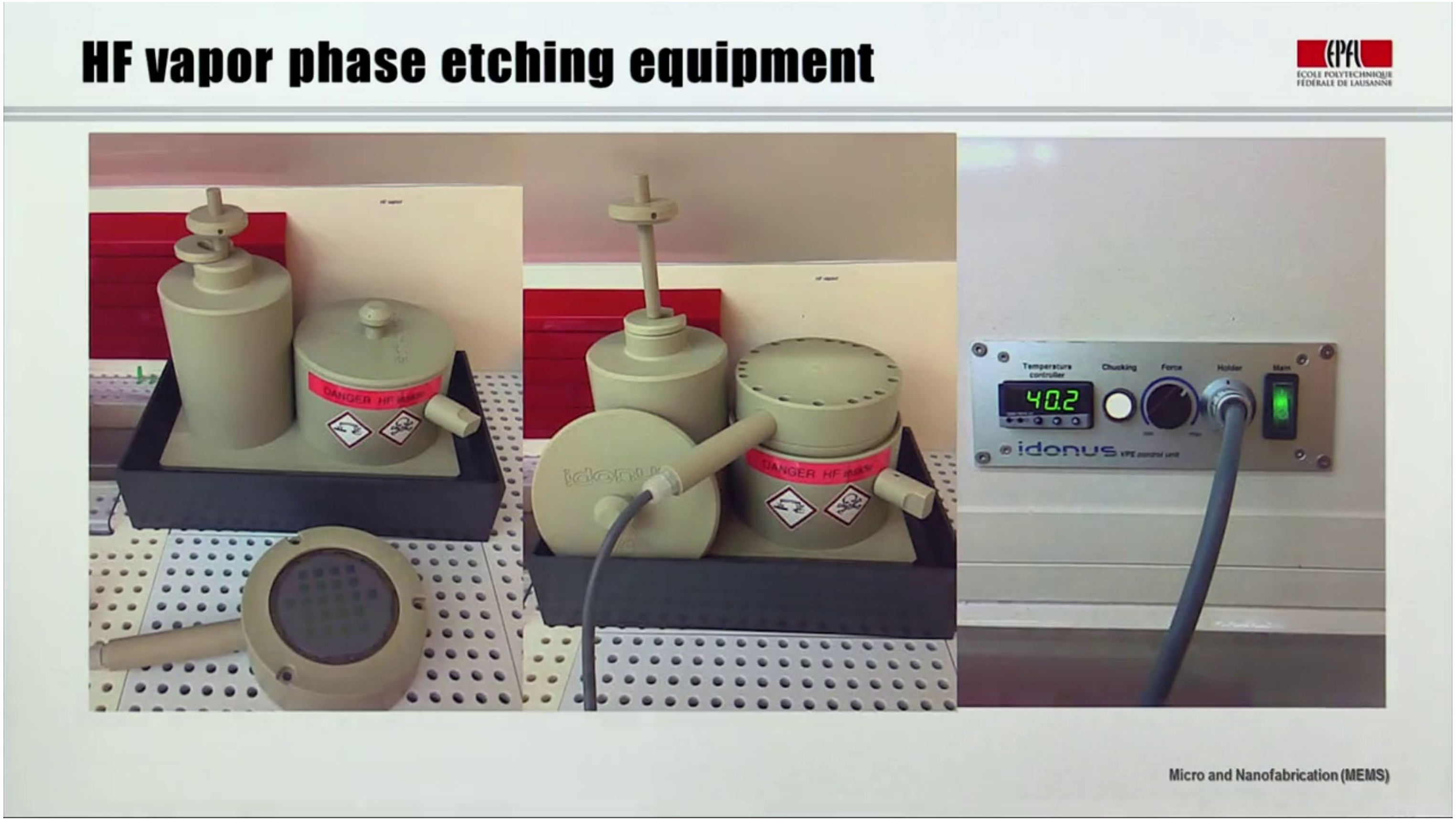
There is also an equipment for live monitoring of the optical emission from the gas to provide information on the materials that are etched away. And this can be used to determine when one has reached the endpoint of an etching process. The reactor is configured with several gas flow lines and mask flow controllers. For example, one uses nitrogen, hydrogen, oxygen, argon gas or any of the halocarbon etching gases. The picture on the right shows a real reactor with in front of it the chamber in which one loads the wafer.



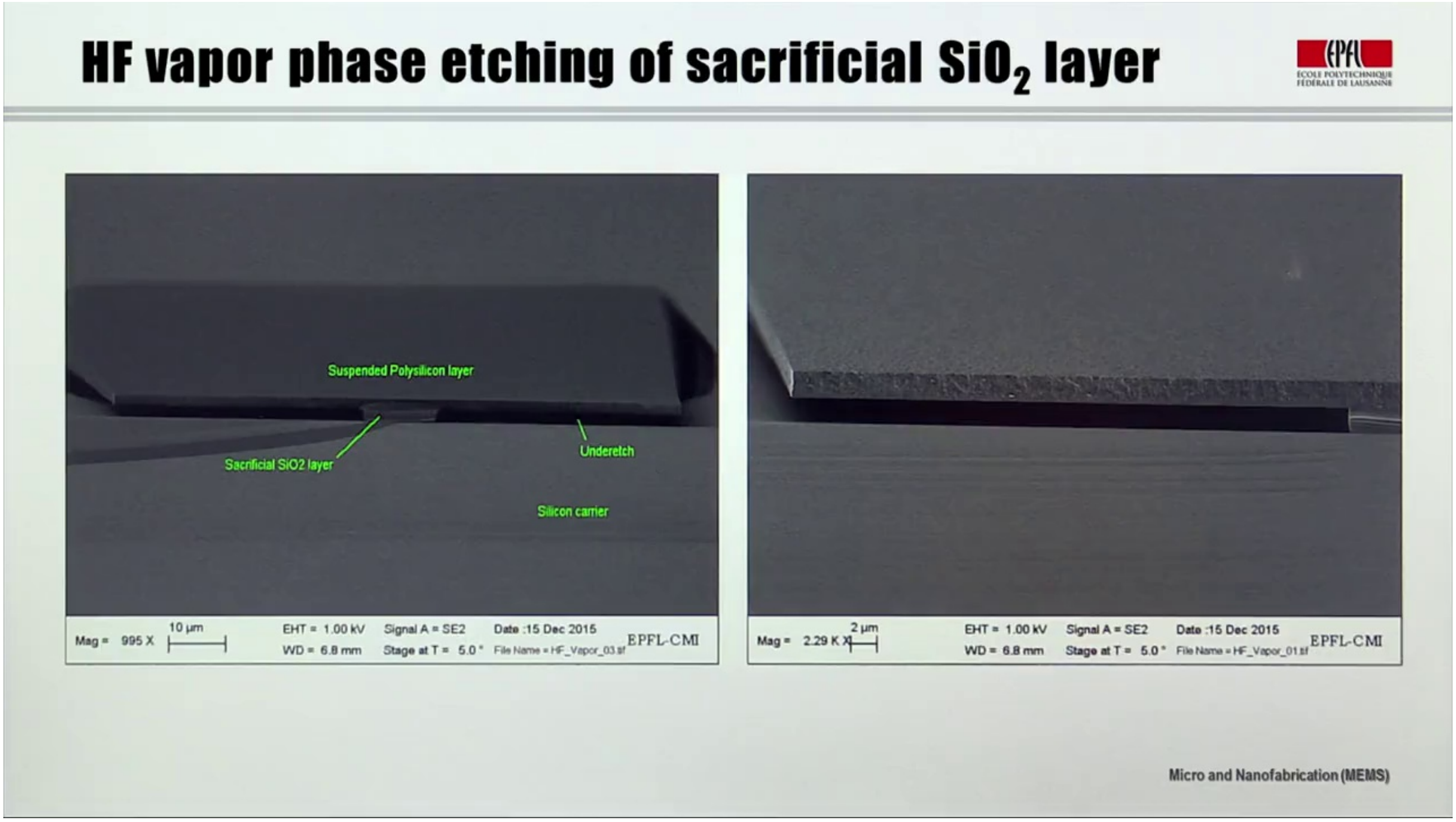
Xenon fluoride gas etching of silicon without development of a plasma is also used in microfabrication. This process requires much simpler equipment than a plasma etcher. The xenon fluoride is placed, in the form of solid crystals, into a closed reactor from which fluorine vapor is spontaneously released, which etches the silicon according to this chemical reaction. The process has an etching rate of a few micrometers per minute. The figure shows a schematic diagram of the etching chamber interfaced with simply a few valves and pumps.



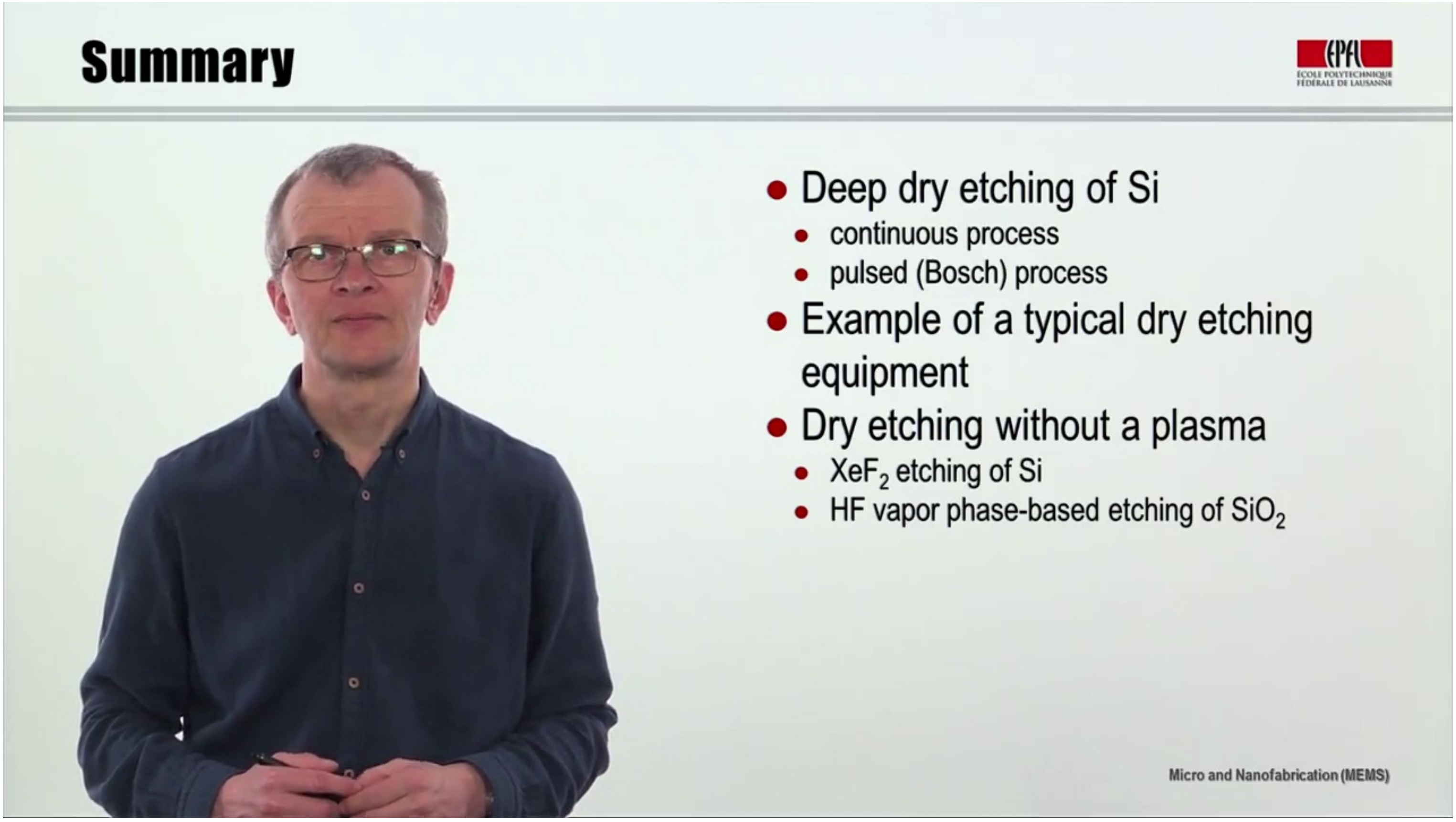
Another example of gas phase etching without a plasma is the etching of silicon dioxide using HF vapor. For hydrofluoric acid vapor phase etching, one only needs a container into which one pours the HF, and a wafer holder to which the wafer is mechanically clamped. The reaction with the HF vapor is written here, and is controlled by the wafer temperature. The technique can be used to remove an oxide layer underneath an etched silicon microstructure to provide a freestanding structure. So here the silicon was etched, then putting it into HF vapor slowly etches away the oxide, until in the middle, these silicon parts are now freely moving, and, of course, they are somewhere anchored to the substrate. In this way, one can release the silicon structure without applying a liquid. If one applies a liquid here, this can give surface tension forces which can deform the delicate mechanical structures.



This slide gives an impression of the equipment that is needed for HF vapor phase etching, which indeed is orders of magnitude less complex and much cheaper than a plasma reactor. There is a container for the HF, and there is control of the temperature, basically.



Here we see how silicon dioxide is partly removed from under a polysilicon layer so that this becomes a freestanding electrode.



In this lesson, we have presented several processes for the deep dry etching of silicon, like the continuous process in which the etching gas and the polymerization gas are simultaneously introduced in the plasma reactor, as well as the pulsed, or Bosch, process in which the two types of gas exposures are alternated. We gave an example of a typical dry etching equipment and also introduced dry etching without a plasma, which requires much less complex and much less sophisticated infrastructure. Subsequently, we introduced xenon fluoride etching of silicon, and HF vapor phase etching of silicon dioxide.