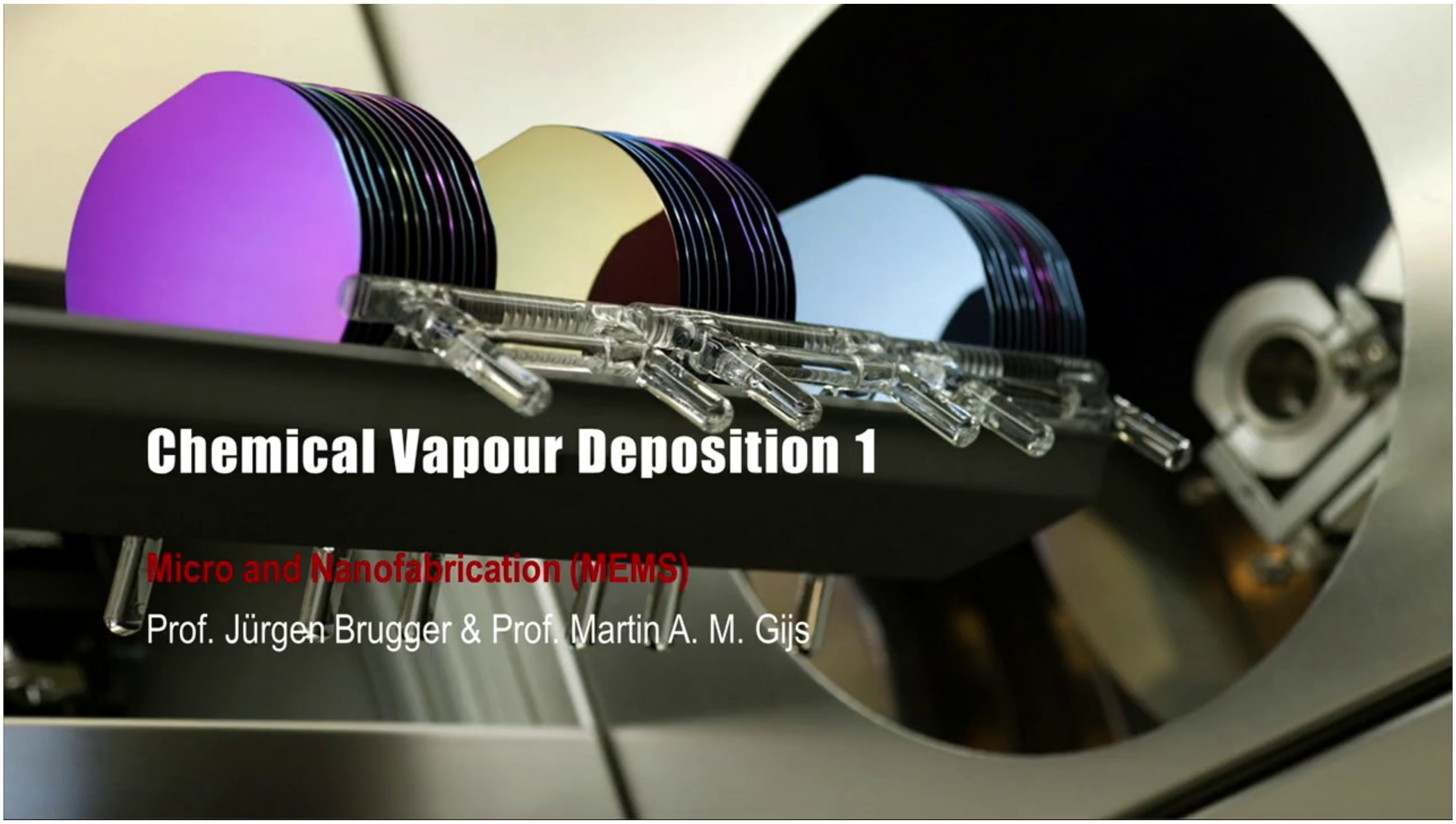
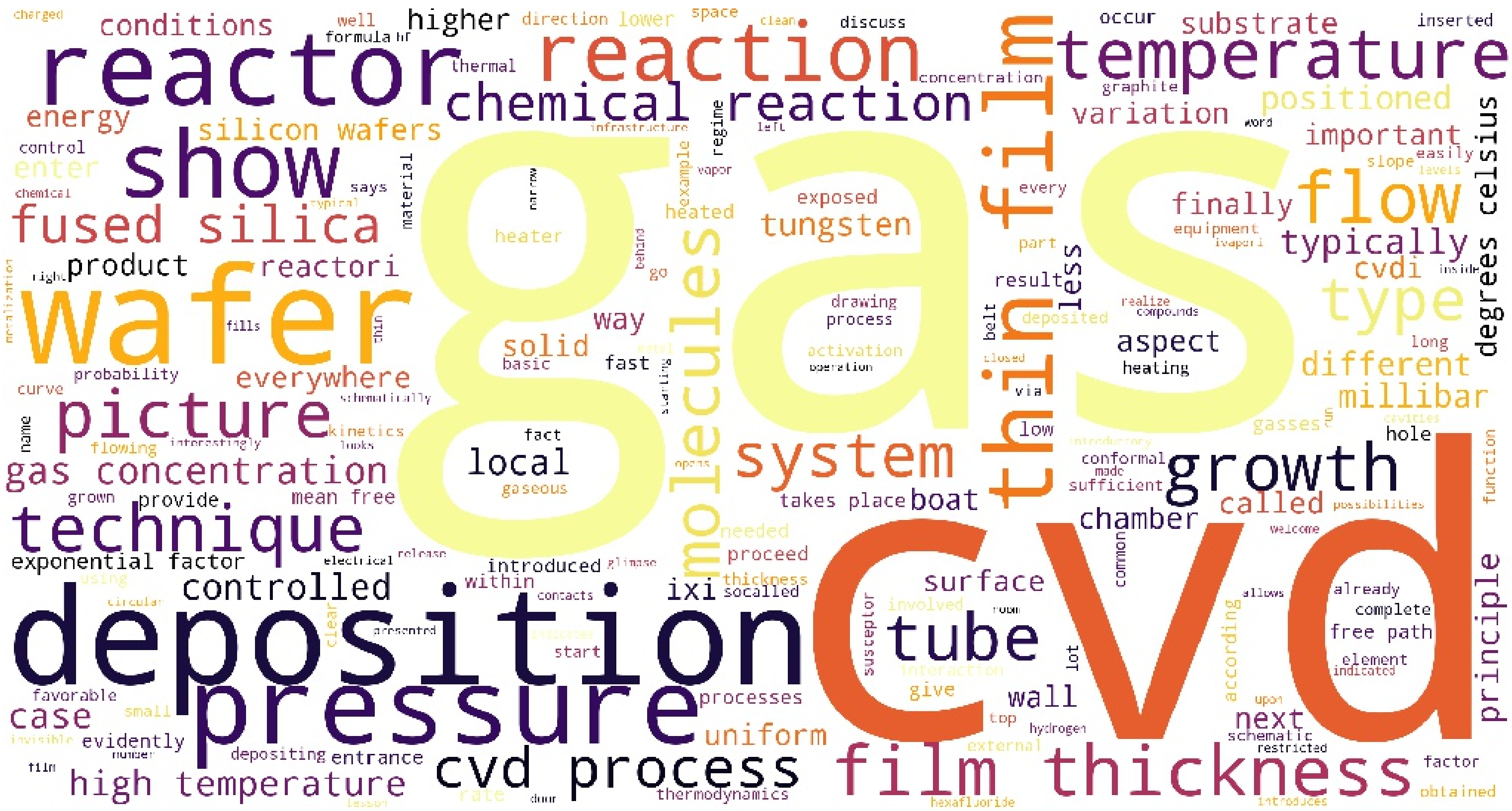


Chemical Vapour Deposition 1

Micro and Nanofabrication (MEMS)

Prof. Jürgen Brugger & Prof. Martin A. M. Gijs



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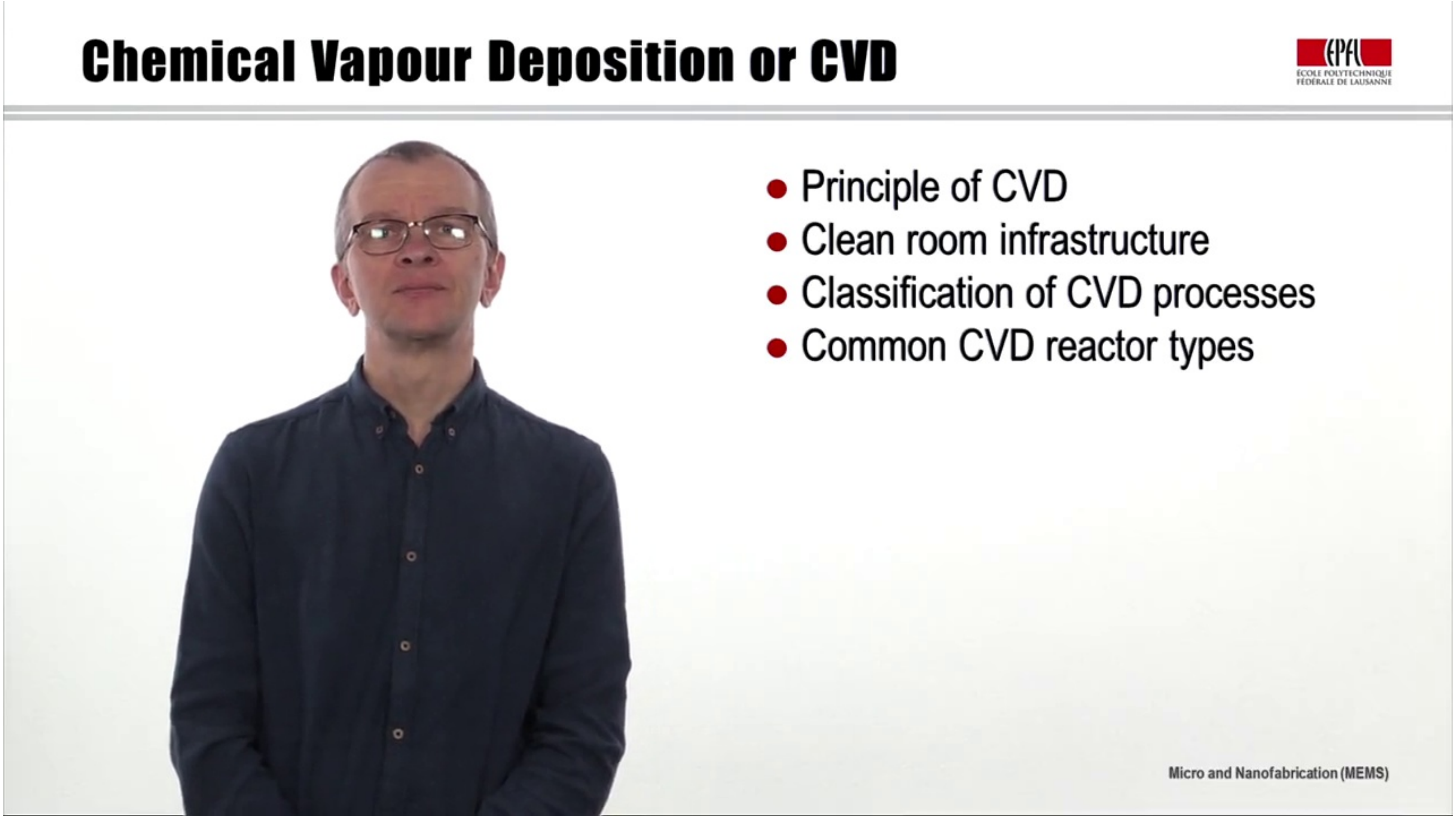
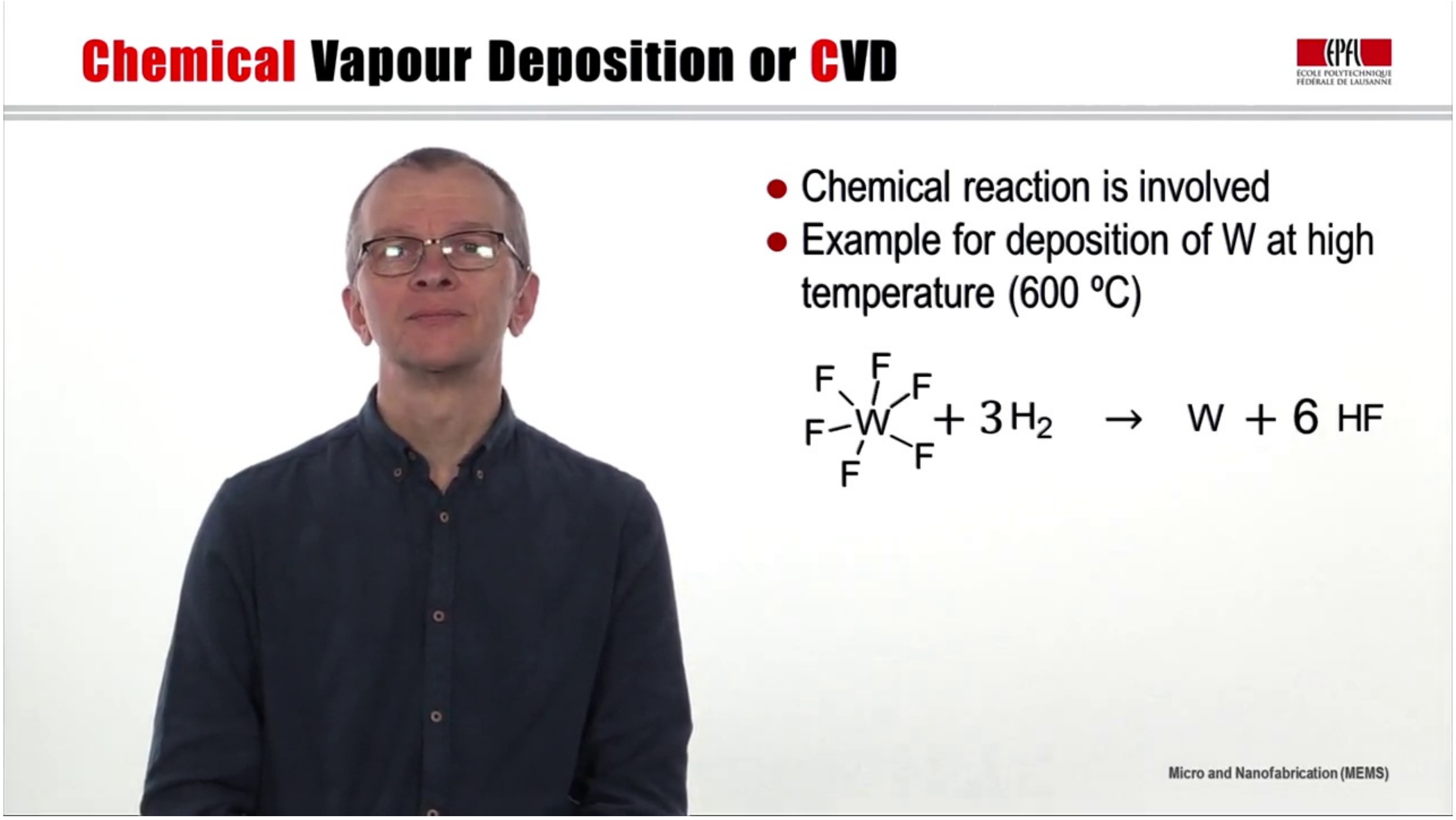


Chemical Vapour Deposition or CVD

- Principle of CVD
- Clean room infrastructure
- Classification of CVD processes
- Common CVD reactor types

Micro and Nanofabrication (MEMS)

Welcome in the introductory lesson on chemical vapor deposition or CVD. Here we will discuss the basic principles of CVD and will show you a glimpse of the clean room infrastructure that is needed to run a CVD process. Different types of CVD techniques will be introduced and finally, a few common CVD reactor types will be presented.

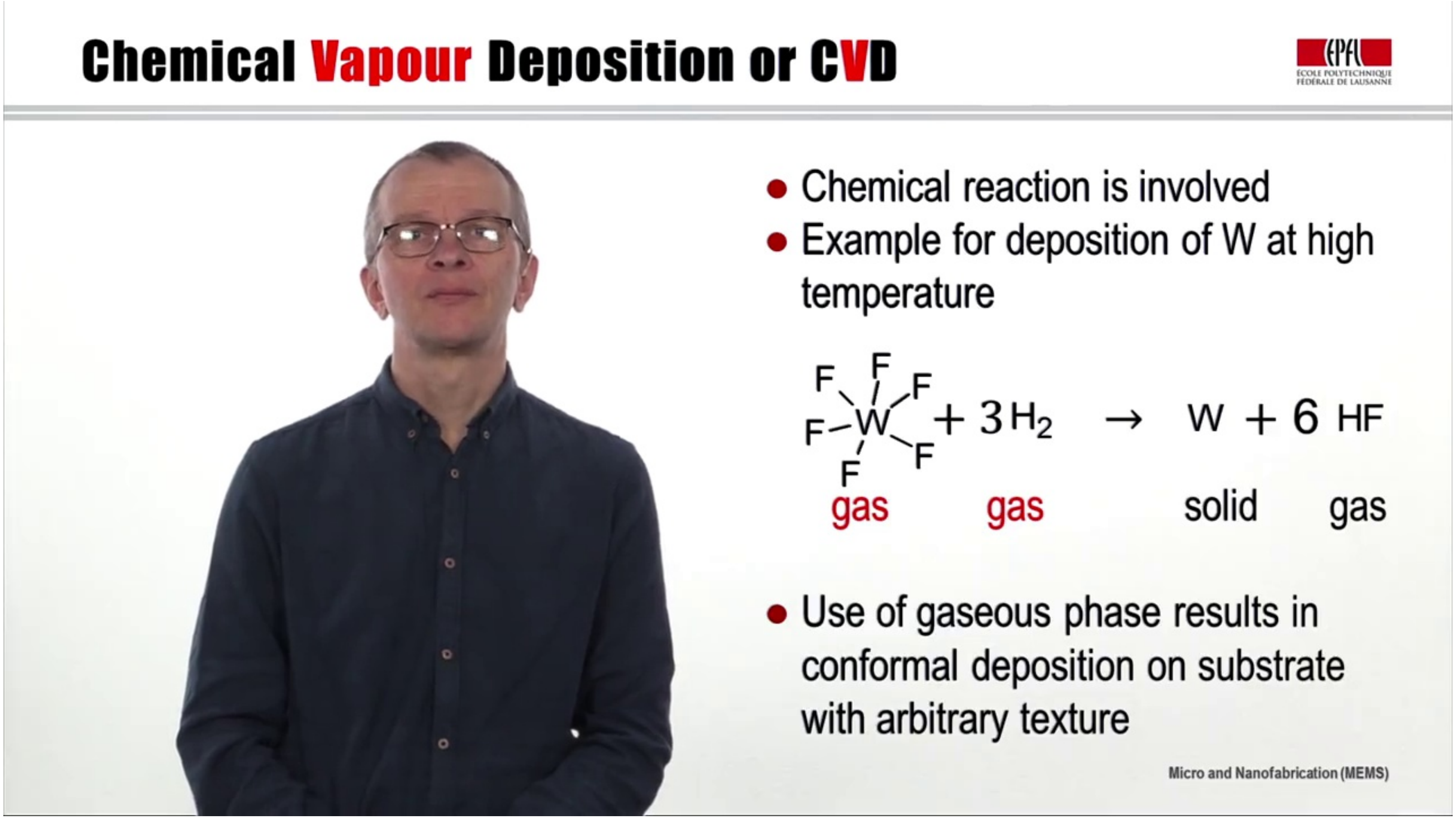


Chemical Vapour Deposition or CVD

- Chemical reaction is involved
- Example for deposition of W at high temperature (600 ºC)

Micro and Nanofabrication (MEMS)

As the name of the technique says, a chemical reaction is involved in depositing a thin film material using CVD. We give, as an example here, the deposition of tungsten at a high temperature of 600 degrees Celsius. To realize this deposition one introduces into a reactor two gasses, tungsten hexafluoride and hydrogen, which, upon chemical reaction, result in the deposition of the metal tungsten and the release of the gas HF.



Chemical Vapour Deposition or CVD

- Chemical reaction is involved
- Example for deposition of W at high temperature

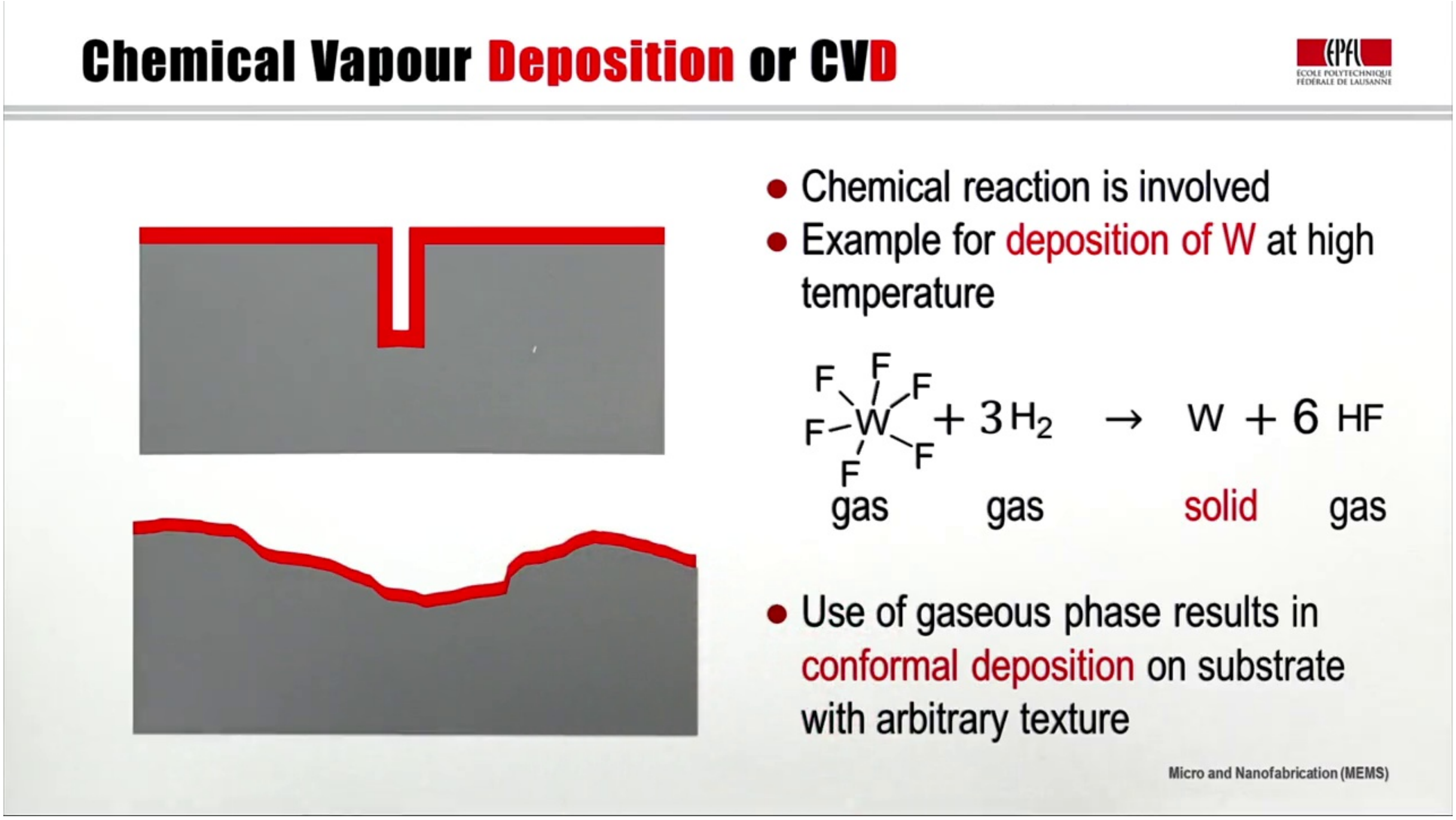
$$+ 3H_2 \rightarrow W + 6\,HF$$

gas gas solid gas

- Use of gaseous phase results in conformal deposition on substrate with arbitrary texture

Micro and Nanofabrication (MEMS)

The word <i>vapor</i> used in this CVD technique indicates that the starting compounds to start a CVD deposition are gasses. As gas fills easily all parts of the reactor, every surface in the reactor is exposed in the same way by the gas. As a result, the solid tungsten is deposited everywhere in the same way, conformal to the substrate.



Chemical Vapour Deposition or CVD

- Chemical reaction is involved
- Example for deposition of W at high temperature

$$\underset{\text{gas}}{WF_6} + \underset{\text{gas}}{3H_2} \rightarrow \underset{\text{solid}}{W} + \underset{\text{gas}}{6\,HF}$$

- Use of gaseous phase results in conformal deposition on substrate with arbitrary texture

Micro and Nanofabrication (MEMS)

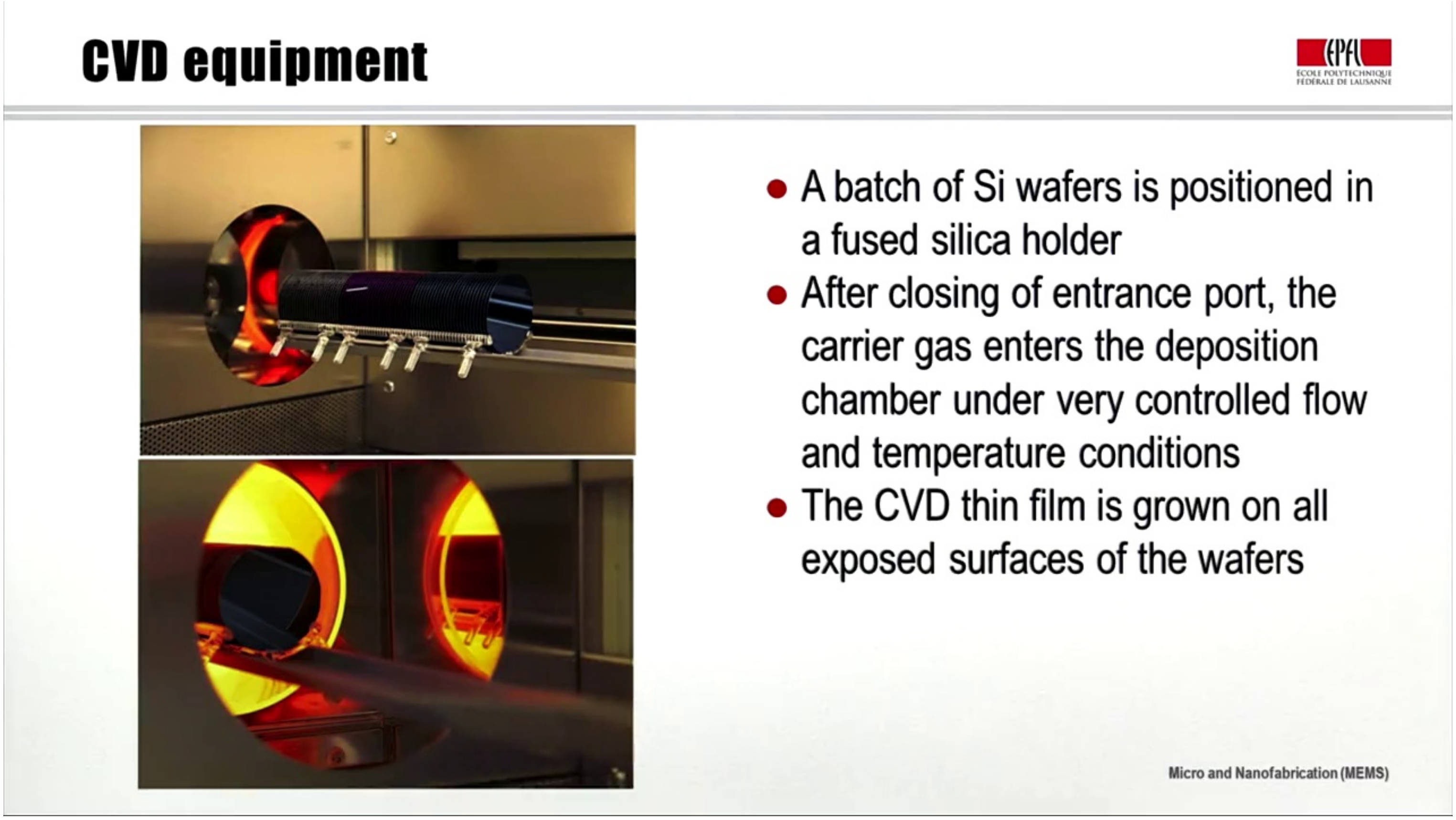
The conformal deposition of the tungsten is schematically indicated in this drawing. More interestingly, from the drawing on the top, it is clear that the gas can also enter into narrow holes or restricted spaces in the substrate. This opens possibilities for the technique to do a metalization inside cavities and provide electrical contacts between different levels on the wafer, for example.

CVD equipment

Example of a thermal CVD reactor

Micro and Nanofabrication (MEMS)

Here we show a typical CVD equipment, how it looks like. The picture on the left shows 4 circular entrances behind which a fused silica reactor is positioned, invisible in this picture. Use of fused silica allows operation until very high temperatures, typically up to 1000 or 1100 degrees Celsius. The picture also shows that boats made with fused silica have been charged with a number of silicon wafers. A boat can enter a tube via an entrance hole after which the door is closed and the CVD process can start. The picture on the right shows an operator who is charging the boat with silicon wafers.

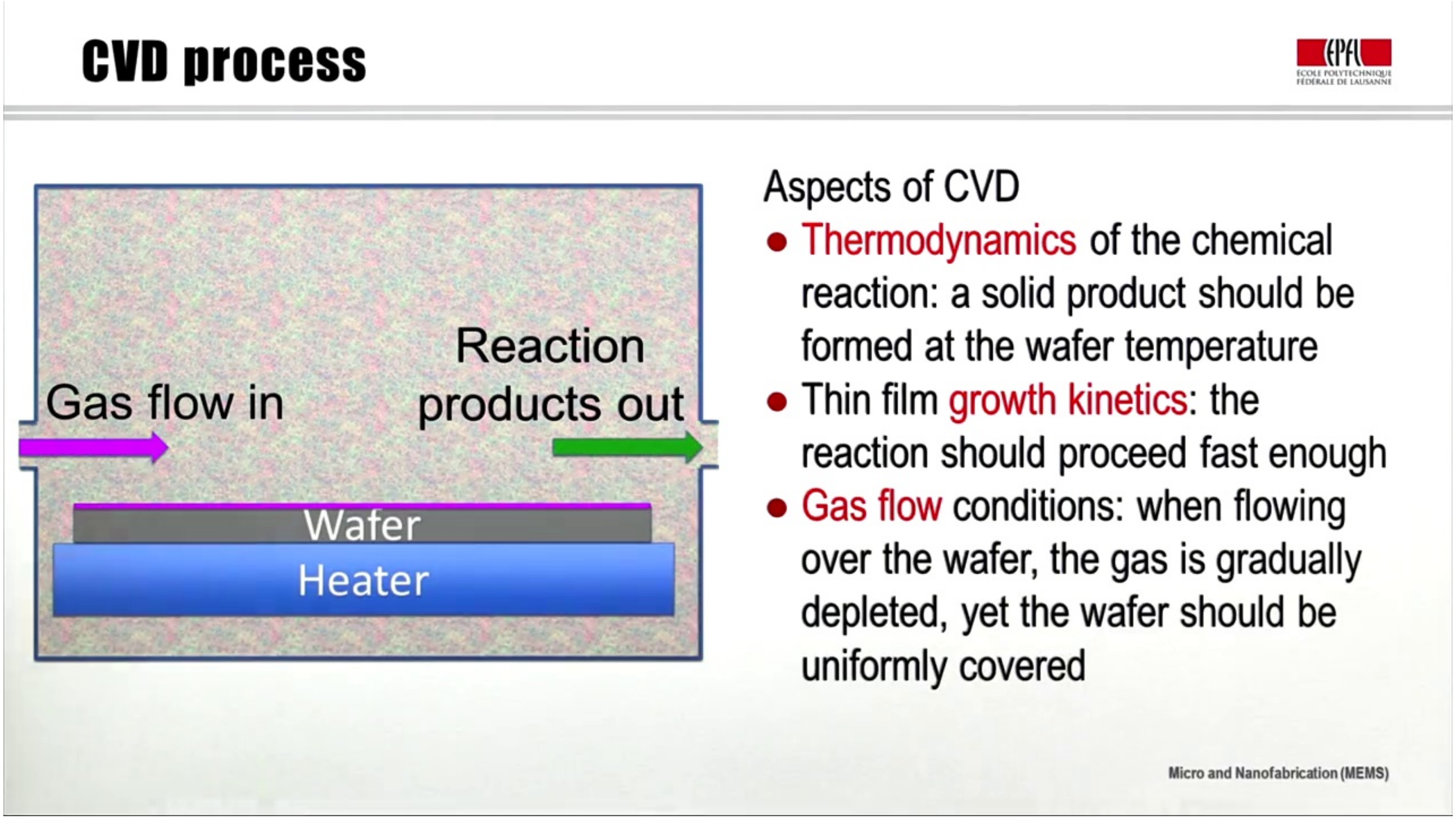


CVD equipment

- A batch of Si wafers is positioned in a fused silica holder
- After closing of entrance port, the carrier gas enters the deposition chamber under very controlled flow and temperature conditions
- The CVD thin film is grown on all exposed surfaces of the wafers

Micro and Nanofabrication (MEMS)

This slide shows the CVD equipment in more detail. The top picture shows a batch of silicon wafers that is ready to be inserted into the fused silica tube. The lower picture shows the silicon wafers that have been moved further in the tube. The yellow color results from the fact that one has switched on the heating elements that surround the fused silica tube. After closing of the entrance port, the carrier gas enters the deposition chamber and one can very accurately control flow and temperature conditions. Evidently, CVD thin films are grown on all exposed surfaces within the tube.



CVD process

Gas flow in

Reaction products out

Wafer

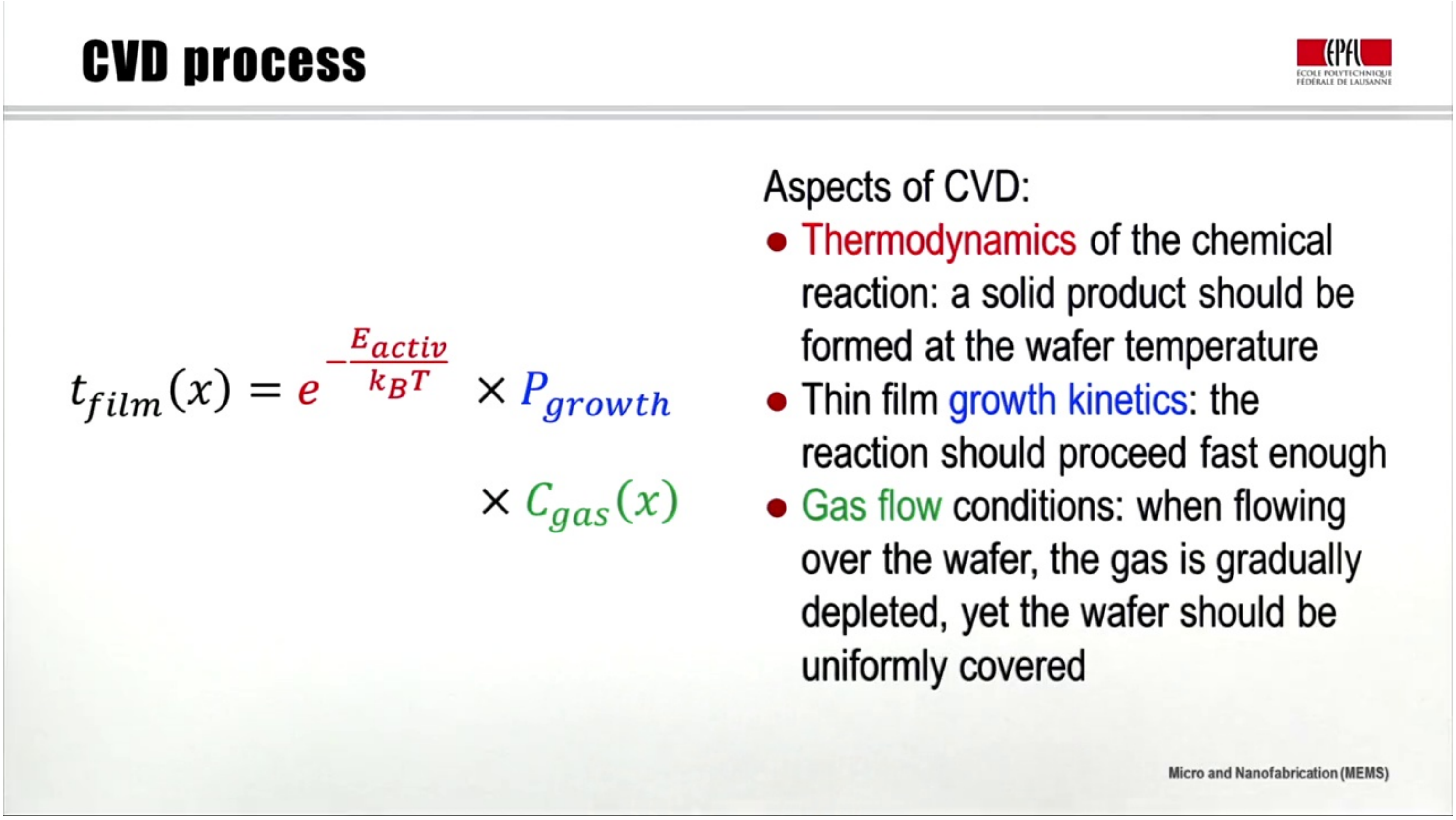
Heater

Aspects of CVD

- Thermodynamics of the chemical reaction: a solid product should be formed at the wafer temperature
- Thin film growth kinetics: the reaction should proceed fast enough
- Gas flow conditions: when flowing over the wafer, the gas is gradually depleted, yet the wafer should be uniformly covered

Micro and Nanofabrication (MEMS)

We will now discuss in a very schematic way what happens in a CVD process. To this purpose we have drawn here a wafer positioned on a heating element. The goal is to deposit by CVD a thin film on the wafer. The wafer and heater are positioned in a reactor chamber from which we can evacuate all residual gasses by pumping. We show here the reactor chamber that has been filled with a controlled gas atmosphere. There is a gas flowing into the reactor which undergoes a chemical reaction at the heated wafer's surface, which leads to the deposition of a thin film. As side products of this chemical reaction gaseous products are produced that are evacuated from the chamber. Different physical principles or aspects are involved for understanding a CVD process. First, one should understand the thermodynamics of the chemical reaction itself. It should be energetically favorable to produce a solid thin film reaction product on the wafer from the gas. Next, the CVD process should show favorable growth kinetics. This means that the reaction should proceed sufficiently fast so that the waiting time for depositing a thin film is not too long. A third important aspect of a CVD process is how the gas flow occurs. When the gas is flowing over the wafer's surface, it will be gradually depleted. However, it is required that a thin deposited film has everywhere the same thickness. Gas flow conditions should be such that this is enabled.



CVD process

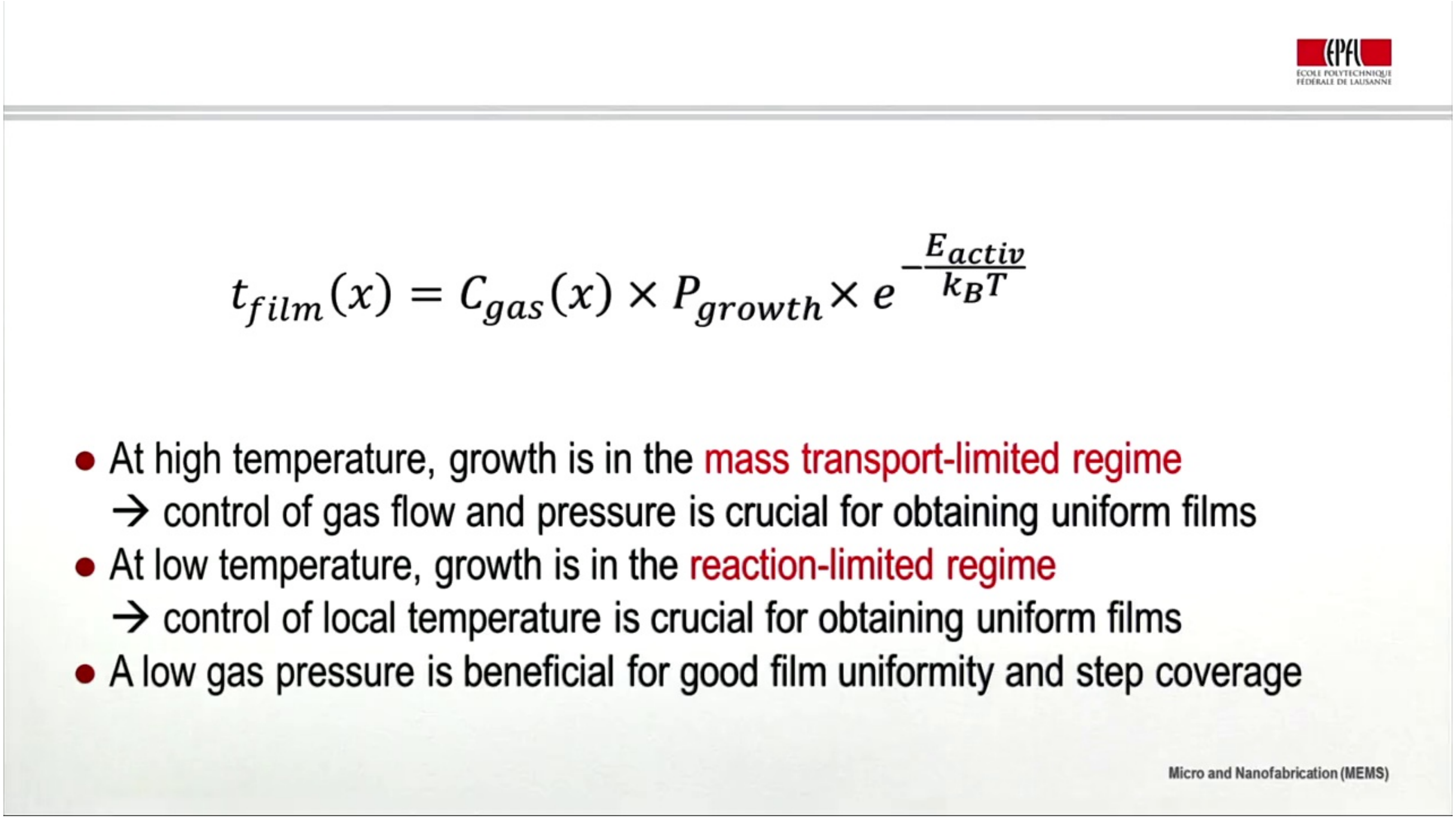
$$t_{film}(x) = e^{-\frac{E_{activ}}{k_B T}} \times P_{growth} \times C_{gas}(x)$$

Aspects of CVD:

- Thermodynamics of the chemical reaction: a solid product should be formed at the wafer temperature
- Thin film growth kinetics: the reaction should proceed fast enough
- Gas flow conditions: when flowing over the wafer, the gas is gradually depleted, yet the wafer should be uniformly covered

Micro and Nanofabrication (MEMS)

If <i>x</i> is the coordinate in the horizontal plane in the direction of the flow, the thin film thickness, as a function of <i>x</i>, is influenced by the just-mentioned fundamental aspects of CVD. Thermodynamics provides an exponential factor which contains the activation energy needed to go from the gaseous to the solid phase as well as the thermal energy. The hotter the wafer becomes, the higher the growth rate will be, in principle. The next aspect in the CVD process is the growth kinetics. If a thermodynamically stable reaction product can be formed in the process this does not say a lot on the rapidity of the deposition. Nucleation of solid material and further growth can be slow and need to be evaluated experimentally. This adds the probability factor <i>Pgrowth</i> to the formula for the thickness of the thin film. Finally, the thin film thickness at the position <i>x</i> is a function of the gas concentration at that point. Mostly one wants that the film thickness is everywhere the same so the gas flow conditions and the gas concentration ideally should not depend on <i>x</i>.

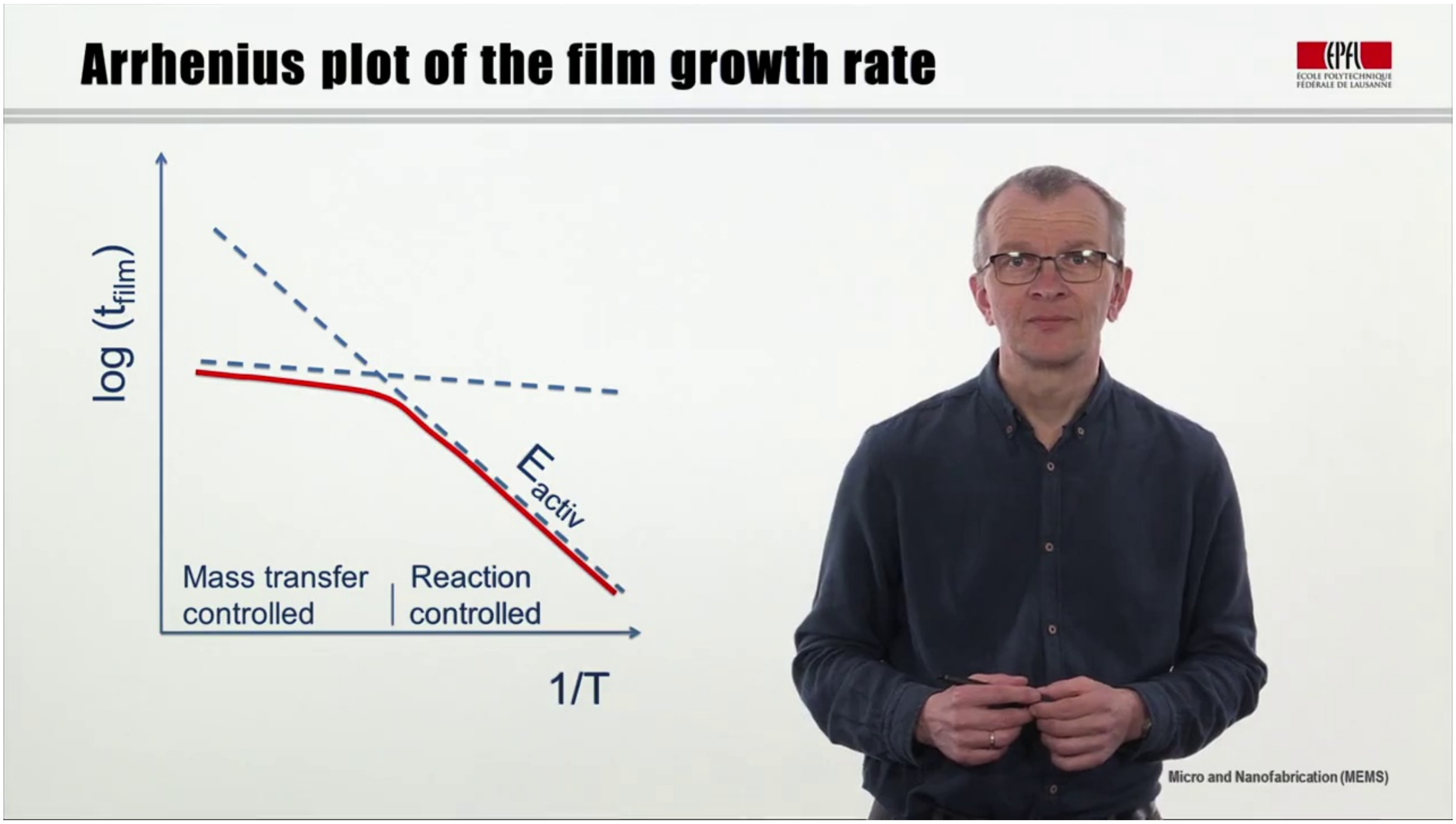


$$t_{film}(x) = C_{gas}(x) \times P_{growth} \times e^{-\frac{E_{activ}}{k_B T}}$$

- At high temperature, growth is in the mass transport-limited regime
  → control of gas flow and pressure is crucial for obtaining uniform films
- At low temperature, growth is in the reaction-limited regime
  → control of local temperature is crucial for obtaining uniform films
- A low gas pressure is beneficial for good film uniformity and step coverage

Micro and Nanofabrication (MEMS)

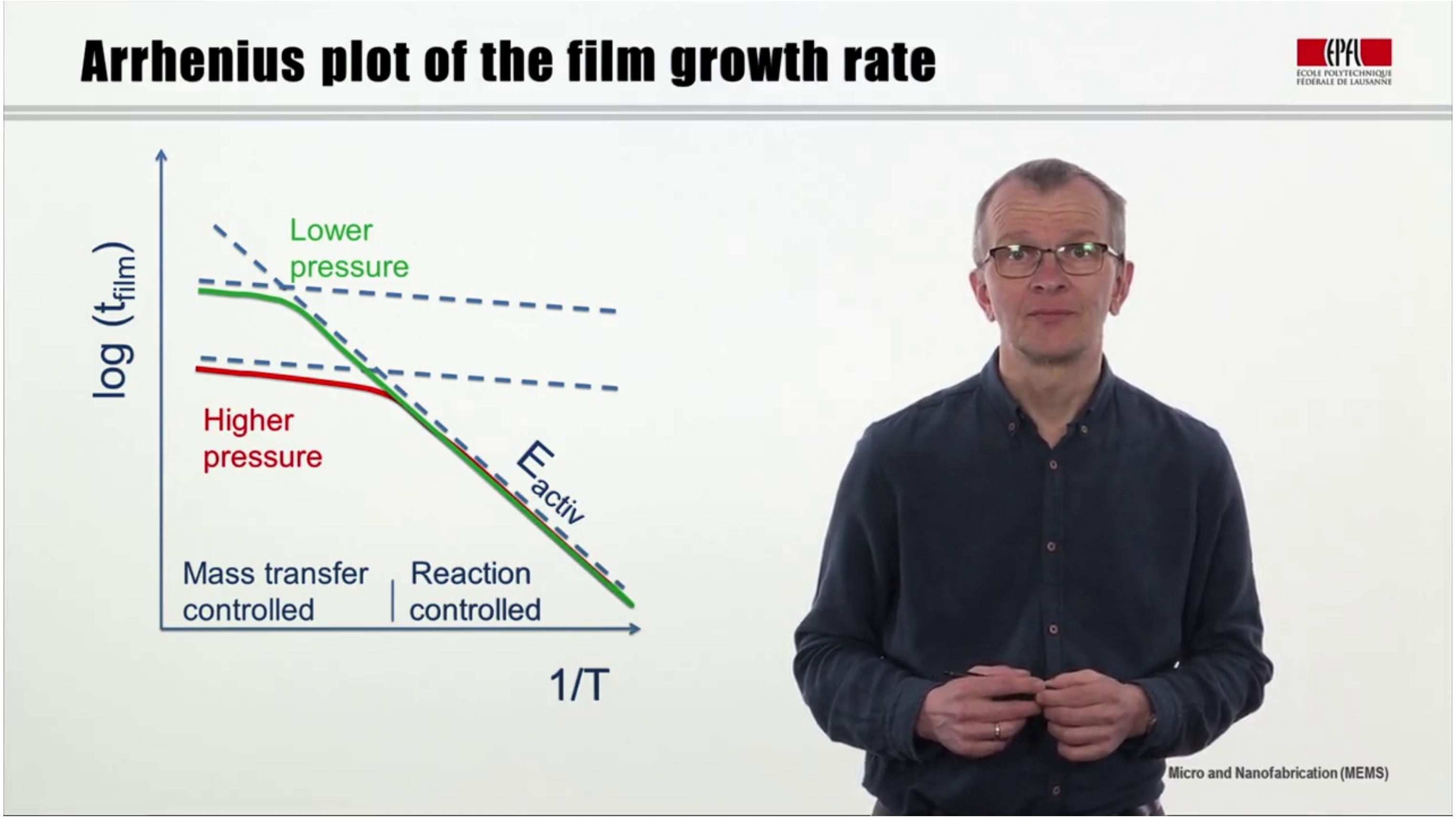
We have written here again the formula for the film thickness. It was already clear that for the reaction to occur, a high temperature of the wafer is needed. In practice, temperatures ranging from a few hundred degrees Celsius to almost a thousand degrees Celsius can be used. If one is at very high temperatures, there is a lot of thermal energy, <i>kT</i>, and the reaction proceeds very fast due to the exponential factor. In this case, the control of the gas flow is very important as the local thin film thickness will be proportional to the local gas concentration. The gas concentration, hence, has to be uniform everywhere in the vicinity of the substrate. If one is at a moderately high temperature, the film growth and the chemical reaction will not proceed that fast. The exponential factor in this case is limiting the growth rate while the gas usually has a uniform concentration within the reactor. In these conditions, the local temperature should be very well controlled as a small temperature variation evidently will give a variation in grown film thickness. Finally, one can say that, at low gas pressure, good film uniformity can be better obtained. Indeed, at low gas pressure, the mean free path of the gas molecules is long so that a short distance local variation of the gas concentration is less important.



Arrhenius plot of the film growth rate

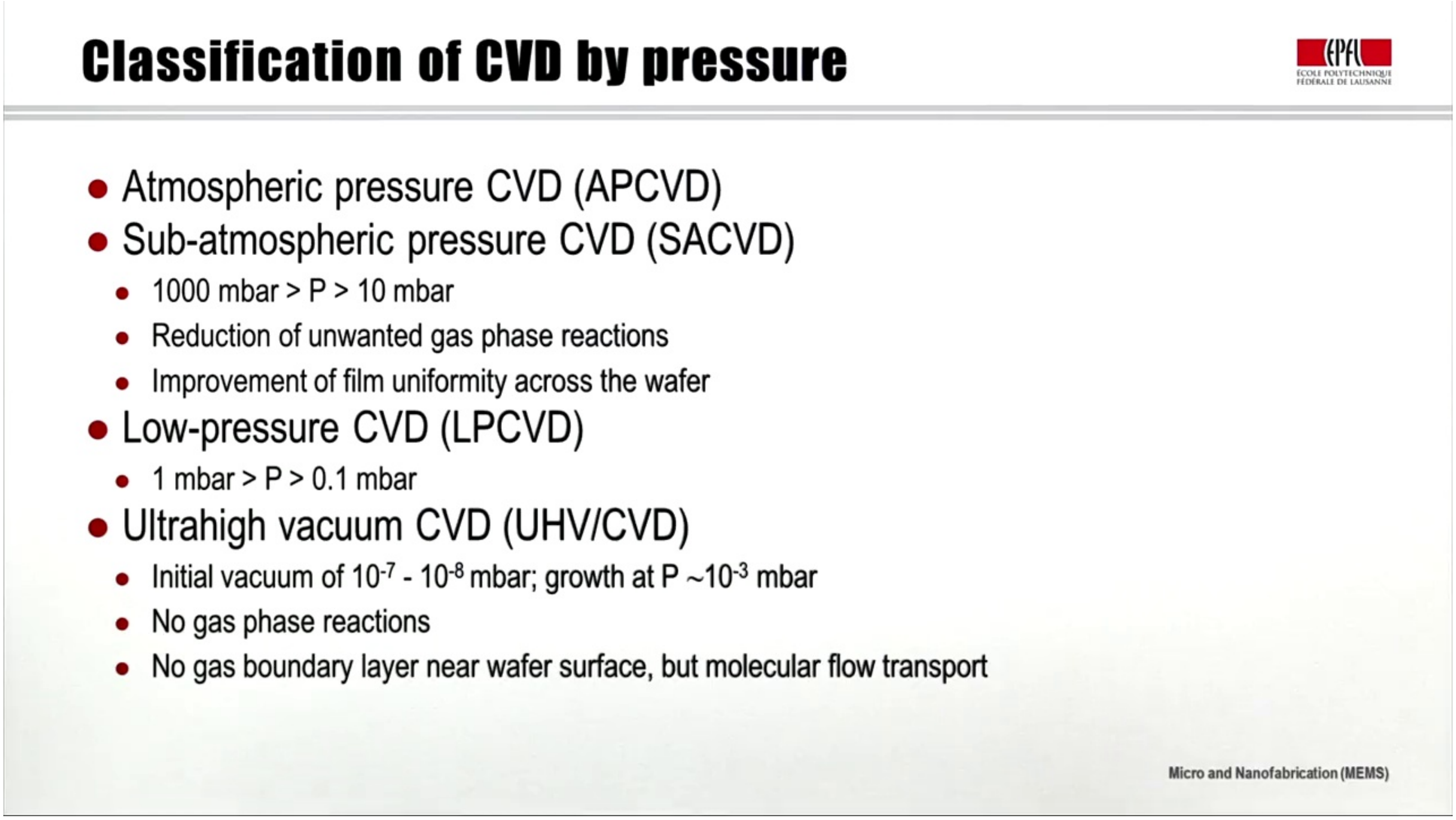
Micro and Nanofabrication (MEMS)

This schematic figure shows the thin film thickness on a logarithmic scale against the inverse of the temperature. When plotted this way, one sees from the exponential factor that a linear slope will correspond to the activation energy of the chemical reaction. If one increases the temperature the film growth rate will go up, but ultimately the gas flow cannot provide sufficient concentration of molecules and the curve will adapt to a much flatter slope. So one can easily discriminate from such a plot the mass transfer controlled and the reaction controlled deposition regimes.



Arrhenius plot of the film growth rate

Suppose the red curve was obtained at higher gas pressure. If one decreases the gas pressure, the deposition will stay longer in the reaction controlled regime. Despite the fact that there are fewer molecules at a lower pressure, the mean free path in the gas is higher so that gas molecules that come from further away from the substrate can be used in the reaction.

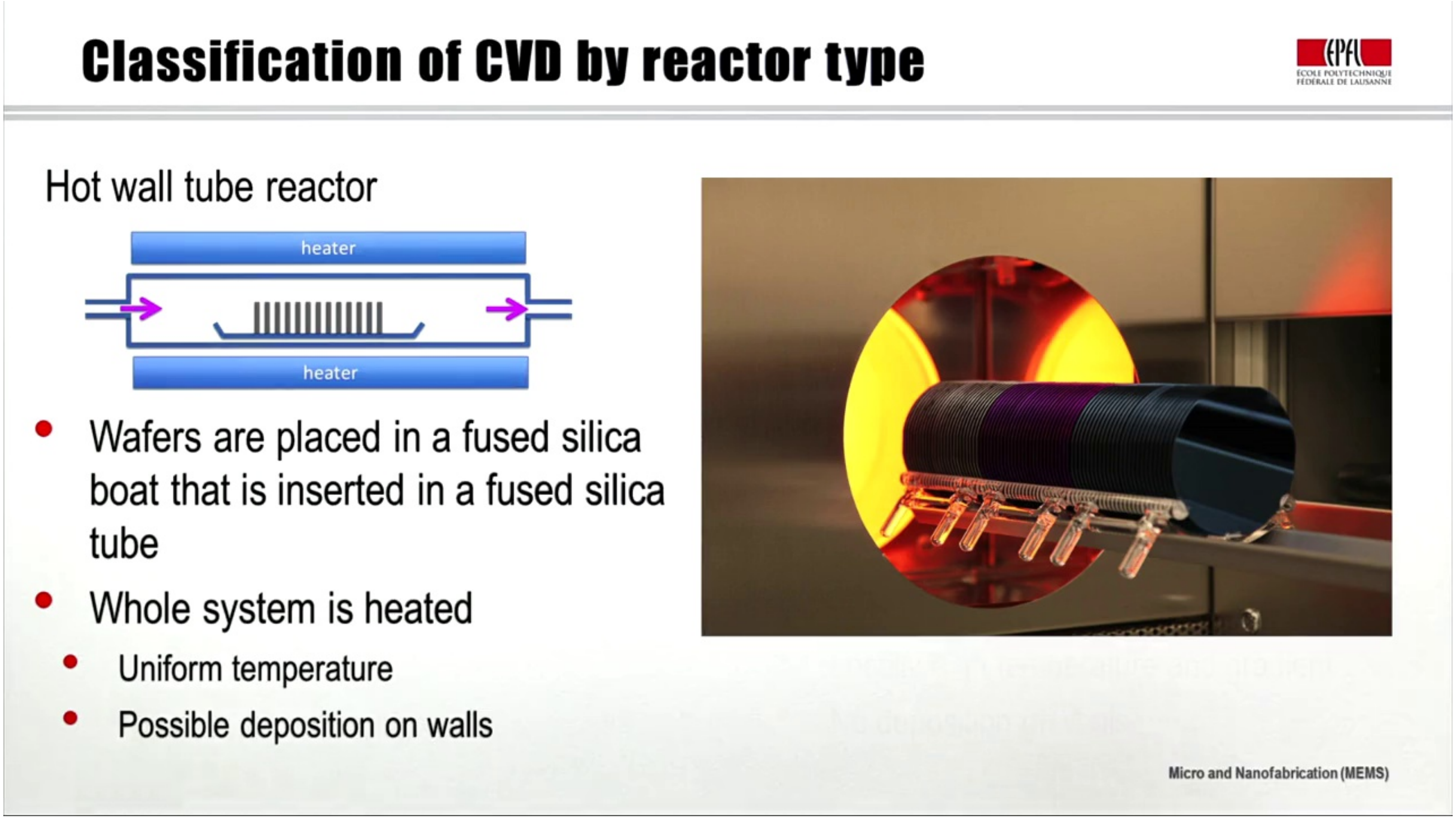


Classification of CVD by pressure

- Atmospheric pressure CVD (APCVD)
- Sub-atmospheric pressure CVD (SACVD)
  - 1000 mbar > P > 10 mbar
  - Reduction of unwanted gas phase reactions
  - Improvement of film uniformity across the wafer
- Low-pressure CVD (LPCVD)
  - 1 mbar > P > 0.1 mbar
- Ultrahigh vacuum CVD (UHV/CVD)
  - Initial vacuum of 10^{-7} - 10^{-8} mbar; growth at P ~10^{-3} mbar
  - No gas phase reactions
  - No gas boundary layer near wafer surface, but molecular flow transport

Micro and Nanofabrication (MEMS)

Because pressure plays such an important role, CVD processes are typically classified according to the pressure at which the deposition takes place. The first technique is called <i>atmospheric pressure CVD</i> or <i>APCVD</i> which, as the name says, uses a gas at atmospheric pressure. The next technique is called <i>sub-atmospheric pressure CVD</i> or <i>SACVD</i> and the pressure of the gas is typically in between 1000 millibar and 10 millibar. The advantage of having a lower pressure is that interaction between different gas molecules is less probable, so that there is less probability for unwanted particle synthesis in the gas itself. Also, because of the increased mean free path of the gas molecules, local variation in gas concentration is reduced so that the film thickness across the wafer is more uniform. The next technique is <i>low-pressure CVD</i> or <i>LPCVD</i> which typically operates in between 0.1 millibar and 1 millibar. Finally, we have <i>ultrahigh vacuum CVD</i> or <i>UHV/CVD</i>, a technique in which the reactor first is pumped down to a very low pressure, after which the growth of the thin film takes place at a pressure of 10^-3 millibar, typically. In this case there is very little interaction between the gas molecules so that the gas behaves less like a viscous liquid but more like an ensemble of individual molecules.



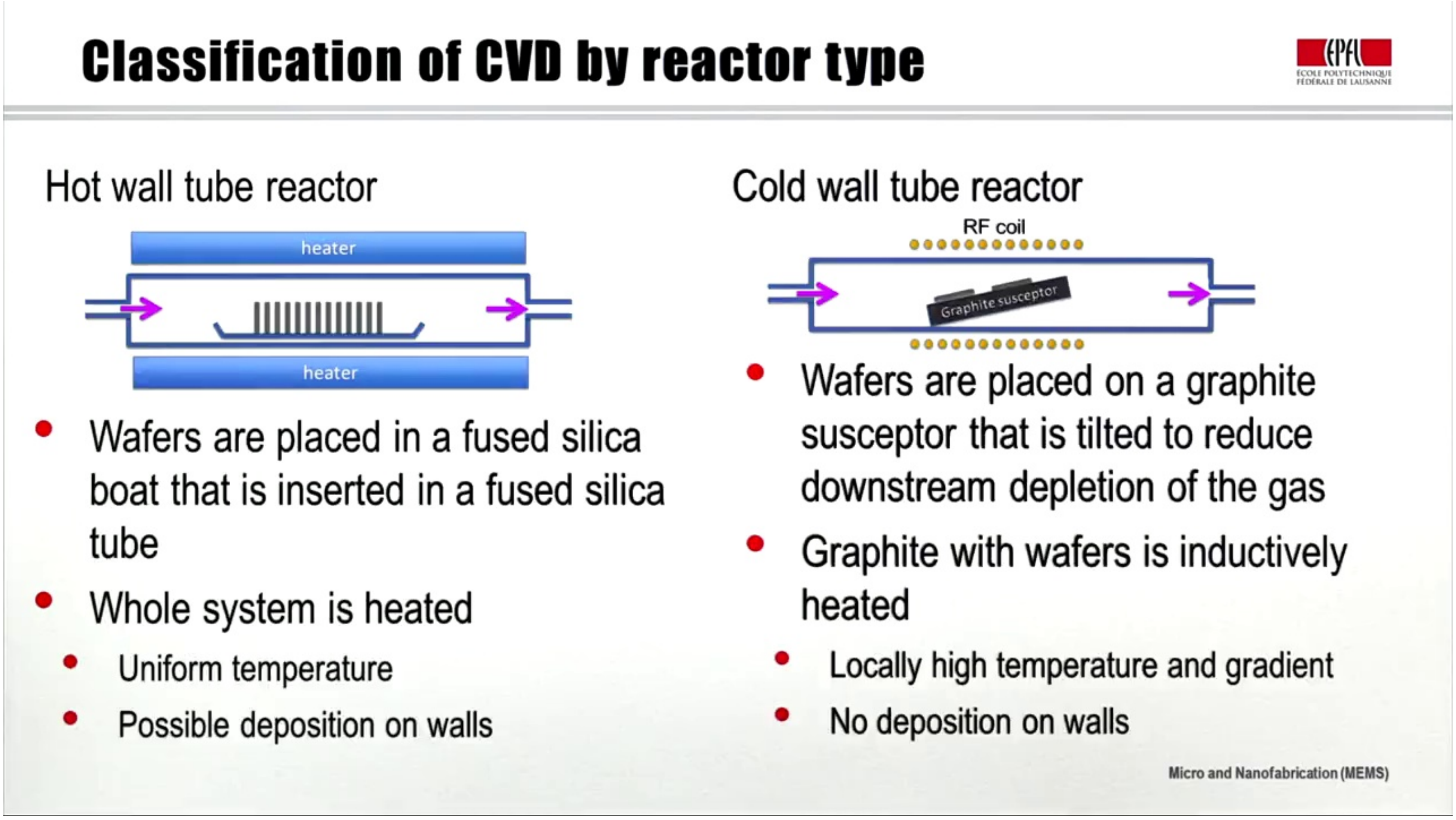
Classification of CVD by reactor type

Hot wall tube reactor

- Wafers are placed in a fused silica boat that is inserted in a fused silica tube
- Whole system is heated
  - Uniform temperature
  - Possible deposition on walls

Micro and Nanofabrication (MEMS)

CVD processes are often categorized according to the reactor type in which they are performed. The first reactor type is called the <i>hot wall tube reactor</i> as we have already seen in the pictures before. In such a reactor, the wafers are placed in a fused silica boat that is to be inserted in the fused silica tube. After that, the complete system is heated so every part is at the same temperature and deposition will be uniform if the gas concentration is sufficient. Note that in this case, deposition also will occur on the walls of the system.



Classification of CVD by reactor type

Hot wall tube reactor

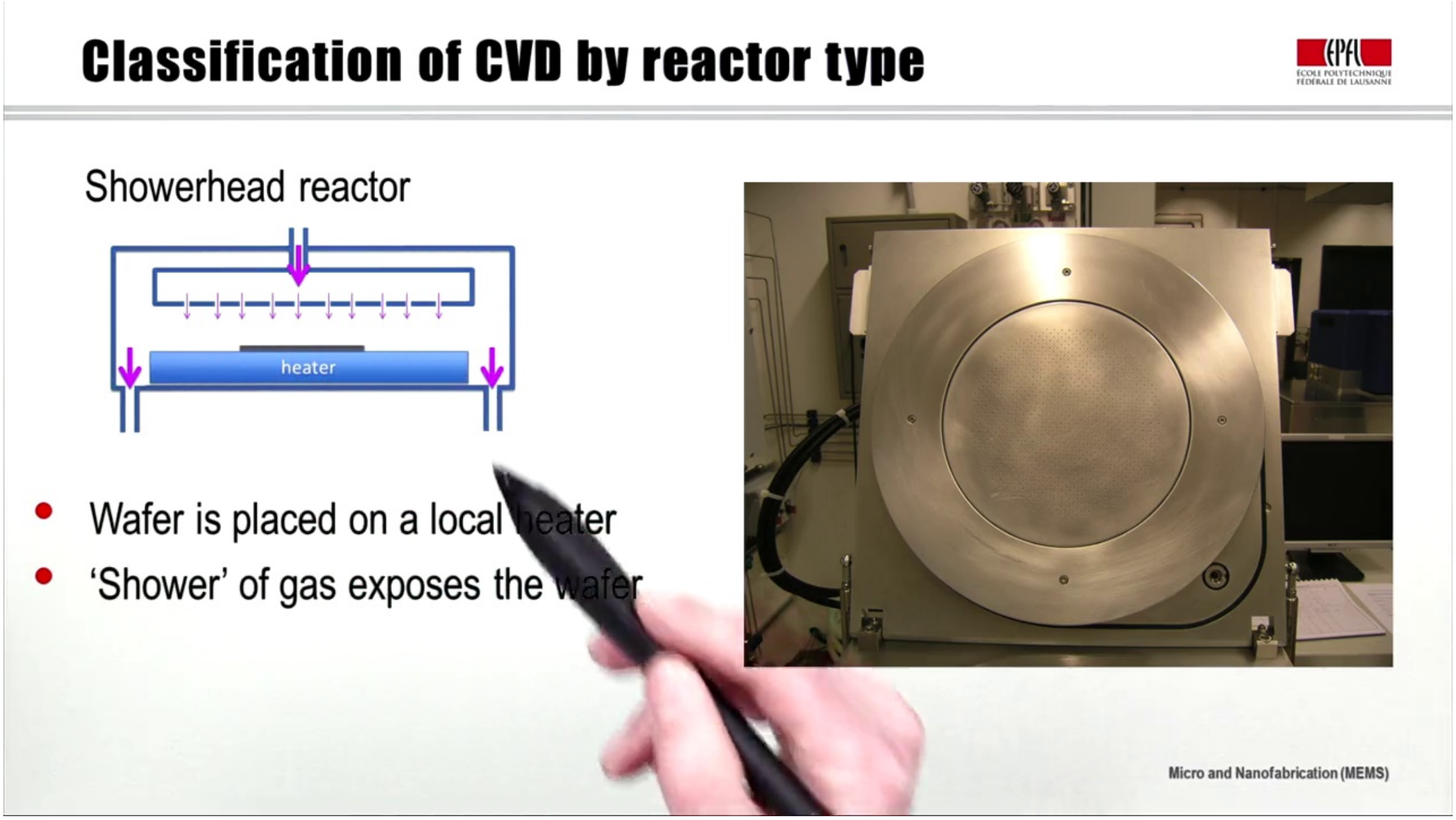
- Wafers are placed in a fused silica boat that is inserted in a fused silica tube
- Whole system is heated
  - Uniform temperature
  - Possible deposition on walls

Cold wall tube reactor

- Wafers are placed on a graphite susceptor that is tilted to reduce downstream depletion of the gas
- Graphite with wafers is inductively heated
  - Locally high temperature and gradient
  - No deposition on walls

Micro and Nanofabrication (MEMS)

Another type of CVD system is called the <i>cold wall tube reactor</i>. In this case, there is no external heater that heats up the complete system, but the wafers are positioned on a conducting graphite susceptor which is heated using an external RF coil. In this case, there is only locally a high temperature and there is a strong temperature gradient. There will be no deposition on the walls of the system and the graphite susceptor is tilted with respect to the direction of the flow typically, to take into account eventual gas depletion effects that would give a thinner film if one goes further downstream of the flow. In such a configuration, the wafers will be exposed always to a fresh stream of gas.



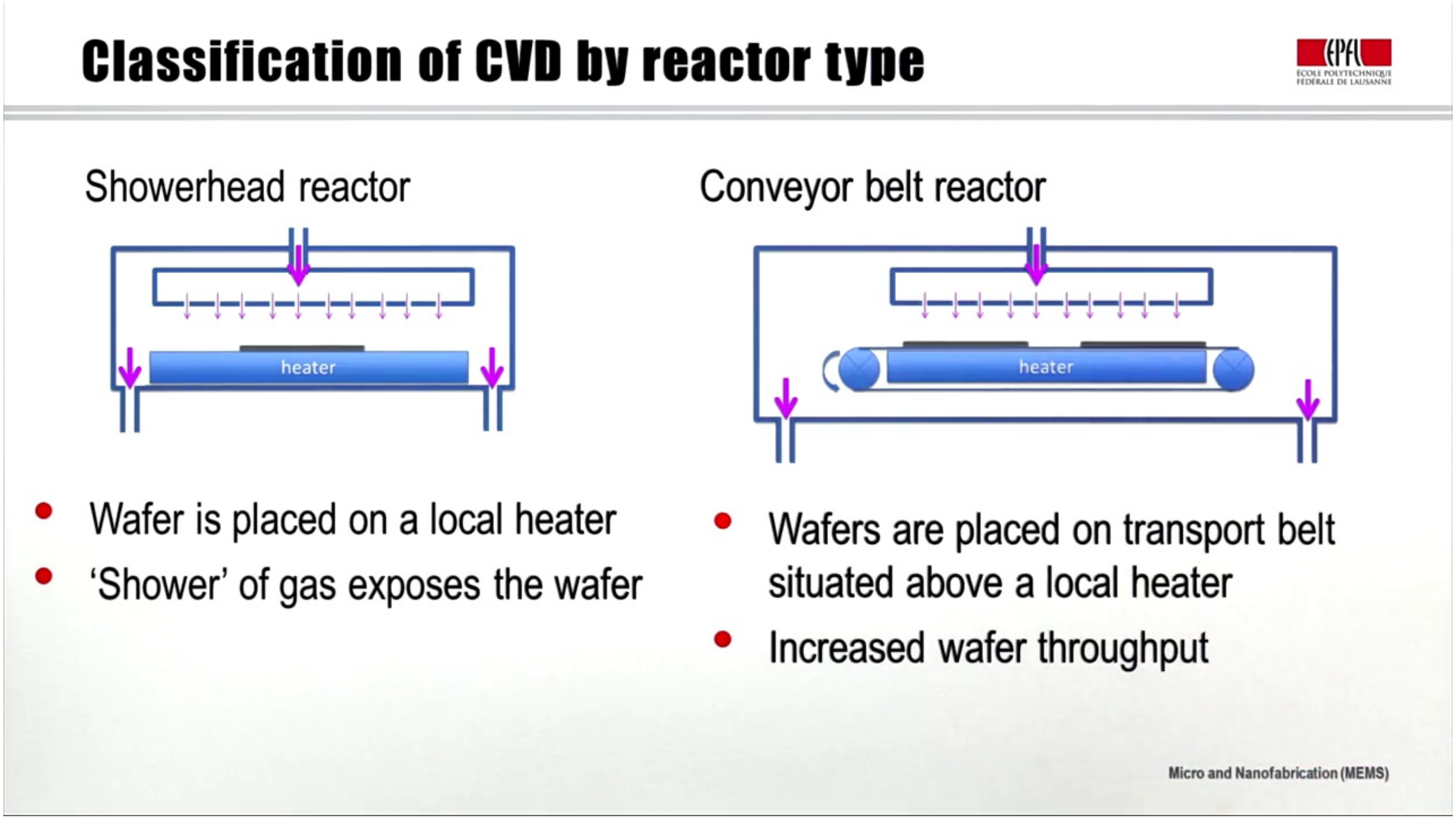
Classification of CVD by reactor type

Showerhead reactor

- Wafer is placed on a local heater
- 'Shower' of gas exposes the wafer

Micro and Nanofabrication (MEMS)

This picture shows the principle of a so-called <i>showerhead reactor</i>. The gas enters a dedicated space within the reactor and exposes the wafer via a multitude of small holes, like a shower of gas.



Classification of CVD by reactor type

Showerhead reactor

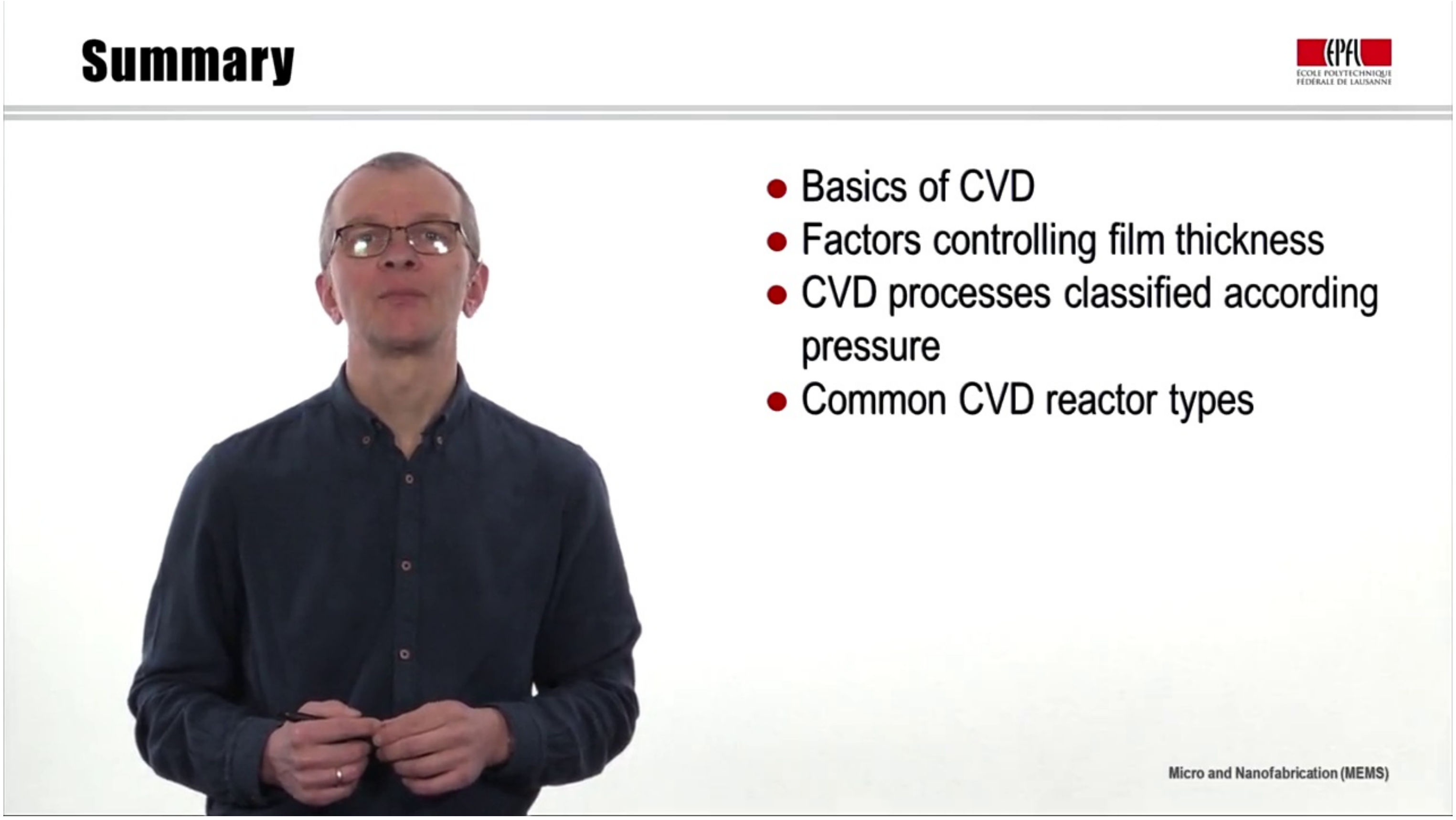
- Wafer is placed on a local heater
- 'Shower' of gas exposes the wafer

Conveyor belt reactor

- Wafers are placed on transport belt situated above a local heater
- Increased wafer throughput

Micro and Nanofabrication (MEMS)

The same principle is used for this so-called <i>conveyor belt reactor</i> in which the wafers are positioned on a transport belt and led over a heater. The wafer through-put of such a system evidently will be higher, so this is a system that is more suitable for industrial production.



Summary

- Basics of CVD
- Factors controlling film thickness
- CVD processes classified according pressure
- Common CVD reactor types

Micro and Nanofabrication (MEMS)

This ends our introduction on CVD. We explained the basic parameters of CVD reaction and process and pointed out the various factors by which the film thickness can be controlled such as the temperature and the local gas pressure. We introduced different types of CVD processes according to the pressure at which the deposition takes place. Also, we have introduced some of the common CVD reactor types.
