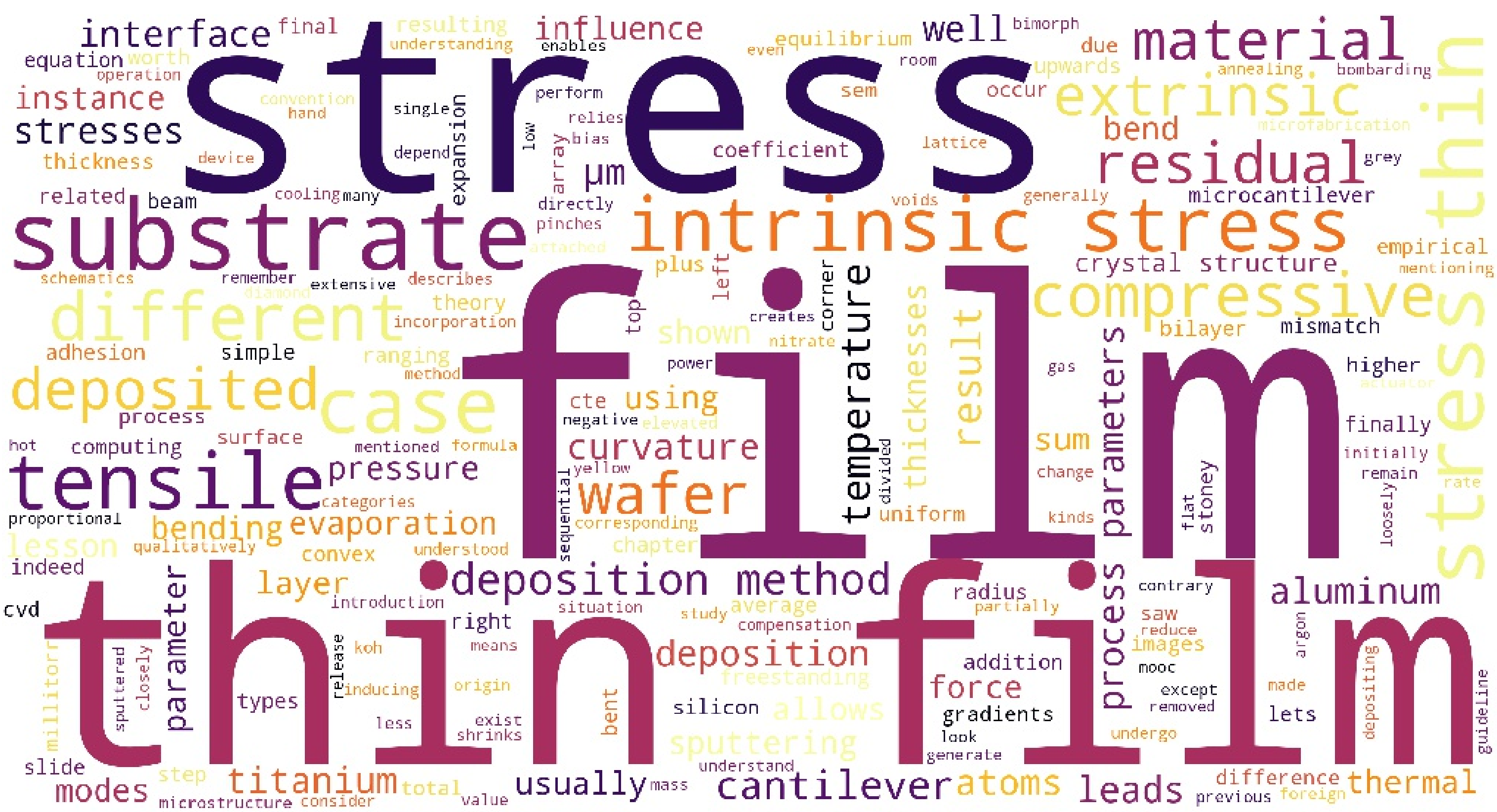

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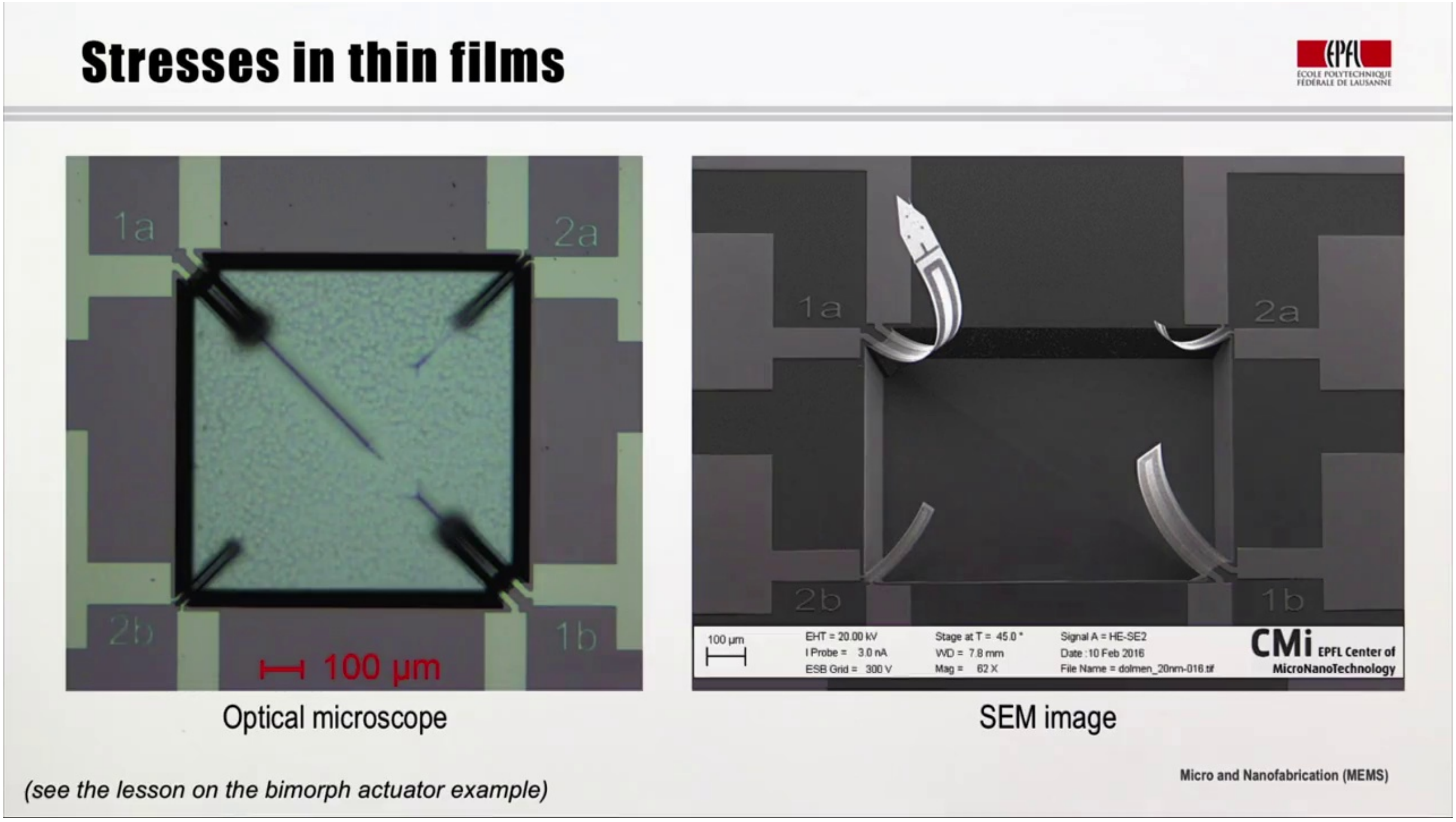
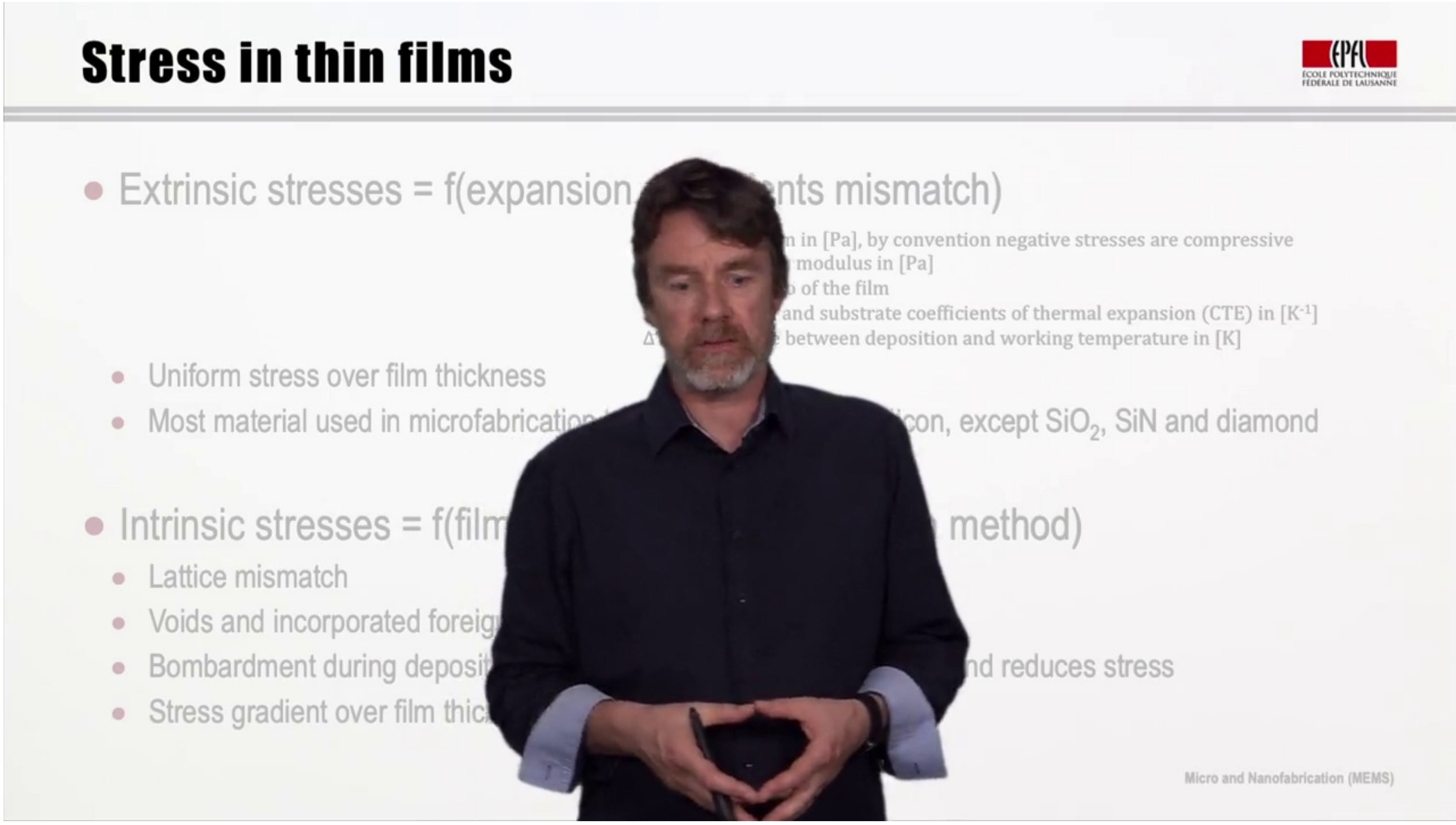
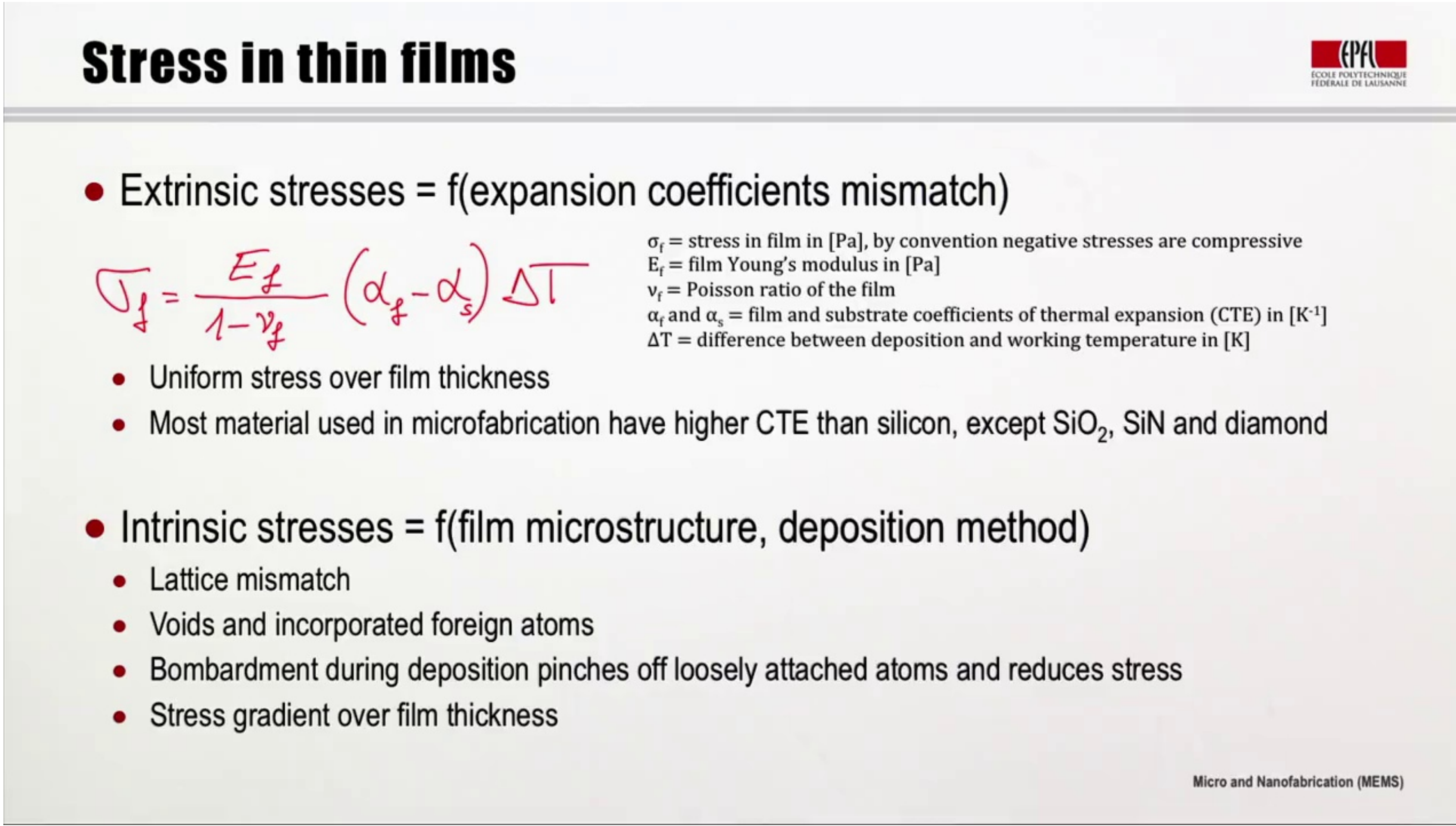


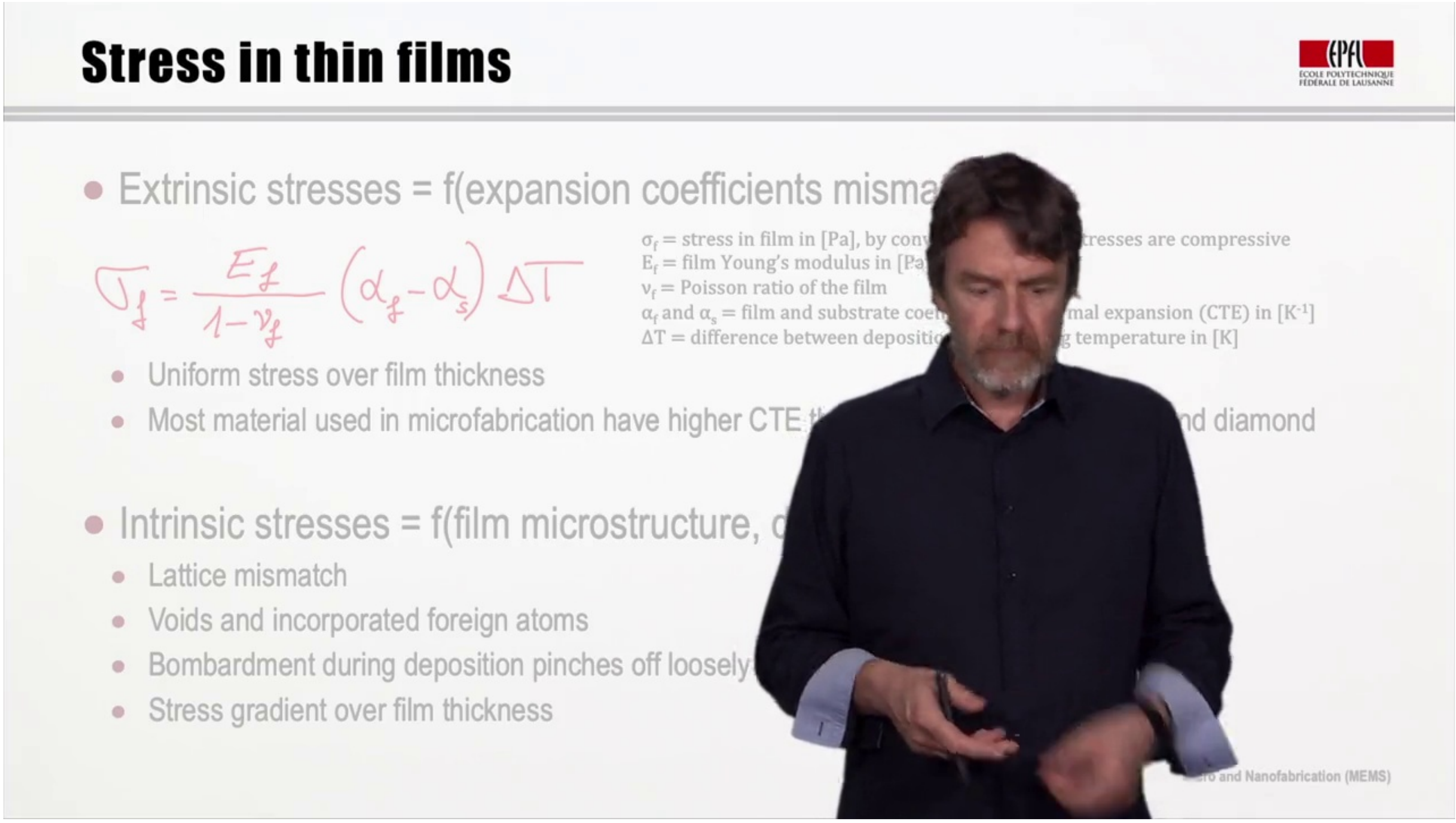
You will remember the case study of the bimorph actuator that we saw in one of the introduction lessons of this MOOC. After the KOH release of the beams, the cantilevers did not remain flat, but were bent upwards. This is due to residual stress in the thin films resulting from the different process steps. Let's now have a more extensive look at the different kinds of stress that exist in the thin films, and to their origin.



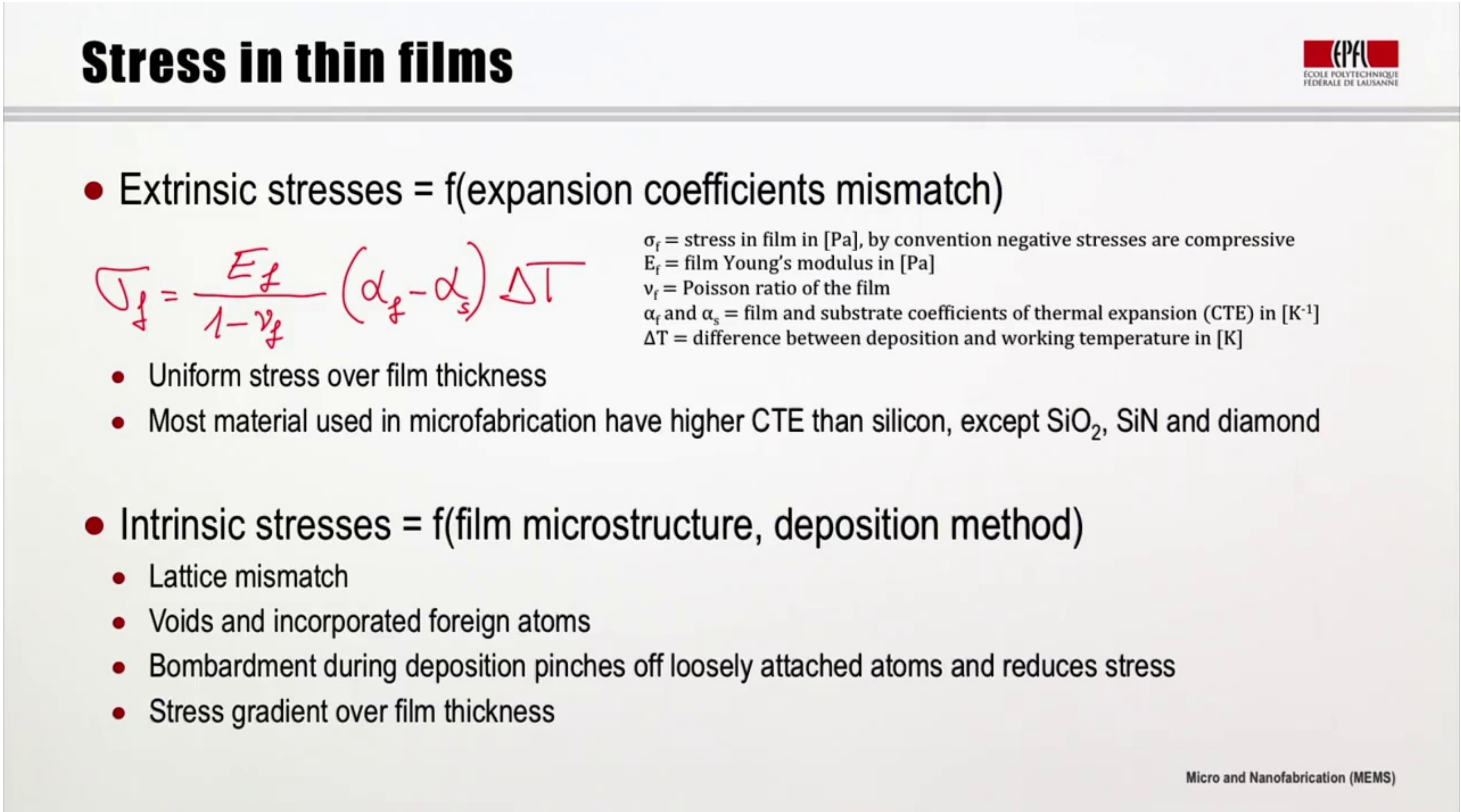
As mentioned in the previous slide, the deposition method and the process parameters influence the crystal structure of the thin film. In addition, they also influence the residual stress in the thin films. Stress in thin films can be divided in two categories:



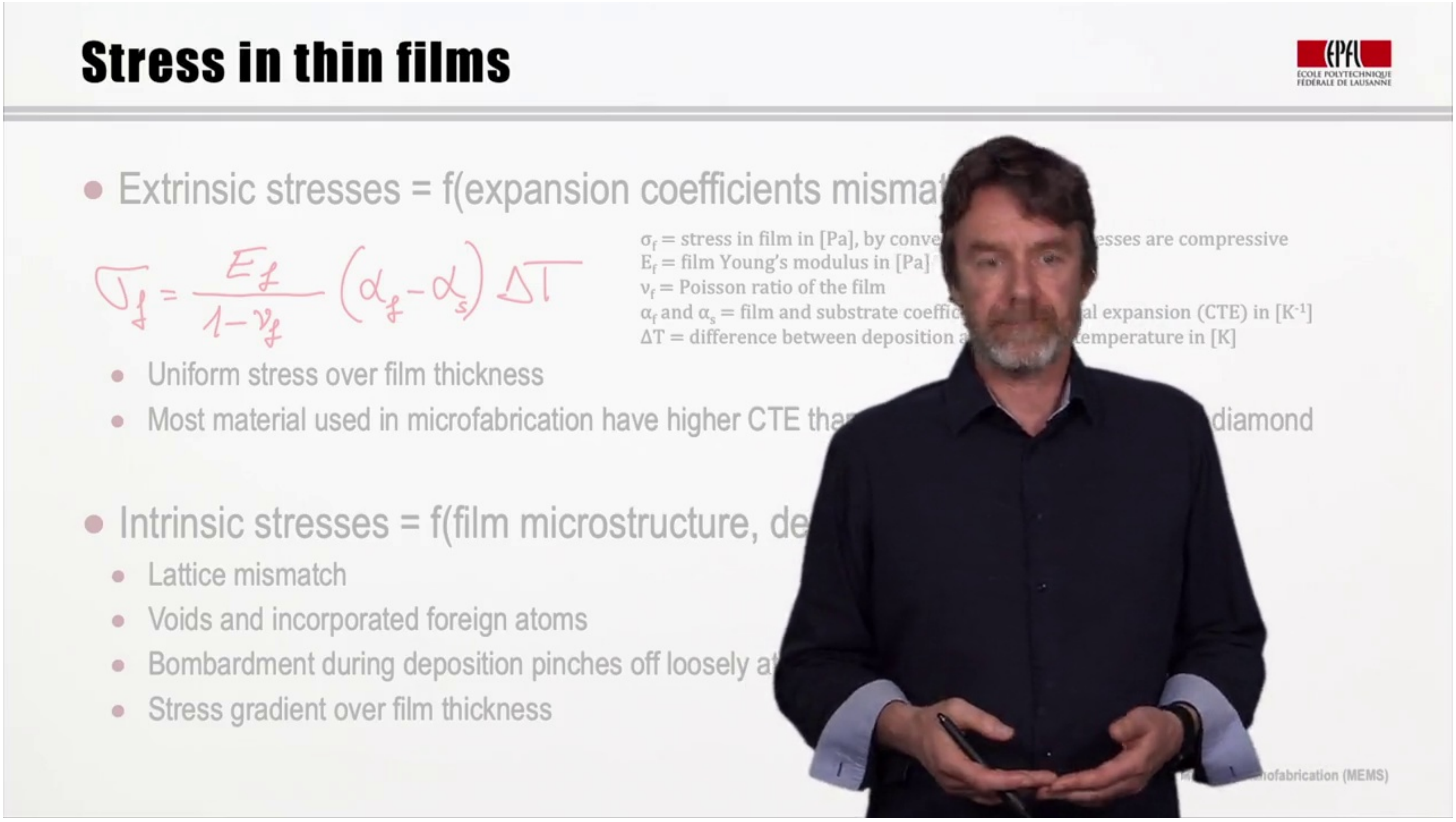
extrinsic stress and intrinsic stress. Extrinsic stress results from a mismatch between the film and the substrate's coefficient of thermal expansion, CTE. If both the film and the substrate undergo the same temperature difference, a simple formula, shown here, describes the stress which is directly proportional to the difference between the two expansion coefficients and to the change in temperature.



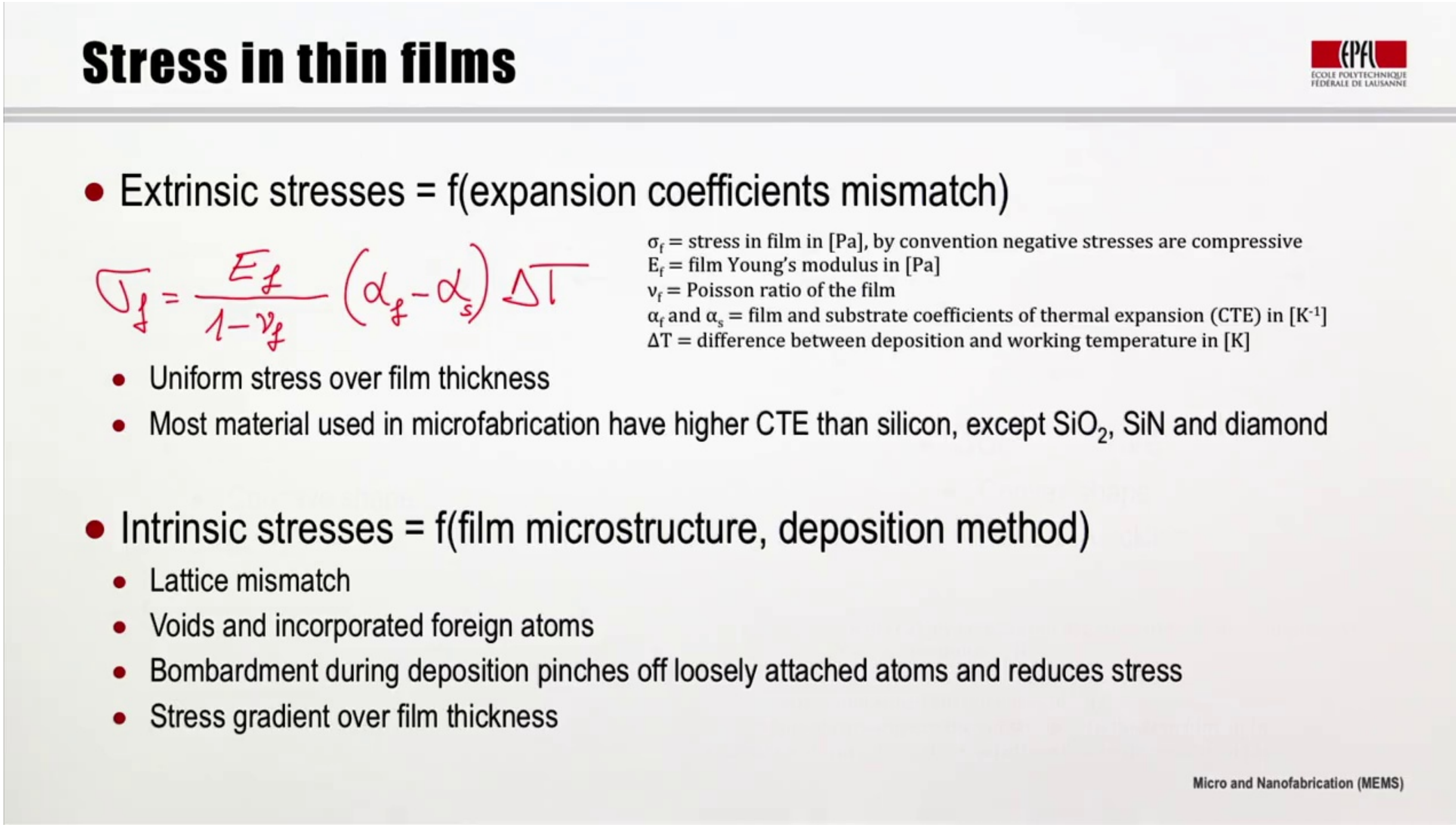
Such a situation occurs, for instance, during cooling after a CVD process. Indeed, during CVD, the film and the substrate are at the same elevated temperature. By convention, a negative stress is compressive and generally extrinsic stresses are uniform over the film thickness. Finally, it is worth mentioning that most materials used in micro-fabrication have a higher CTE value than silicon except SiO2, silicon nitrate, and diamond.



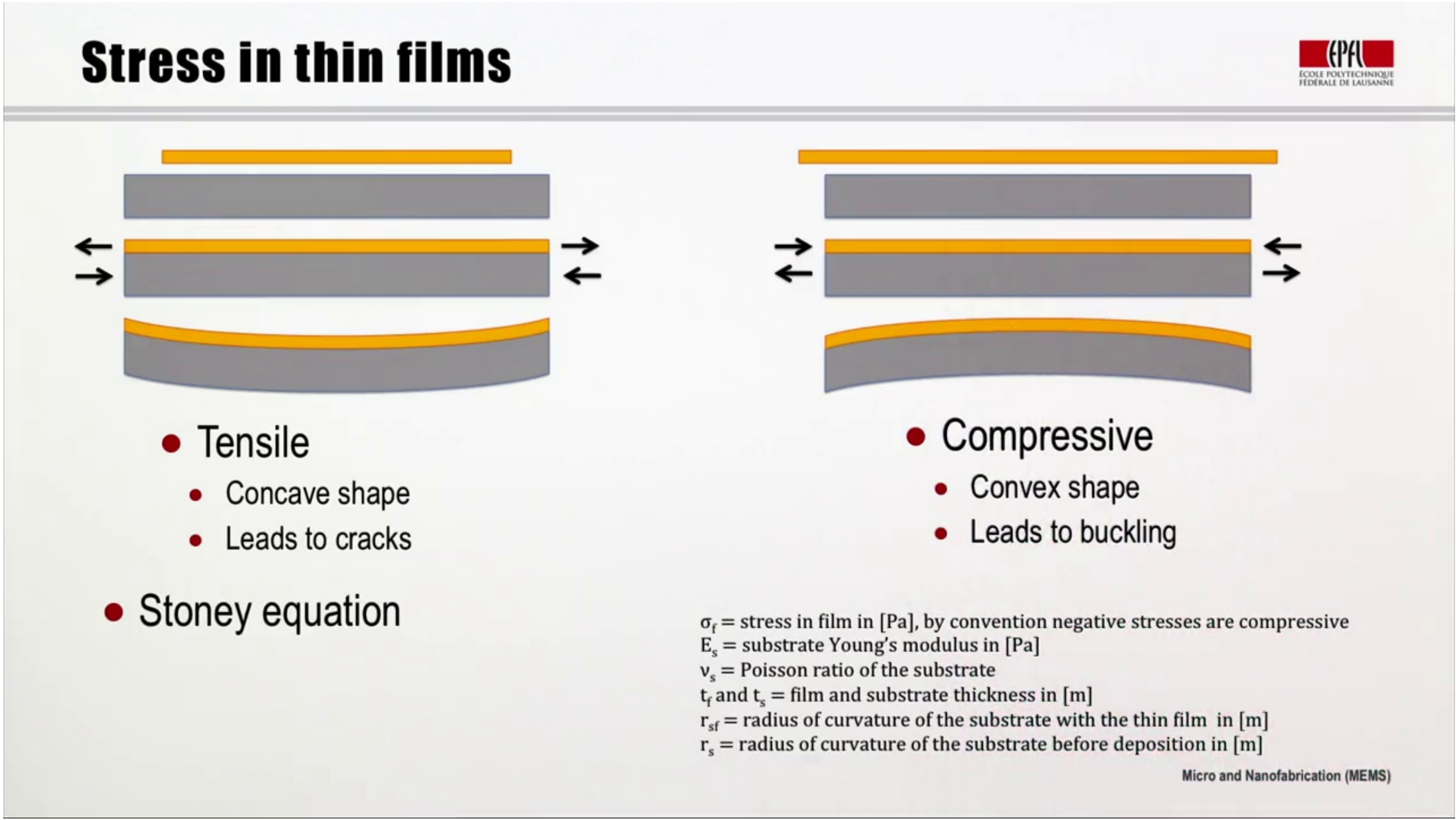
On the other hand, intrinsic stress is less understood. There is no simple theory that allows computing them. Their understanding relies on empirical results. Intrinsic stress is closely related to the film material, and microstructure, as well as to the deposition method and parameters. For instance, a lattice mismatch between the film and the substrate, or the incorporation of voids and foreign atoms generate intrinsic stress. On the contrary, bombarding the substrate during the deposition pinches off loosely attached atoms which can reduce stress, and intrinsic stress is not uniform over the film thickness, which creates stress gradients. These gradients are inducing the bending of cantilevers, even if they are made of a single layer material. Intrinsic stress can be partially removed by means of an annealing step.



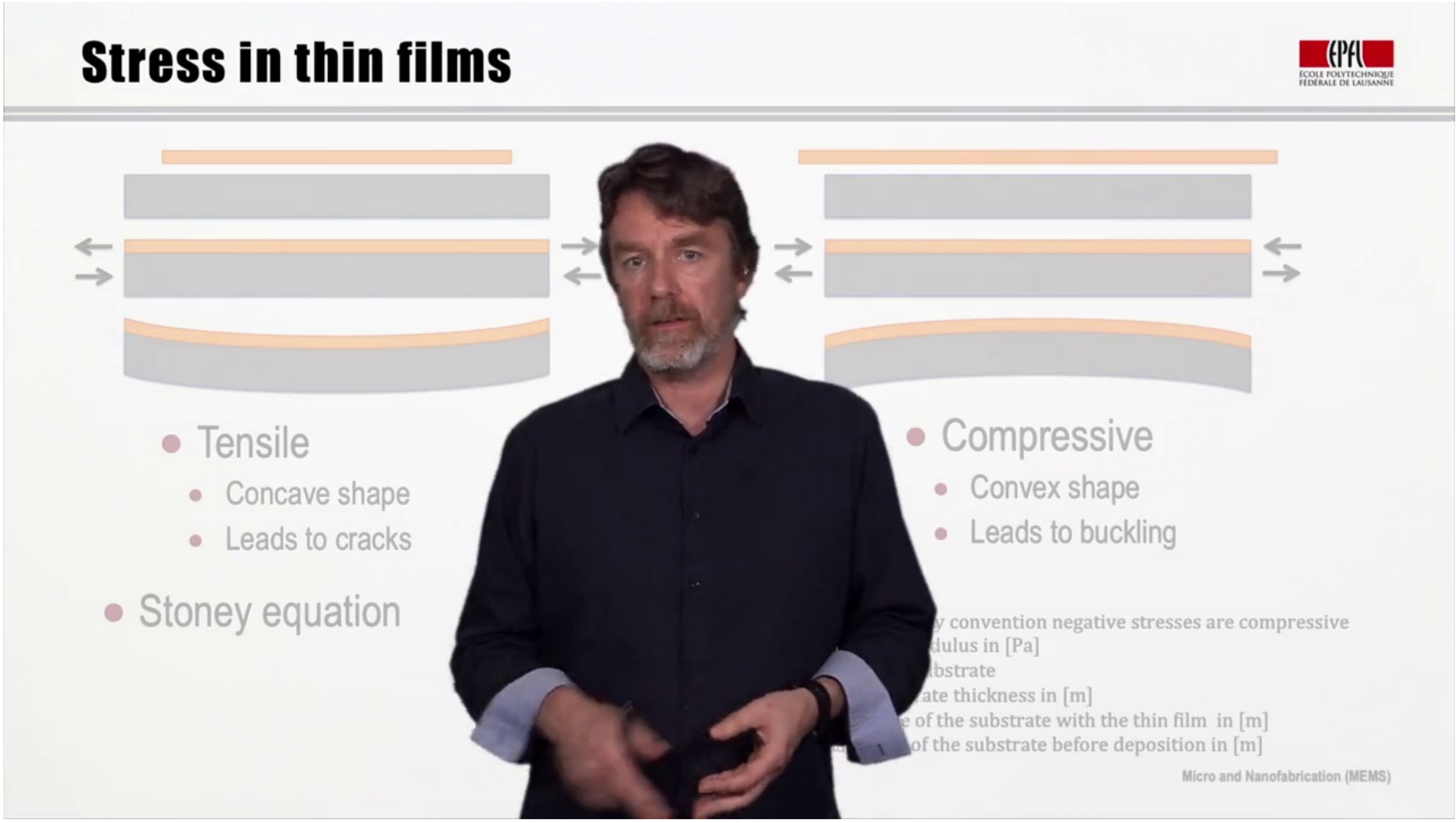
The total stress in a thin film is equal to the sum of the extrinsic and the intrinsic stress. Usually films deposited by evaporation result in tensile stress. Stress in sputtered films depend on many parameters, such as bias power, argon pressure, sputtering gas mass, substrate temperature and deposition rate.



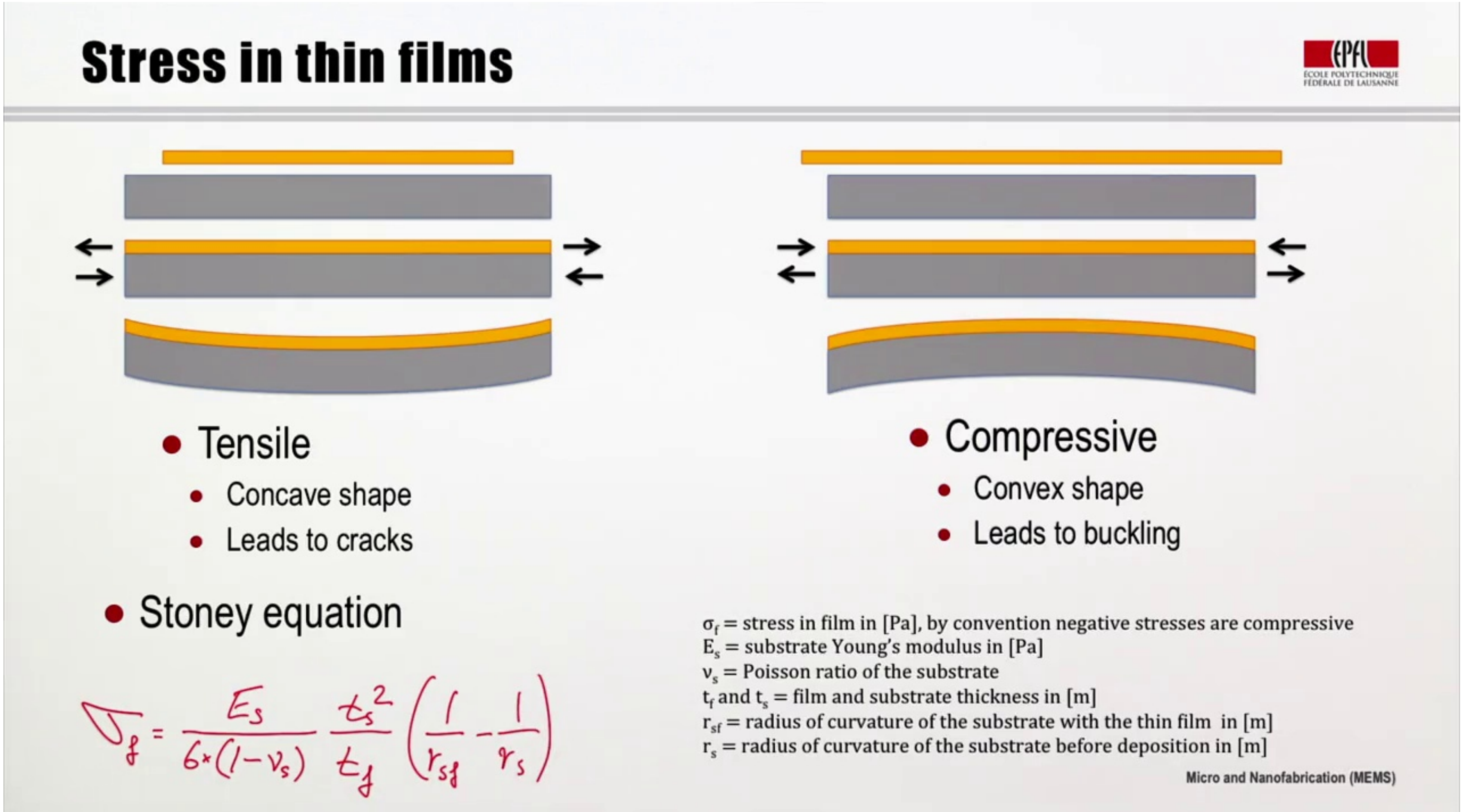
As a guideline, sputtering at low pressure at about 1 millitorr usually results in compressive stress, while sputtering at higher pressure, 10 millitorr, usually results in tensile stress. Depositing sequential layers with tensile and compressive stress enables to perform stress compensation.



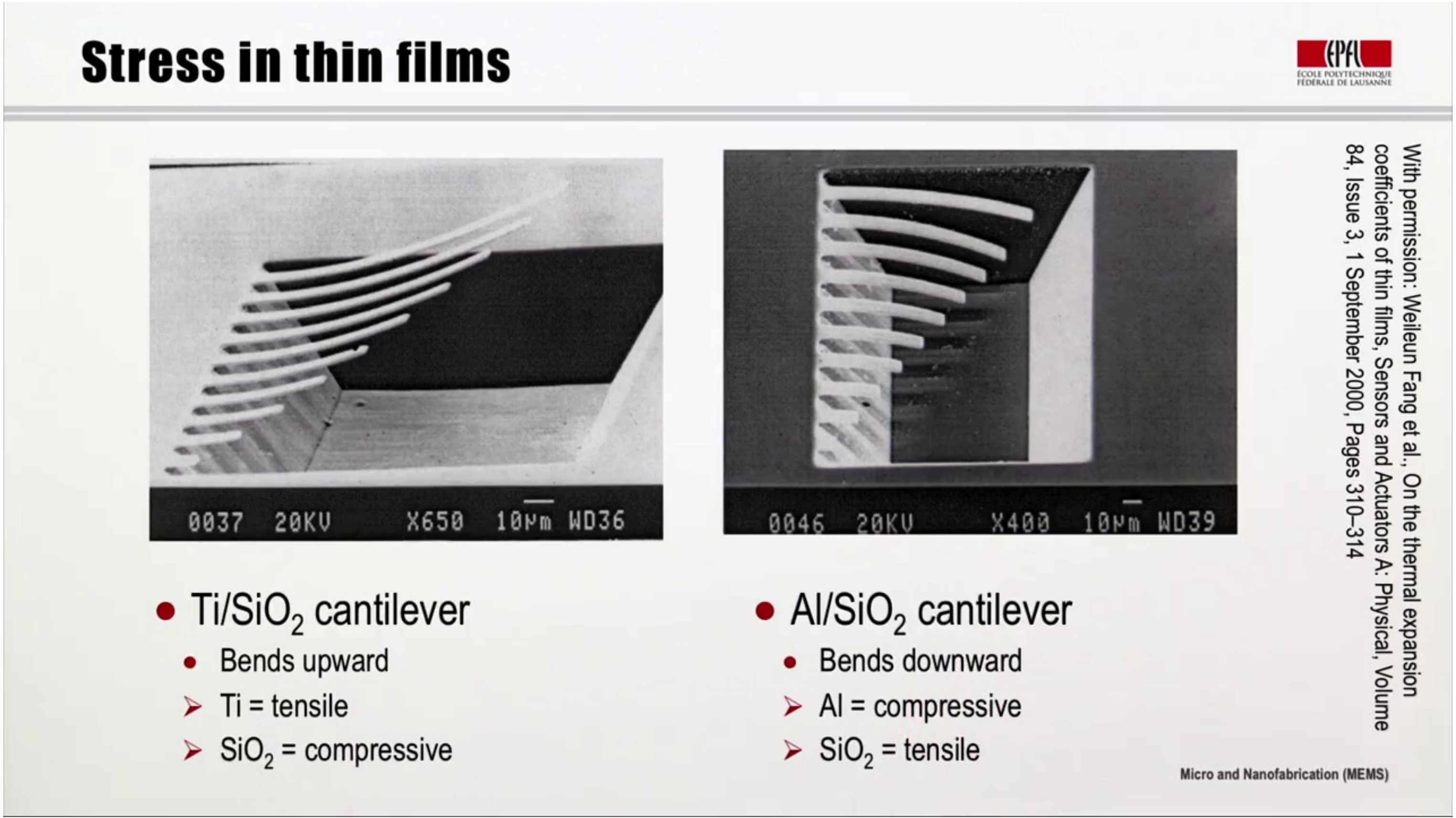
Residual stress in thin films leads to substrate or device curvature. To qualitatively understand why, let's consider the schematics on the top left corner of this slide. This is the case corresponding to an extrinsic tensile stress. If a thin film, here in yellow, is deposited by operation on a substrate, here in grey, at room temperature, for instance, the film, which is initially hot, shrinks more relatively to the substrate, which is cold. However, the lateral dimension of the substrate and of the thin film have to be the same. Therefore, the film is under tensile stress while the substrate is under compressive stress. Shown here, in this second line of the drawing. To satisfy the sum of the force's equilibrium, the tensile force in the film is equal to the compressive force in the substrate. However, the mechanical equilibrium is not satisfied yet because of the sum of the moment. Thus, the wafer and the film bend in a concave way, for the case of tensile thin films. Indeed, the film tends to retrieve its shorter, unstressed state. In the case of compressive thin films, in the top right corner, the same reasoning leads to convex bending of the film.



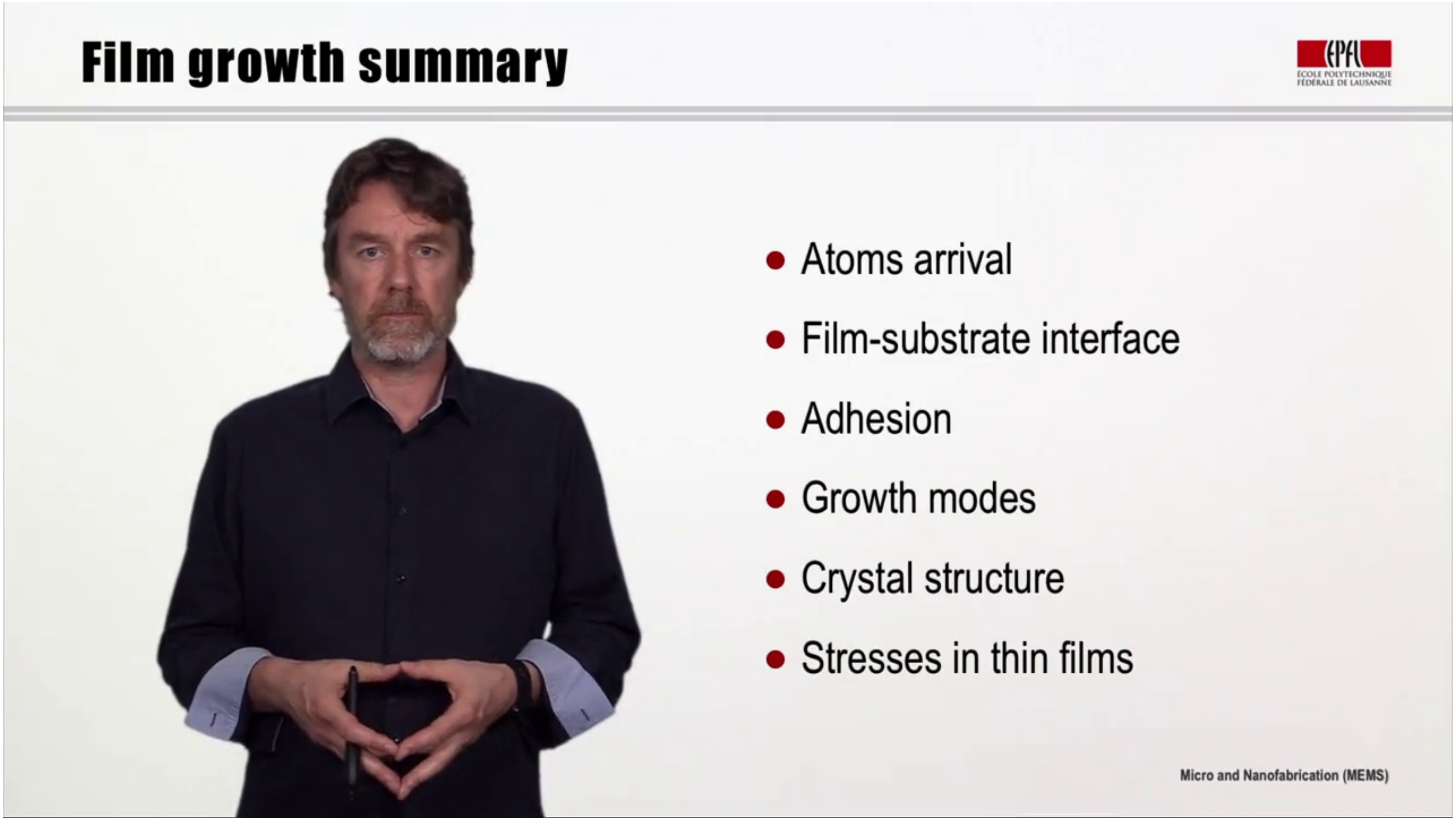
It is worth to notice that if a wafer with a thin film was manually bent, a tensile stress in the thin film would occur in the case of a convex shape. It is the opposite, then, for residual stresses. Tensile stress in thin films leads to cracks while compressive stress leads to buckling.



The well-known Stoney equation quantitatively relates the wafer curvature to the residual stresses in the thin film. By measuring the radius of curvature of the wafer before and after the film deposition and knowing the substrate and film thicknesses, it is possible to compute the average stress in the thin film.



Here we see 2 SEM images showing 2 different cantilever arrays. In both cases, we have free-standing SiO2 films, 1 to 1 µm thick grown by thermal oxidation at 1050°C. They are between 40 and 200 µm long. The bilayer microcantilevers were obtained after an additional titanium (left) and aluminum (right) that was deposited onto the SiO2 cantilevers. The aluminum films with thicknesses ranging from 0.3 to 1.7 µm were deposited using thermal evaporation. In addition, the titanium films with thicknesses ranging from 0.1 to 0.3 µm were deposited using electron beam evaporation. The SEM images here show the bilayer microcantilever array and their respective bending due to intrinsic stress. In the case of titanium, it bends upwards, and in the case of aluminum it bends downwards. In both cases, we have SiO2 as material plus the titanium. And here we have the SiO2 plus the aluminum. So we can obtain different types of stresses in free-standing cantilevers, by playing with different material compositions.



In this chapter we first saw that depending on the chemistry, the deposition method and the process parameters, atoms can either be chemisorbed or physisorbed at the wafer surface. Once arrived on the surface the atoms stay, move or desorb. Once the film starts to grow, an important parameter is the film substrate interface. Will the film adhere or not? To answer this question, thermodynamics allows computing interface stability and several types of different interfaces were shown in this lesson. We have seen that all the following factors influence the thin film adhesion: interface compatibility, substrate cleanness and deposition method, as well as adhesion layers. Film growth can be categorized into different modes, which are 2D, 3D and columnar modes. These modes, as well as the resulting film crystal structure are strongly dependent on the deposited material, the deposition method, as well as on the process parameters. There is no general theory that allows determining the final crystal structure of a thin film. Some empirical data can sometimes be used, but most of the time, the trial and error method is required. Finally, as a signature of the deposition method and process parameters, residual stress in thin film was also studied. Extrinsic stress is differentiated from intrinsic stress, and the final total average stress in a thin film can be related to the radius of curvature of the wafer using the Stoney equation. With this lesson, we close the chapter on physical vapor deposition.