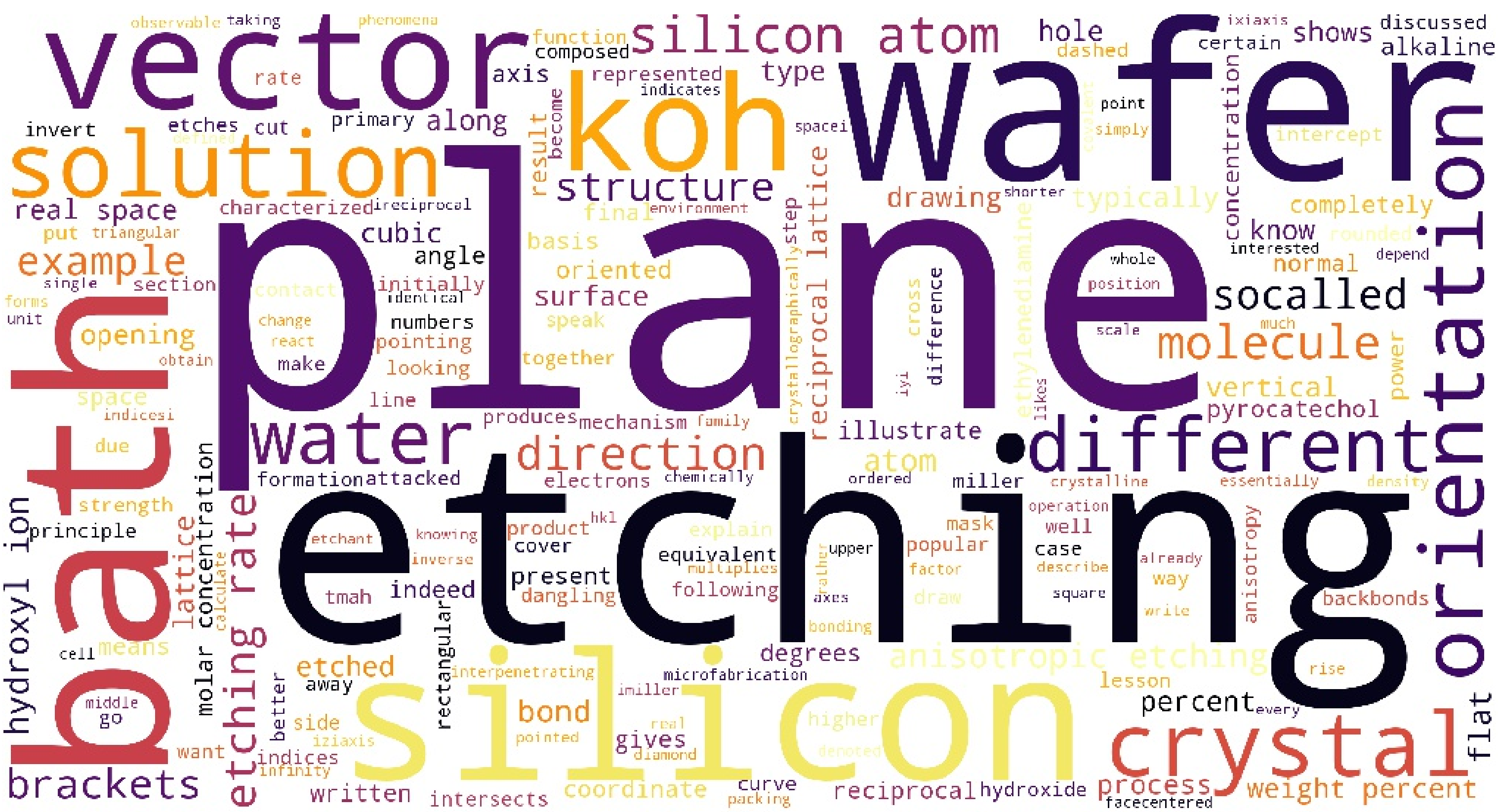

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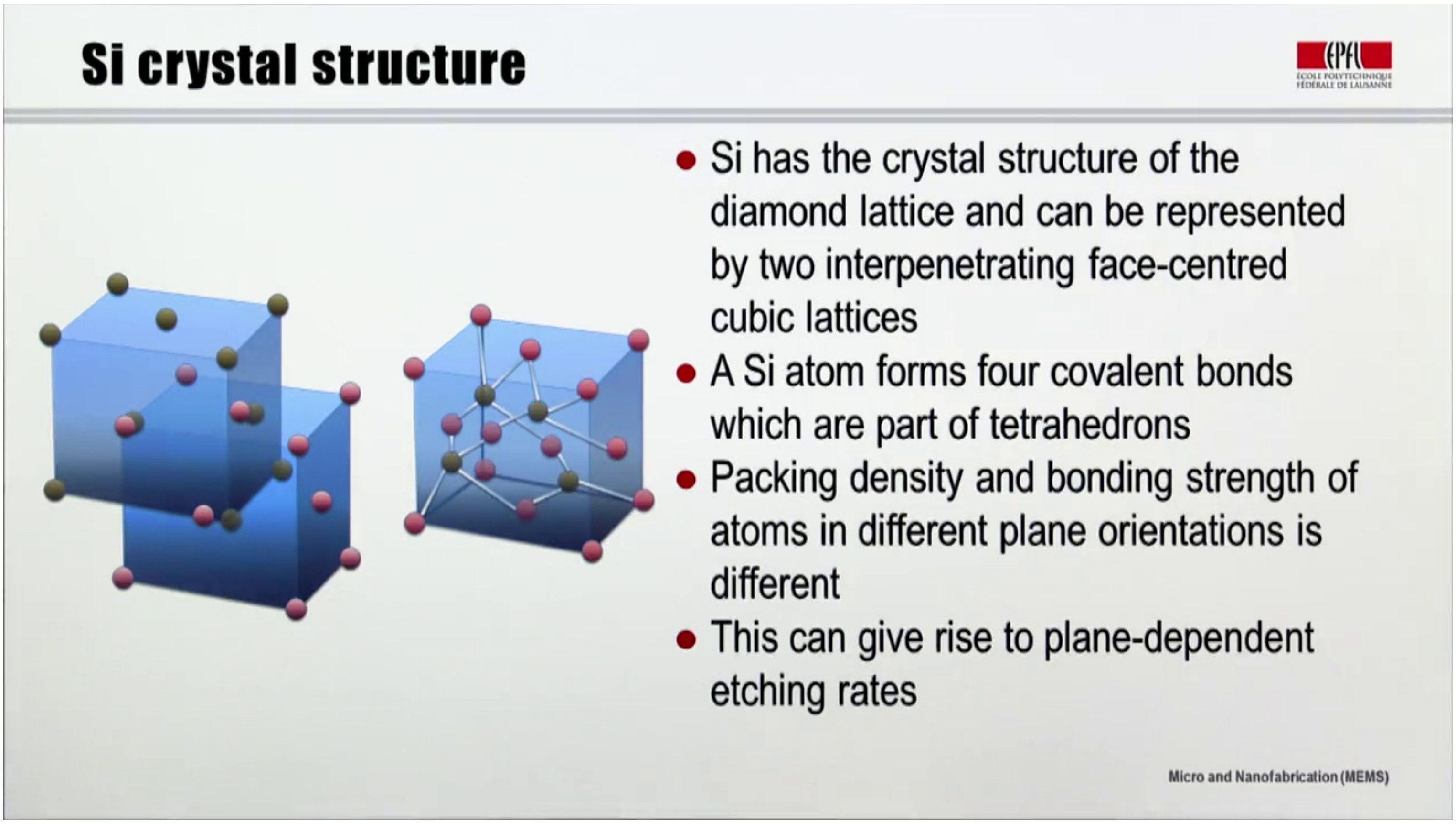
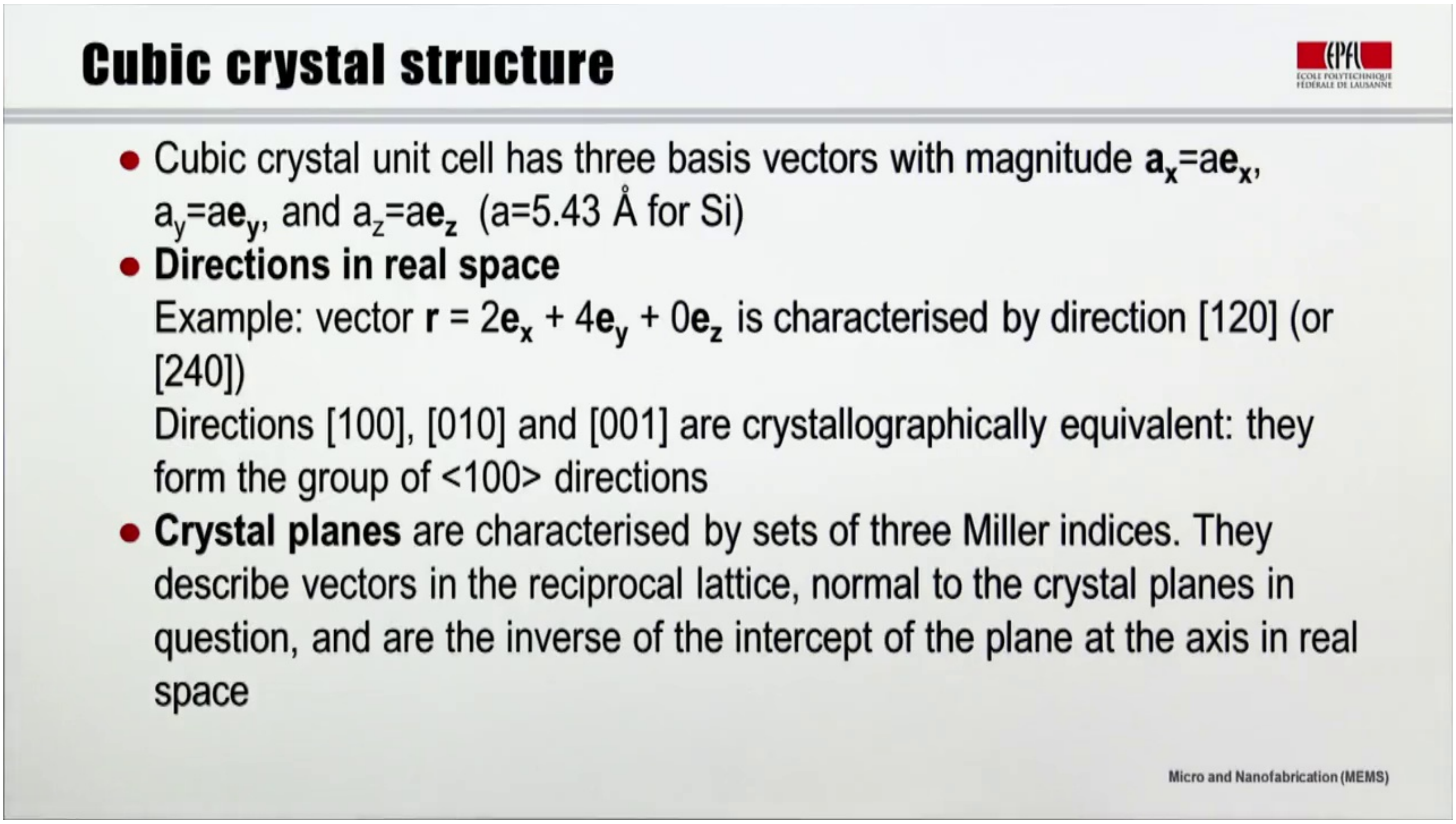
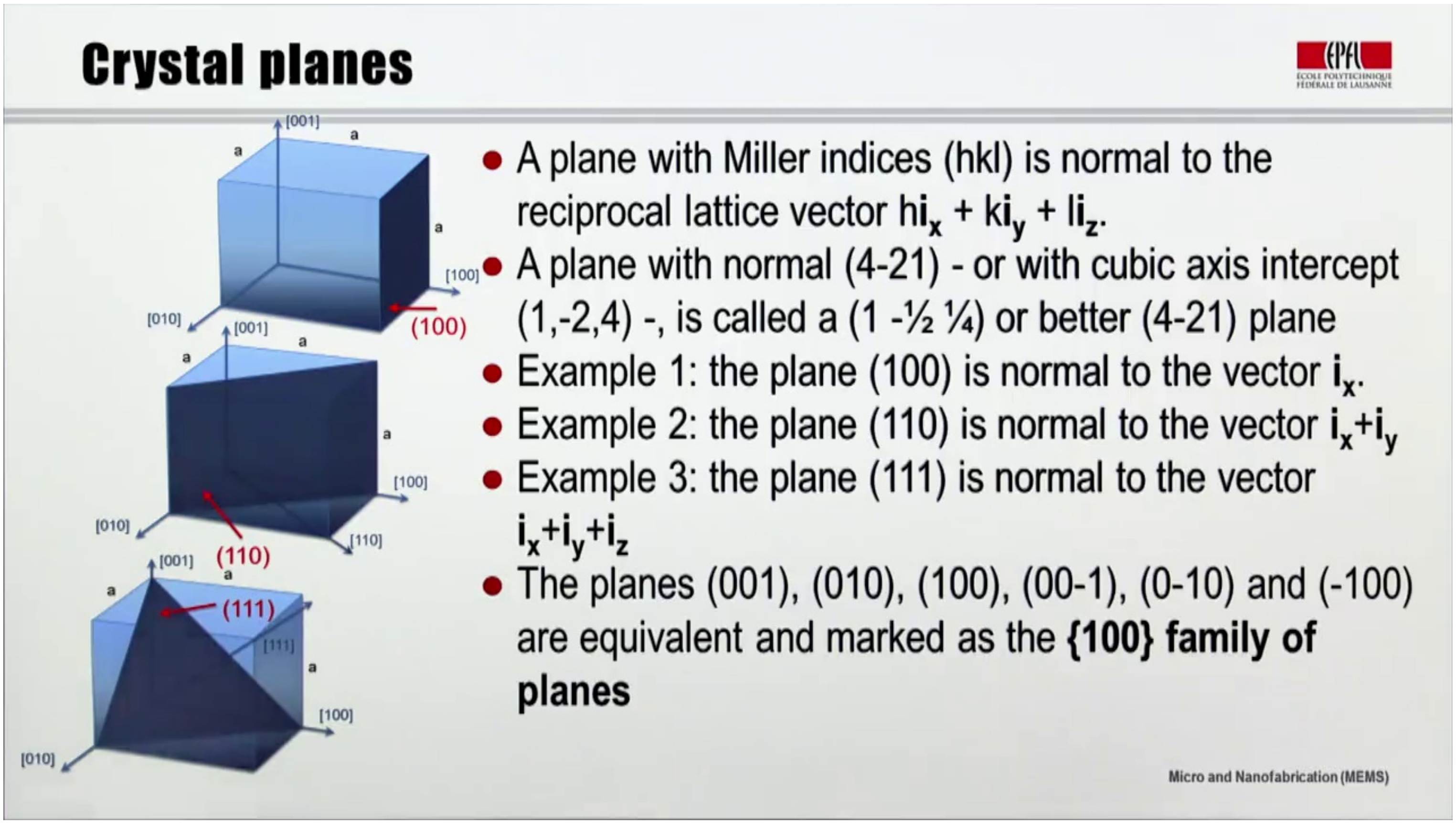
In this lesson, we will explain the anisotropic etching of silicon by which certain crystal planes will be chemically attacked by an etchant, while other planes will not react. These etching phenomena are observable because the silicon wafer is essentially single crystalline, that is, it has an ordered lattice structure on the scale of the wafer. We will explain the etching mechanism and some of the etching baths that can be used.



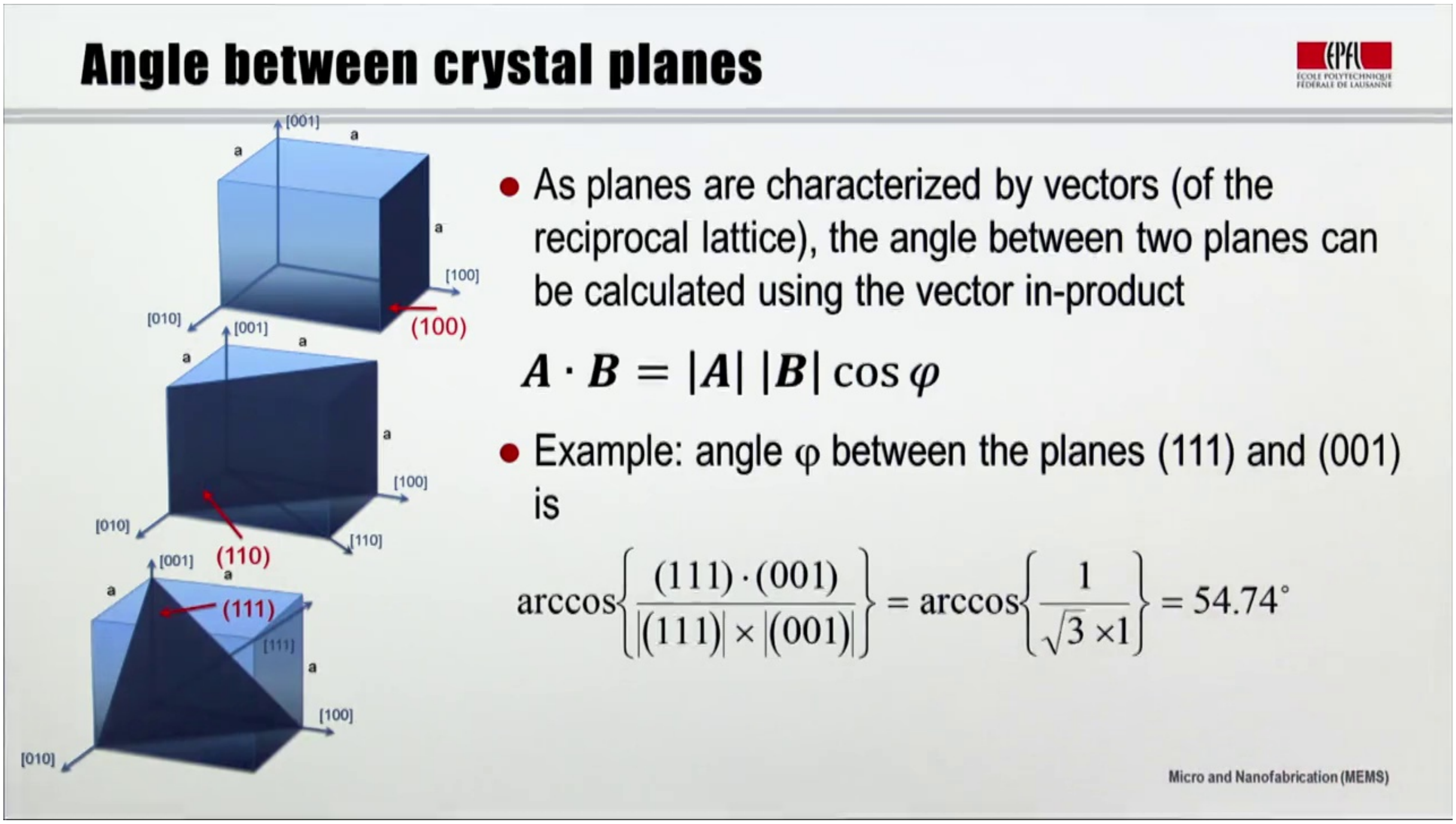
These drawings illustrate the silicon crystal structure which is that of a diamond lattice and can be represented by two interpenetrating face-centered cubic lattices. A silicon atom forms four covalent bond with other silicon atoms. If one cuts the silicon crystal along different planes, one will see that the packing density of atoms and the bonding strength between silicon atoms on different plane orientations is different. And this gives rise to etching rates that can depend on the plane orientation.



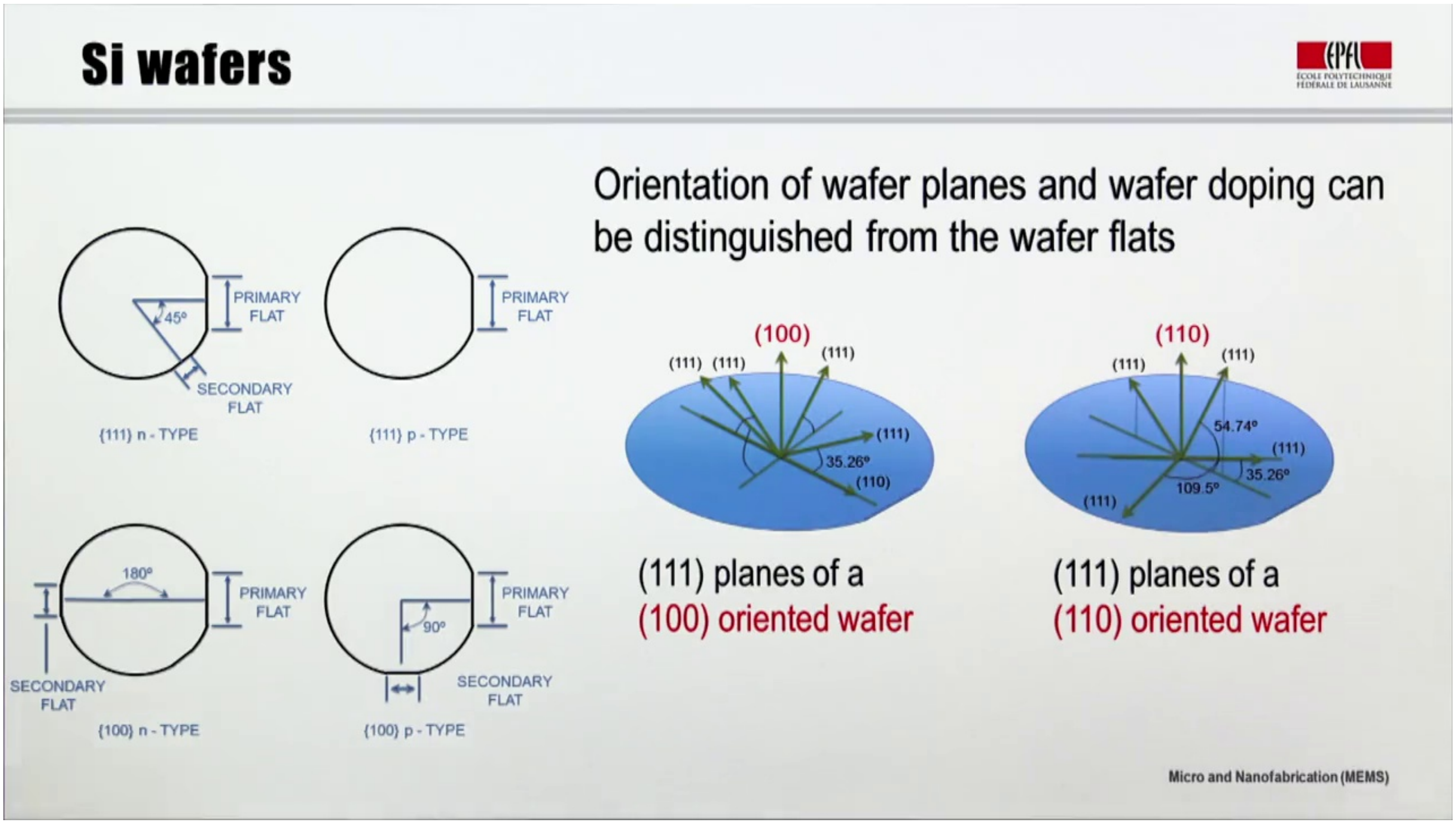
A cubic crystal unit cell has three basis vectors and every point in real space can be written as the coordinate of a vector written in function of the three basis vectors. A real space coordinate or vector can be represented by three numbers as put in between the square brackets. So this direction is the same as this direction, only the vector here is shorter by a factor of two. In the crystal, the directions [100], [010] and [001] are crystallographically equivalent. One is along a different axis but for the environment of the silicon atom, there is no difference. If one wants to speak of all these directions, together, one puts 1 0 0 with these triangular brackets: <100>. In micro-fabrication, we are not so much interested in knowing the real space coordinate of each atom, but rather, we would like to know how the crystal planes are oriented in the wafer. A crystal plane can be characterized by three so-called <i>Miller indices</i> which describe a vector in the so-called <i>reciprocal space</i> that is normal to the crystal plane. The Miller indices are defined by taking the inverse of the intercept of the plane at each axis in real space, and we illustrate that now in the following.



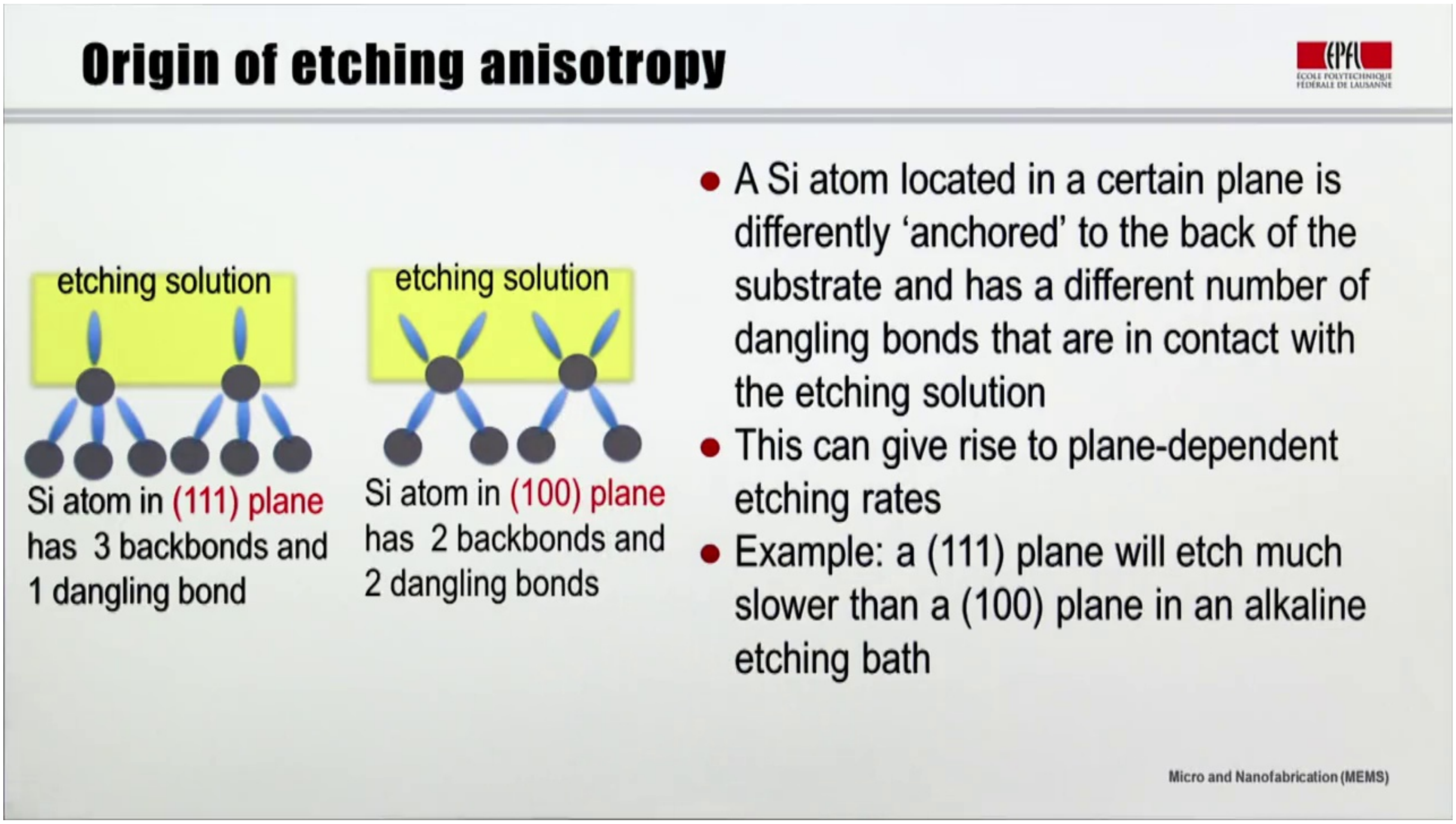
A plane with Miller indices (hkl), and we use here now rounded brackets because it’s a plane, is normal to this reciprocal lattice vector where these are the basis vectors of the reciprocal lattice, these three. A plane with a normal (4-21), means that the plane intercepts the three cubic axes at 1, -2 and 4. Indeed, if we invert 1, -2 and 4, we obtain this reciprocal lattice vector and as one likes better whole numbers, one multiplies this vector by 4 to get this vector. By this operation, the orientation of the vector does not change, so it’s the same plane. As we already pointed out, a reciprocal space vector is denoted by the rounded brackets. The upper drawing illustrates the position of a (100) plane which intersects the <i>x</i>-axis at 1, and the <i>y</i> and <i>z</i>-axis at infinity. So if we invert these, we get (100) The planes (001), (010), (100), and so on are equivalent, and if you want to speak of all of them together, we write it with these brackets: {100}. So this means this is the family of identical planes. In the same way, the drawing in the middle indicates the (110) plane. And the drawing below, the (111) plane. So this intersects, for example, each axis at one.



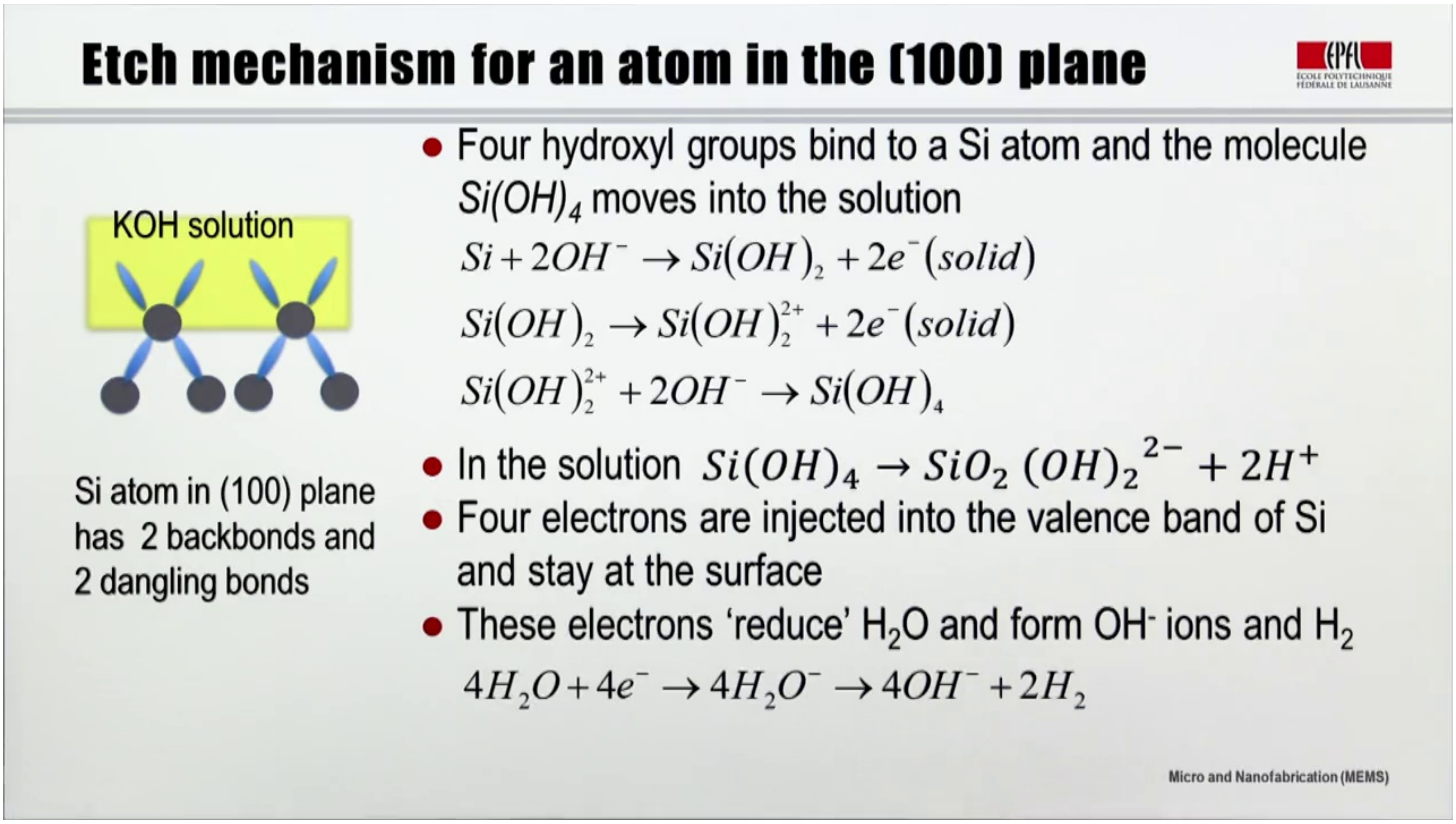
As planes are characterized by vectors of the reciprocal lattice, one can simply calculate the angle between two planes by calculating the vector inner product; this product. And as an example, the angle <i>phi</i> between the planes (111) and (001), is 54.74 degrees.



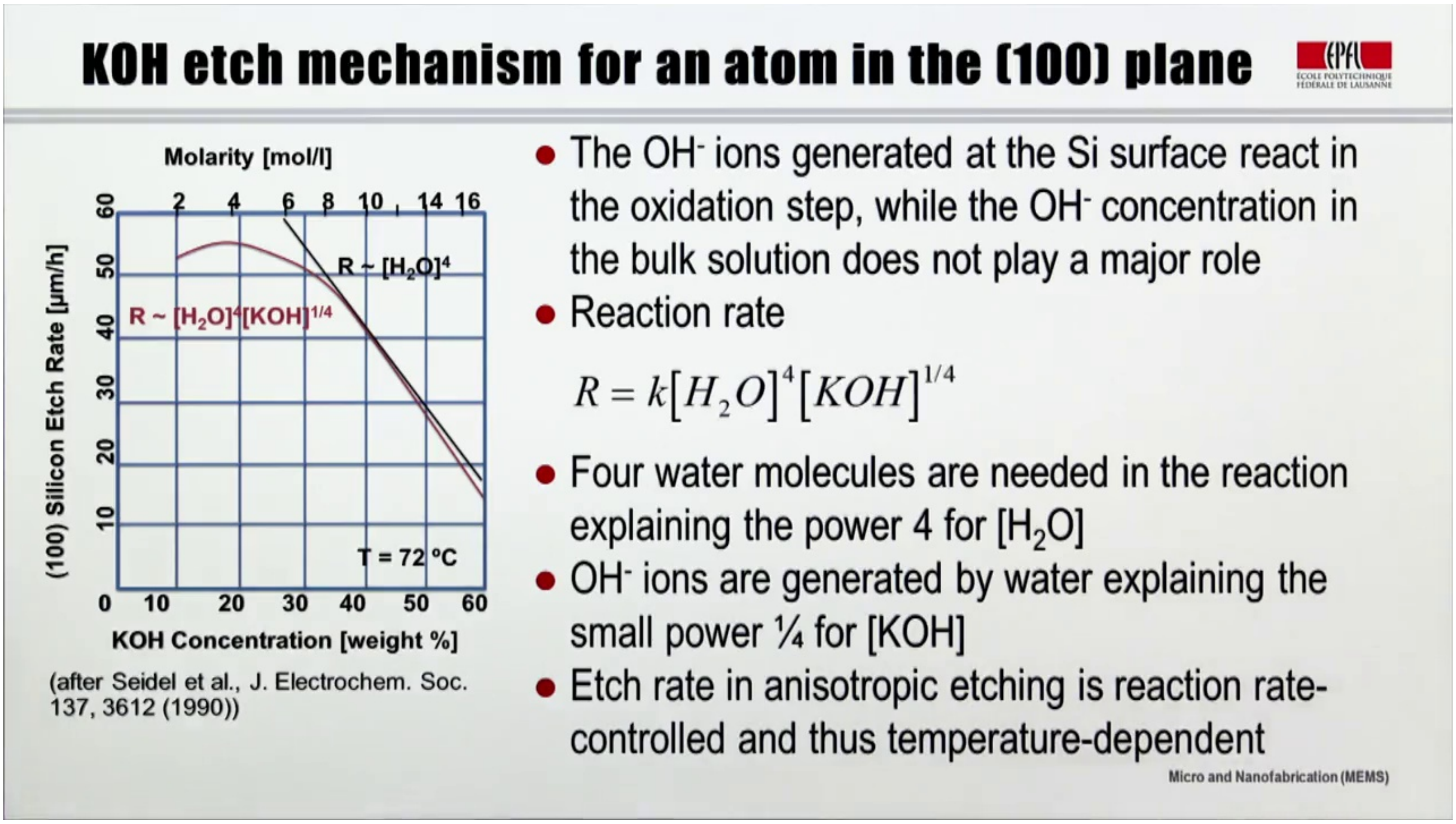
If one has in mind a cubic crystal structure, one can know the orientation of the different planes. For example, if the surface of the wafer has a (100) orientation, there are four (111) planes that have each an angle of 54.74 degrees with the plane of the wafer. If the wafer has been cut from a crystal that had a (110) orientation, two (111) directions are now pointing outside of the wafer and two (111) directions are inside. That means in this case, the (111) plane is vertical. There are two vertical (111) planes for a (110) oriented wafer. In practice, wafers have so-called <i>flats</i>: a primary flat and a secondary flat. Here, there's only a primary flat. If you see a wafer, in principle you know by looking at the flats what is the type of orientation of the wafer. So here is the orientation and here is the (100) orientation, and also you know the type of doping in the wafer by looking at the flats.



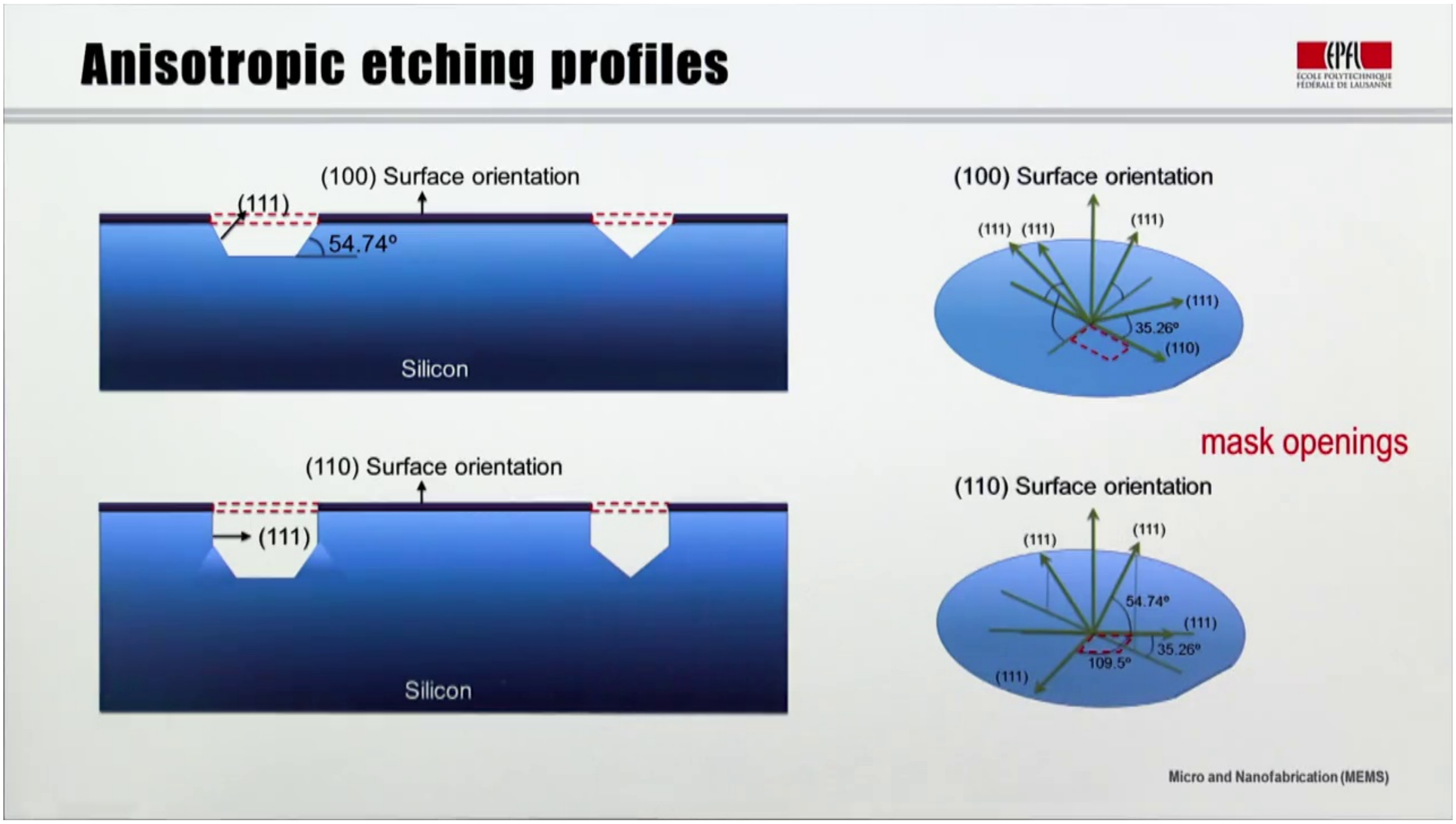
The reason why an etching bath preferentially attacks a certain lattice plane, and does not etch another plane is illustrated here. A silicon atom that is present in a (111) plane has three backbonds to the interior of the silicon wafer and one dangling bond which is interfacing with the etching solution. So this bond can be attacked by chemical molecules from the etching solution. A silicon atom within a (100) plane has only two backbonds and two dangling bonds pointing in the etching solution. The second type of silicon atom is hence less well anchored to the silicon wafer and will be more easily etched away.



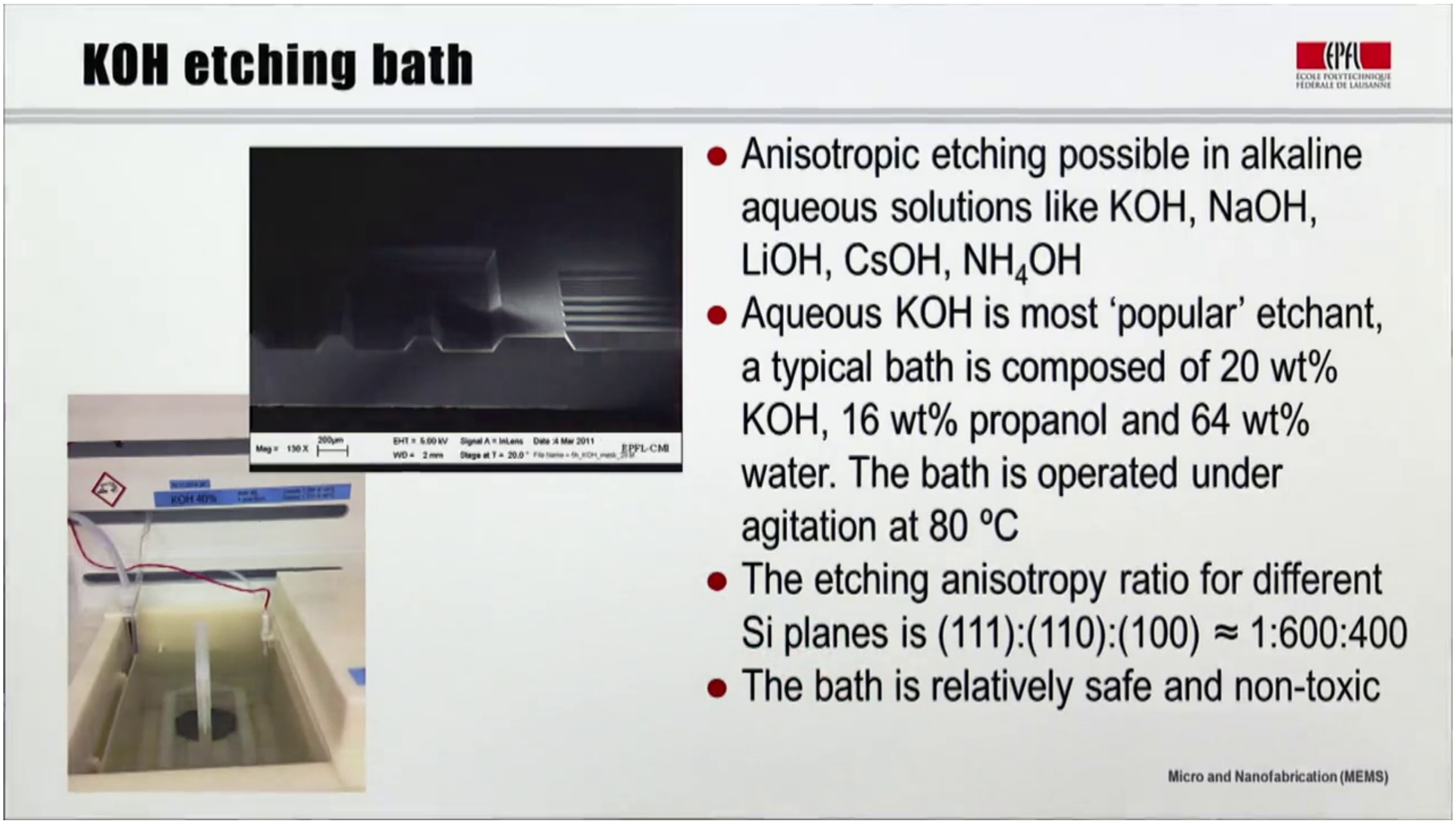
An example of such an etching bath is potassium hydroxide or KOH solution. In such a bath, 4 hydroxyl ions bind progressively to a silicon atom in a two-step process leading to the formation of this molecule. This molecule is called <i>silicic acid</i>. It is converted in the solution to this molecule and into two protons. The four electrons that came from the four hydroxyl ions have been injected in the silicon. These four electrons, they are used here to generate four new hydroxyl ions so that there is no charging of the silicon and the etching continues.



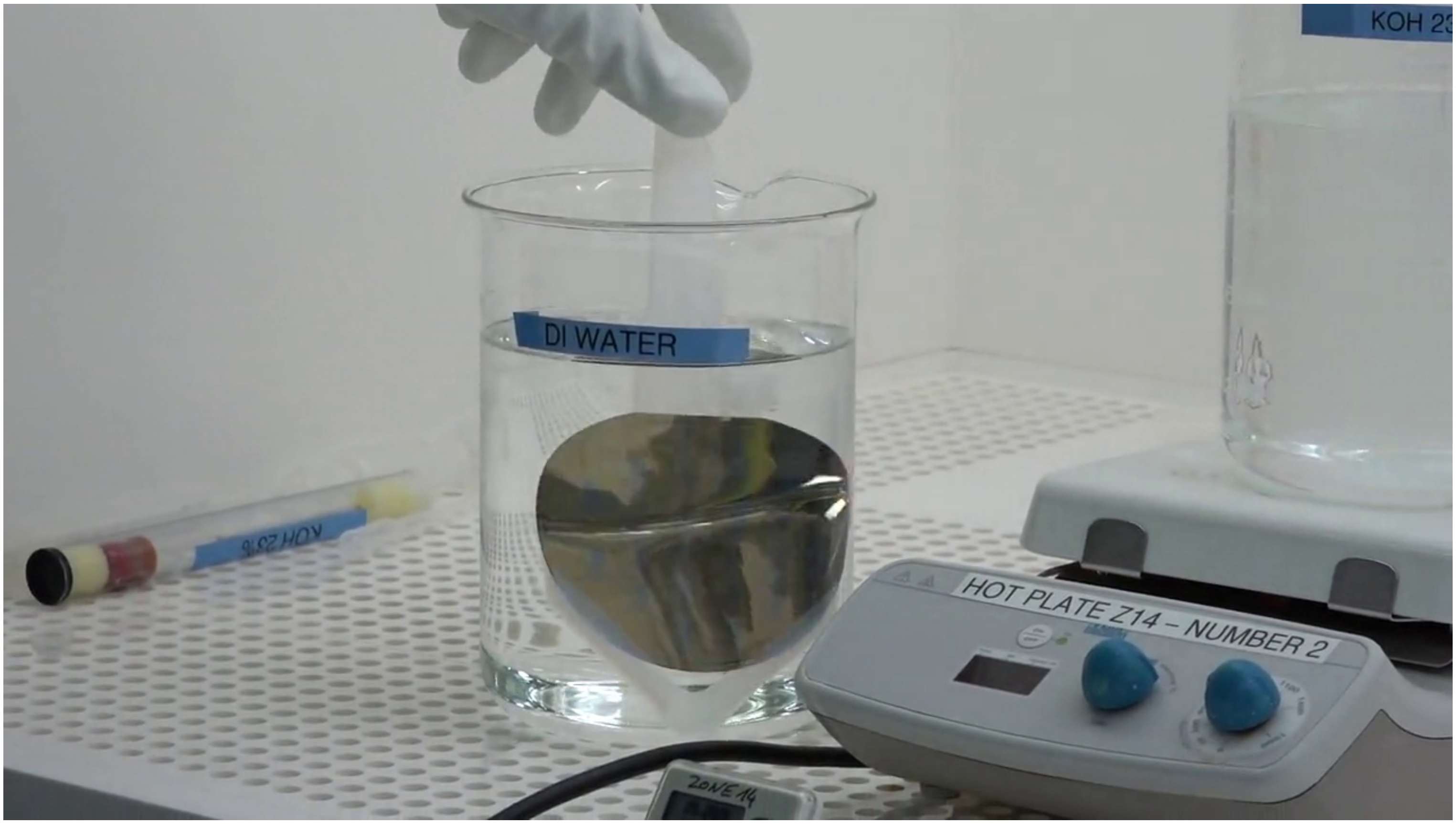
The four hydroxyl ions that are generated at the silicon surface originate from water molecules and not from hydroxyl ions initially present in the KOH solution. The reaction rate of the KOH etching bath can be written as this formula and between brackets, you have the molar concentrations. So this is the molar concentration of water, if there is more water, the concentration of water is higher. The power of four gives the water concentration the most prominent importance, while the KOH has only a power of 1/4. The red curve shows the actual etching rate as a function of the KOH concentration. And we indeed see if there is more KOH dissolved in the water, the etching rate goes down. The black curve gives the power of four dependence on the water molar concentration. Note that this etching rate was for atoms on a (100) plane while to first order, there is no or very, very little etching of atoms on a (111) plane.



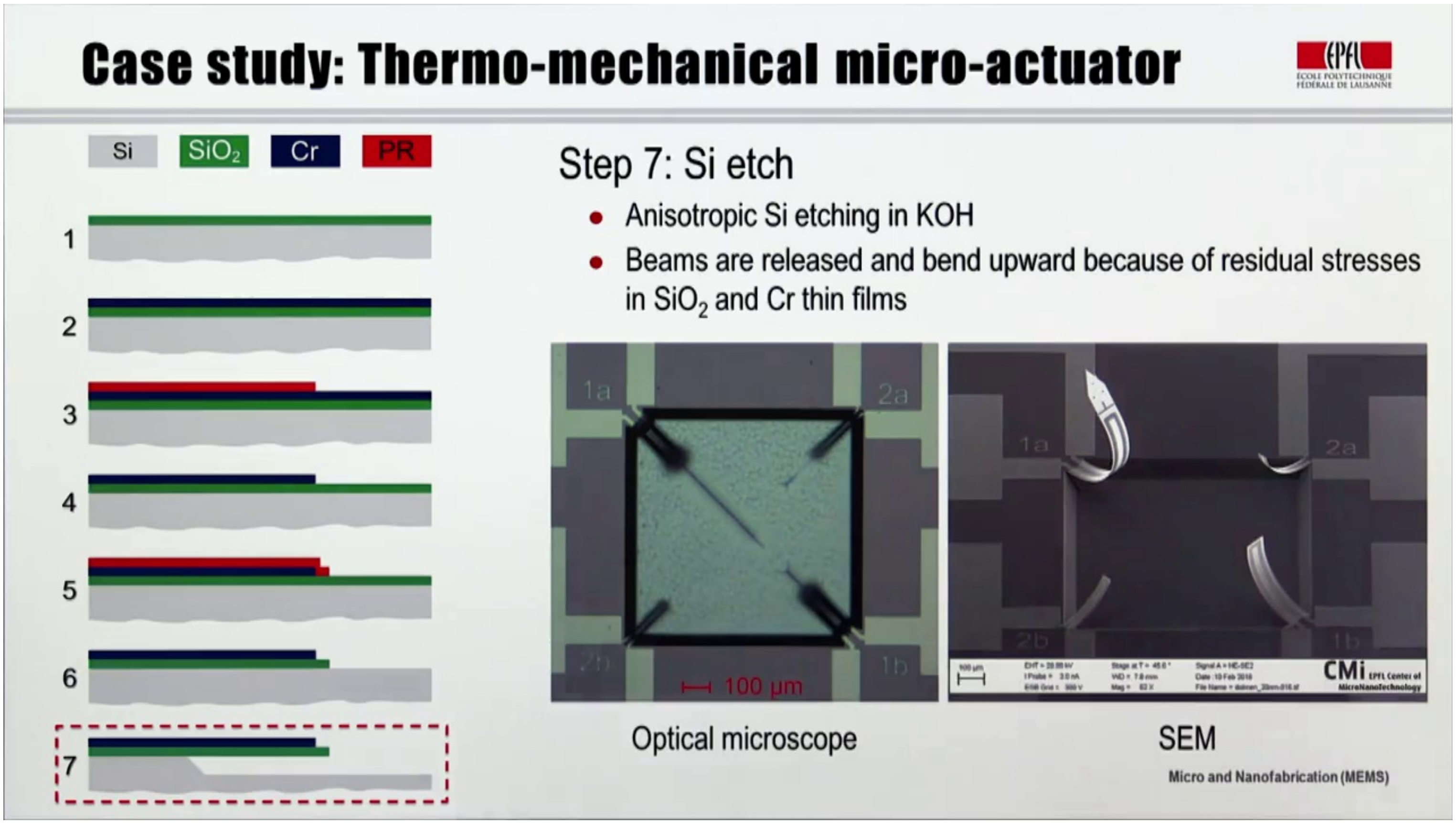
We draw here again our wafer with (100) surface orientation and cover it completely with the masking layer, except for a rectangular opening that is oriented along the (110) direction. The diagram on the left side shows the same wafer in cross section with two of these rectangular openings also indicated by the dashed lines. Atoms along the (100) plane will be etched away. So etching will go vertical and if one encounters a (111) plane like here or here, there will be no etching. So gradually, the (111) planes will become visible. The hole here has reached the final V shape and no further etching will happen. In a similar way, we can draw again our wafer with (110) surface orientation, cover it completely with a mask material and make now an opening in the mask, given by this dashed line again. So this opening is parallel to the (111) directions. If we look to the cross section of the wafer after etching, we see following profiles with the structure on the right representing a hole in its final state where only (111) planes are in contact with the KOH solution, and this (111) plane indeed is vertical.



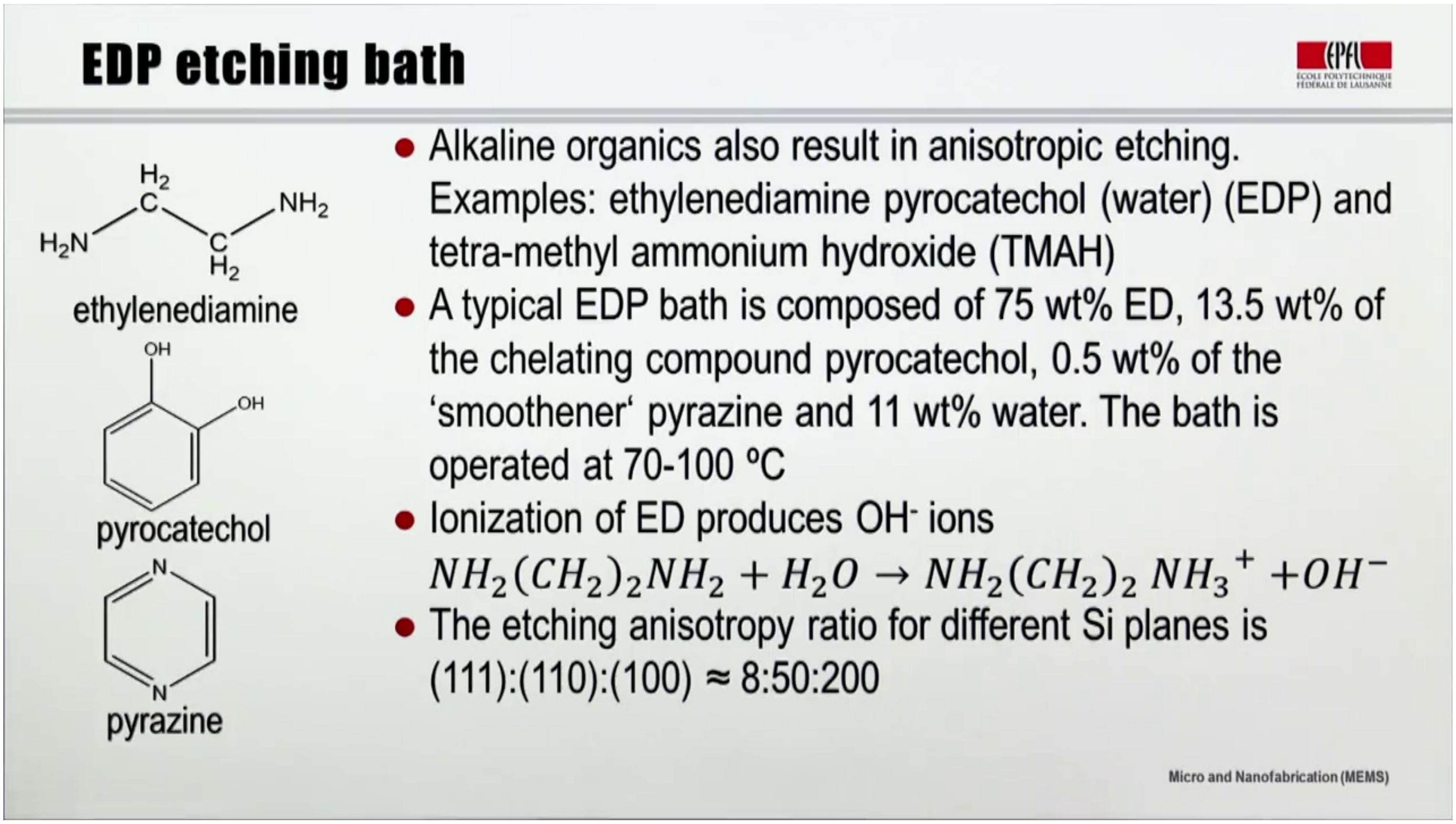
Anisotropic etching is possible in different alkaline aqueous solutions but the most popular solution is the KOH bath. It is typically composed of 20 weight percent of KOH, 16 weight percent of propanol and 64 weight percent of water. The bath is typically operated under agitation at 80 degrees Celsius. These are the etching anisotropies for different silicon planes. Here we see that the (100) plane etches 400 times faster than the (111) plane. So the (111) plane etching rate is not completely zero. The etching rate of a (110) plane is 600 times higher than that of a (111) plane. The picture shows the result after a KOH etching process and one recognizes typically these V-shaped channels and holes. And this is the KOH etching bath.



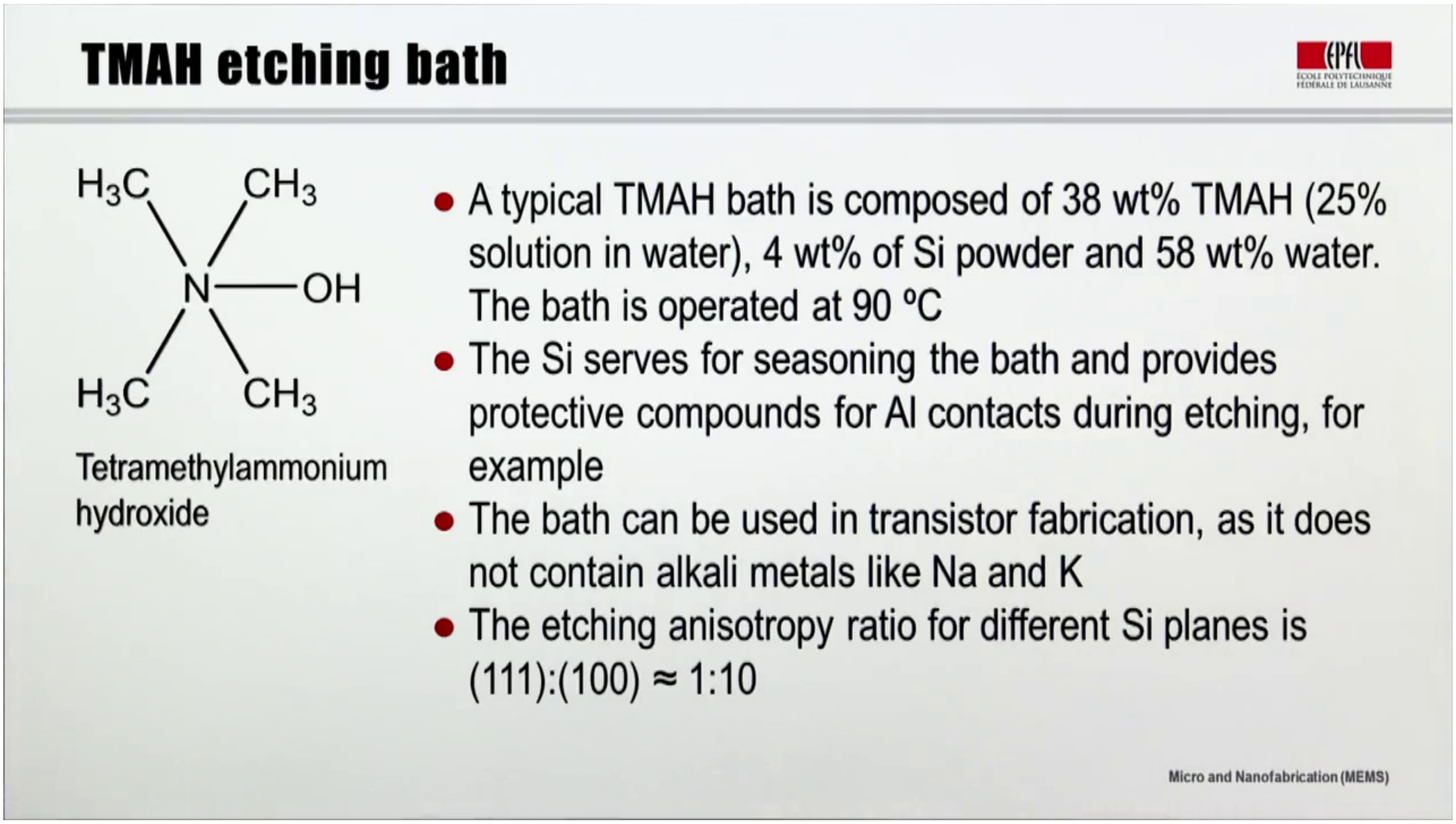
This video shows the etching of a silicon wafer in a KOH solution. Initially, the wafer is in a beaker of deionized water and then transferred to the KOH solution. One observes the formation of hydrogen gas during etching. In principle, the etching can go on for hours if deep structures need to be etched.



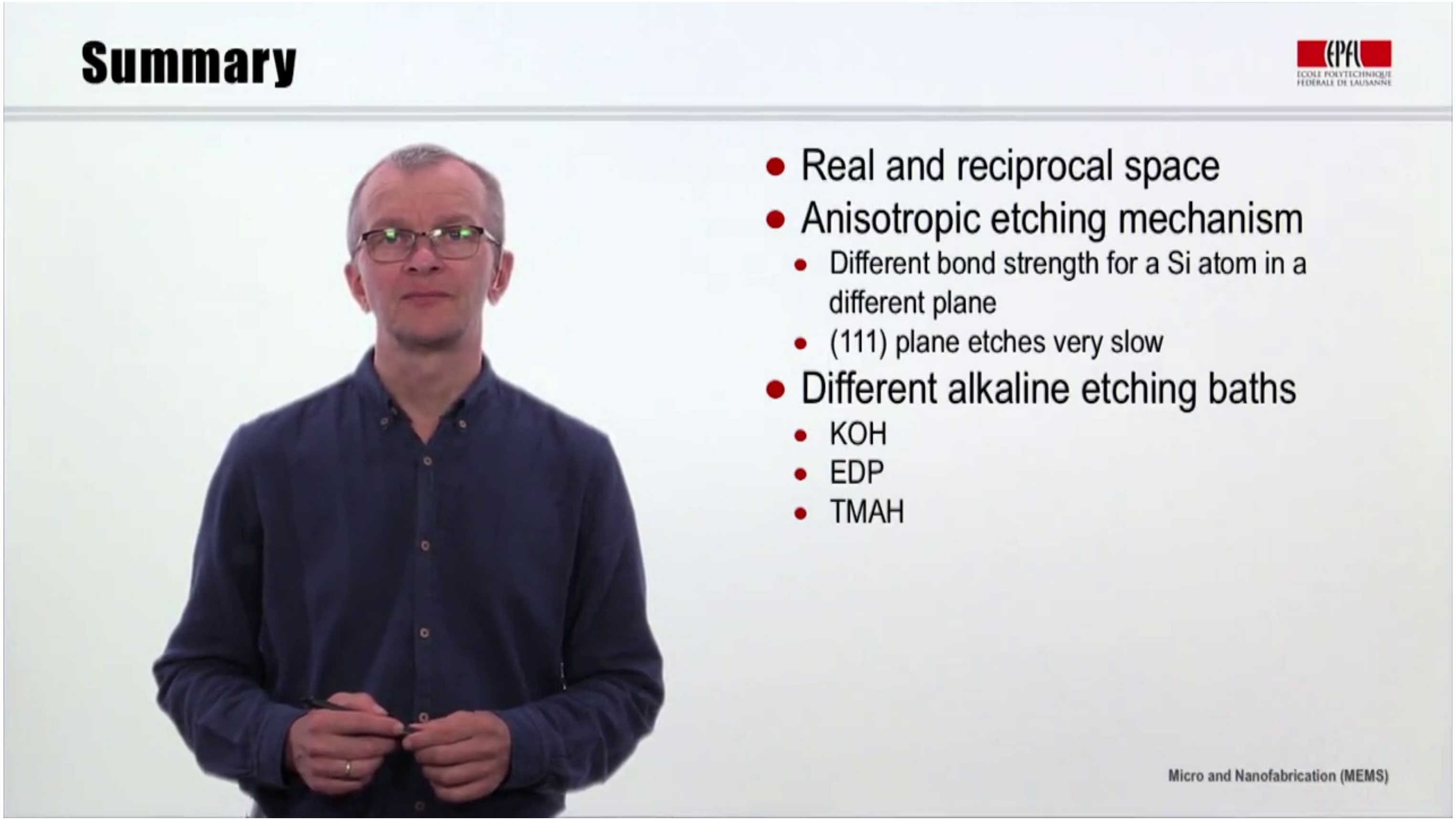
KOH etching was used also in the final step of our case study of the thermo-mechanical actuator. It was the process step that released the cantilever beam from the wafer by anisostropic underetching of the silicon. While there are several options that can be used to underetch, such as dry plasma etching, and isotropic silicon etching, anisotropic etching of silicon was used here due to its simplicity and efficiency for this type of structure. The inclined side walls of the etched hole immediately make it clear that we used an anisotropic etching process.



Also so-called <i>alkaline organic baths</i> are used for anistropic silicon etching. A well known example is the ethylenediamine bath with addition of pyrocatechol molecules, so-called <i>EDP</i> bath. It is composed typically of 75 percent of ethylenediamine, 13.58 percent of pyrocatechol, a half percent of pyrazine, and 11 percent of water. Ionization of the ethylenediamine produces this ion and the hydroxyl ion. That is why it becomes an alkaline bath. Pyrocatechol is a chelating molecule. Two of such molecules with these fingers can grab a silicon atom and transport it into solution. We also present here, the etching anisotropy rates for different silicon planes using this bath. So the ratio of the etching rate for example, of a (111) plane and a (100) plane is 8:200.



A third popular bath is the tetramethylammonium hydroxide bath or TMAH bath which produces good results by adding a few weight percent of silicon powder in the bath during etching. This is a so-called seasoning of the bath and it results in better aluminium contacts that are preserved during the etching. The etching anisotropy is lower than for the two other baths.



In this lesson, we have discussed the anisotropic etching of silicon. We gave a reminder of real and reciprocal space vectors whereby a reciprocal space vector is characterizing a crystal plane. We explained the anisotropic etching mechanism which is due to a difference in bond strength for a silicon atom on a different plane. We found that a (111) plane etches very slowly. Finally, we discussed different alkaline etching baths like KOH, EDP and TMAH.