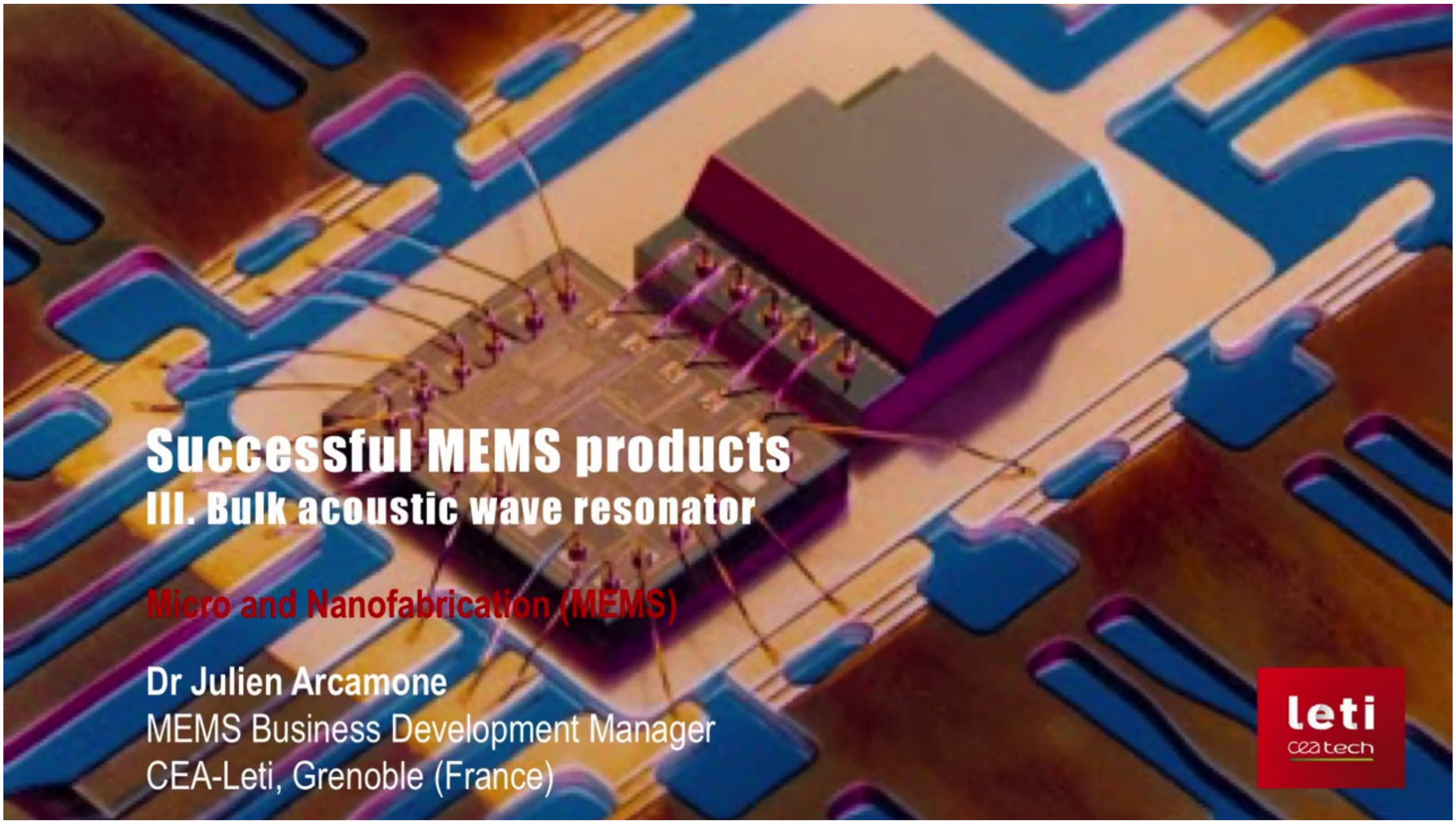

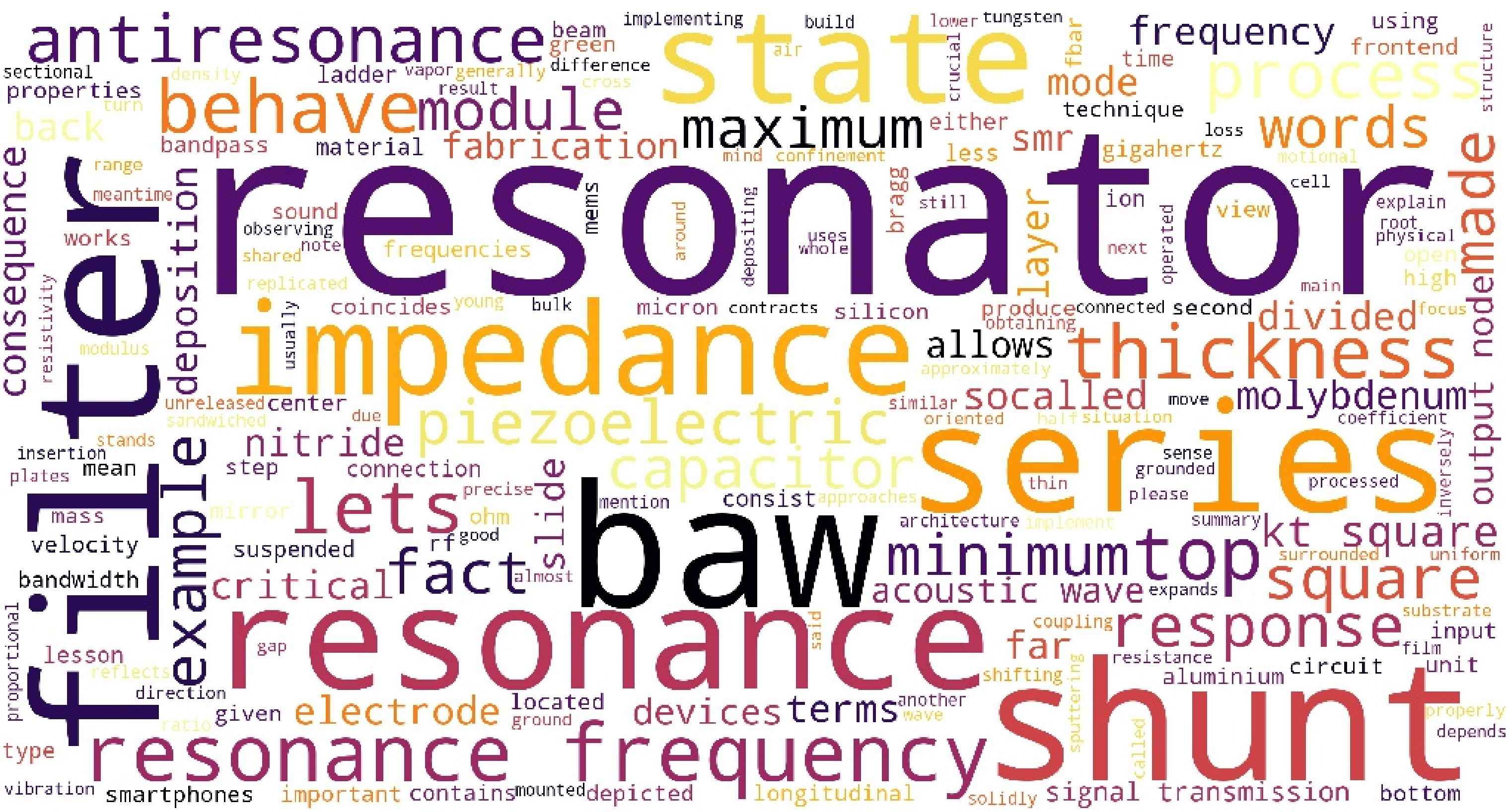

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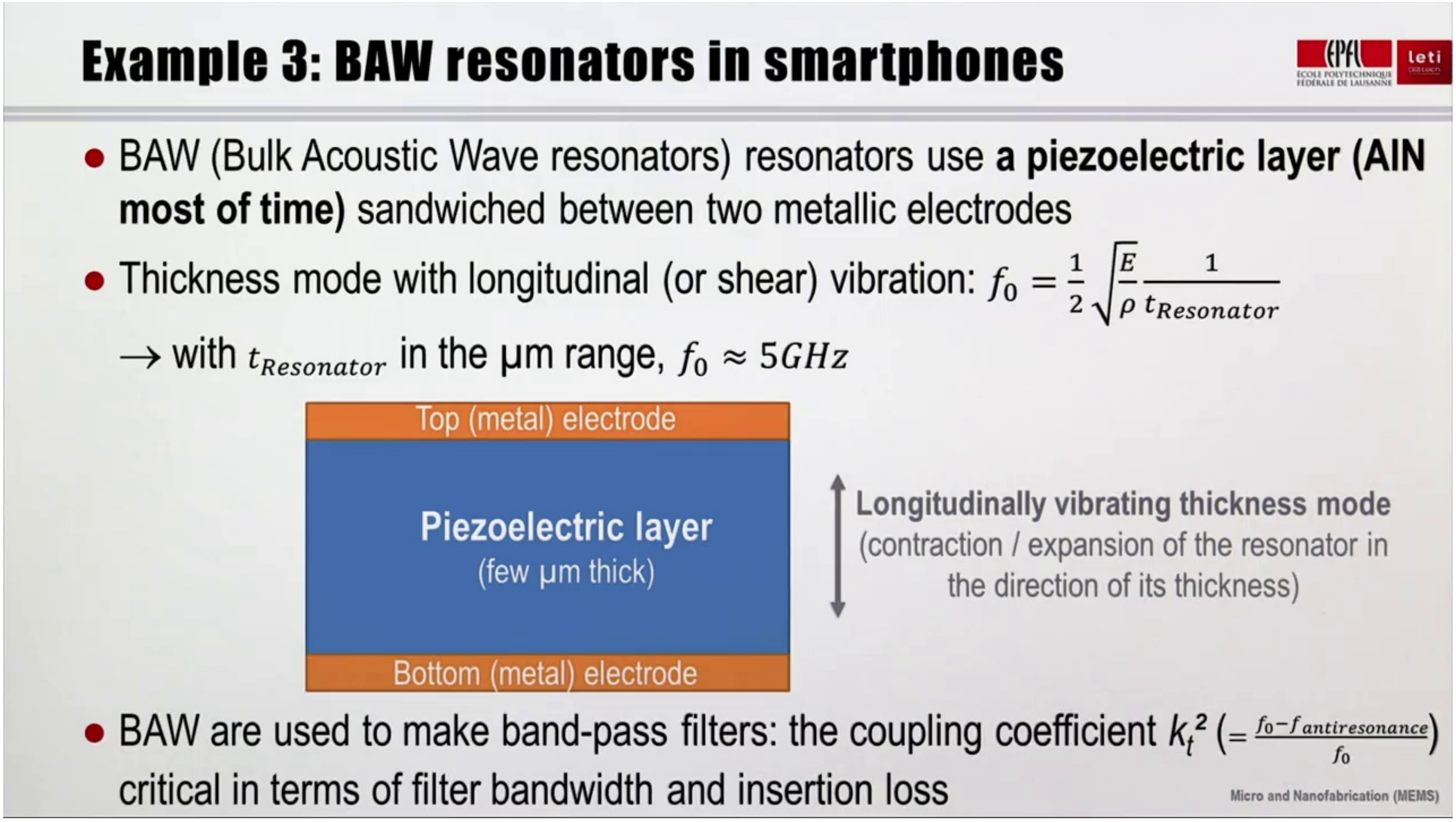
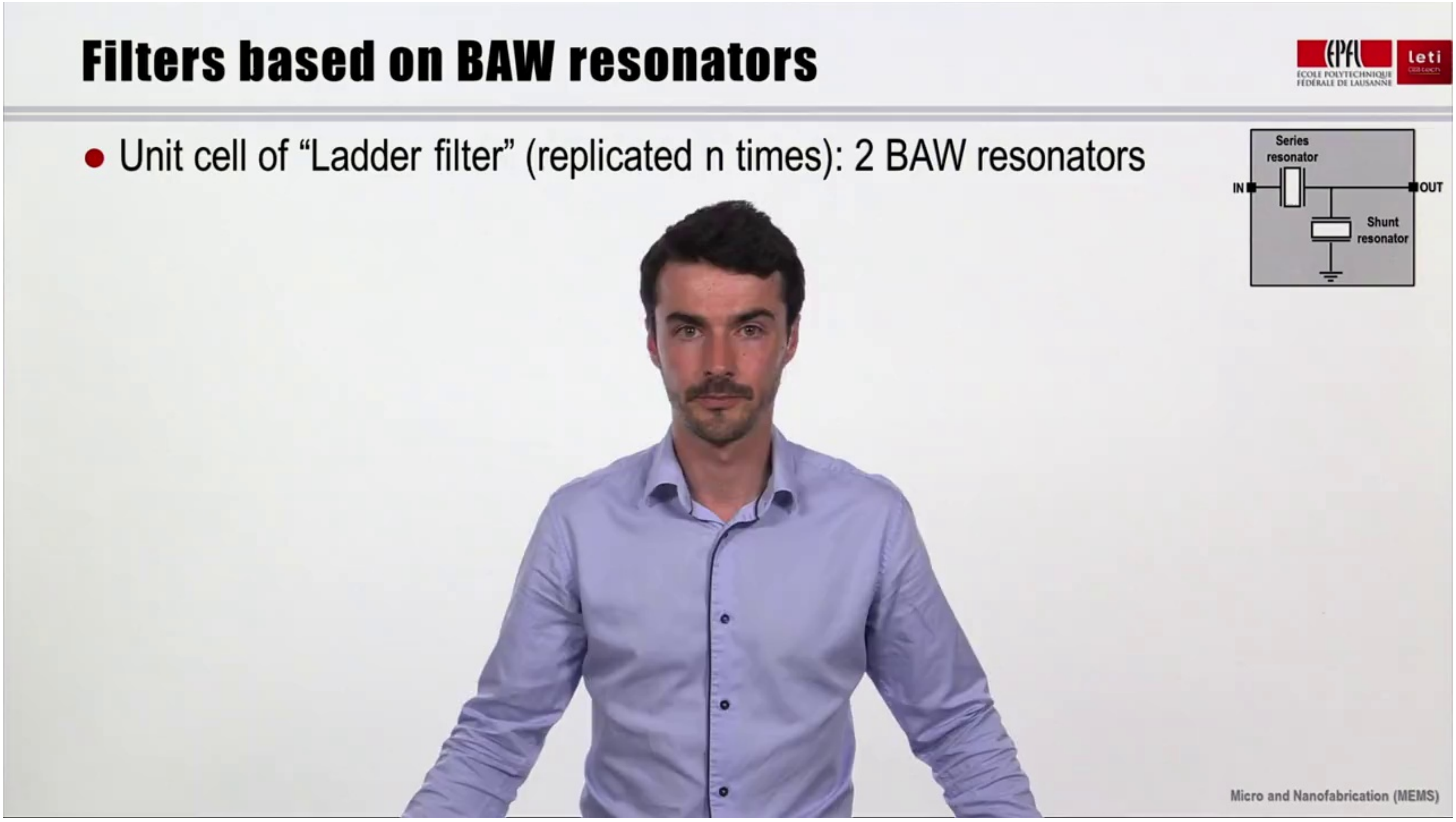
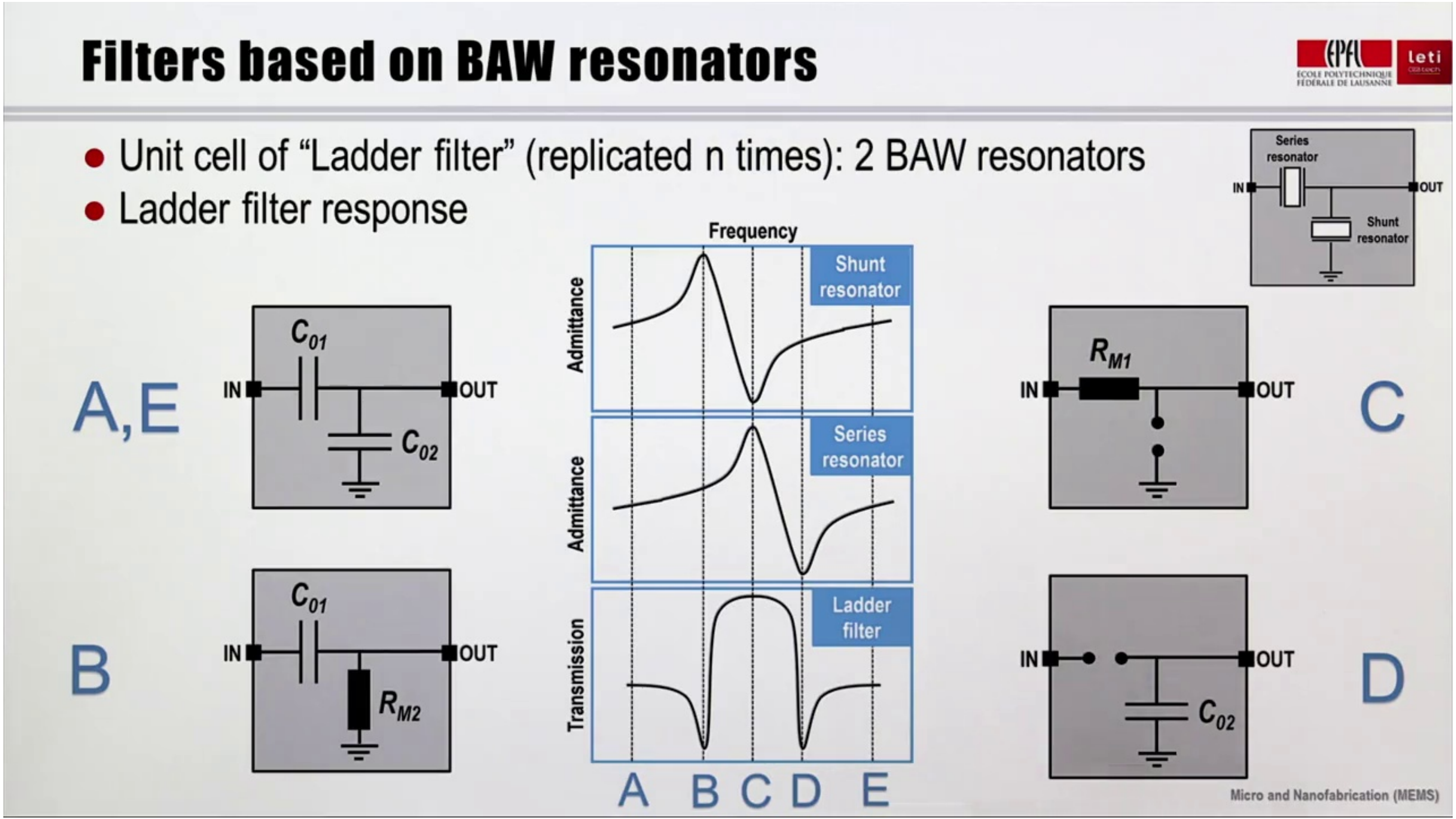


Let’s move to example 3 : BAW resonators in smartphones. As I said, BAW stands for Bulk Acoustic Wave resonators. The resonance frequency is generally in the range of the gigahertz. In terms of structure, BAW uses a piezoelectric layer made of aluminium nitride most of the time sandwiched between a bottom and a top electrode, usually made of molybdenum. In terms of resonance mode, a thickness mode, either with longitudinal or shared vibration is operated. In the longitudinal mode, the resonator expands and contracts all the time in the direction of its thickness. Its resonance frequency is half the velocity of sound divided by the resonator thickness. The velocity of sound is the square root of the young modulus divided by the density. With a thickness of 1 micron approximately, the resonance is around 5 gigahertz. BAW resonators are used to implement band-pass filters - I will get back to this in the next slide. In this sense, the so-called KT square coupling coefficient is critical in terms of filter bandwidth and insertion loss. The KT square is given by the ratio between the difference between the resonance frequency and the antiresonance frequency divided by the resonance frequency. In fact, the KT square depends on piezoelectric material properties. Therefore, the deposition and further process of the piezoelectric layer is crucial.

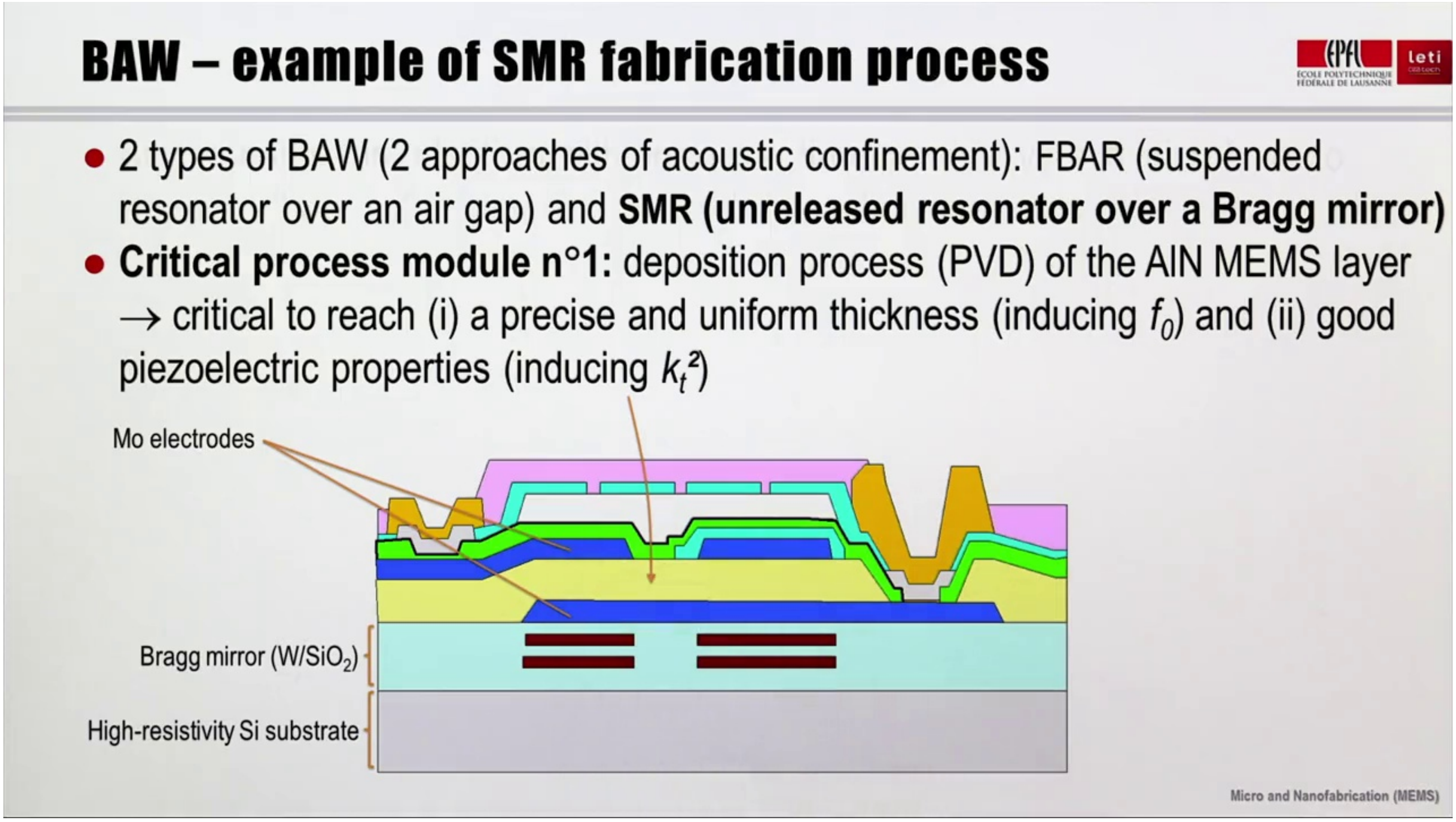


How can we build a filter using BAW resonators? Basically by implementing a ladder filter architecture. Its unit cell that can be replicated n times contains 2 BAW resonators : a series one and a shunt one connected to ground.

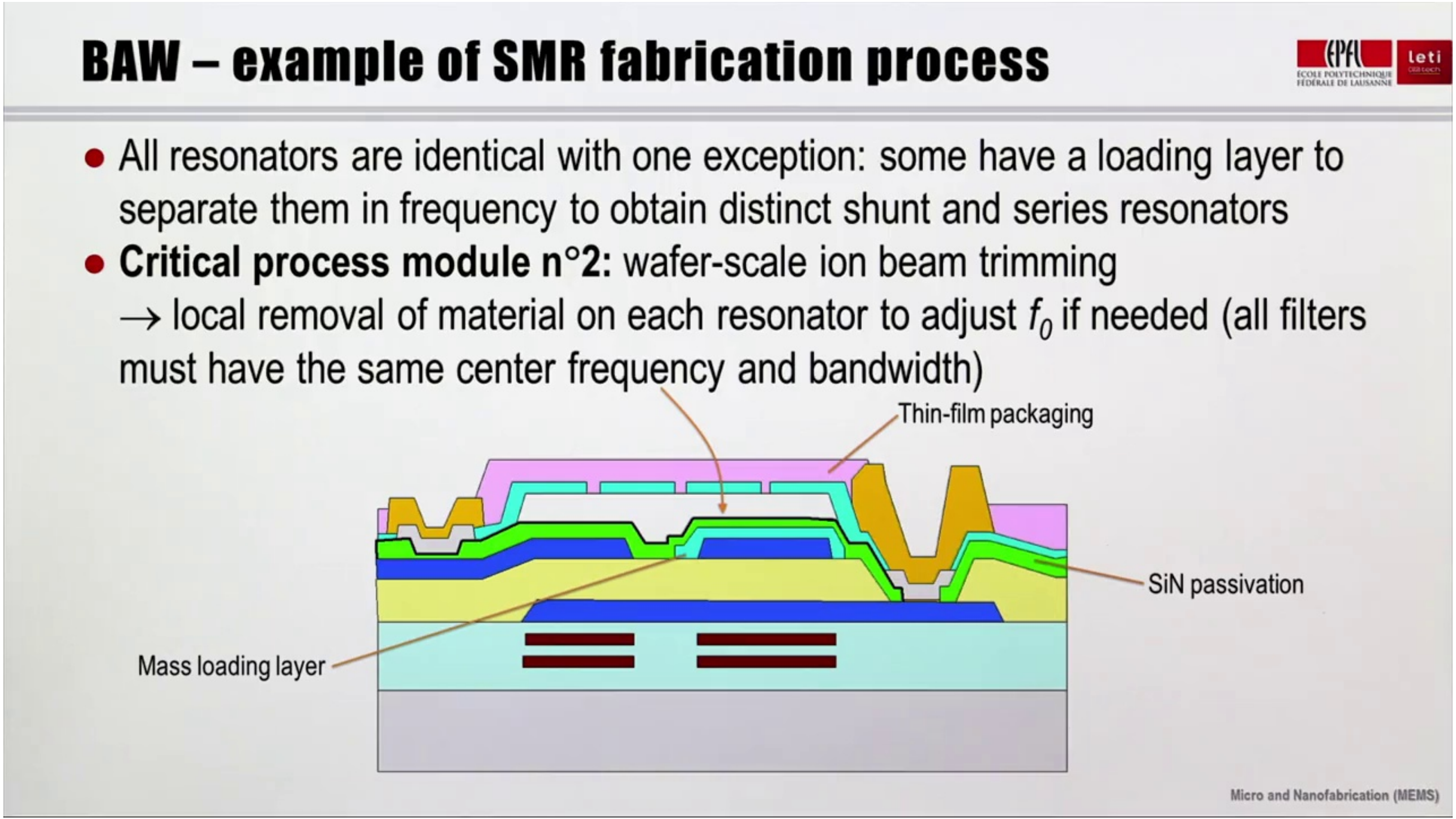


Let's explain how it works by observing the filter response. At the center of the slide, the frequency response of the shunt resonator is depicted at the top. The one of the series resonator is depicted here and this is the response on the whole filter. Please note that the shunt resonator response is shifting down to lower frequencies, such that the shunt antiresonance coincides with the series resonance. In state A, both resonators are far from the resonance frequency. Therefore, they both behave as capacitors. In state B, the series resonator is still far from resonance. And it behaves as a capacitor while the shunt one is at resonance. In other words, its impedance is minimum. In fact, in this state, its impedance is equal to its so-called motional resistance which is less than 1 ohm. As a consequence, the output node is almost grounded and there is no signal transmission. In state C, the series resonator is at resonance. In other words, its impedance is minimum and of less than 1 ohm. In the meantime, the shunt one is at its antiresonance. In other words, it is at its maximum impedance and it behaves as an open circuit. As a consequence, the impedance between input and output nodes is minimum and a signal transmission is maximum. In state D, the series resonator is at its antiresonance, in other words, at its maximum impedance. And it behaves as an open circuit. The shunt one is far from resonance and behaves as a capacitor. As a consequence, the impedance between input and output nodes is maximum and the signal transmission is minimum. In state E, the situation is very similar to state A. Both resonators behave as capacitors.

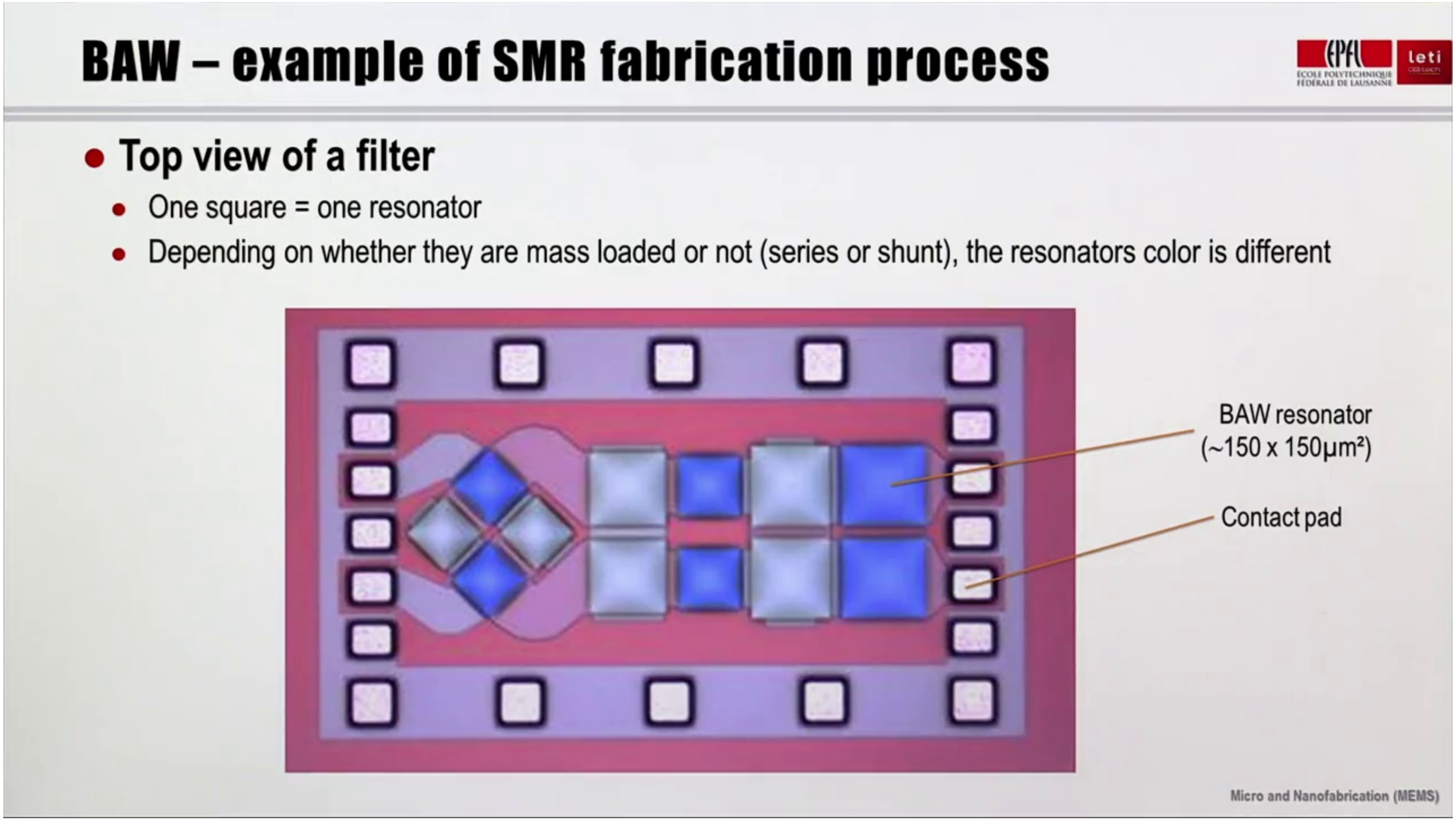
So this is basically a summary of how a ladder filter using BAW resonators works. Let's turn to the fabrication process of BAW. Let's first mention that there are 2 types of BAW due to the fact that there are 2 main approaches of acoustic wave confinement. So called FBAR, thin Film Back Acoustic wave Resonators are suspended resonators over an air gap. So-called SMR, Solidly Mounted Resonators, consist of unreleased resonators, so I mean not suspended, located over a Bragg mirror that reflects back the waves. We will focus on this type.



This is a cross sectional view of an SMR, processed on a high resistivity silicon substrate. You can see the Bragg mirrors here which are made of tungsten plates surrounded by SiO2. The first critical process module consists in depositing an aluminium nitride layer by physical vapor deposition on top of a properly oriented molybdenum bottom electrode. This sputtering technique allows obtaining first, a precise and uniform thickness - have in mind that the resonance frequency is inversely proportional to the thickness - and second, good piezoelectric properties which result in high KT square. The top electrode is also made of molybdenum.

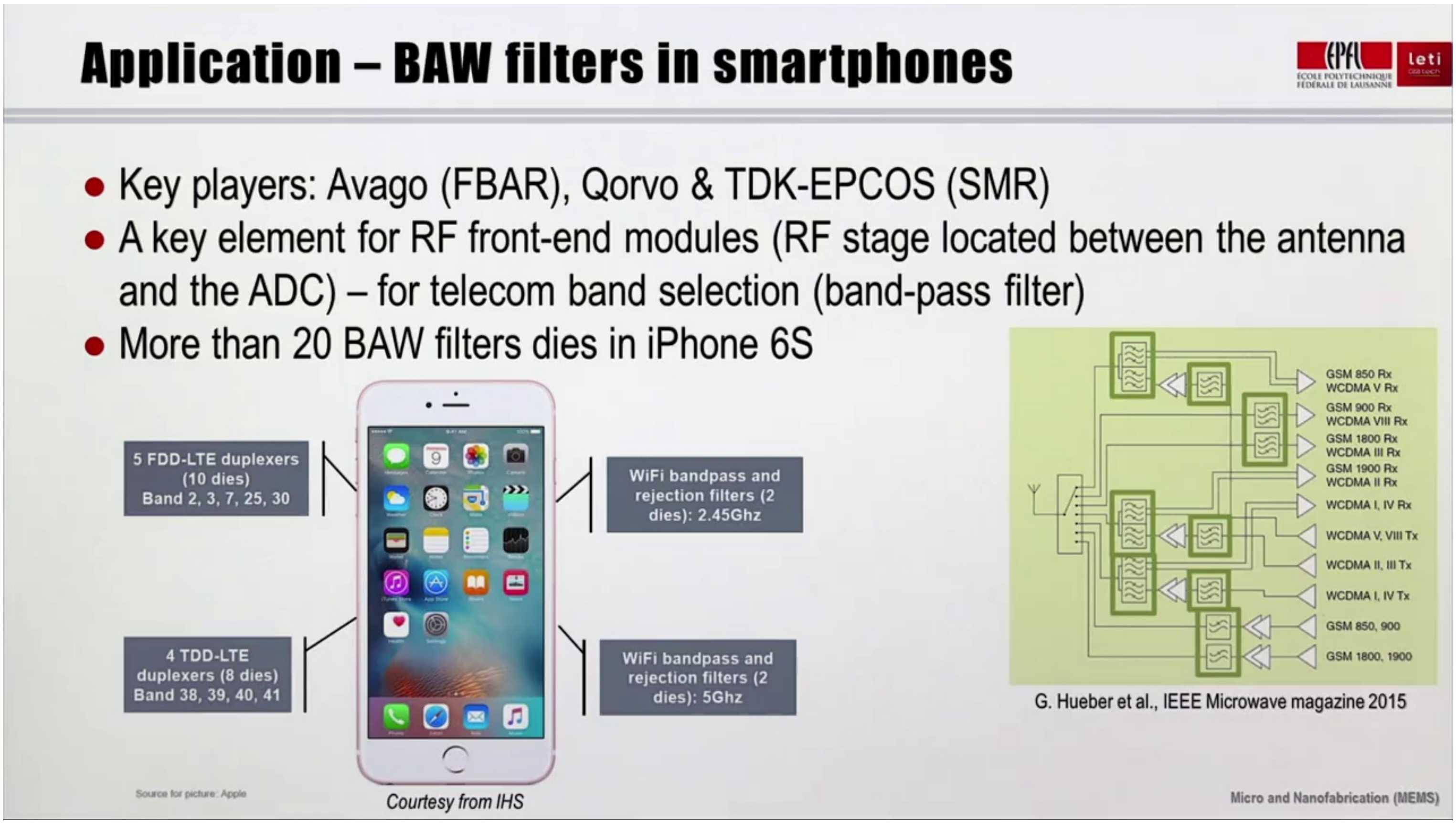


Another important step is the mass loading of shunt resonators. In fact, shunt and series resonators are identical by design. Then, this mass deposition on top of the shunt resonators allows to adequately decrease the resonance frequency so that the antiresonance coincides with the series resonator resonance, as I explained in the previous slide. The second critical process step is wafer-scale ion beam trimming. By locally removing some material, the ion beam allows precisely adjusting the resonance frequencies of each series and shunt resonators. It's indeed very important that each filter has the same bandwidth and center frequency. The resonators have a silicon nitride passivation, in green and are capped with a thin-film packaging, in pink, to provide them with an hermetic and clean cavity at ambient pressure.



This optical microscope image shows the top view of a filter chip at the end of the fabrication process. Basically, the white squares and rectangles are metallic contact pads. And the coloured squares are BAW resonators which have a typical 150 by 150 square micron area. Depending on whether they are mass-loaded or not, I mean series or shunt, the resonator's colour is different.

So let’s talk about application now. First, which MEMS companies sell these kinds of devices? Let’s cite Avago that produces FBARs and Qorvo and TDK-EPCOS that produce SMR’s.



BAW band-pass filters have become a key element of RF front-end modules of smartphones. Such modules are essentially the RF stage located between the antenna and the analog digital convertor. In this context, BAW filters are used to select a given telecom band. In green, you can see all the filters present in this example of front-end module. And for example the iPhone 6S contains more than 20 BAW filters dies either for 4G or LTE connection or for Wi-Fi connection.

I would like to wrap up this lesson. We have analysed 3 examples of commercially successful MEMS devices All these devices have been sold in the hundreds of millions of units and all of them rely on advanced micro and nano fabrication techniques that you will see in the upcoming lessons of this MOOC. Thanks for your attention.