

Course material

Course:

## Micro and Nanofabrication (MEMS)

Video:

### 1.3 Successful MEMS products, III Bulk acoustic wave resonator

Concepts (extracted from automatically generated subtitles):

**Baw resonators. Resonance frequency. State b. Band-pass filters. State e. So-called kt. Example of front-end module. Unit cell. Bulk acoustic wave resonators. State. Important step. Frequency response of the shunt resonator. State c. First mention. Baw stands.**



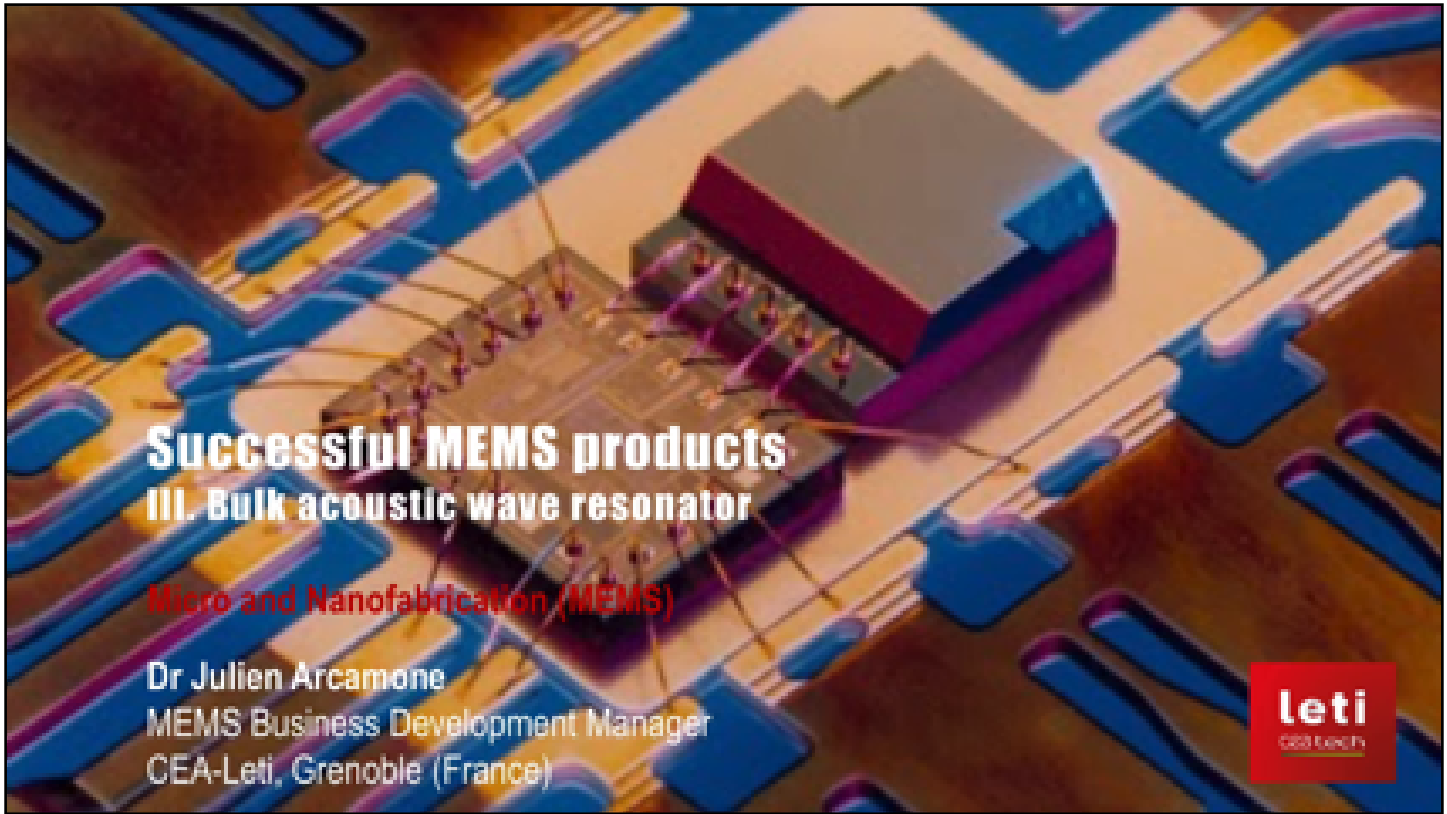
[to video sequence search](#)  
(within Micro and Nanofabrication (MEMS).)



[to video](#)

Center for Digital Education. More educational support material here:

<https://www.epfl.ch/education/educational-initiatives/cede/educational-technologies-gallery/boocs-en/>  
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notes

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summary

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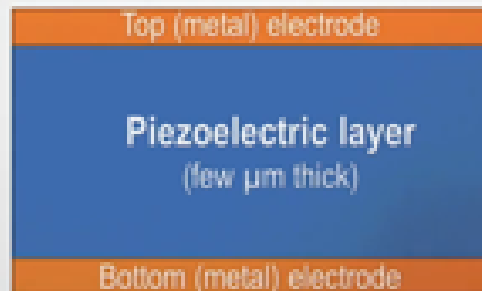


## Example 3: BAW resonators in smartphones

- BAW (Bulk Acoustic Wave resonators) resonators use a **piezoelectric layer (AlN most of time)** sandwiched between two metallic electrodes

- Thickness mode with longitudinal (or shear) vibration:  $f_0 = \frac{1}{2} \sqrt{\frac{E}{\rho}} \frac{1}{t_{Resonator}}$

→ with  $t_{Resonator}$  in the  $\mu\text{m}$  range,  $f_0 \approx 5\text{GHz}$



Longitudinally vibrating thickness mode  
(contraction / expansion of the resonator in the direction of its thickness)

Micro and Nanofabrication (MEMS)

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.

notes

summary

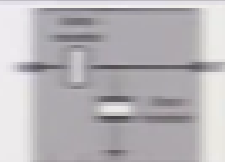
0m 1s



## Filters based on BAW resonators

EPFL

- Unit cell of "Ladder filter" (replicated  $n$  times): 2 BAW resonators



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.

### notes

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### summary

1m 13s



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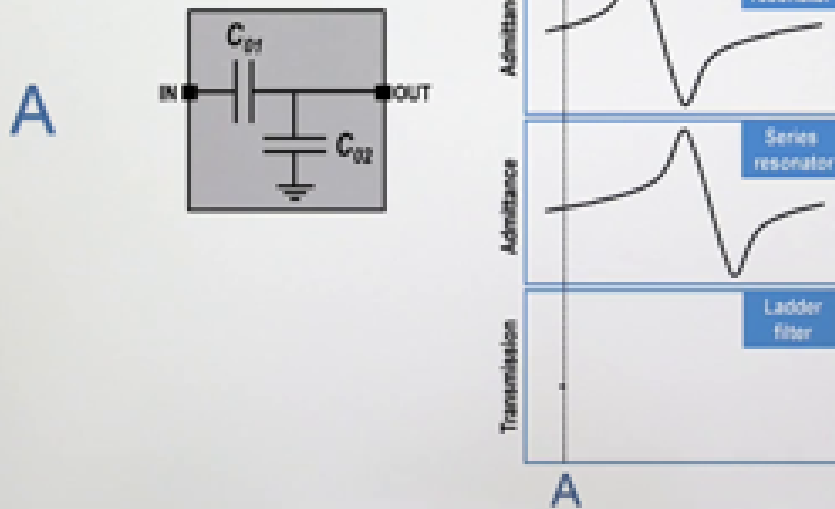
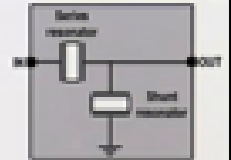
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# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



Mems and Nanofabrication (MEMS)

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.

notes

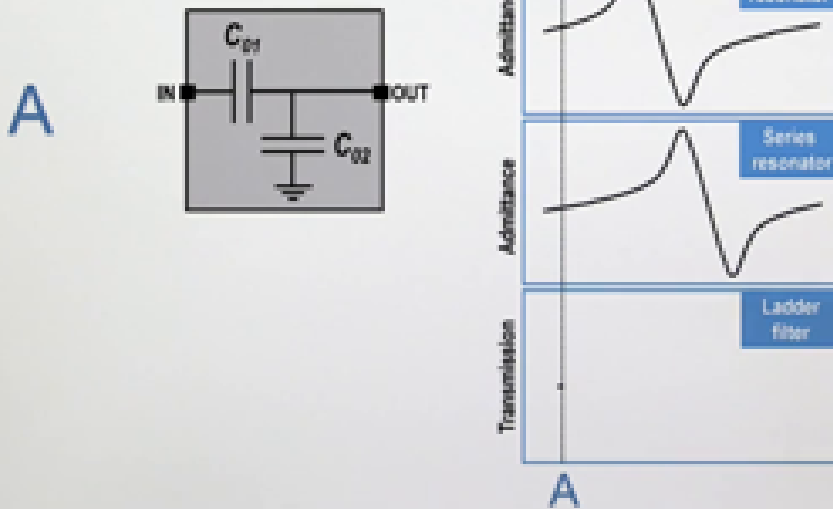
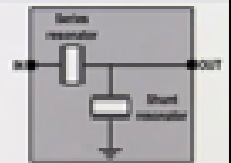
summary

1m 54s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



Micro and Nanofabrication (MEMS)

The one of the series resonator is depicted here and this is the response on the whole filter.

notes

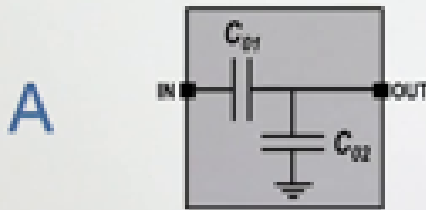
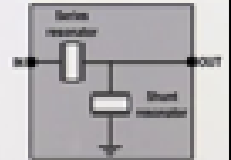
summary

2m 25s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



A

Micro and Nanofabrication (MEMS)

Please note that the shunt resonator

notes

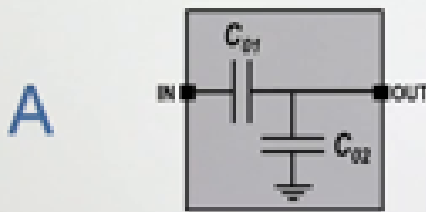
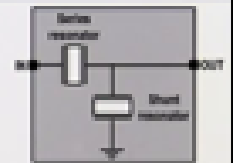
summary

2m 33s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



A

Mems and Nanofabrication (MEMS)

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.

notes

summary

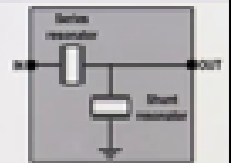
2m 38s



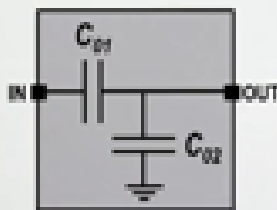


# Filters based on BAW resonators

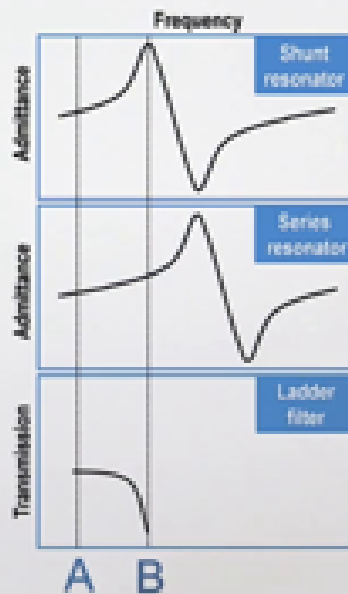
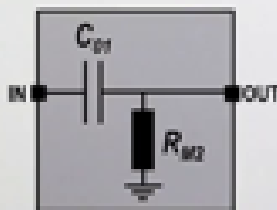
- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



A



B



Micro and Nanofabrication (MEMS)

Therefore, they both behave as capacitors.

notes

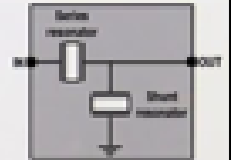
summary

2m 56s

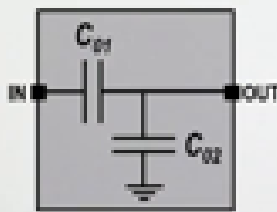


# Filters based on BAW resonators

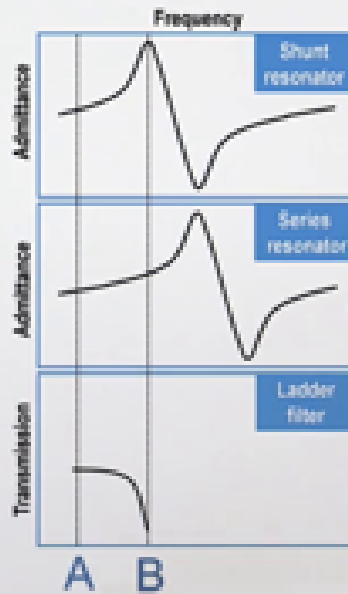
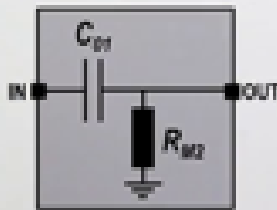
- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



A



B



Micro and Nanofabrication (MEMS)

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

notes

summary

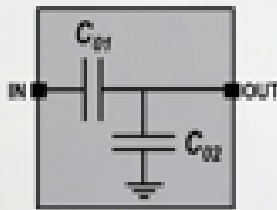
3m 3s



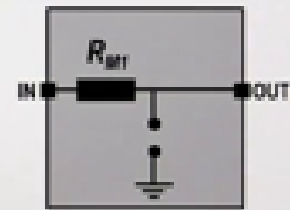
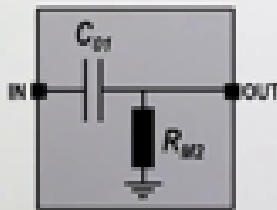
# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response

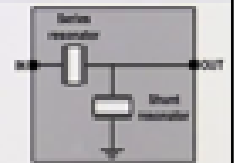
A



B



C



is almost grounded and there is no signal transmission.

notes

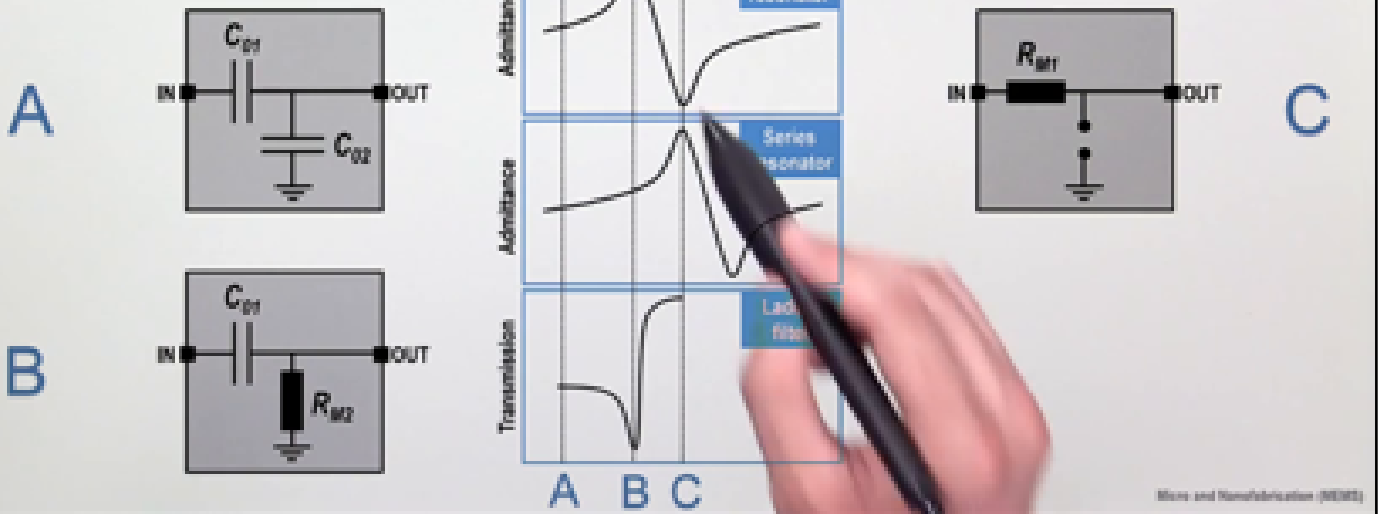
summary

3m 37s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



In state C, the series resonator is at resonance. In other words, its impedance is minimum and of less than 1 ohm.

notes

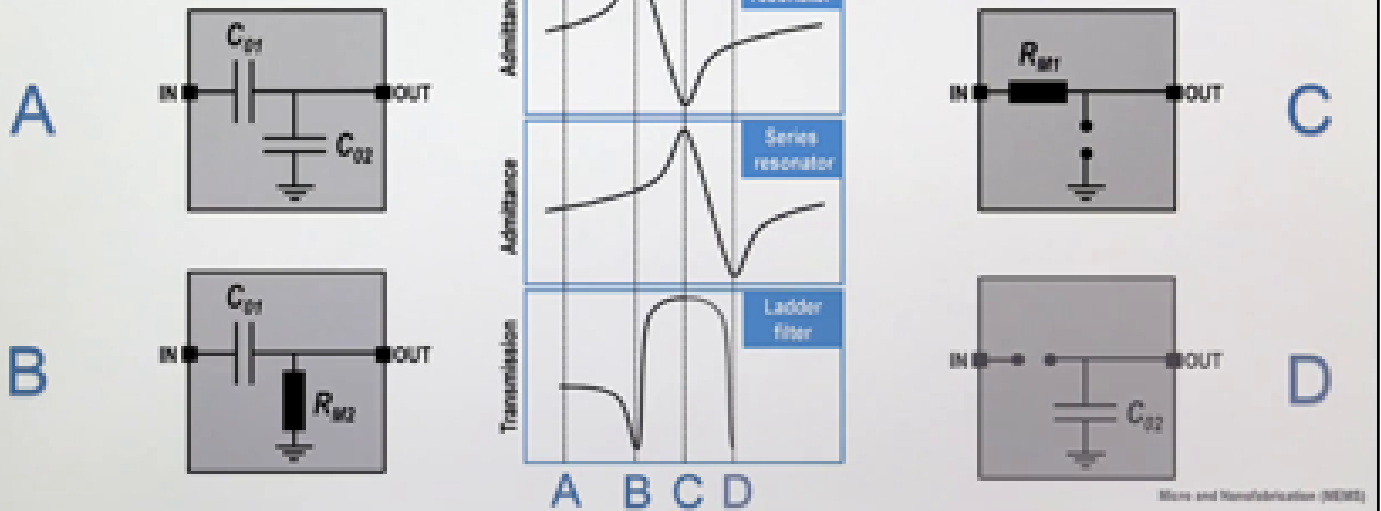
summary

3m 44s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



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.

notes

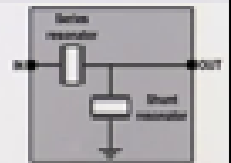
summary

3m 54s

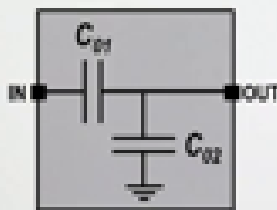


# Filters based on BAW resonators

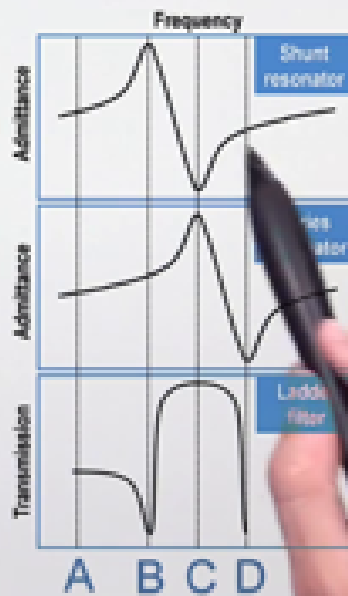
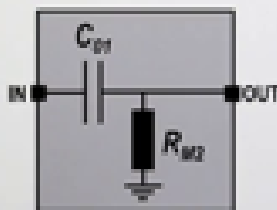
- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



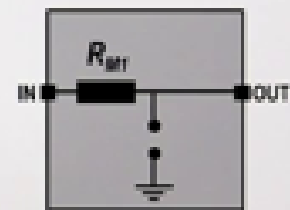
A



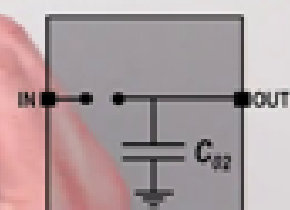
B



C



D



In state D, the series resonator is at its antiresonance, in other words, at its maximum impedance. And it behaves as an open circuit.

notes

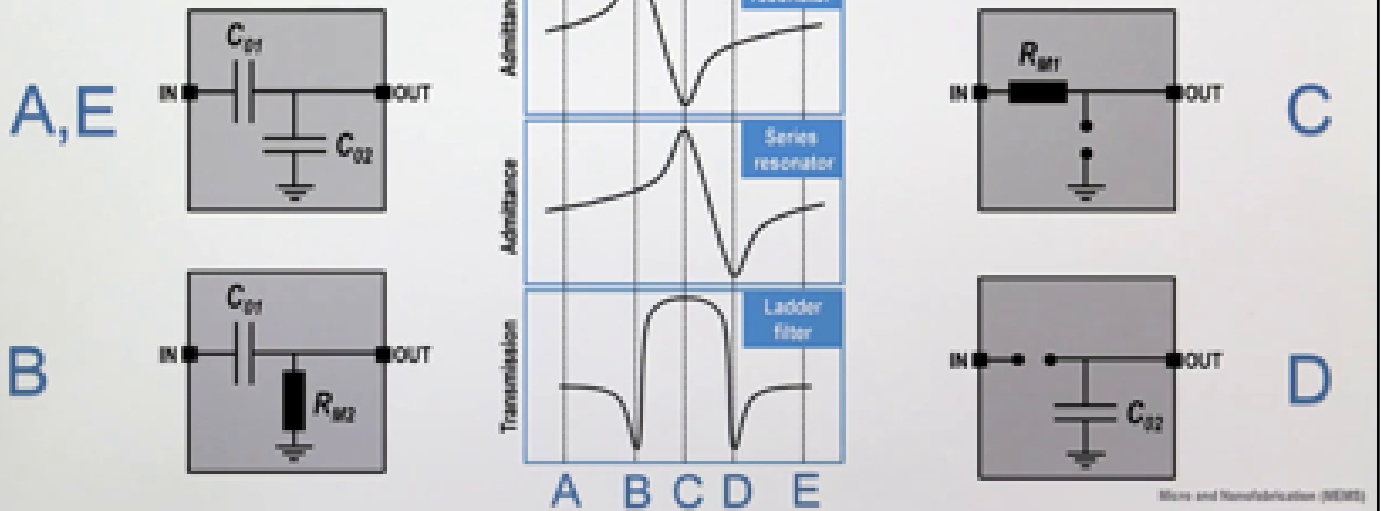
summary

4m 17s



# Filters based on BAW resonators

- Unit cell of "Ladder filter" (replicated n times): 2 BAW resonators
- Ladder filter response



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

notes

summary

4m 30s



# BAW – example of SMR fabrication process

- 2 types of BAW (2 approaches of acoustic confinement): FBAR (suspended resonator over an air gap) and SMR (unreleased resonator over a Bragg mirror)



Micro and Nanofabrication (MEMS)

BAW resonators works.

notes

summary

5m 1s





# BAW – example of SMR fabrication process

- 2 types of BAW (2 approaches of acoustic confinement): FBAR (suspended resonator over an air gap) and **SMR (unreleased resonator over a Bragg mirror)**



Micro and Nanofabrication (MEMS)

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.

notes

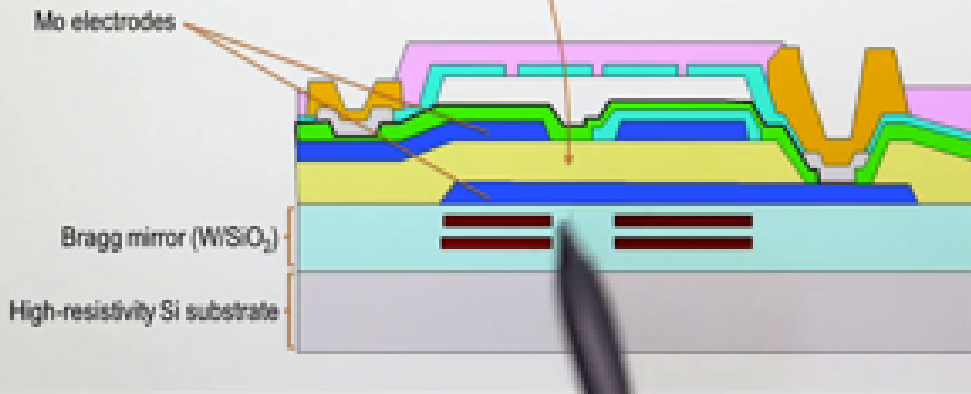
summary

5m 5s



# BAW – example of SMR fabrication process

- 2 types of BAW (2 approaches of acoustic confinement): FBAR (suspended resonator over an air gap) and **SMR (unreleased resonator over a Bragg mirror)**
- **Critical process module n°1:** deposition process (PVD) of the AlN MEMS layer → critical to reach (i) a precise and uniform thickness (inducing  $f_0$ ) and (ii) good piezoelectric properties (inducing  $k_t^2$ )



Micro and Nanofabrication (MEMS)

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 SiO<sub>2</sub>. 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.

notes

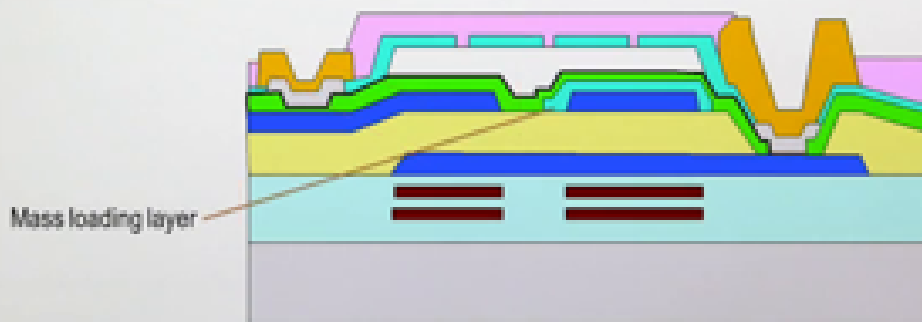
summary

5m 43s



# BAW – example of SMR fabrication process

- All resonators are identical with one exception: some have a loading layer to separate them in frequency to obtain distinct shunt and series resonators



Micro and Nanofabrication (MEMS)

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  $KT^2$  square. The top electrode is also made of molybdenum.

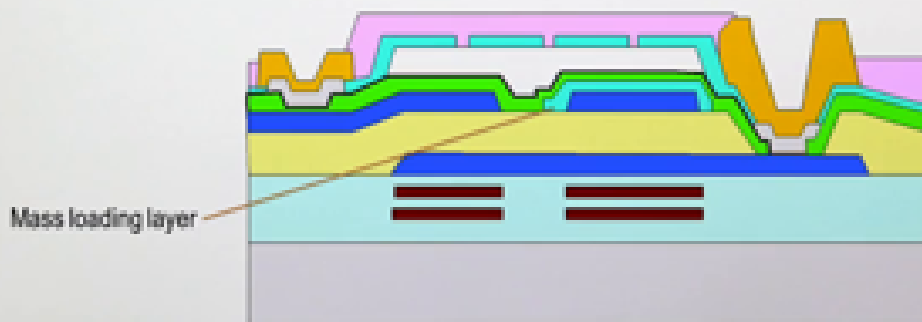
notes

summary

6m 13s



- All resonators are identical with one exception: some have a loading layer to separate them in frequency to obtain distinct shunt and series resonators



Micro and Nanofabrication (MEMS)

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

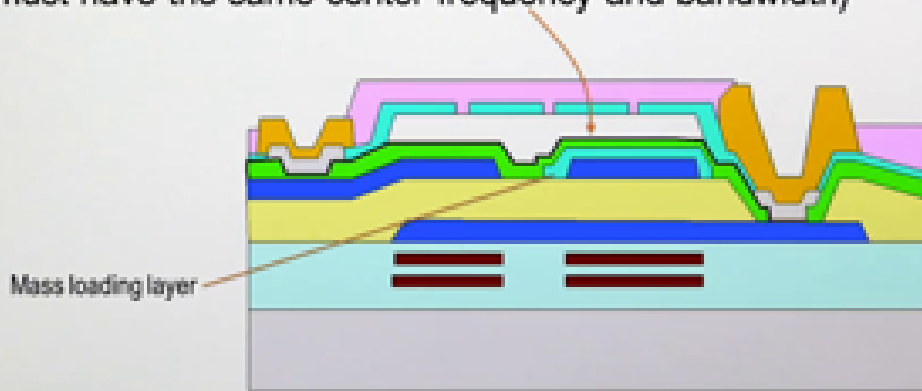
notes

summary

6m 38s



- All resonators are identical with one exception: some have a loading layer to separate them in frequency to obtain distinct shunt and series resonators
- **Critical process module n°2: wafer-scale ion beam trimming**  
→ local removal of material on each resonator to adjust  $f_0$  if needed (all filters must have the same center frequency and bandwidth)



Micro and Nanofabrication (MEMS)

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.

notes

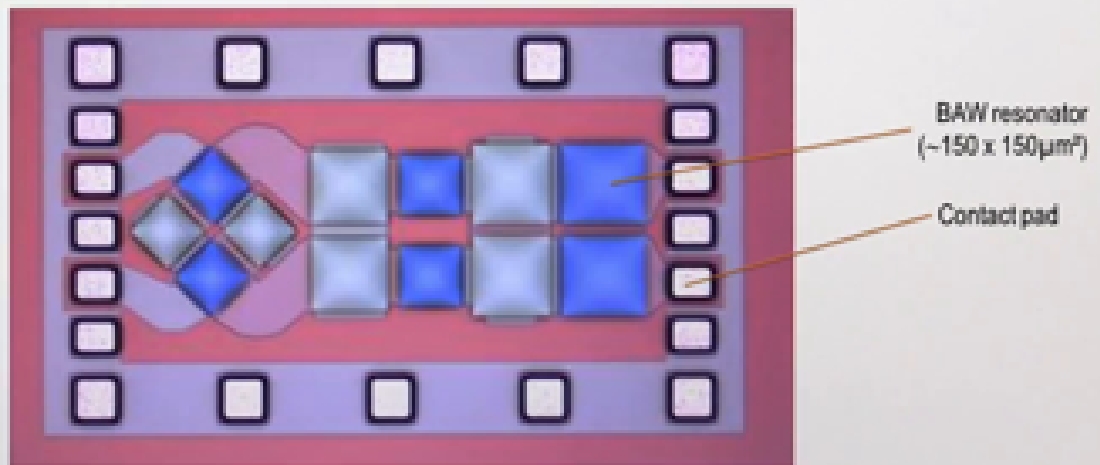
summary

6m 58s



## • Top view of a filter

- One square = one resonator
- Depending on whether they are mass loaded or not (series or shunt), the resonators color is different



Micro and Nanofabrication (MEMS)

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.

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7m 25s



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Biology and Microbiology (2003)

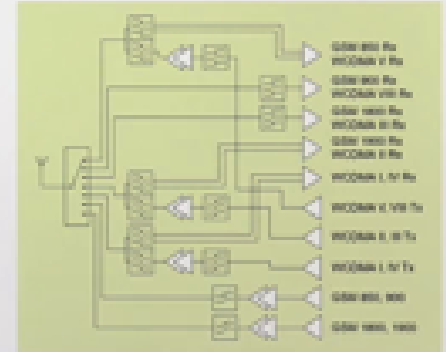
notes

7m 45s



# Application – BAW filters in smartphones

- Key players: Avago (FBAR), Qorvo & TDK-EPCOS (SMR)
- A key element for RF front-end modules (RF stage located between the antenna and the ADC) – for telecom band selection (band-pass filter)



Courtesy from IHS

Micro and Nanofabrication (MEMS)

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

notes

summary

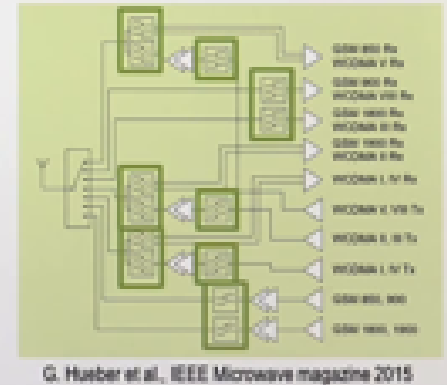
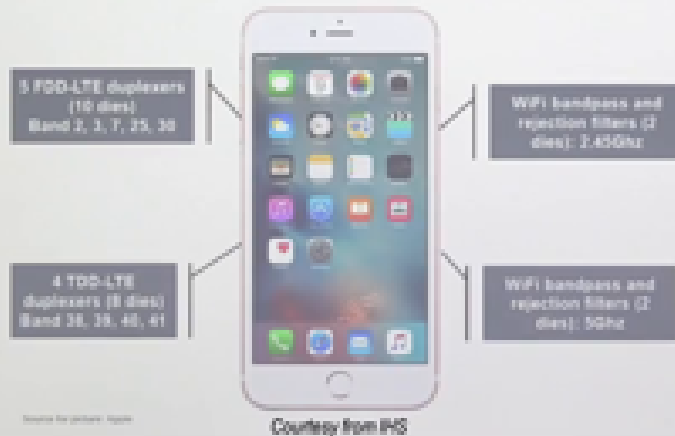
8m 18s





# Application – BAW filters in smartphones

- Key players: Avago (FBAR), Qorvo & TDK-EPCOS (SMR)
- A key element for RF front-end modules (RF stage located between the antenna and the ADC) – for telecom band selection (band-pass filter)
- More than 20 BAW filters dies in iPhone 6S



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.

notes

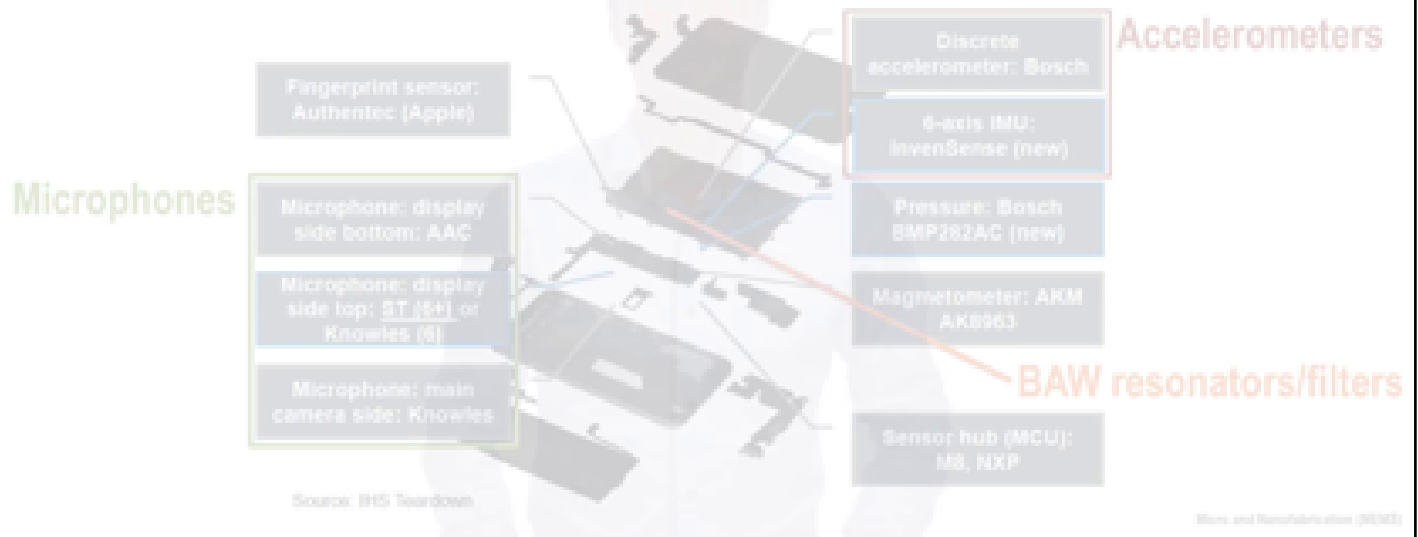
summary

8m 37s



# Successful MEMS products that we use every day

- MEMS are now ubiquitous in our daily life
- 3 focuses in this course



And for example the iPhone 6S contains more than 20 BAW filters dies either for 4G or LTE connection or for Wi-Fi connection.

notes

summary

9m 5s



# Successful MEMS products that we use every day

- MEMS are now ubiquitous in our daily life
- 3 focuses in this course
- Sophie Giroud, Guillaume Jourdan (Accelerometers)
- Stephanus Louwers (Microphones)
- Alexandre Reinhardt (BAW)

## Microphones

- Jérémie Bouchaud

- Dave Monk

NB: NXP and Freescale have merged on 7 Dec 2015, under the company name NXP.

Source: IHS iTechner

Micro and Nanofabrication (MEMS)

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.

## notes

## summary

9m 20s

