Advanced MEMS and Microsystems

Dr. Danick Briand & Prof. Guillermo Villanueva

Practical Aspects: Info on lecturers

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6 Guests lecturers
Industrial seminars

Lecture content

1. Practical aspects of the course (live)

- Course position and structure
- Schedule
- Content
- Evaluation

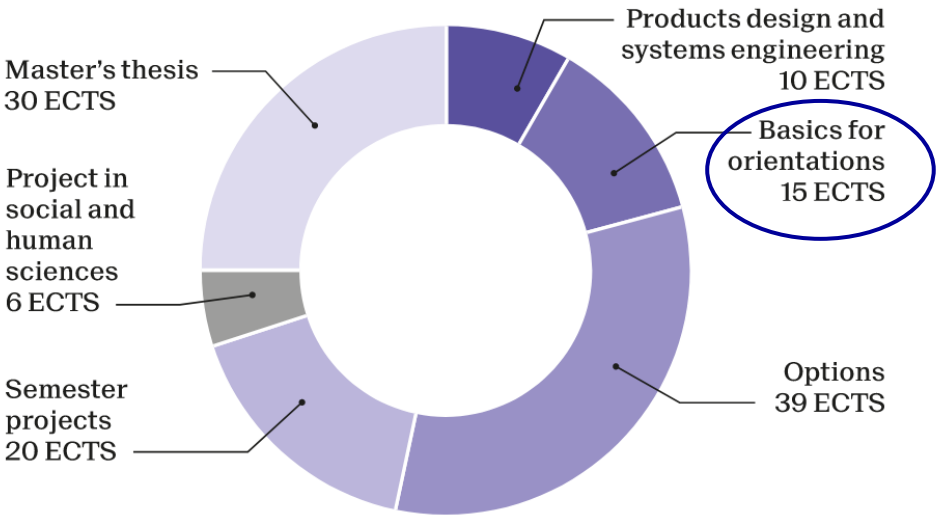
2. Introduction to MEMS and trends in the field (live)

- What are MEMS's and why are they used ?
- Where do you „find" MEMS?
- What is possible now?
- Where are we going and what can we expect in the future?

3. Transducing principles: Pre-recorded lectures to watch

Position of the course in the Master program

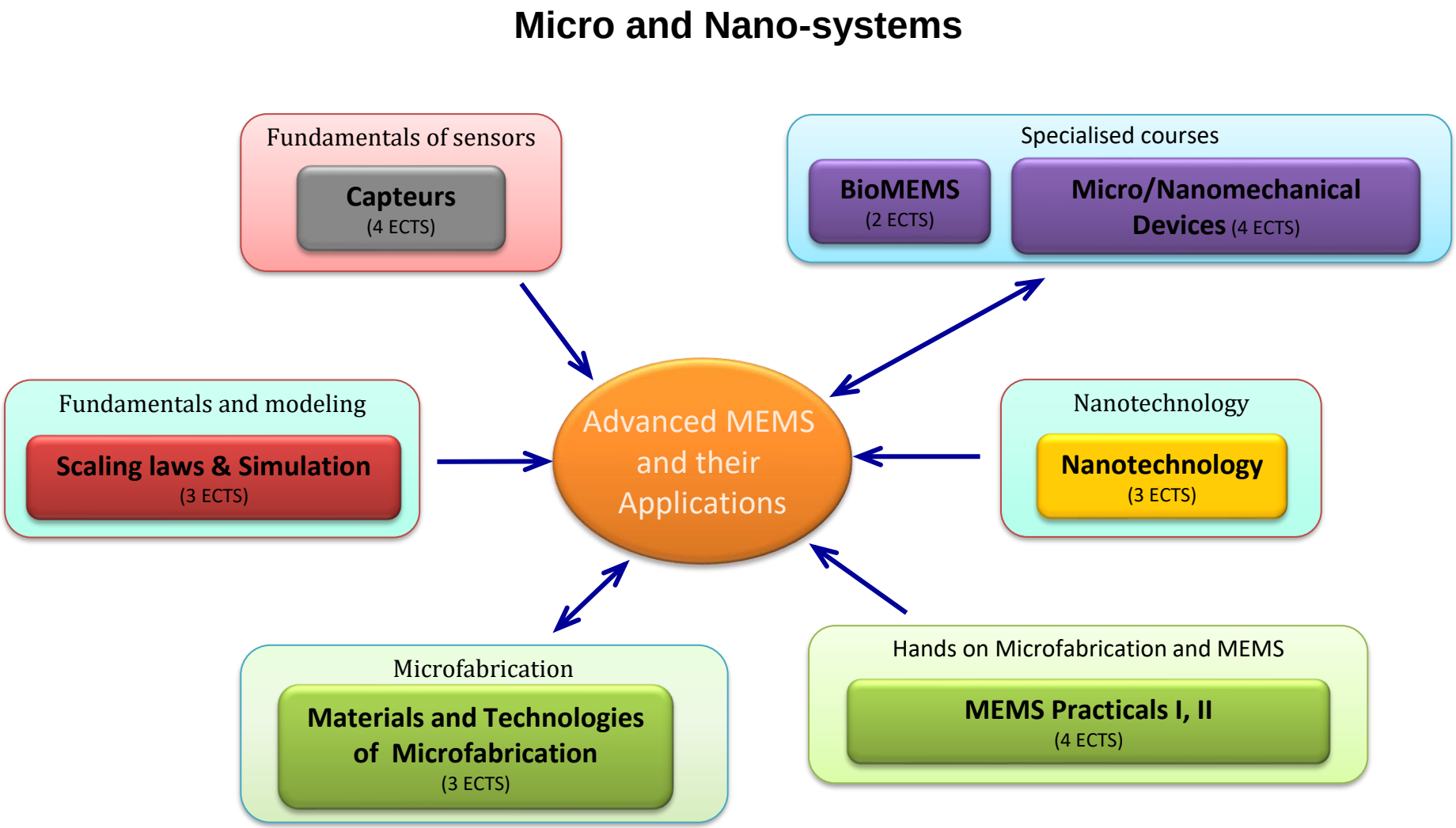
- **Basics for orientations in the Master program in Microengineering**



	Orientations			Credits
Basics for orientations	**A**	**B**	**C**	**15**
Advanced MEMS & microsystems		B		3
Applied and industrial robotics			C	2
Applied machine learning	A	B	C	4
Apprentissage et intelligence artificielle	A	B	C	4
Fundamentals & processes for photovoltaic devices	A	B	C	3
Imaging optics	A			3
Introduction to additive manufacturing			C	3
Laser fundamentals and applications for engineers	A	B		3
Manufacturing systems and supply chain dynamics			C	3
Materials processing with intelligent systems			C	3
Metrology	A	B		3
Micro/Nanomechanical devices		B	C	4
Nanotechnology	A	B		3
Optical design with ZEMAX	A			3
Optical detectors	A	B		3
Scaling laws in micro & nanosystems		B		2
Selected topics in advanced optics	A			3
Smart sensors for IoT		B	C	3

- 3 h / week on Tuesday 10:15 – 13:00
- Number of ECTS: 3
- Evaluation: Oral examination + Presentation + Seminars

Position of the course in the Master program



Prerequisites

Basic knowledge on:

- Sensors
- Transducing principles
- Microfabrication techniques and processes

As complement available on the Moodle:

- Recorded lecture and slides on Transducing principles
- Slides on Microfabrication for MEMS and Scaling laws

Alternatively and as extra readings:

- Find the course notes from other Bachelor and Master courses (Capteur, Microfabrication)
- Books on sensors and MEMS microfabrication (see slide 15 for references)

Learning outcomes

- Explain the operation principles of advanced micro- and nanosystems
- Describe the technology to develop advanced micro- and nanosystems
- Apply a concept of a micro- and nano-device into a real device considering the scaling laws and boundary conditions involved
- Present the basics of implementation of MEMS into products
- List the trends in the sensors and MEMS field

Course content

	Commercial trends	R&D trends
MEMS Sensors	x	x
MEMS Actuators	x	x
Optical MEMS	x	x
RF-MEMS	x	x
MEMS Resonators	x	x
NEMS	x	x
Thermal & Gas Sensors	x	x
Packaging – 3D integration	x	x
Energy harvesters	x	x
Power MEMS	x	x

Course content and schedule

Dates	Topics	Lecturers
18.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva
25.02	Sensors part I Exercices	D. Briand
04.03	Sensors part II Industrial seminar #1	D. Briand
11.03	Students presentations	D. Briand / G. Villanueva
18.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand
25.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva
01.04	RF-MEMS	G. Villanueva
08.04	NEMS	G. Villanueva
15.04	Interactive session	D. Briand / G. Villanueva
29.04	Thermal and gas sensors Industrial seminar #4	D. Briand
06.05	Packaging	D. Briand
13.05	Packaging Industrial seminar #5	D. Briand
20.05	PowerMEMS Industrial seminar #6	D. Briand
27.05	Quiz + oral exam instructions Evaluation of the course	All

Course support and evaluation

Format

- Courses will be given as PPT presentations LIVE in class

Moodle

- Course notes available in PDF format
- Links to the Recorded lectures during Covid time*
- Template for the students presentations and information about the seminars

Evaluation

- 10% for your presentation on a MEMS device on March 11th
- 10% on your answers to the questions for the seminars
- 80% Individual oral examination to happen in June-July 2025

* As a support but not replace the lectures in class, which are changing from year to year

Oral examination

- **20 minutes** examination
- **2 questions** to be randomly picked in a set of 27 questions
- The **list of questions** to be prepared is available **on the moodle**
- The examination can involve references to the **Industrial seminars**

Students presentations

- **5 min presentation by Team of 2 students** on an Advanced MEMS Device
- Requires homework during these first weeks
- Content: **Focus on MEMS devices in commercial products**
  - Historic and status (of the MEMS device only)
  - Operation principle
  - MEMS implementation
  - Characteristics (via data sheets)
  - Packaging & system integration
  - Products and current applications
- 6 slides (1 per bullet point): Use the template available on Moodle
- Selection of your device by team of **2 students** via this google drive link: Link for topics selection
- **Date: 11th of March**

Student presentations – choice of topics

Topics	Research / Commercial		Topics	Research / Commercial
MEMS / Microsystems			**NEMS**	
Accelerometer	Commercial		Hollow cantilever	Research
Gyroscope	Commercial		Surface stress bio-measurements	Research
Pressure sensor	Commercial			
Magnetometer for compass	Commercial		**Optical MEMS**	
Microphone	Commercial		Interference Modulation Display	Commercial
Flow sensor	Commercial		Shutter Display	Commercial
Inkjet print head	Commercial		Tunable Infrared Detector	Commercial
Metal-oxide gas sensor on Si	Commercial		Pico Projector Displays	Commercial
Humidity sensor	Commercial		Grating Light Valve	Commercial
Integrated atomic force probe	Commercial		2 x 2 Fiber Optic Switch	Commercial
Analytical Gas Detector Preconcentrators + uGC + sensors	Research + commercial		Optical Cross Connects	Research / Comm
Piezoelectric energy harvester on Si	Research		Variable Optical Attenuator	Research
Microfabricated thermoelectric energy harvester	Commercial		Silicon Photonic MEMS Switches	Research
RF Switches	Commercial		Shutter Array (James Webb Space Telescope)	Research
Duplexer	Commercial			
MEMS oscillator for clocks	Commercial			
CMUT & PMUT ultrasonic transducers	Commercial			
Ultrasound fingerprint sensor	Commercial			
MEMS speaker	Commercial			

See OneDrive for all topics: OneDrive link for topics selection

Industrial seminars

Date	Title	Speaker
04.03.2025	Safran Navigation & Timing: High performance MEMS inertial sensors	Nadège Frantz, **Safran Sensing Technologies**
18.03.2025	Optical MEMS – the renaissance of Mechanics in a watchmaking country	Cornel Marxer **Sercalo**
25.03.2025	Sensirion: From ETH start-up to global leader in environmental and flow sensing	Lukas Bürgi **Sensirion**
29.04.2025	APIX: NEMS based gas chromatograph	Eric Colinet **APIX analytics**
13.05.2025	Packaging and hybridization: The valorization of MEMS technologies	Michel Despont **CSEM**
20.05.2025	Triaxis, a 3D magnetometer for human-like manipulation	Théo Le Signor **Melexis**

Mandatory: Absence needs to be justified by email to Danick Briand !

- 30 minutes + 15 minutes for discussion
- A list of questions and answer form are available on moodle
- **Answers to questions are due the week after at the latest** (if not, grade = 1)
- **Content of seminars + their questions will be part of the final oral exam**

Course content and structure: References Books

MEMS, Microfabrication and Microsystems

- Stephen Senturia (Editor in chief), MEMS Reference Shelf, Springer, 2010 and later.
- Advanced Micro & NanoSystems, Wiley-VCH book series, 10 volumes, 2004 and later
- Gregory T.A. Kovacs, Micromachined Transducers Sourcebook, McGraw-Hill, 1998, 911 pp.
- Marc Madou, Fundamentals of Microfabrication and Nanotechnology, 3rd Edition, CRC Press, 2011
- Sami Franssila, Introduction to Microfabrication, John Wiley & Sons, 2004, 402 pp.
- Julian W. Gardner, Microsensors: Principles and Applications, John Wiley & Sons, 1994, 331 pp.
- S.M. Sze, Semiconductor Sensors, John Wiley & Sons, 1994, 550 pp.
- Ljubisa Ristic, Sensor Technology and Devices, Artech House, 1994, 524 pp.

Web / Online

- MEMS Express by MNX Foundry: www.mems-exchange.org
- MEMS Journal; weekly Newsletter: http://www.memsjournal.com/
- MEMS industry group https://www.semi.org/en/communities/msig
- www.memsnet.org
- http://www.findmems.com

Course content and structure: MEMS Glossary

https://www.memsnet.org/glossary/

Course content and structure: Journals and Conferences

Scientific journals

- Journal of Micro-Electro-Mechanical Systems, IEEE
- Journal of Micromechanics and Microengineering, IOP
- Sensors and Actuators A and B, Elsevier
- IEEE Sensors Journal, IEEE
- Smart Materials and Structures, IOP
- Analytical Chemistry, ACS
- Lab on Chip, RSC
- Journal of the Electrochemical Society, ECS…

Selection,…
by far not complete!

There are many national and regional events and journals.

Conferences

- MEMS
- Transducers
- Eurosensors
- IEEE Sensors Conference
- IEEE Optical MEMS and Nanophotonics
- SPIE Photonics West – MEMS & MOEMS
- International Meeting on Chemical Sensors (IMCS)
- Micro and Nano Engineering (MNE)
- Micromechanics Europe (MME)
- PowerMEMS
- MicroTAS
- Society meetings: Electrochemical Society (ECS) and Material Research Society (MRS) …

LESSON 1 – INTRODUCTION

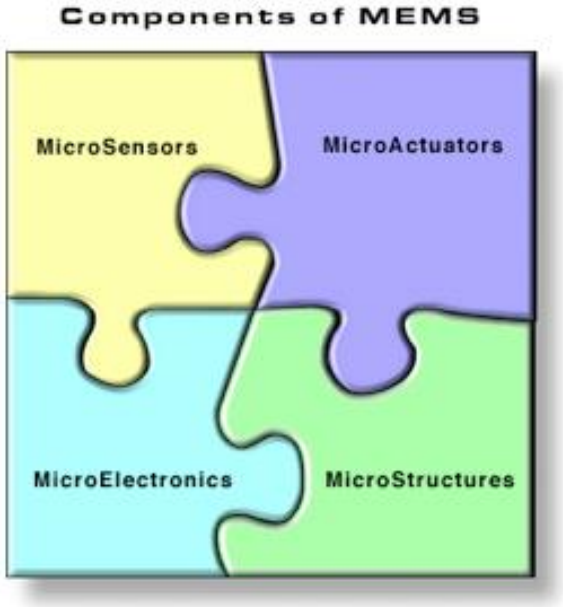
Dr. Danick Briand

Introductory video to MEMS

https://www.youtube.com/watch?v=CNmk-SeM0ZI

MEMS: Micro-Electro-Mechanical Systems

« MEMS is the integration of mechanical elements, sensors, actuators, and sometimes electronics, on a common substrate (Si, glass, plastic) through microfabrication technology. The micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the wafer or add new structural layers to form the mechanical and electromechanical devices. »



Micro-Electro-Mechanical Systems:

Miniaturised devices with other functionalities than purely electronic

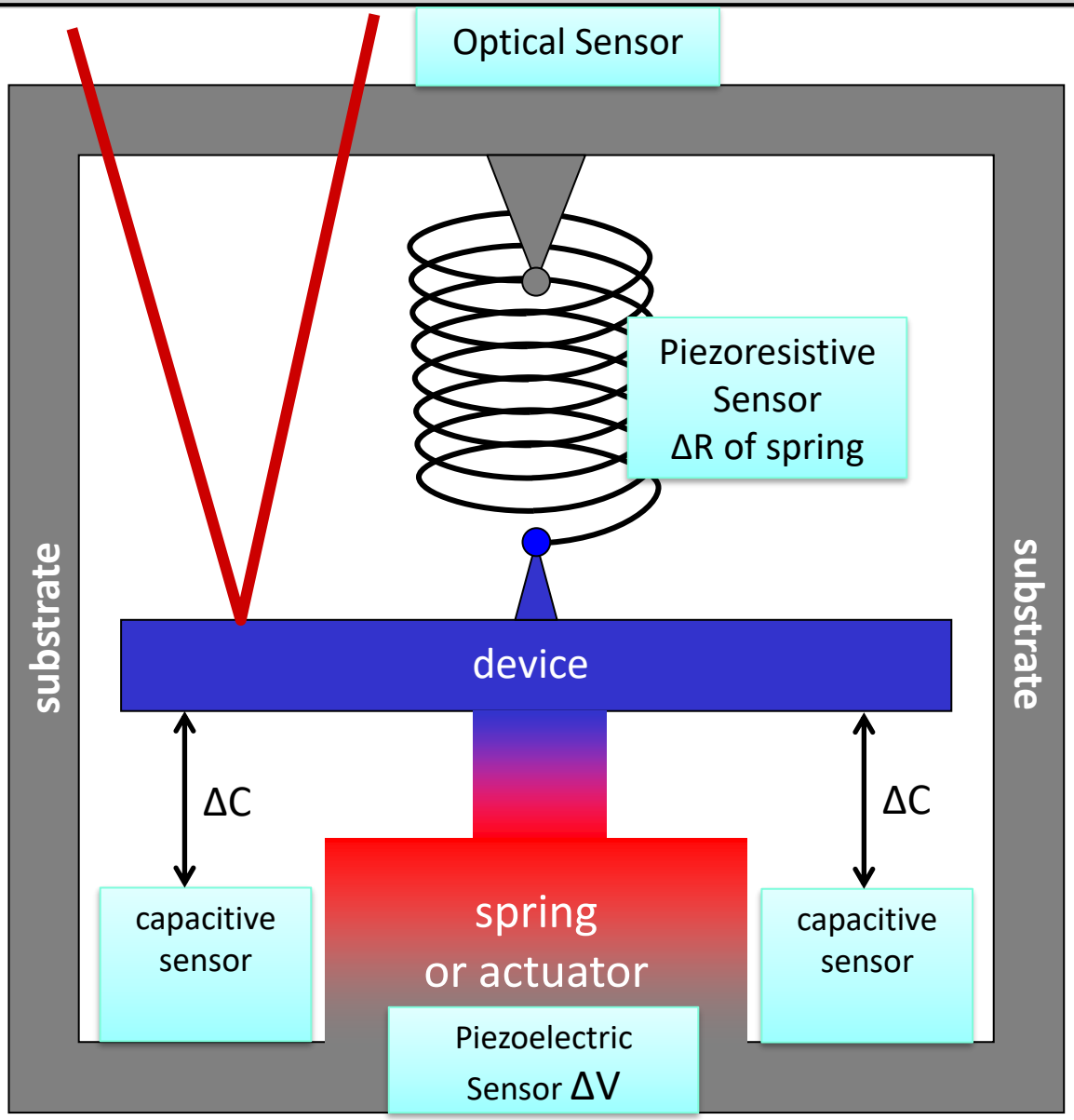
General operating principle:

- In general, the systems requires initiation using electro-mechanical transducers (actuator) or external pertubation for its actuation
- The mechanical movement (static or dynamic) which is generated is transformed in an electrical quantity via an electro-mechanical transducer for detection
- By essence, it is a multi-physics system which combines different fields of science and engineering

MEMS intro : MEMS Actuator & Sensor: General Concept

MEMS Elements

1. Device (mass, mirror, etc)
2. Actuator (one-way)
   - **Electrostatic**
   - **Magnetic**
   - **Piezoelectric**
   - **Thermal**
3. Restoring force (spring)
4. Sensor for position detection
   - **Piezoresistive**
   - **Capacitive**
   - **Piezoelectric**
   - **Optical**



MEMS intro: Microsystems Definitions

- The term MEMS is used frequently, but many organizations use the term *"Microsystems"* or the acronym *MST* for *MicroSystem Technology*.

- Microsystems/MST has a significantly broader meaning than MEMS. While devices fabricated with IC technology that include moving or moveable parts for actuation or sensing are of course included, so are other categories of very compact device types where shape is critical to functionality, including both passive and active devices having no mechanical parts.

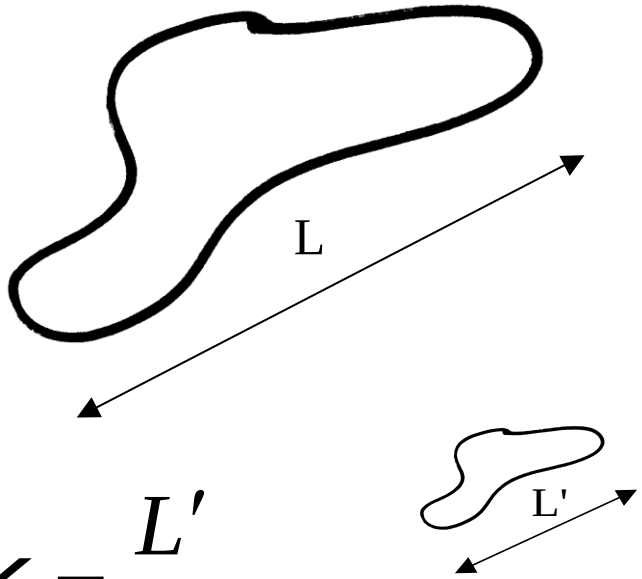
- The field of MST also includes work that seeks to incorporate such devices into highly compact systems.

MEMS intro: Why Microsystems / MEMS ?

- **Increased functionalities compared to ICs with sensing and actuating**
- **Size**
  - benefit of scaling effects
    - higher sensitivity, faster, better performances, low power consumption
  - less materials
  - reduced reagents consumption
  - portable devices
- **Device characteristics**
  - faster process:
    - shorter distances
    - molecular diffusion (mixing)
  - parallel detection (array of sensors and/or actuators)
  - improved system performance
  - lower power consumption
- **Technology**
  - batch fabrication => mass production (costs savings)
  - higher integration
  - reproducibility
  - reliability

Scaling laws

- Mechanics and physics rules are the same as the macro scales (not or a few quantum effects), it is the relative importance of the forces that are modified



$$K = \frac{L'}{L}$$

Magnitude	Scaling factor
length (*L*)	K
area (*A*)	K^2
volume (*V*), i.e. mass (*m*)	K^3
surface to volume ratio	K^{-1}
stiffness (*k*)	K
resonance frequency (f_0)	K^{-1}
mass responsivity (*R*)	K^{-4}
thermal time constant (τ)	K

MEMS Intro: Why Silicon for MEMS ?

Physical Property	Silicon	Steel
Thermal expansion (10^{-6} /°K)	2.6	12.0
Density (g/cm^3)	2.33	8-9
Young's Modulus (GPa)	170*	210
Poisson's ratio	0.42*	0.30
Shear Modulus (GPa)	57*	80
Microhardness (kg/mm^2)	~1200*	300 – 1000
Ultimate strength (GPa)	7*	0.5 – 2.0

- Strong
- Light weight
- Single crystal
- Micromachinable

→ Low moment of inertia
→ Low mechanical loss
→ Brittle, but elastic

** depending on the crystallographic orientation*

MEMS intro: Silicon Technology in Swiss Mechanical Watches

Silicon escapement wheels and anker

Silicon Hairsprings

Silicon balance wheel

photos: CSEM, Patek Philippe

MEMS Intro: Why Silicon for MEMS ?

- **Good mechanical properties**
  - The elasticity of Si is comparable to that of steel
  - Stiffer than steel due to its low density
  - Lighter than aluminium
  - Low cost, high reliability

- **Good electrical properties**
  - Can be doped $\Rightarrow$ Piezoresistive
  - Dielectrics available
    - SiO_2 : thermally grown or vapor deposited (CVD), and Si_3N_4 (CVD)
    - These two silicon compounds (silicon nitride, silicon oxide)have excellent physical and chemical properties for surface micromachining

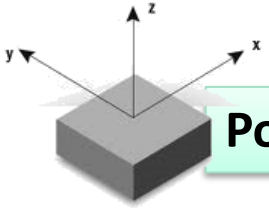
- **Good chemical properties**
  - Single crystal or polycrystalline
  - Easily etched and anisotropic etching possible

MEMS intro: Sensors, What can be measured ?

Over the past several decades MEMS researchers and developers have demonstrated an extremely large number of microsensors for almost every possible sensing modality

Temperature

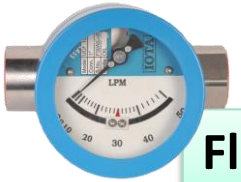
Pressure



Position

Magnetic fields

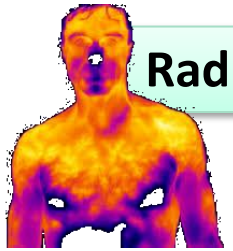
Humidity



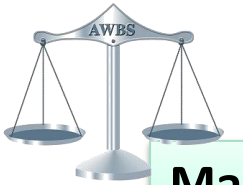
Flow

Soundwaves

Surface stress



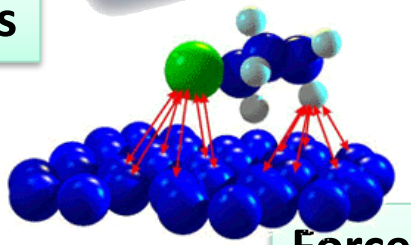
Radiation (IR)



Mass

Inertial forces

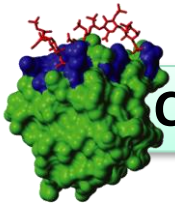
(acceleration – angular rate)



Forces

Magnetic
Van der Waals
Coulomb
…

Proximity



Chemical Species

Etc …

MEMS intro: Actuators, What can be actuated ?

- optical switches and mirrors to redirect or modulate light beams
- independently controlled micromirror arrays for displays
- microbeams for RF signal switches (on/off)
- microresonators for a number of different applications
- microvalves for control of gas and liquid flows
- micropumps to develop positive fluid pressures
- microflaps to deliver drugs
- …

MEMS intro: Sensors and Actuators Overview

SENSORS

Movement
- Accelerometers
- Gyroscopes
- Magnetometers
- IMUs (6 to 9 DOF)
- Pressure
- Sound and ultra sonic

Environment
- Gas
- Humidity
- Particles
- Temperature

Optical sensors
- FTIR
- Fingerprint
- PIR & thermopiles
- Hyperspectral
- ALS, RGB
- Micro bolometers
- Vision
- 3D sensing

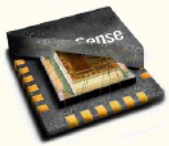
"closed" package 6 to 9+ DOF combos

"open" package environmental combos

Possible integration with environment combos

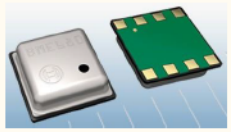
Optical combos

Possible integration with opto combos



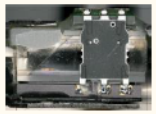
InvenSense MPU9250

ST pressure sensor


Bosch BME680


Infineon microphone

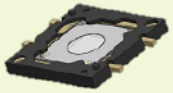

FLIR Lepton One


Apple dot projector

ACTUATORS

Optical MEMS
- Micromirrors
- Auto-Focus
- Optical benches


Texas Instruments DLP


poLight AF

Microfluidics
- Ink jet heads
- Drug delivery
- Biochips


Debiotech micro pump

RF
- Switch
- Filter
- Resonator


Avago-Broadcom FBAR Filter


SiTime oscillator

Micro structures
- Micro tips
- Probes
- Watches components


Spiromax Patek Philippe

- µspeakers

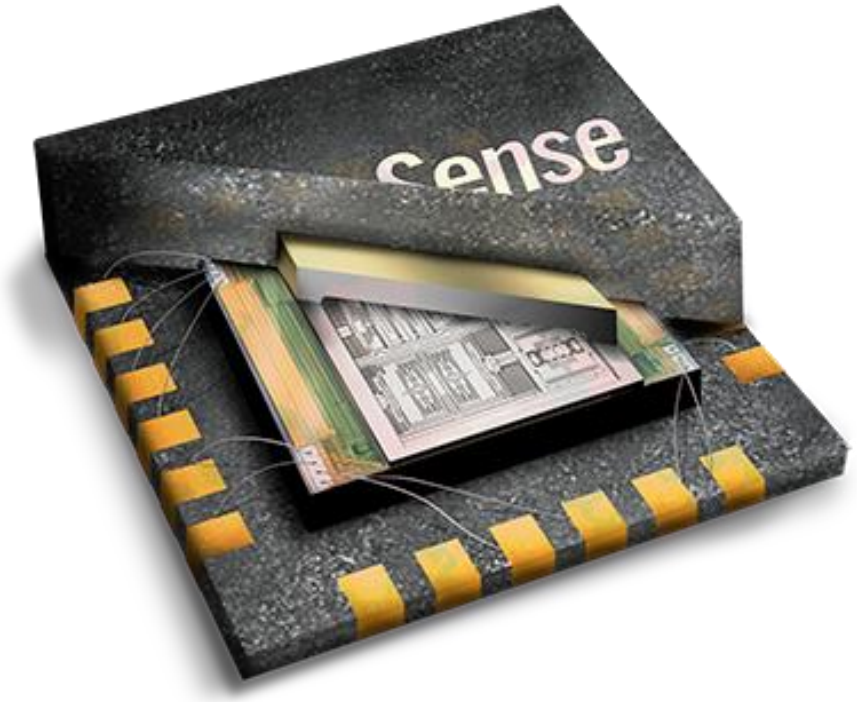

Audio Pixels MEMS-based speaker

- Ultra sonic fingerprint

Qualcomm fingerprint sensor

What is a MEMS in terms of product?

A MEMS chip + an ASIC (Application Specific Integrated Circuit)
everything integrated in an packagage



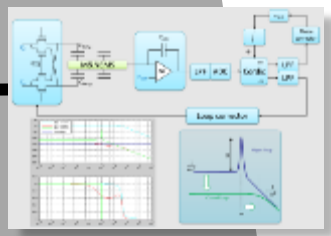
- MEMS price for the consumer market: about 1 US$
- Roughly 1/3 of the cost for the MEMS chip, 1/3 for the ASIC, 1/3 for packaging, the packaging itself, and the test of the component

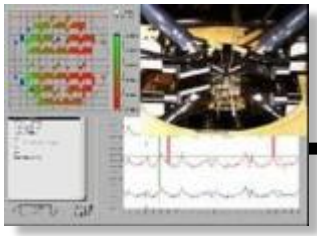
MEMS intro: From a Chip to a MEMS Component

Prototyping

Assembling 3D

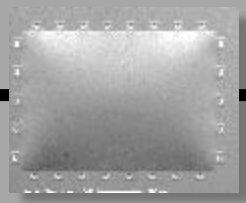
Design ASIC

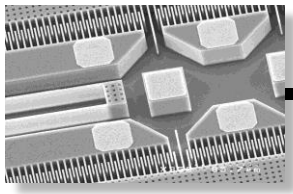




Characterization

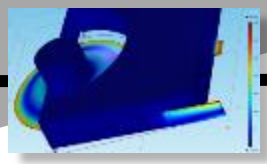
Packaging WLP & TFP

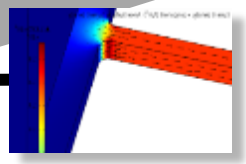




Fabrication technologies

MEMS Design





From CEA-LETI

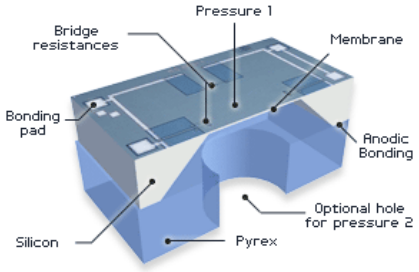
The paradigme « One product, one process »

- Far from the standardization of CMOS technologies
- Not (yet?) a generic platform for multi-sensors

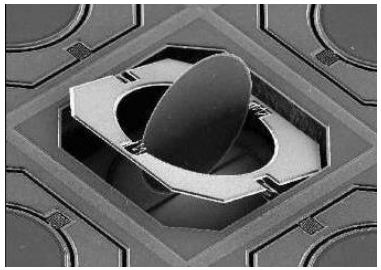
No CAD tools fully integrated (EDA)

- It exists Design Kits (DK) for the layout but no software with all the design integrated (such as Spice or equivalent)
- Design particular to MEMS with combination of analytical (ex. Matlab) and finite element methods (ex. ANSYS, COMSOL)
- Some actors like SoftMems and Coventor are proposing partially integrated environments (Design via device simulation & electronics, Process simulation)

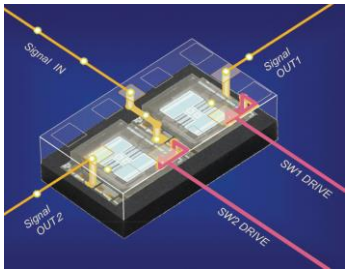
MEMS Intro: Microsystems Device Categories



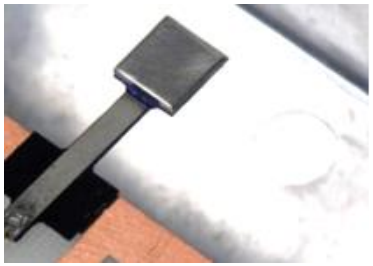
"Classical" MEMS



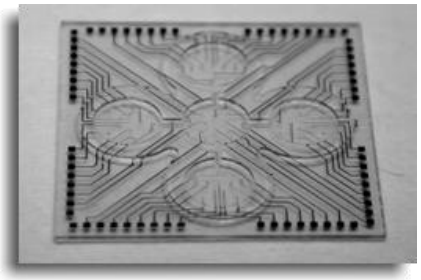
Optical MEMS / MOEMS



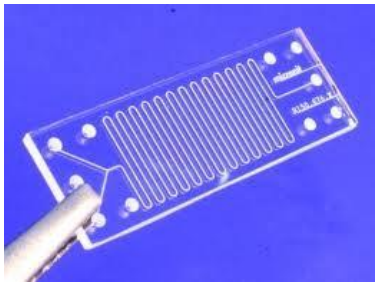
RF MEMS



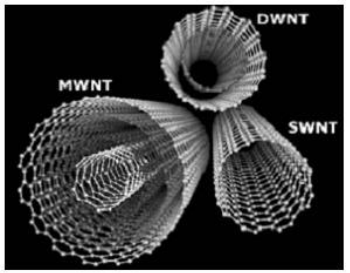
Power MEMS



Bio MEMS



Microfluidics



NEMS

NOTE: IC's and ASIC's are not ME<u>M</u>S…. there is no *<u>M</u>echanics* in there**.**

Danick Briand

- Bachelor and Master in Engineering Physics

  - EPM Montréal and INPG Grenoble

- PhD in Microtechnology from the University of Neuchâtel (2001)

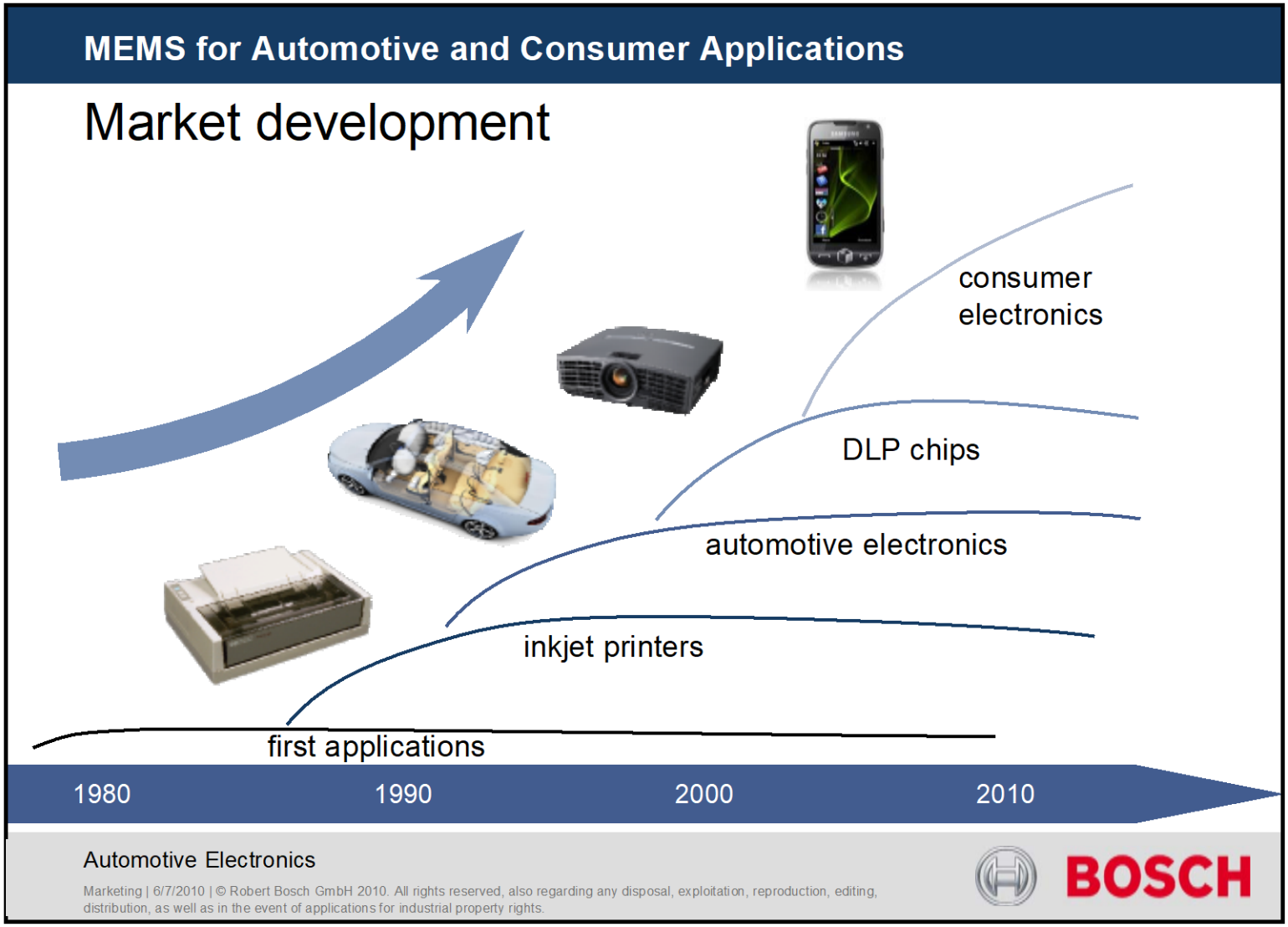
  - Micromachined gas sensors

- Now Group Leader MEMS and Printed Microsystems at LMTS

  - Teaching at Bachelor, Master and Doctoral program in Microengineering

  - Researching on environmental friendly microfabrication processes and microsystems

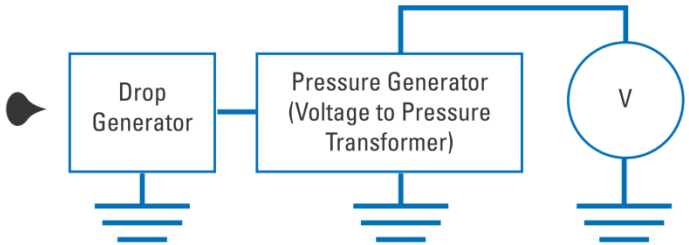
Enseignant-Chercheur
EPFL-Microcity Neuchâtel

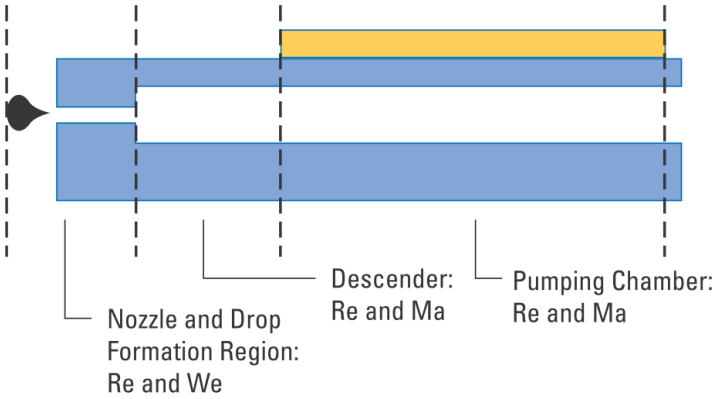


Dr. Jiri Marek, Robert Bosch GmbH
"MEMS for Automotive and Consumer Applications", IMS Chips 2010

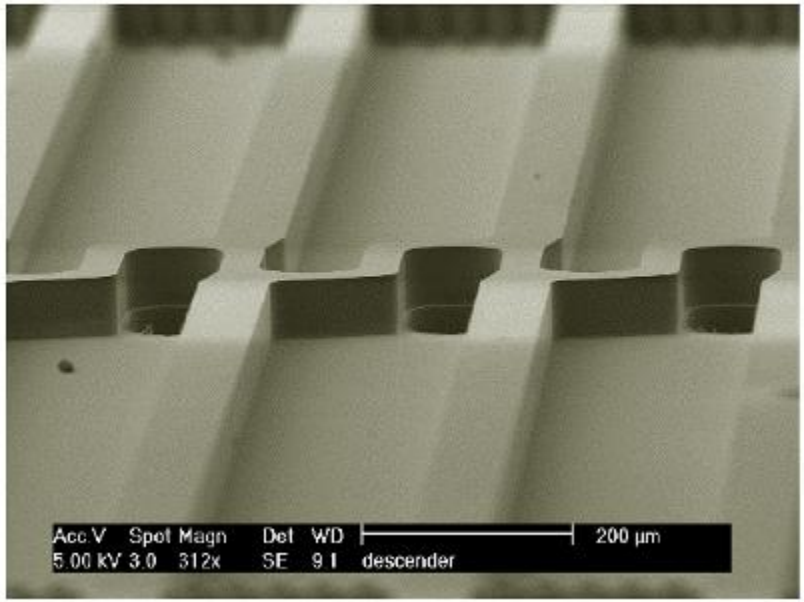
MEMS Intro: Early MEMS -Inkjet print head

Dimatix
FUJIFILM
TM



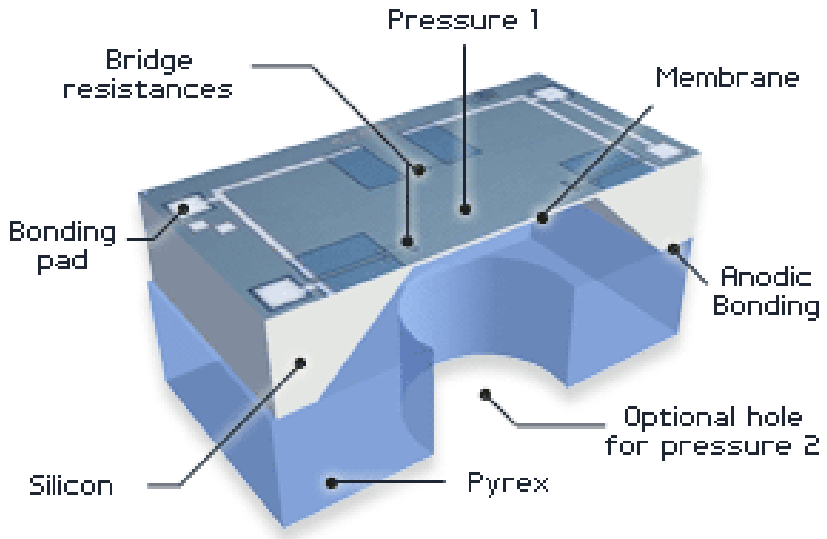


Fluidic Descender



photos: Spectra and Dimatix

MEMS Intro: Early MEMS – Pressure sensors



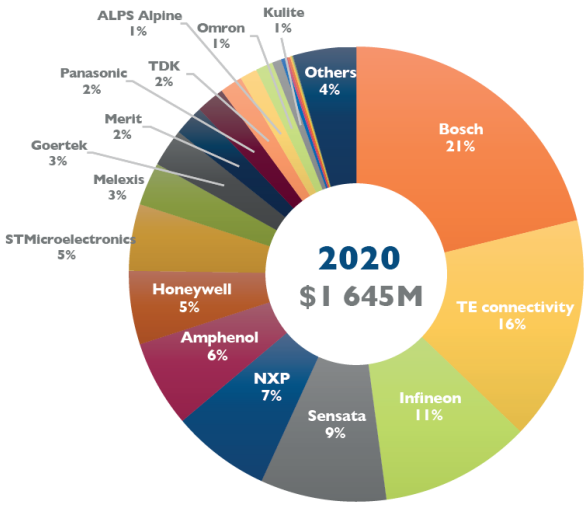
Source photos: TE Connectivity, Bevaix, CH

MEMS Intro: Early MEMS – Pressure sensors

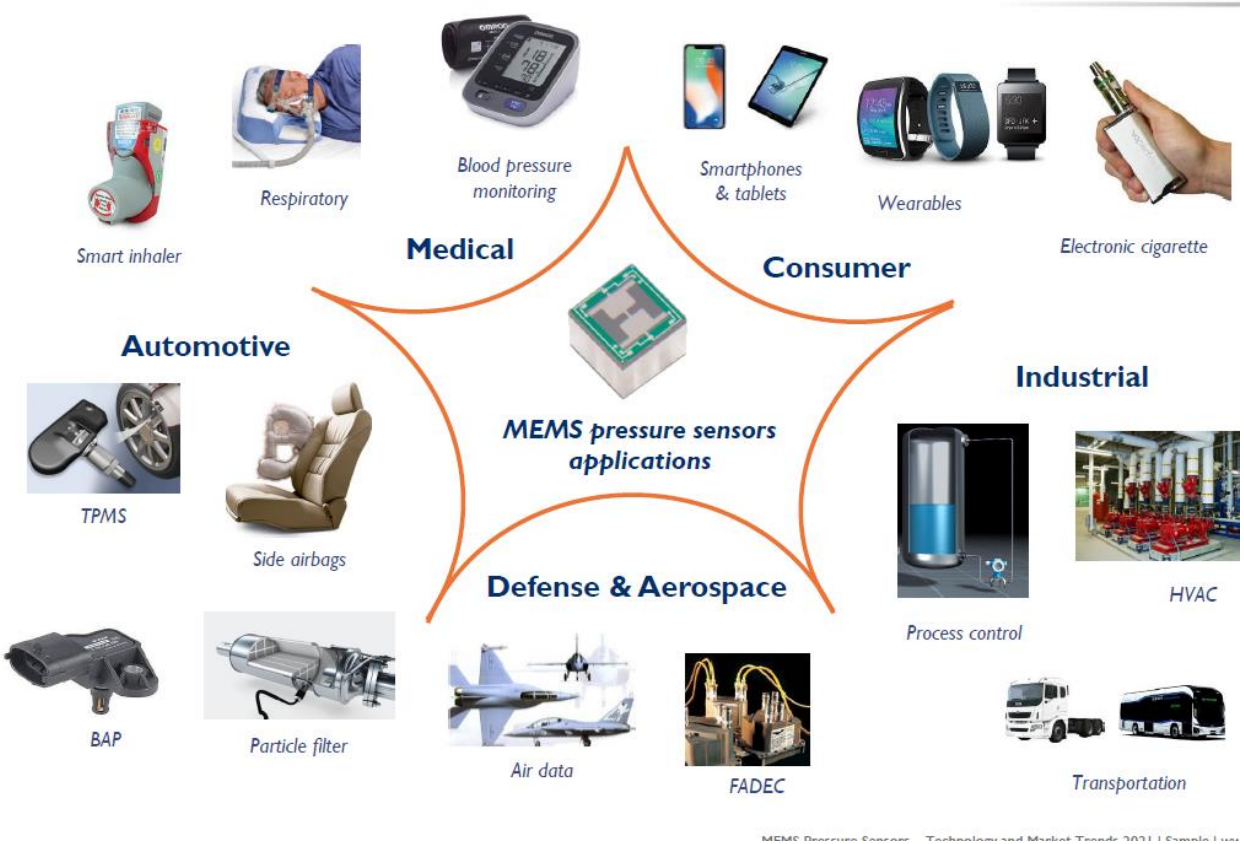
MEMS PRESSURE SENSOR - APPLICATIONS

Overview

2020 MEMS pressure sensor players revenues ($M)

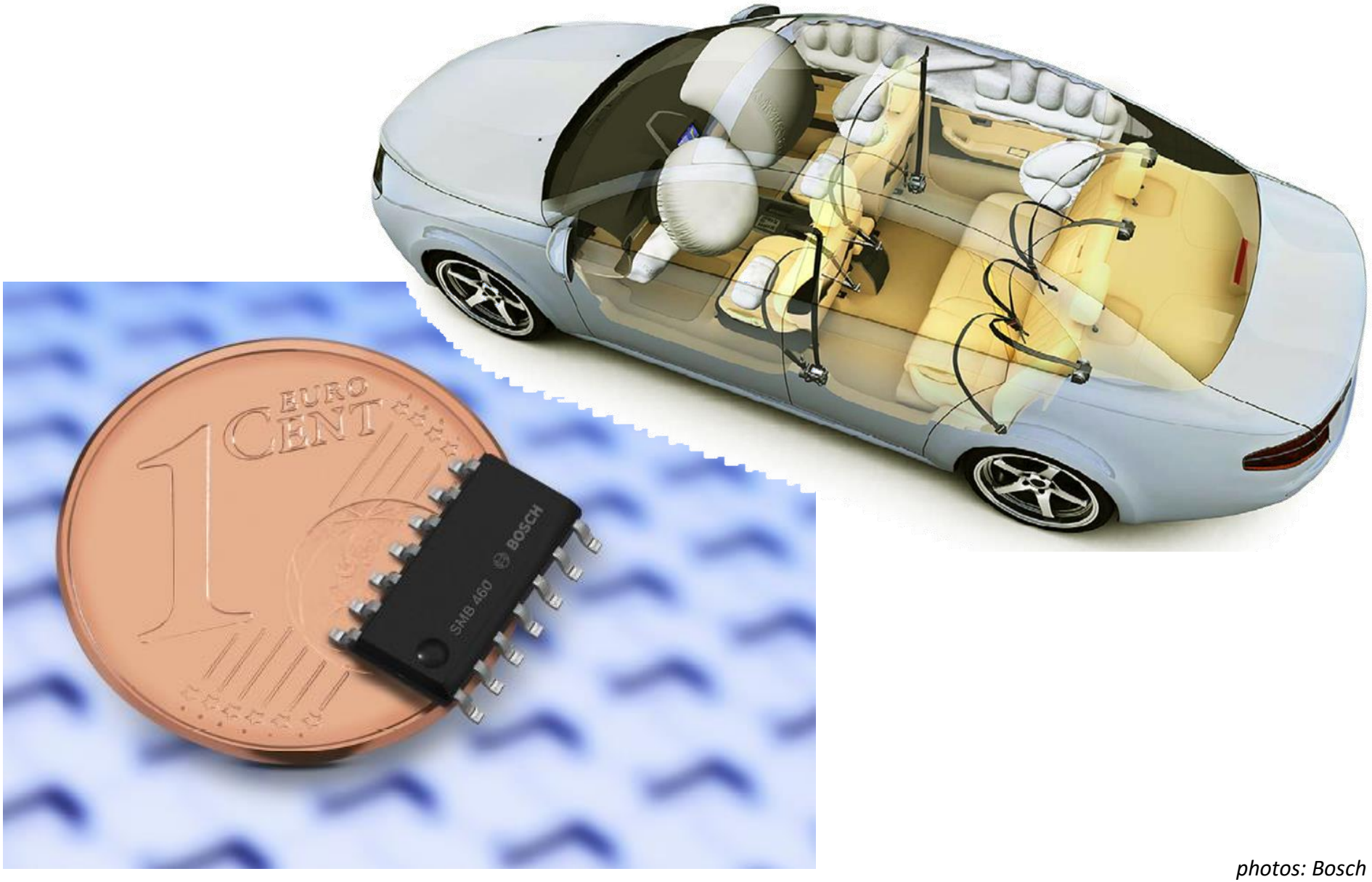


(Yole Développement, April 2021)



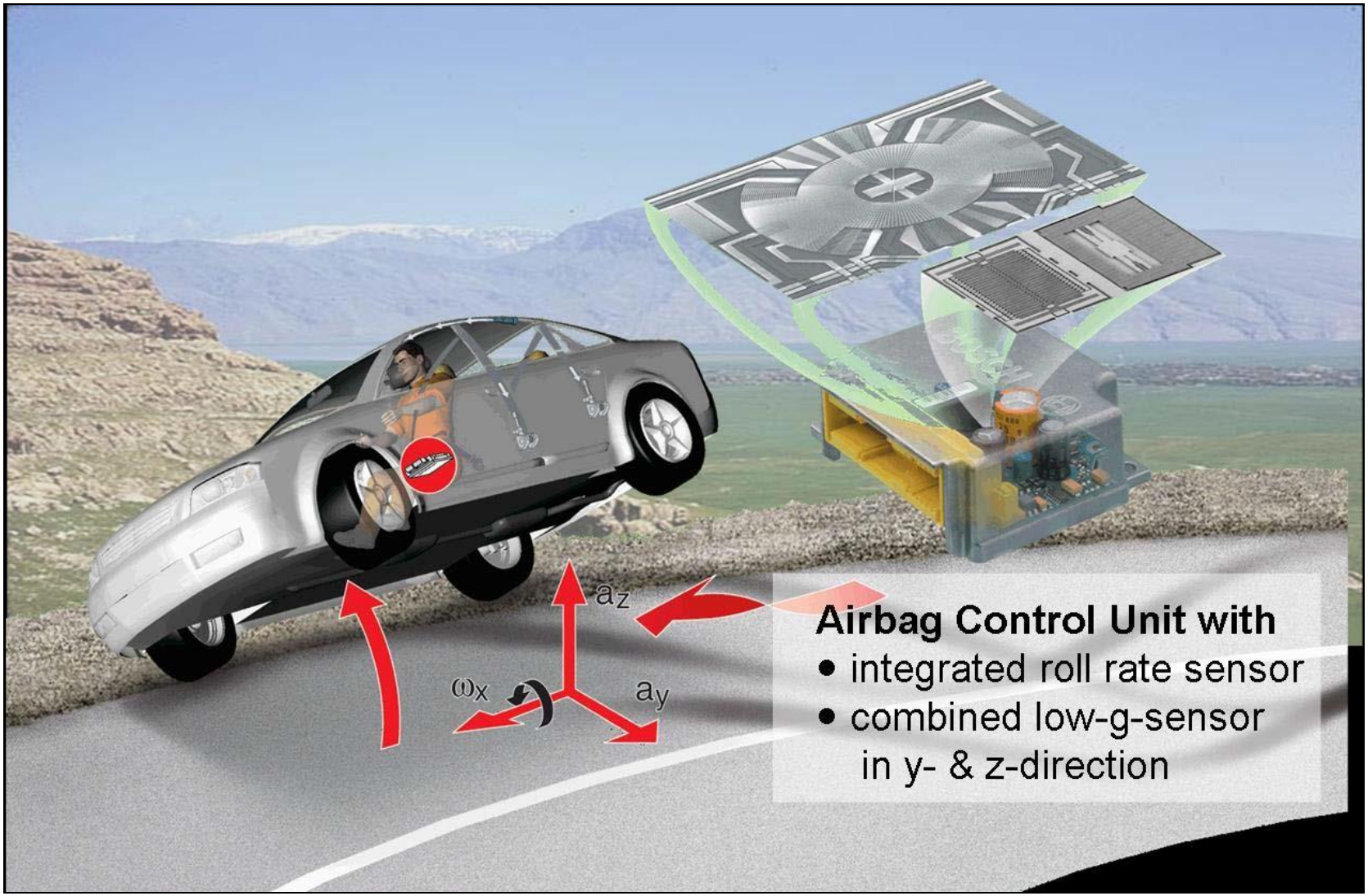
MEMS pressure sensors still experiencing strong growth

MEMS Intro: Airbag Sensors – Accelerometers



photos: Bosch

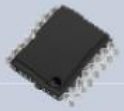
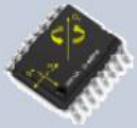
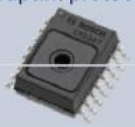
MEMS Intro: Roll-Over – Angular Sensor



photos: Bosch

Bosch MEMS Sensors

Product portfolio automotive sensors (modules)

Acceleration sensors	Angular rate sensors	Combined inertial sensors	Pressure sensors	Mass flow sensors
				
Central/peripheral acceleration sensor for occupant protection 	**Rollover sensor** for occupant protection  **SMG10x**	**Combined inertial sensor** (yaw rate and acceleration sensor) for VDC 	**Low pressure sensor** for engine control 	**Mass flow sensor** for engine management 
Low-g acceleration sensors for VDC, RoSe and active suspension 	**Yaw rate sensor** for VDC 		**Pressure sensor** for occupant protection 	
			High pressure sensor for engine and brake systems 	

125 Bosch 1886–2011 Research and Technology Center North America

11

BOSCH

VDC: Vehicule Dynamic Control

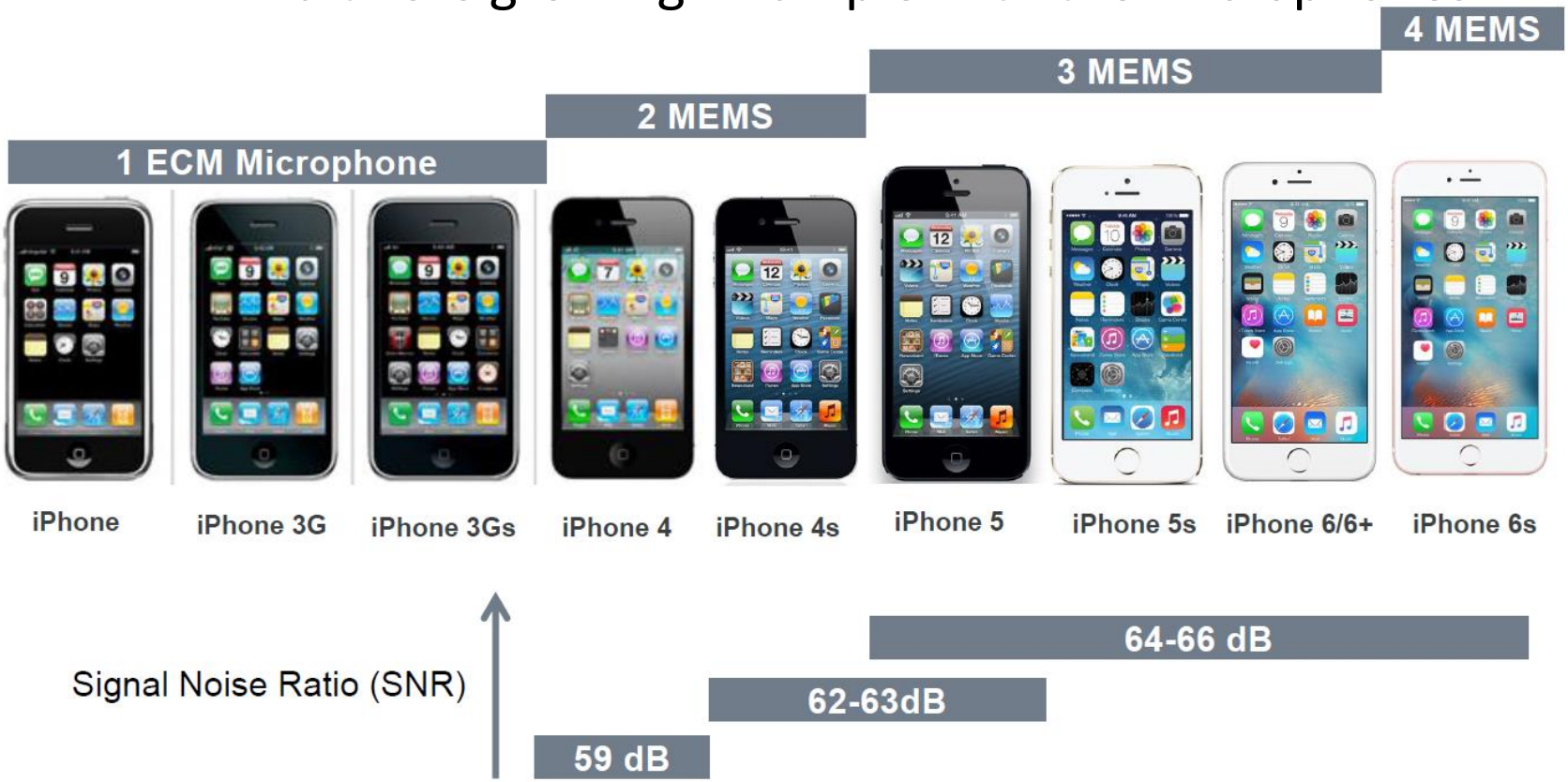
Gary O'Brien, Ph.D. at SEMICON West, July 12, 2011
New MEMS Devices Aimed at Emerging Consumer and Automotive Applications

MEMS intro: MEMS in Smartphones

(Source : Sensors for Cellphones and Tablets 2016 Market & Technology report, Yole Développement, June 2016)

MEMS are now omnipresent in our daily life

And this is growing. Example with the Microphones:

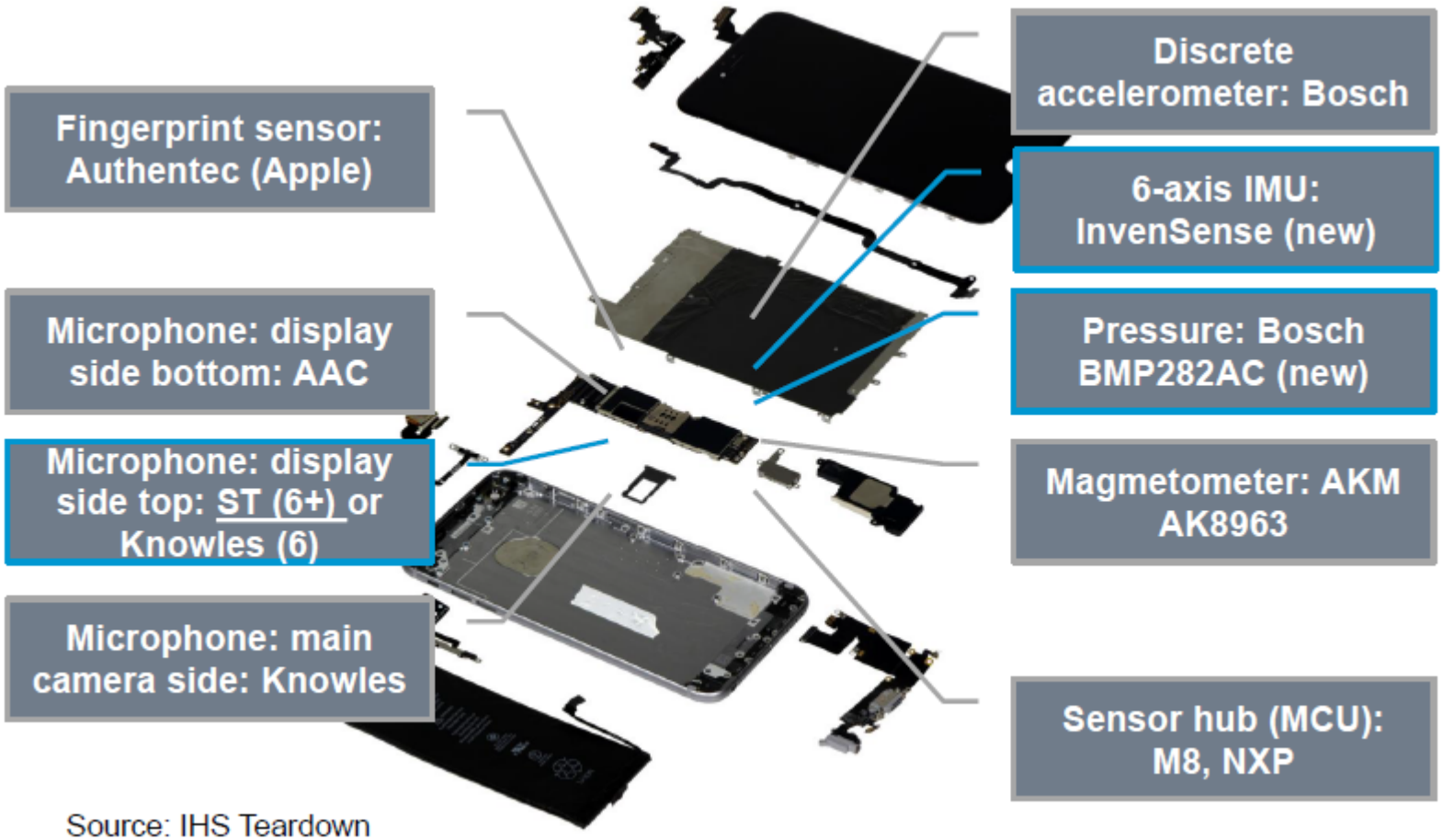


Source for pictures Apple

The need for three or four microphones is driven by hands-free calling, voice commands for Siri, better audio fidelity in video recording, noise cancellation, and improved call and recording performance.

MEMS are now omnipresent in our dialy life

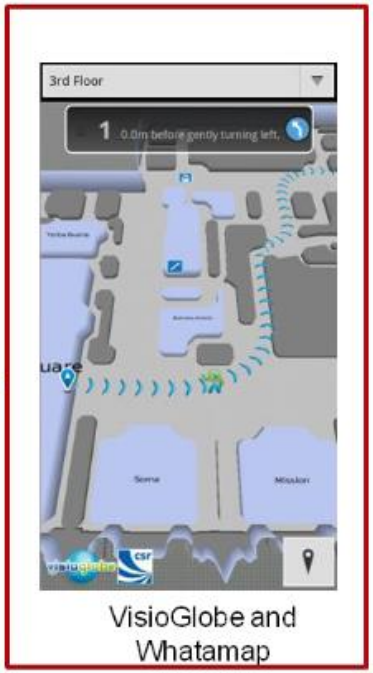
Ex: in smartphone (iPhone 6)



Source: IHS Teardown

MEMS intro: Indoor Navigation through sensor fusion

+



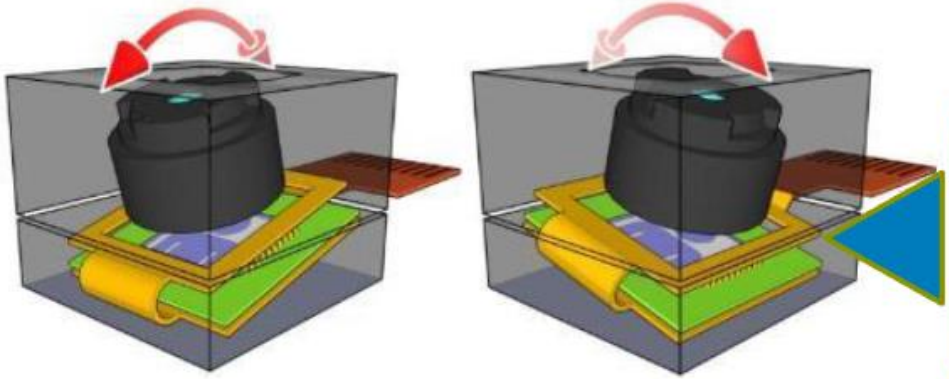
=

Accel + Gyro + Magnet + Pressure Sensor
+ WiFi (indoor) / GPS (outdoor)

life.augmented

COMPANY CONFIDENTIAL

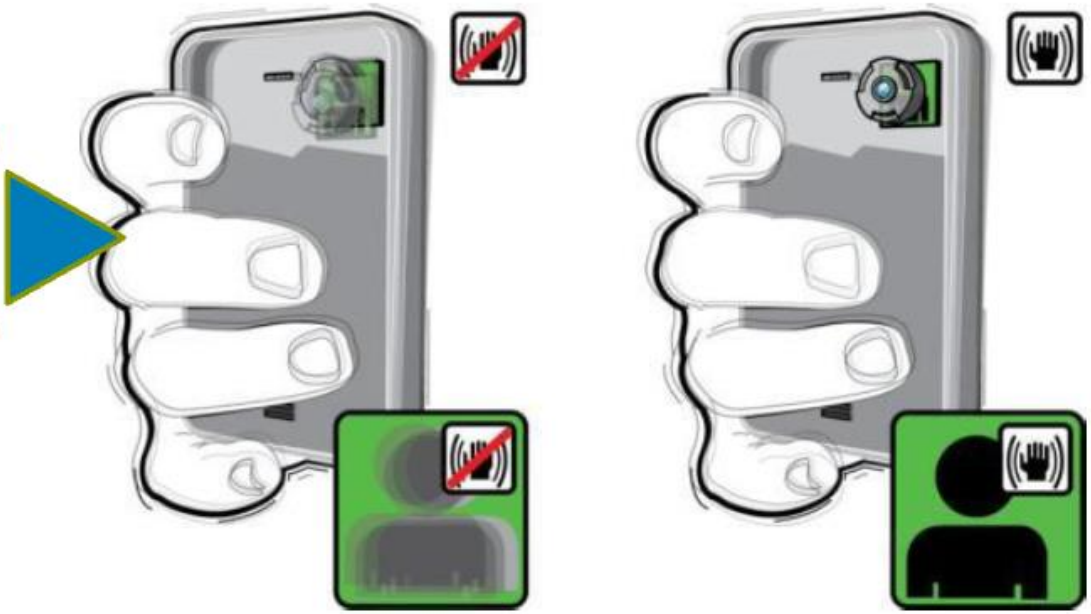
MEMS for optical image stabilization



Both pitch & yaw tilt are measured by a gyroscope and compensated by the OIS actuator

The lens and sensor are tilted together with SMA wire on all 4 sides of the camera

With OIS enabled, the optics tilt inside the camera but remain still to the subject – giving a sharp image



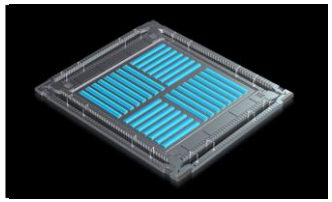
OIS: Optical Image Stabilization

MEMS FOR OPTICAL IMAGE STABILIZATION

New option for optical image stabilization: MEMS technology. Two major players → MEMSDrive (China) and Sheba Microsystems (Canada)

The MEMS OIS technology consumes less power and is more accurate than the VCM OIS technology.

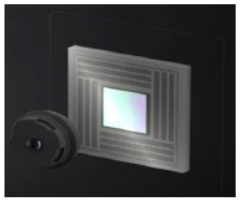
MEMSDrive



Courtesy of MEMSDrive

- Five axis:
  - Pitch
  - Yaw
  - Roll
  - x/y translation
- Sub-micron accuracy
- In-compensation within 10ms
- 100 times less energy consumption than VCM OIS (~10 mW)
- 70% smaller than VCM
- Compatible with SMT, Die-attach

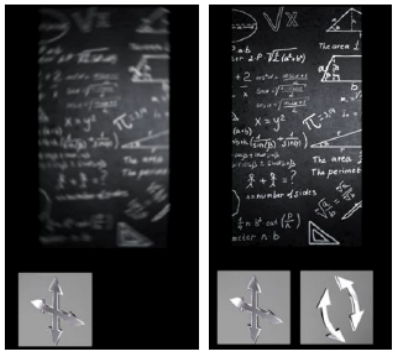
SHEBA MICROSYSTEMS



Courtesy of Sheba Microsystems

- Three axis:
  - Pitch
  - Yaw
  - Roll
- Submicron accuracy
- 200-500Hz depending on the load
- Low power < 2 mW

Comparison between VCM and MEMS technology:



VCM MEMSDrive

YOLE Développement

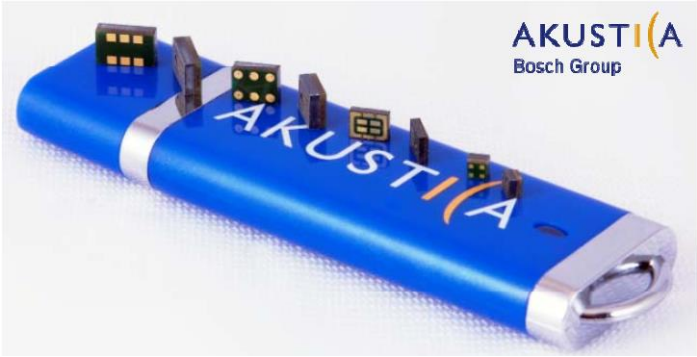
Status of the MEMS Industry 2021 | Sample | www.yole.fr | ©2021

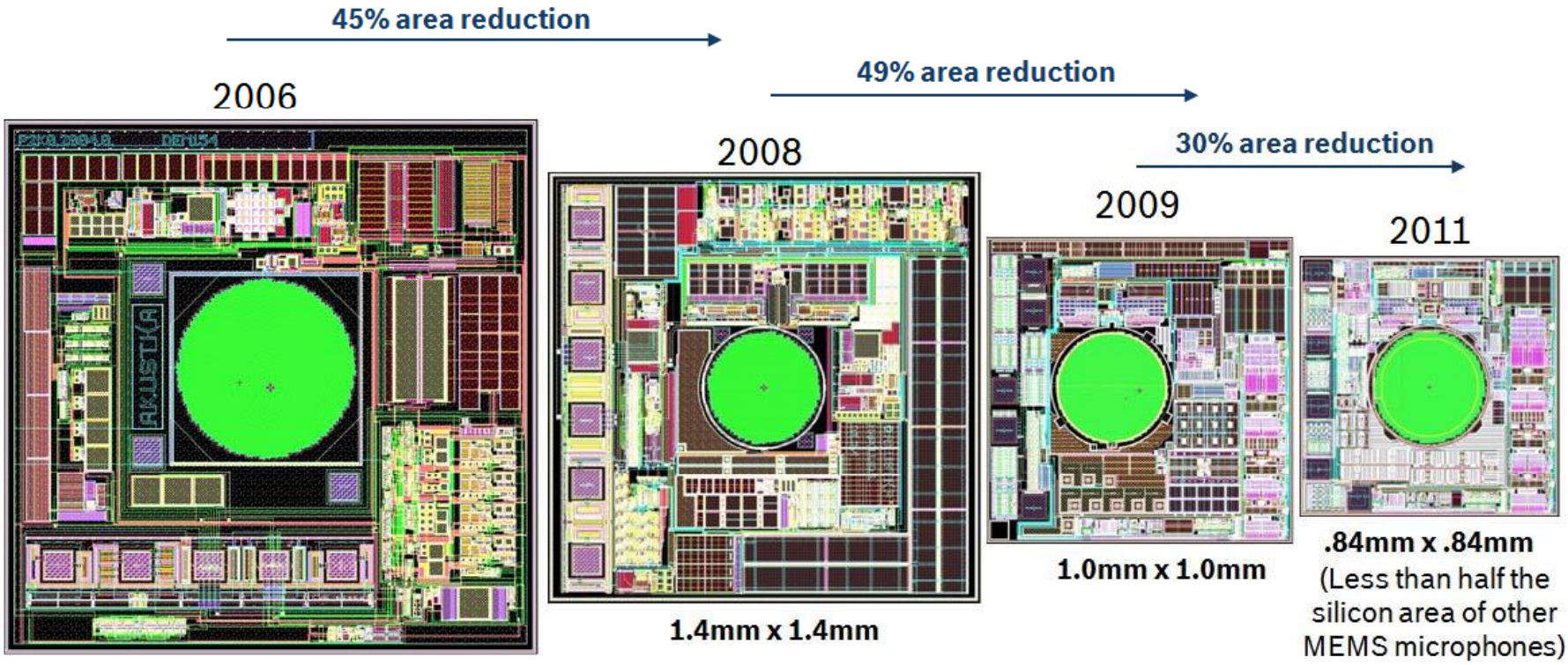
VCM: Voice Coil Motor

MEMS intro: Size Reduction

E.g. Bosch – Akustica: Digital Microphones

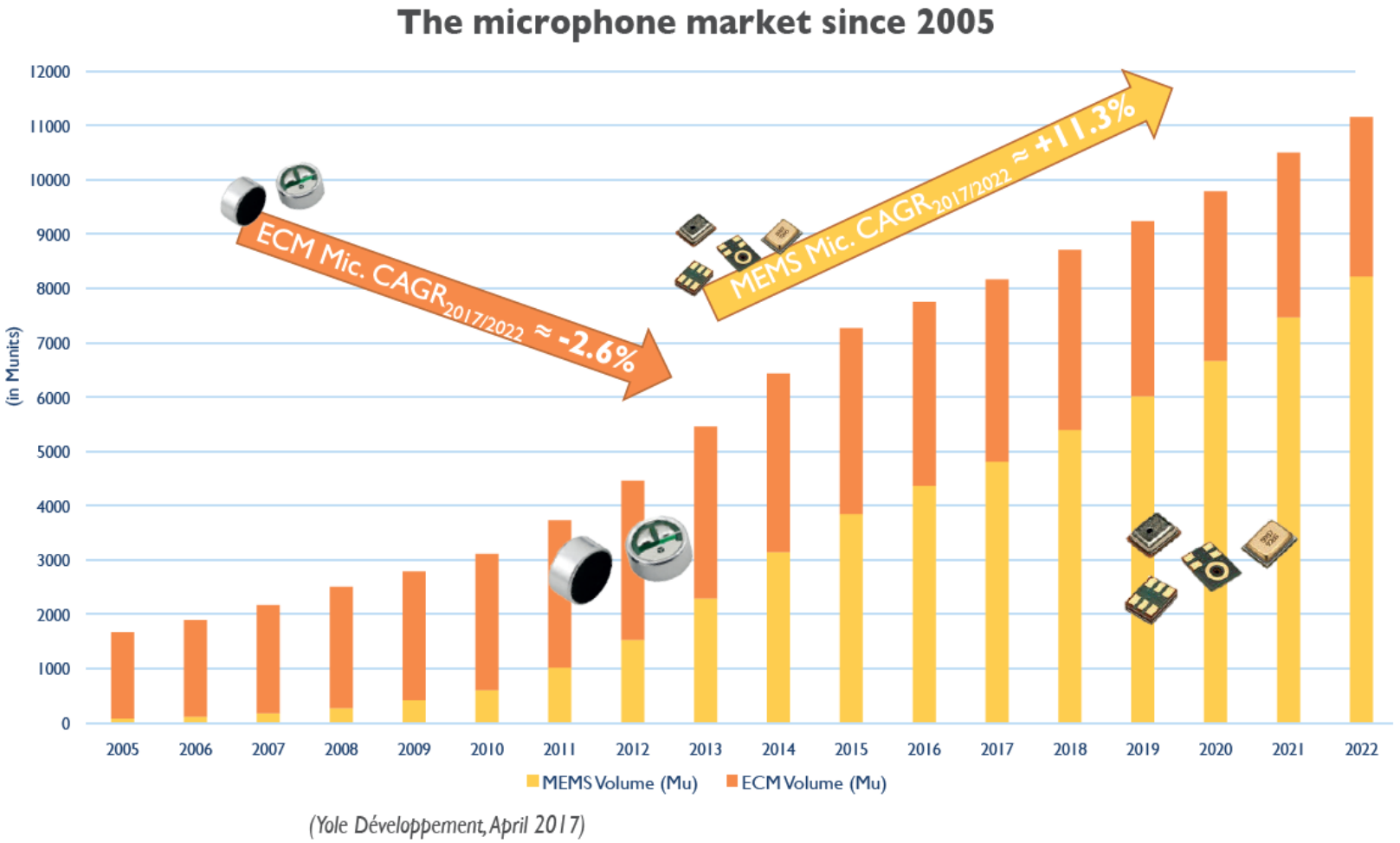
- Monolithic MEMS CMOS technology
- 80% less surface within 5 years
- Cost reduction & New markets





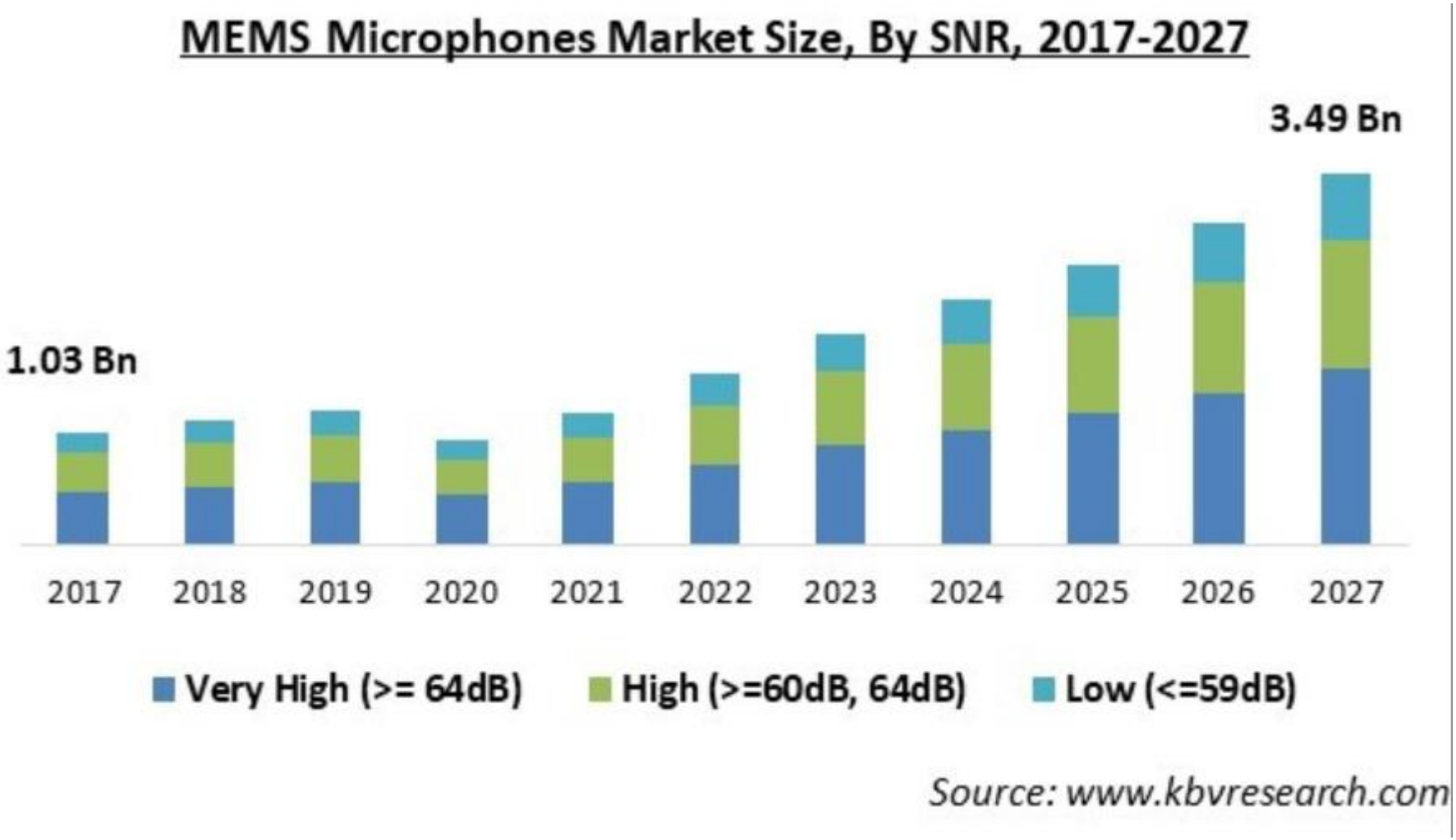
Gary O'Brien, Ph.D. at SEMICON West, July 12, 2011
New MEMS Devices Aimed at Emerging Consumer and Automotive Applications

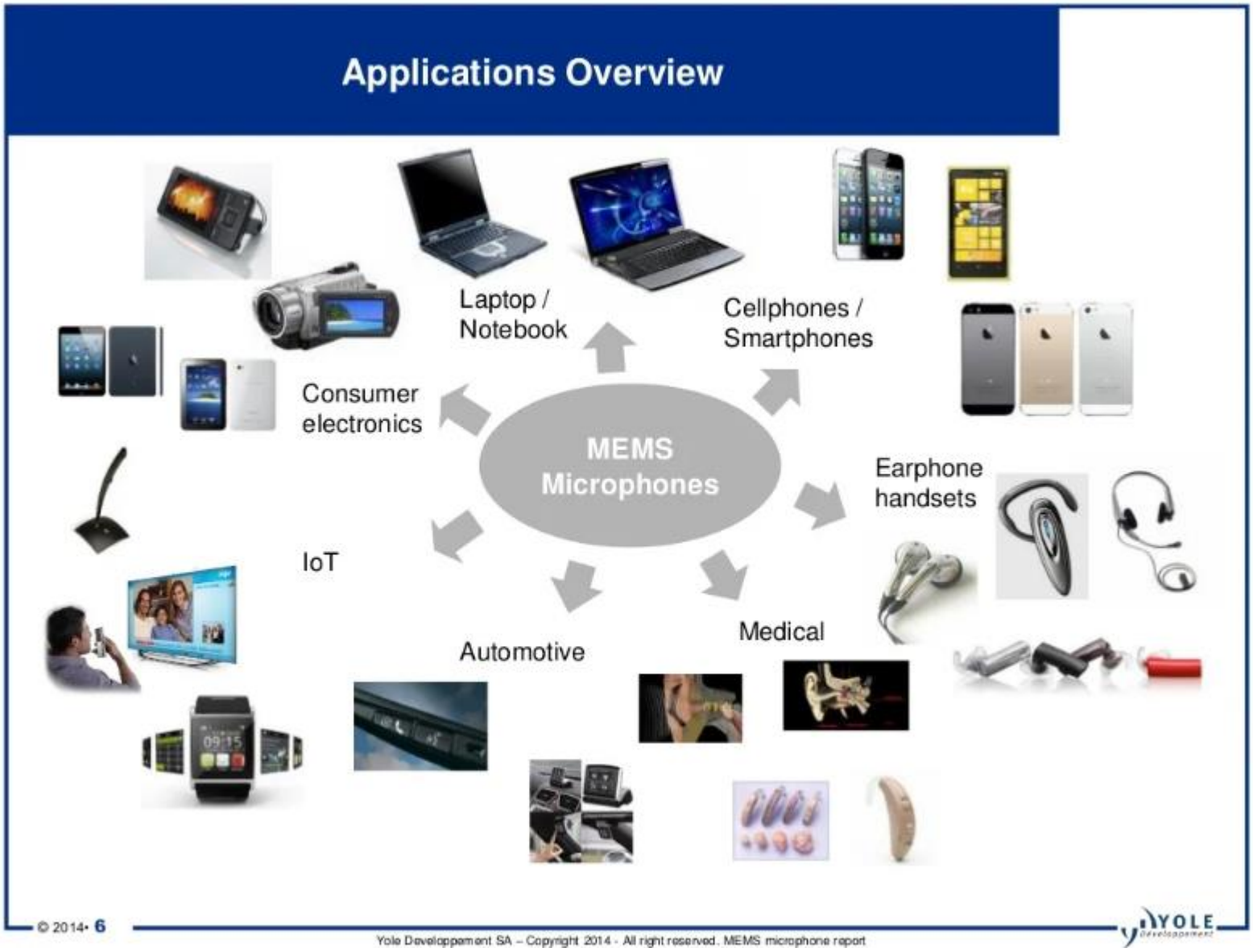
MEMS intro: Microphones



ECM: Electret Condenser Microphone

MEMS intro: Microphones




Applications Overview
MEMS Microphones
Laptop / Notebook
Cellphones / Smartphones
Consumer electronics
Earphone handsets
IoT
Automotive
Medical
© 2014• 6
Yole Developpement SA – Copyright 2014 - All right reserved. MEMS microphone report
YOLE

- Accelerometers
- Gyroscopes

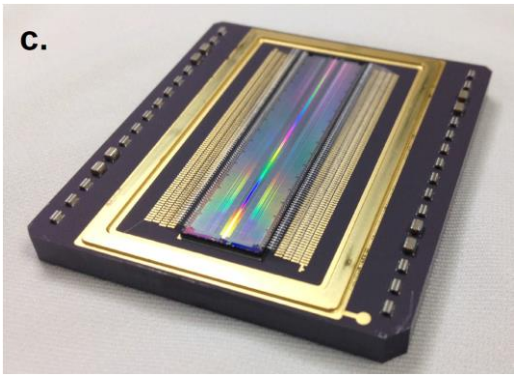
Nintendo – Wii

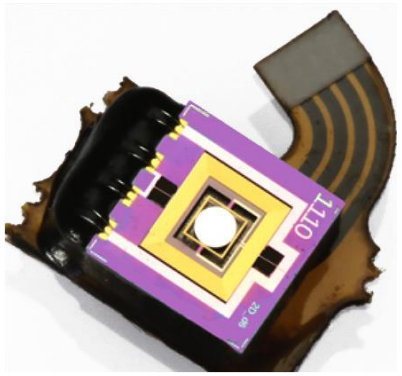
photos: Nintendo

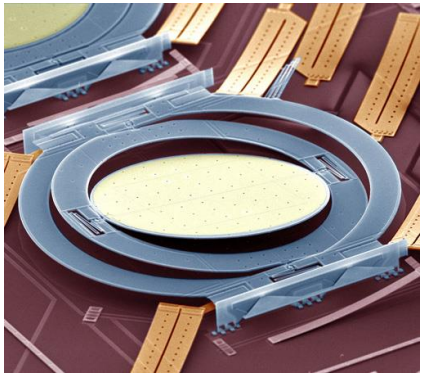
https://www.youtube.com/watch?v=OG1yvv1BABQ&feature=fvst

-

Micro – **O**pto – **E**lectro – **M**echanical **S**ystems **(MOEMS)**

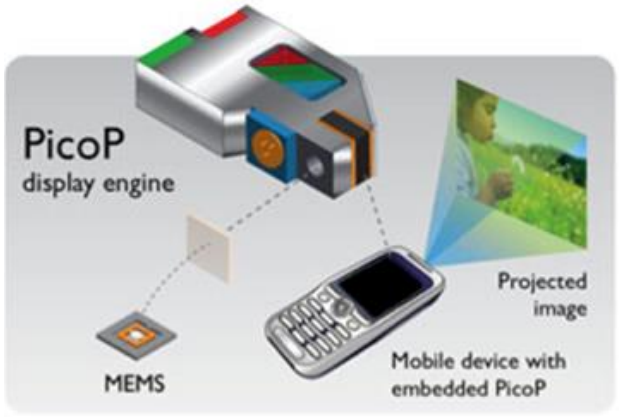


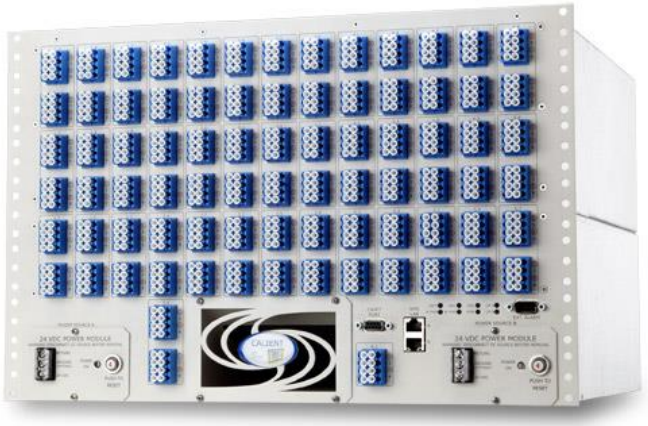




Engineering & Design

Devices in Systems



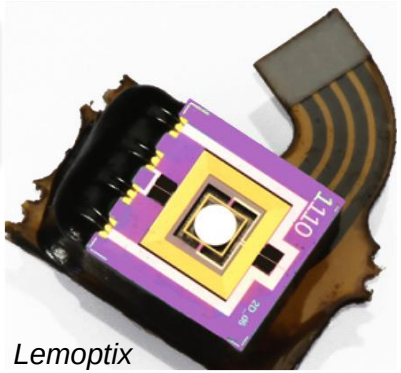


Consumer Electronics and Mobile

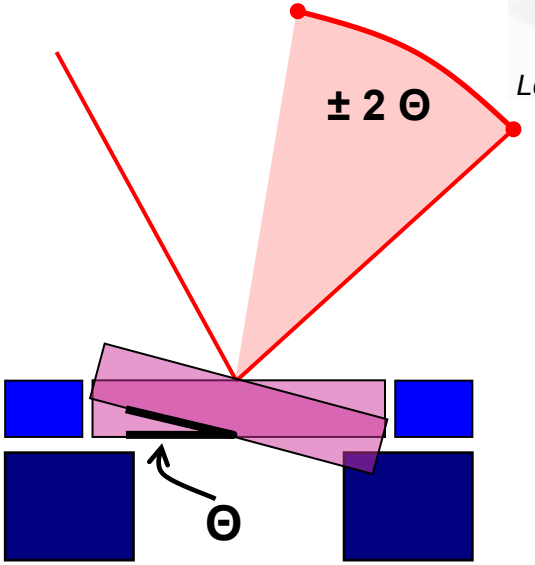
Telecommunications

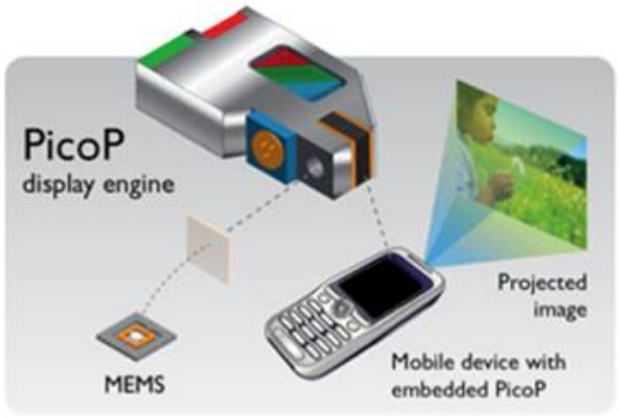
MOEMS Intro: Pico-Projectors

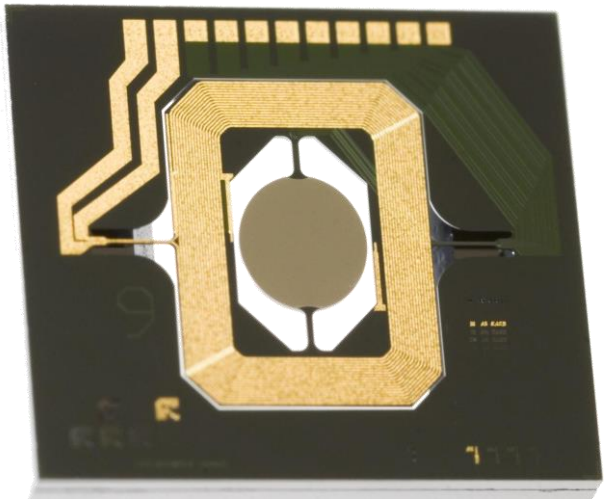
MEMS Inside!



Lemoptix



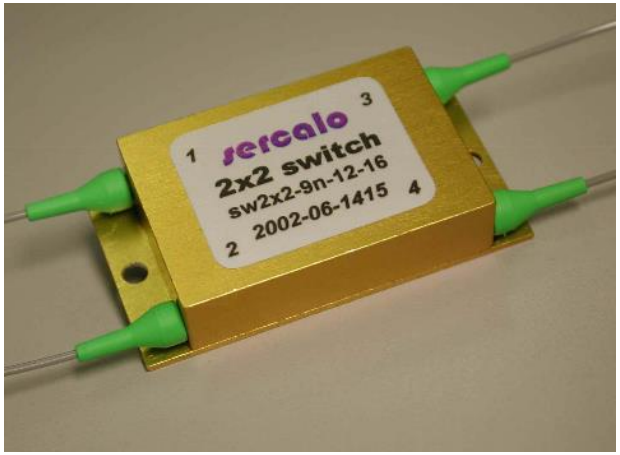




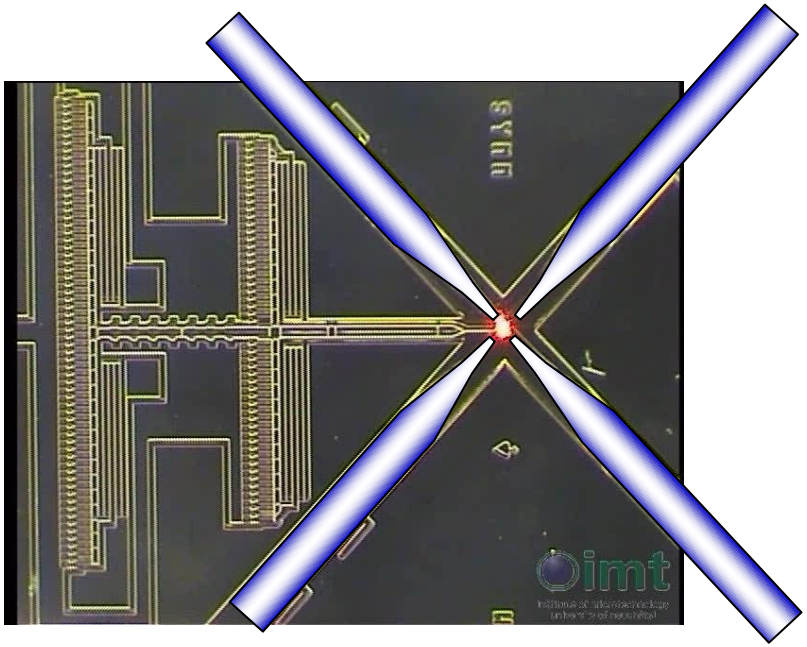
Consumer Electronics and Mobile

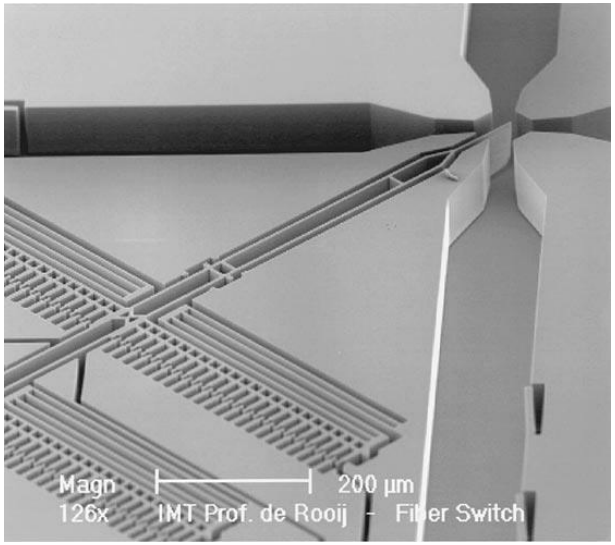
Source: http://www.microvision.com
Source: Courtesy of Prof. Hakan Ürey, Koç University, Turkey

MOEMS : Fiber-Optic MEMS Switches



MEMS Inside!

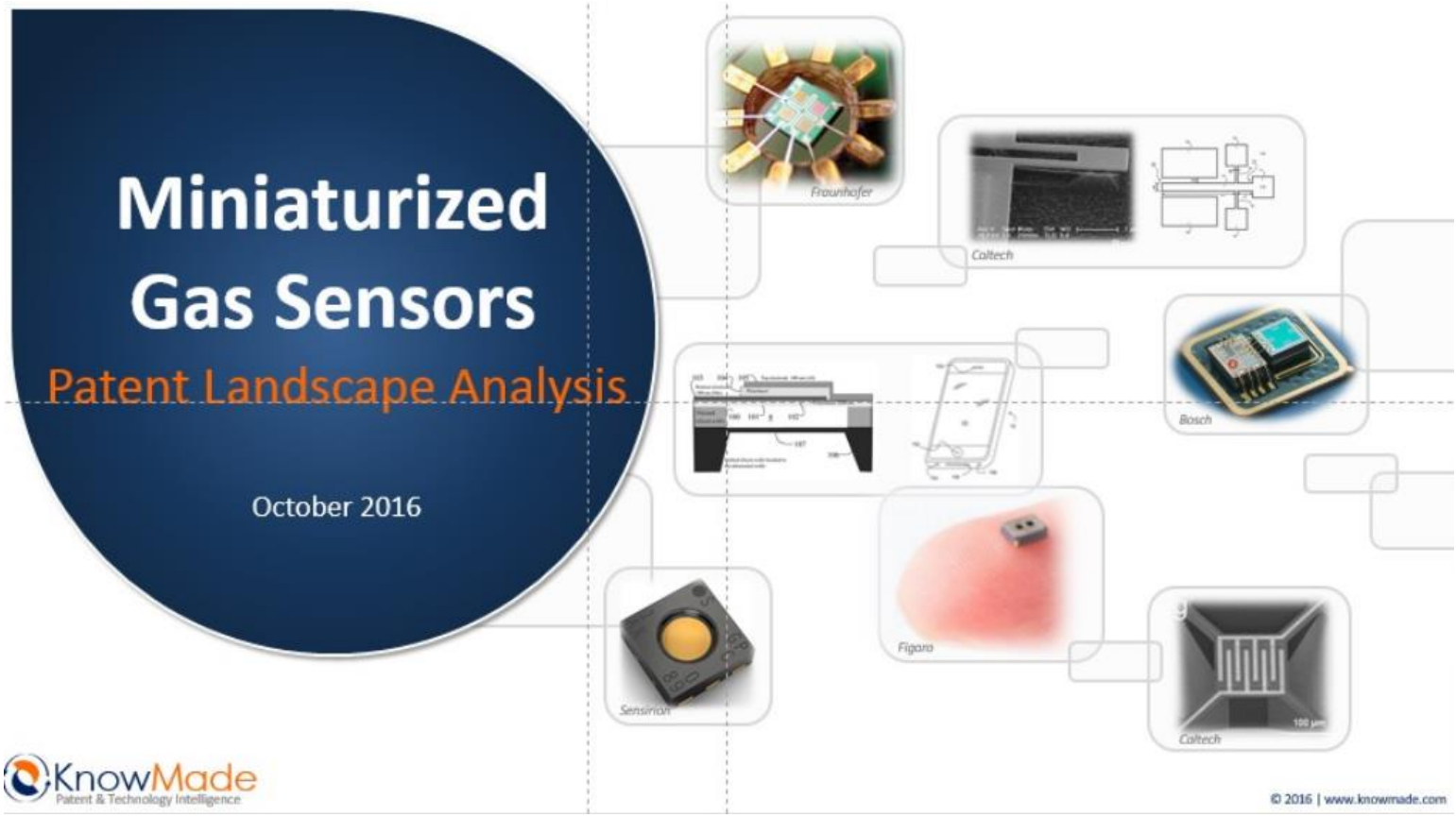




Telecommunications

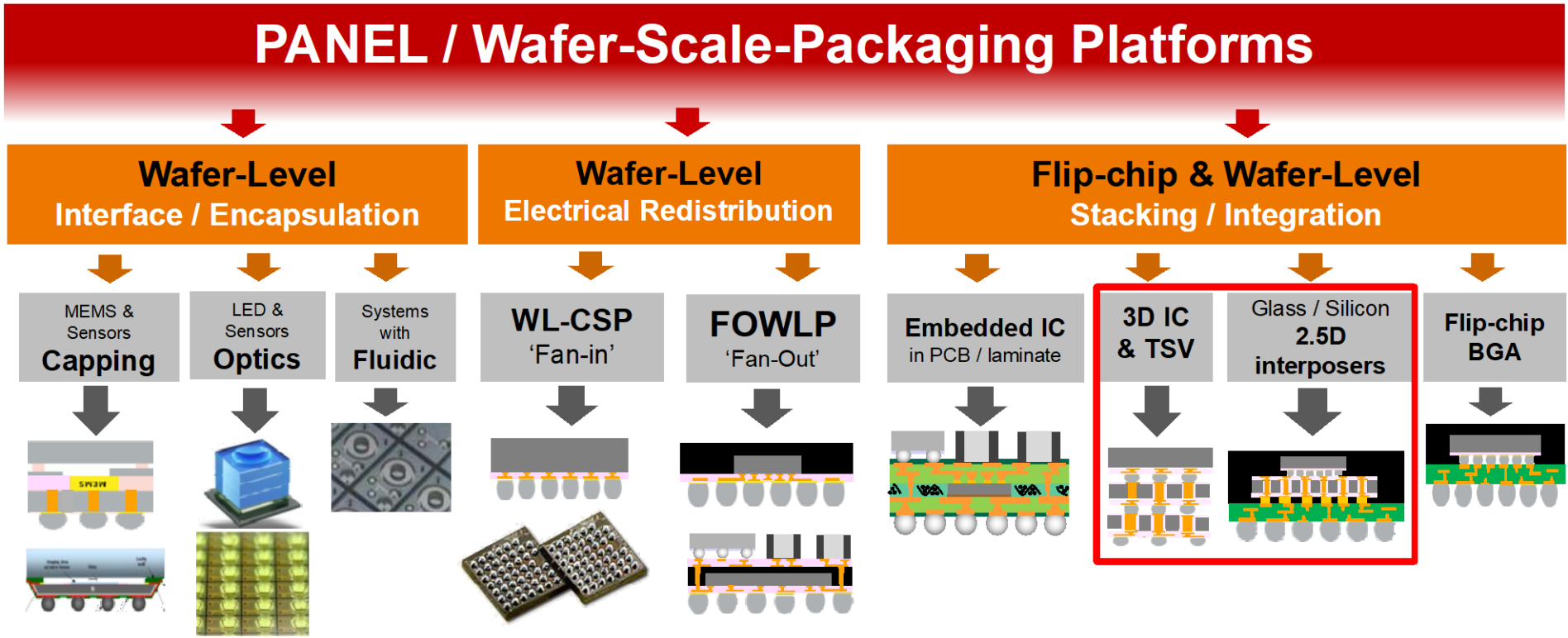
Marxer & de Rooij, IEEE JLT, 1999

Micromachined gas sensors on silicon at high volume and low cost



MEMS intro: 3D Integration & Advanced Packaging

- Packaging technologies
- Encapsulation necessary for MEMS
- Many options → Increased density of functionalities in a compact volume



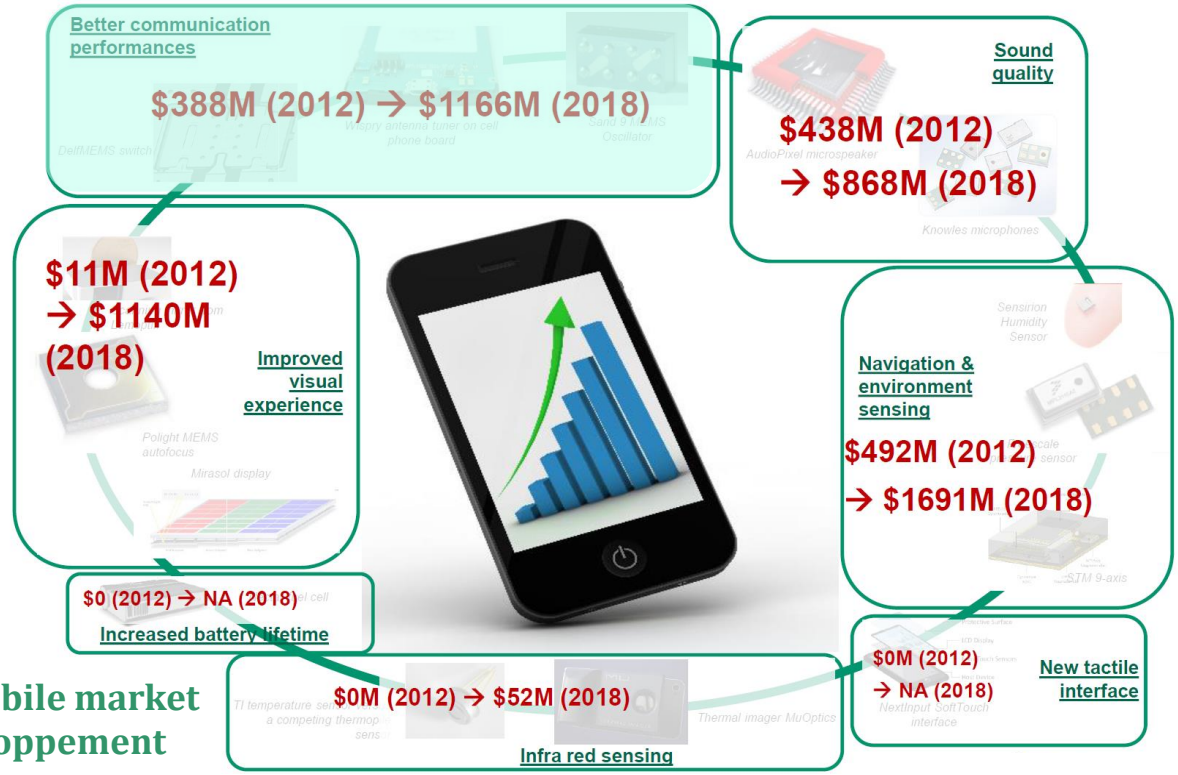
YOLE DÉVELOPPEMENT

Guillermo Villanueva

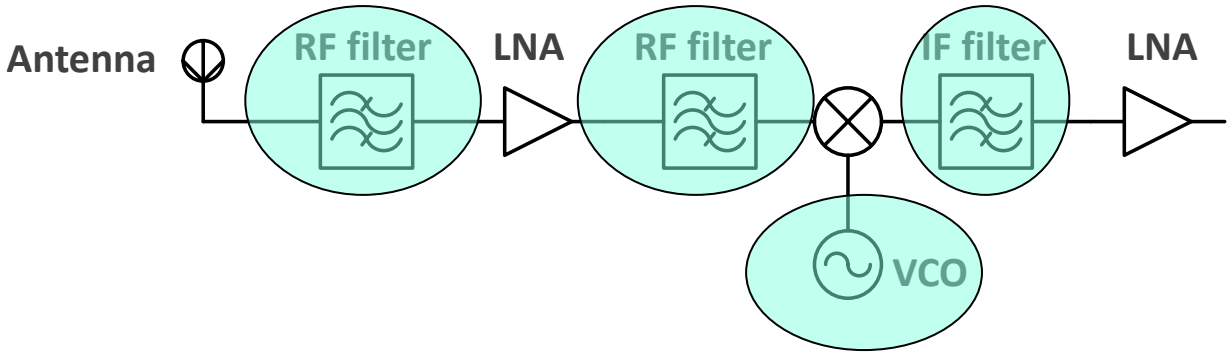
- Things to remember:
  - Spaniard
  - Physicist in Education, Engineer by training
  - Resonators

Professor and Head
Advanced NEMS group

MEMS intro: Resonators

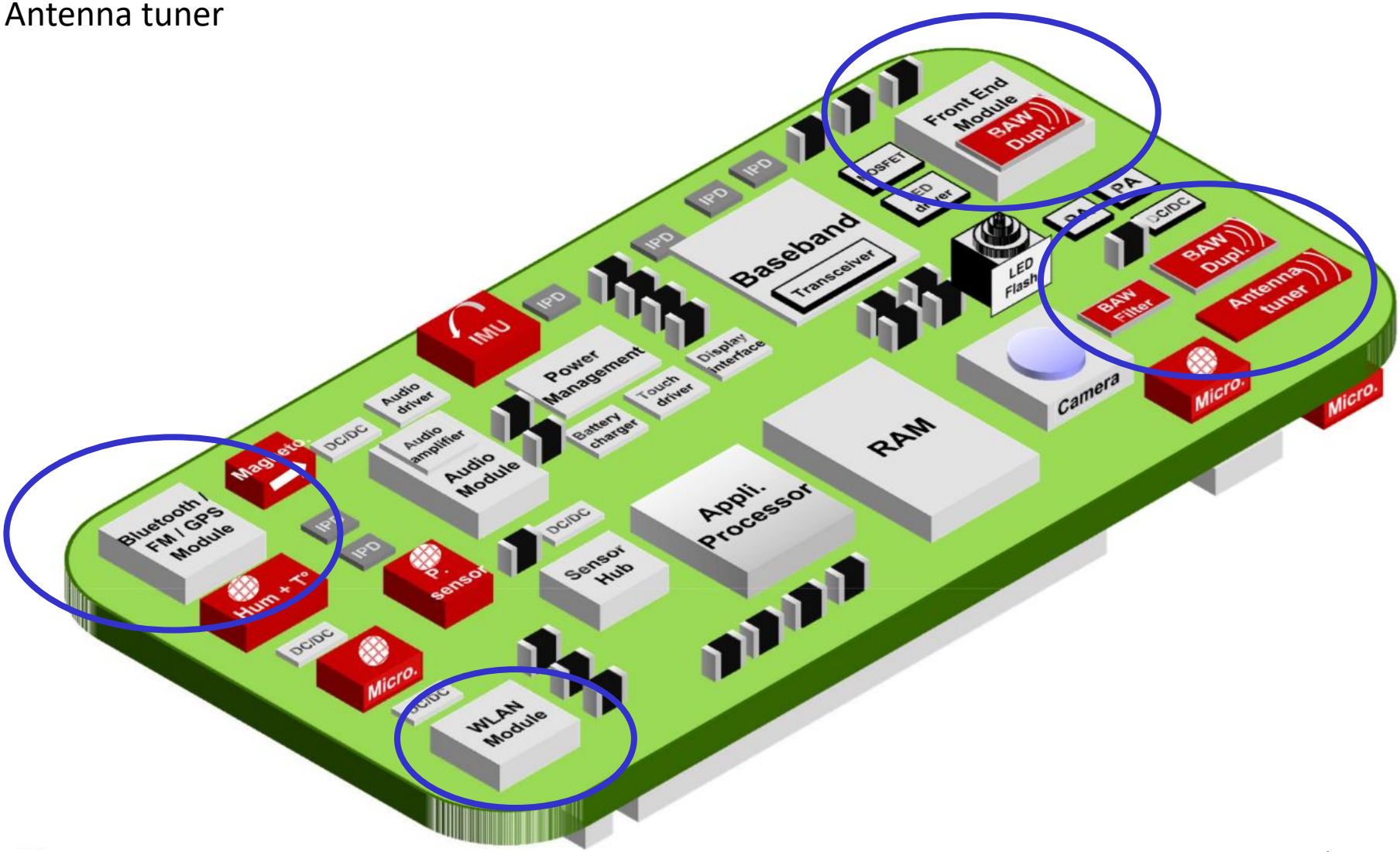


MEMS for mobile market
© Yole Developpement



MEMS intro: MEMS resonators in Smartphones

- BAW filters and duplexers
- Antenna tuner

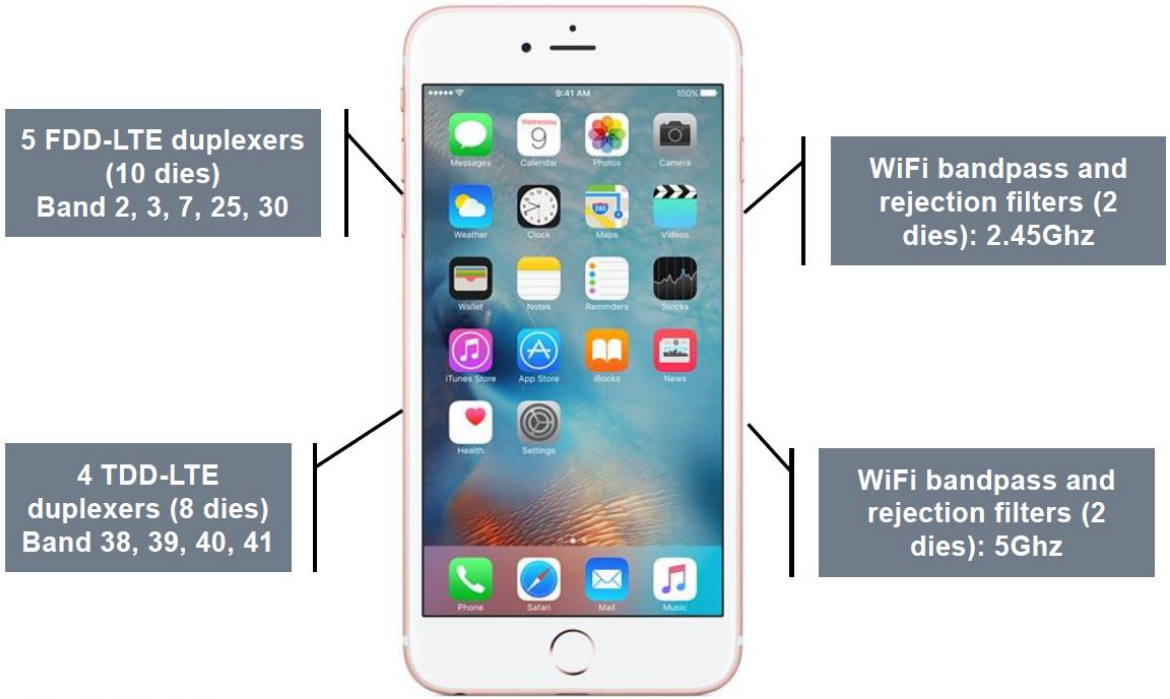


source: Yole.com

MEMS intro: MEMS resonators in Smartphones

- **Strong arrival of BAW resonators**
- **Together with the emergence of 4G+ and 5G**
- **Duplexers and bandpass/notch filters**

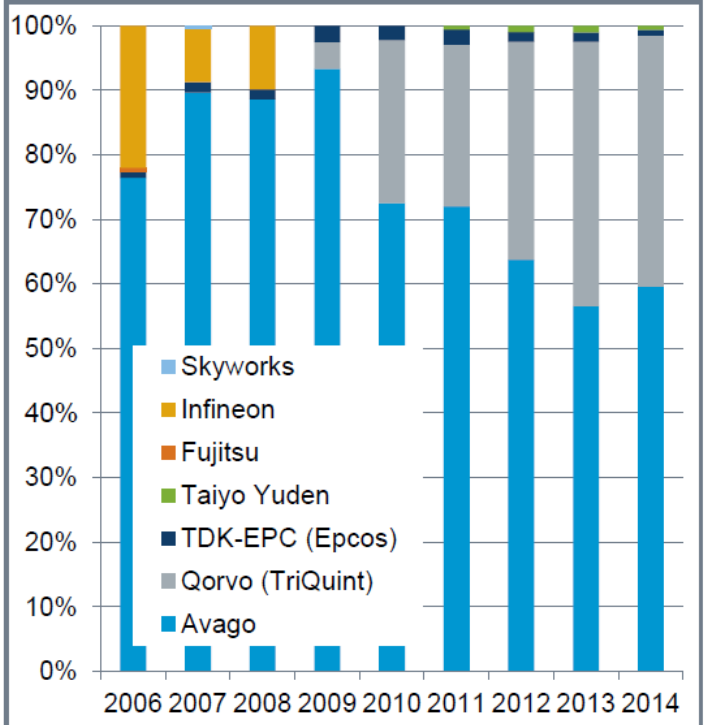
More than 20 BAW filter dies in the iPhone 6s



Source for picture: Apple

9

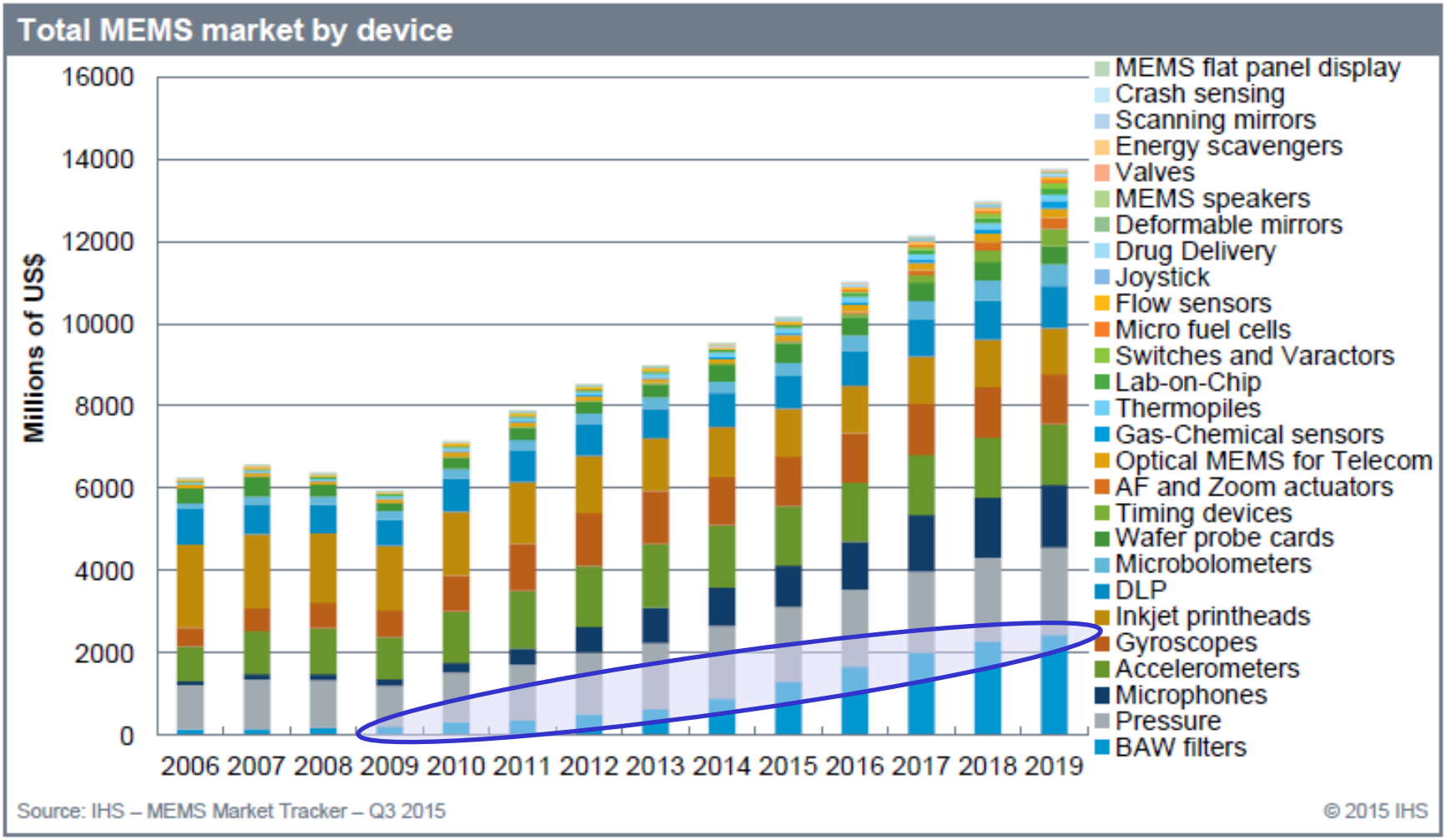
BAW Revenue Market Shares



Source: IHS – MEMS and Sensors for CE & Mobile Intelligent Service, H2 2015

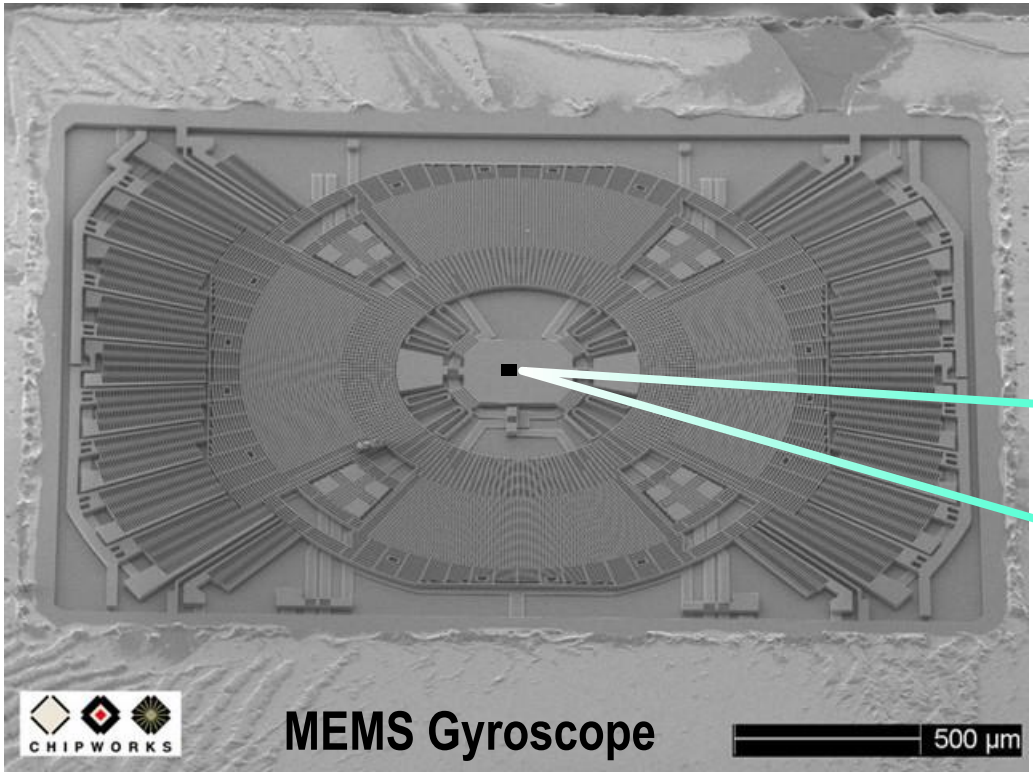
MEMS intro: MEMS resonators in Smartphones

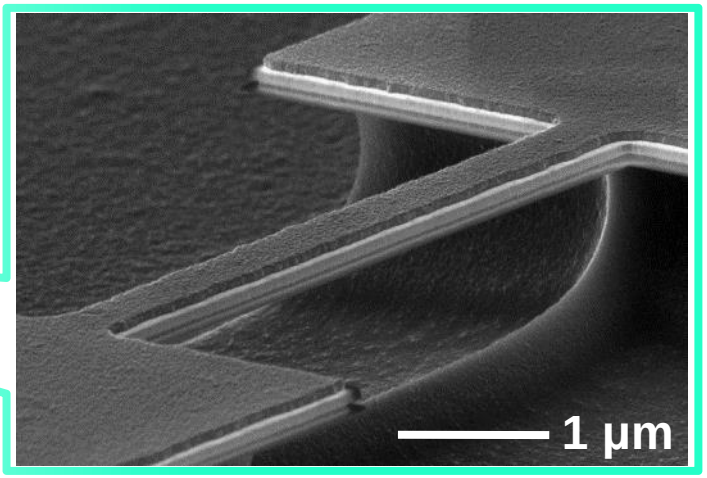
- **Strong arrival of BAW resonators**
- **Together with the emergence of 4G+ and 5G**
- **Duplexers and bandpass/notch filters**



NEMS

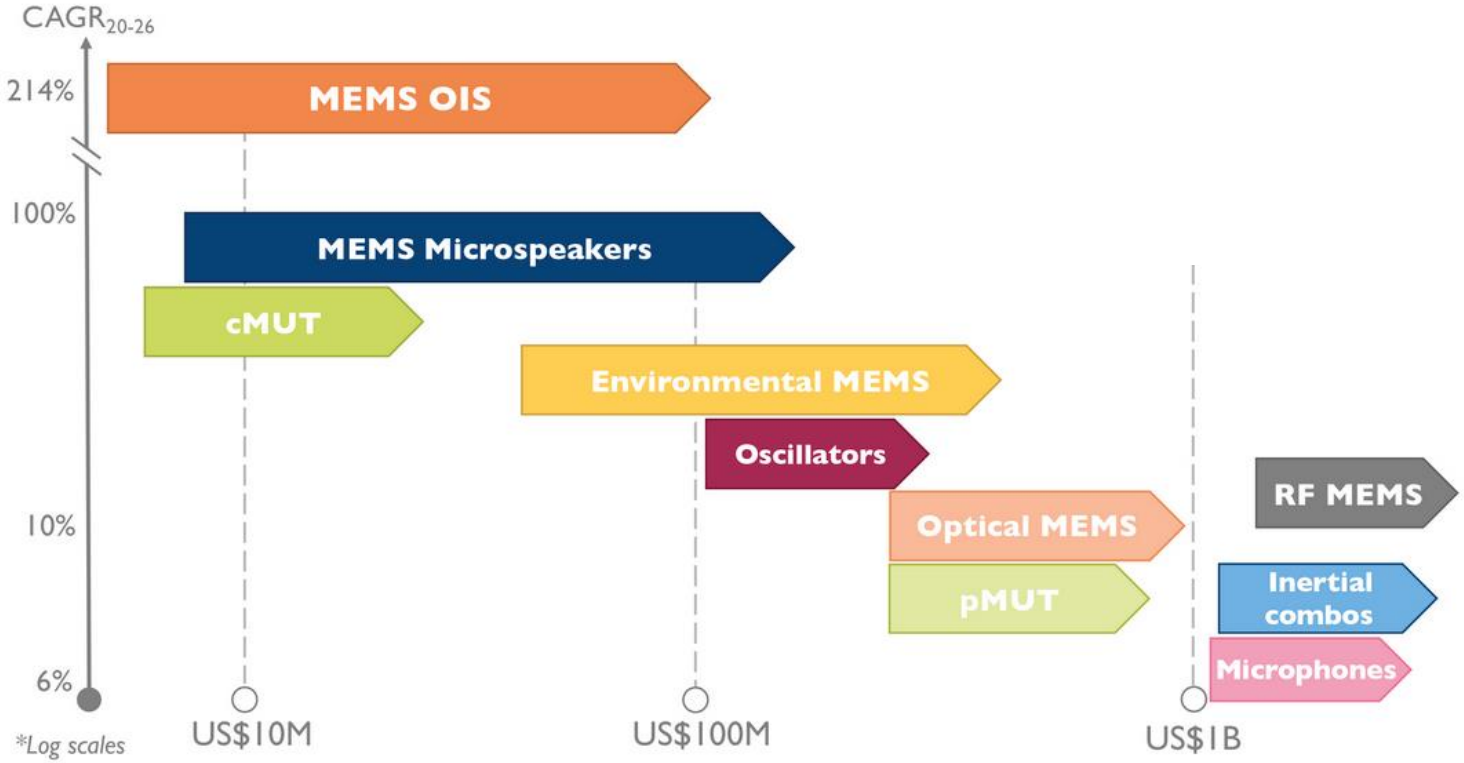
- **Nano Electro Mechanical Systems**
- **“Simple” mechanical objects**
- **Dimensions** $\lesssim 1\ \mu m$





2020-2026 MEMS industry best growth opportunities: revenues vs. CAGR*

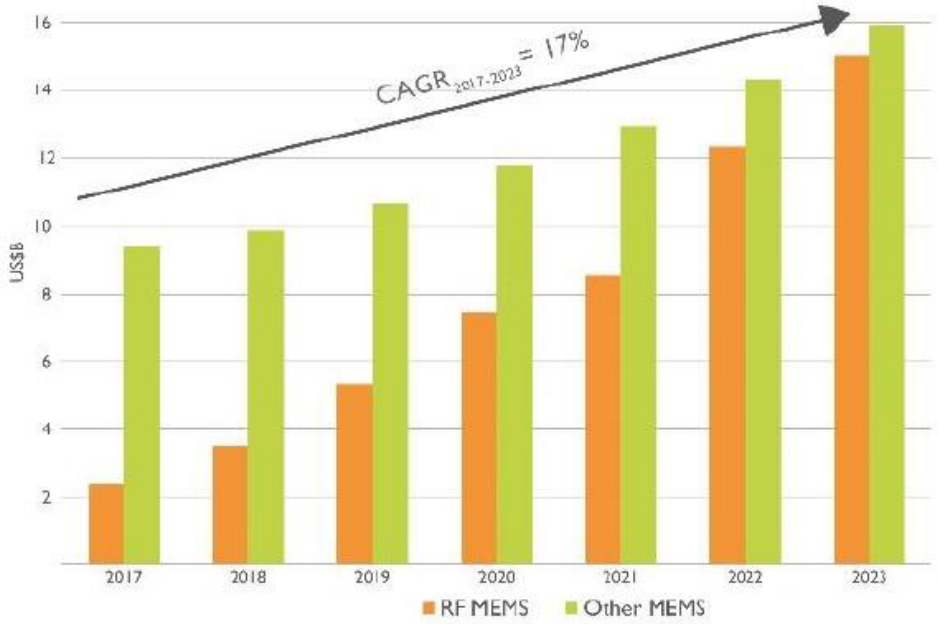
(Source: Status of the MEMS Industry 2021 report, Yole Développement, 2021)



> 50% growth for consumer market

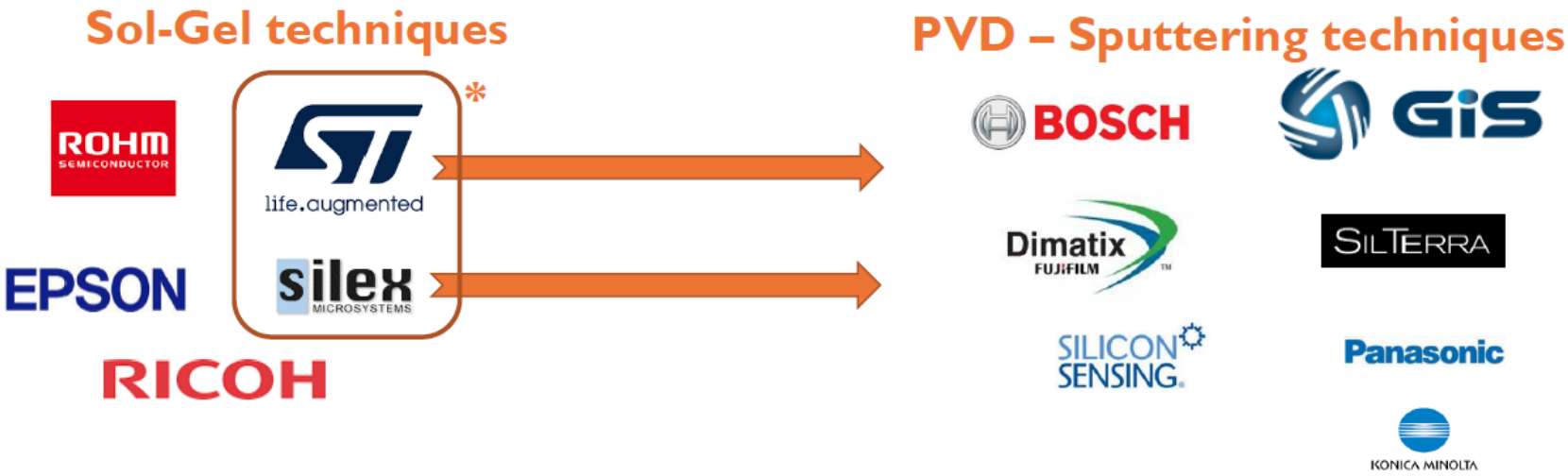
2017-2023 MEMS market forecasts: RF vs. other devices

(Source: Status of the MEMS Industry 2018 report, Yole Développement, May 2018)

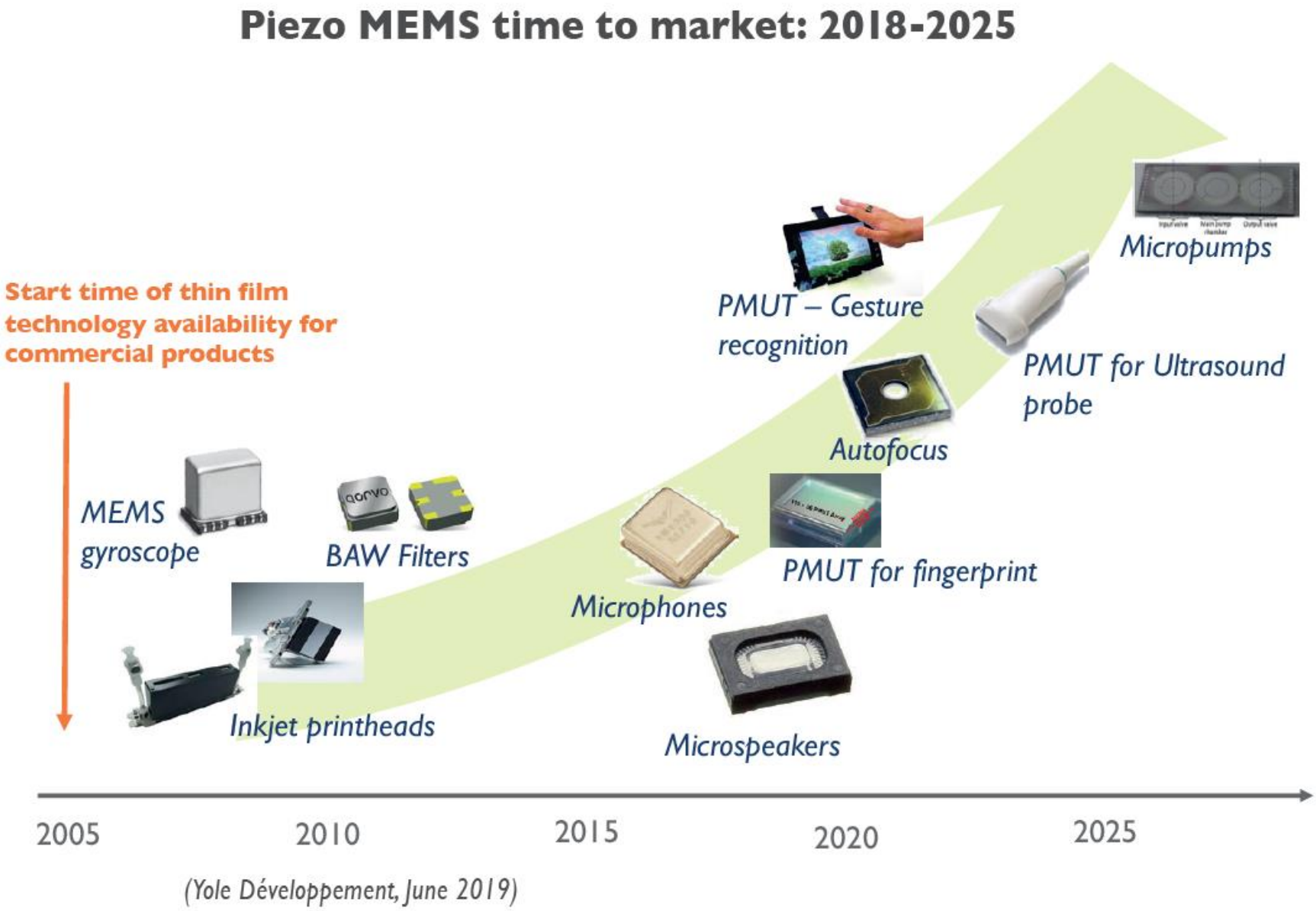


PiezoMEMS technologies: trends in the deposition techniques

- PiezoMEMS family of products includes, among others sensors and actuators such as inkjet printheads, BAW, microphones, microspeakers, optical MEMS, MEMS autofocus…
- Experience in piezoMEMS manufacturing is increasing, and we observe some changes in the industry with PVD, and particularly sputtering techniques becoming the deposition technology of choice.



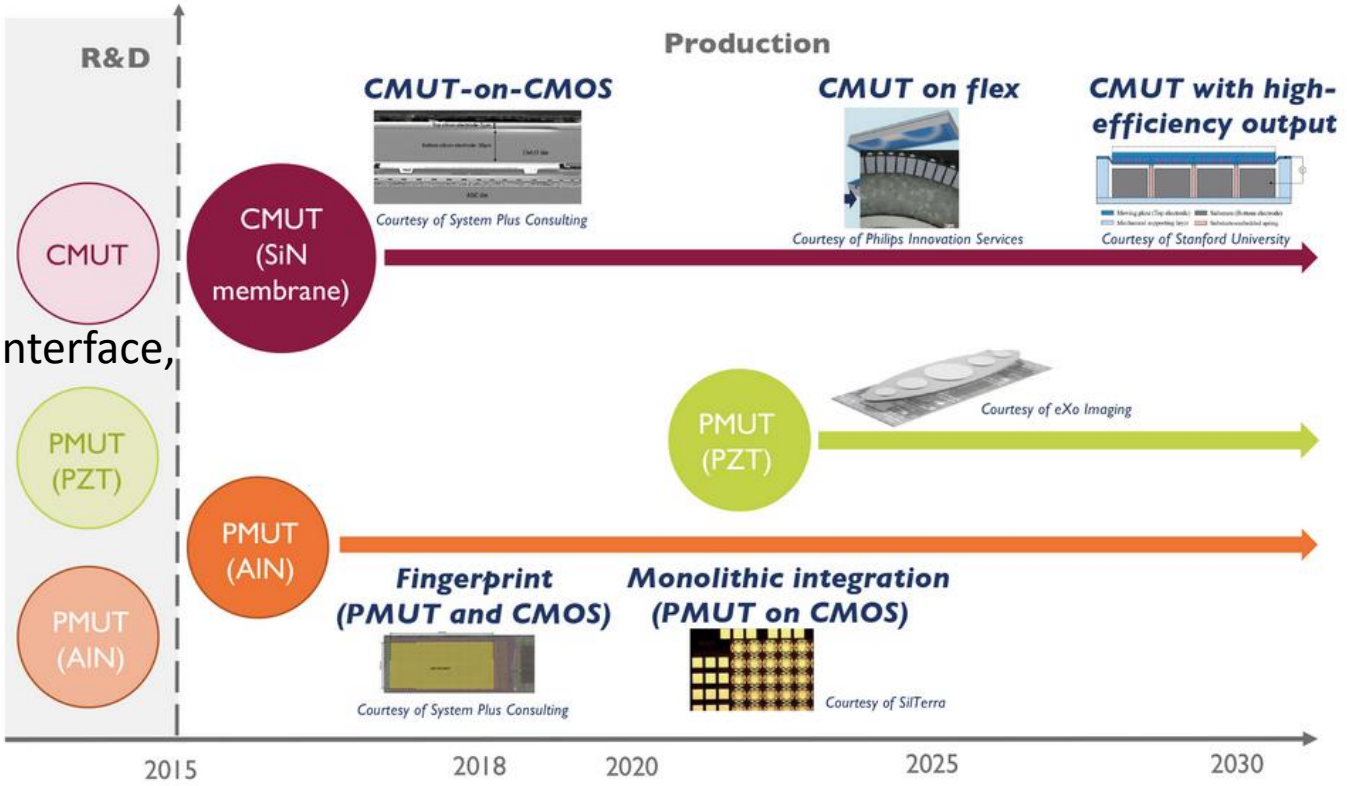
* *Keeping both sol-gel and sputtering techniques in-house*


Piezo MEMS time to market: 2018-2025
Start time of thin film technology availability for commercial products
MEMS gyroscope
BAW Filters
Inkjet printheads
Microphones
Microspeakers
PMUT for fingerprint
PMUT – Gesture recognition
Autofocus
PMUT for Ultrasound probe
Micropumps
2005
2010
2015
2020
2025
(Yole Développement, June 2019)

Imaging
at low cost
for
human machine-interface,
finger print,
echography…

Ultrasound technologies roadmap CMUT & PMUT focus

(Source: Ultrasound Sensing Technologies 2020, November 2020 report, Yole Développement, 2020)



CMUT: Capacitive Micromachined Ultrasonic Transducers - PMUT: Piezoelectric Micromachined Ultrasonic Transducers
AlN: Aluminum Nitride - PZT: Lead Zirconate Titanate - CMOS: Complementary Metal Oxide Semiconductor

YOLE Développement

MEMS MICROSPEAKER MARKET TRENDS

3
Main drivers

Sound Quality

High fidelity sound quality
Low distortion

Thinner Devices

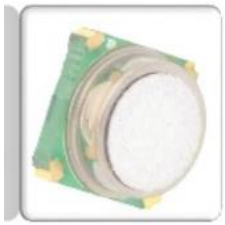
Reducing speaker box volume

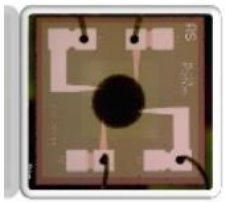
More Output Power with Lower Power Consumption

Startups

Arioso	Audio Pixels	Sonic Edge	USound	xMEMS
• Fraunhofer IPMS spin-off. • Initial funding €2.6M (2020). • Based on NED electrostatic actuators.	• In development for a long time - over 15 years. • No real product yet as performance is not clear.	• Founded in 2019. • Raised $80k for its MEMS microspeaker technology via an EU project.	• Established in 2014. • Initial funding €17M. • Last round (May 2019) raised $30M.	• California startup. • Claims a "true MEMS-based speaker", a membrane and actuator monolithically integrated. • Has raised $11M in funding since 2017.

FUTURE CHALLENGES & ROADMAP FOR GAS AND PARTICLE SENSORS





ams

AMS source

Size (sub mm²) **& cost reduction**

Using MEMS manufacturing for gas sensors and e-noses

Intelligence

AI

Edge computing

Combo

Pressure

Humidity

VOC, CO_2

Temperature

PM1-10

Low power (10s of mW)

CNT

Printing process

Increased selectivity (to the ppb)

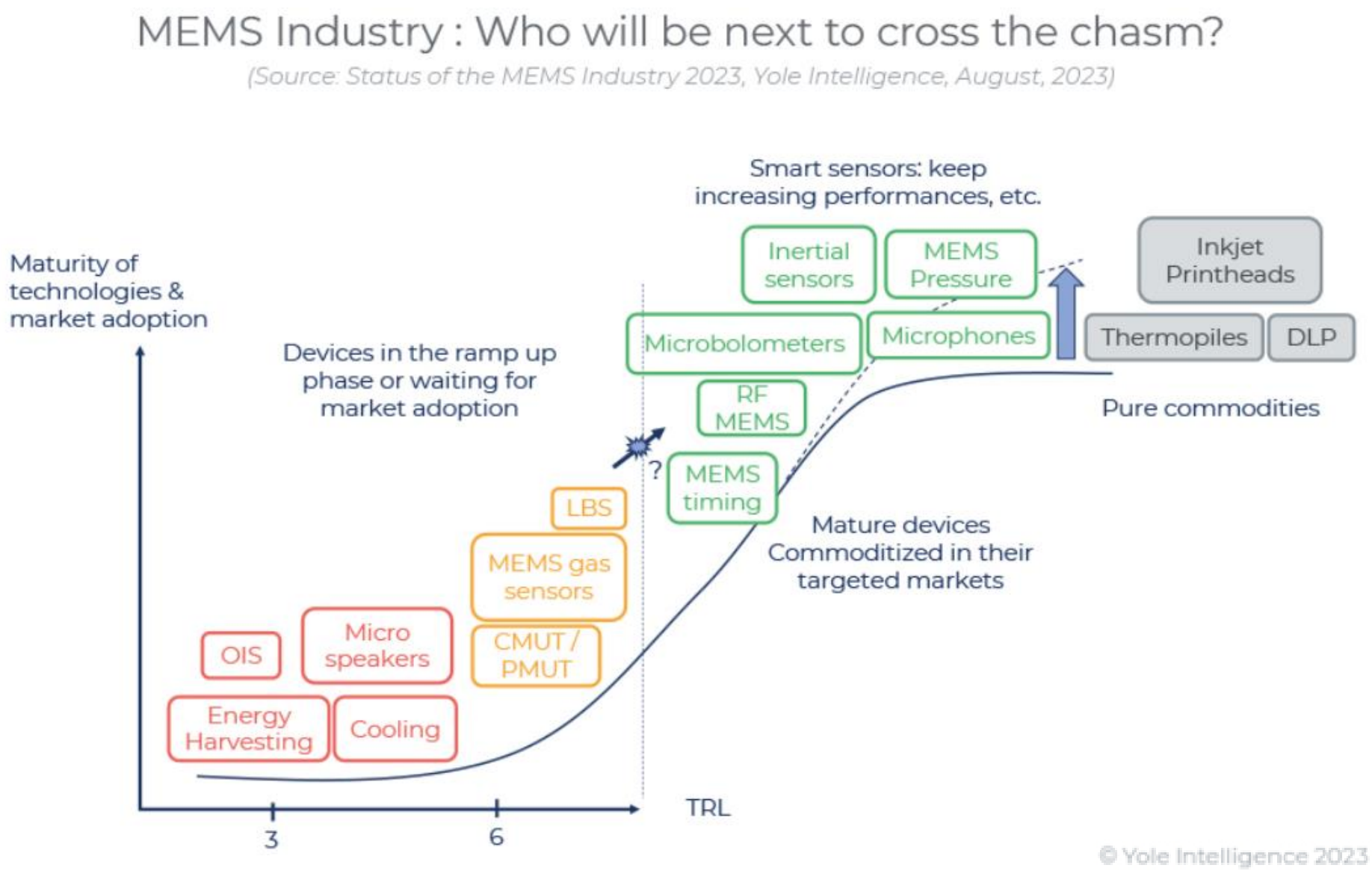
Multi-pixels for detection of multiple gases (MOS)

Dual-channels for detection of multiple gases (NDIR)

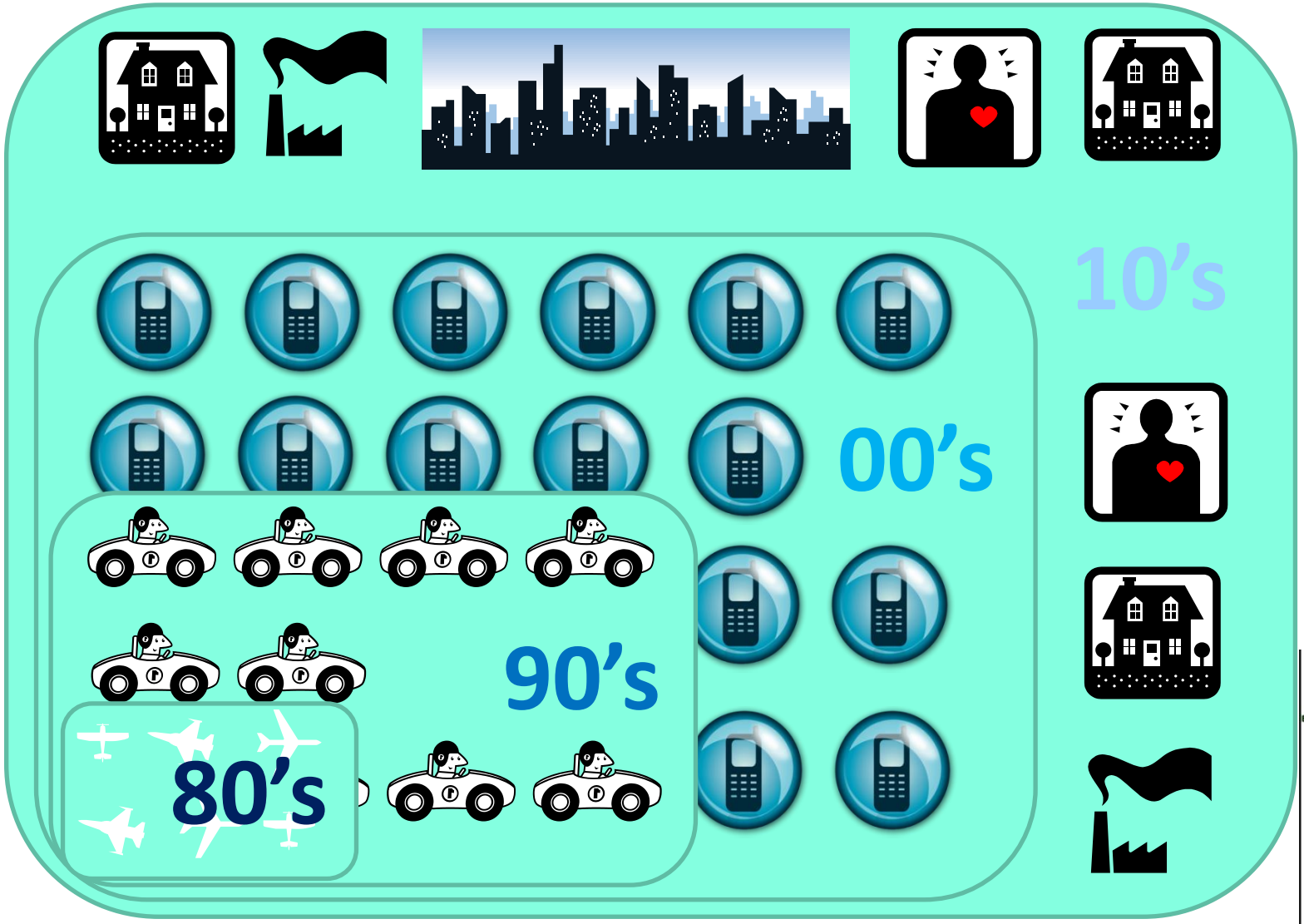
UFPM (<1µ)

From LED to LD source for PM

MEMS intro: Maturity

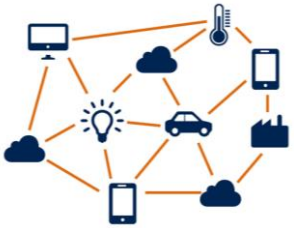


MEMS intro: Historical Perspective

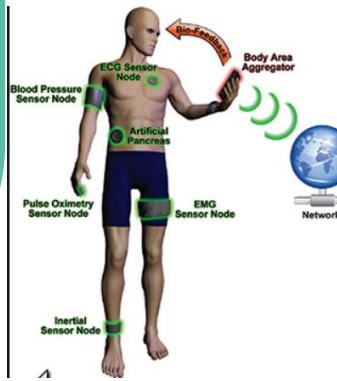


Upcoming waves

- IoT



- Wearables



From CEA-LETI

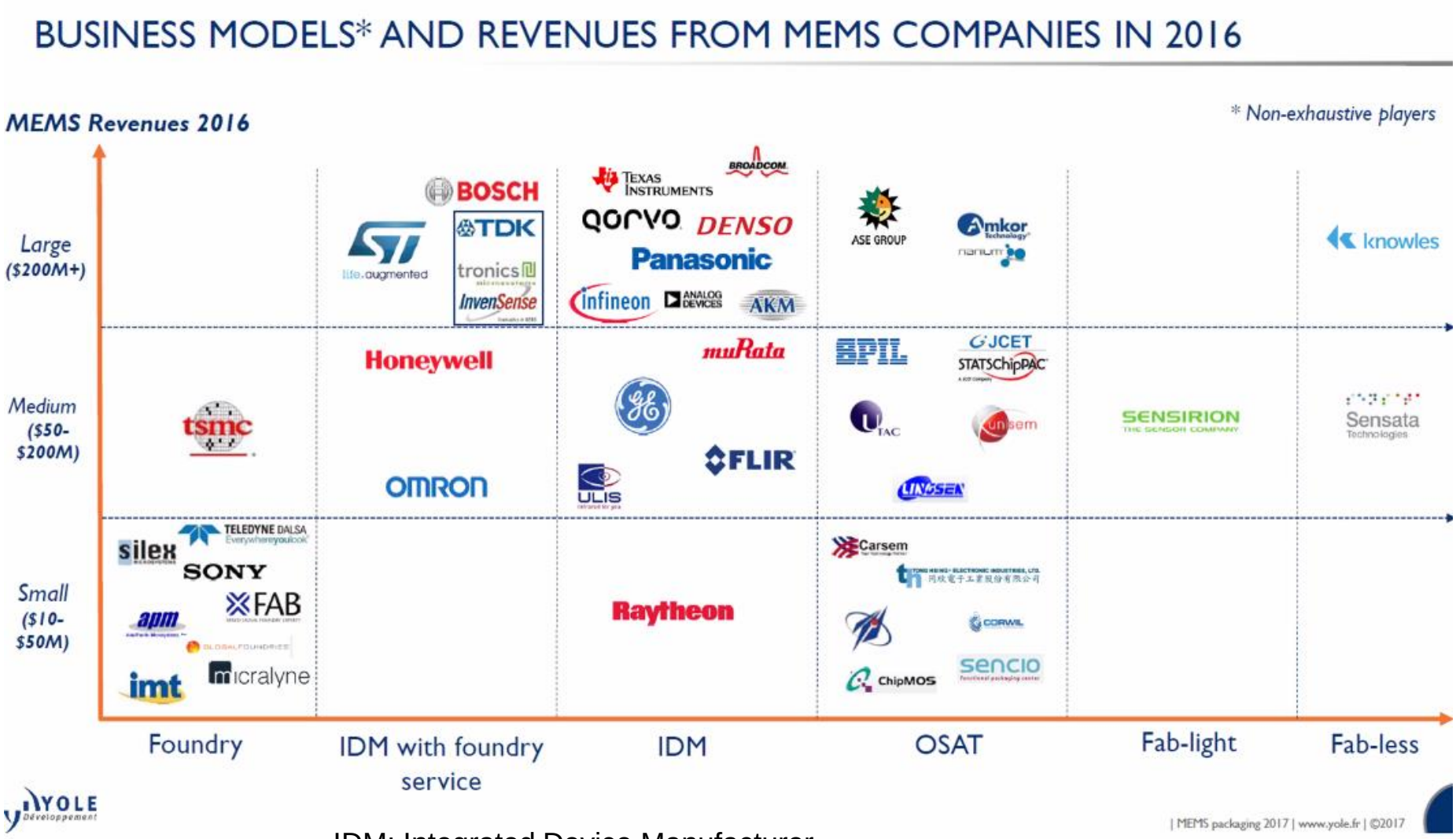
MEMS intro: Industrial Actors

From CEA-LETI

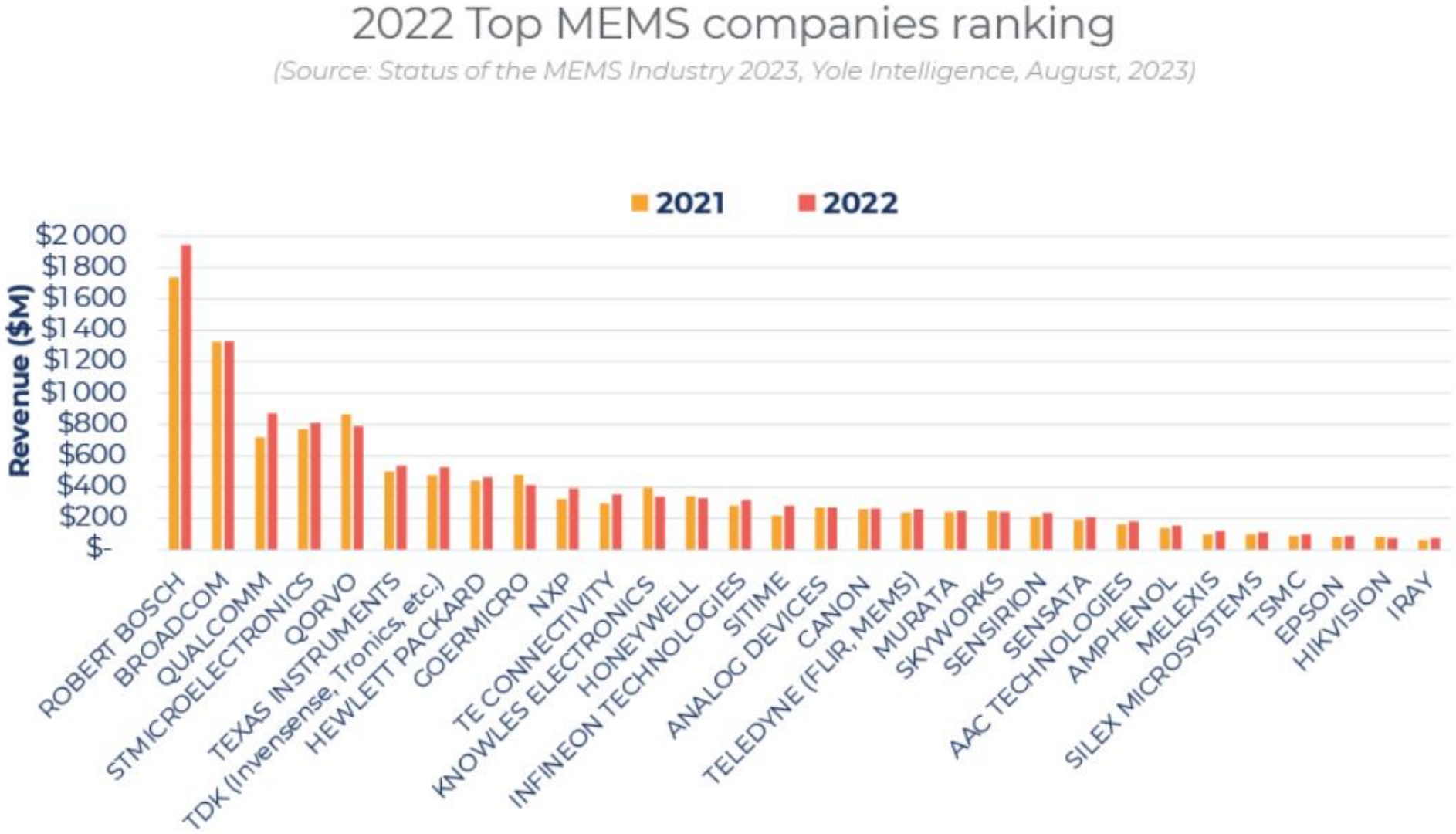
MEMS intro: Industrial Actors

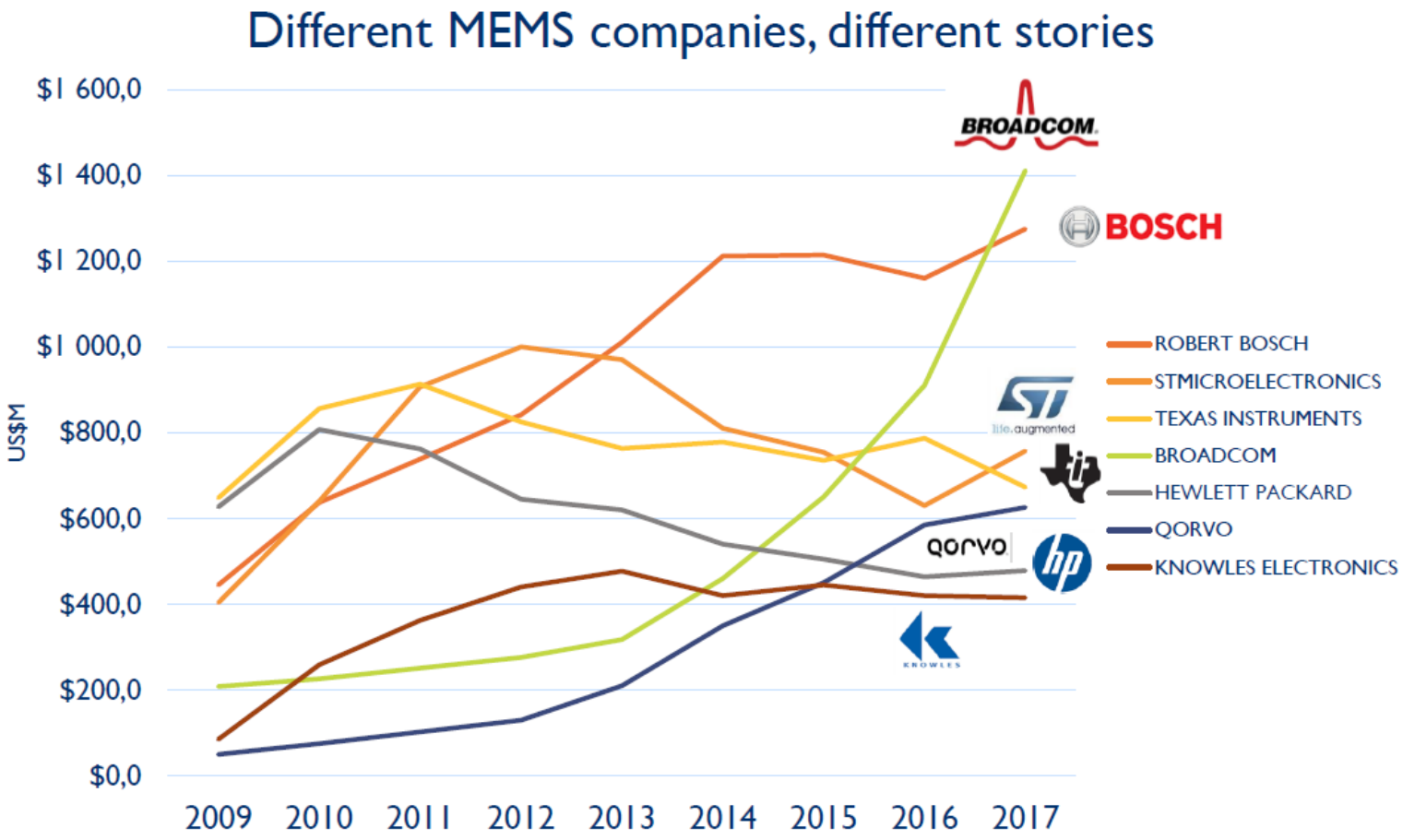
- **Bosch:** Inertial MEMS inertiels (Accelerometers, gyros, magnetometers), pressure sensors / for automotive and 'consumer'
- **ST:** Inertial MEMS, Pressure sensors, microphones, + fab / mainly for 'consumer'
- **TI:** DLP (Digital Light Processor) for projectors
- **HP:** Inkjet print heads
- **Avago:** BAW filters for FEM (front-end module)
- **Denso:** Inertial MEMS / for the automotive
- **Panasonic:** Inertial MEMS/ for the automobive
- **Qorvo:** BAW filters for FEM (front-end module)
- **InvenSense:** Inertial MEMS, pressure sensors, microphones
- **Freescale:** Inertial MEMS, pressure sensors / mainly for automotive
- **Knowless:** Microphones

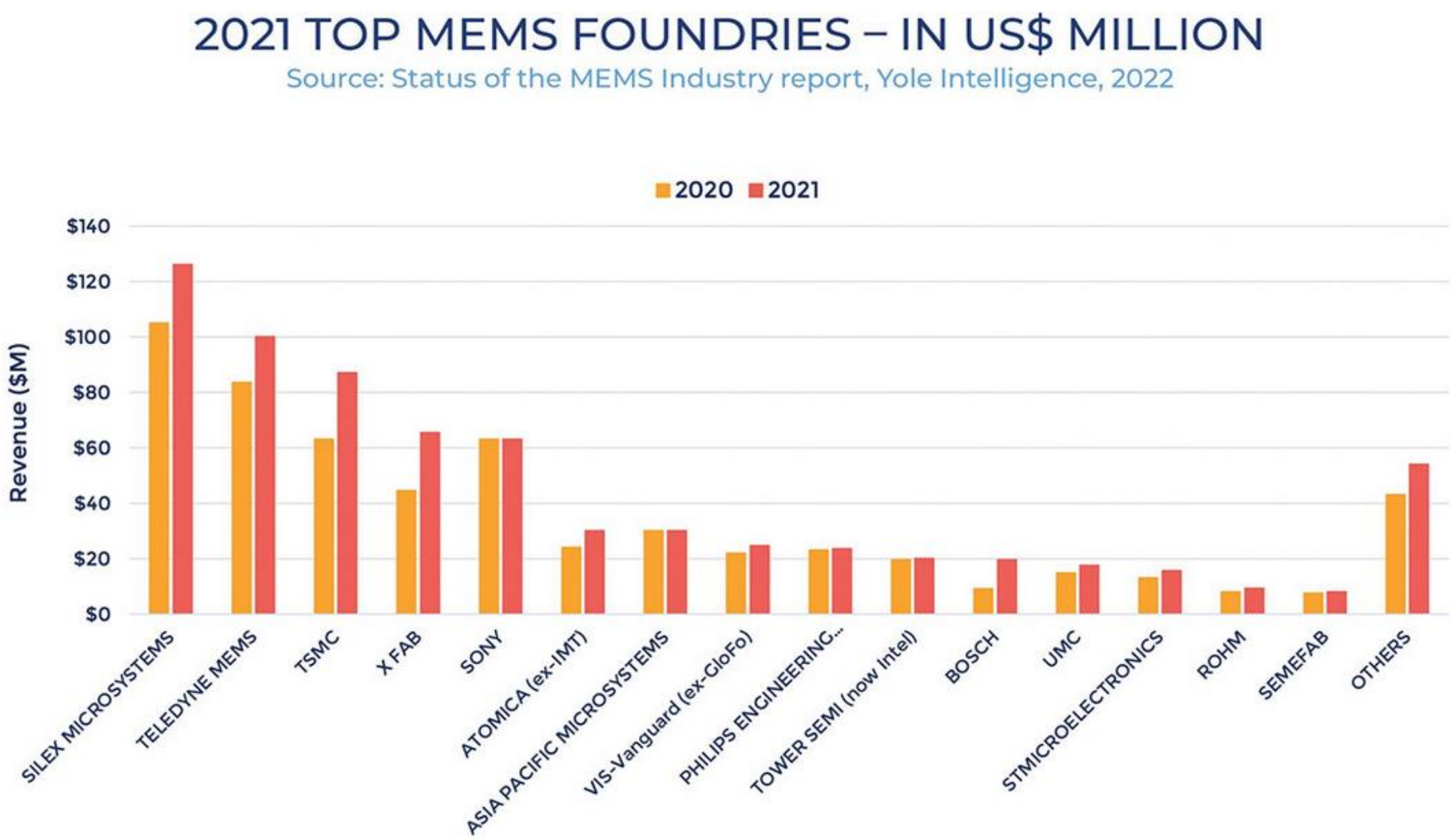
From CEA-LETI



IDM: Integrated Device Manufacturer
OSAT: Outsourced Semiconductor Assembly & Test

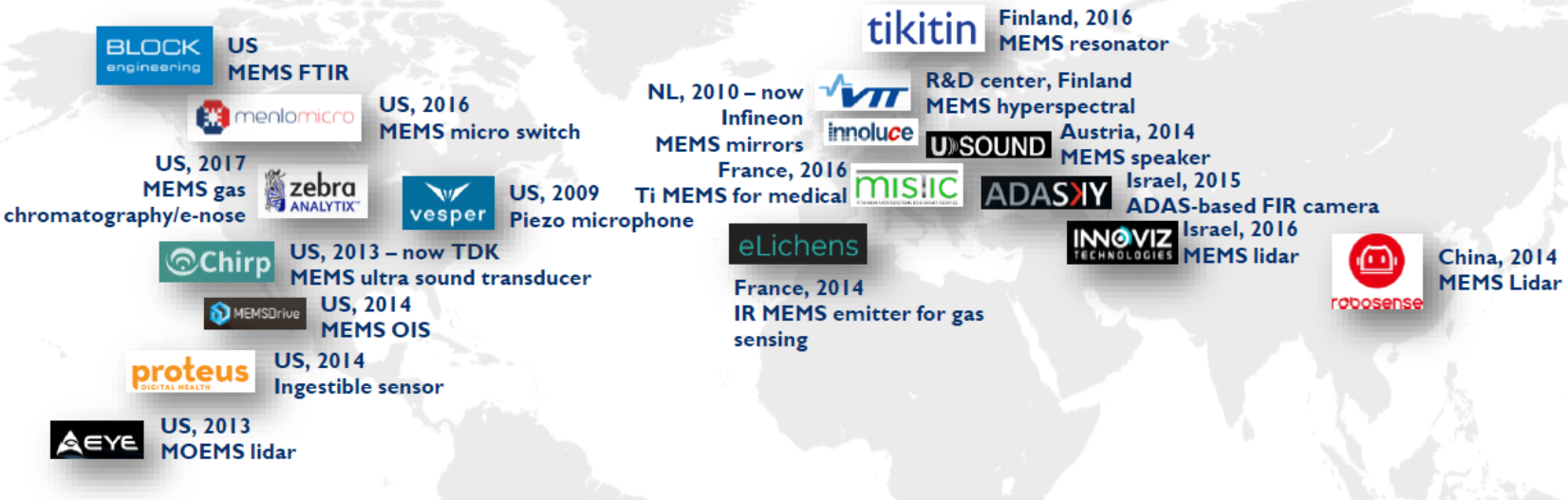

2022 Top MEMS companies ranking
(Source: Status of the MEMS Industry 2023, Yole Intelligence, August, 2023)
2021
2022
Revenue ($M)
$2 000
$1 800
$1 600
$1 400
$1 200
$1 000
$800
$600
$400
$200
$-
ROBERT BOSCH
BROADCOM
QUALCOMM
STMICROELECTRONICS
QORVO
TEXAS INSTRUMENTS
TDK (Invensense, Tronics, etc.)
HEWLETT PACKARD
GOERMICRO
NXP
TE CONNECTIVITY
KNOWLES ELECTRONICS
HONEYWELL
INFINEON TECHNOLOGIES
SITIME
ANALOG DEVICES
CANON
TELEDYNE (FLIR, MEMS)
MURATA
SKYWORKS
SENSIRION
SENSATA
AAC TECHNOLOGIES
AMPHENOL
MELEXIS
SILEX MICROSYSTEMS
TSMC
EPSON
HIKVISION
IRAY



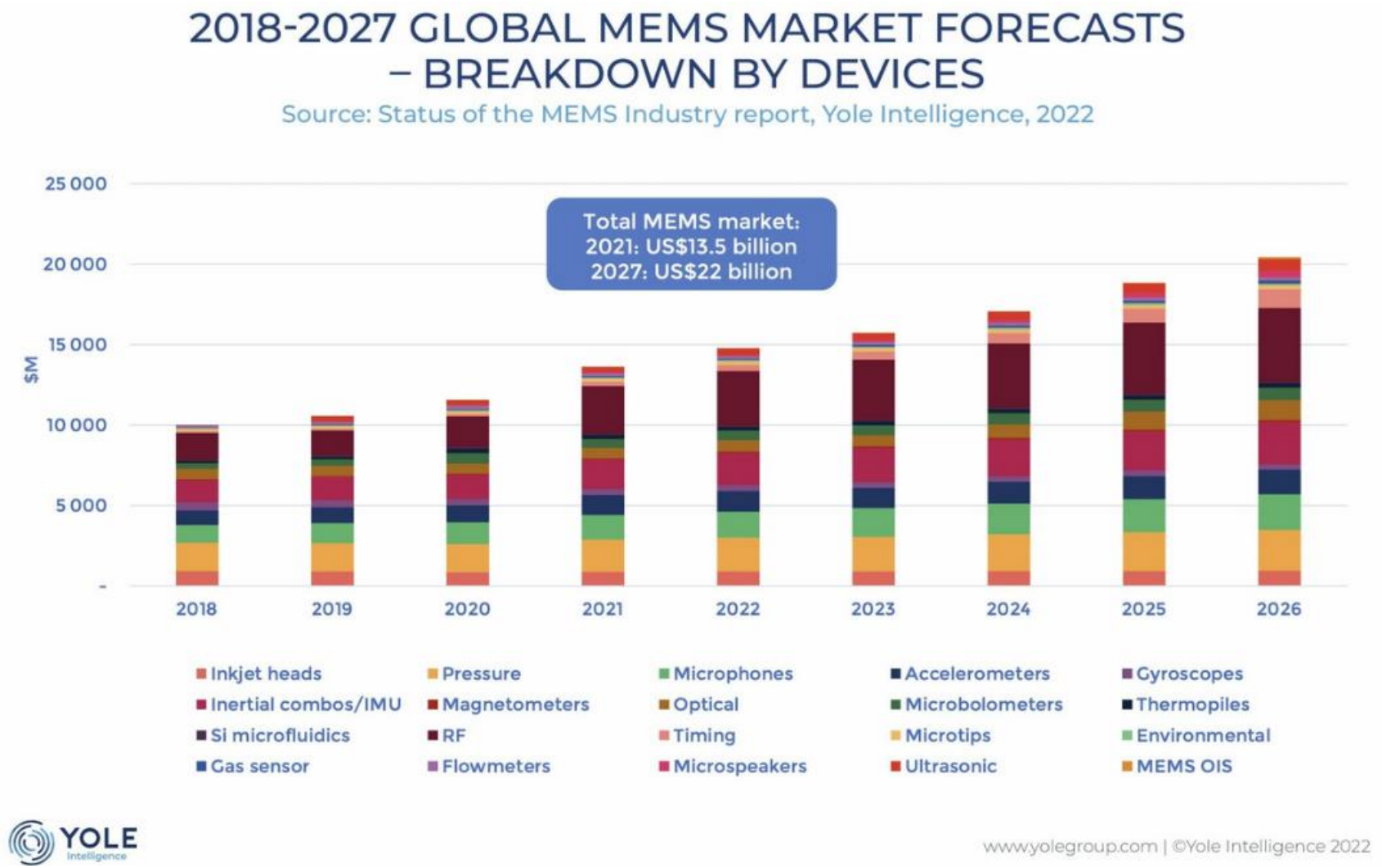


YOLE Intelligence

MEMS IS STILL AN INNOVATIVE TECHNOLOGY – STARTUPS TO FOLLOW



These MEMS startups are today paving the way to new type of MEMS sensors and actuators: piezo MEMS, titaniumMEMS, FTIR, e-nose, ultra-sounds and acoustic, FIR and hyperspectral, micro mirrors, switches, resonators.


2018-2027 GLOBAL MEMS MARKET FORECASTS – BREAKDOWN BY DEVICES
Source: Status of the MEMS Industry report, Yole Intelligence, 2022
Total MEMS market:
2021: US$13.5 billion
2027: US$22 billion
$M
25 000
20 000
15 000
10 000
5 000
-
2018
2019
2020
2021
2022
2023
2024
2025
2026
Inkjet heads
Pressure
Microphones
Accelerometers
Gyroscopes
Inertial combos/IMU
Magnetometers
Optical
Microbolometers
Thermopiles
Si microfluidics
RF
Timing
Microtips
Environmental
Gas sensor
Flowmeters
Microspeakers
Ultrasonic
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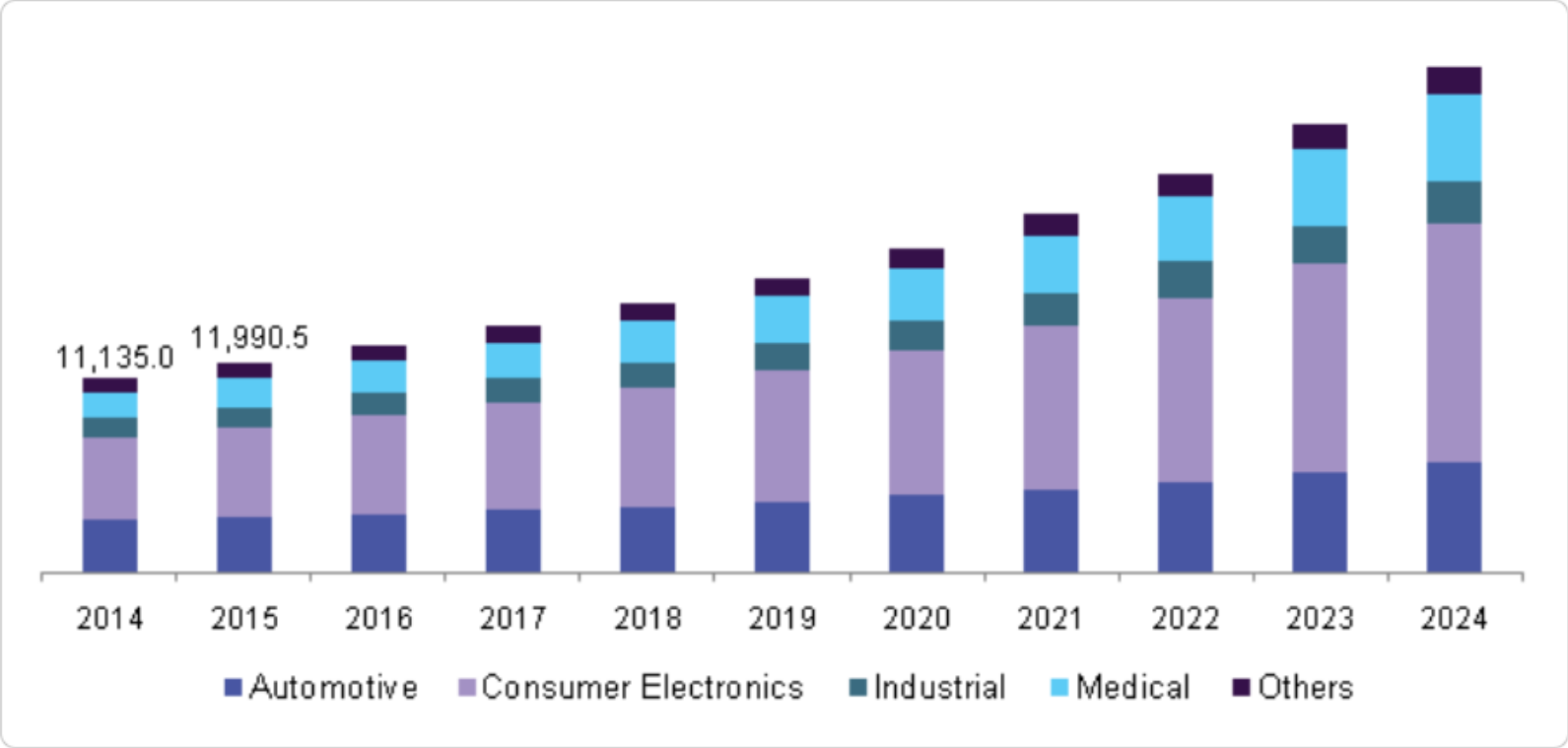
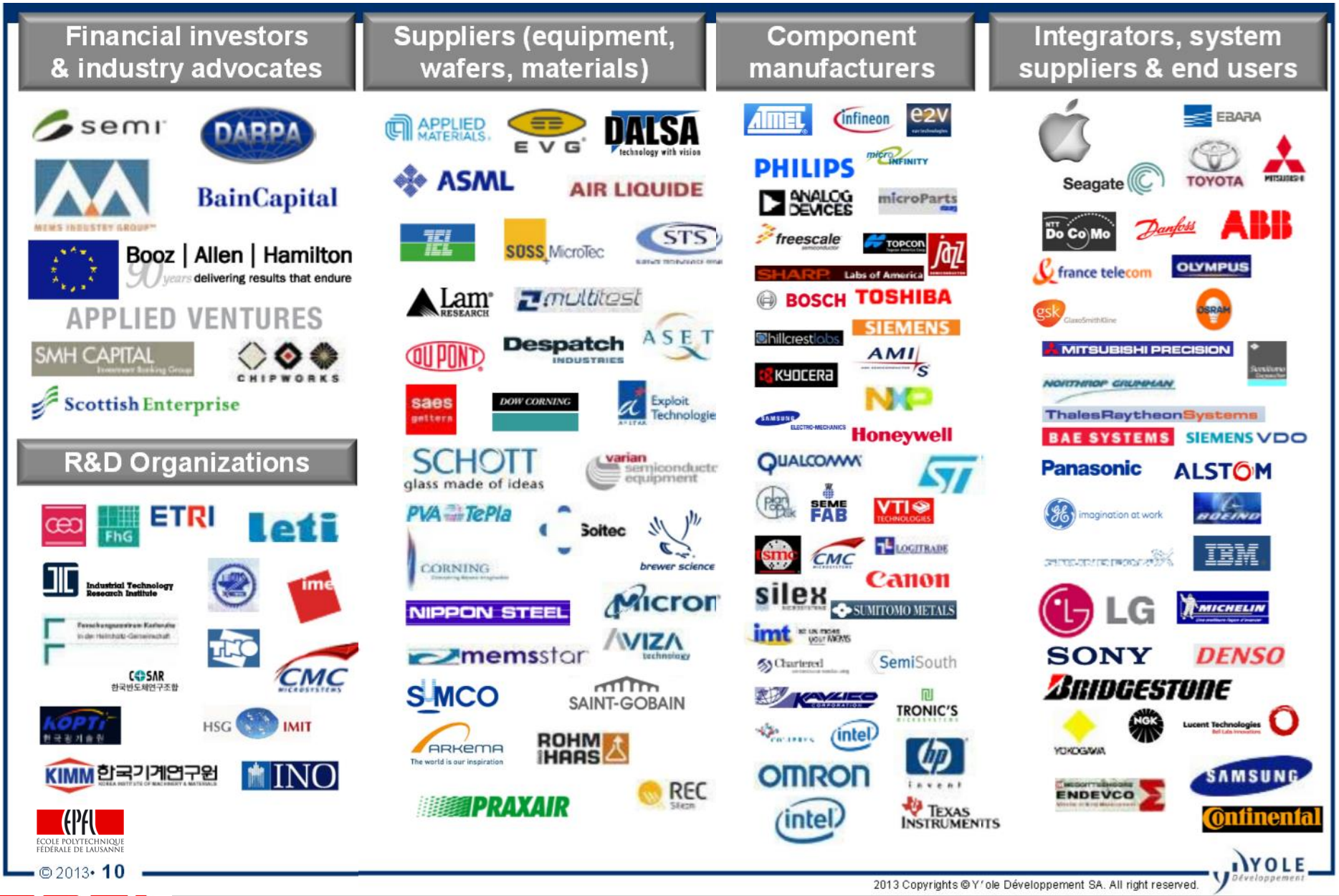
MEMS intro: Market by Applications

Global MEMS market by application, 2014 - 2024 (USD Million)



Grand View Research Report

MEMS intro: Market Players



MEMS chip

- 'MEMS designer': multi-physics modelling and simulation
- Engineer 'Process Integration': to define the process flow
- Test engineer for their characterization

Electronics - ASIC

- ASIC designer: analogic and/or numeric

And also

- Softwares: data/signal treatment, sensors fusion
- Application development engineers
- Field application engineers
- Business development
- Market analysis

MEMS intro: R&D areas

- **Materials:**
  - Polymeric, Nanomaterials, Bio-materials
- **MEMS design and fabrication:**
  - Higher performing and emerging components
  - CMOS technology: electronics integrated
  - Multi-MEMS
  - Packaging: wafer level, thin flat
- **Systems:**
  - Smart systems integration
    - Multi-sensors / sensors fusion
    - Electronics, power source, communication
    - 3D integration
- **Applications**

Conclusions

1. **Practical aspects of the course**
   - When, where, how, who, what….

2. **Course position and structure**
   - Other EPFL classes that cover MEMS, microsystems, microfabrication.
   - How and where does this class fit in.
   - Literature, Journals and conferences

3. **Introduction to MEMS**
   - What are MEMS's and why are they used ?
   - Where do you „find" MEMS?

4. **Trends in the sensor and MEMS field**
   - What is possible now?
   - Where are we going and what can we expect in the future?