EE607: MICROELECTROMECHANICAL SYSTEMS (MEMS)

- Instructor: Prof. Eun Sok Kim (eskim@usc.edu, PHE 602, 740-4697)
  Office Hours: Monday and Friday 3:00 - 3:50pm
- Class Time and Place: Friday 9:00 – 11:50am GFS 221
  Monday 5:00 – 5:50pm GFS 221
- Textbook: Fundamentals of MEMS by E.S. Kim (1st Edition Published April 2021 by McGraw Hill)
- EE 607 covers technology methods and physical principles of MEMS including survey of current MEMS.
- Prerequisite: Understanding of basic microfabrication technology is useful, but is not required.
- The following books may be helpful on some specific topics of the course.
  - Micromachined Transducers Sourcebook by Gregory Kovacs
  - Fundamentals of Microfabrication by Marc Madou
  - Introduction to Microelectromechanical Systems Engineering by Nadim Maluf
  - Microsystem Design by Stephen Senturia
  - RF MEMS Theory, Design and Technology by Gabriel Rebeiz
  - Microsensors, MEMS and Smart Devices by Julian Gardner, et al.
  - Foundations of MEMS by Chang Liu

Course Contents and Grading

- Week 1: Introduction to MEMS
- Week 2: Basic Microfabrication (Ch. 1)
  - Photolithography, Soft Lithography, Thin-Film Deposition, Electroplating, Wafer Bonding, etc.
- Weeks 3 - 4: Micromachining (Ch. 2)
  - Bulk Micromachining, Surface Micromachining, Dry Micromachining
- Week 5: Transduction Principles (Ch. 3)
  - Electrostatic and Capacitive, Electromagnetic, Piezoelectric, Electrothermal, Uncooled IR Imaging
- Week 6: RF MEMS (Ch. 4)
  - Micromechanical Resonators, Film Bulk Acoustic Resonators, Tunable Capacitors, RF Switches
- Week 7: Optical MEMS (Ch. 5)
  - Projection Display, Optical Cross Connect, Fabry–Perot Photonic Crystal, Filter, Interferometer
- Weeks 8 - 10: Mechanics and Inertial Sensors (Ch. 6)
  - Statics and Dynamics, Beam and Plate Theories, Accelerometers, Vibratory Gyroscopes
- Week 11: Thin-Film Properties (Ch. 7)
  - Residual Stress, Piezoelectric Films, Material Properties Expressed as Tensor
- Week 12: SAW/BAW Sensors, Pressure Sensors, Microphones (Ch. 7)
- Week 13: Microfluidic Systems and Bio-MEMS (Ch. 8)
  - Microchannels and Droplet Formation, Microvalves, Micropumps, Micromixers, Lab-on-Chip
- Week 14: Power MEMS (Ch. 9)
- **Grading:** Homework: 25%, One Midterm Exam: 30%, Final Exam: 45%.
  - All exams are open books and notes.

Homework Assignment

	From “Fundamentals of MEMS”	*Tentative* Due Dates
HW 1	Q1.10, Q1.12, Q1.13, P1.4	Jan. 23
HW 2	Q2.1, Q2.6, Q2.13, P2.4	Feb. 6
HW 3	Q2.9, Q2.15, Q2.16, P2.5	Feb. 13
HW 4	Q3.8, Q3.12, Q3.13, P3.6	Feb. 24
HW 5	Q4.3, Q4.6, Q4.9, Q4.12	Mar. 3
HW 6	Q5.2, Q5.5, Q5.7, Q5.11	Mar. 20
HW 7	Q6.4, Q6.7, Q6.12, P6.3	Mar. 31
HW 8	P6.6, P6.7, P6.8	Apr. 7
HW 9	Q7.3, Q7.5, Q7.7, P7.3	Apr. 14
HW 10	Q8.1, Q8.4, Q8.5, Q to be assigned	Apr. 21
HW 11	Q9.1, Q9.4, P9.1, P9.4	Apr. 28

Additional Course Information

- Midterm Exam: *Tentatively* March 10 (Friday)
- Final Exam: 4:30 – 6:30pm on May 8 (Monday)

- MEMS Journals and Conferences:
  - IEEE/ASME Journal of Microelectromechanical Systems
  - Journal of Micromechanics and Microengineering
  - Sensors and Actuators Journal (Elsevier Sequoia Publishing, Switzerland)
  - Sensors and Materials Journal (Japan)
  - Sensors Magazine
  - International Conference on Solid-State Sensors and Actuators (Transducers Conf.)
  - Solid-State Sensor & Actuator Workshop, Hilton Head Island, SC (Hilton Head Workshop)
  - Micro Electro Mechanical Systems (MEMS) Workshop/Conference.

Statement on Academic Conduct and Support Systems

Academic Conduct

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in *SCampus* in Section 11, *Behavior Violating University Standards* https://scampus.usc.edu/1100-behavior-violating-university-standards-and-appropriate-sanctions/. Other forms of academic dishonesty are equally unacceptable. See additional information in *SCampus* and university policies on scientific misconduct, http://policy.usc.edu/scientific-misconduct/. Discrimination, sexual assault, and harassment are not tolerated by the university. You are encouraged to report any incidents to the *Office of Equity and Diversity* http://equity.usc.edu/ or to the *Department of Public Safety* http://capsnet.usc.edu/department/department-public-safety/online-forms/contact-us. This is important for the safety whole USC community. Another member of the university community – such as a friend, classmate, advisor, or faculty member – can help initiate the report, or can initiate the report on behalf of another person. The *Center for Women and Men* http://www.usc.edu/student-affairs/cwm/ provides 24/7 confidential support, and the sexual assault resource center webpage sarc@usc.edu describes reporting options and other resources.

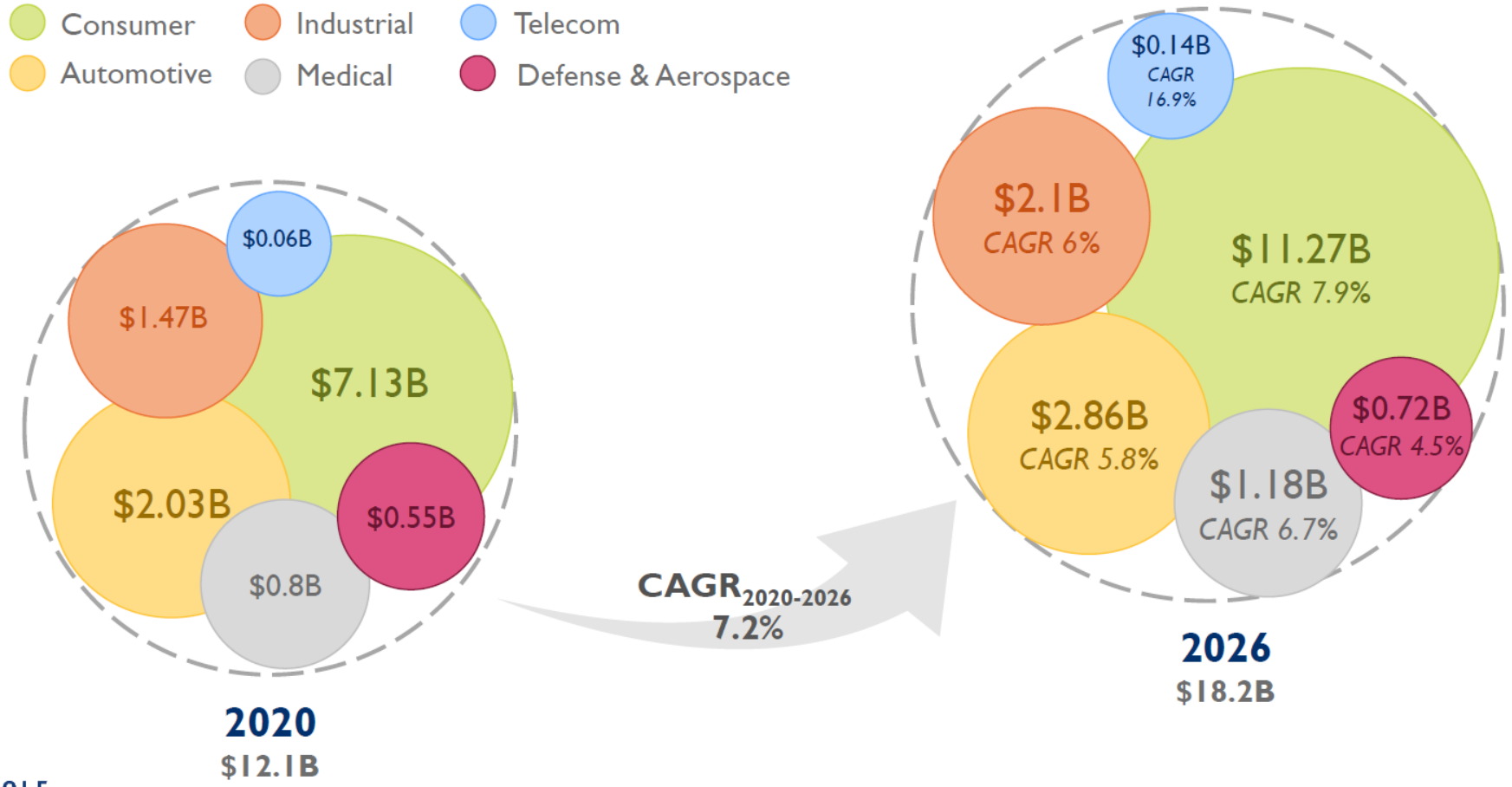
Support Systems

A number of USC's schools provide support for students who need help with scholarly writing. Check with your advisor or program staff to find out more. Students whose primary language is not English should check with the *American Language Institute* http://dornsife.usc.edu/ali, which sponsors courses and workshops specifically for international graduate students. The *Office of Disability Services and Programs* http://sait.usc.edu/academicsupport/centerprograms/dsp/home_index.htmlprovides certification for students with disabilities and helps arrange the relevant accommodations. If an officially declared emergency makes travel to campus infeasible, *USC Emergency Information* http://emergency.usc.edu/will provide safety and other updates, including ways in which instruction will be continued by means of blackboard, teleconferencing, and other technology.

Diversity Statement

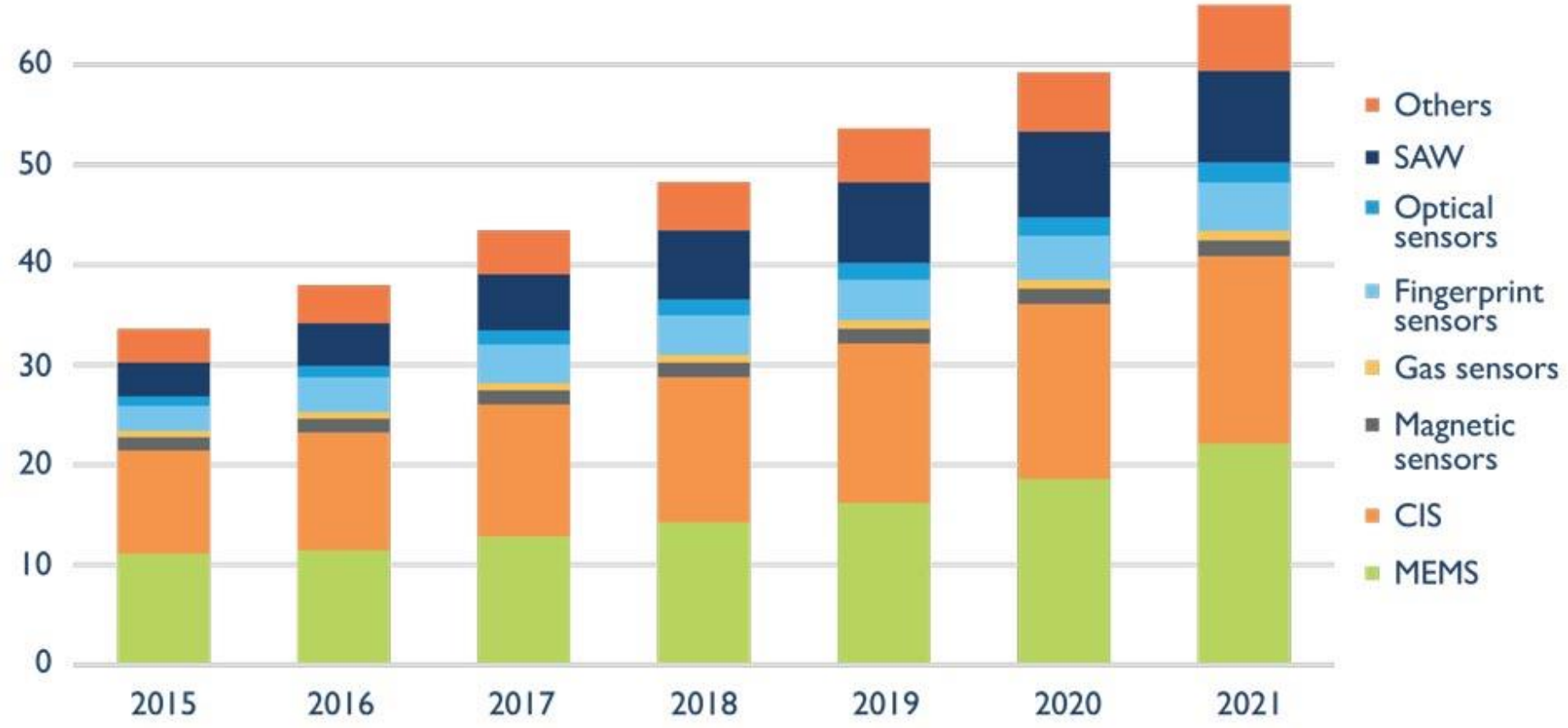
The diversity of the participants in this course is a valuable source of ideas, problem solving strategies, and engineering creativity. I encourage and support the efforts of all of our students to contribute freely and enthusiastically. We are members of an academic community where it is our shared responsibility to cultivate a climate where all students and individuals are valued and where both they and their ideas are treated with respect, regardless of their differences, visible or invisible.

MEMS MARKET DYNAMICS FORECAST BY END-MARKET

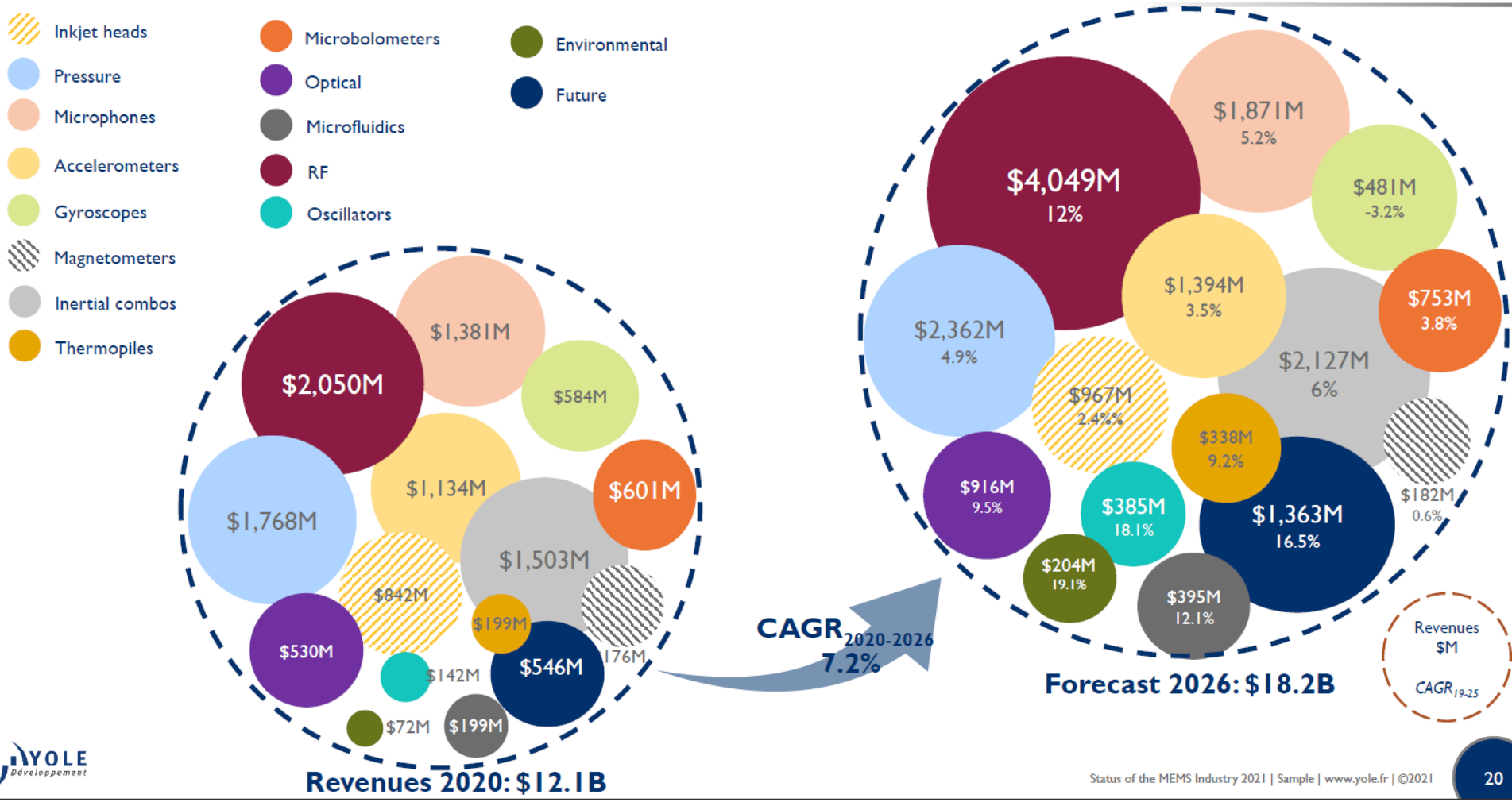


MEMS and sensors revenue market in B$

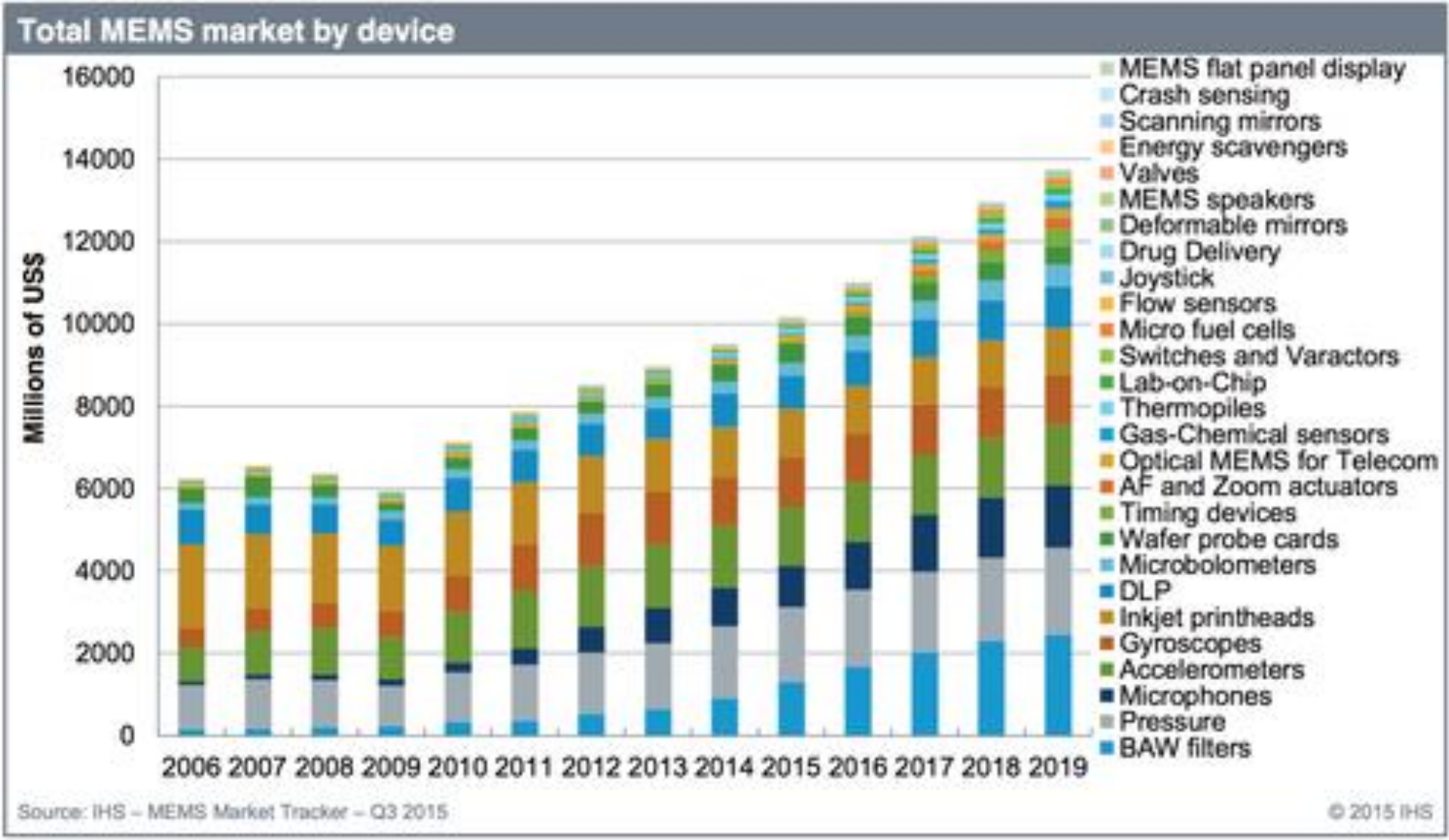
(Source : Status of the MEMS Industry 2017, June 2017, Yole Développement)



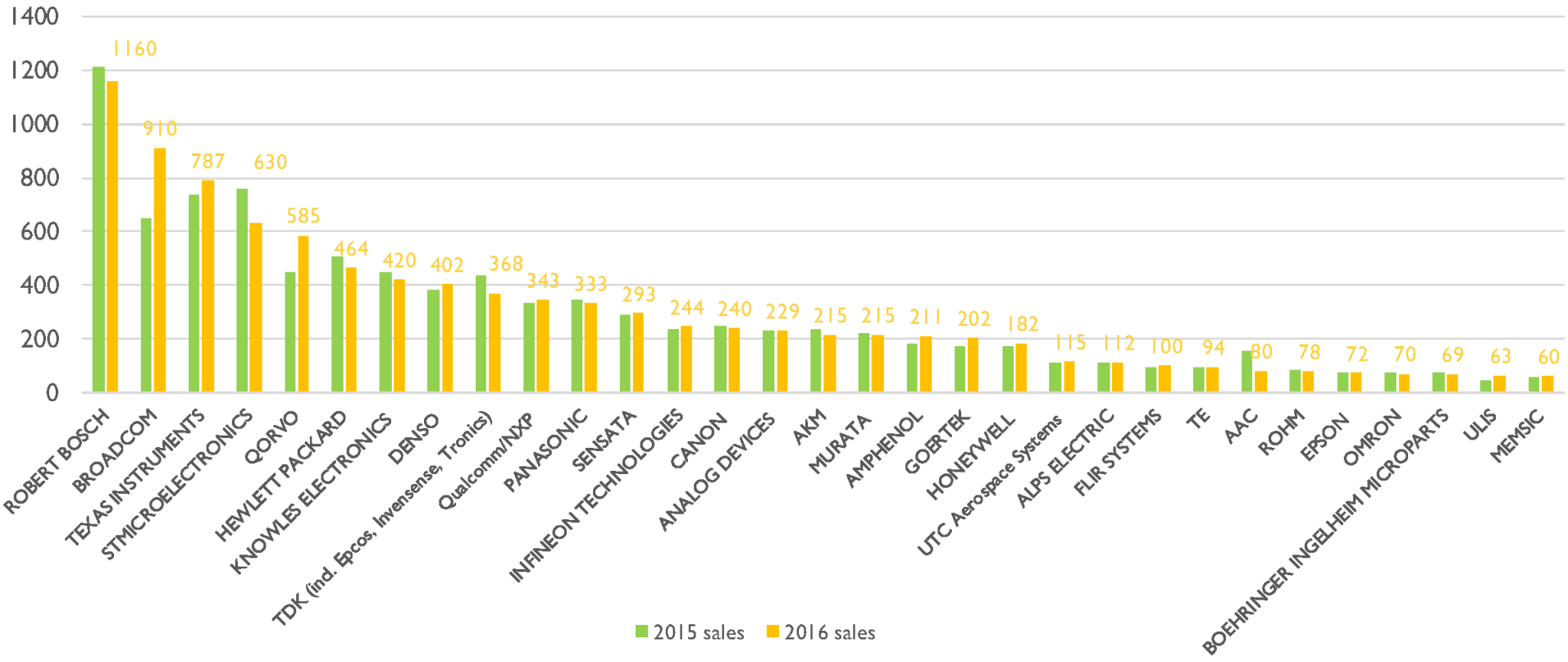
MEMS MARKET DYNAMICS BY DEVICE



MEMS Market by Device – Q3 2015

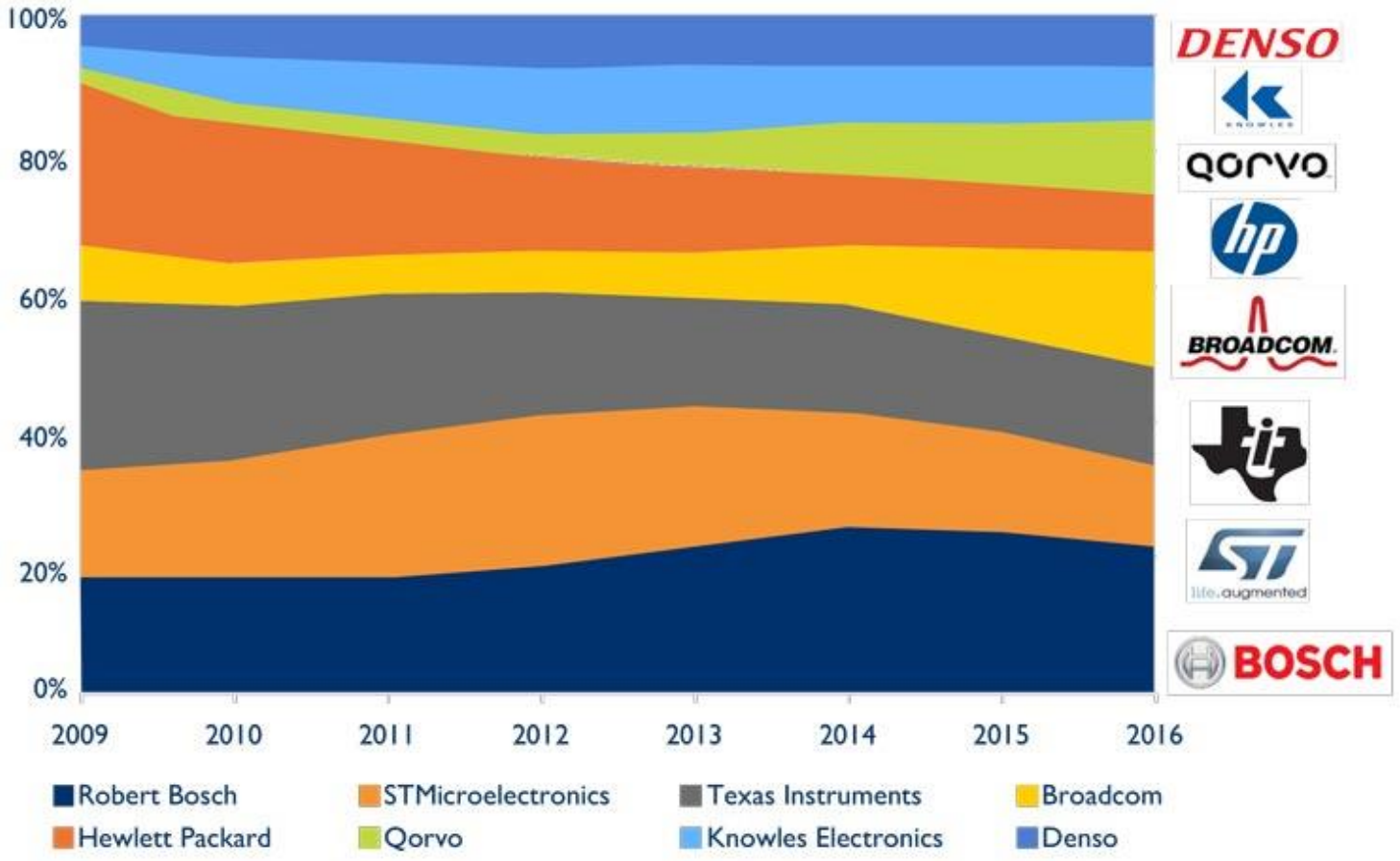


Top 30 MEMS Companies by Revenue ($M) in 2016



Relative market share history for the top eight MEMS players

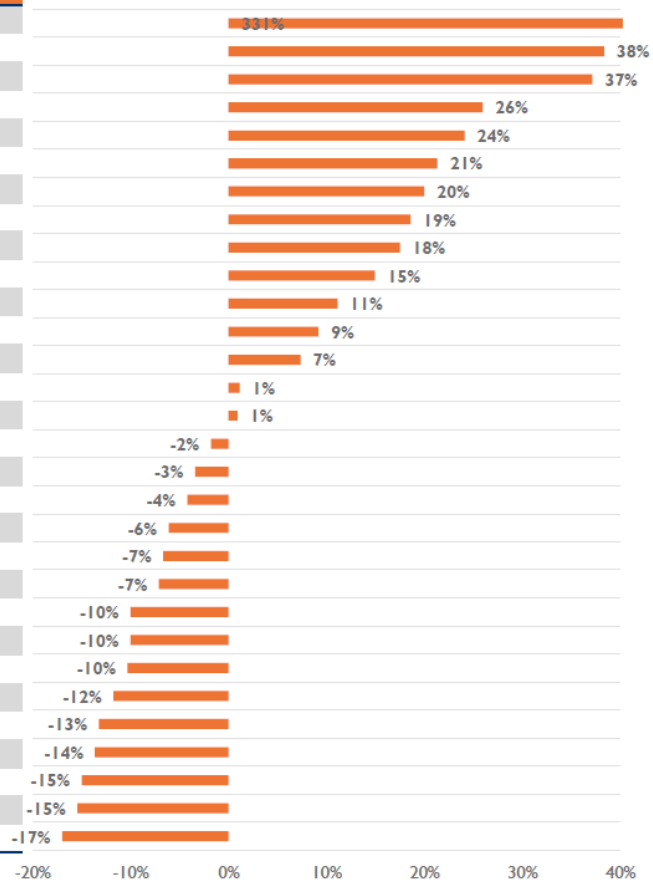
(Source : Status of the MEMS Industry 2017, June 2017, Yole Développement)



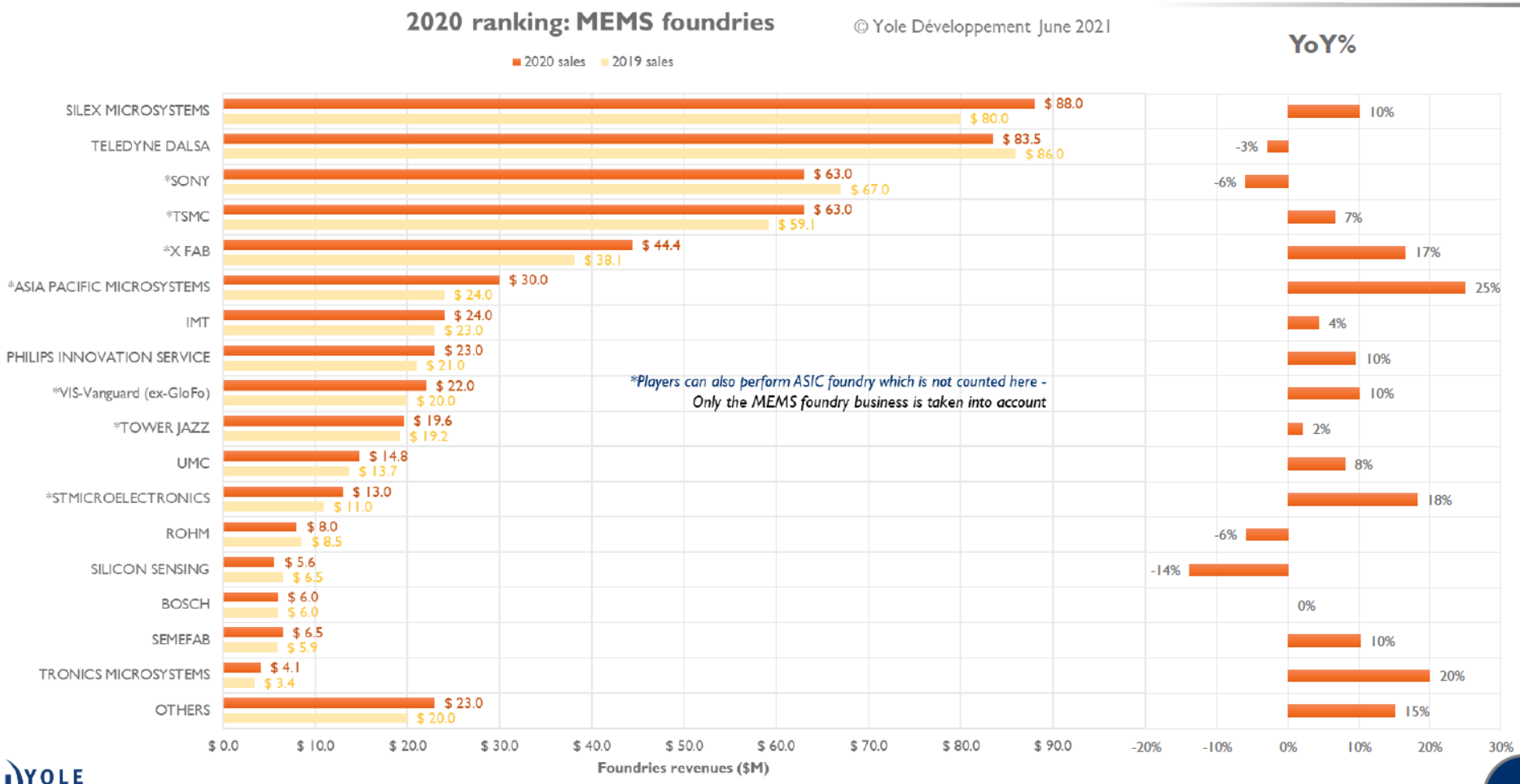
TOP-30 PLAYERS GROWTH RANKING

RF MEMS companies had the biggest MEMS business growths followed by thermal MEMS and microphones.

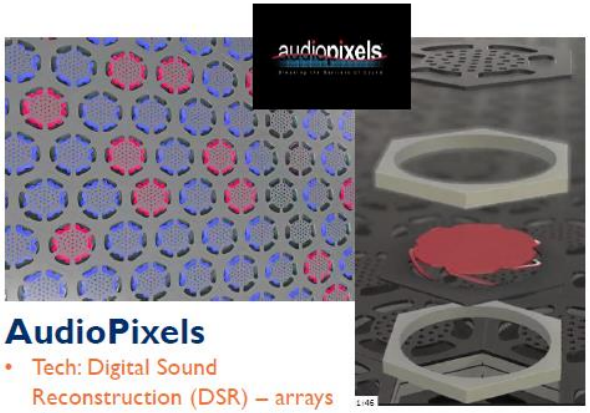
Player	2019	2020	YoY
GUIDE IR	$ 20	$ 84	331%
SI TIME	$ 84	$ 116	38%
QORVO	$ 490	$ 672	37%
AAC	$ 131	$ 165	26%
FLIR SYSTEMS	$ 110	$ 137	24%
MELEXIS	$ 61	$ 74	21%
BROADCOM	$ 991	$ 1,189	20%
CANON	$ 222	$ 264	19%
GOERMICRO	$ 400	$ 470	18%
LYNRED (ex-ULIS)	$ 101	$ 116	15%
AMPHENOL	$ 108	$ 120	11%
INFINEON TECHNOLOGIES	$ 305	$ 333	9%
ROBERT BOSCH	$ 1,599	$ 1,716	7%
STMICROELECTRONICS	$ 604	$ 611	1%
TDK	$ 393	$ 397	1%
AKM	$ 224	$ 220	-2%
ALPS ALPINE	$ 118	$ 114	-3%
EPSON	$ 86	$ 82	-4%
RF 360 (Qualcomm+EPCOS)	$ 82	$ 77	-6%
ANALOG DEVICES	$ 255	$ 238	-7%
KNOWLES ELECTRONICS	$ 465	$ 432	-7%
HONEYWELL	$ 290	$ 261	-10%
MURATA	$ 240	$ 216	-10%
HEWLETT PACKARD	$ 493	$ 442	-10%
SENSATA	$ 149	$ 132	-12%
TE CONNECTIVITY	$ 300	$ 260	-13%
NXP	$ 301	$ 260	-14%
COLLINS AEROSPACE	$ 120	$ 102	-15%
PANASONIC	$ 285	$ 241	-15%
TEXAS INSTRUMENTS	$ 595	$ 494	-17%



MEMS FOUNDRIES RANKING



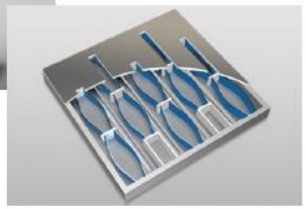
MEMS MICROSPEAKERS: DIFFERENT STRUCTURES



AudioPixels

- Tech: Digital Sound Reconstruction (DSR) – arrays of pressure generating drivers

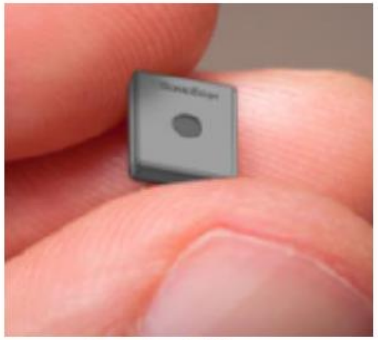
ARIOSO SYSTEMS



Arioso Systems

- Size: 10mm²
- Up to 120 dB SPC
- Tech: All-Silicon Nanoscopic Electrostatic Drive (NED)

SONICEDGE

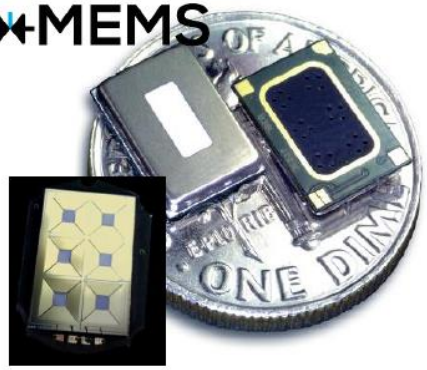


Sonic Edge

N/A

Principle: modulation of an ultrasound signal to generate a high quality sound

xMEMS



xMEMS

- Full bandwidth (20Hz-20kHz) with flat frequency response at 115dB SPL (sealed)
- Size: 50mm3
- Thickness: <1mm thickness
- Better SPL/mm3
- Tech: Monolithically integrated piezo-MEMS

U))) SOUND

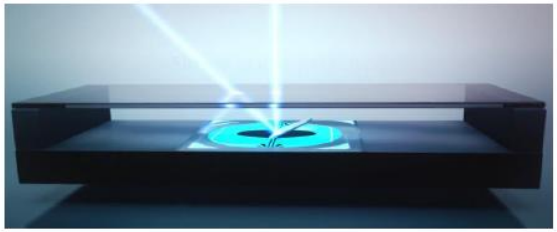
Usound

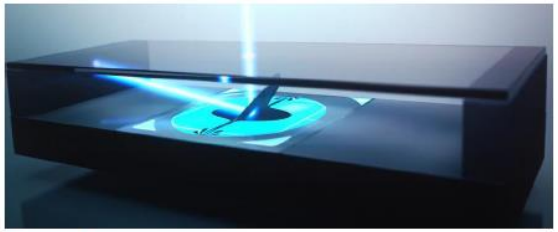
- Size: 4.7mm x 6.7mm
- Width: 1.6 mm
- Up to 74 dB SPC
- Tech: MEMS PZT actuators with classic membrane on top

OPTICAL MEMS STAND-ALONE MIRRORS

Bubble MEMS for LiDAR and AR/VR applications

With a simple planar packaging, it is impossible to have a 180° scanning → limited performances at large scanning angles

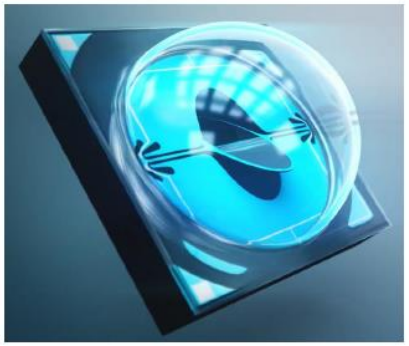




Courtesy of OQmented

Bubble MEMS could be the next generation of packaging for stand-alone mirrors.

OQmented has developed "Bubble MEMS": a wafer-level packaging technique, using a spherical vacuum encapsulation. Done in 8" platform.

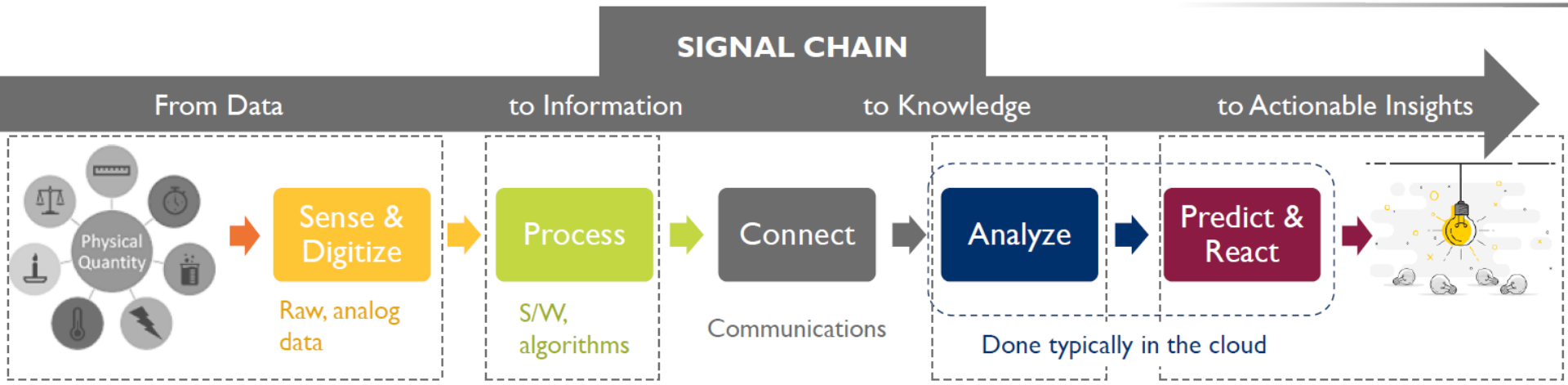


Courtesy of OQmented

- Spherical → **180° scanning**
- Wafer-level packaging → **high volumes**
- Vacuum encapsulation
  - → no moisture and dust
  - → better **reliability** and **lifetime**
- Unique Lissajous scanning:

Faster screen refresh rate than normal scanning

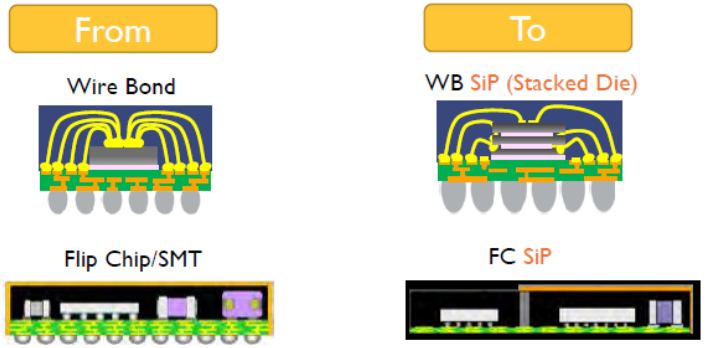
HETEROGENEOUS INTEGRATION: MOVING UP THE SIGNAL CHAIN



Heterogeneous integration is key

Challenges for heterogeneous integration (source IRDS 2020):

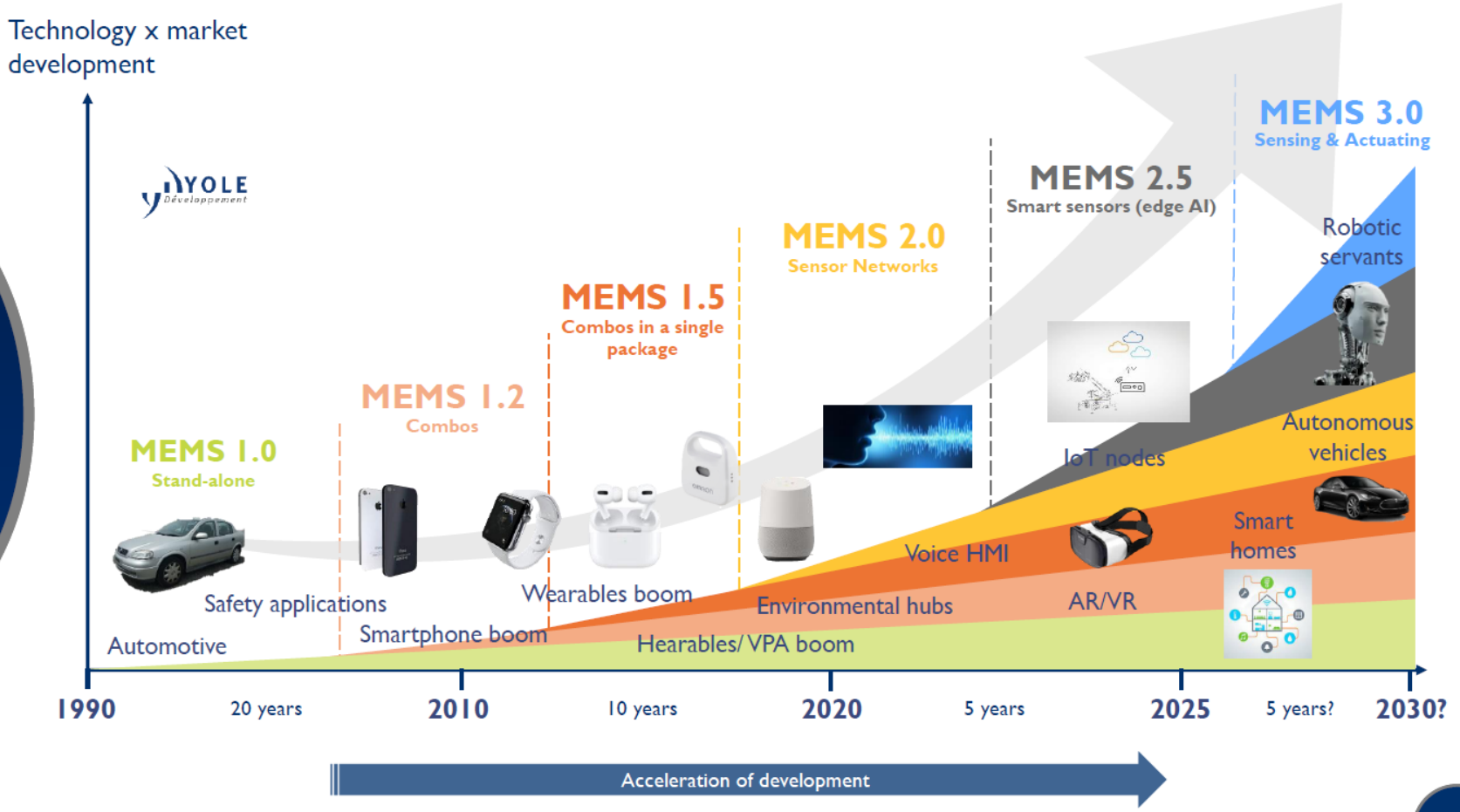
- Increase sensor performance, signal integrity and system-level performance while reducing cost
- Integration of different components (MEMS, ASIC, antennas, power sources, etc) that use different materials and processes under the same advanced package → SiP type, like its already used?



Emergence of new SiP-like packaging technologies will be required to address the needs for heterogeneous integration for functional performance and faster time-to-market.

EVOLUTION OF MEMS SENSORS

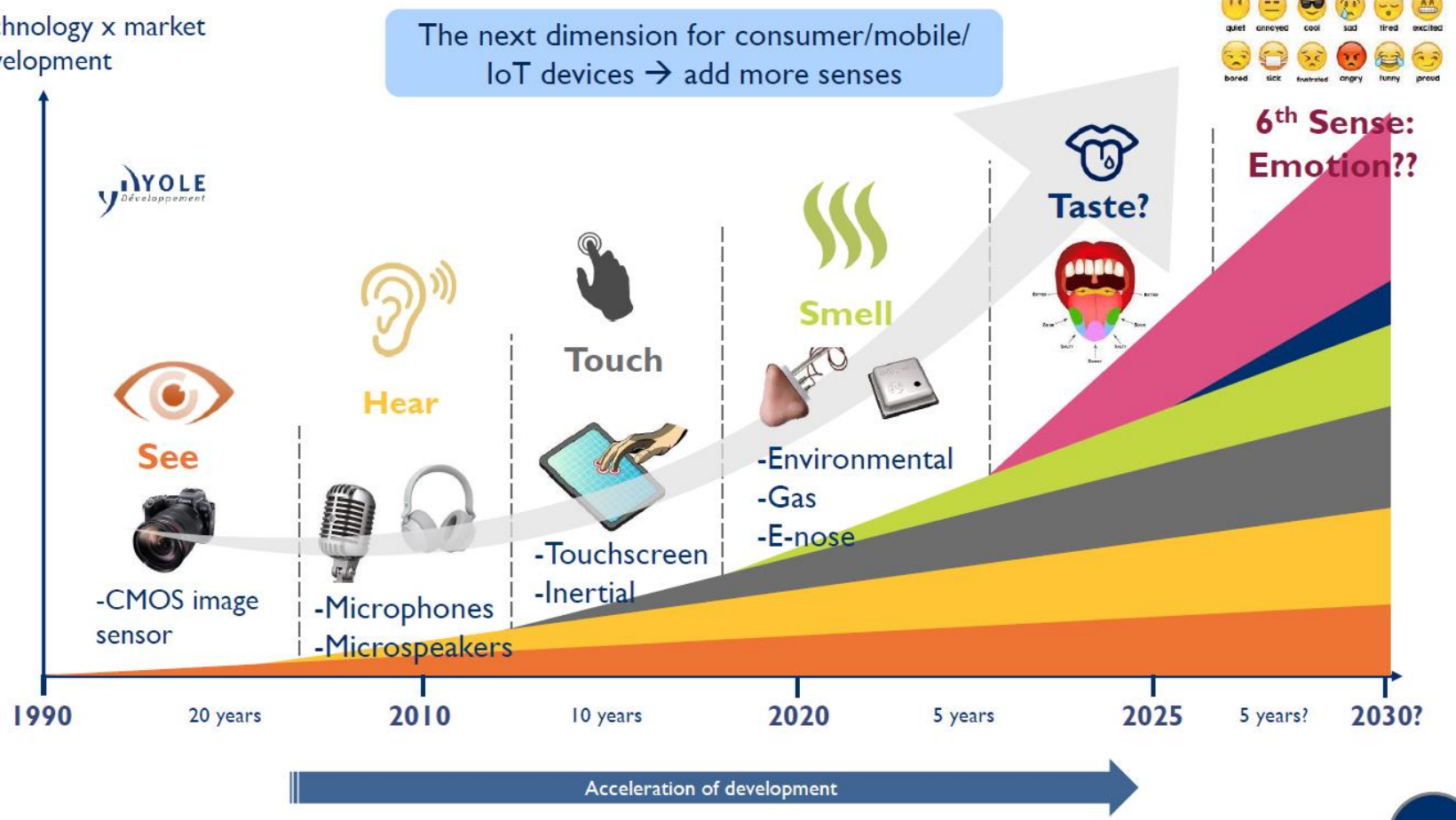
MEMS have a long history and are continuously evolving. Exciting times lie ahead with acceleration of development, as sensors become more intelligent.



EVOLUTION OF SENSING?

From the first image sensors decades ago, to current gas sensors, the capabilities of sensors are ever evolving.

We still have yet to see taste sensors, but emotion sensing has already appeared.



Commercial MEMS

- MEMS Accelerometers
  - Mobile phones for human machine interface, wearable devices, etc.
  - Automotive air bag deployment and electronic stability program (ESP)
- MEMS Gyroscopes
  - Mobile phones (human machine interface), inertial navigation, etc.
  - Automotive ESP
- Pressure Sensors
  - Mobile phones
  - Industrial, medical and automotive instrumentation
- MEMS Microphones (for mobile phones)
- Optical MEMS
  - Deformable mirror array for projection display and flat panel display
- RF MEMS
  - Film Bulk Acoustic Resonators for RF-front end filters for mobile phones
  - RF switch for tunable capacitor and automatic test equipment
  - Silicon micromechanical and piezoelectric MEMS resonator for timing
- Ink-jet Print Head
- Internet of Things, Wearable Technology

MEMS Technology and Systems

- Advantages
  - Miniaturization
  - Microelectronics (i.e., Integration with IC Circuits)
  - Multiplicity (e.g., array of 300,000 pixels)
  - Mass Manufacturability due to Batch Processing

- Commercially Successful MEMS
  - TI's Digital Light Processing (DLP) for Projection Display
  - MEMS Accelerometers and Gyroscopes
  - Film Bulk Acoustic Resonators (FBAR) for RF Front-end Filtering
  - MEMS Microphones

- Challenging, but exciting!!!
  - multi-disciplinary
  - enabling for product differentiation
  - impactful
  - open-ended