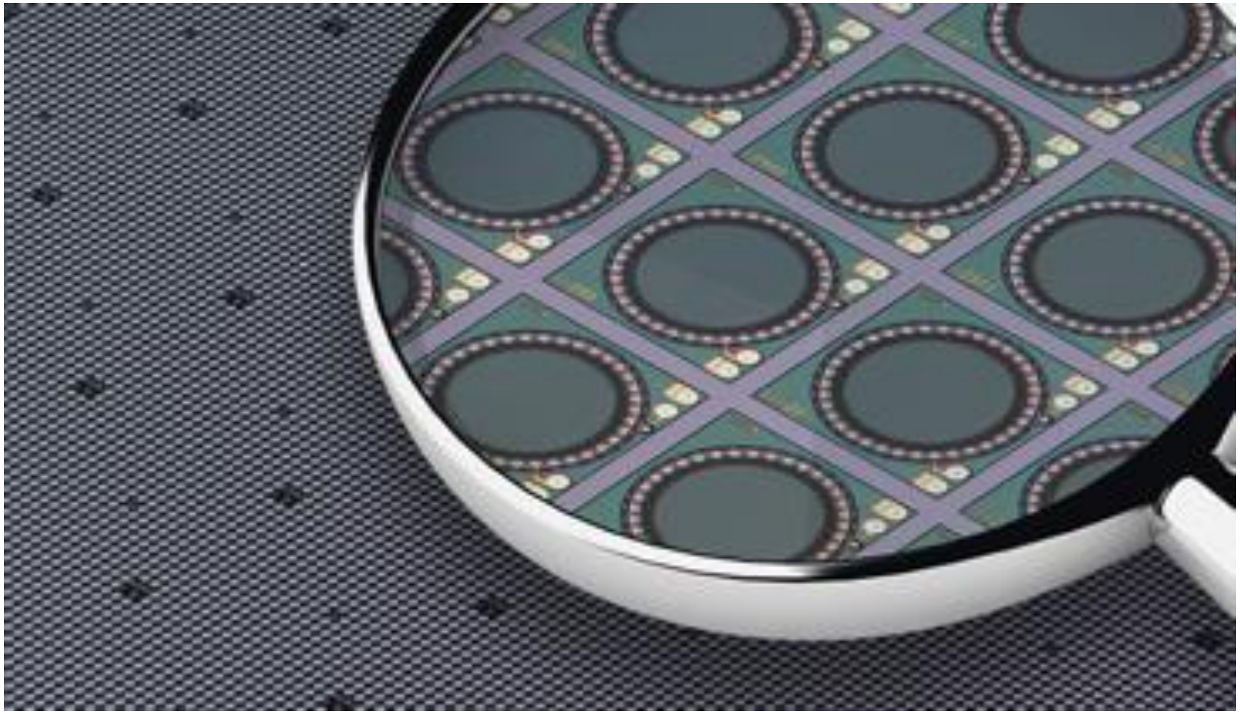
Advanced MEMS and Microsystems

Dr. Danick Briand & Prof. Guillermo Villanueva

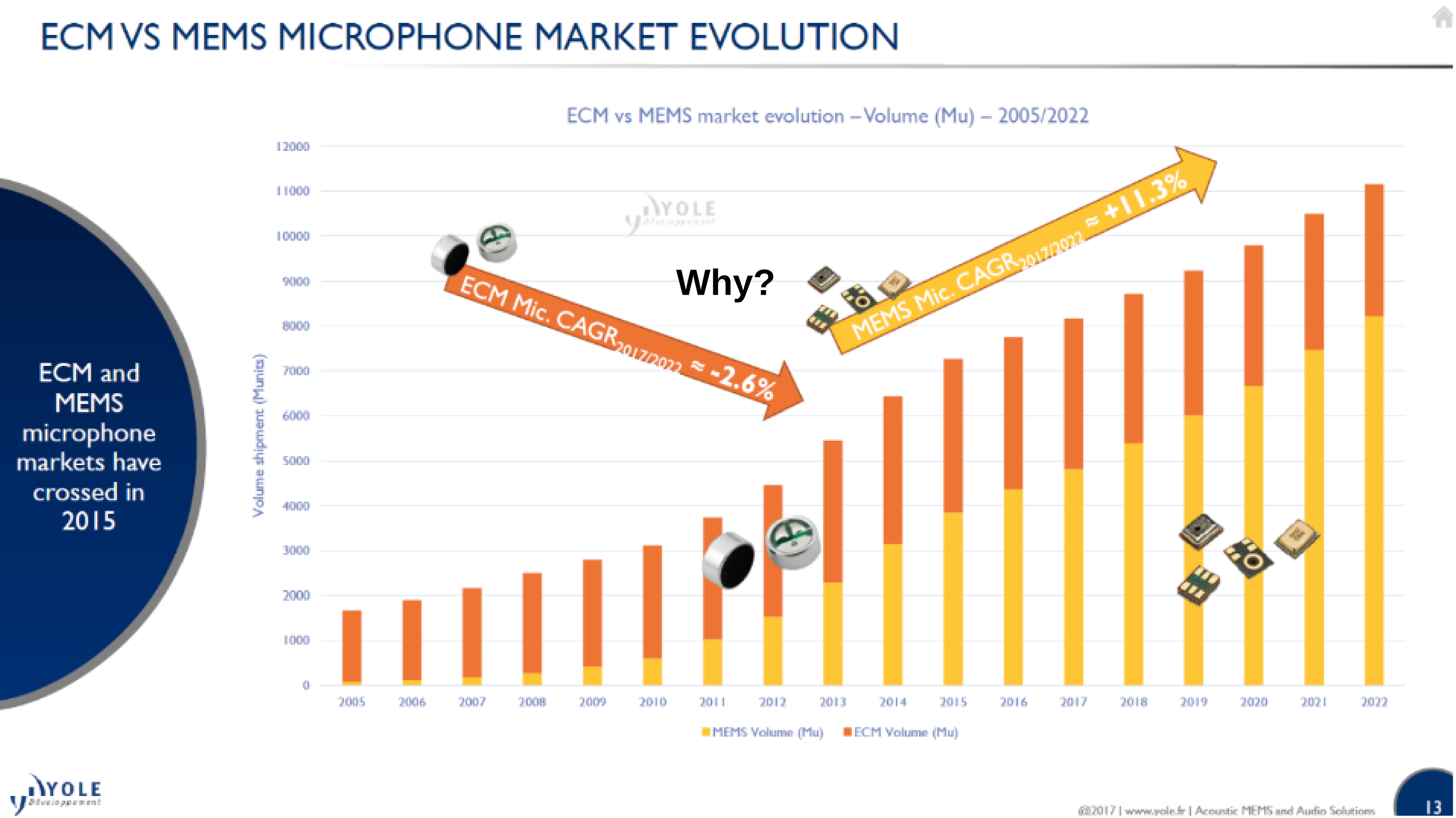
Course content and schedule

Dates	Lectures	Lecturers	Mean
20.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva	Live
27.02	Sensors part I Exercices	D. Briand	Live
05.03	Sensors part II Industrial seminar #1	D. Briand	Live
12.03	Students presentations	D. Briand / G. Villanueva	Live
19.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand	Live
26.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva	Live
09.04	RF-MEMS	G. Villanueva	Live
16.04	NEMS	G. Villanueva	Live
23.04	Interactive session	D. Briand / G. Villanueva	Live
30.04	Thermal and gas sensors Industrial seminar #4	D. Briand	Live
07.05	Packaging	D. Briand	Live
14.05	Packaging Industrial seminar #5	D. Briand	Live
21.05	PowerMEMS	D. Briand	Live
28.05	Quiz + oral exam instructions Evaluation of the course	All	Live



MEMS MICROPHONES

Image source: eetimes



ECM VS MEMS MICROPHONE MARKET EVOLUTION
ECM vs MEMS market evolution – Volume (Mu) – 2005/2022
ECM and MEMS microphone markets have crossed in 2015
Why?
ECM Mic. CAGR2017/2022 ≈ -2.6%
MEMS Mic. CAGR2017/2022 ≈ +11.3%
Volume shipment (Munits)
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022
MEMS Volume (Mu)
ECM Volume (Mu)
YOLE Développement
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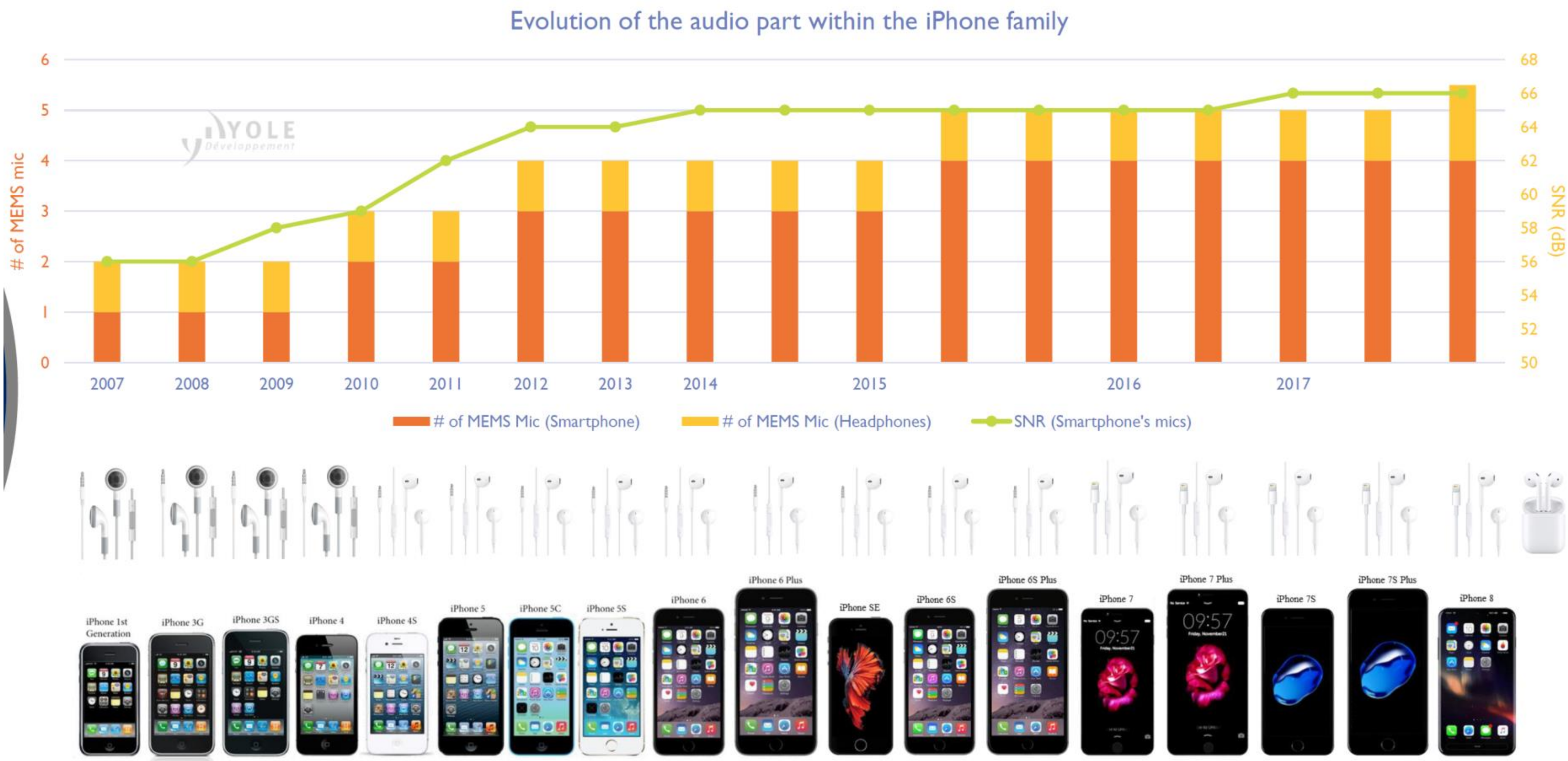
MEMS Microphones

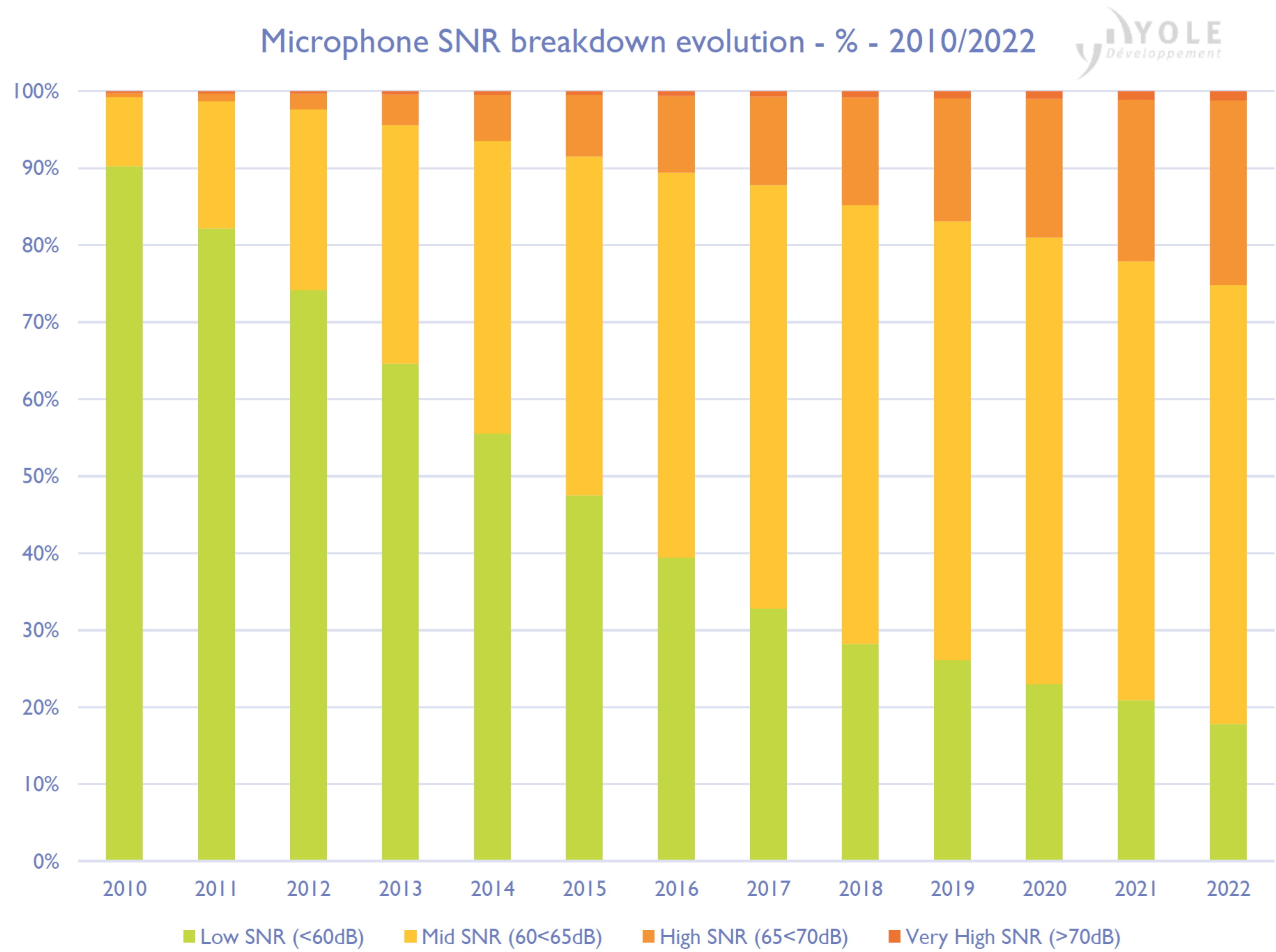


Several Microphones for improved

- ***Hands-free calling***
- ***Siri Voice Commands***
- ***Audio Fidelity in Video Recording***
- ***Noise Cancellation***
- ***Audio Recording***

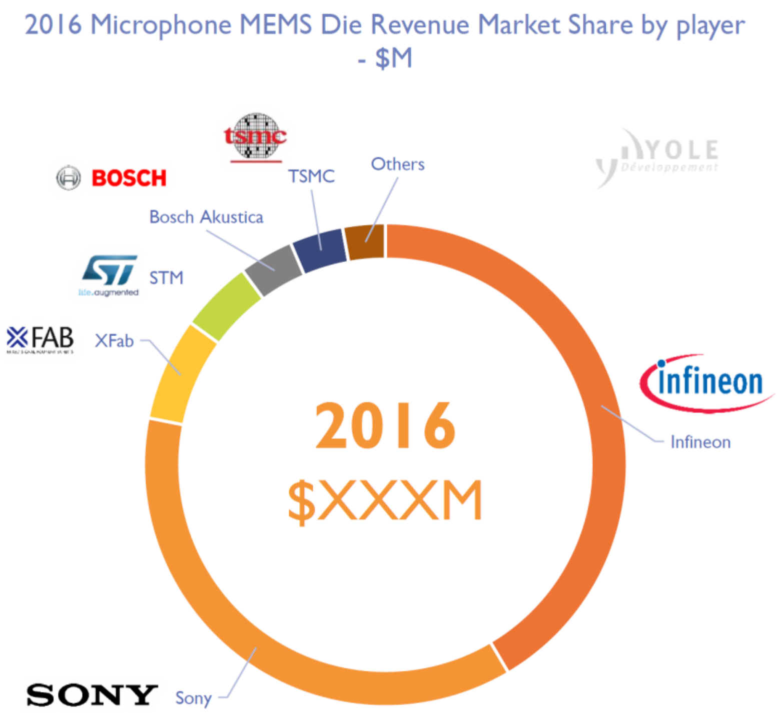
- ***MEMS Microphones have become a commodity***
- ***Manufacturers can select from multiple vendors with similar performance***

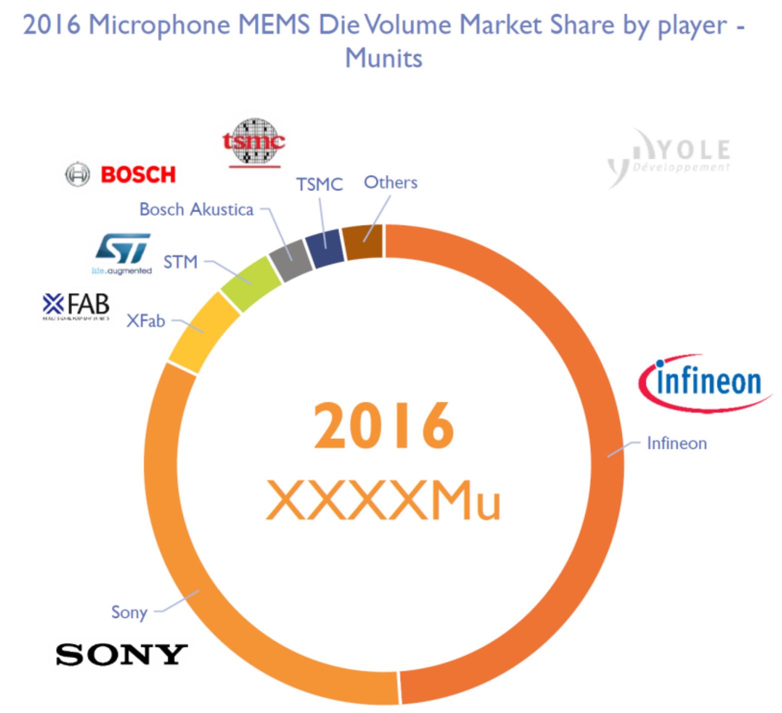
MEMS Microphones – Performance



MEMS Microphones – By player

By player

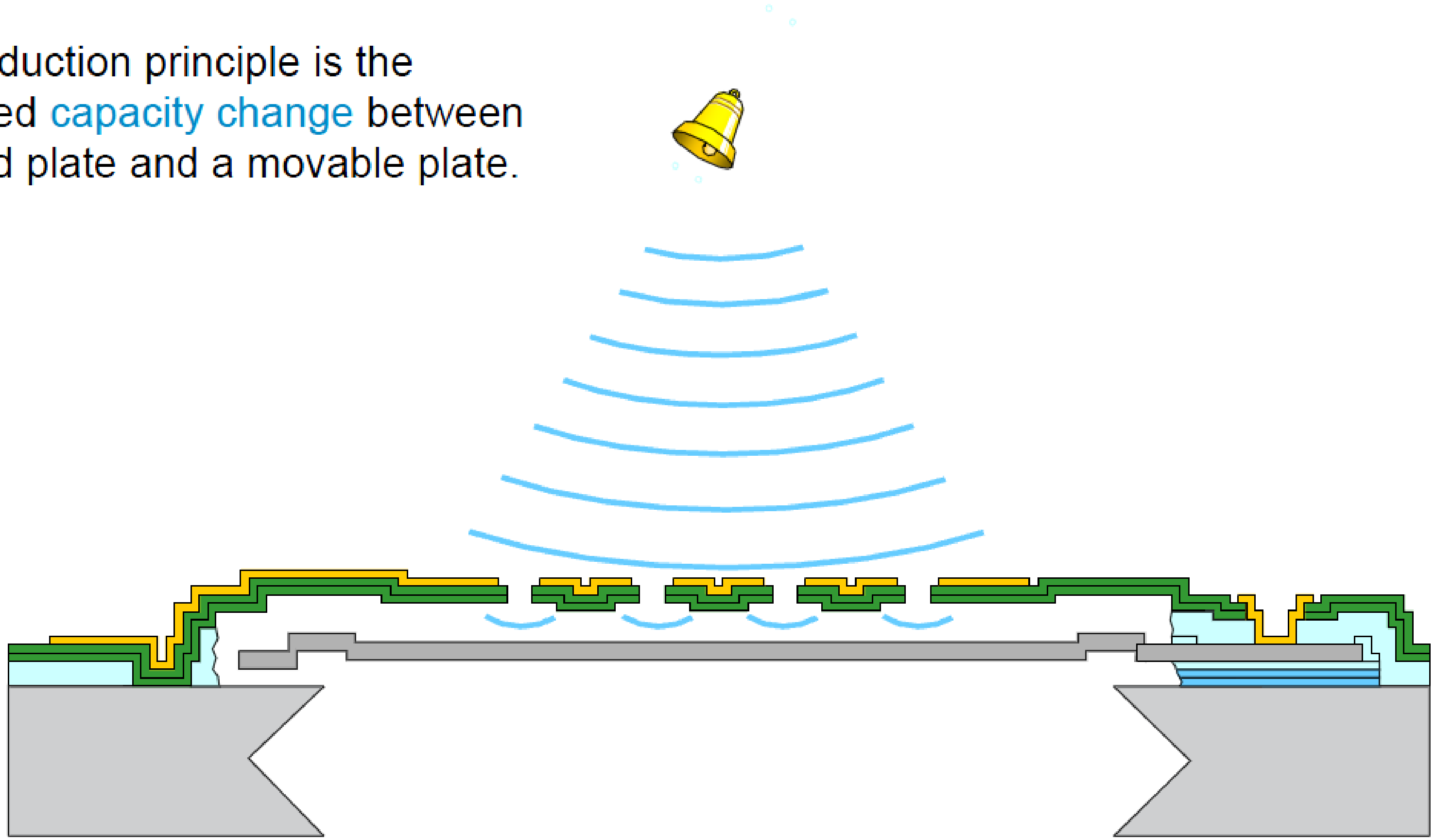




MEMS Microphones – Fields of Application

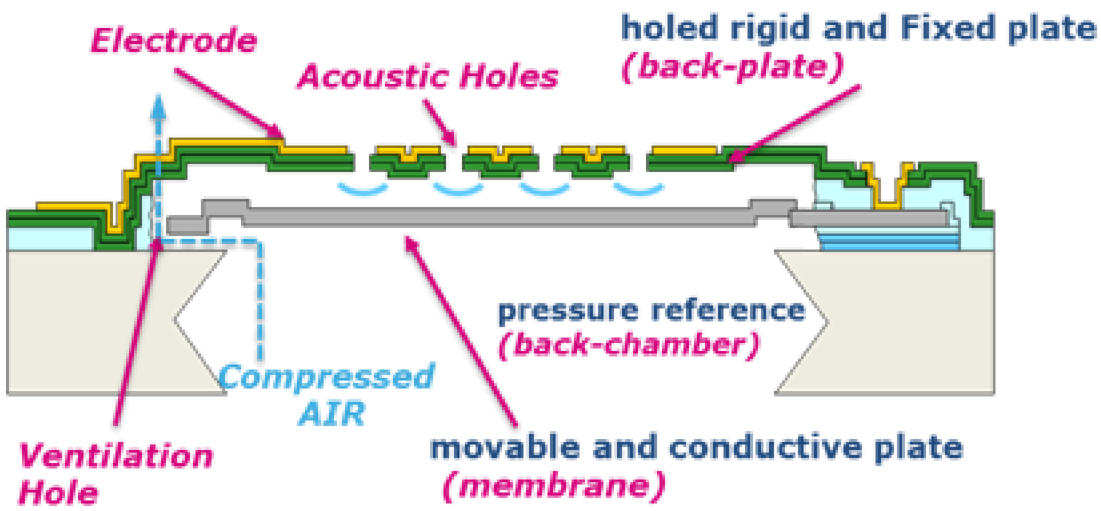
MEMS Microphones: Capacitive Readout

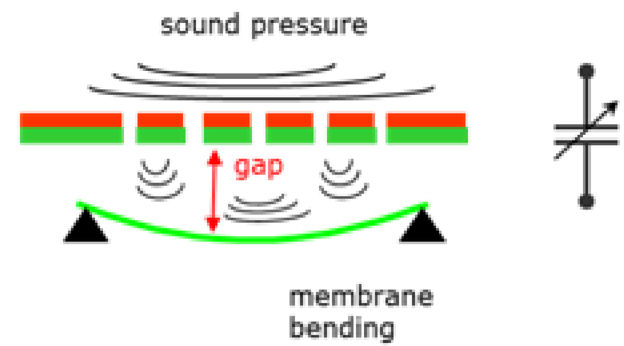
Transduction principle is the coupled capacity change between a fixed plate and a movable plate.



- Which parts are moving?
- What are the holes for?
- Why is the bottom plate disconnected?

MEMS Microphones





Source: ST Micro, Application Note 4426

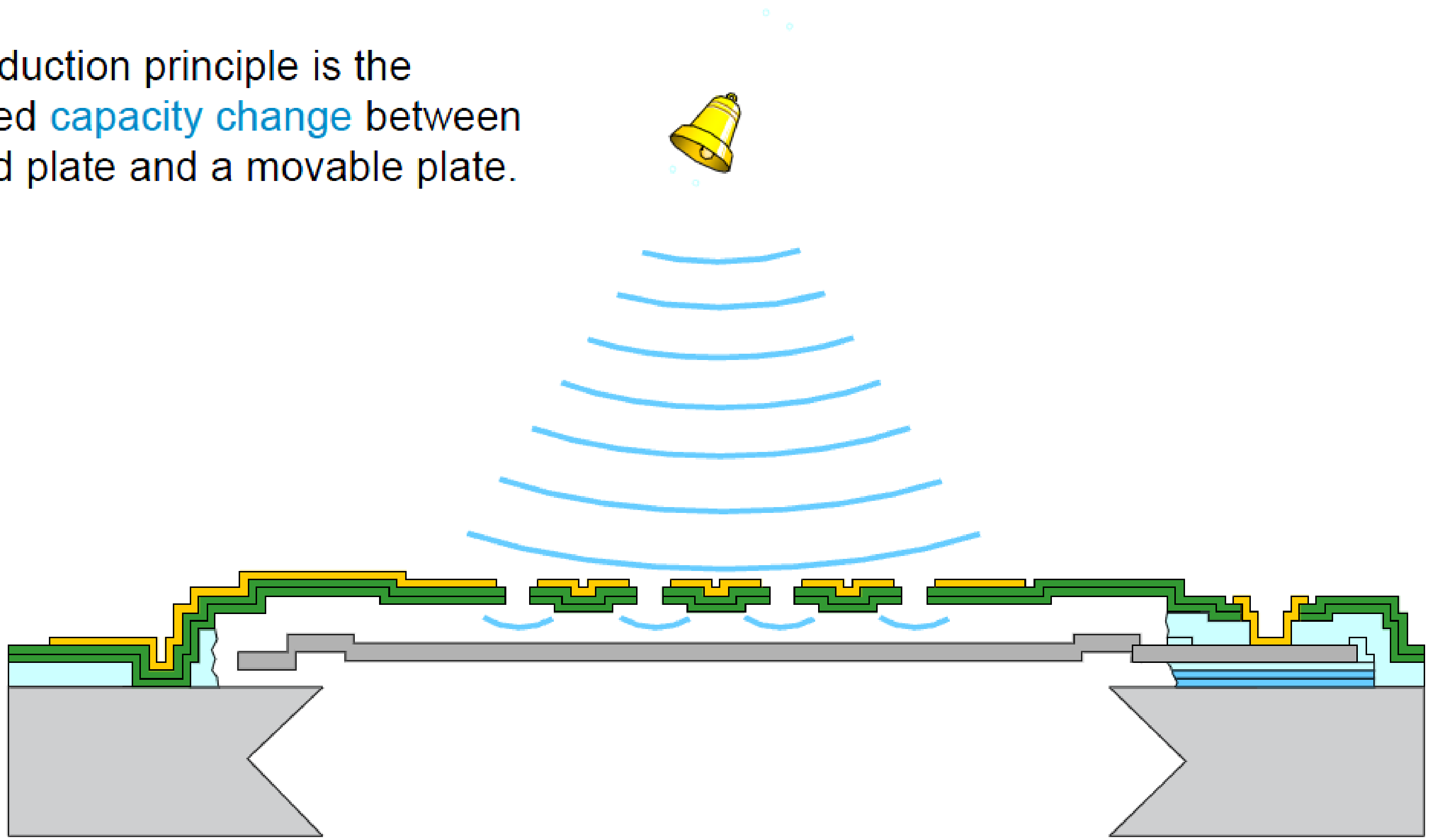
- **capacity change between a fixed plate (back-plate) and a movable plate (membrane)**

- **Capacitive change caused by the sound, passing through the acoustic holes, that moves the membrane modulating the air gap comprised between the two conductive plates**

- **The Ventilation hole allows the air compressed in the back chamber to flow out and consequently allowing the membrane to move back**

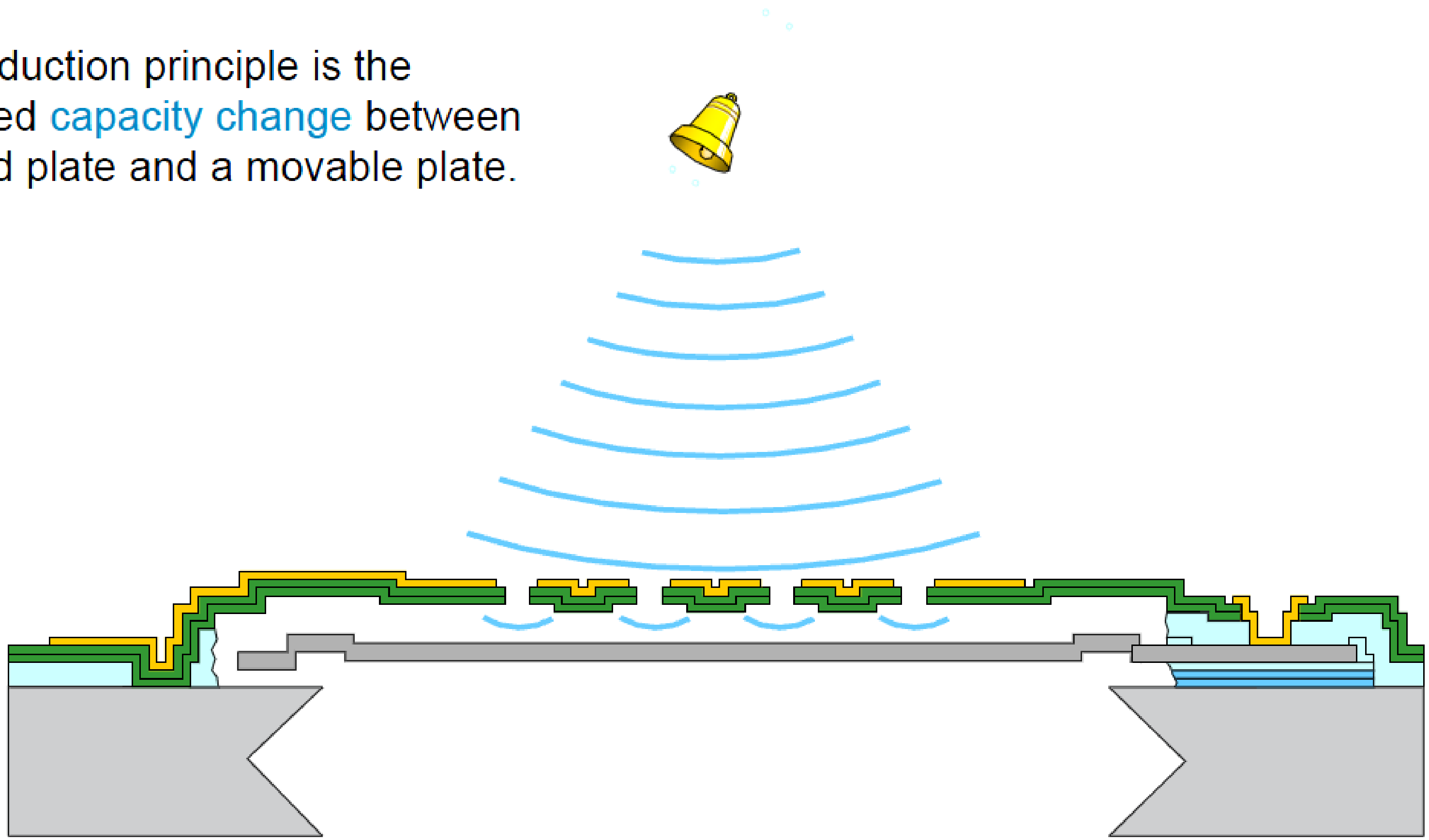
MEMS Microphones: Capacitive Readout

Transduction principle is the coupled capacity change between a fixed plate and a movable plate.



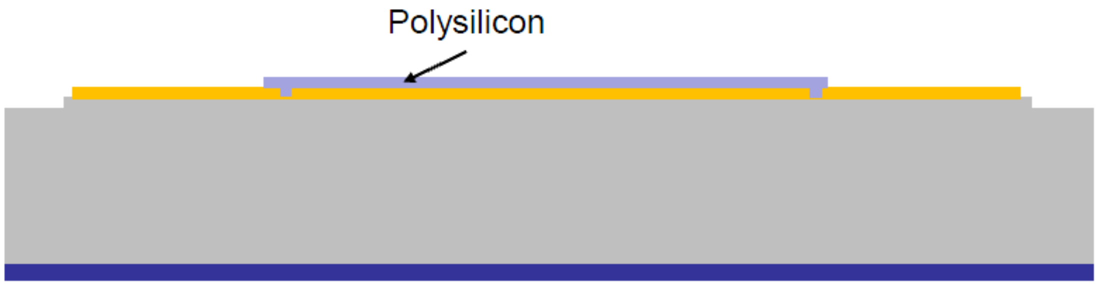
MEMS Microphones: Capacitive Readout

Transduction principle is the coupled capacity change between a fixed plate and a movable plate.

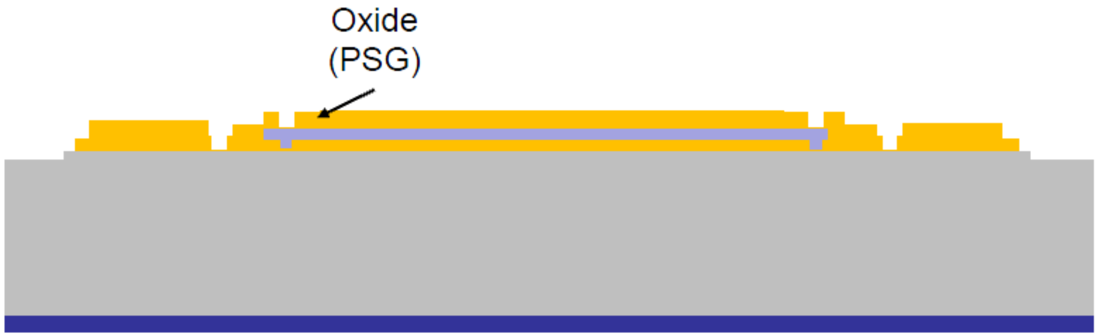


MEMS Microphones – Fabrication process

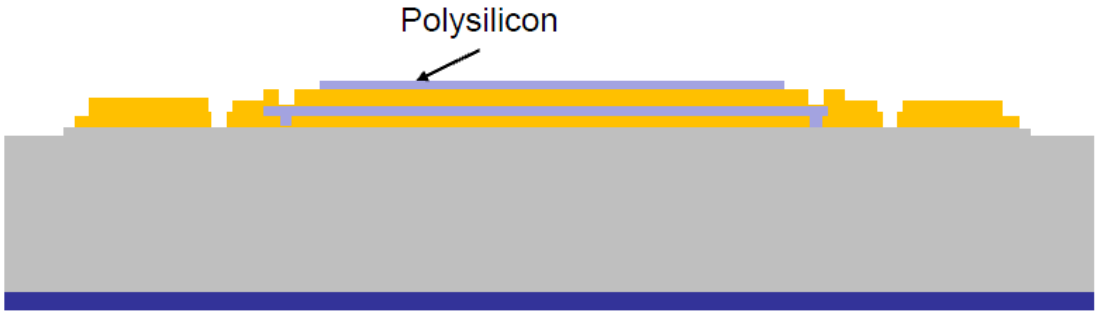
- Diaphragm
  - Poly 1 – 1µm



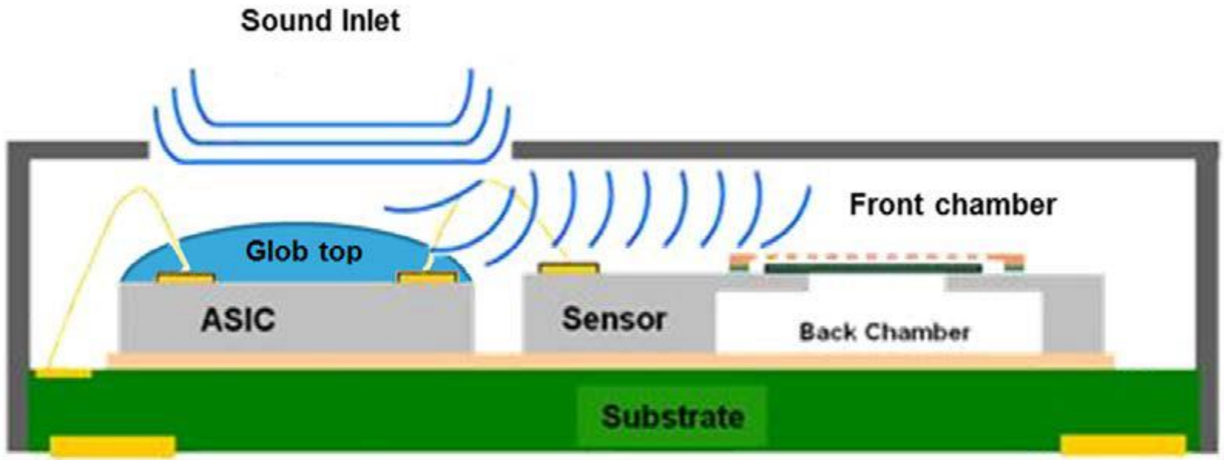
- Sacrificial layer 2
  - PSG – 3.6µm



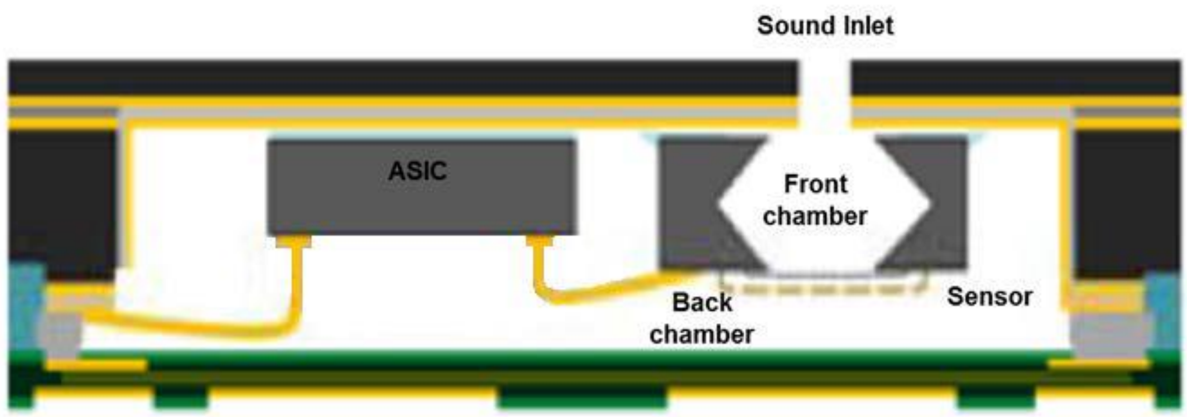
- Backplate Electrode
  - Poly 2 – 0.5µm



Sound Inlet Strategies



better protection from particles, easier assembly

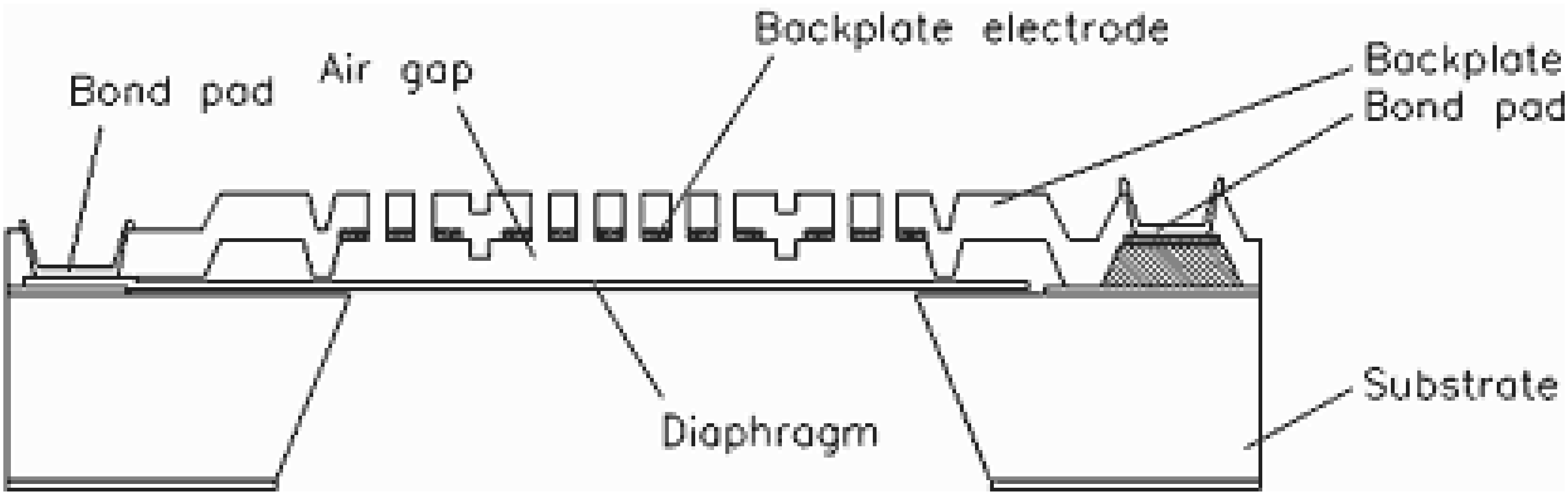


better SNR, more challenging assembly

Source: ST Micro, Application Note 4426

MEMS Microphones – Knowles

- Capacitive read out
- Surface micromachining → "SUMMiT V" process
- For hearing aids
- More than 1 billion devices sold

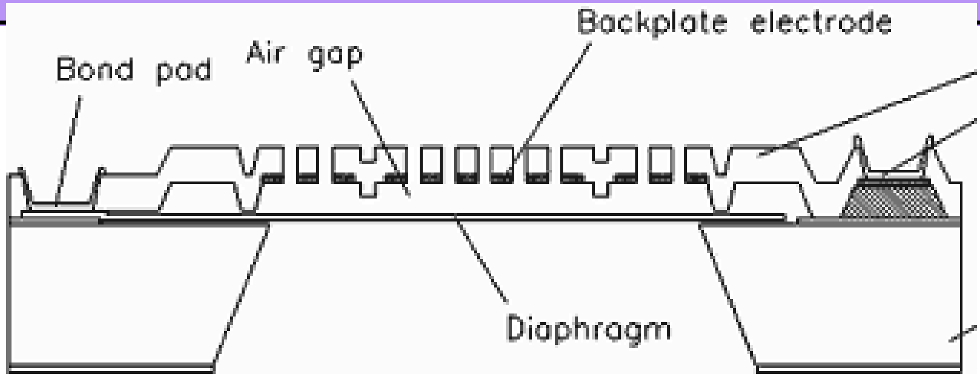


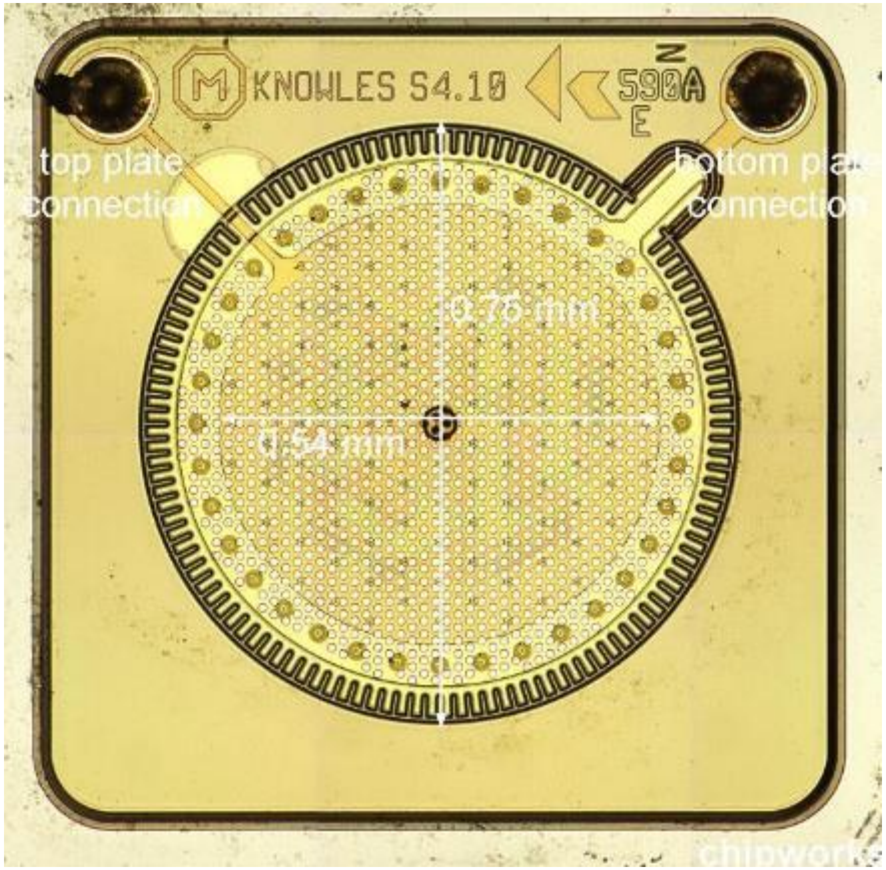
1. surface and bulk micromachining
2. Diaphragm: low-stress polySi membrane
3. Back-Plate: thick polySi + highly tensile SiN (rigid reference electrode)

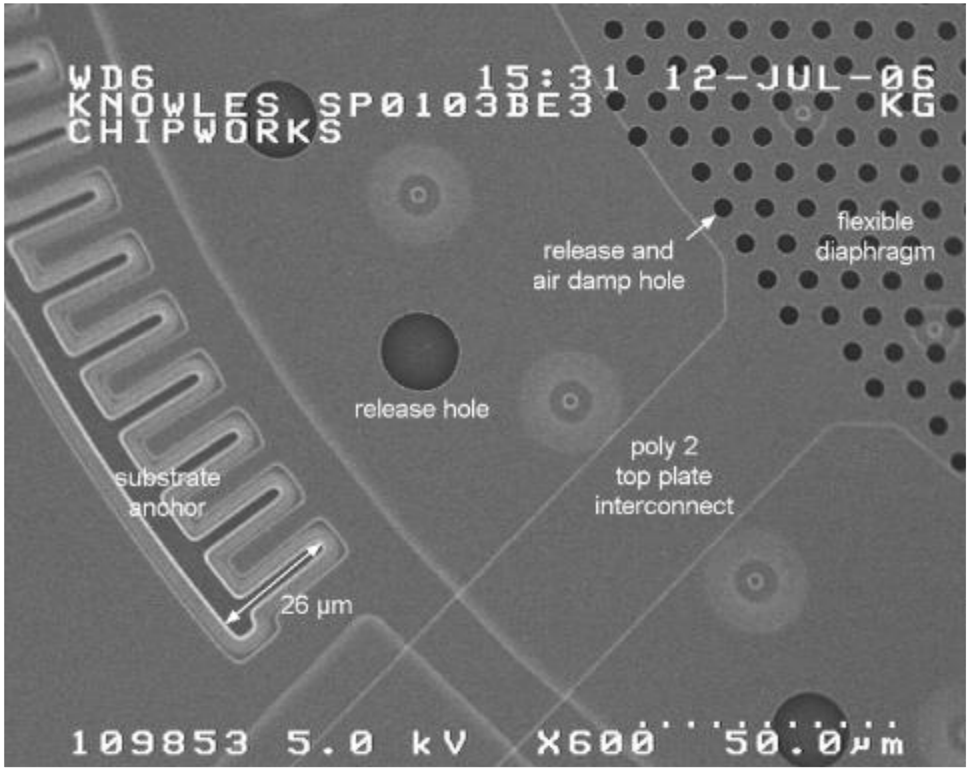
Source: http://uk.farnell.com
http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

MEMS Microphones – Knowles

- Capacitive read out
- “SUMMiT V“ process, 11 masks
- For hearing aids
- More than 1 billion devices sold

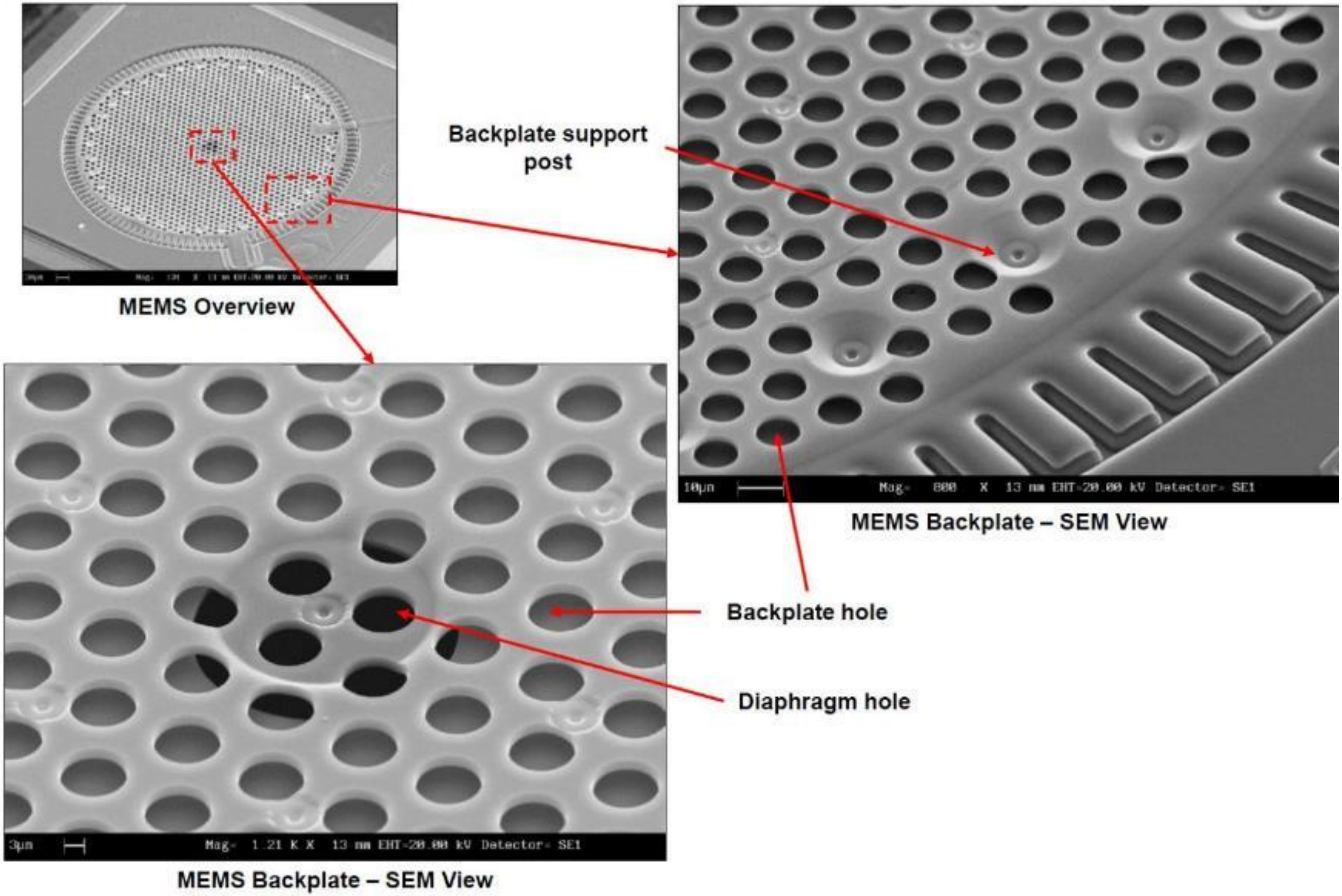






Sourcee http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

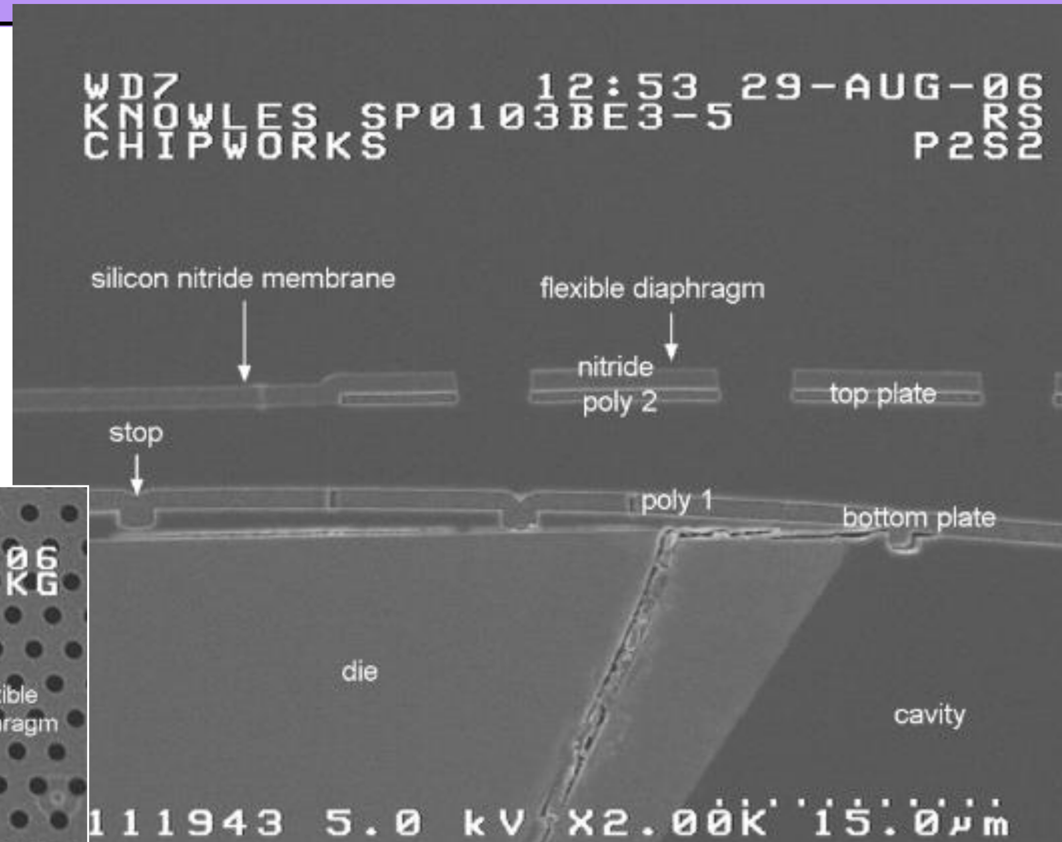
MEMS Microphones – Knowles

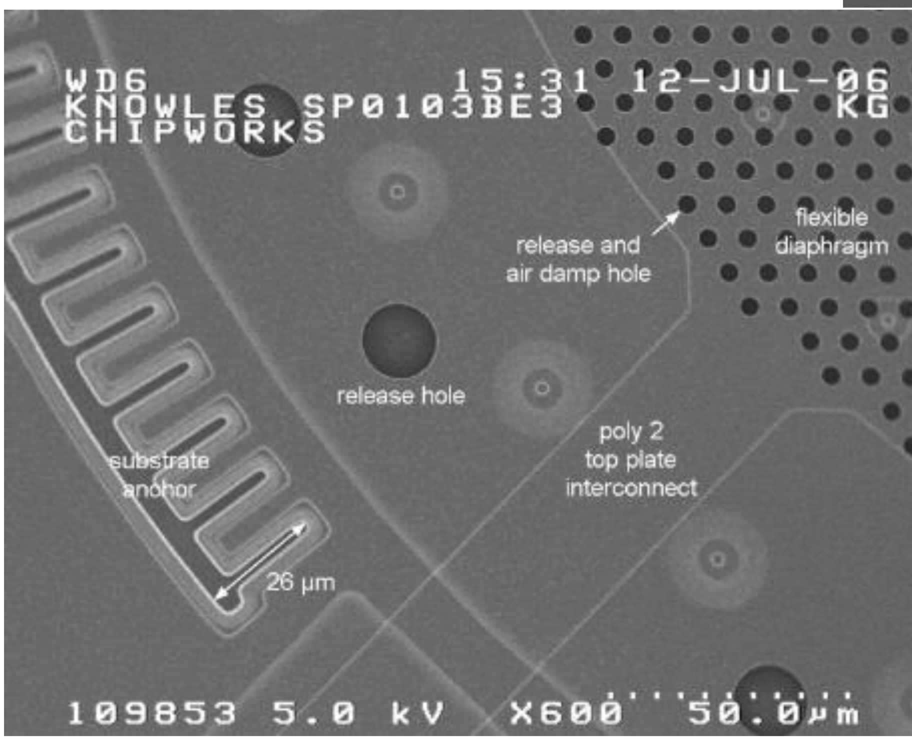


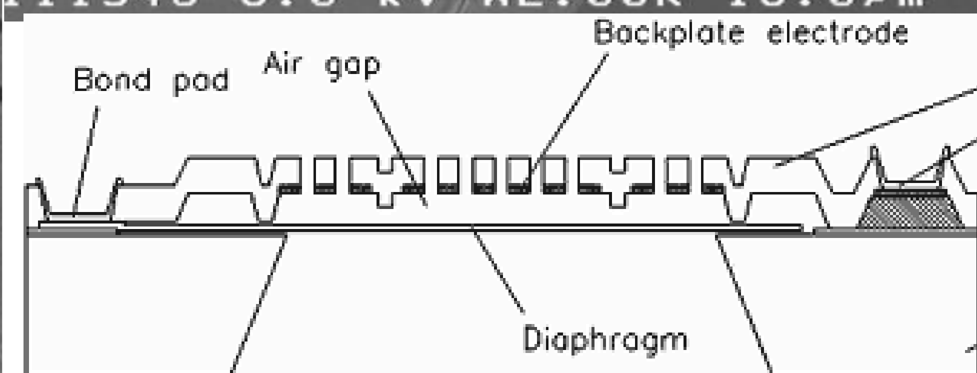
 Knowles SPU0409LE5H – MEMS Microphone

MEMS Microphones – Knowles

- Capacitive read out
- "SUMMiT V" process
- Silicon nitride membrane
- Poly-silicon electrodes
- Layers thickness:
  1 µm poly-Si, 1.5 µm Si_3N_4



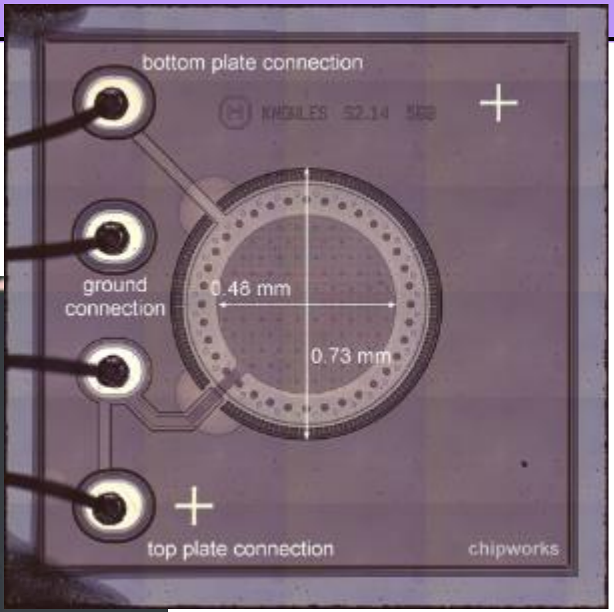


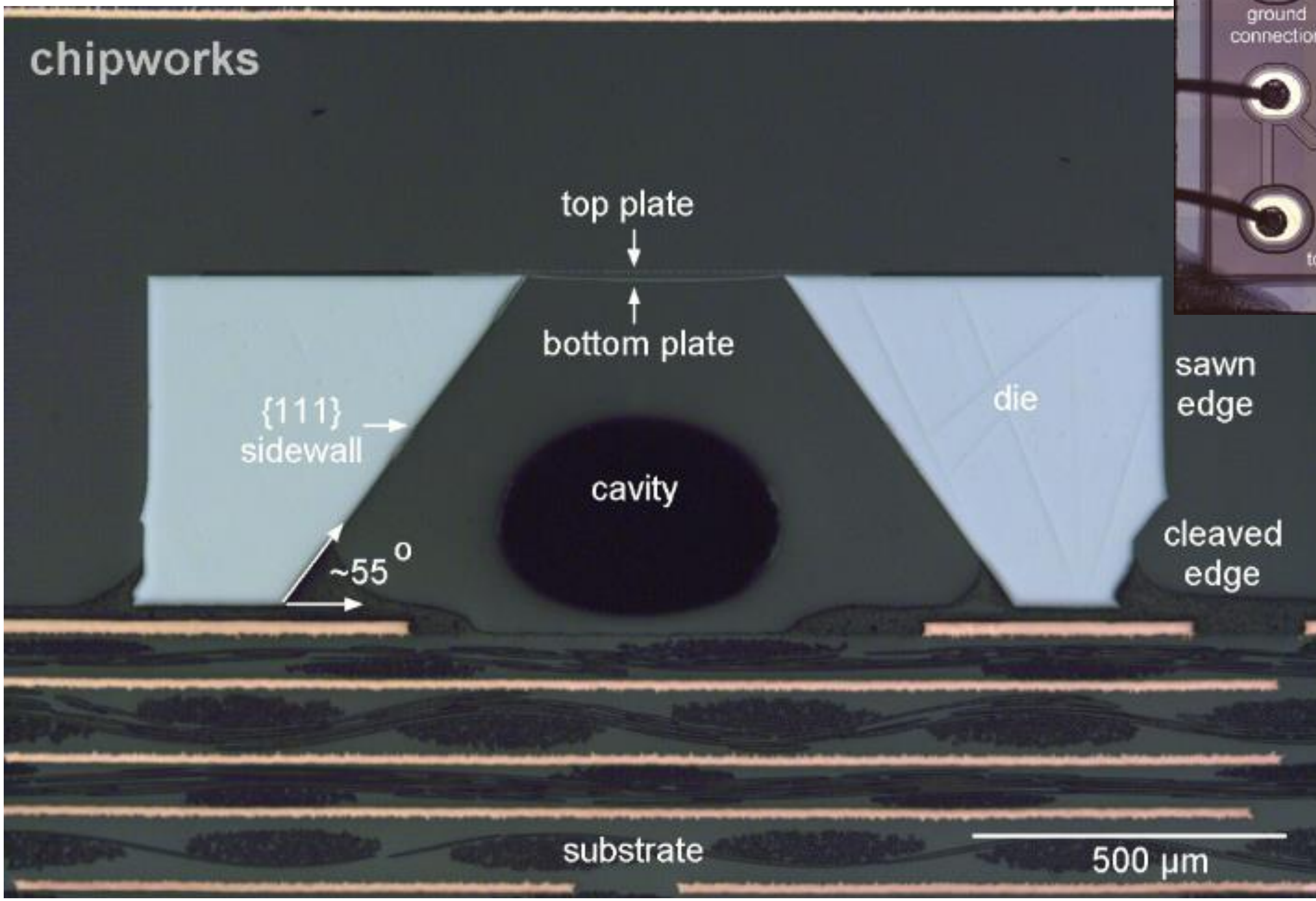


Sourcee http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

MEMS Microphones – Knowles

- **"SUMMiT V" process**
- **Partial dicing/sawing + cleaving**

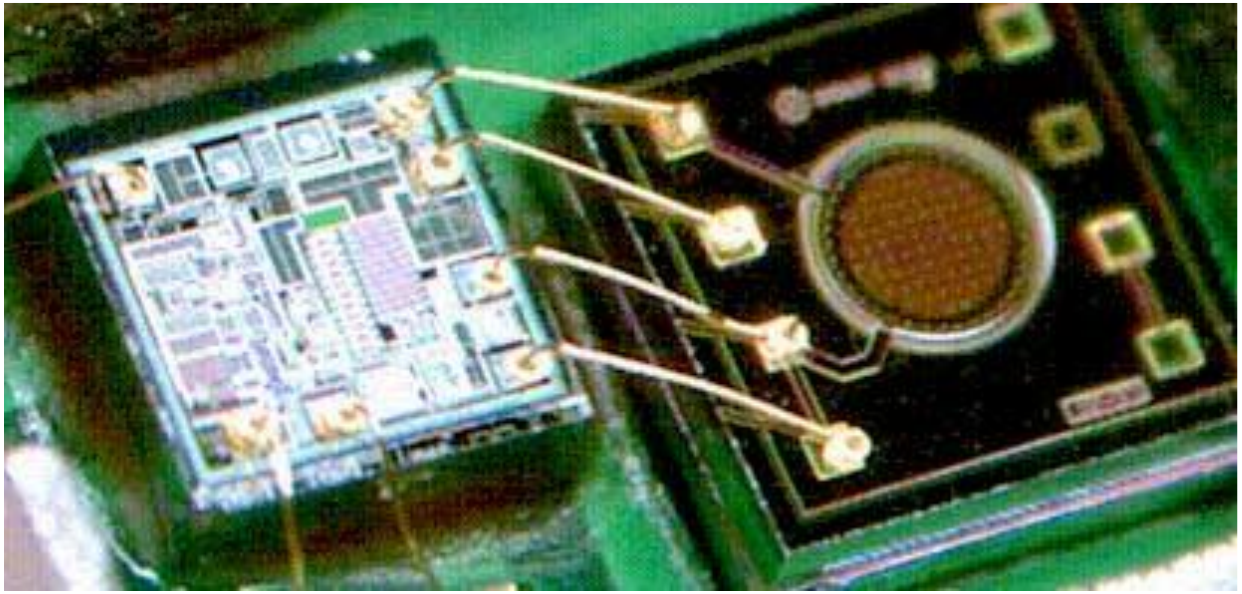


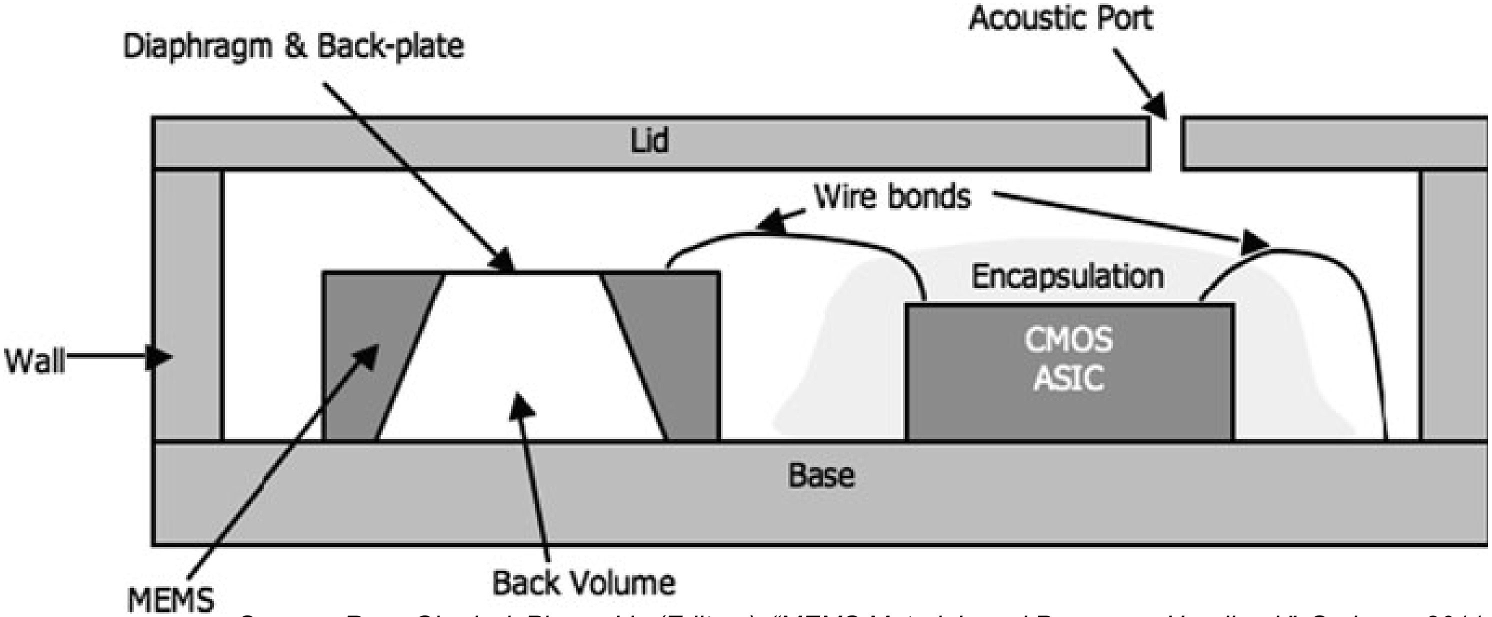


Sourcee http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

MEMS Microphones – Knowles

- **Separate electronics**
- **For hearing aids**
- **Mobile devices**
- **Acoustic port “far” away**





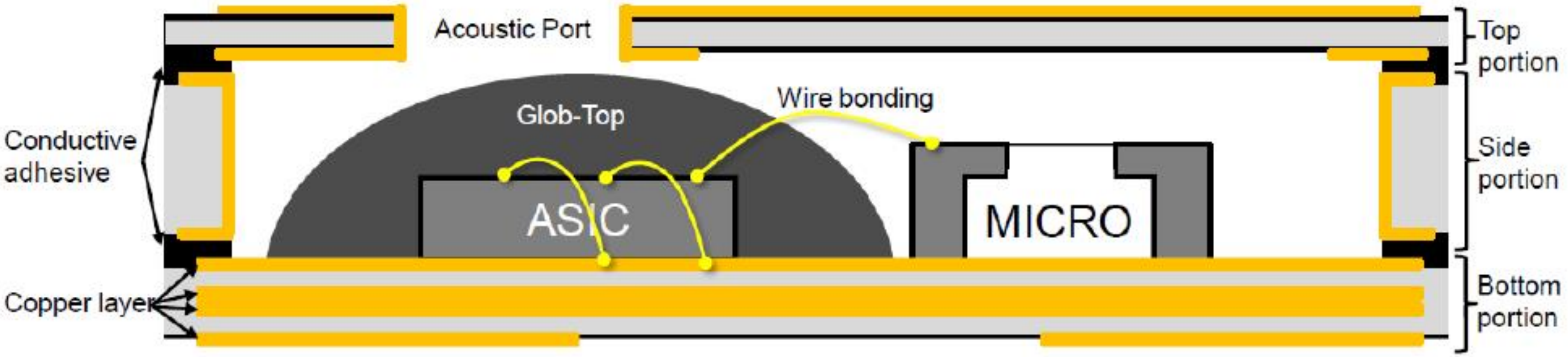
Source: Reza Ghodssi, Pinyen Lin (Editors), “MEMS Materials and Processes Handbook”, Springer, 2011, DOI 10.1007/978-0-387-47318-5, and http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

MEMS Microphones – Knowles

- The Package is composed by three portions of FR4 PCB electrically connected with a conductive adhesive.
- The two dies are glued on the bottom portion of the package and wire bonded.
- The ASIC die is encapsulated with a glob-top epoxy resin.

4.72mm x 3.76mm x 1.25mm

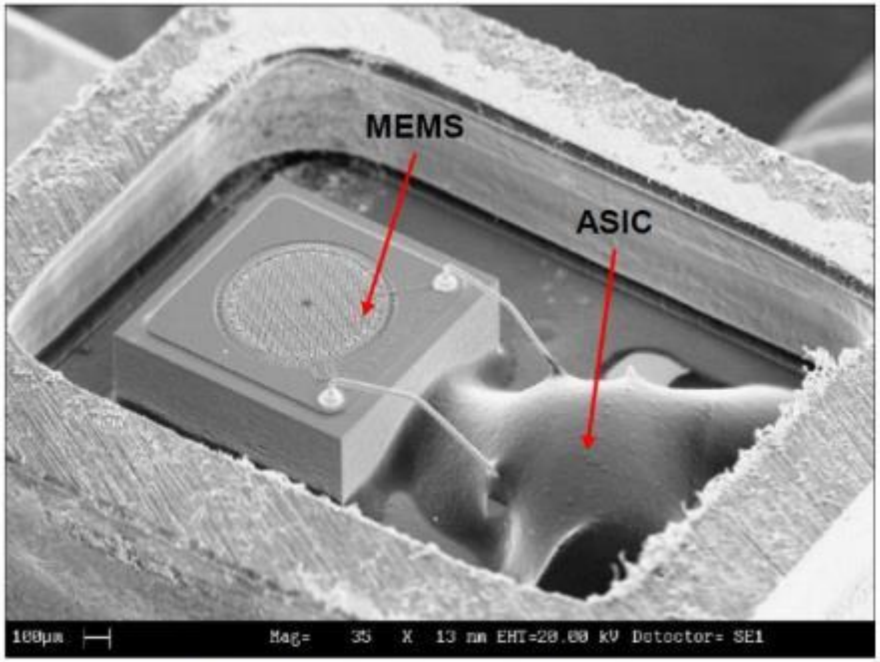
Package Side view



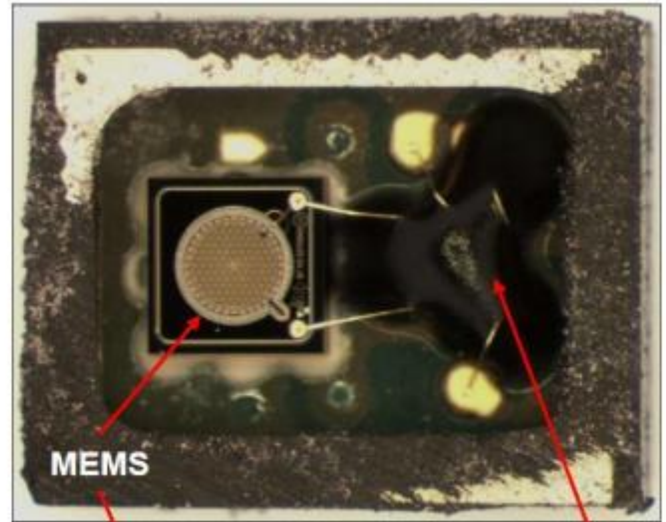
Schematic package composition

SYSTEMPlus CONSULTING

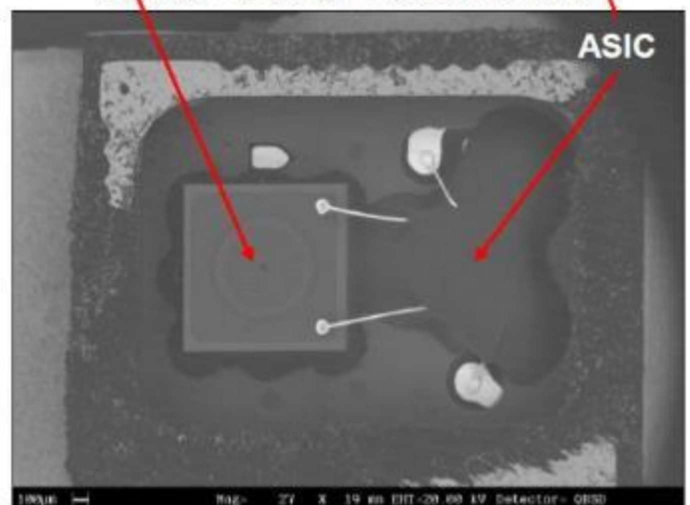
MEMS Microphones – Knowles



Package Opening – SEM top view



Package Opening – Optical top view



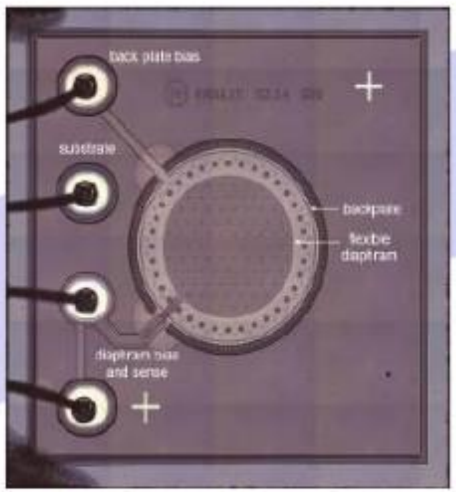
Package Opening – SEM top view

Bonding material: Gold
Bonding diameter: 20µm

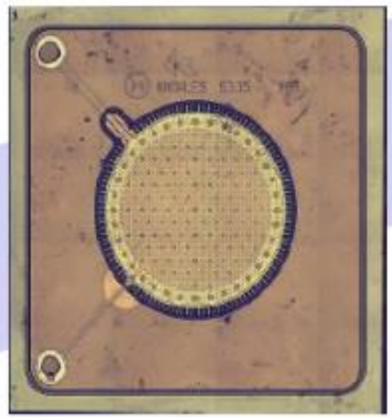
Bonding number: 5
- ✓ Between ASIC & Package: 3
- ✓ Between MEMS & ASIC: 2

Knowles SPU0409LE5H – MEMS Microphone

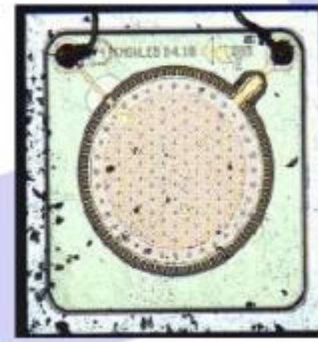
MEMS Microphones – Die size reduction



2006 Knowles S2.14, 1.6 mm x 1.6 mm, MEMS microphone die, with a 0.64 mm diameter diaphragm. The Knowles microphones use a separate ASIC die.



2007/2008 S3.15 is 1.35 mm x 1.35 mm and features only two bond pads, as compared to the four seen on the S2.14. The diaphragm is 0.64 mm in diameter.



2010 S4.10 microphone. The microphone die is only 1.1 mm x 1.1 mm, with a 0.64 mm diaphragm. It is worth noting that Knowles does not appear to have changed the basic layout of the technology, rather they have been shrinking the die, thus allowing them to lower the cost. They have achieved greater than 50% shrink in the die area between the S2.14 product and the newer S4.10 product, implying a doubling of the chip yield per wafer, while keeping the microphone diaphragm constant in size.

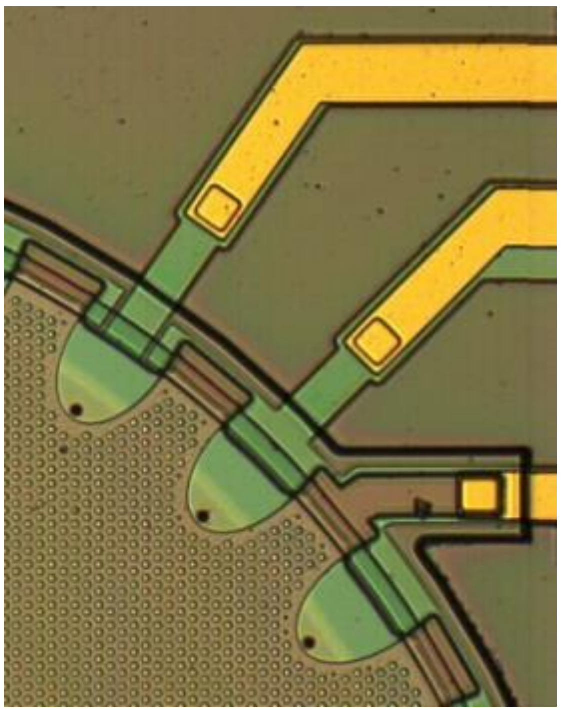
CHIPWORKS

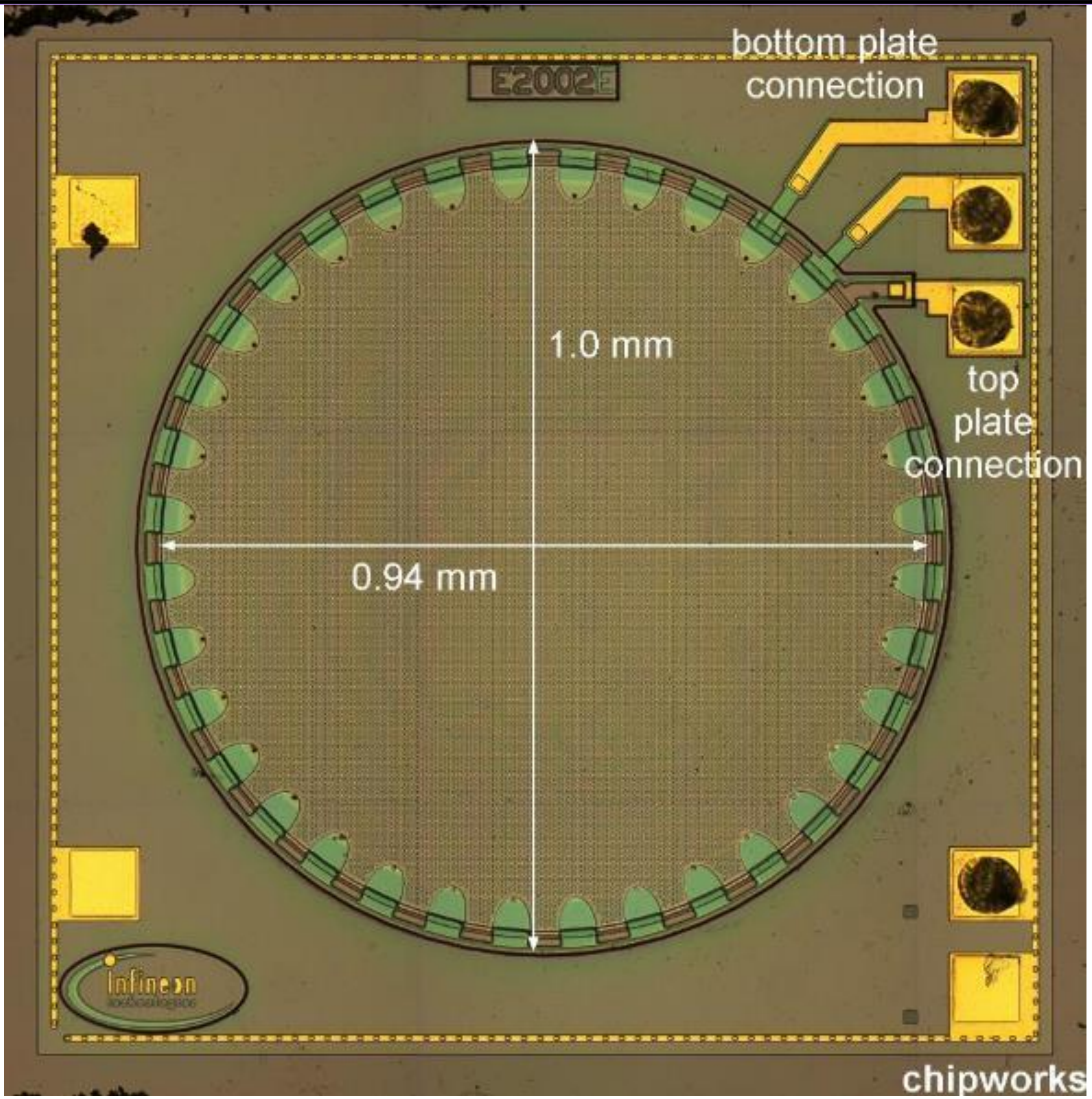
Why is the Membrane the same size?
What allows size reduction of the chip?

MEMS Microphones – Others

Infineon

- **Found in the iPhone 4**
- **Three electrodes**
    - **Microphone diaphragm**
    - **Top plate**
    - **Poly-Si guard ring**



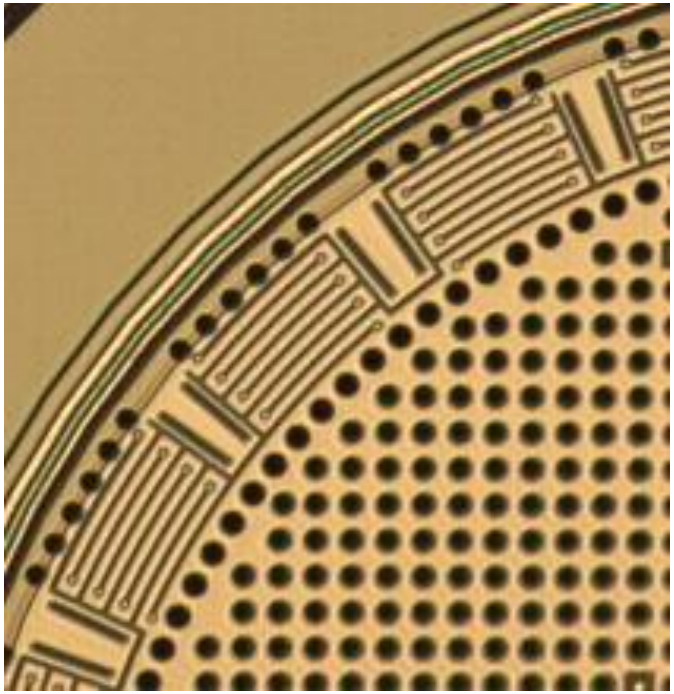


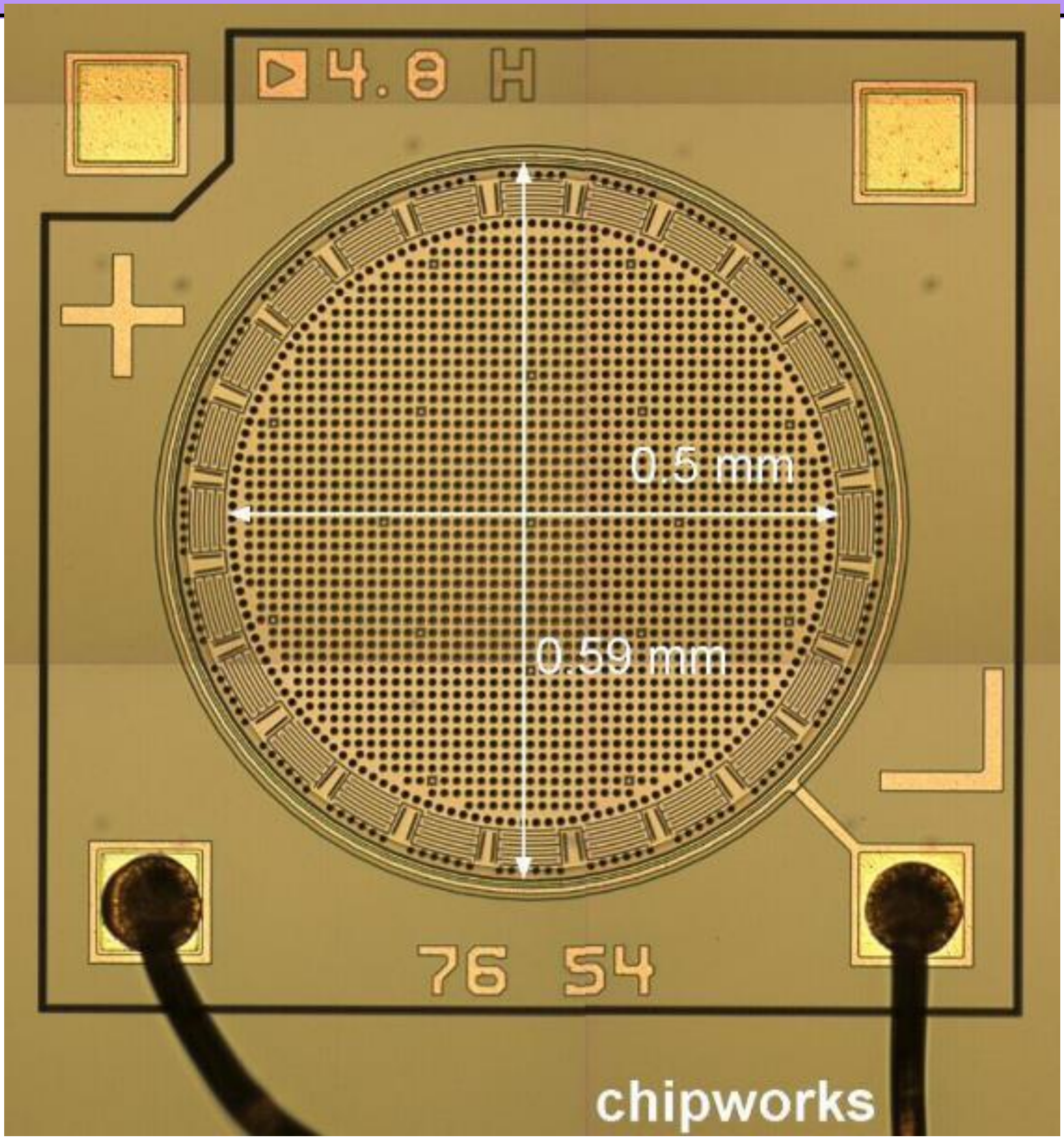
Sourcee http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

MEMS Microphones – Others

Analog Devices

- **Found in the iPod Nano 5G**
- **Two electrodes**
- **Special springs to reduce stress in membrane**





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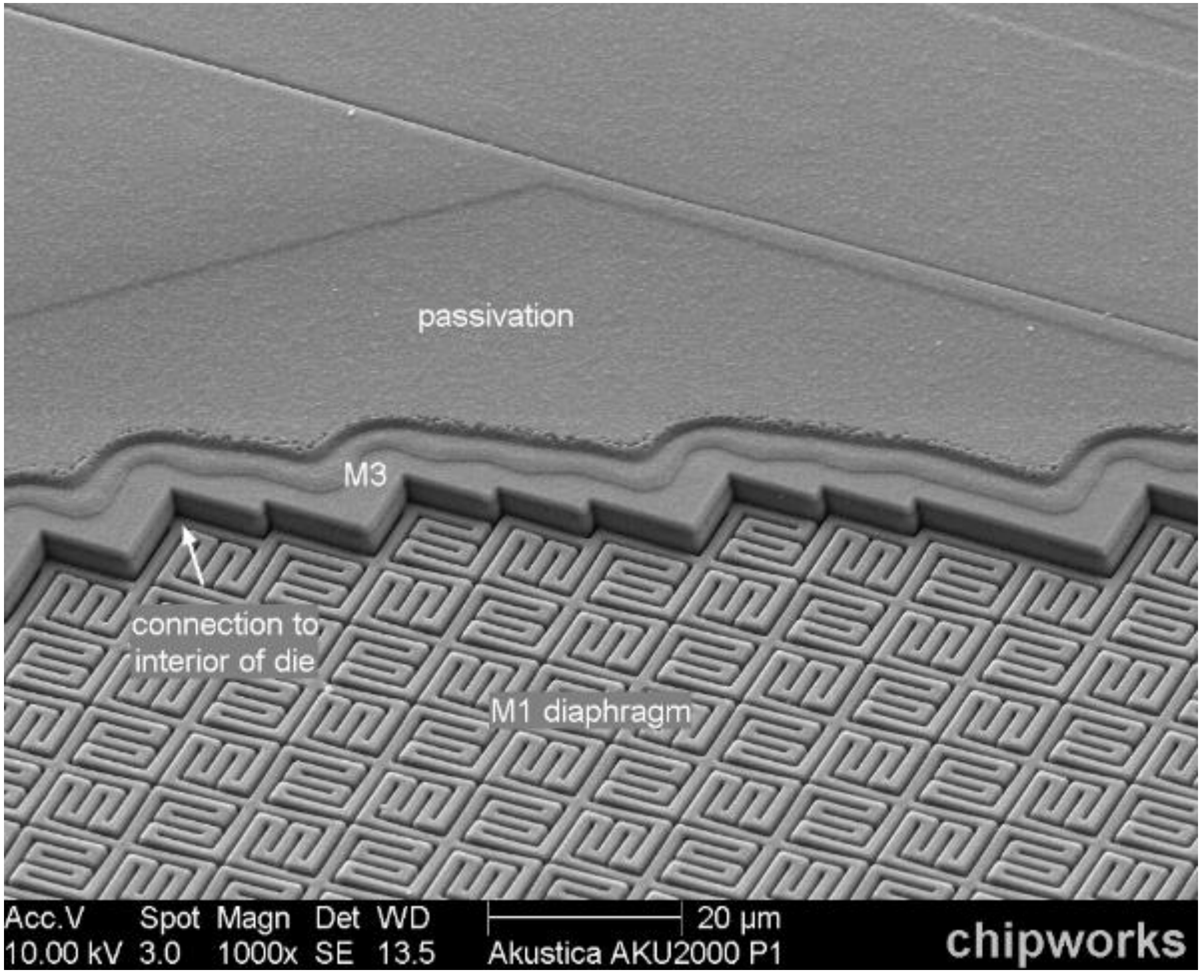
MEMS Microphones – Akustica (Bosch Group)

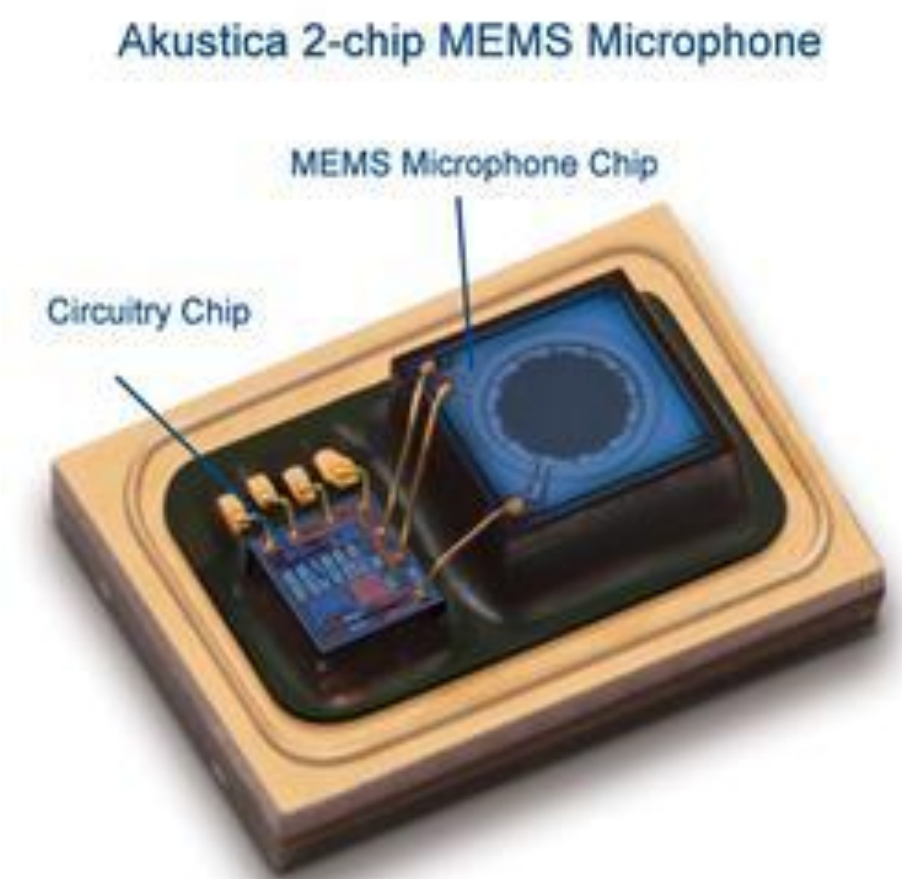
Akustica / Bosch Group

- **First MEMS company that uses CMOS !**
- **Metal layers for diaphragm:**
  - **M1 & M3**
- **CMOS will allow for integrated electronics!**
- **Meander pattern to reduce stress in membrane**



Sourcee http://www.memsinvestorjournal.com/2011/03/overview-of-mems-microphone-technologies-for-consumer-applications.html

Akustica: 1-chip vs. 2-chip solution



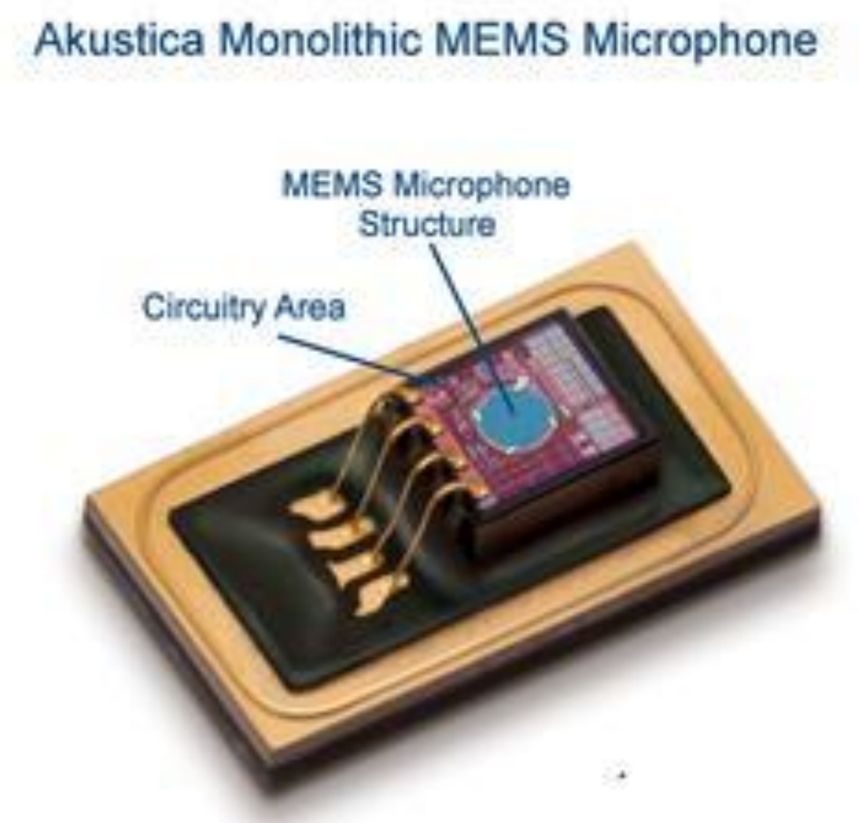


Image Source: Akustica

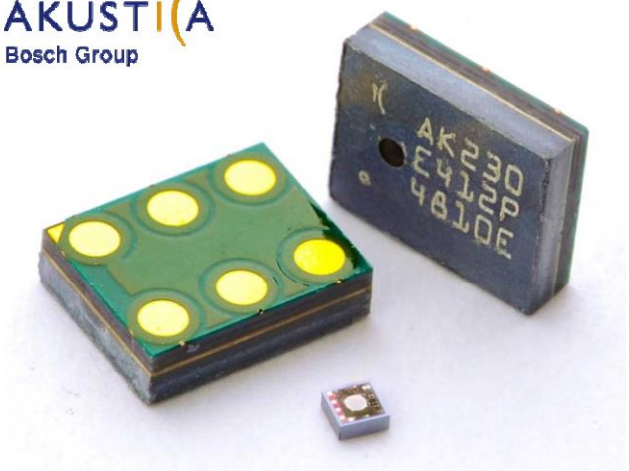
MEMS Microphones – Akustica (Bosch Group)

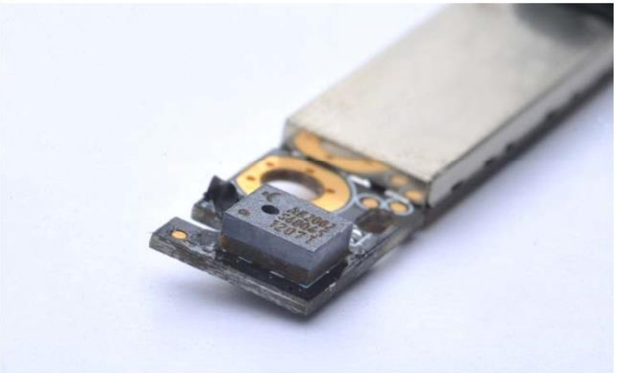
SEMICON West, July 12, 2011

Bosch, Reutlingen Site(s)

- World's Smallest Monolithic MEMS Device
- Fully-Integrated Digital Microphone
- 0.70mm² Single-Chip Die Includes
  - Acoustic Transducer
  - Pre-Amplifier
  - Sigma-Delta Modulator
- 1st Akustica MEMS Microphone to leverage Bosch MEMS Design & Production expertise
- Industry-Standard Form, Fit & Function
- Used by World's Leading PC OEMS

AKUSTICA
Bosch Group





125 Bosch 1886–2011 Research and Technology Center North America

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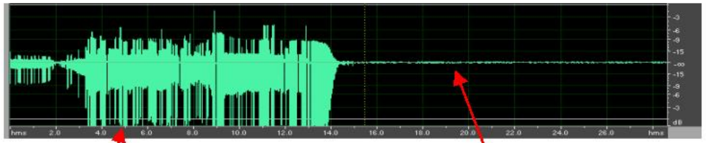
RTC5-NA, SEMICON West Presentation | 7/12/2011 |

BOSCH

SEMICON West, July 12, 2011

AKU230 Digital Microphone

- **Market need:** Improved voice quality in laptops for online communication
- **Design Challenge:** Overcome noisy notebook environments
- **Solution:** Digital MEMS Microphones
  - Enables movement of microphones to laptop display
  - Eliminates audio-signal interference from RF and EM noise sources
  - Single-wire stereo output for microphone arrays



Audio signal with interference (analog microphone)

Interference-free audio signal (digital microphone)

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Research and Technology Center North America

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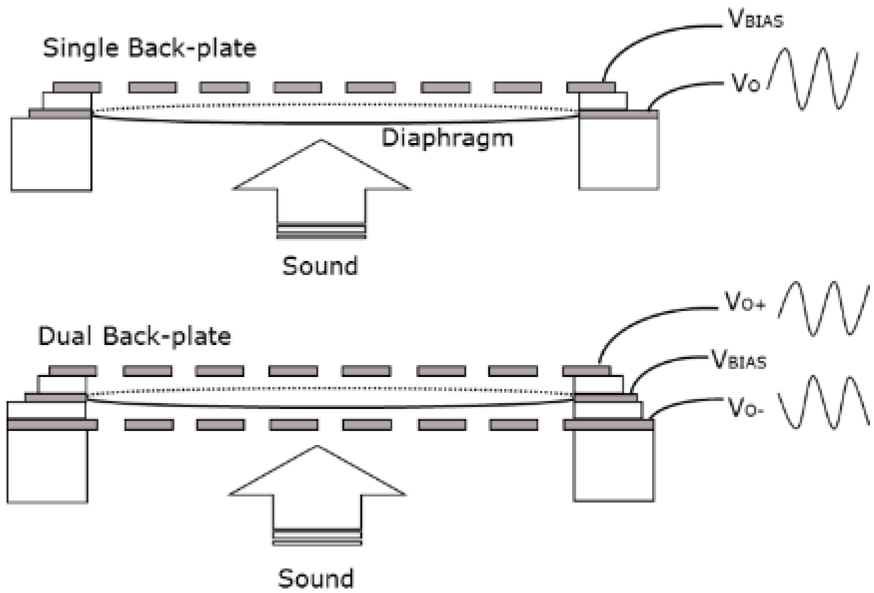
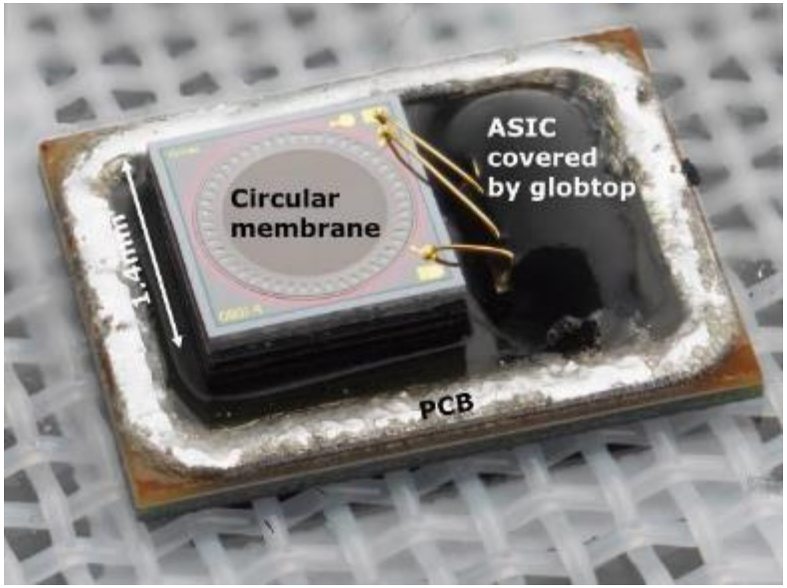
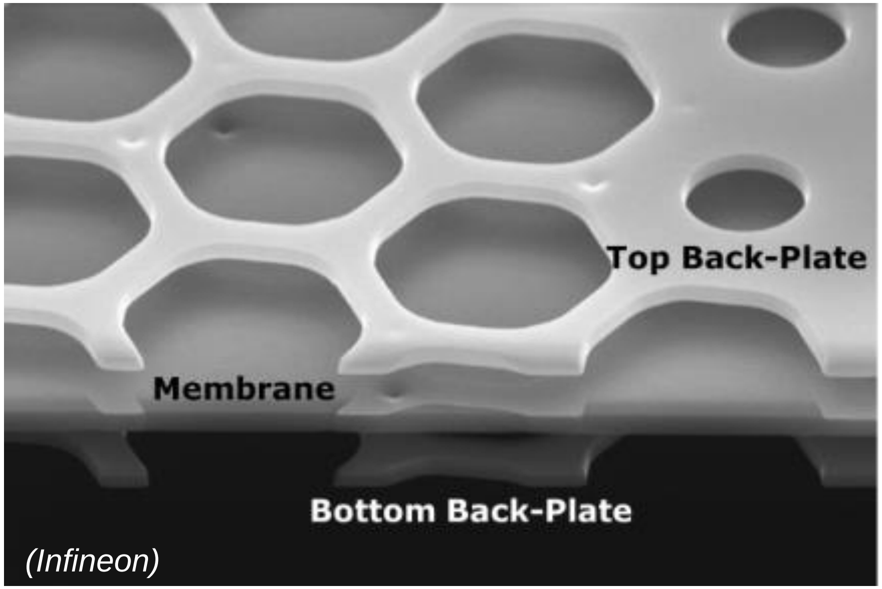
BOSCH

MEMS Microphones – Differential Readout

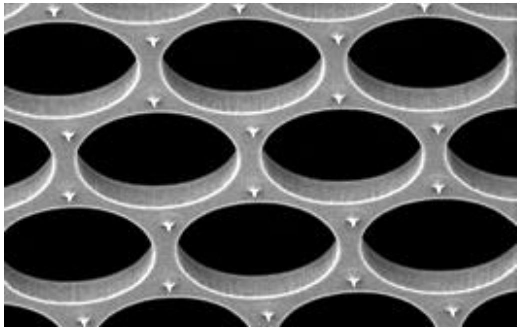






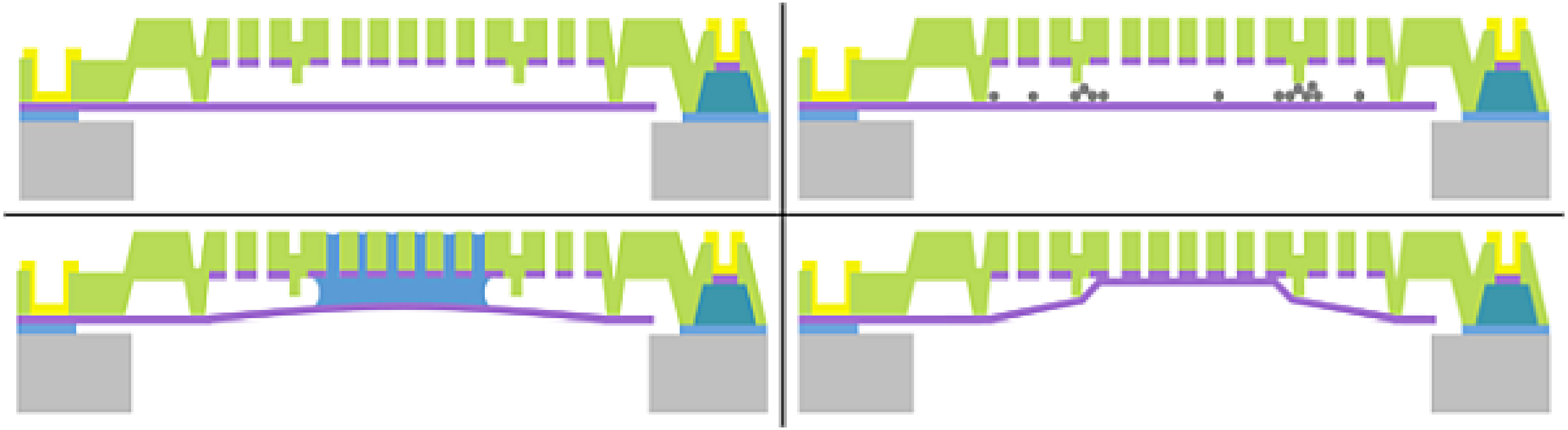
- loud sounds - high deformations – distortions
- differential read-out

- Release Process?
- Spikes?

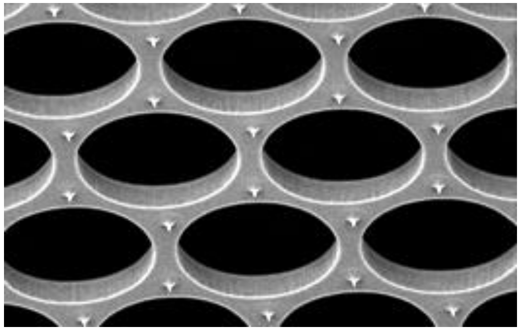


http://www.analog-eetimes.com/news/mems-microphone-design-better-audio/page/0/1

MEMS Microphones – Failure Mechanisms



1) **Particle damage → obstructing diaphragm motion**
2) **Stiction due to water damage**
3) **Stiction due to mechanical shock / acoustic overload.**



Source: EDN Network

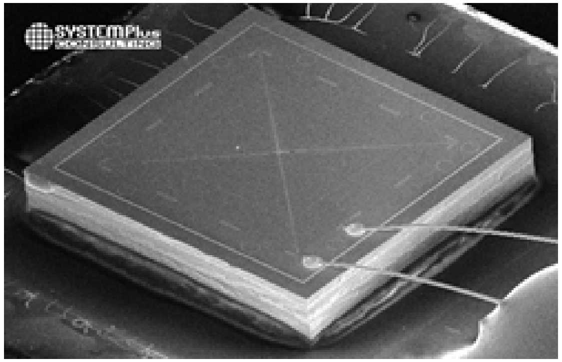
http://www.edn.com/design/analog/4457396/3/SmartEverything-and-the-rise-of-the-microphone-array

MEMS Microphones – Moving to Piezoelectric

iMicronews Report
22 Feb 2017

Vesper VM1000 Piezoelectric Microphone

First piezoelectric MEMS microphone could disrupt consumer applications



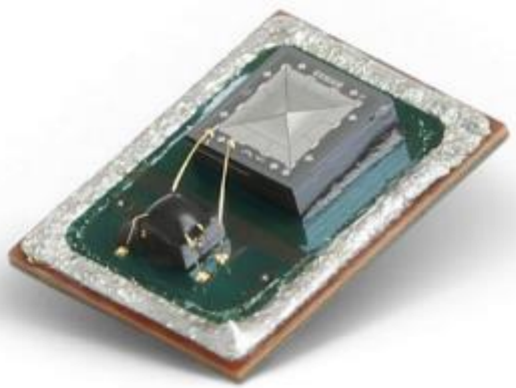
Vesper has developed the first piezoelectric MEMS technology in a microphone. This breaks new ground in the MEMS microphone world, which has been exclusively composed of capacitive silicon MEMS for more than ten years. It is a very robust technology. The VM1000 is an IP68 microphone, meaning it is water and dust proof, taking a step toward the waterproof smartphone.

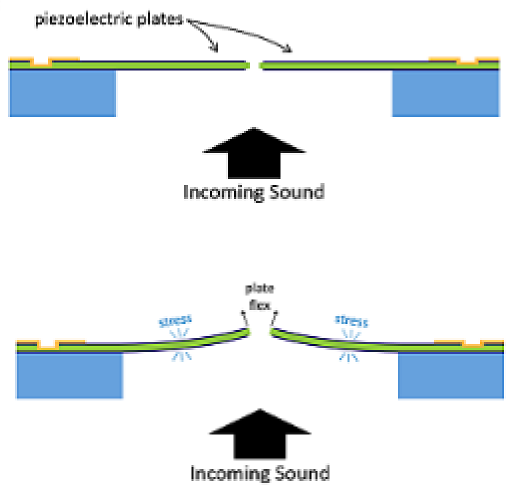
- Particle and Humidity Tolerance
- Suitability for Arrays (Beamforming)
- Piezoelectric Materials

VM1000

Piezoelectric MEMS Microphone

Create the most acoustically rich consumer products for all sound environments. From smartphones and wearables to smart home devices, consumers use sound-enabled products in the real world. That's why MEMS microphones have to work in real-world environments, not just some of the time, but all of the time. Vesper's VM1000 does just that.





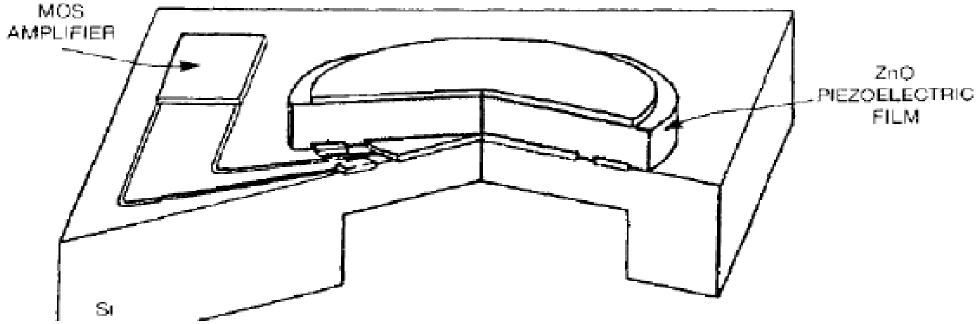
…stay tuned…

Credits go to
Prof. D. Horsley

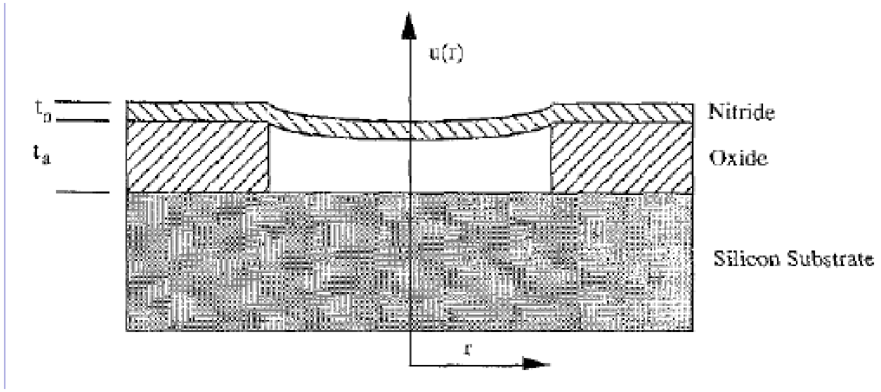
BSAC

MICROMACHINED ULTRASONIC TRANDSDUCERS (MUT)

30+ Years of MUTs

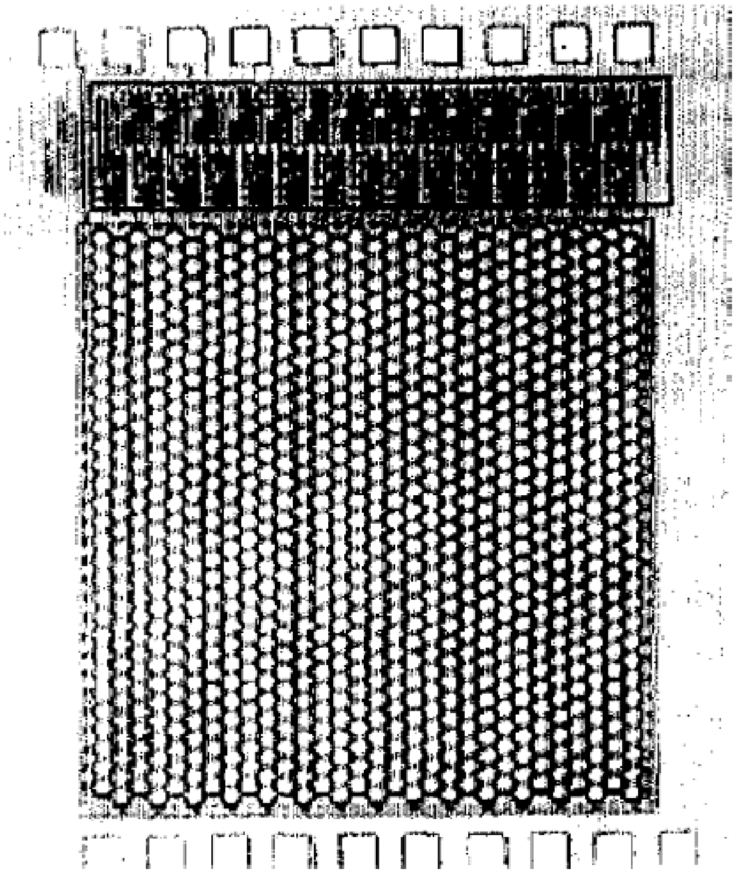


PMUT
Royer et al (Honeywell)
SNA 1983



CMUT
Haller & Khuri-Yakub
(Stanford)
IUS 1994

30+ Years of MUTs



30x30 CMUT Array

Surface micromachined ultrasound transducers in CMOS technology

Eccardt, Niederer, Scheiter, Hierold (Siemens)

IUS 1996

What has changed? What do we have now?

- **Technology**
  - PZE materials have greatly improved
  - Well developed manufacturing
  - MEMS foundries
  - Packaging…
- **Market**
  - Strong market pull for new sensors
  - IoT, drones, AuV, AR/VR, …
  - Phones!

Nature shows the way - Bats

- **Use ultrasounds to navigate**
- **Identify insects from wing velocity**
- **Target mosquitoes from a meter away**

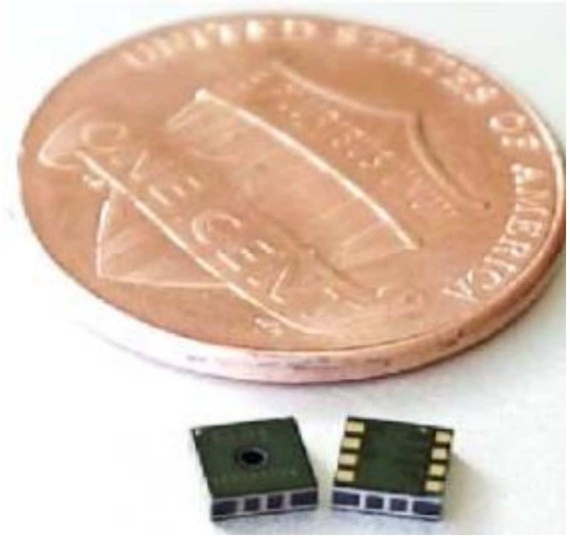
Existing (conventional) Ultrasonic Transducers

- **High output pressure**
- **Directionality possible**

- **Inefficient coupling to air**
  - **Matching layer needed**
- **Not suited for consumer electronics**
- **Lots of electronics to process signal**

MUTs – Micromachined Ultrasonic Transducers

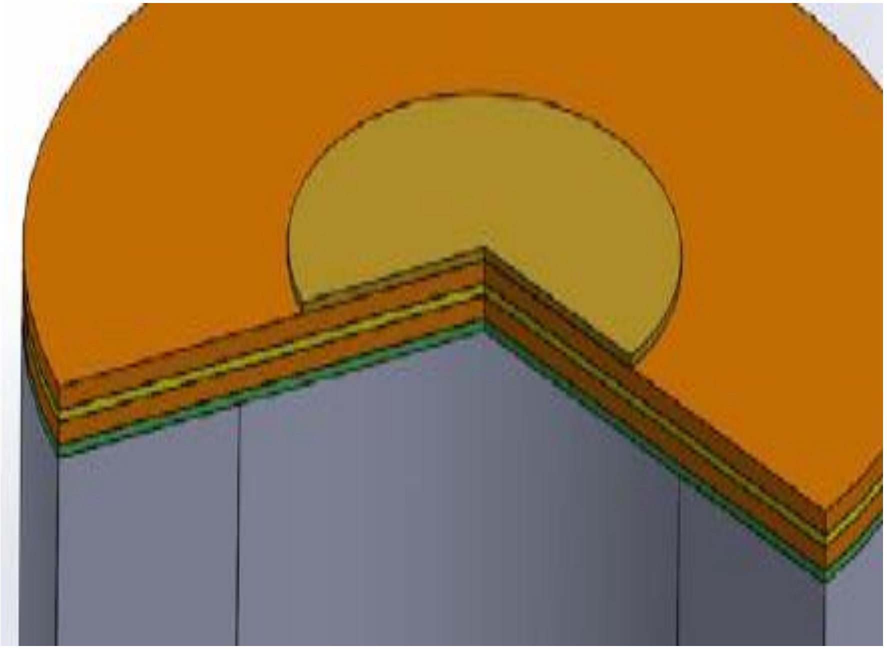
- **Extremely low power (15 µW)**
- **Long range (>1 m)**
- **Small size (1000x smaller than conventional)**
- **Digital interface**
  - **All signal processing on-chip**
  - **Autonomous operation for always-on sensing**



CHIRP microsystems

Features of MUTs

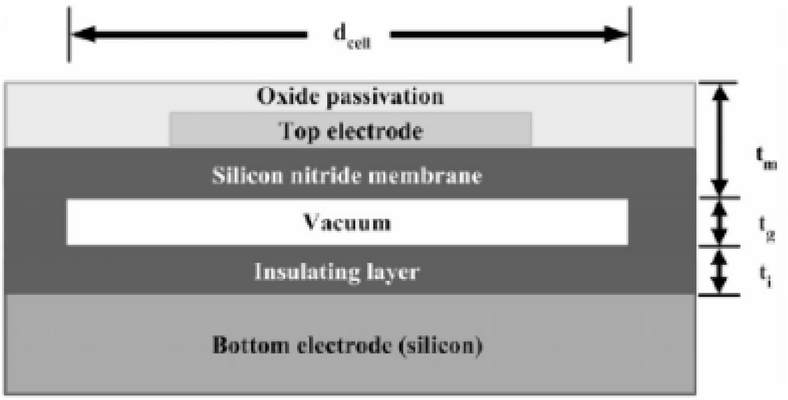
- **Suspended plate**
- **Low acoustic impedance → Large coupling**
- **Array fabrication possible**
- **Plate properties tunable via micro-patterning**



Actuating Air-Coupled MUTs

- **Goal: Large output pressure**
  - **Large transducer displacement**
  - **Piezoelectric actuation**

<u>Capacitive (CMUT)</u>



Wygant et al., IEEE TUFFC 2009

VS.

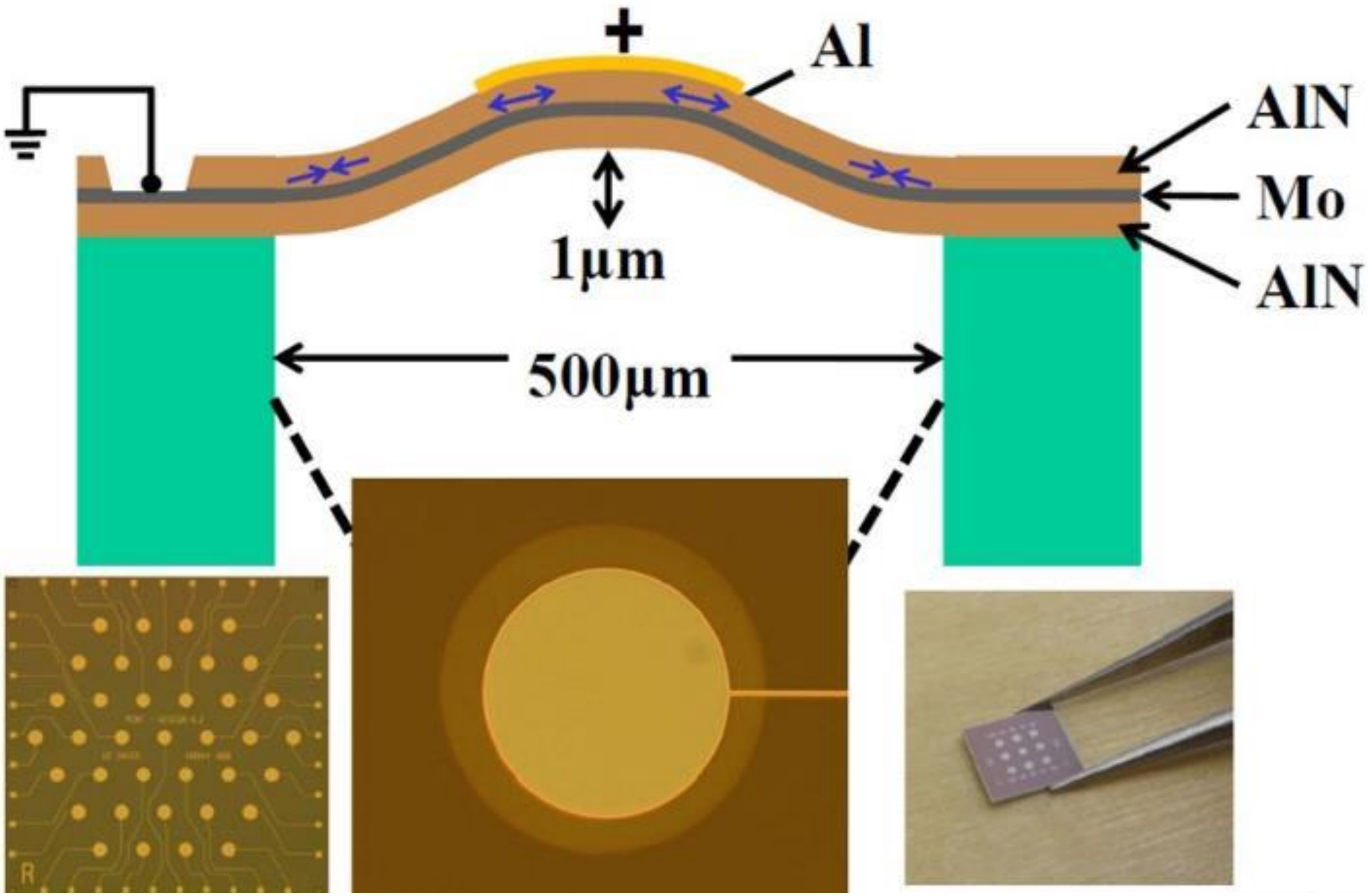
<u>Piezoelectric (PMUT)</u>

S. Shelton et al., IEEE IUS, 2009

R. Przybyla et al., IEEE Sensors J., 2011

16

Typical AlN PMUT cross section



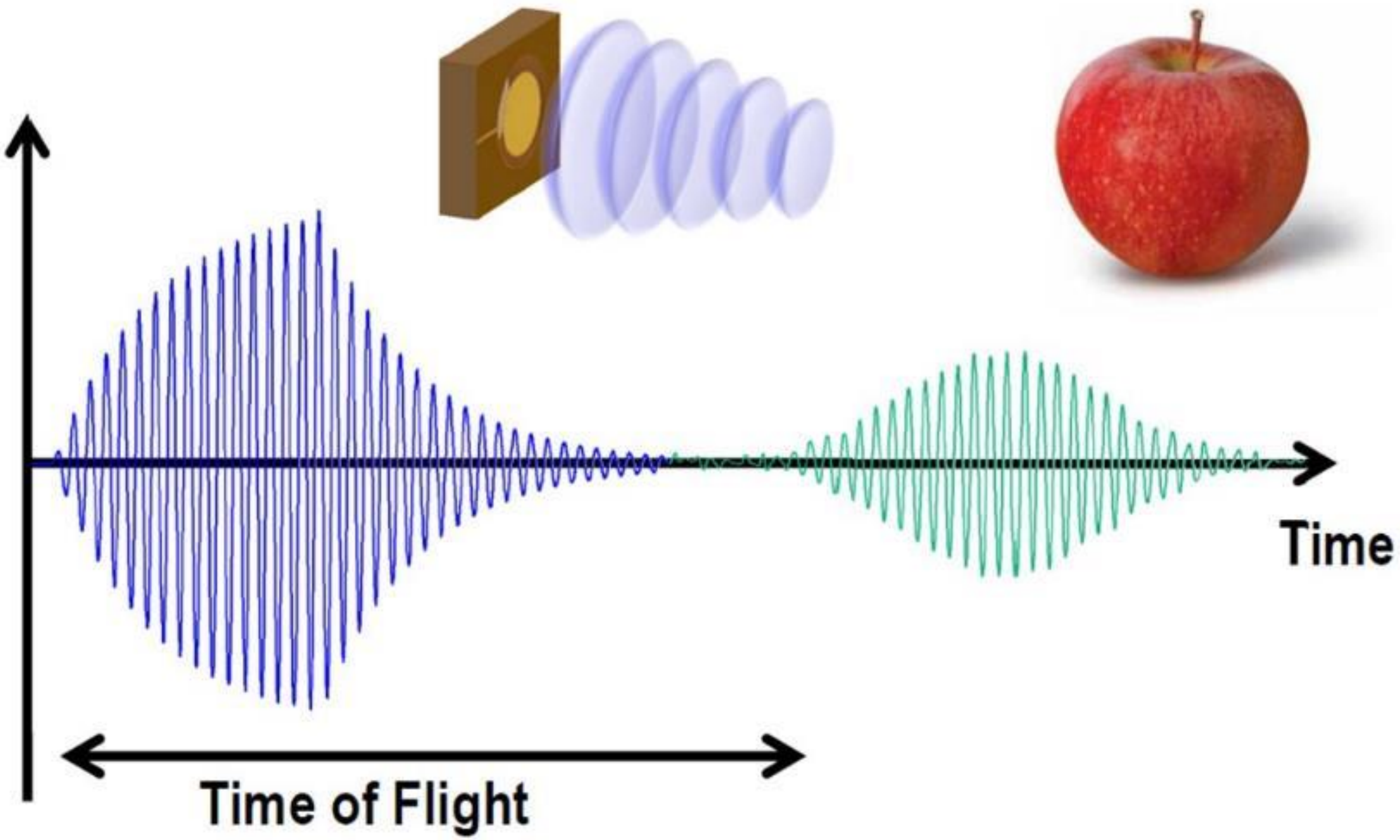
PZE materials for PMUTs

		AlN	PZT	ZnO
Transmission	$\boldsymbol{e_{31}}\left(\frac{\mathrm{C}}{\mathrm{m}^2}\right)$	-1	-15	-1
	$\boldsymbol{\varepsilon_{33,rel}}$	10	1020	11
Reception	$\frac{\boldsymbol{e_{31}}}{\boldsymbol{\varepsilon_{33}}}\left(\frac{\mathrm{GV}}{\mathrm{m}}\right)$	-11	-1.6	-10

Time of Flight (ToF) with PMUTs

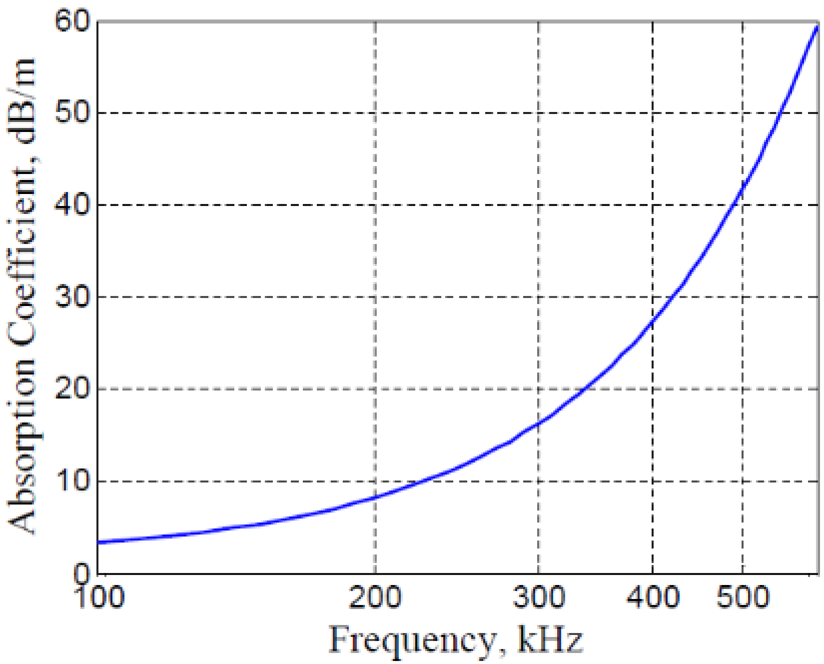
How does it work ToF?

- What frequency is better to be used?
- What determines the accuracy?



Air Absorption

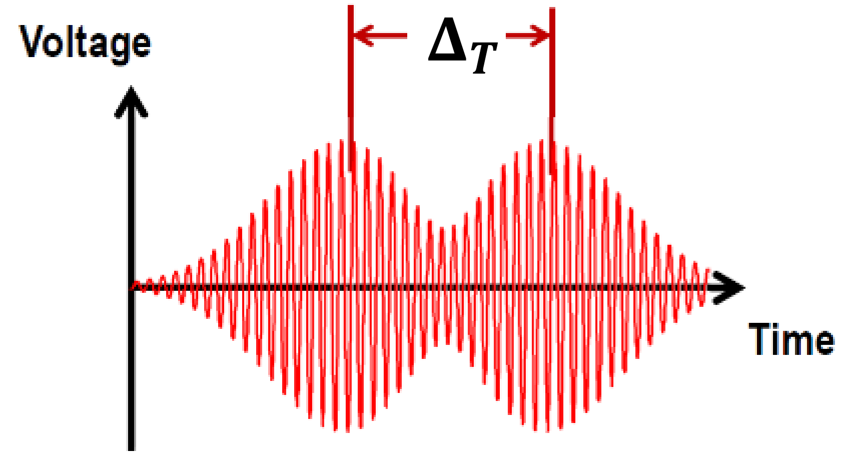
Frequency	Absorption loss	Range
40 kHz	1 dB/m	10 m
200 kHz	10 dB/m	1 m
800 kHz	100 dB/m	10 cm



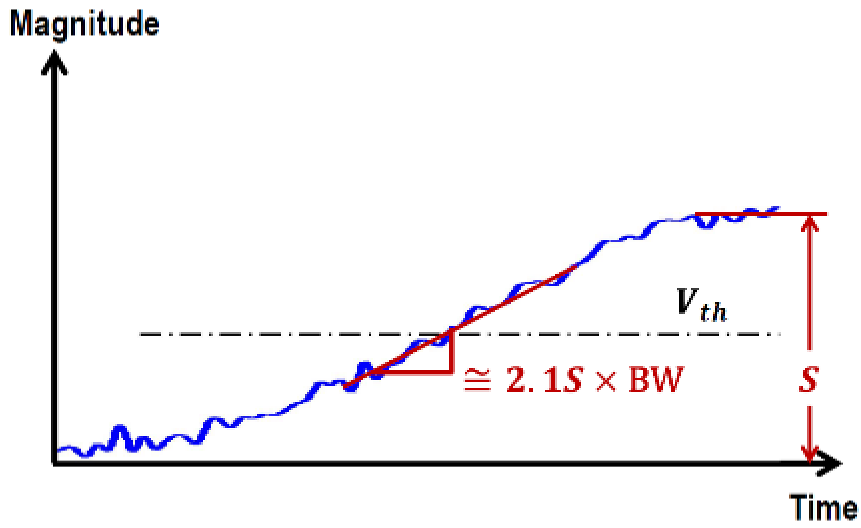
D.A. Horsley, R.J. Przybyla, M.H. Kline, S.E. Shelton, A. Guedes, O. Izyumin, and B.E. Boser, IEEE MEMS 2016

Resolution, Accuracy, Bandwidth

$$\Delta_r \approx \Delta_T \cdot c \approx 0.4\frac{c}{BW}$$

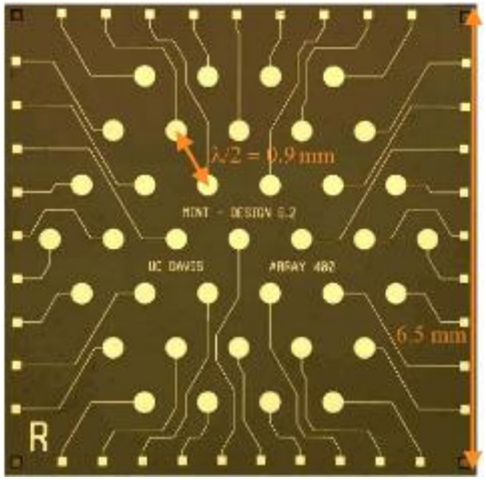


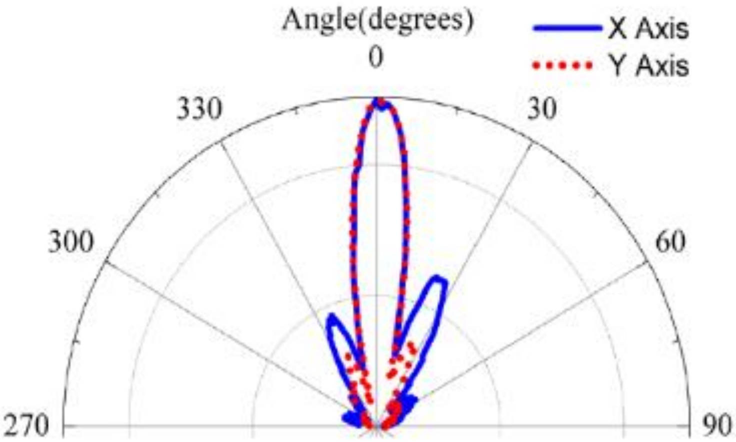
$$\sigma_r \approx \frac{c}{2BW}\frac{1}{2.1\sqrt{SNR}}$$

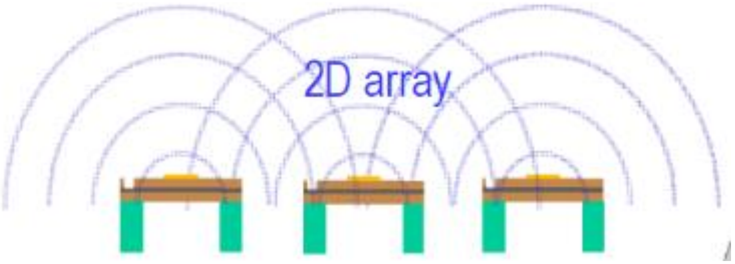


Phased Arrays

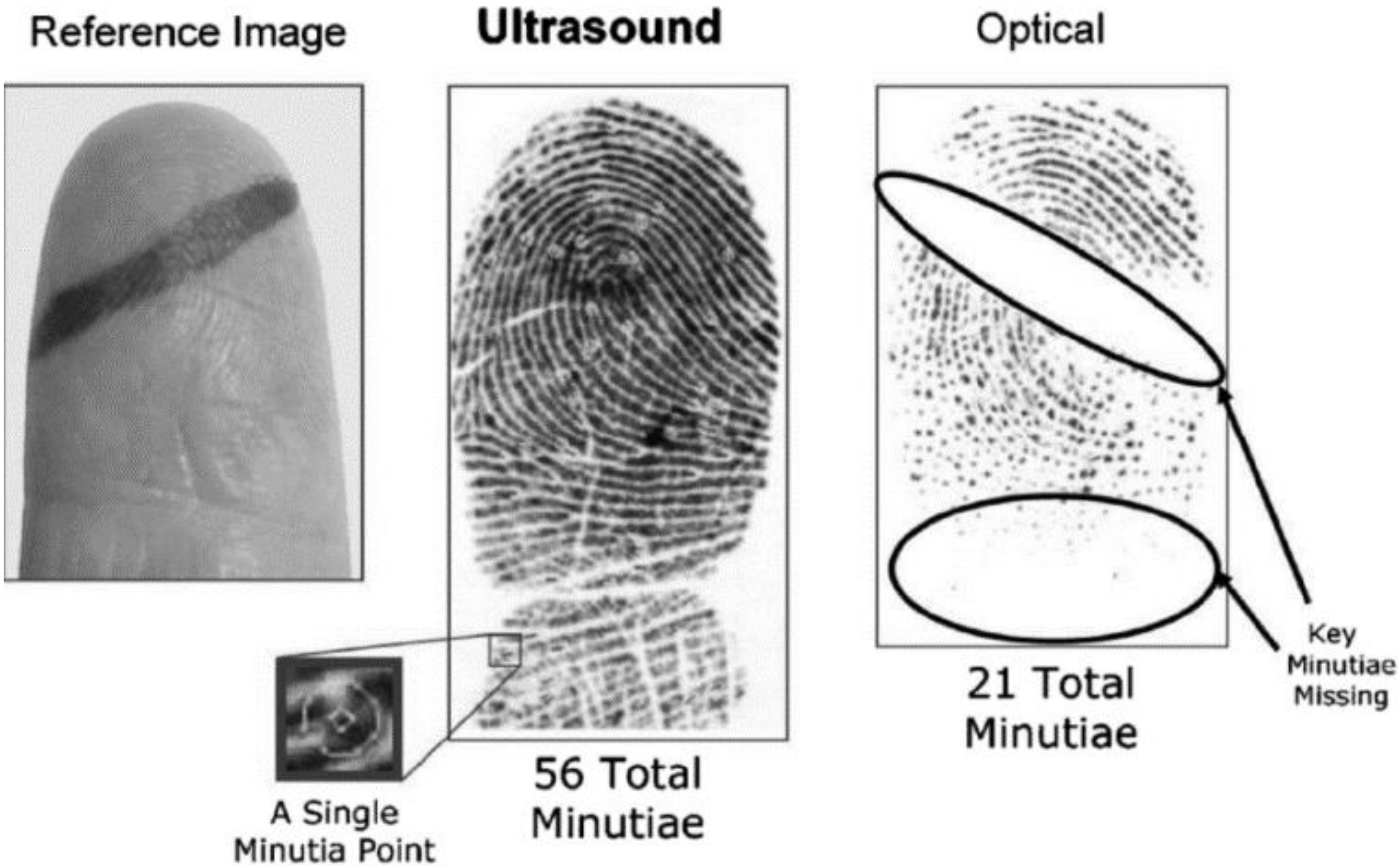
- **Using 2D arrays of PMUTs:**
  - **Power scales N^2**
  - **By dephasing each PMUT, we can control shape of beam**
  - **Beam width $\frac{\pi}{N}$**
  - **Spacing $\frac{\lambda}{2}$**





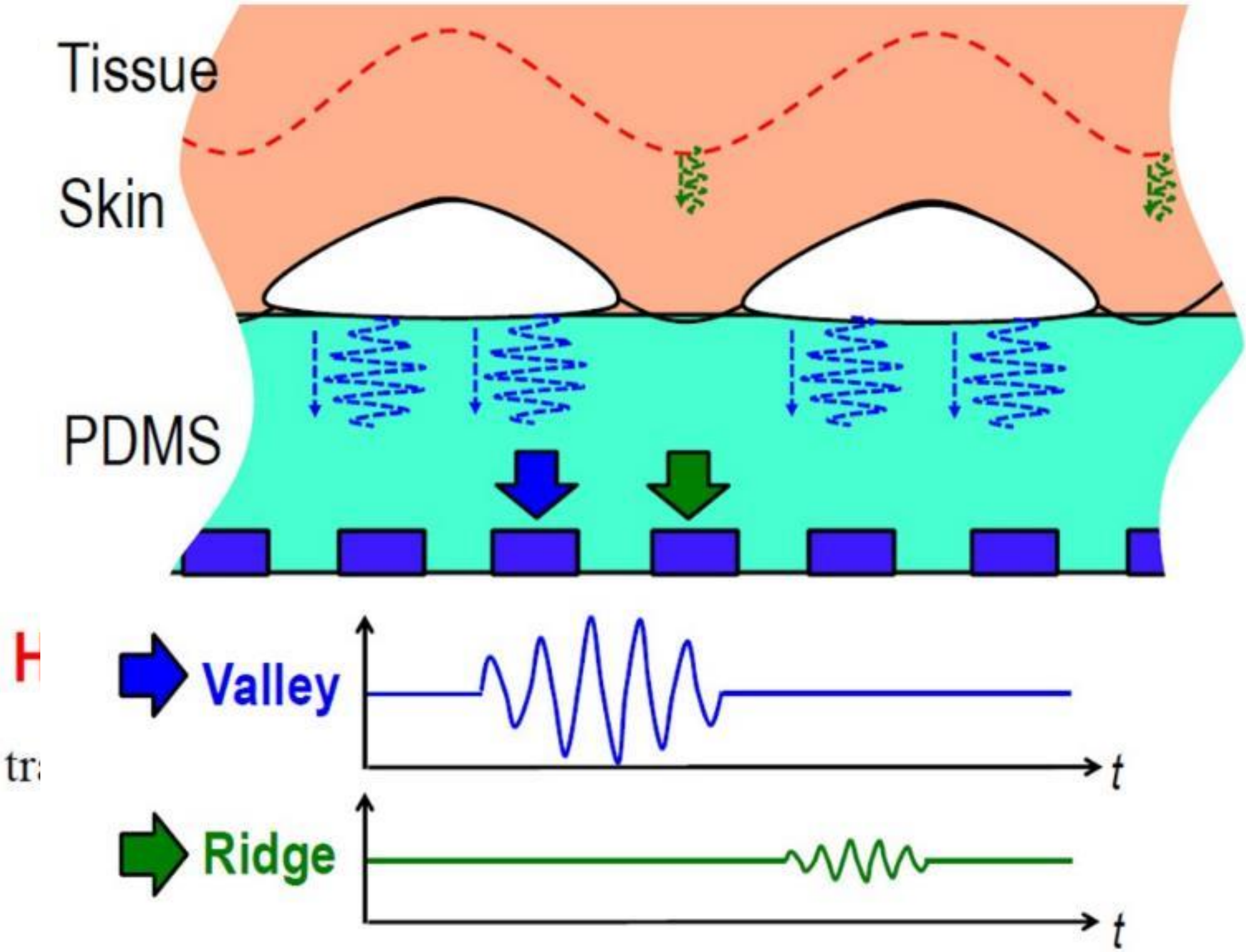


Ultrasound Fingerprint Sensor



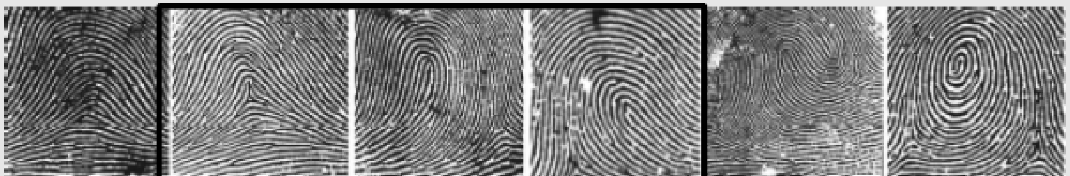
J. K. Schneider, “Ultrasonic Fingerprint Sensors”, Avances in Biometrics, 2008

Operational Principle



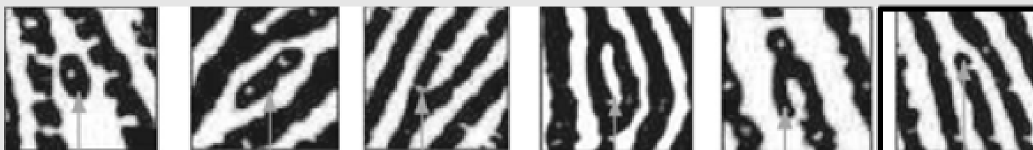
Biometric Identity

Level 1 Features: Pattern



Left/Right/Double Loop

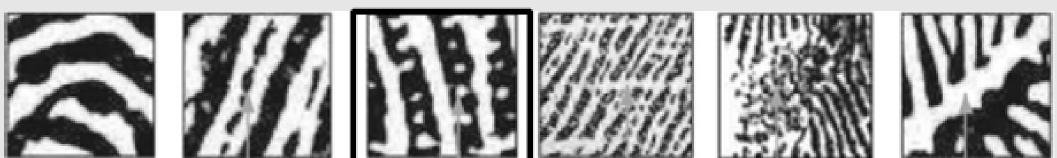
Level 2 Features: Minutia Points



Ending

FBI Standard 500 dpi

Level 3 Features



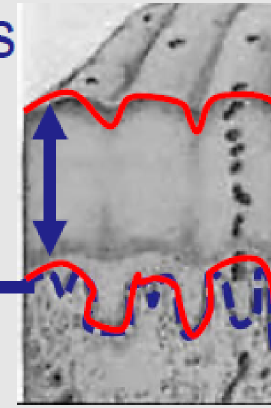
Pores

500+ dpi

Epidermis

~200 µm

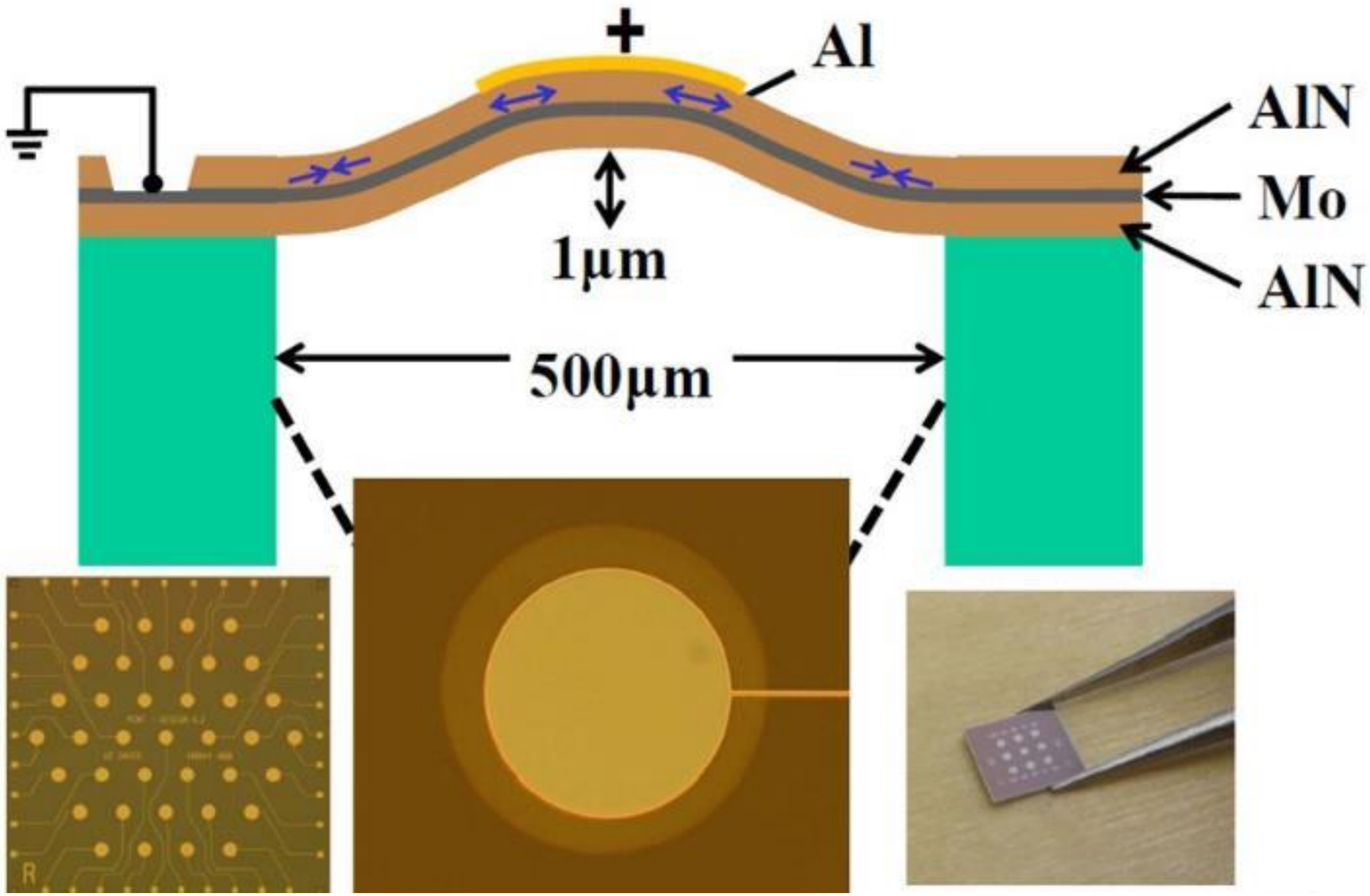
Dermis



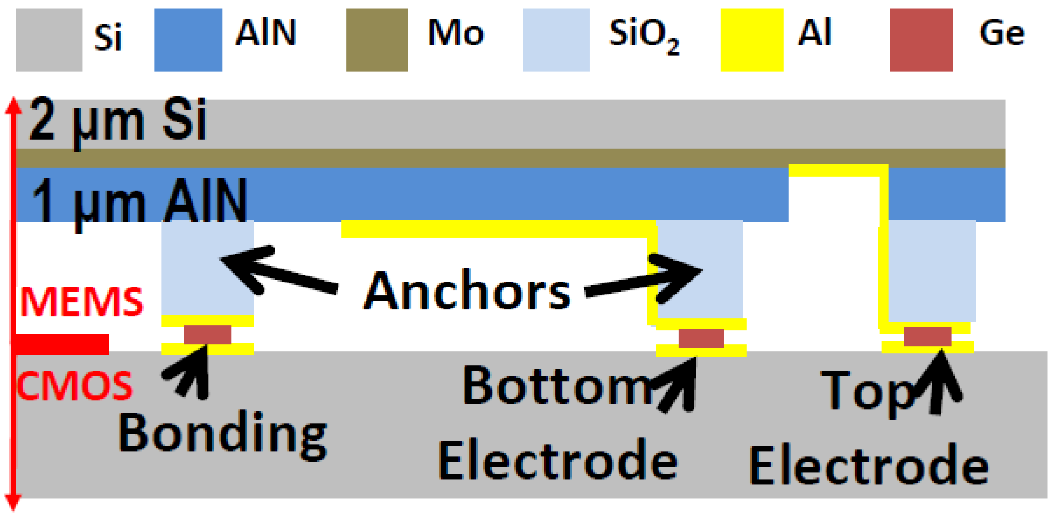
Sensor Resolution Requirement

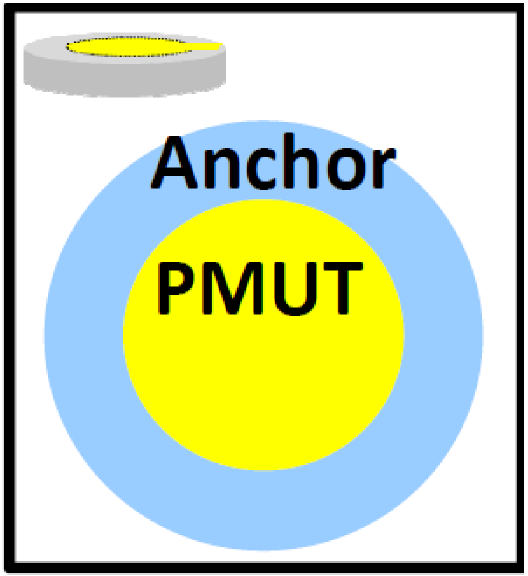
Lateral	500 dpi
Axial	200 µm

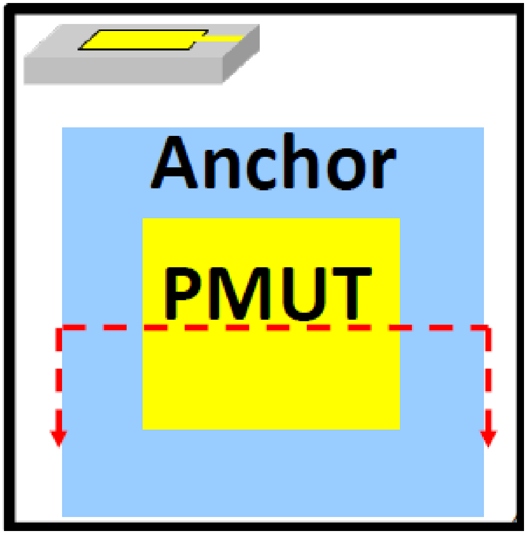
Typical AlN PMUT cross section



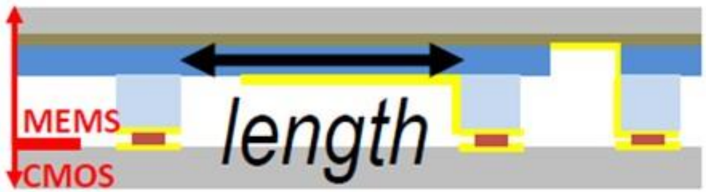
PMUT Cross-Section with electronics



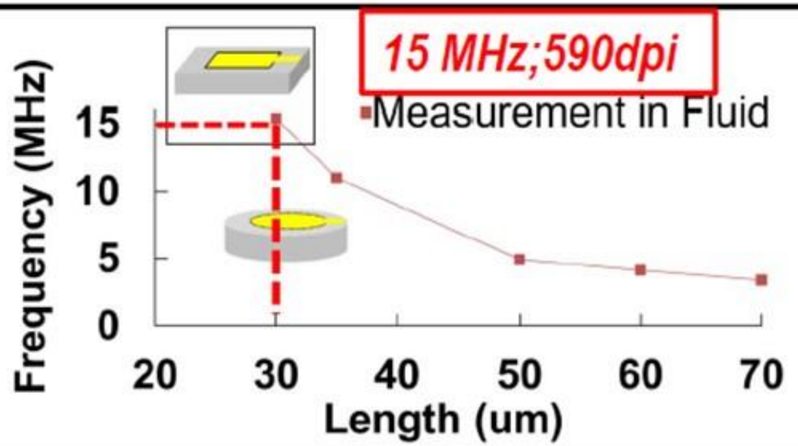




PMUT Design

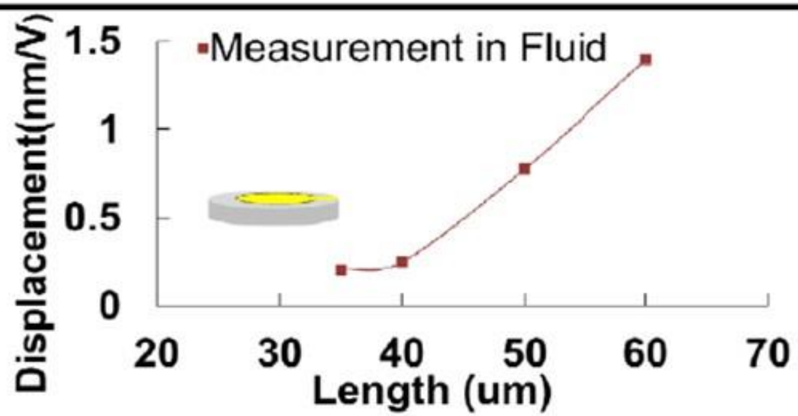


$$f \sim \frac{1}{l^2}$$



$$d_p \sim l^2$$

$$p \sim f \times d_p$$



$$L \downarrow \rightarrow DPI \uparrow$$

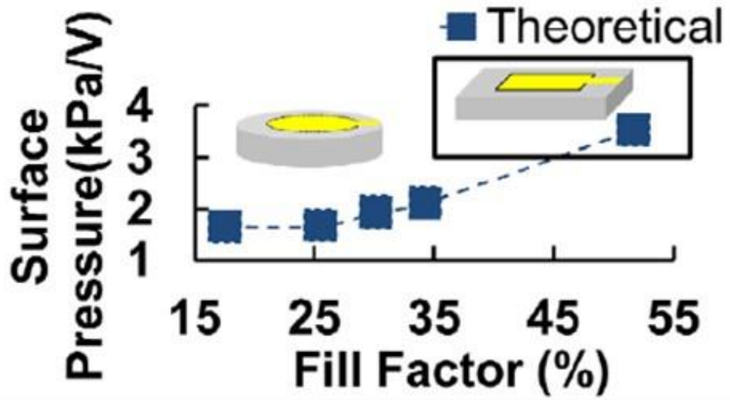
$$L \downarrow \rightarrow freq \uparrow$$

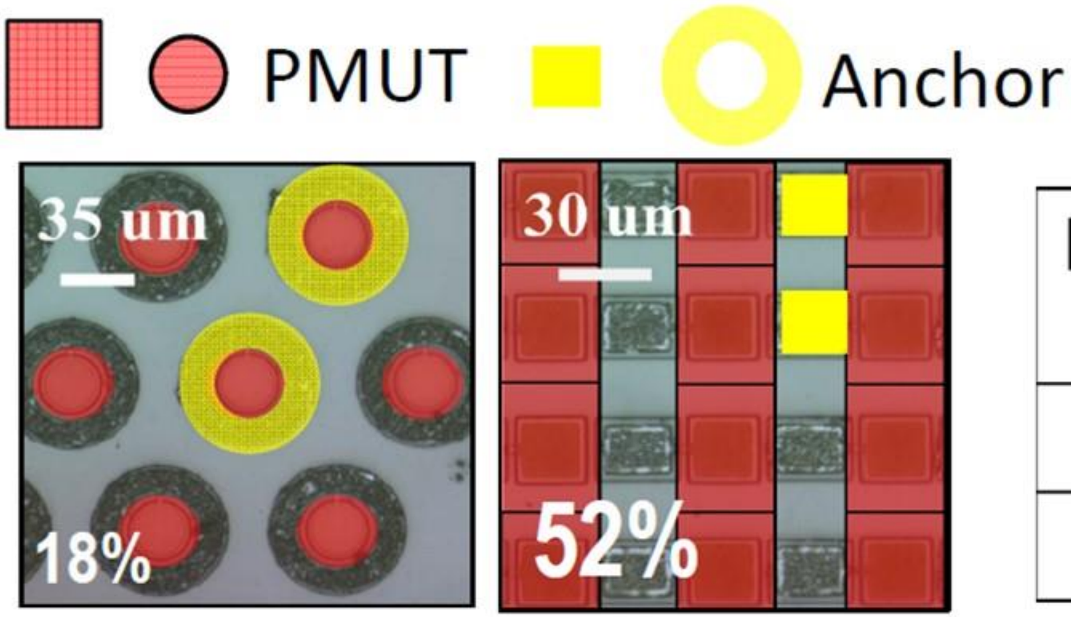
$$L \downarrow \rightarrow Pressure \downarrow$$

PMUT Array Design

$$p \sim \sqrt{FF}$$

$$Fill\ Factor(FF) \stackrel{\text{def}}{=} \frac{PMUT\ Area}{Total\ Area}$$

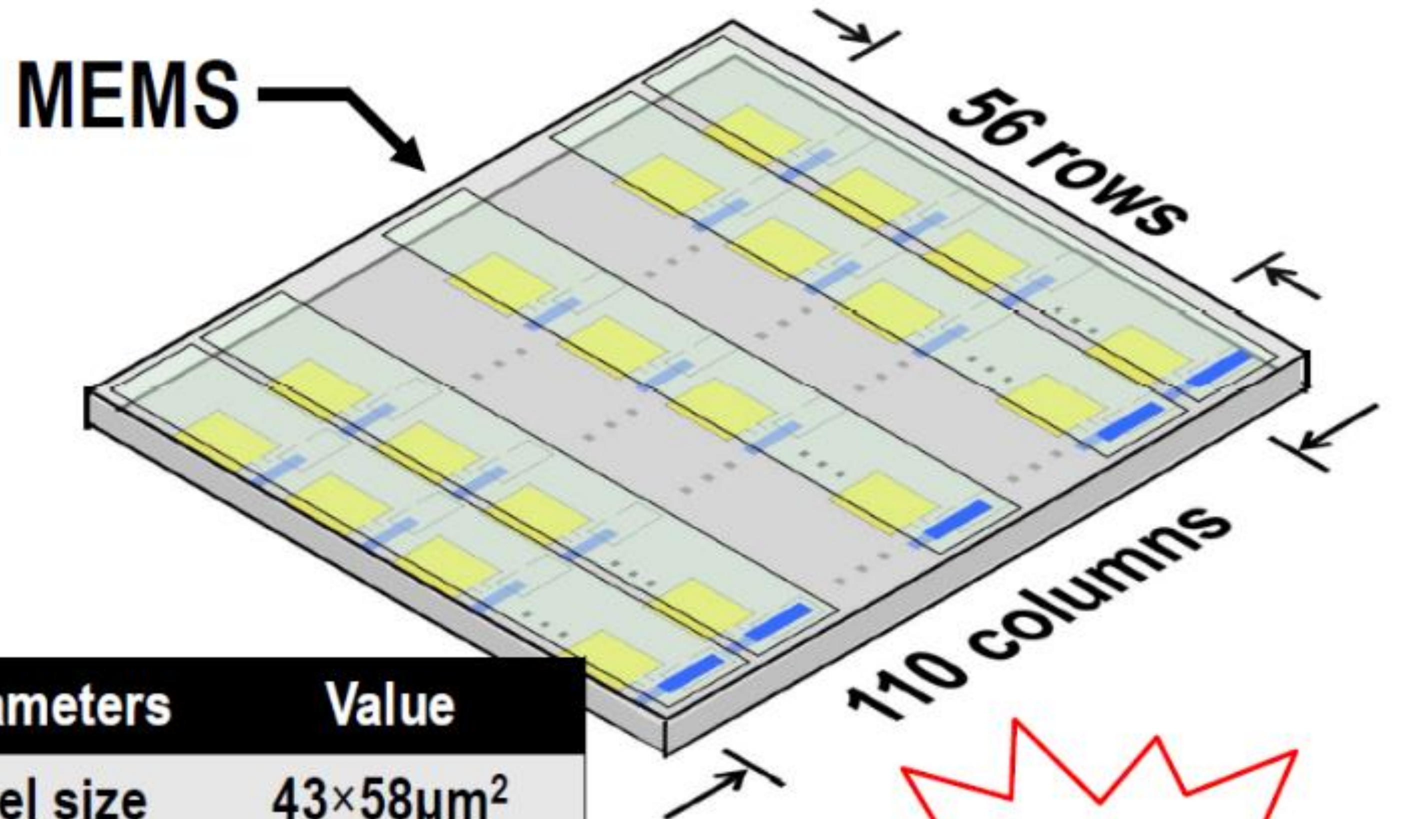




Fill Factor	Pressure at 500 µm
18%	1.6 kPa
52%	8.1 kPa

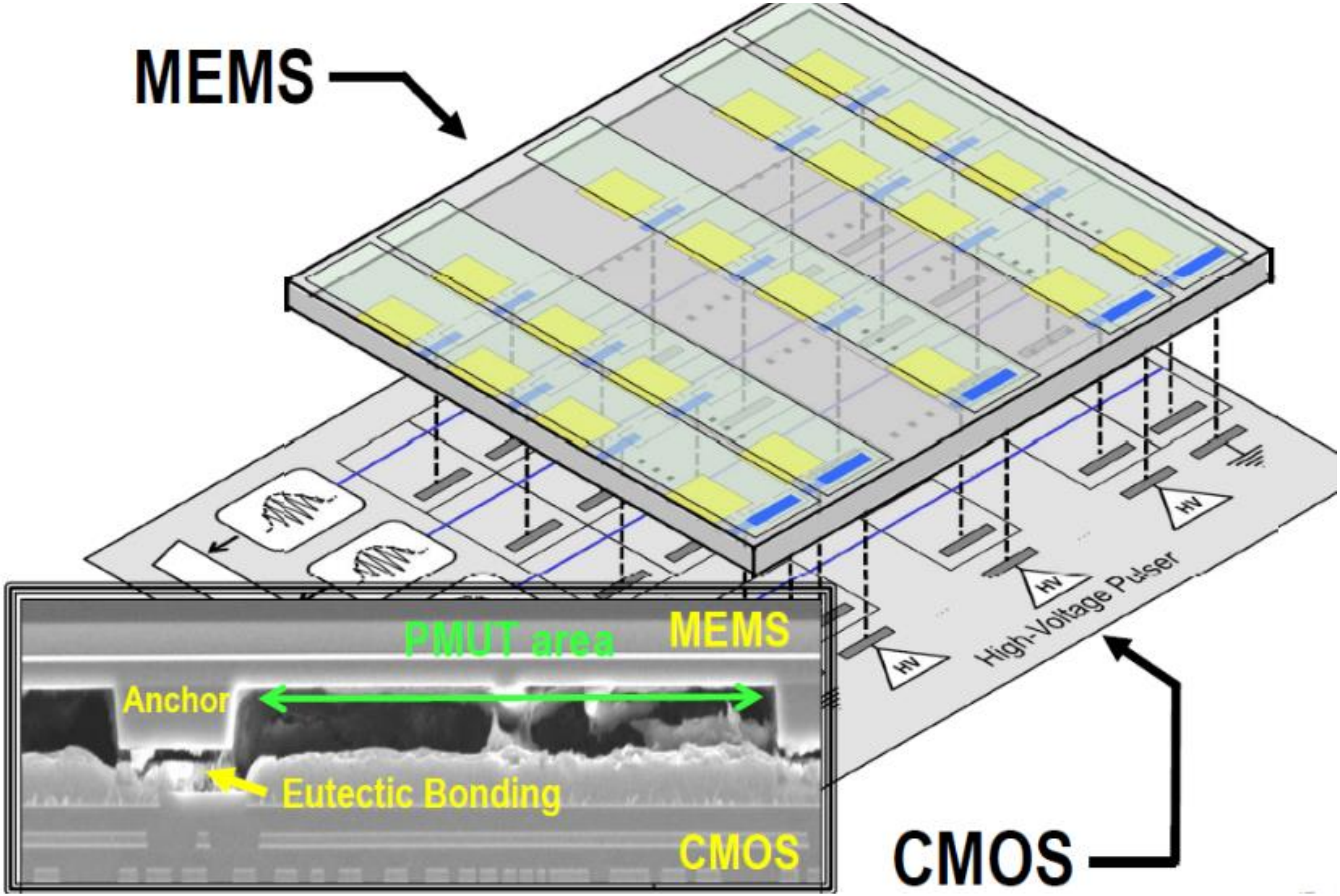
X. Jiang et al, "Monolithic 591x438 DPI Ultrasonic Fingerprint Sensor," IEEE MEMS 2016.

Array of sensors

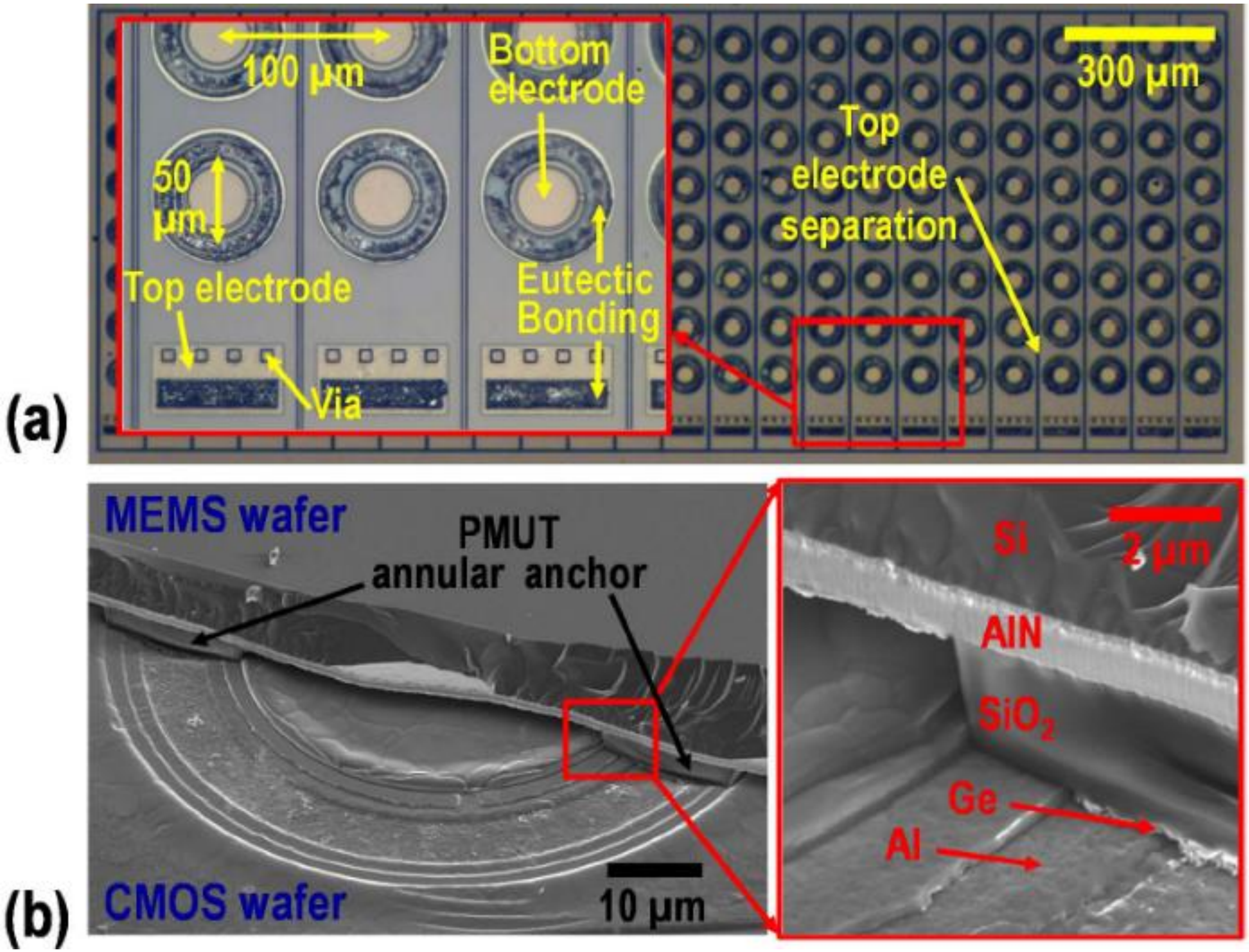


Parameters	Value
Pixel size	43×58μm²
Resolution	582×431 dpi
Fill-factor	51.7%

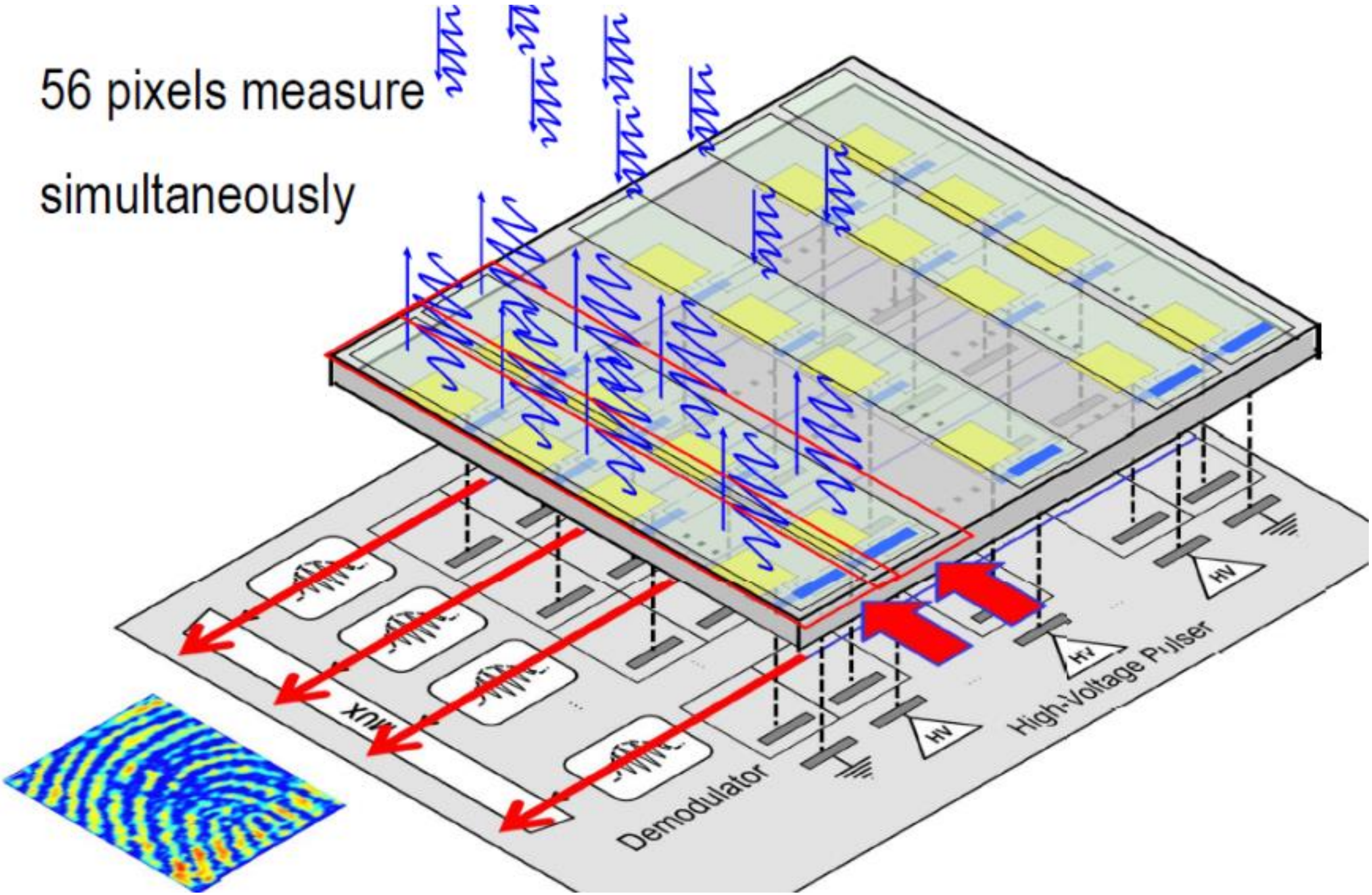
Array of sensors



Array of sensors



Array of sensors



MICROSPEAKERS

Some new companies on the block

XMEMS

Arioso