Piezoelectric Micromachined Ultrasonic Transducers in Consumer Electronics

the Next *Little* Thing?

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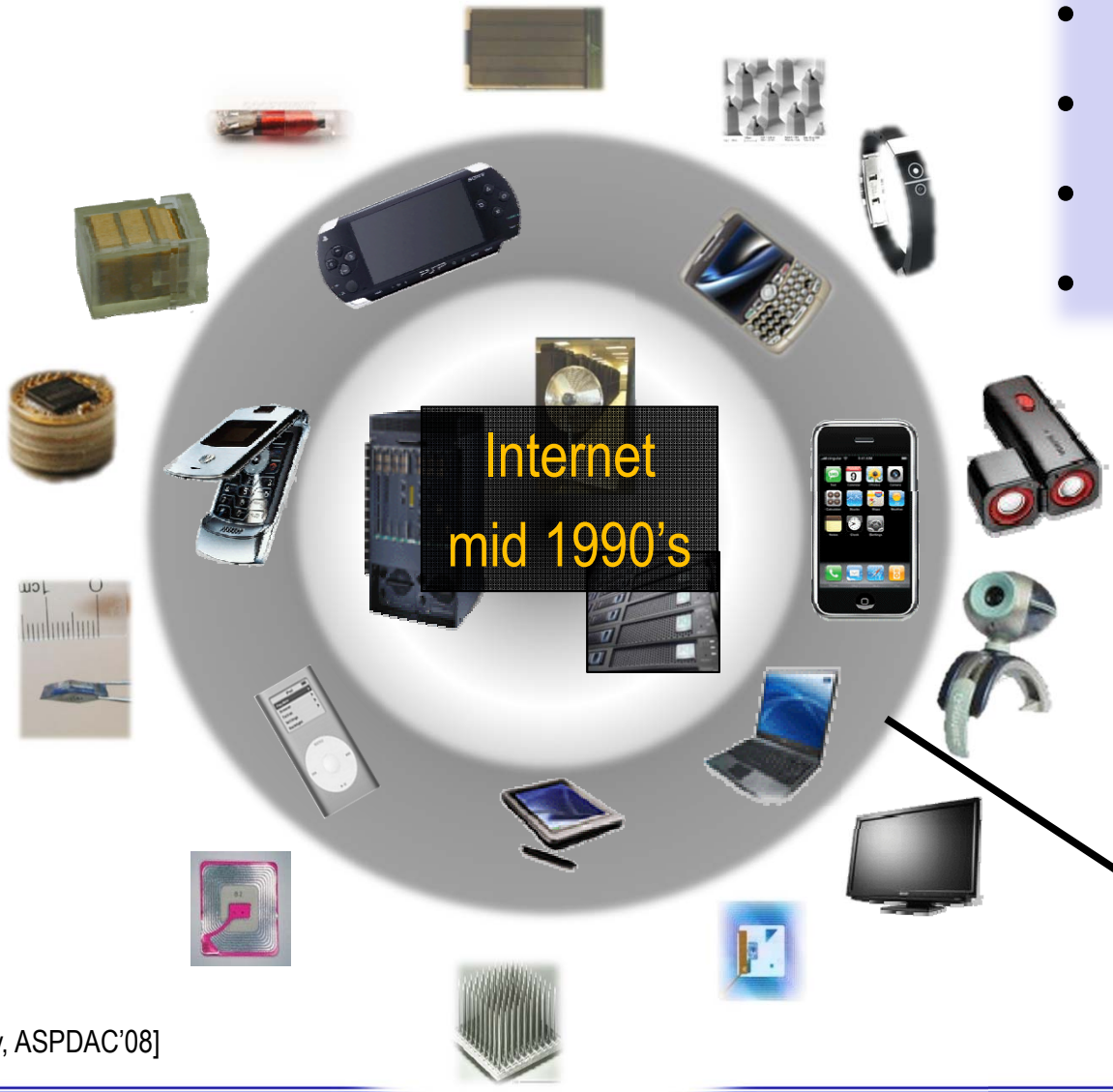
Seminar, Tohoku University

April 28, 2017

UCDAVIS
UNIVERSITY OF CALIFORNIA

BSAC

2030 Vision for MEMS



Sensors

- **New modalities**
- **Ultralow power**
- **Low cost**
- **Small size**

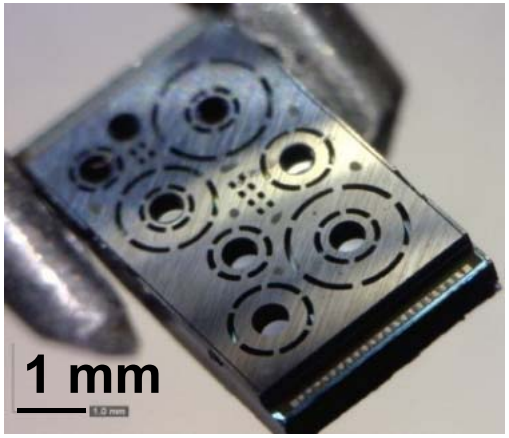
Next 15 years:

- IoT
- Teraswarm
- Trillion Sensors

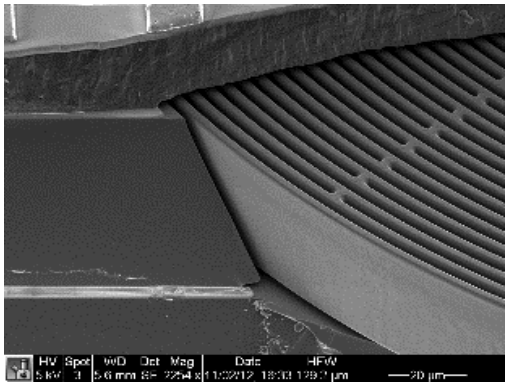
[J. Rabaey, ASPDAC'08]

Horsley Group Current Research

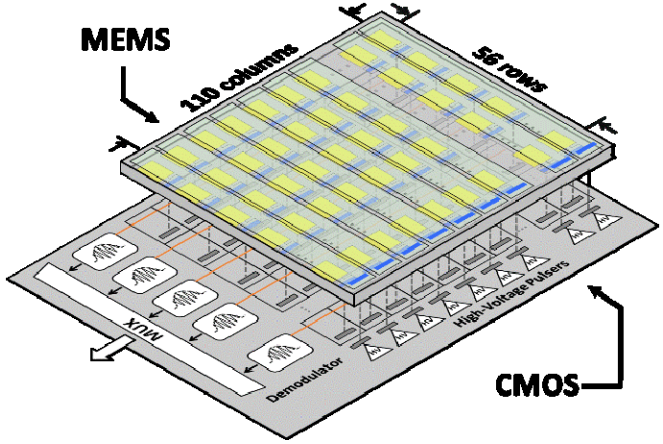
Low-Power Microsensors

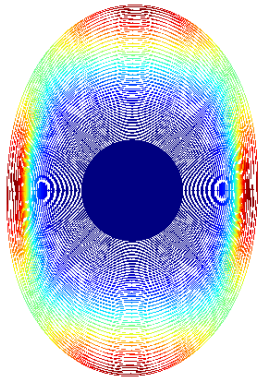


Dynamics & Control Issues in MEMS

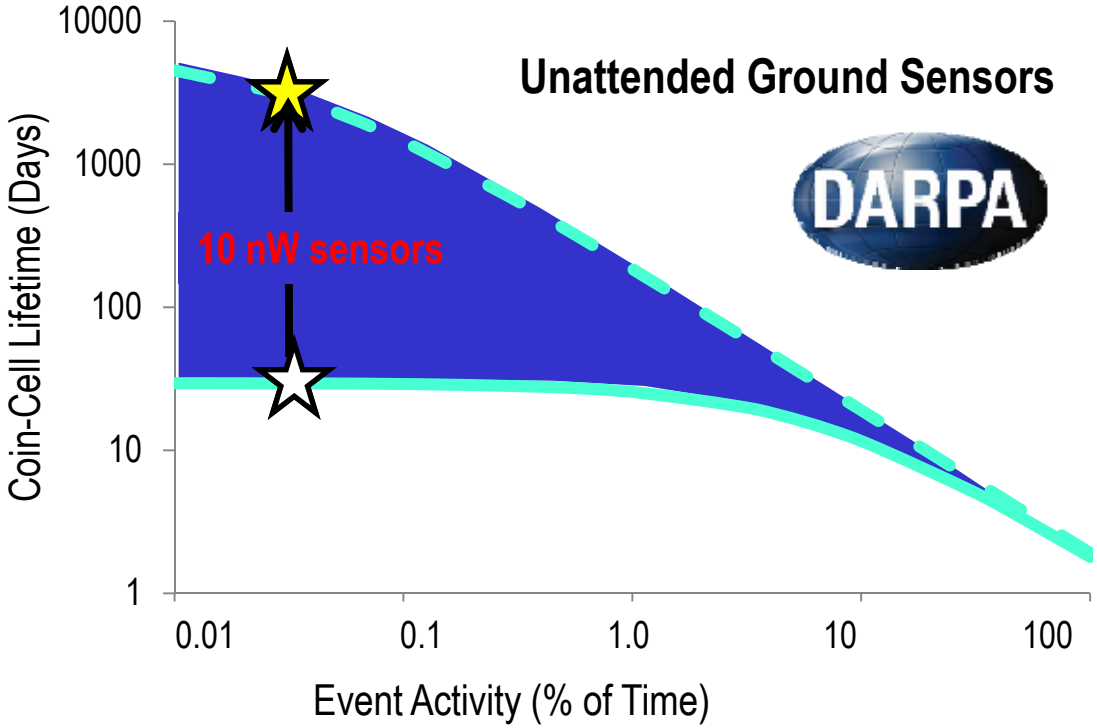


Ultrasonics & Acoustics

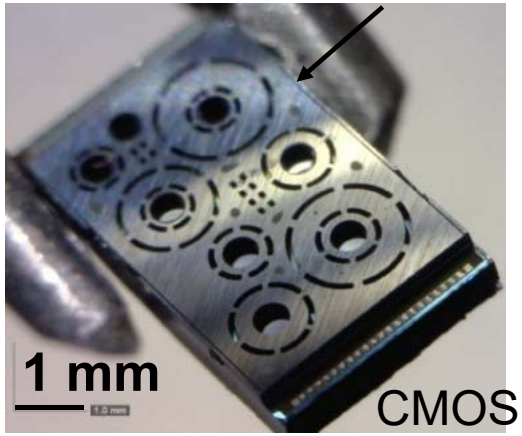




Ultralow Power Sensors



Piezoelectric MEMS

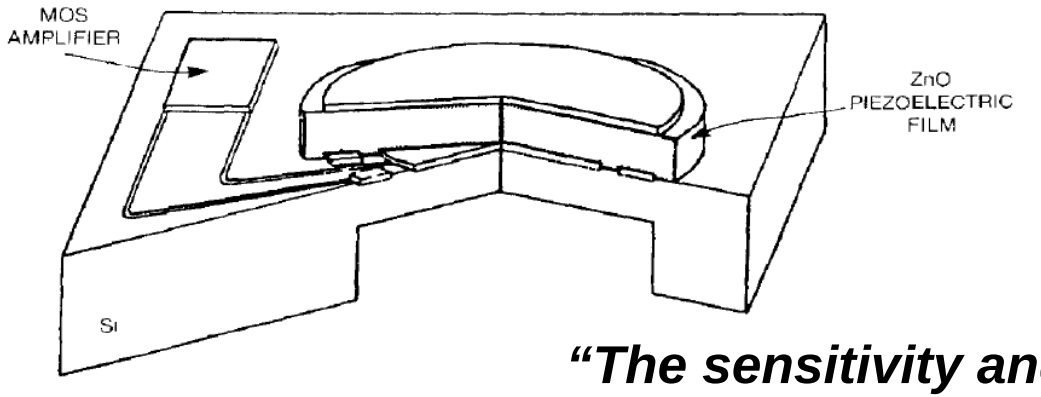


- **Program Goals:**
  - Accelerometer & microphone < 10 nW (10,000x below state-of-the-art)
  - On-board analog/digital signal processing to recognize events
- **Our innovations**
  - Passive amplification at the transducer level
  - Zero-bias voltage piezoelectric sensors

PMUTs in Consumer Electronics Outline

- History and motivation
- Air-coupled ultrasonic transducers
- Time of Flight (ToF) rangefinding
- Phased-array ultrasonics
- Ultrasonic Fingerprint sensor

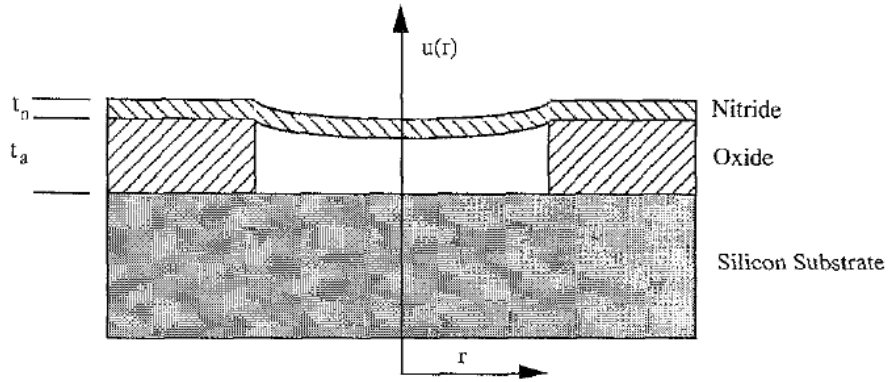
30+ Years of MUTs



PMUT

Royer et al (Honeywell)
SNA 1983

"The sensitivity and SNR of the ZnO acoustic sensor … do not compare well with … commonly used electret microphones"

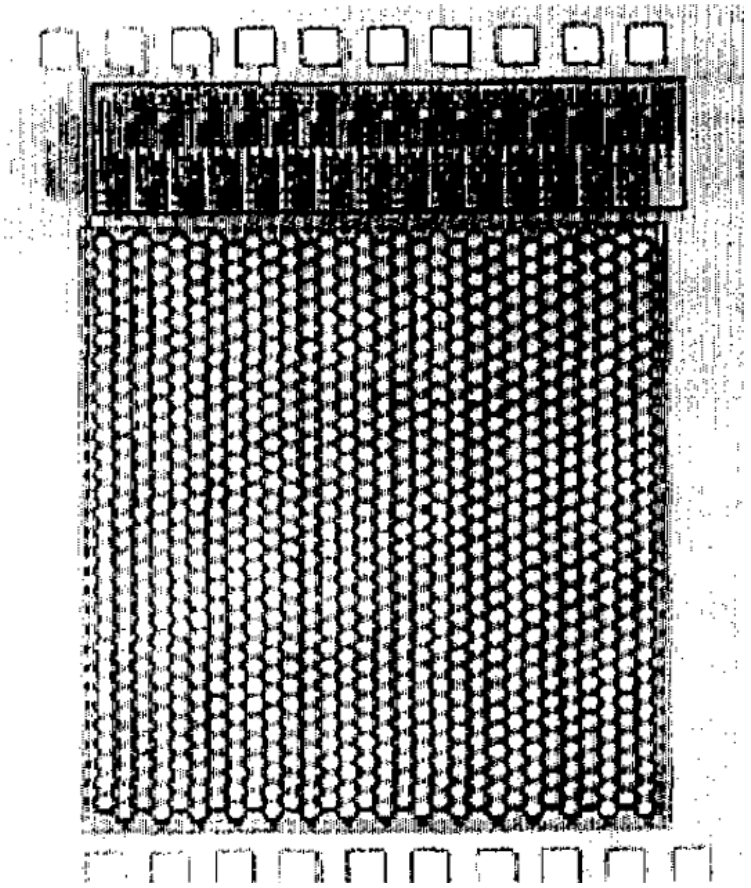


CMUT

Haller & Khuri-Yakub
(Stanford)
IUS 1994

"MUTs enjoy the inherent advantages of microfabrication, which include low cost, array fabrication, and the possibility to integrate electronics either on chip or as a multi-chip module."

Integration demonstrated 20 years ago(!)



30x30 CMUT Array

Surface micromachined ultrasound transducers in CMOS technology

Eccardt, Niederer, Scheiter, Hierold (Siemens)
IUS 1996

"new microfabrication technologies have emerged, allowing a highly reproducible fabrication of electrostatically driven membranes."

20 Years of Inertial Sensors

A lot has happened in two decades

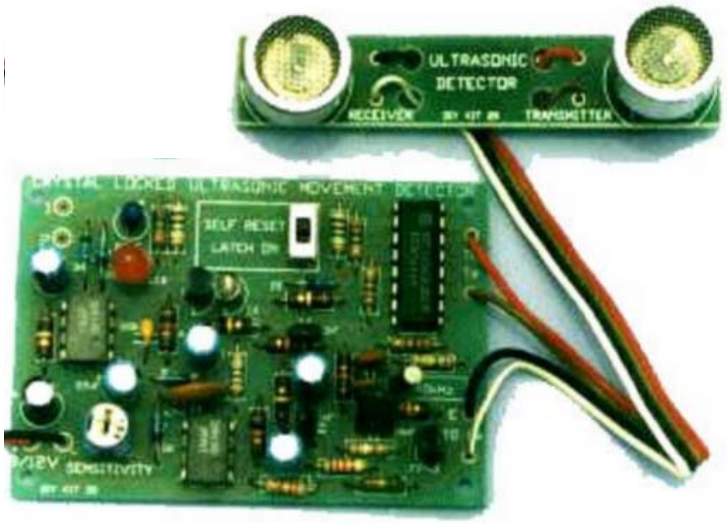
1990's Gyroscope

2016 Gyroscope

20 Years of Ultrasonic Sensors

A different story…

1990's Ultrasonic Rangefinder



- Discrete, thru-hole electronics
- Big U/S transducers

2016 Ultrasonic Rangefinder

- IC replaces many discretes
- Same old U/S transducer

What's New Today?

Technology

- Piezoelectric materials greatly improved
- Well-developed manufacturing infrastructure
  - MEMS foundries, packaging & test suppliers

Market

- Strong market pull for new sensors
  - IoT, drones, autonomous vehicles, AR/VR, new interface technology
- Every flagship phone needs a fingerprint sensor

Outline

- History and motivation
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- Time of Flight (ToF) rangefinding
- Phased-array ultrasonics
- Ultrasonic fingerprint sensor

Observations from Nature

Uses ultrasound to navigate

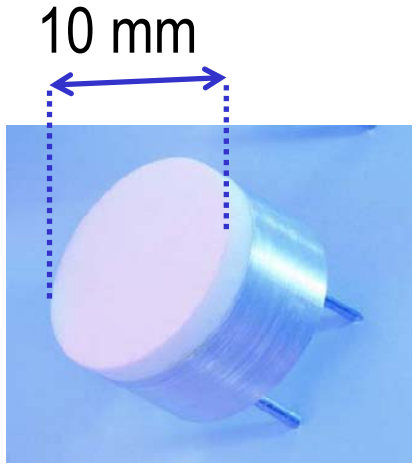
Identifies insects from wing velocity

Targets mosquitoes from 80 cm away

[D.R. Griffin, J. Animal Behaviour, 1960]

Existing Ultrasonic Transducers

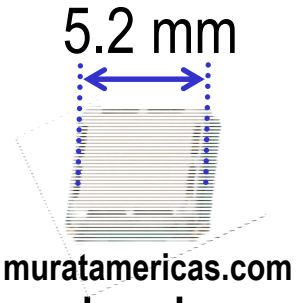
- Advantages:
  - High output pressure
  - Directional, if desired



senscomp.com

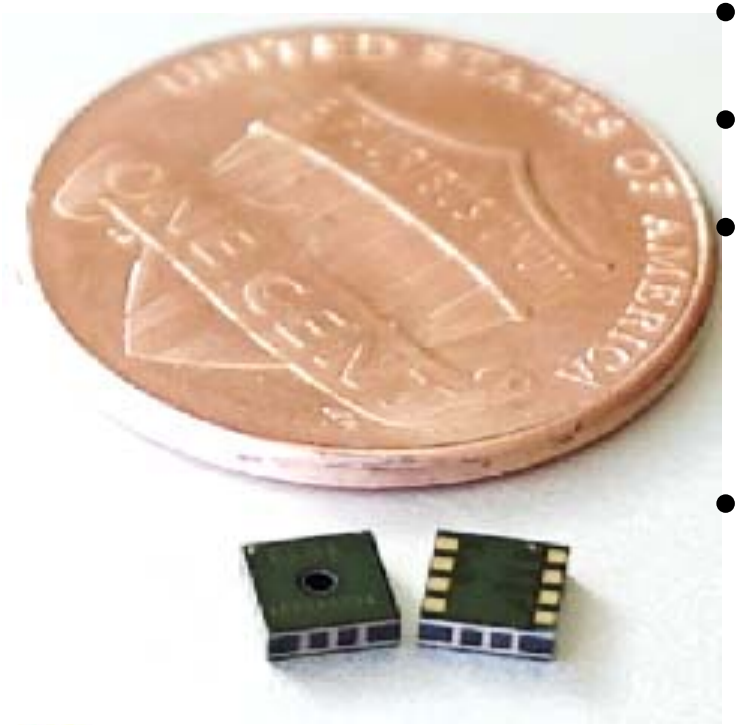
maxbotix.com

- Disadvantages:
  - Inefficient coupling to air
  - Matching layers required
  - Too big for consumer electronics
  - Dumb sensor. Lots of external electronics required.



muratamericas.com

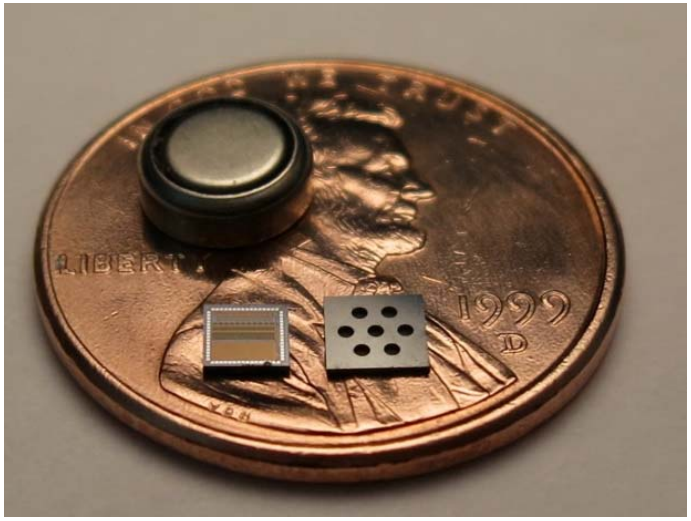
Micromachined Ultrasonic Transducers

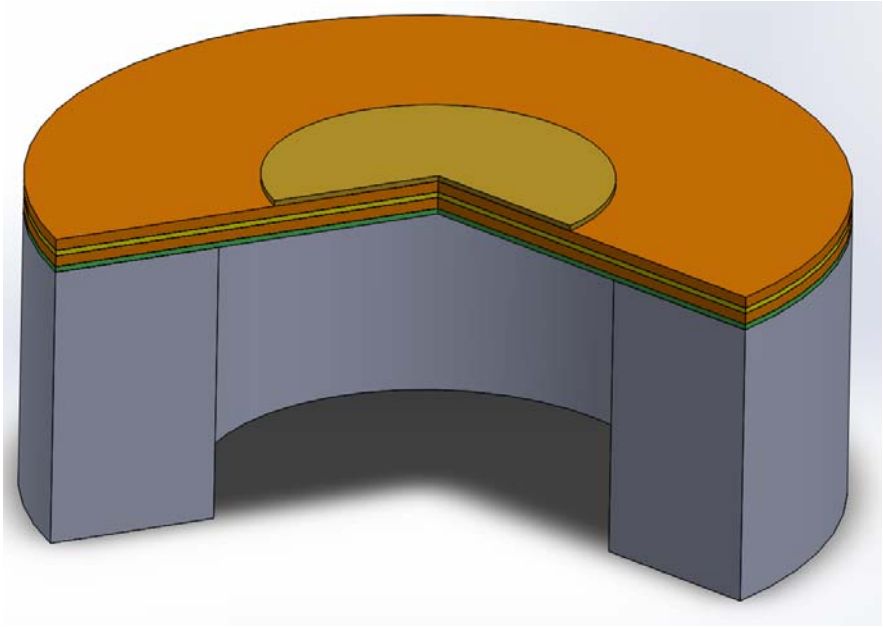


CHIRP microsystems

- Extremely low power (15 μW)
- Long range > 1 m
- Small size
  - 1000x smaller volume than conventional U/S transducer
- Digital interface
  - All signal processing performed on-chip
  - Autonomous operation for always-on sensing (host CPU can be in sleep mode)

Features of MUTs





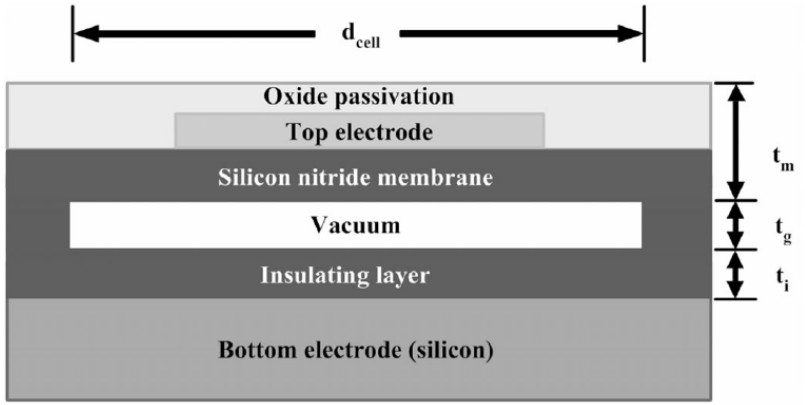
- Suspended plate structure
- Increased coupling due to low acoustic impedance
- Array fabrication possible
- Micro-patterning allows mechanics to be modified

Actuating Air-Coupled MUTs

Want:

- Large output pressure despite air's low acoustic impedance
  - ⟶ **Large transducer displacement**
  - ⟶ **Piezoelectric Actuation**

Capacitive (CMUT)



Wygant et al., IEEE TUFFC 2009

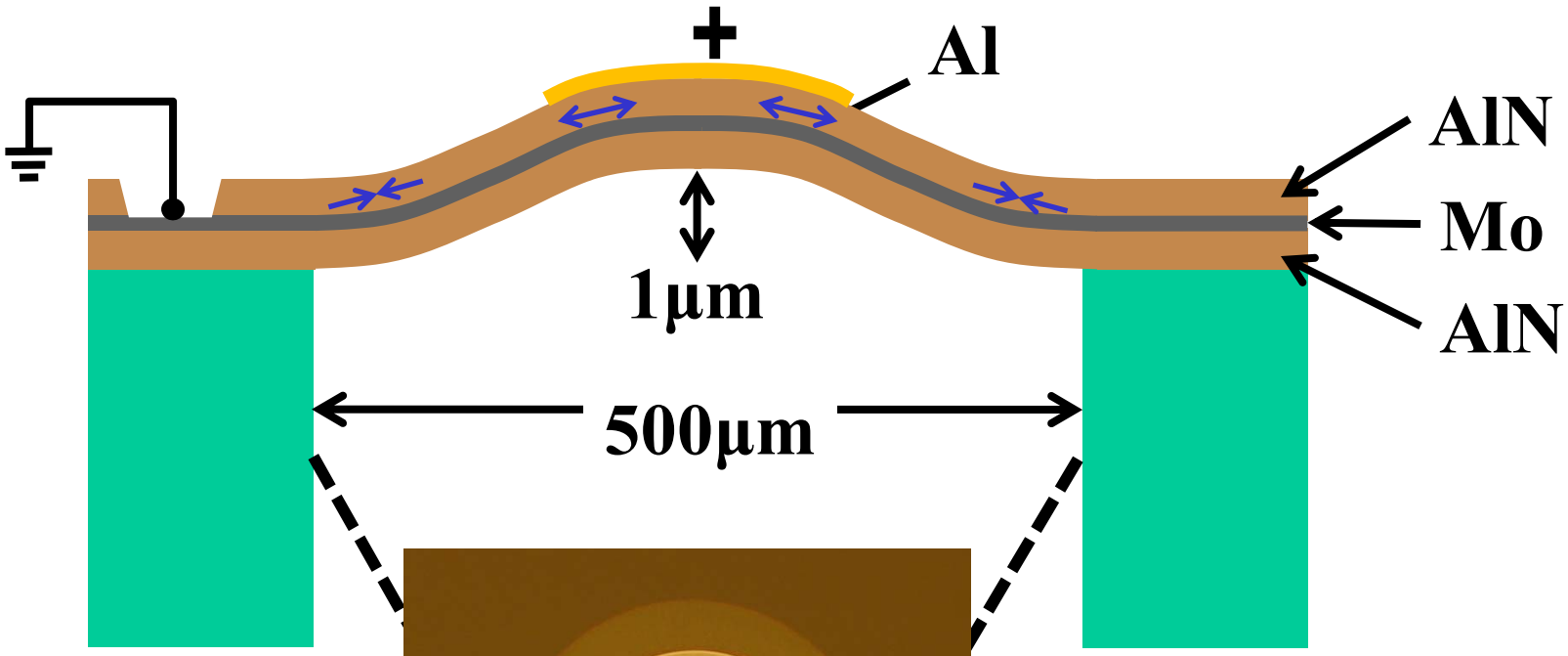
vs.

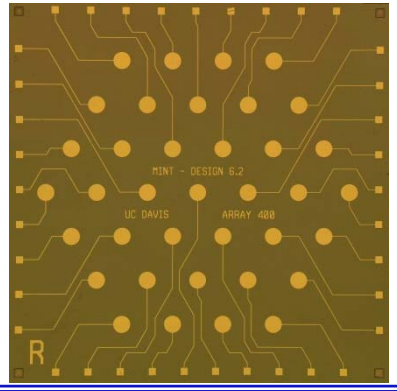
Piezoelectric (PMUT)

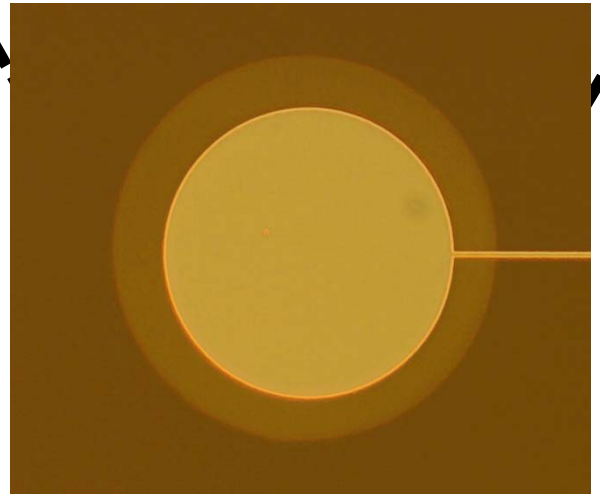
S. Shelton et al., IEEE IUS, 2009

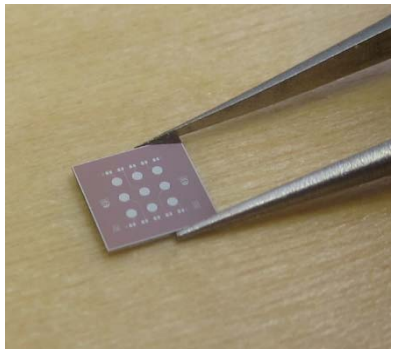
R. Przybyla et al., IEEE Sensors J., 2011

Aluminum Nitride (AlN) PMUT Cross Section









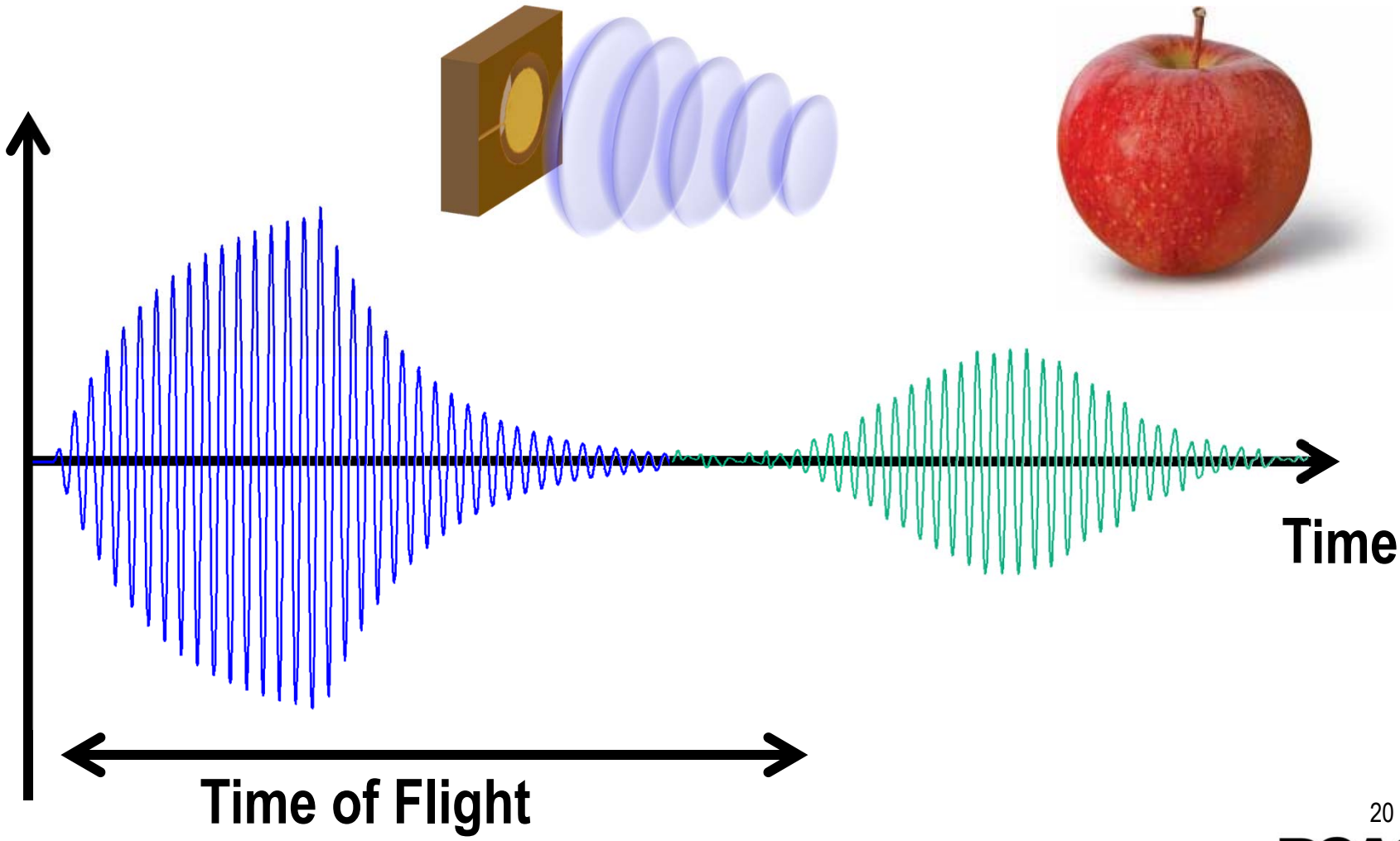
Comparing Piezoelectric Materials: Materials for PMUTs

Metric	Property	Units	AlN	PZT	ZnO
Transmitter Sensitivity	$e_{31,f}$	C m^{-2}	-1.05	**-14.9**	-1.0
	ε_{33}	-	10.5	1020	10.9
Receiver Sensitivity	$e_{31,f} / \varepsilon_{33}\varepsilon_0$	GV/m	**-11.3**	-1.64	-10.3

Outline

- History and motivation
- Air-coupled ultrasonic transducers
- Time of Flight (ToF) rangefinding
- Phased-array ultrasonics
- Ultrasonic fingerprint sensor

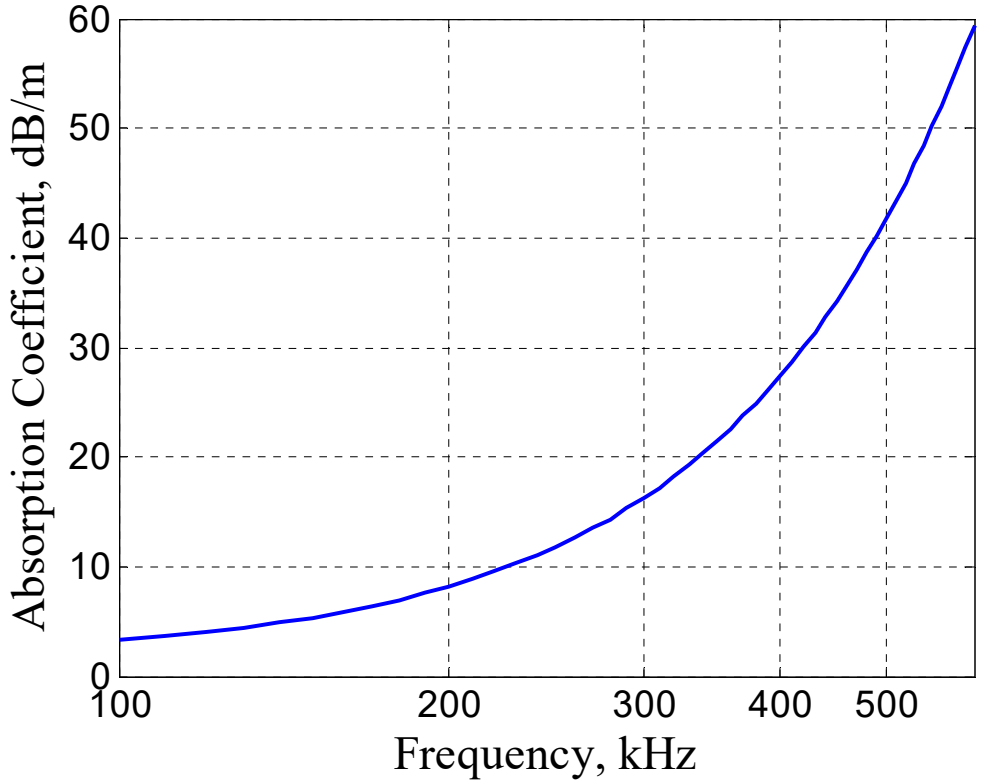
ToF Range Measurement: TX & RX Signals



ToF Range Measurement

- What frequency should be used?
- What determines the accuracy?

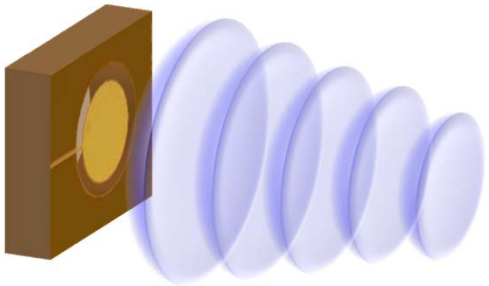
Air Absorption & Max Range Depend on Frequency

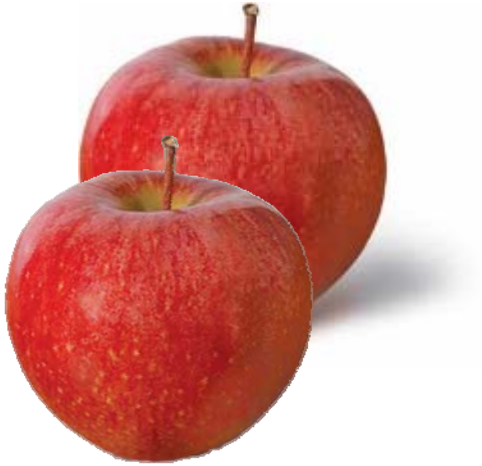


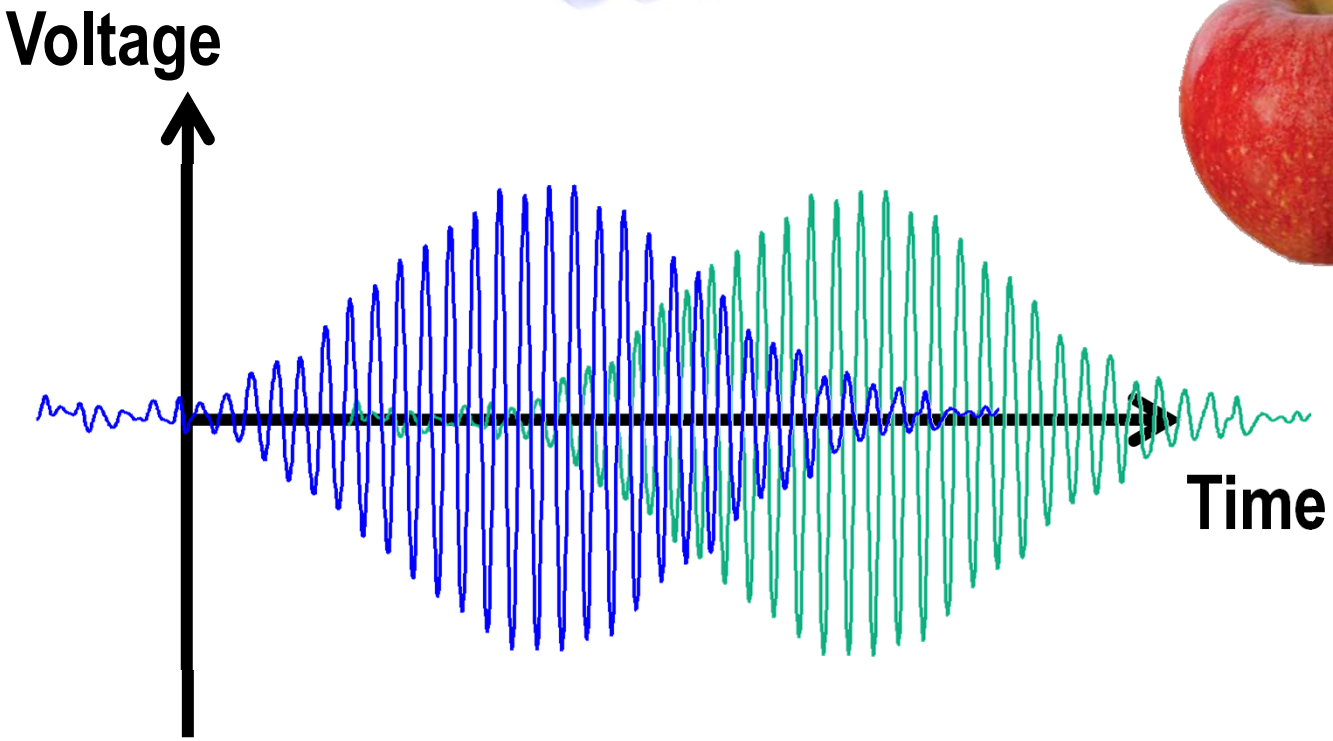
- Absorption loss:
  - 1 dB/m @ 40kHz
  - 10dB/m @ 200kHz
  - 100 dB/m @ 800kHz
- Pulse-echo range:
  - 10 m @ 40 kHz
  - 1 m @ 200 kHz
  - 10 cm @ 800 kHz

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

BW determines axial resolution

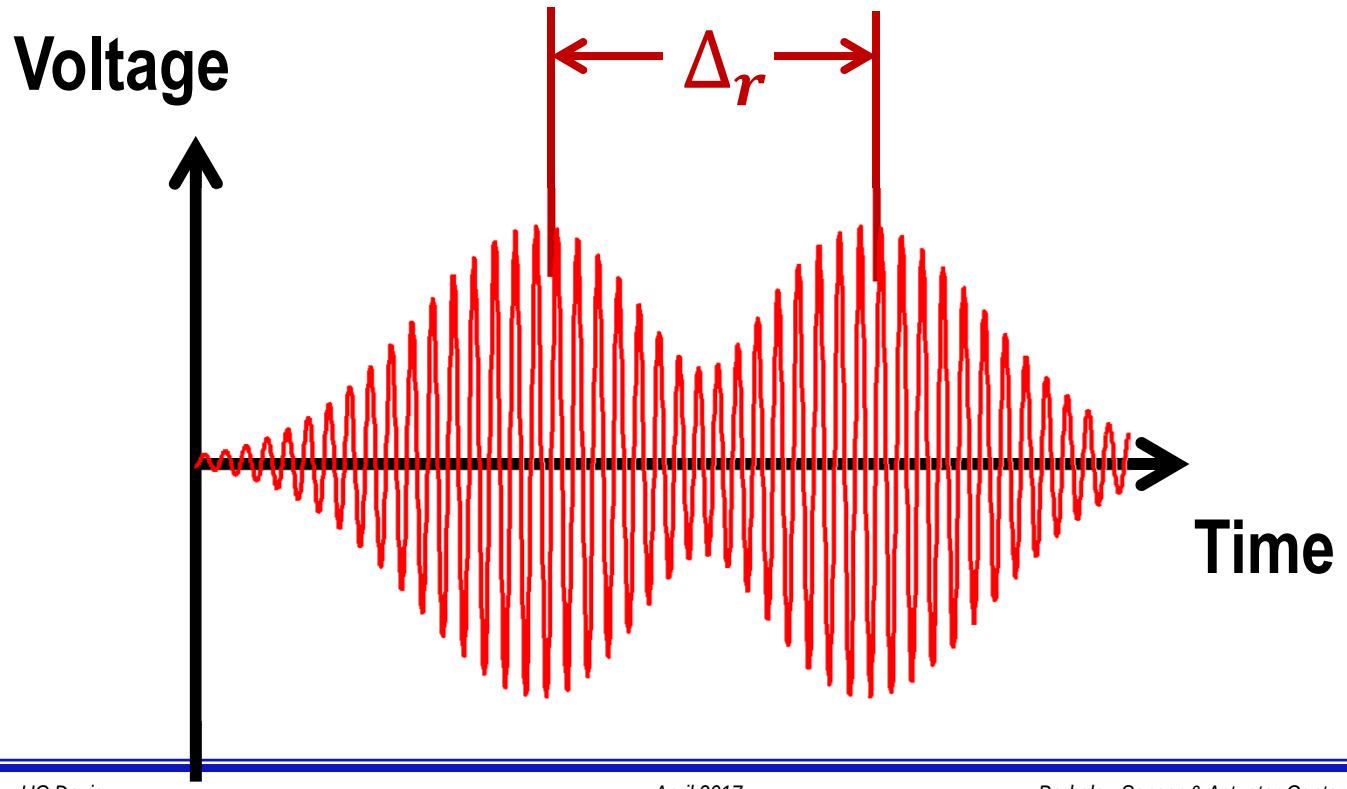




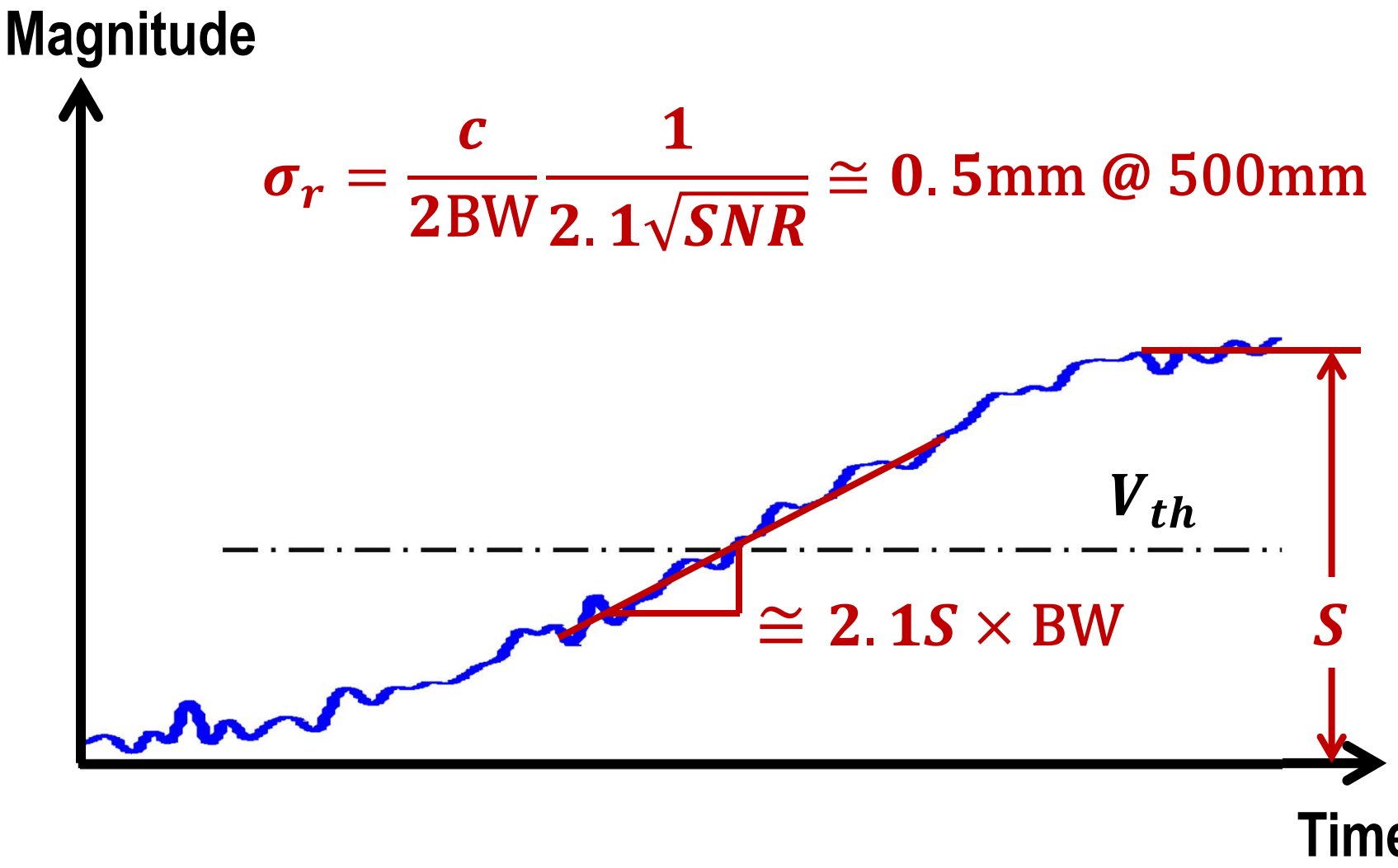


BW determines axial resolution

$$\Delta_r = \frac{c}{2}\left(T_p + \frac{0.27}{BW}\right) \cong \frac{c}{2}\frac{0.77}{BW} \cong 1\text{cm}$$



BW & SNR determine accuracy



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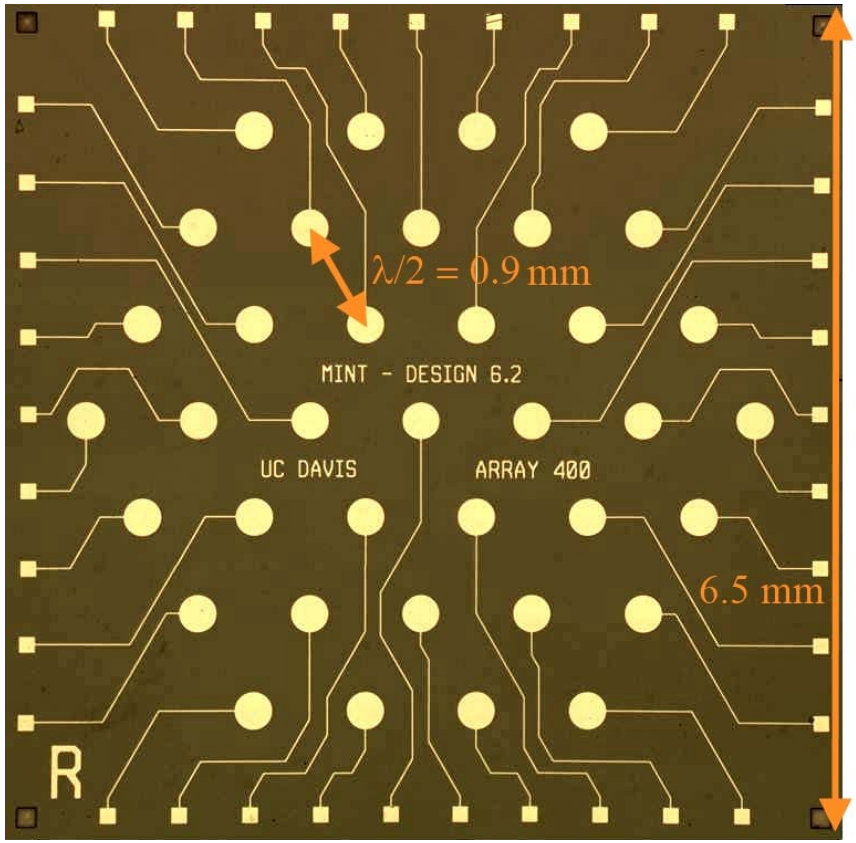
Chip-Scale Phased Array

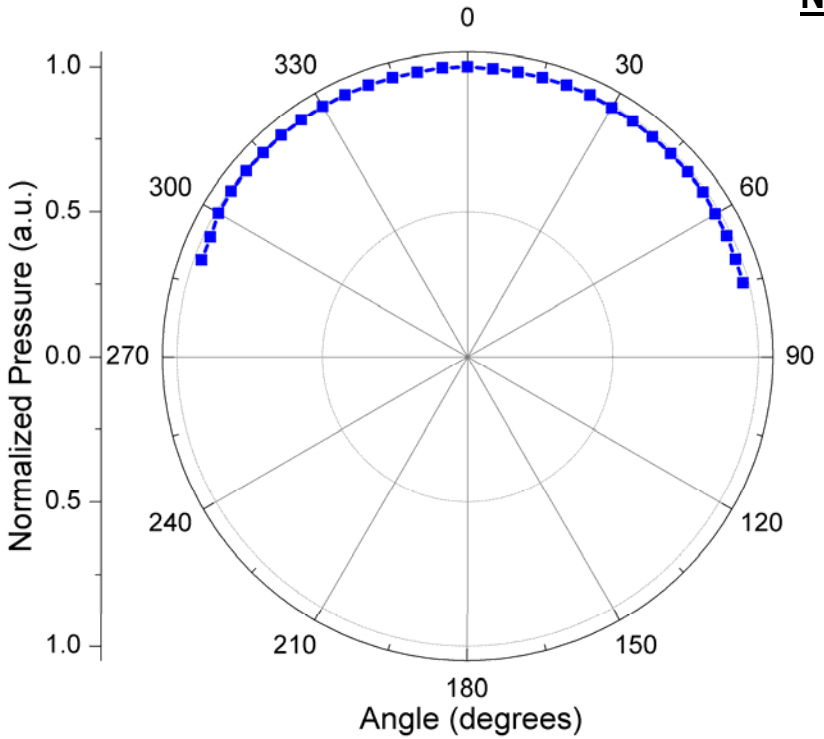
- 2D array of transducers:
  - Output power on-axis: N^2
  - Number of elements sets beam width
    - Beam width ~180°/N for linear array
  - Individual electrodes enable electrical beam steering
  - Spacing ~λ/2 = 0.9mm @ 200 kHz

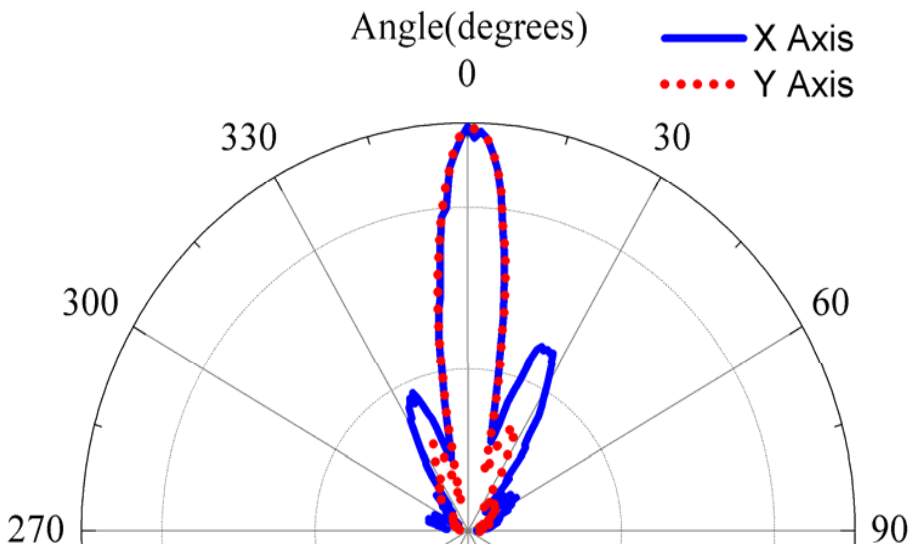
37-Element Array

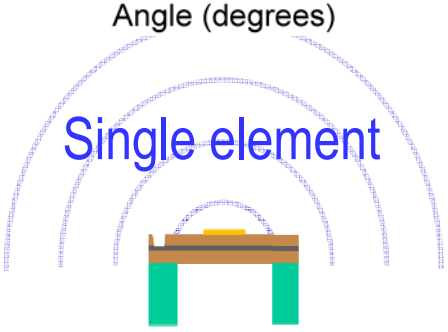


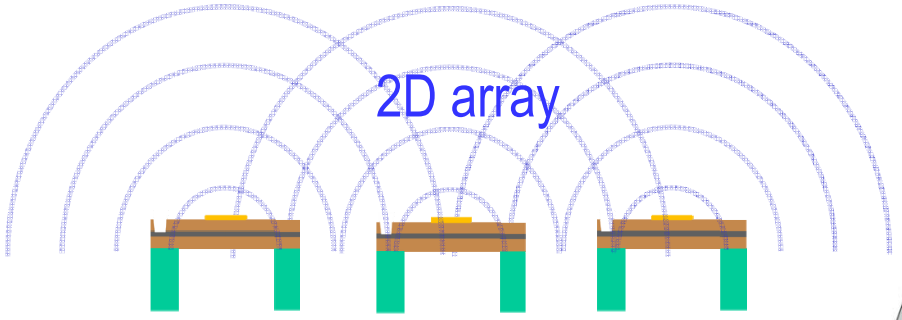
Phased Arrays are Directional

Narrow beam improves SNR & spatial resolution









S. Shelton, A. Guedes, R. Przybyla, R. Krigel, B. Boser, D.A. Horsley, 2012 Solid-State Sensors Actuators & Microsystems Workshop, Hilton Head SC, June 2012.

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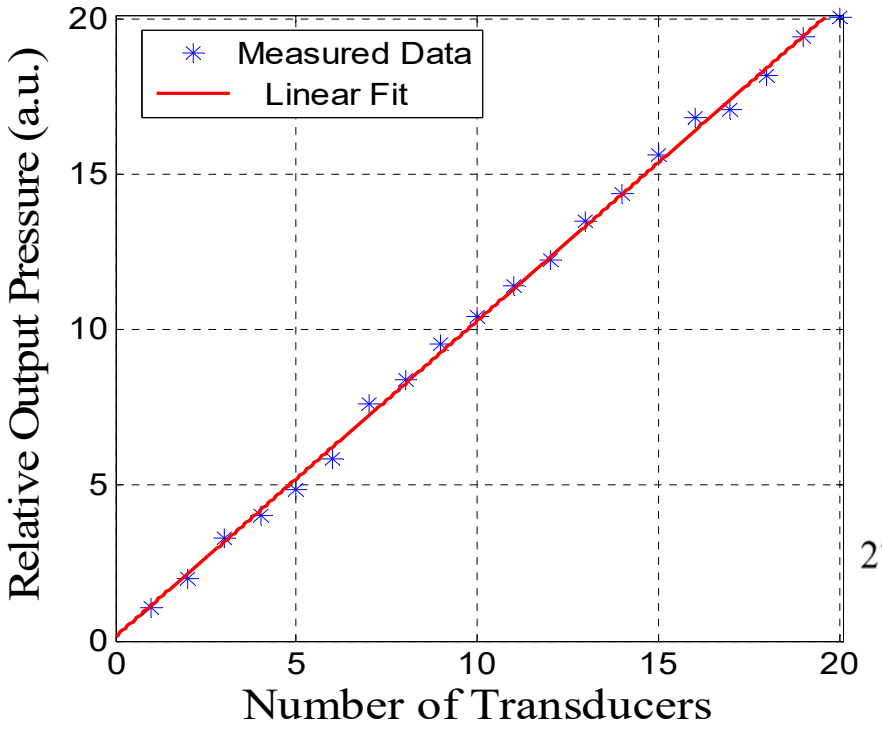
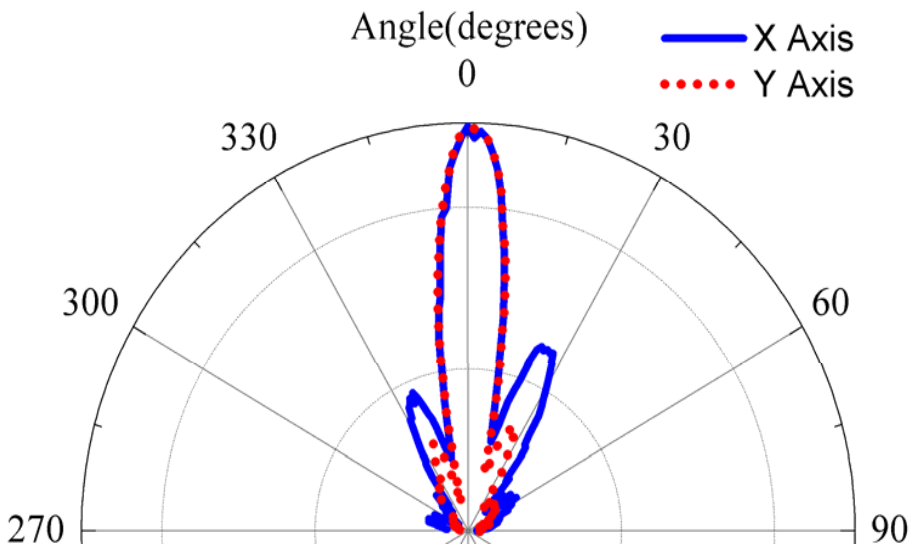
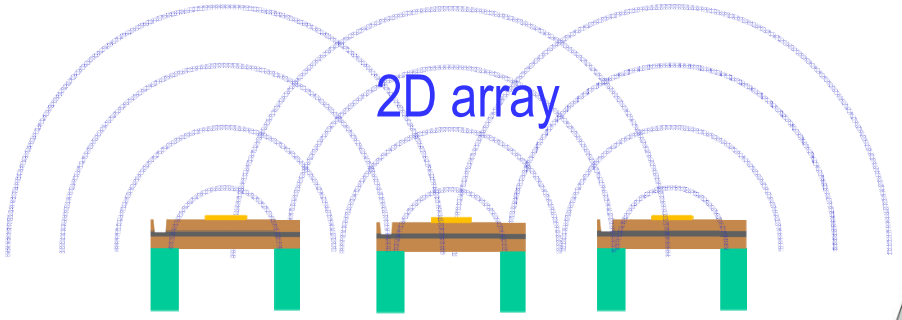


Output SPL Scales with N

Narrow beam improves SNR & spatial resolution





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- Ultrasonic fingerprint sensor

Ultrasonic Fingerprint Sensor

Qualcomm® Snapdragon Sense™

Go ahead, get your hands dirty.

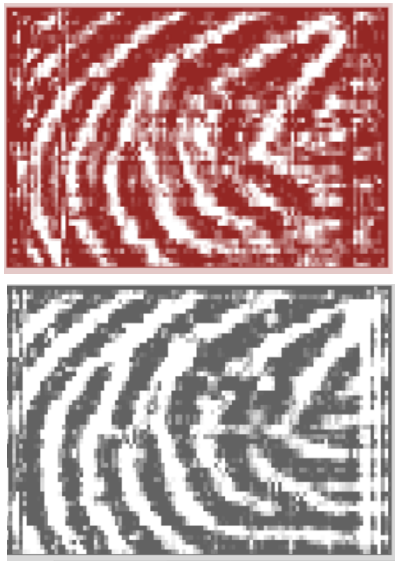
UC Davis, UC Berkeley, InvenSense

EE Times — Connecting the Global Electronics Community

News & Analysis

3-D Fingerprint Scanner Beats Apple's

Super-secure MEMS scanner may obsolete passwords

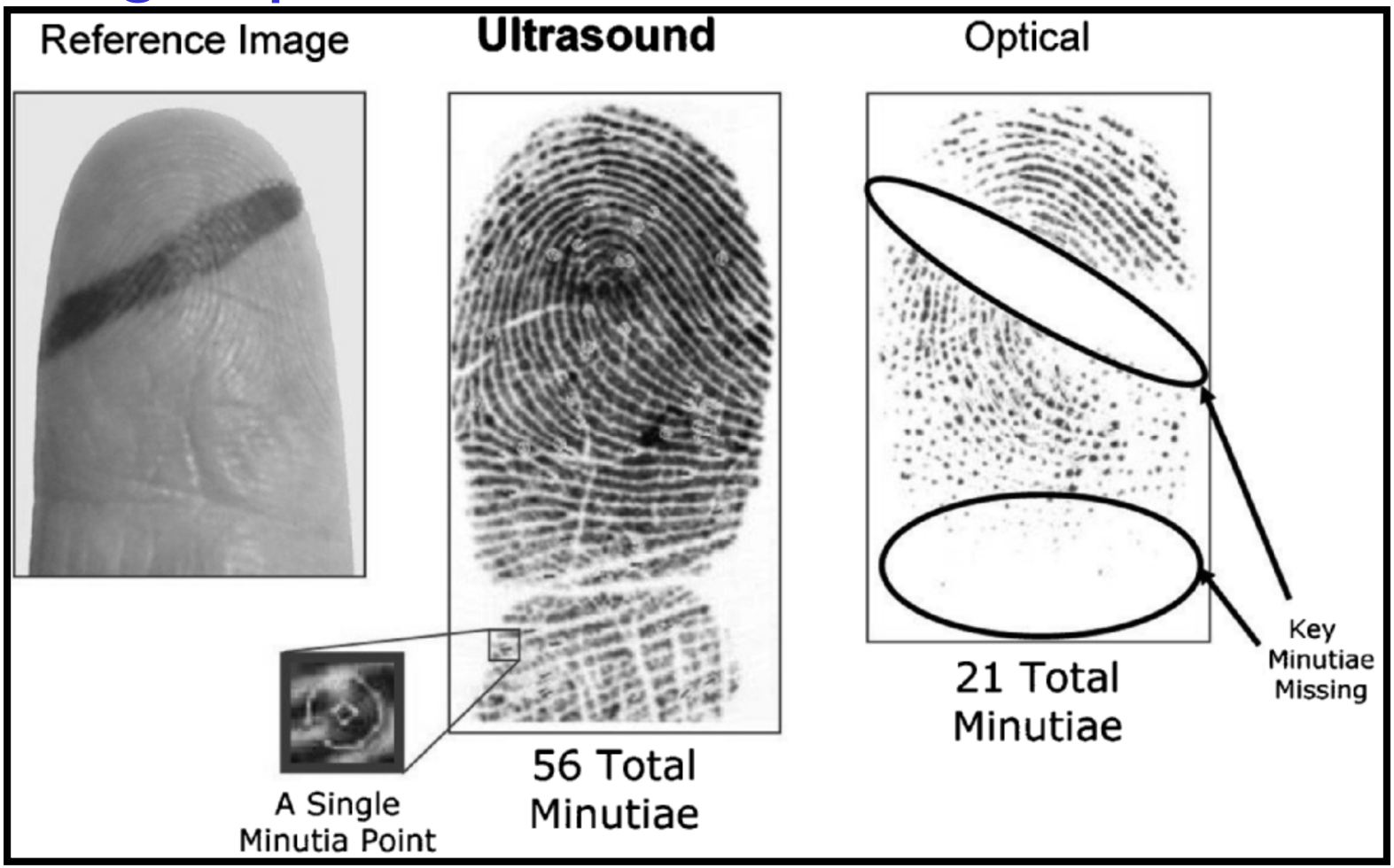


Jiang, et al, MEMS 2016

Tang, et al, ISSCC 2016

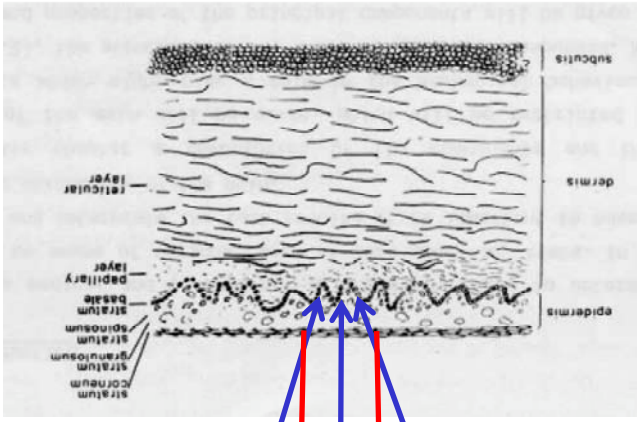
InvenSense® Announces UltraPrint™ Mass-Manufacturable Ultrasound Fingerprint Touch Sensor Solution

Ultrasound vs. Optical Fingerprint Sensor



J. K. Schneider, "Ultrasonic fingerprint sensors," in Advances in Biometrics. 2008

State of the art: Commercial Ultrasonic Fingerprint Sensor



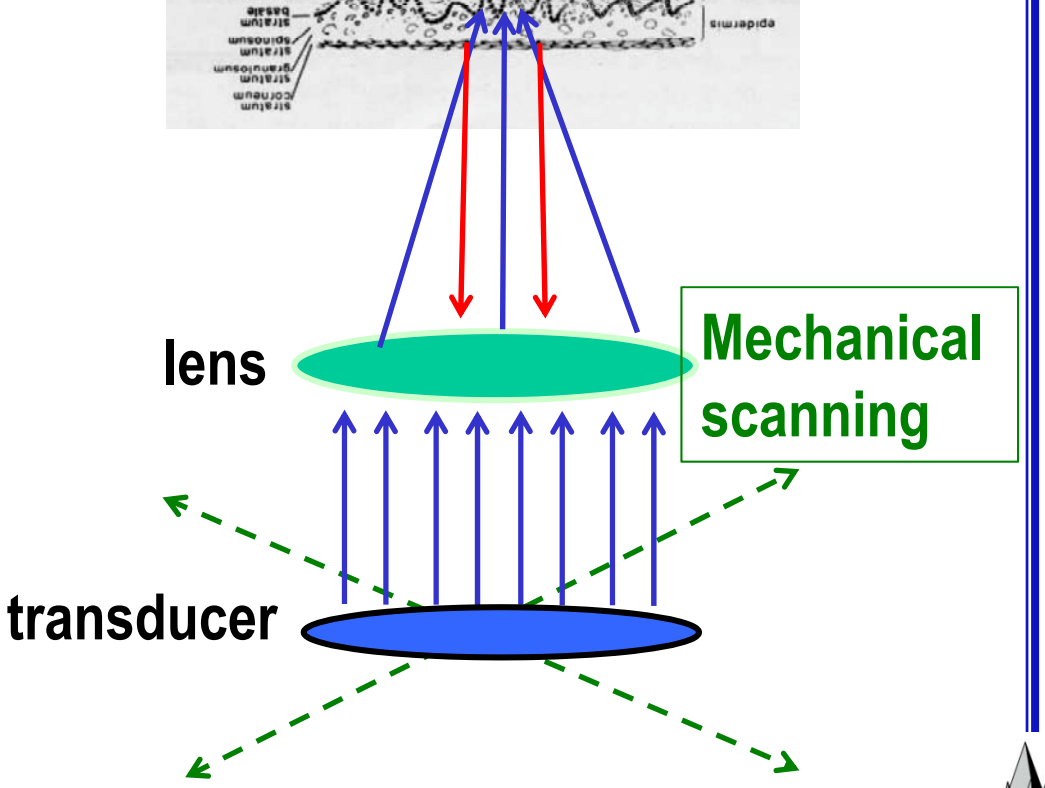
Pros:

➔**Dermal detection**

Cons:

➔**Large system**

➔**mechanical scanning**

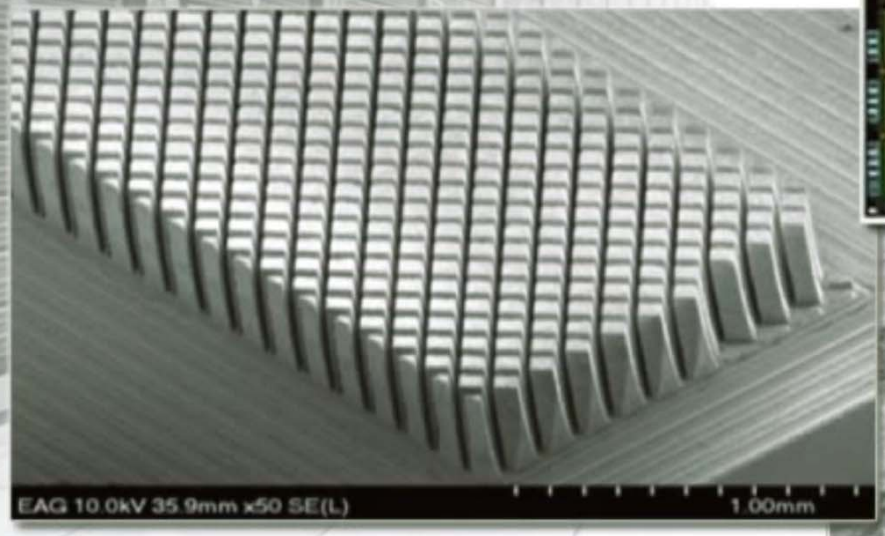


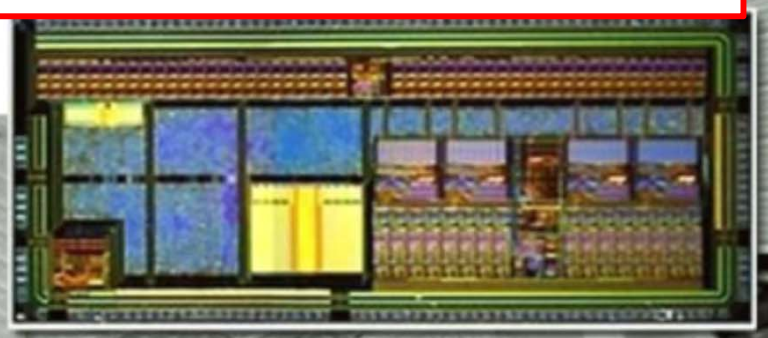
Reference: Ultra-scan®, U.S. patent 5224174

Bulk Piezo Fingerprint Sensors

Drawbacks:

- **Interconnect is challenging**
- **Readout based on resonator Q (no advantage over capacitance)**
- **High manufacturing cost.**

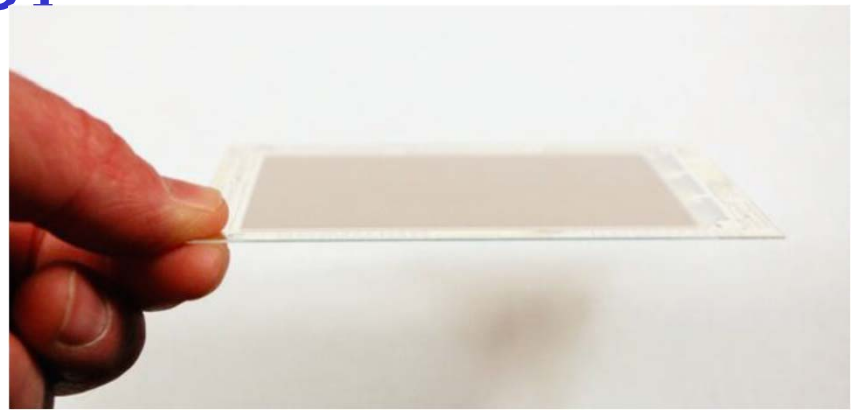


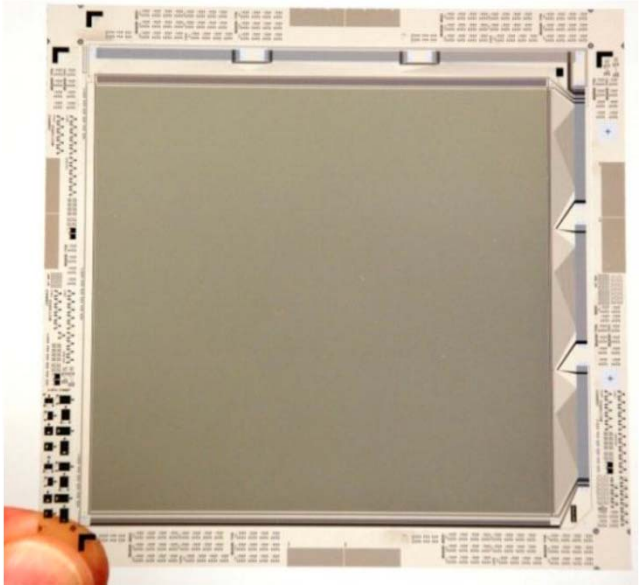


Sonavation Inc.

Qualcomm's Ultrasonic Fingerprint Sensor

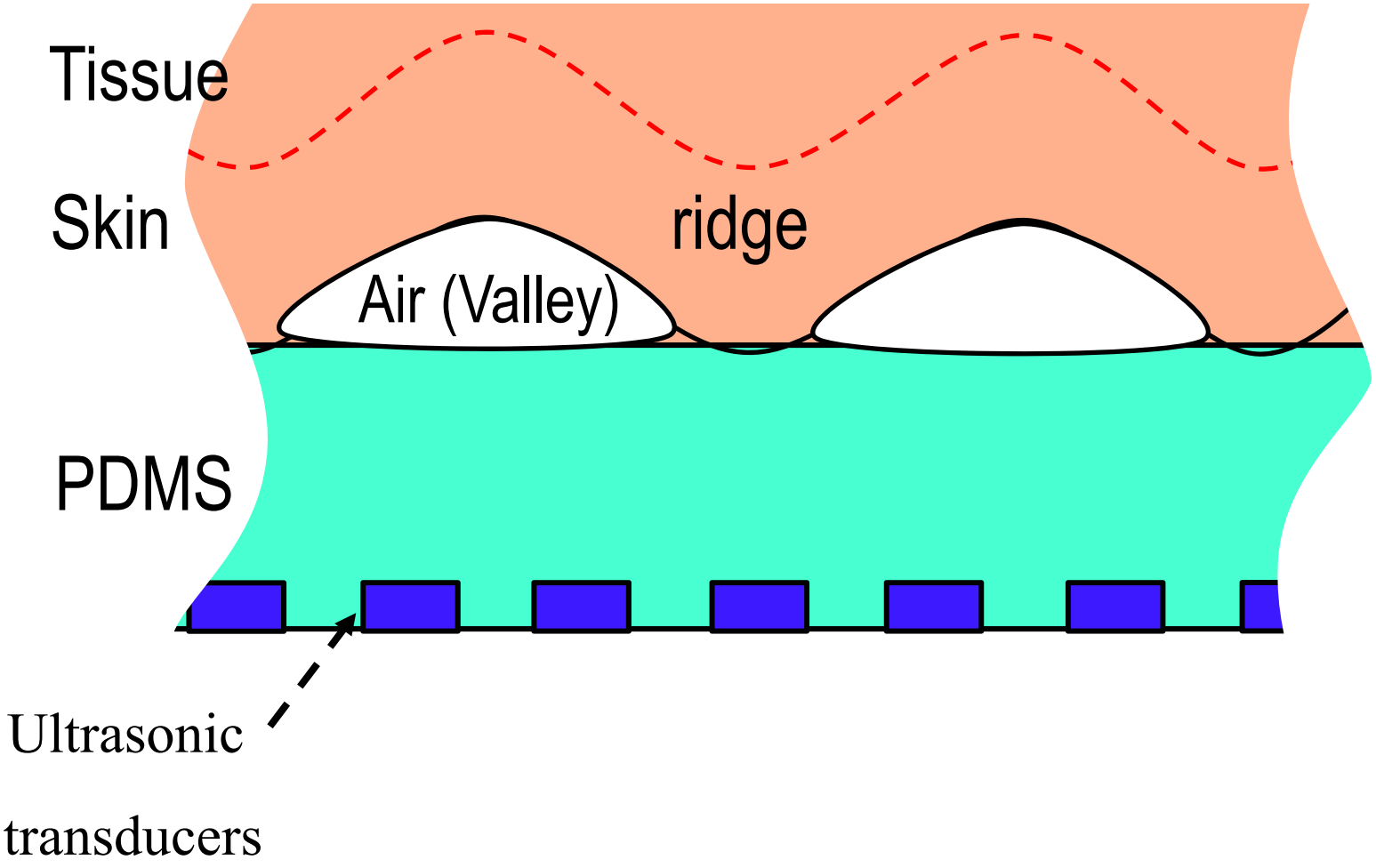
- TFT-based manufacturing
- 500 dpi
- Scalable to virtually any size
- Single-finger, four-finger, and full hand sensor.



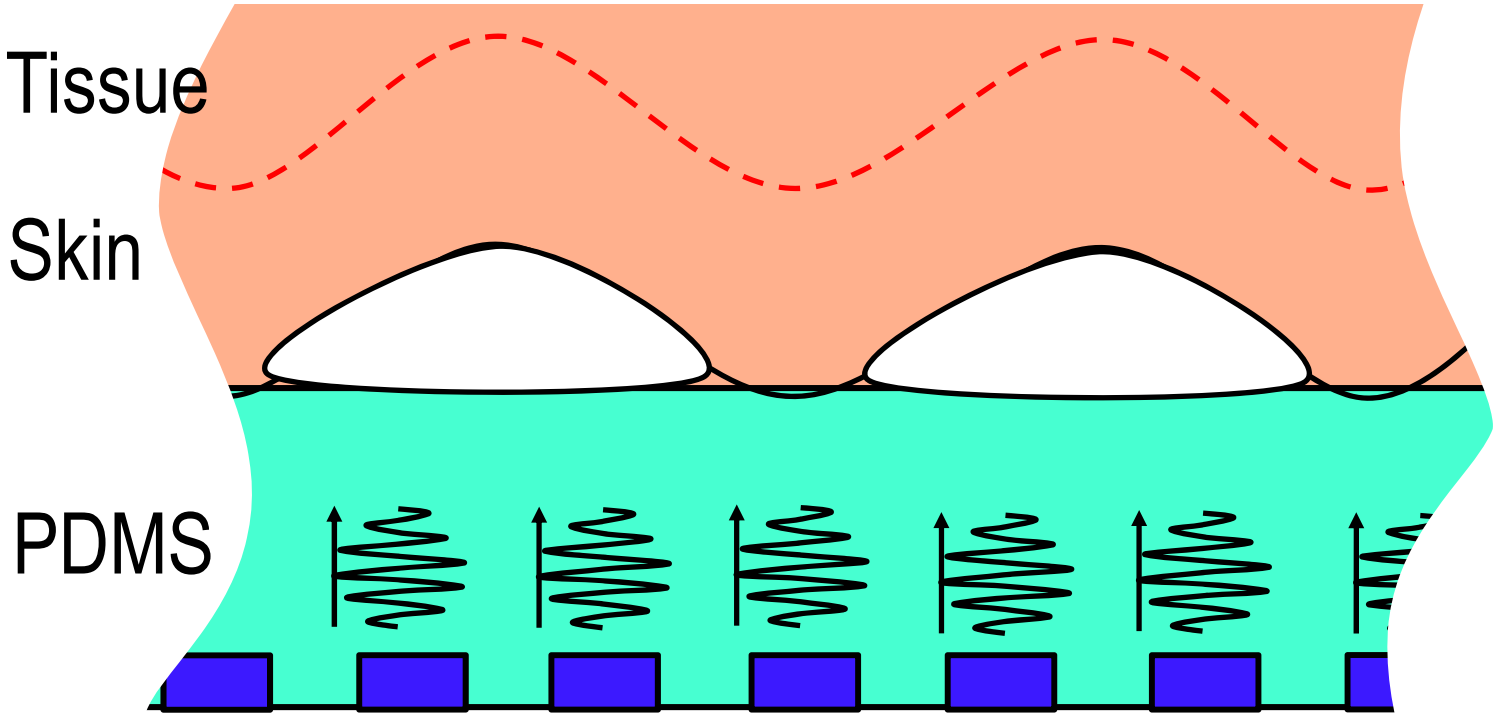


J. K. Schneider, "Biometrics Within the Wireless and Mobile Computing Industry," 2013

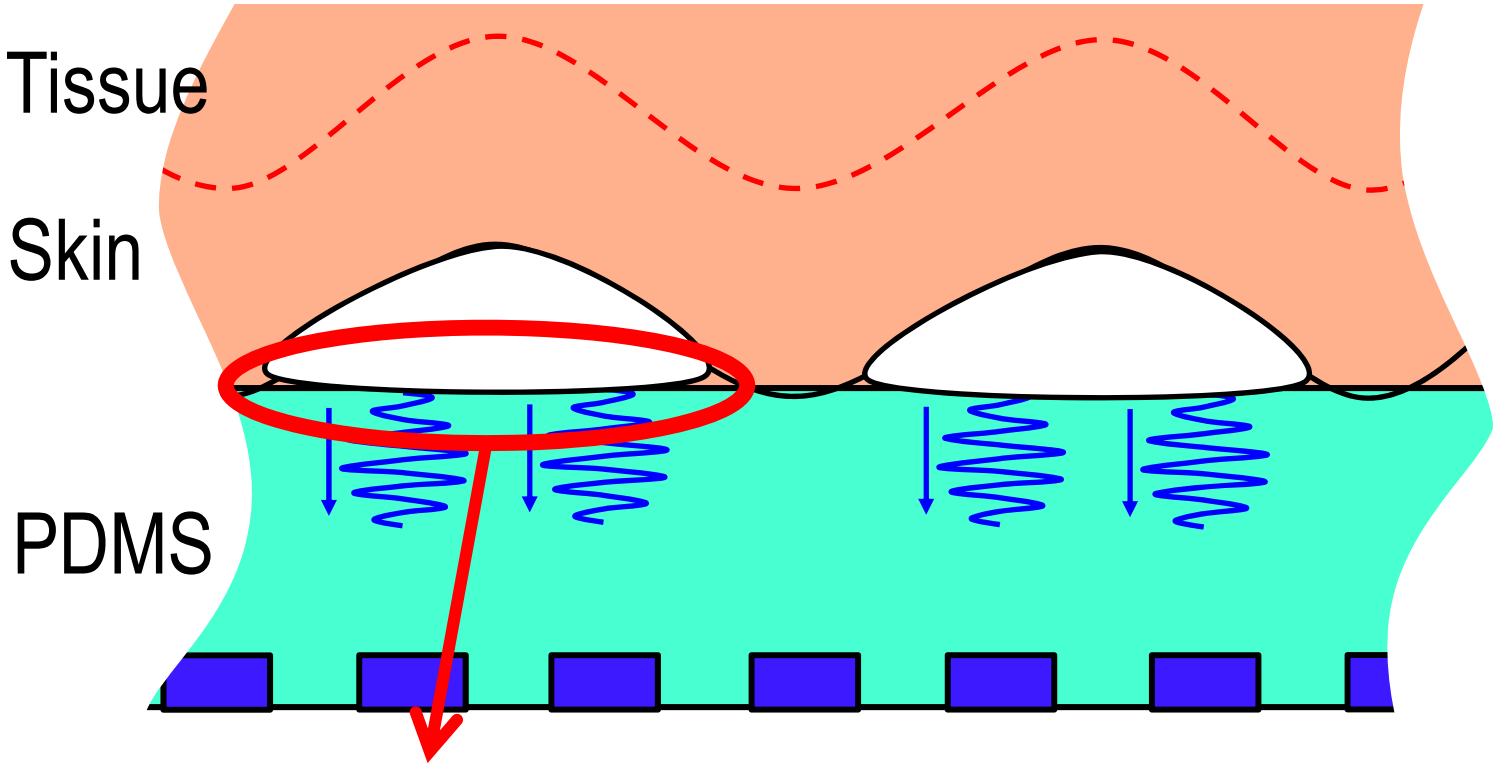
Operating Principle



Operating Principle

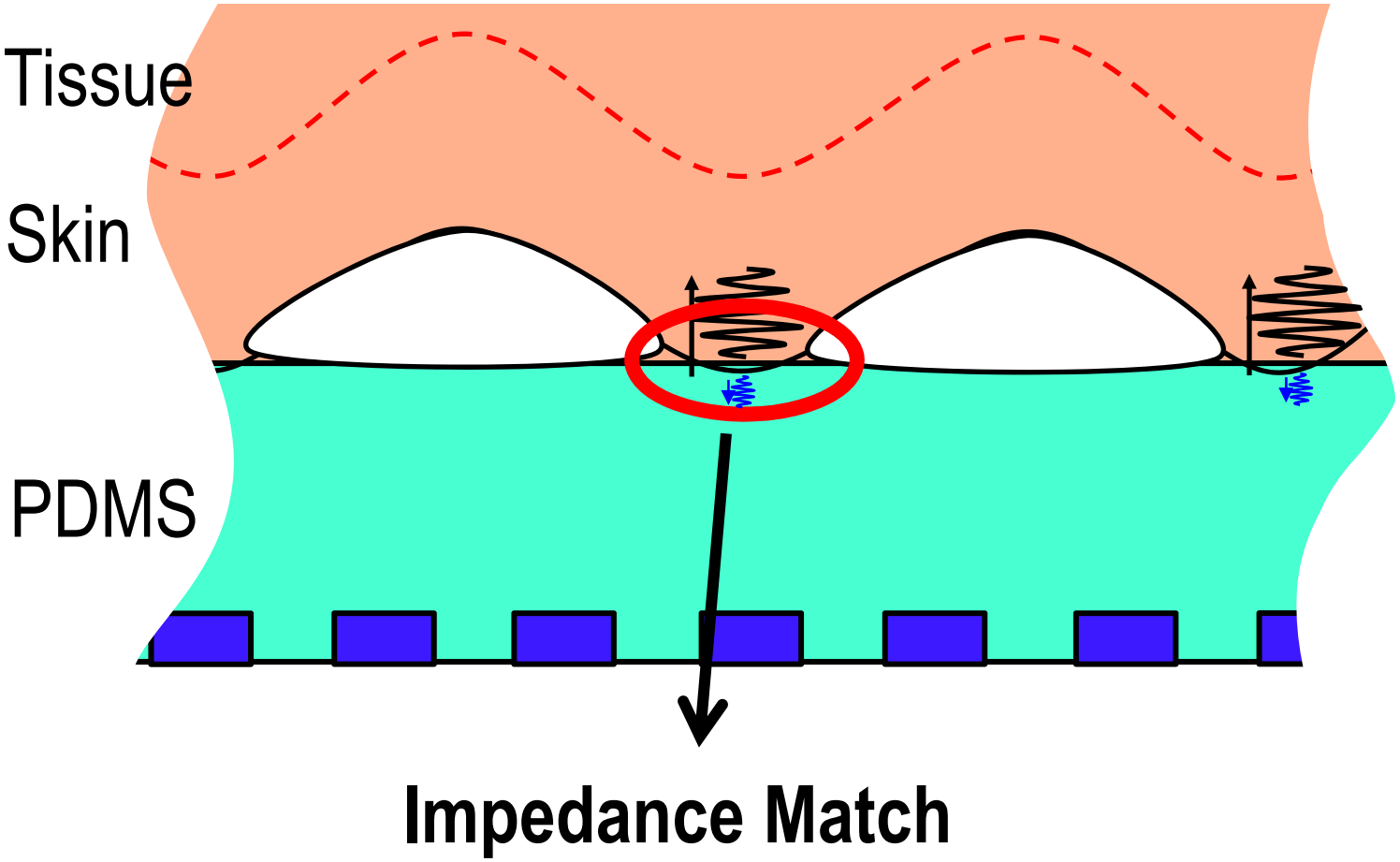


Operating Principle

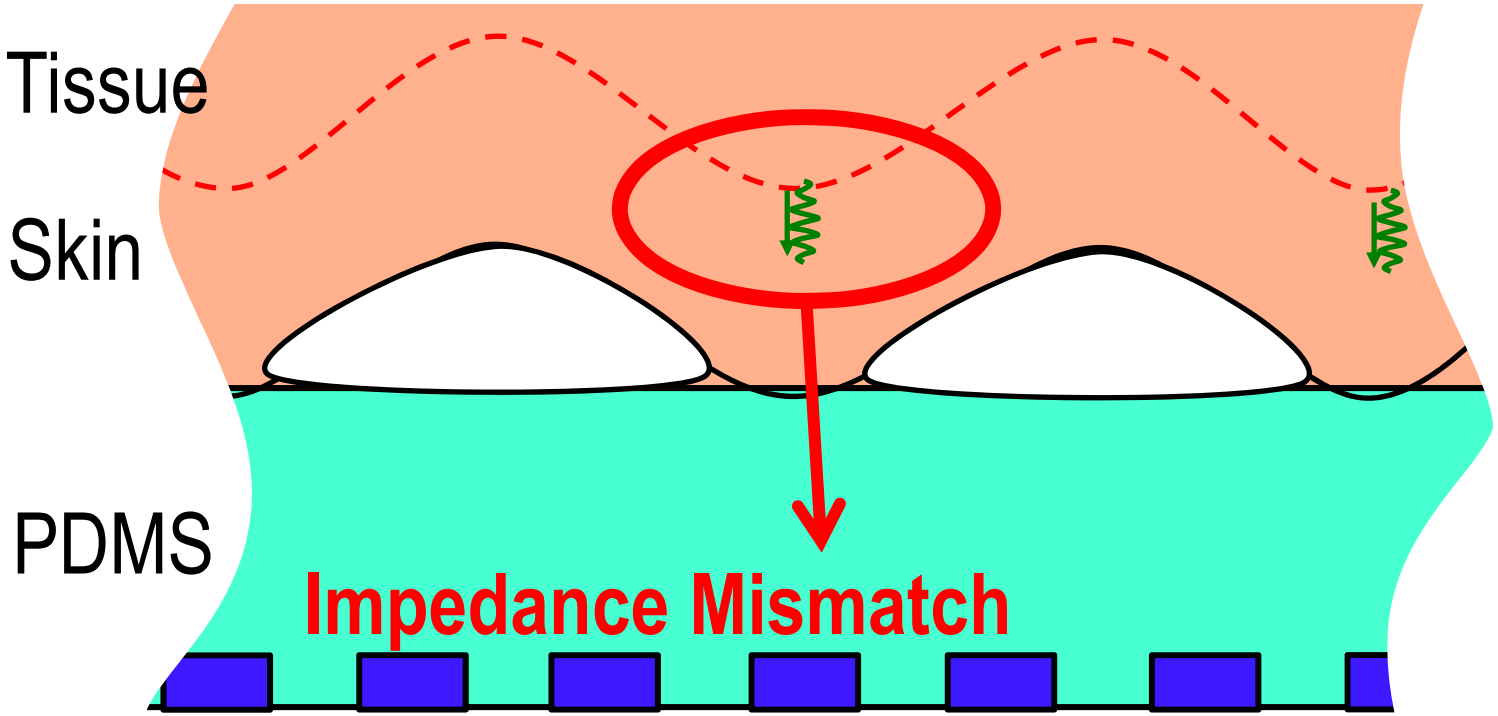


Huge Impedance Mismatch

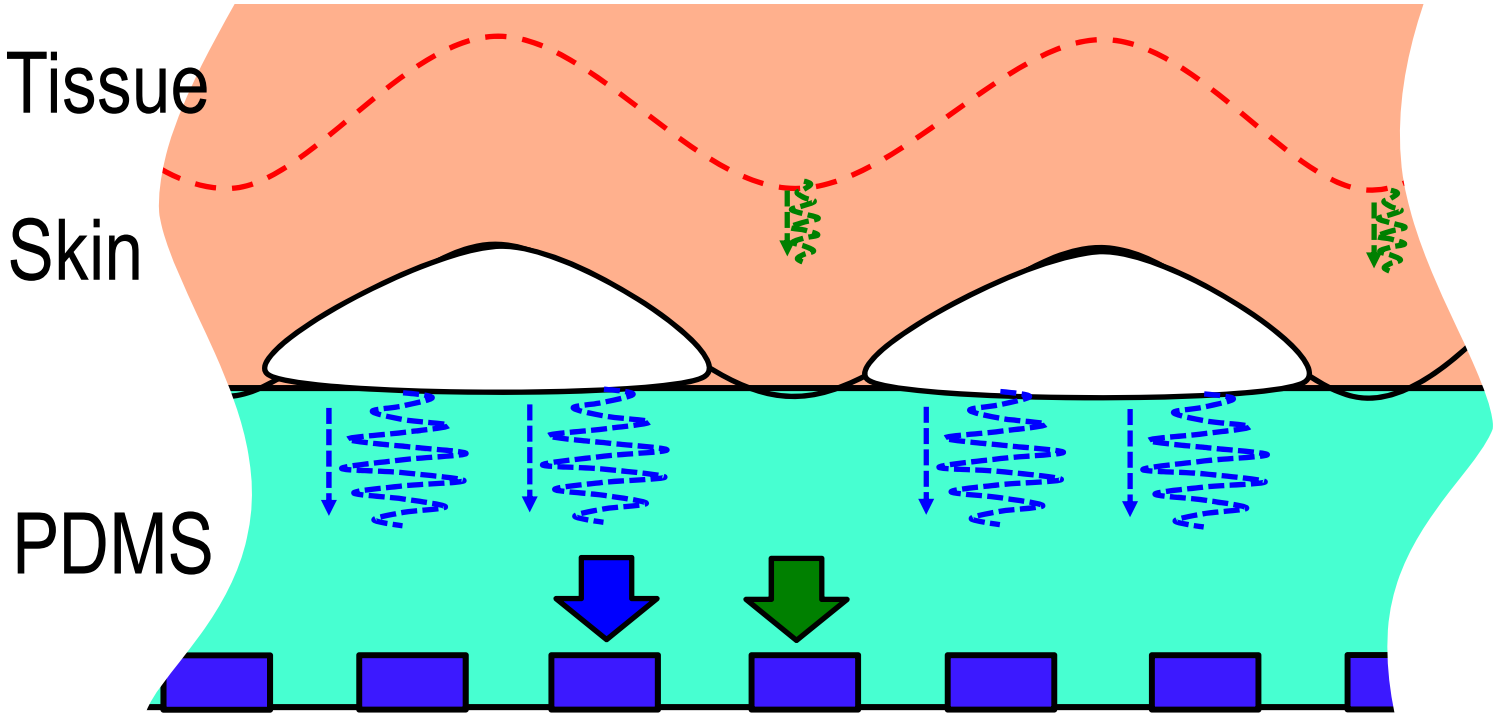
Operating Principle

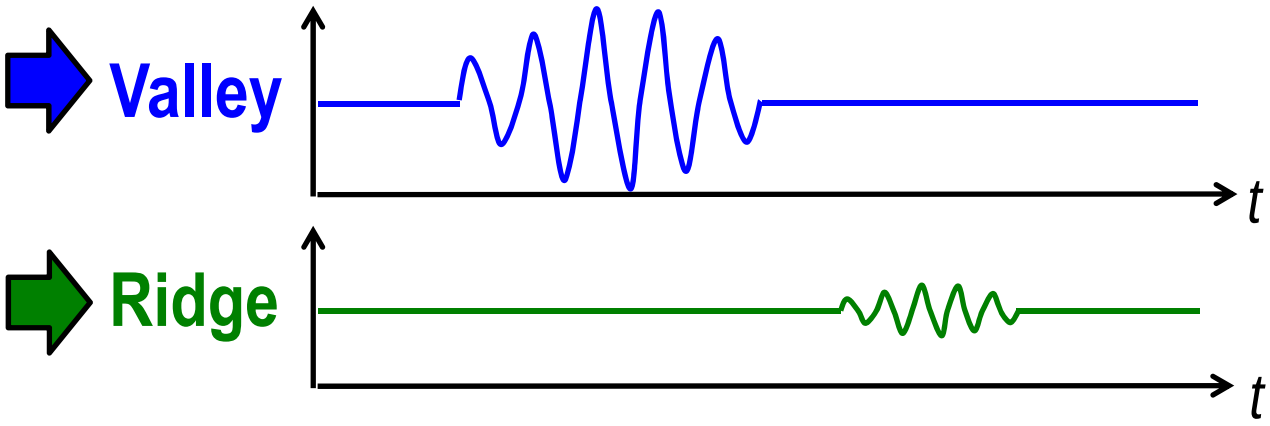


Operating Principle



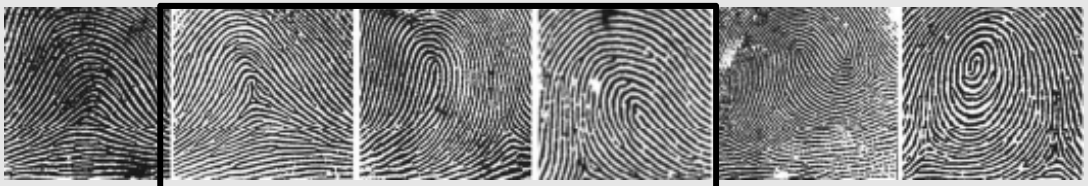
Operating Principle





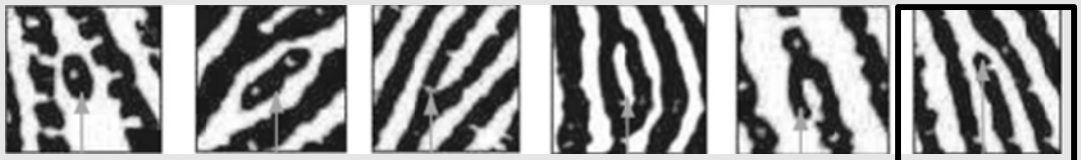
Fingerprint - Biometric Identity

Level 1 Features: Pattern



Left/Right/Double Loop

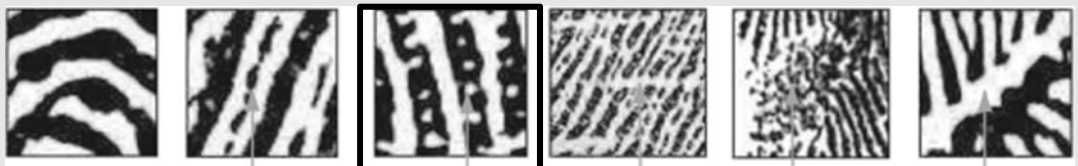
Level 2 Features: Minutia Points



Ending

FBI Standard 500 dpi

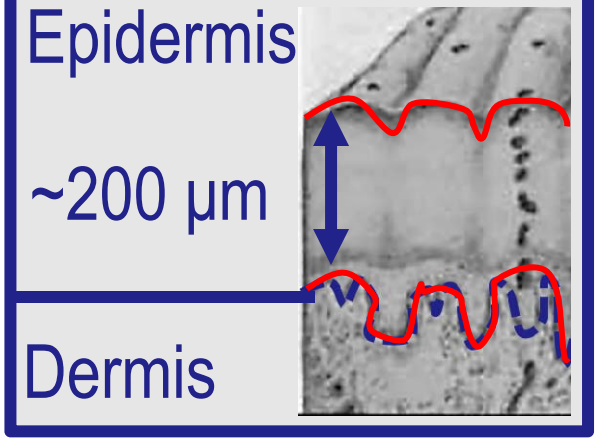
Level 3 Features



Pores

500+ dpi

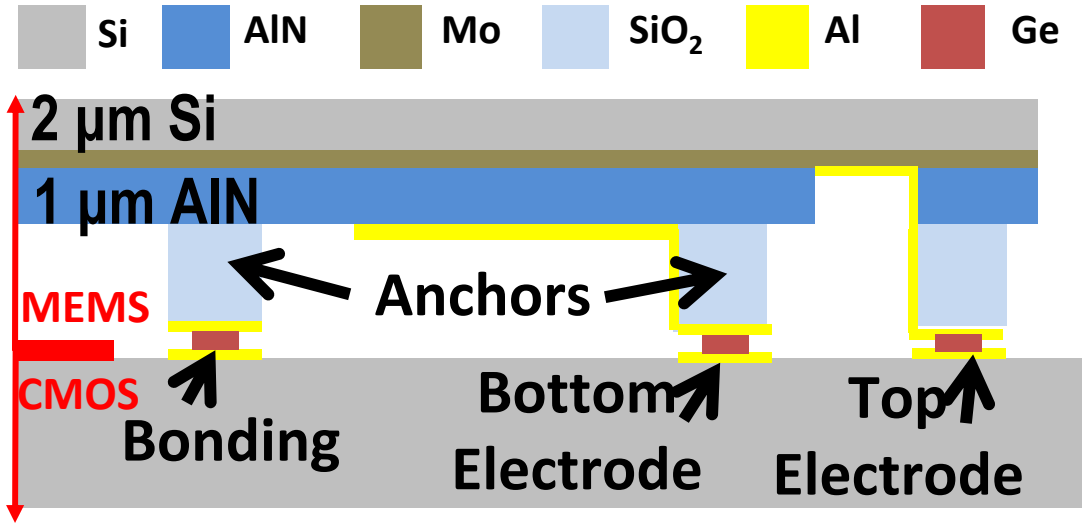
Jain, et al. IEEE, (2007)

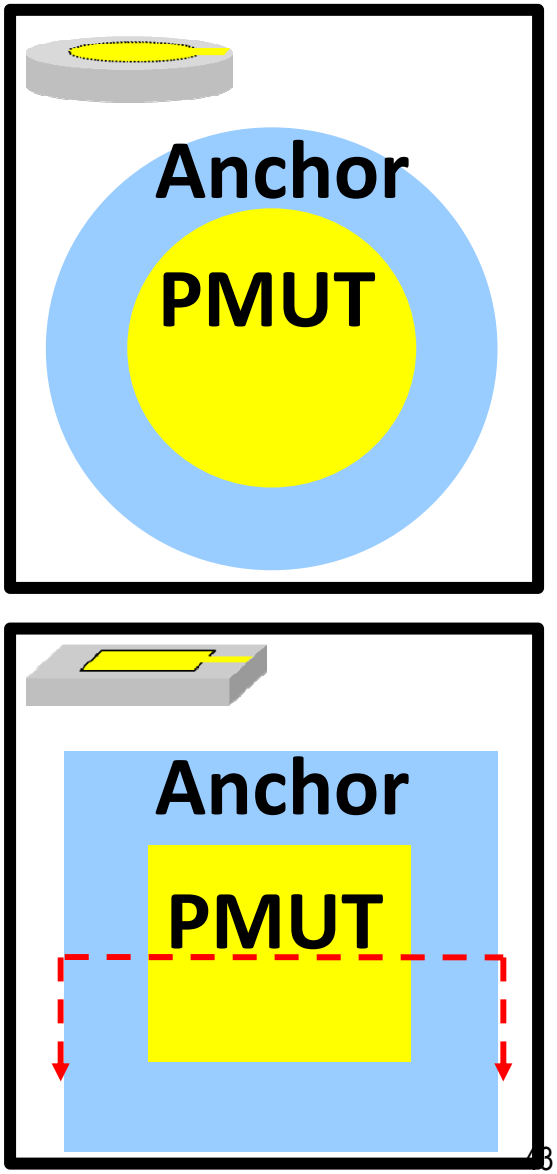


Sensor Resolution Requirement

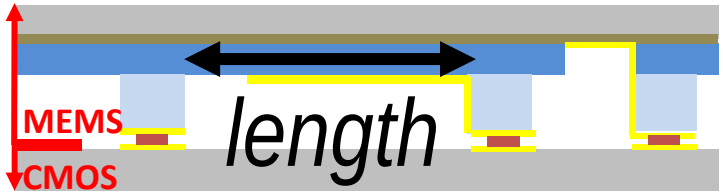
Lateral	500 dpi
Axial	200 µm

PMUT Cross-Section

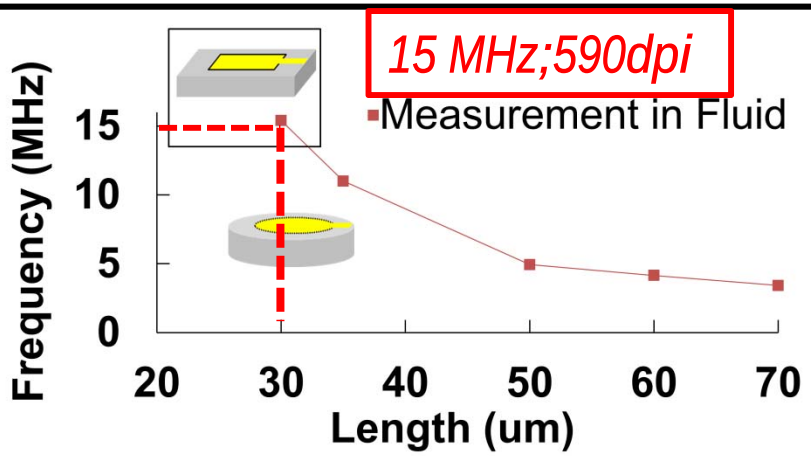




Individual PMUT Design



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

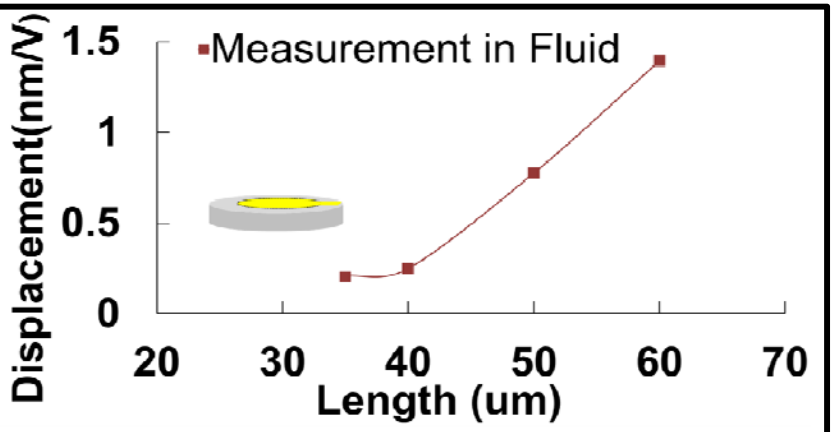


Length↓ ➡ DPI↑

Length↓ ➡ Frequency↑

$$d_p \sim l^2$$

$$p \sim f \times d_p$$



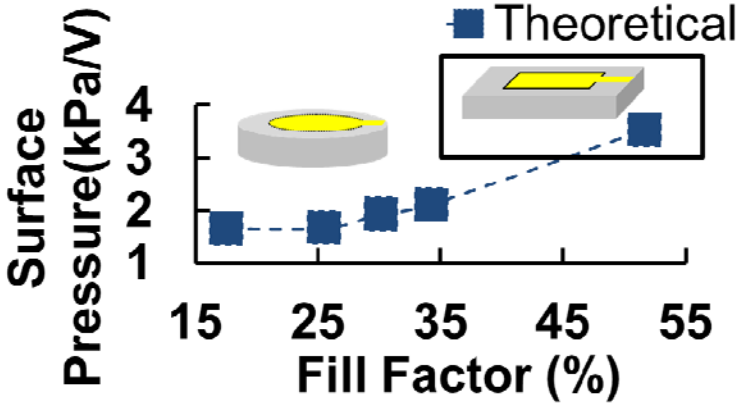
$$p \sim A \sim l^2$$

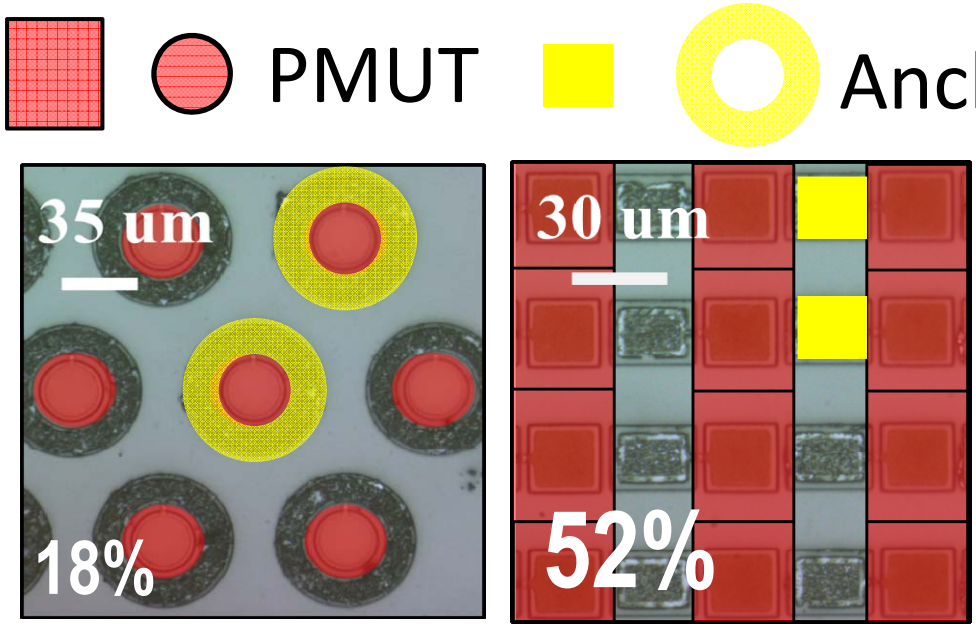
Length↓ ➡ Pressure↓

PMUT Array Design

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

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

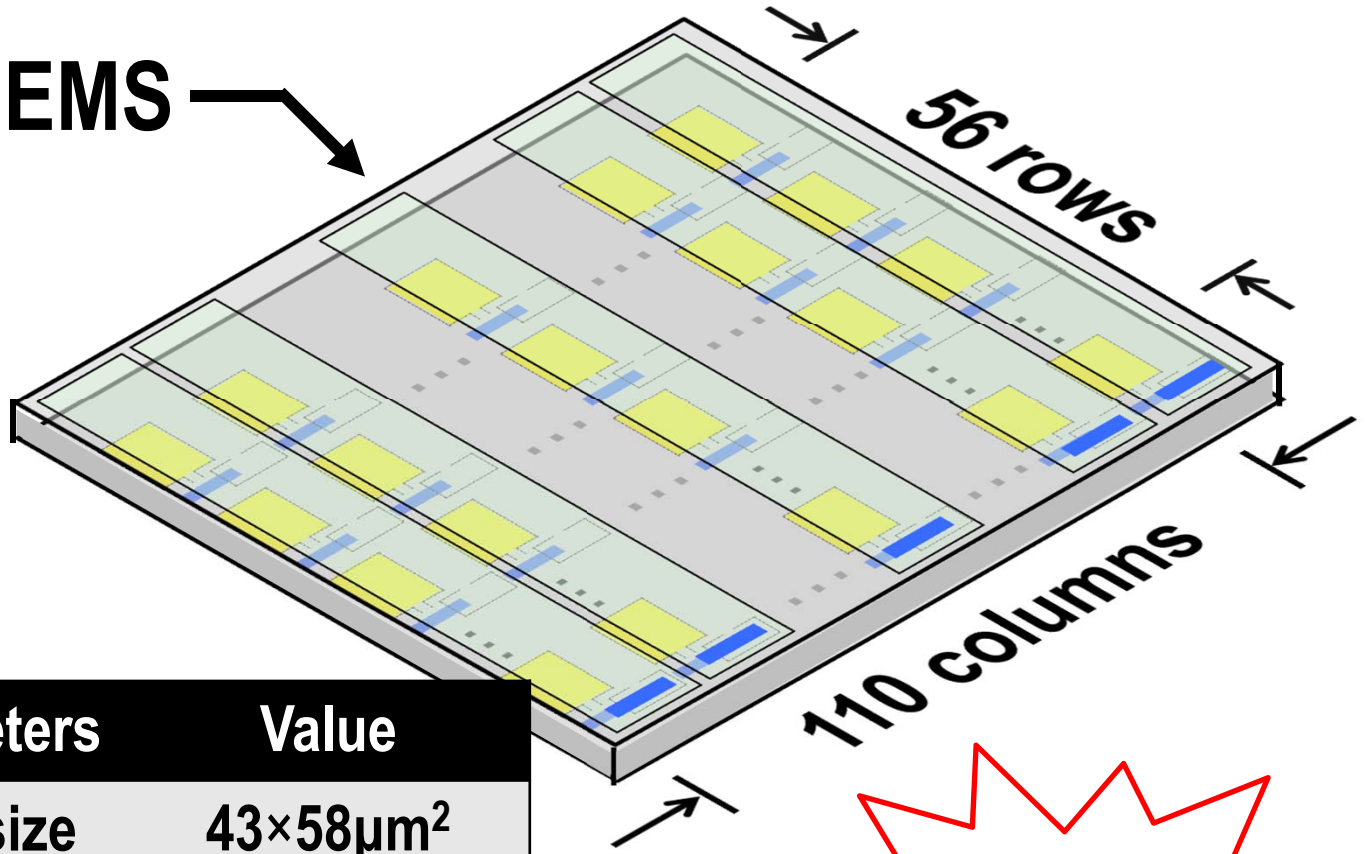




Fill Factor	Pressure at 500 µm
18%	1.6 kPa
52%	8.1 kPa

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

Sensor Array

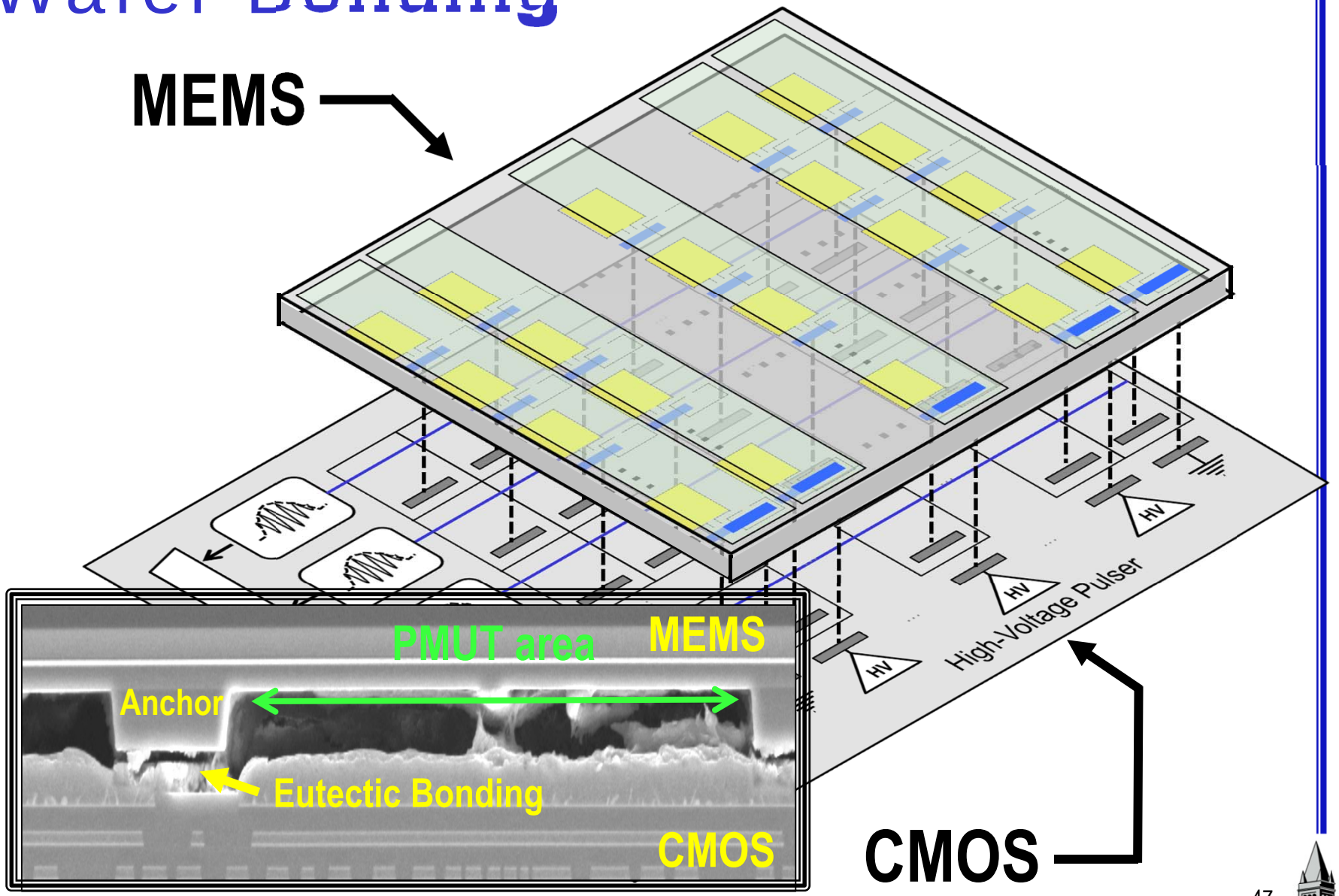


Parameters	Value
Pixel size	43×58μm^2
Resolution	582×431 dpi
Fill-factor	51.7%

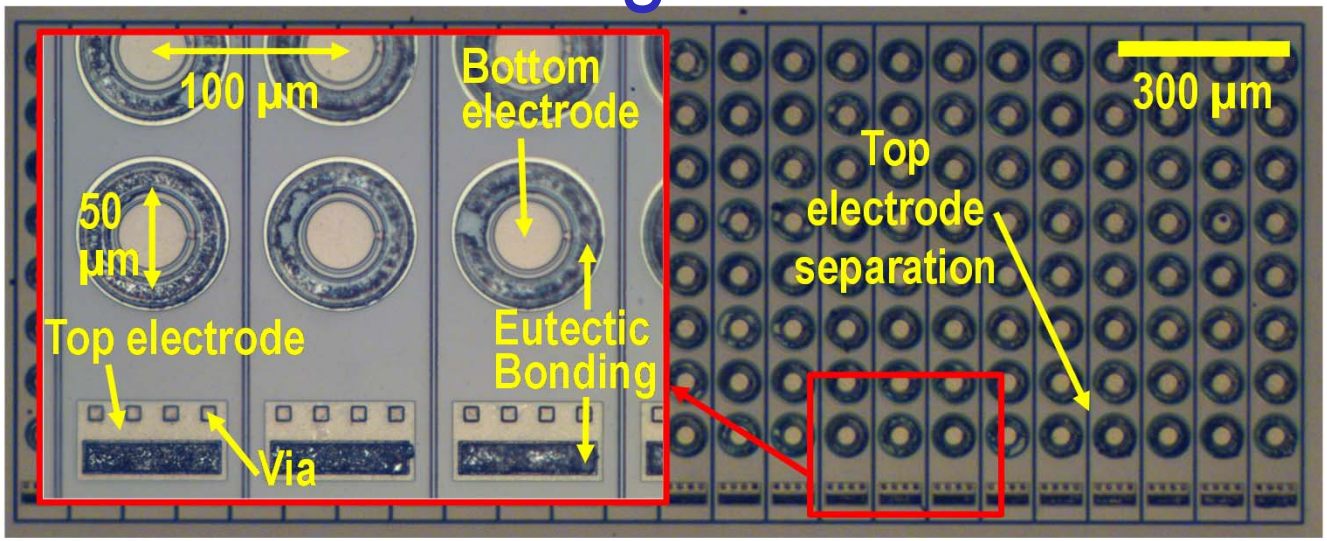
6160 pixels

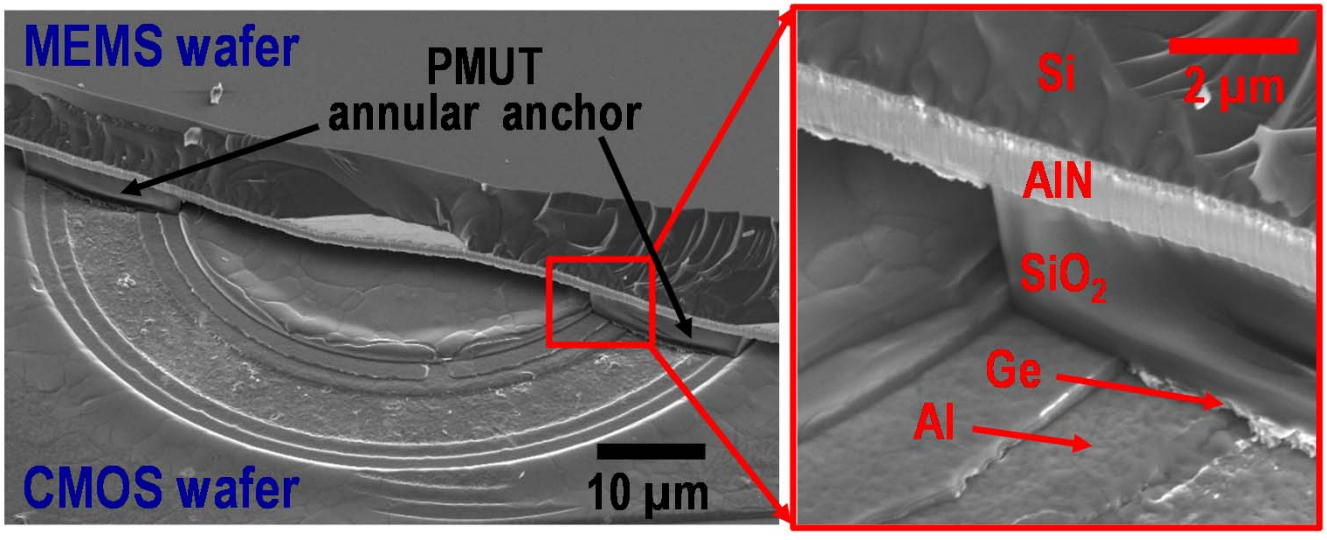
H. Tang et al, "11.2 3D Ultrasonic Fingerprint Sensor on a Chip," 2016 ISSCC, pp. 202-203

Wafer-Bonding



Optical and SEM Images

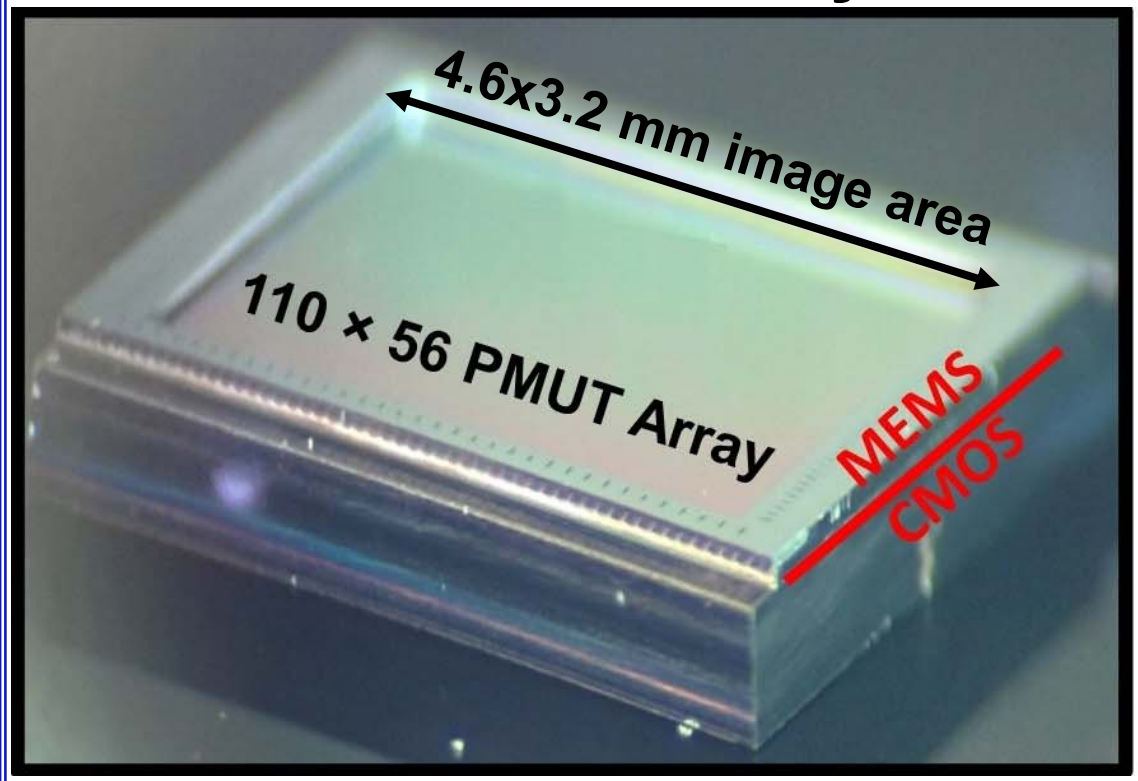




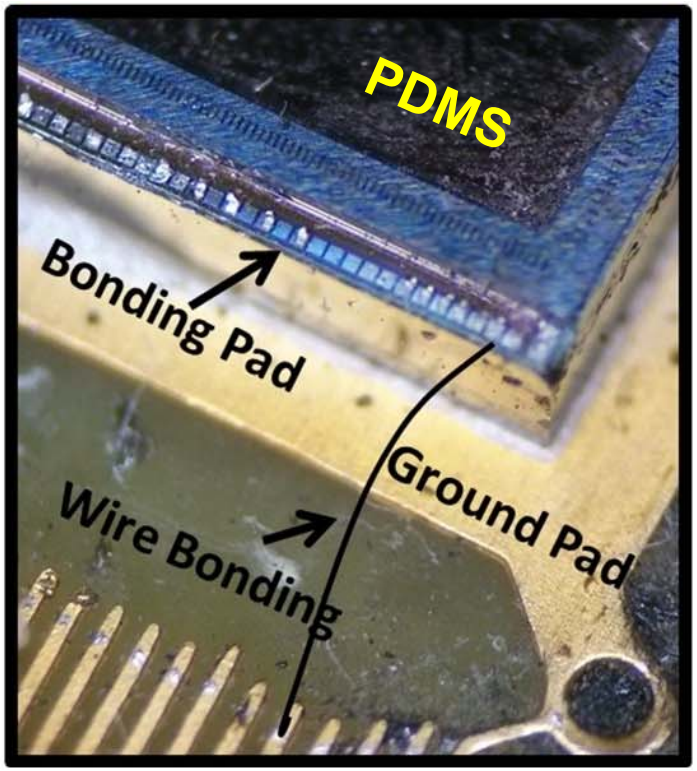
Y. Lu, et al, "Ultrasonic fingerprint sensor using a piezoelectric micromachined ultrasonic transducer array integrated with complementary metal oxide semiconductor electronics," APL , vol. 106, p. 263503, 2015

Sensor Die

Before Assembly



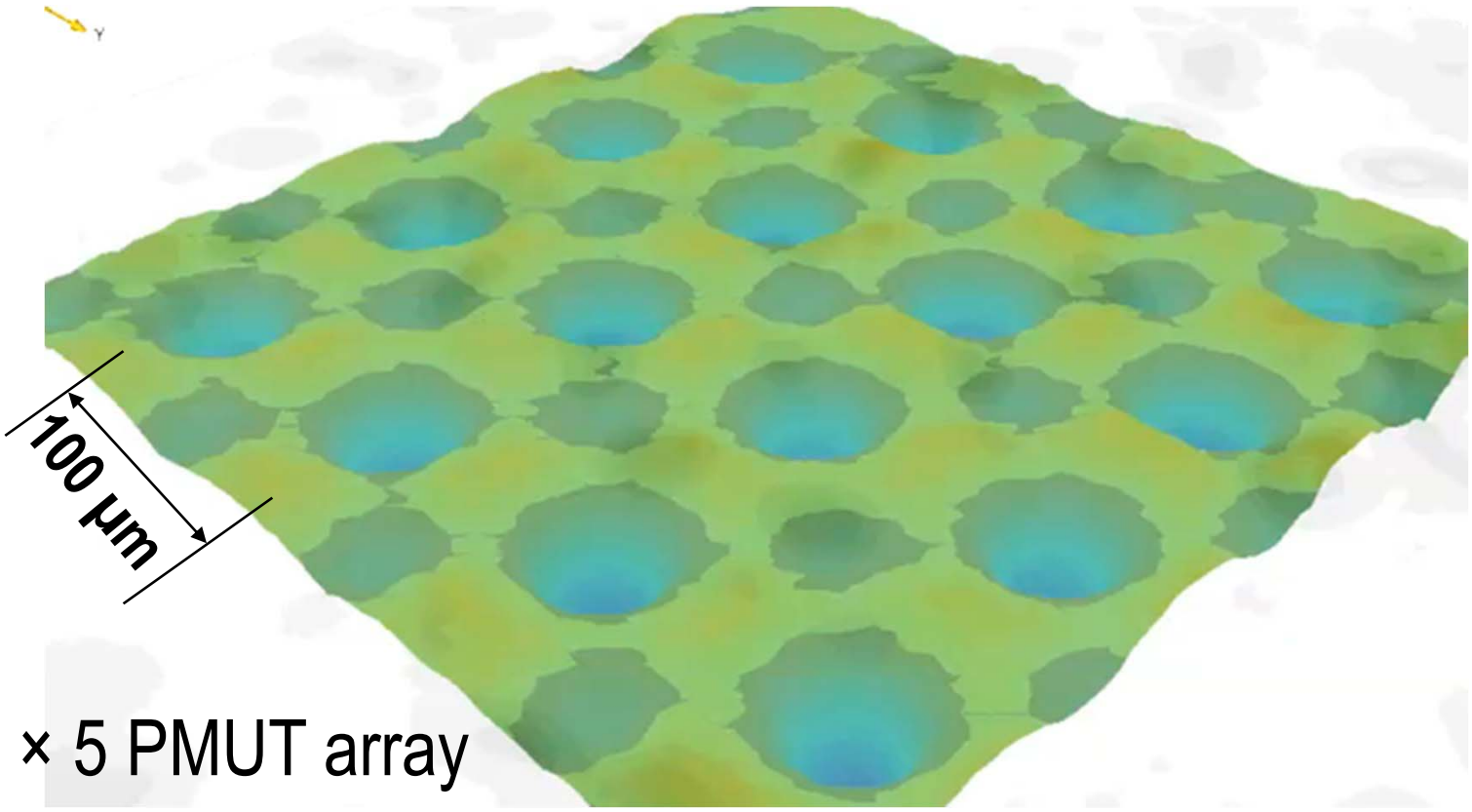
Assembled



X. Jiang et al, "Monolithic 591x438 DPI ultrasonic fingerprint sensor" IEEE MEMS 2016, pp. 107-110.

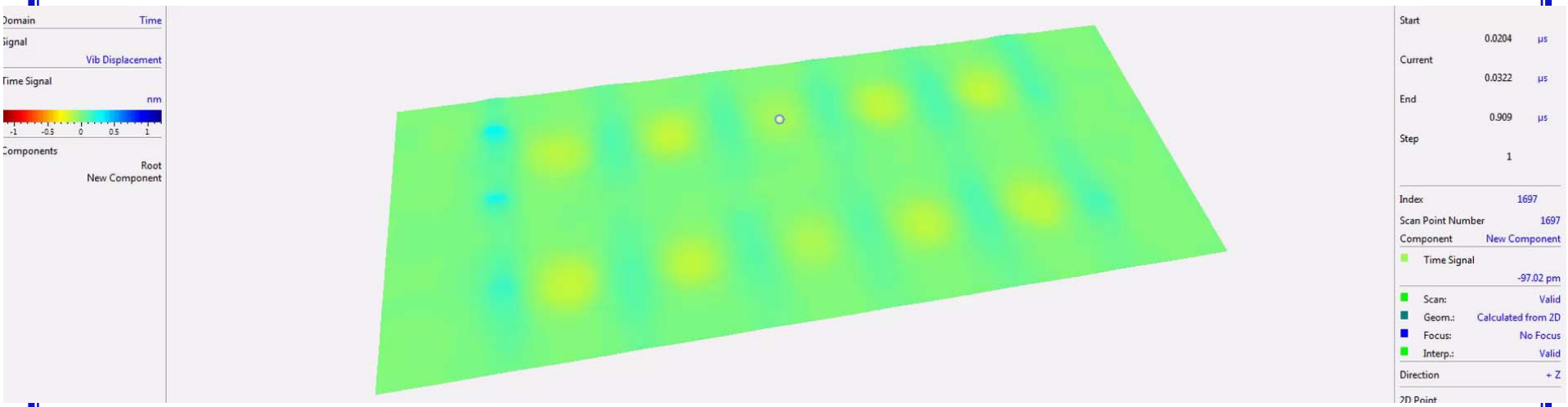
J.M. Tsai, et al, "Versatile CMOS-MEMS integrated piezoelectric platform", *Transducers* 2015, pp. 2248-2251

PMUT motion at 28 MHz captured via LDV



5 × 5 PMUT array

TX Pulse Dynamics

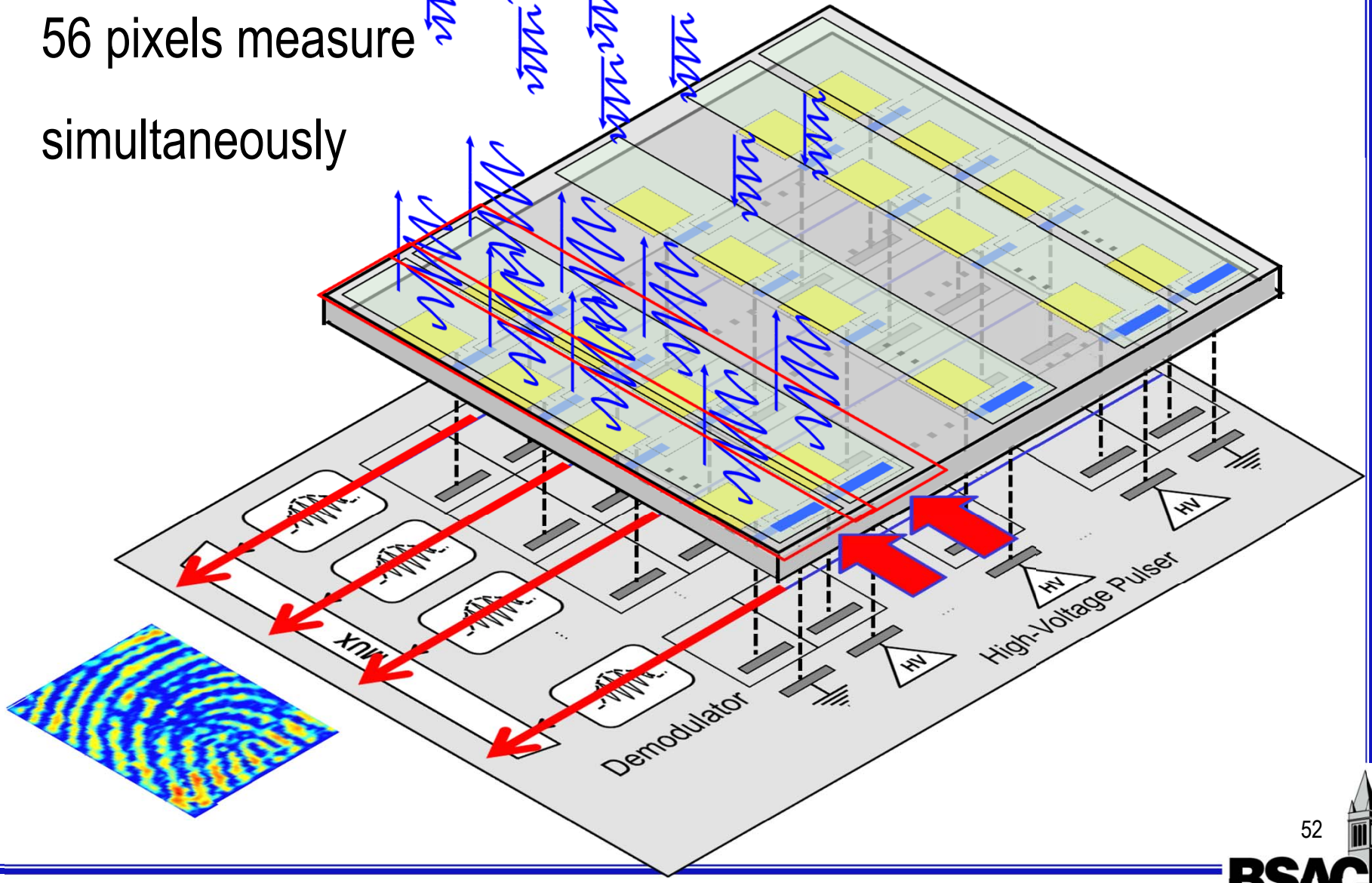


- Imaged through PDMS coupling layer
- 5 columns excited with 2-cycle 14 MHz pulse
- Antiphase motion can be seen between PMUTs

Measurement Cycle

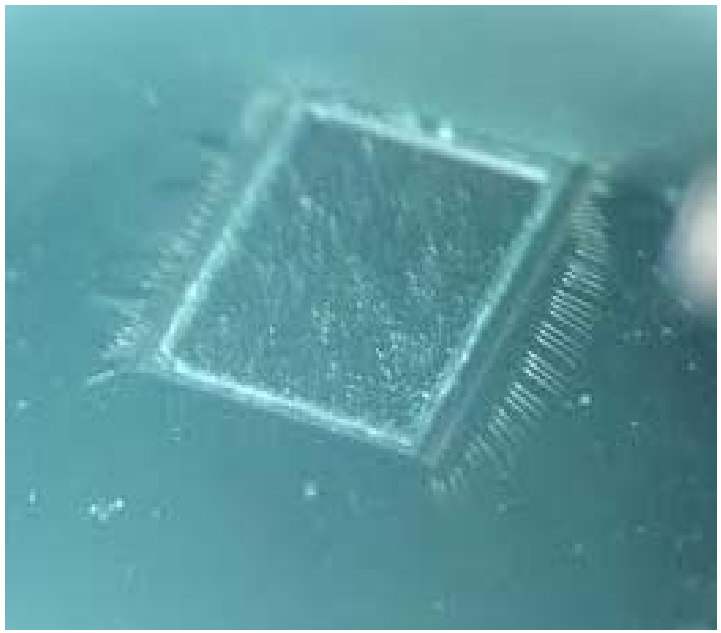
56 pixels measure

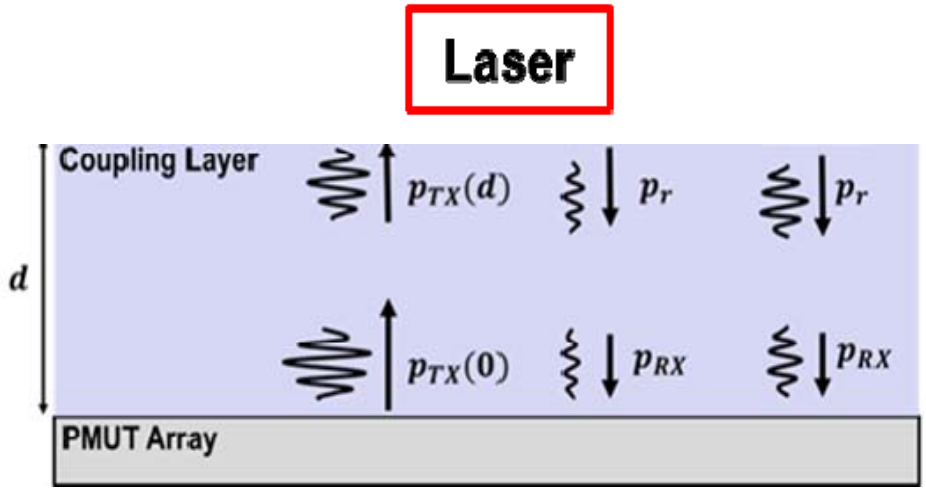
simultaneously



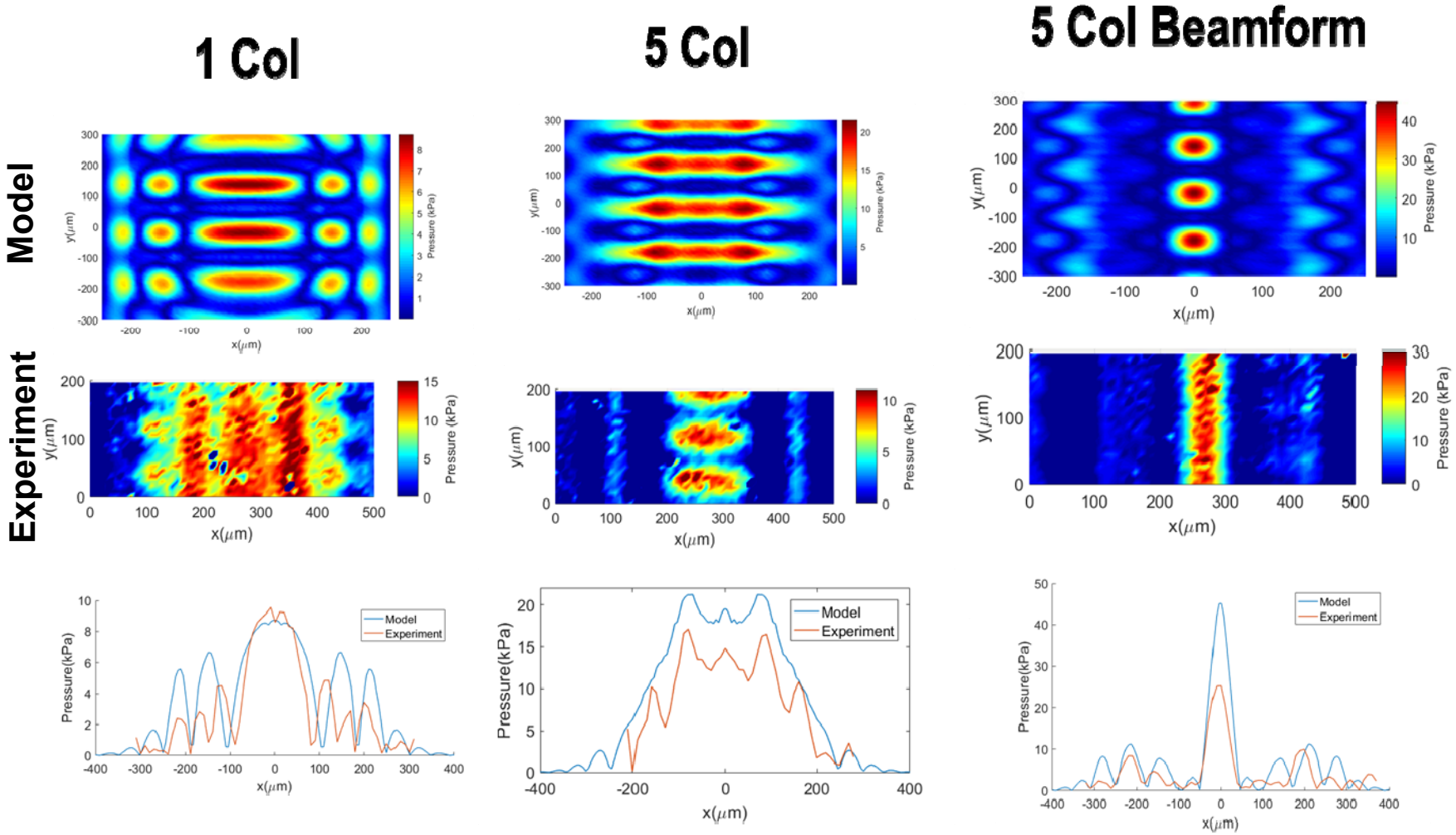
Pressure Field Images

- Ultrasonic pressure field at the PDMS coupling layer surface is imaged using a scanning LDV

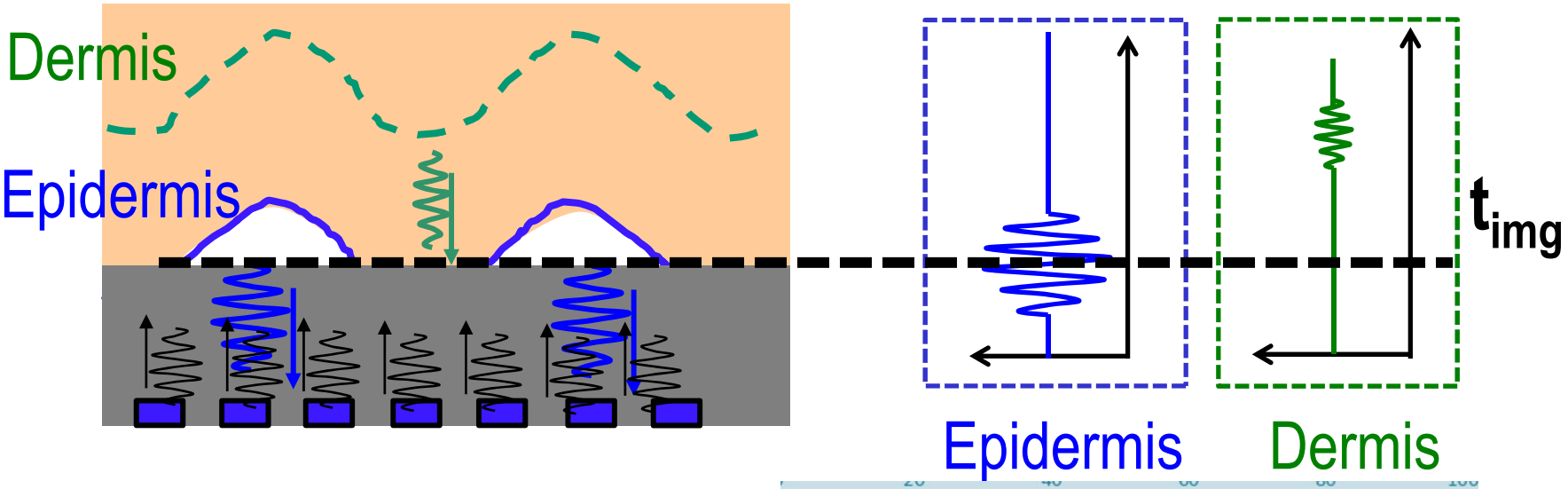


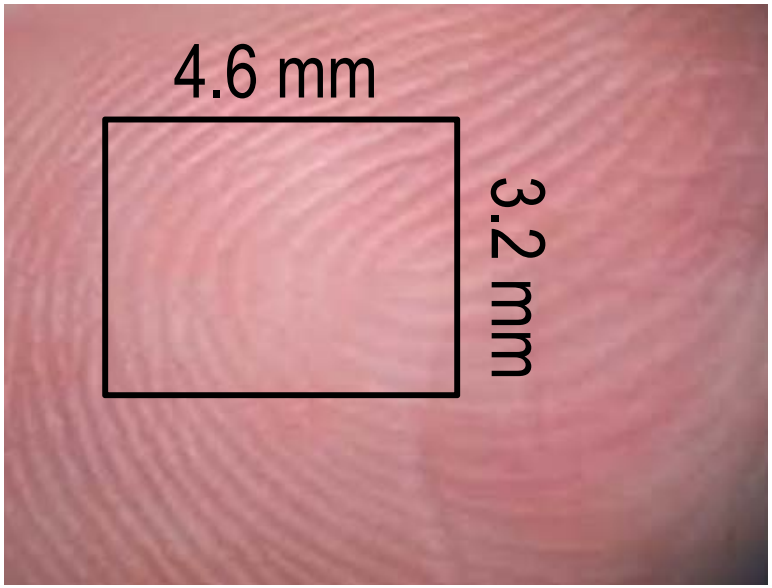


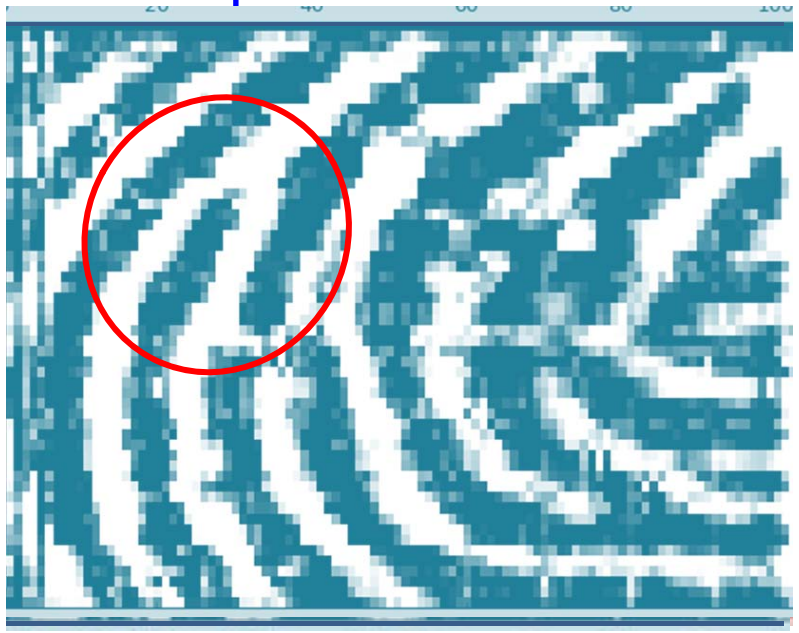
Pressure Field Images



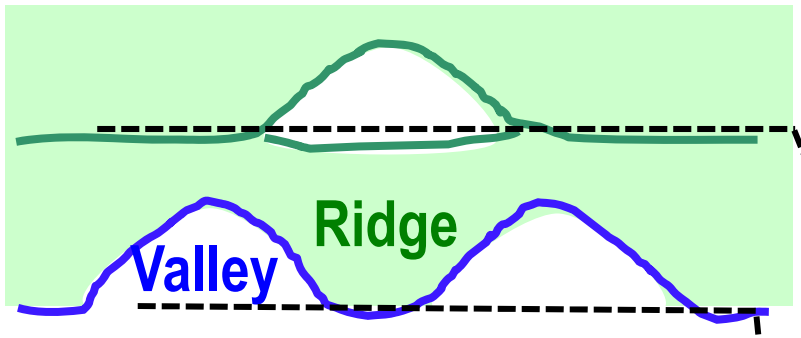
Pulse Echo Fingerprint Image

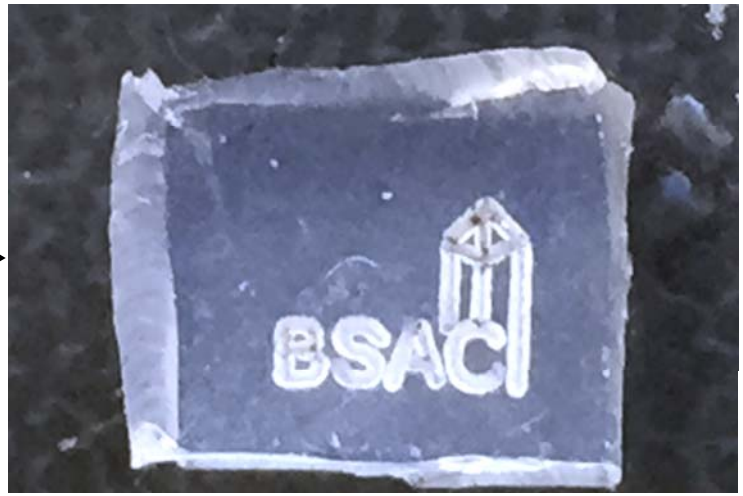


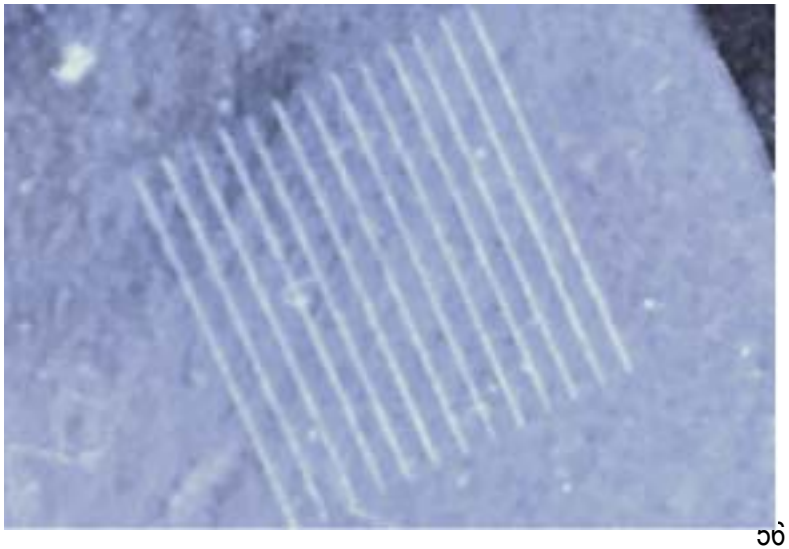




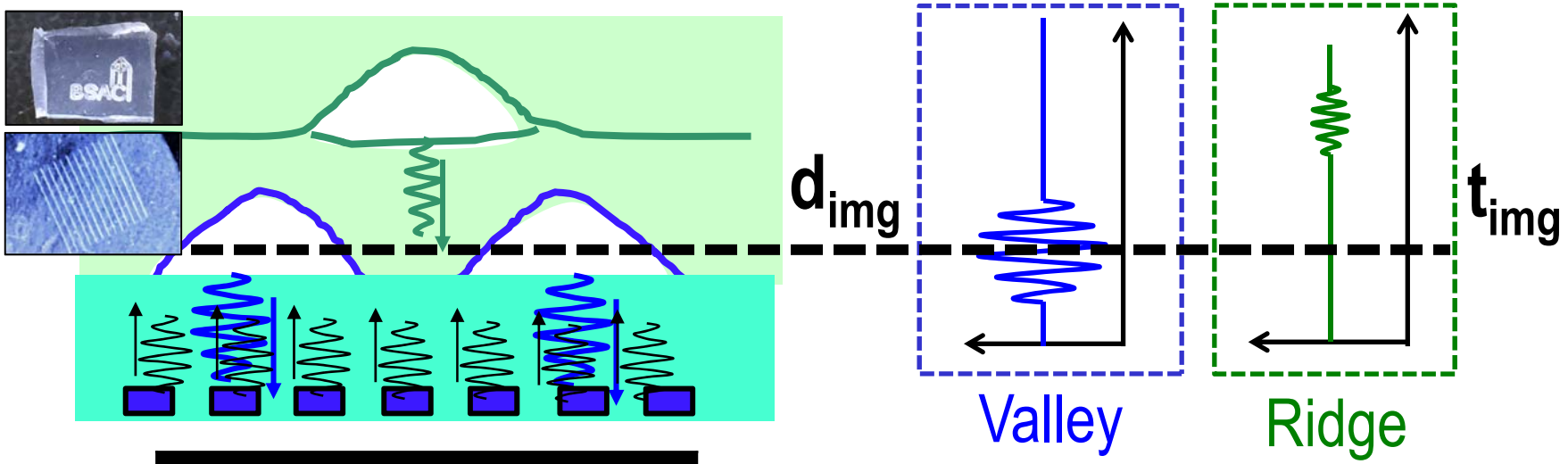
Multi-Layer Phantom







Multi-Layer Phantom

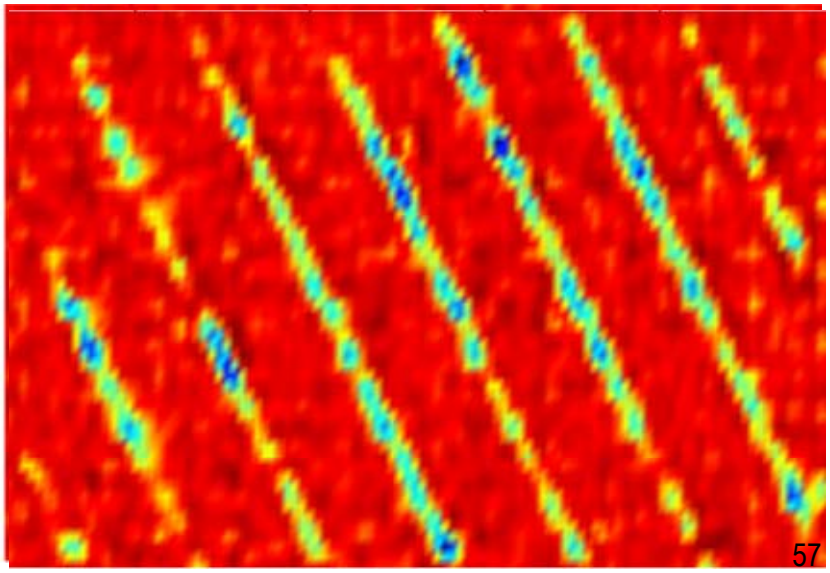


Normal Operation

- ✓ E/ Image: 280µJ
- ✓ 2.8mW @ 10fps
- ✓ Throughput: 380fps

Wakeup Mode

- ✓ E/ Image: 25µJ
- ✓ 5µW @ 2fps



Summary & Conclusions

After 30+ years, PMUTs are a disruptive technology for consumer electronics

- PMUTs and other piezo-MEMS are poised for a big impact thanks to maturity of **thin-film piezoelectric materials**.
- **In air:** Tiny 0.5 mm PMUTs have over **1 m range**.
- **In tissue:** pulse-echo fingerprint imaging demonstrated w/ **1.8V supply**.

Acknowledgments

UCDAVIS
UNIVERSITY OF CALIFORNIA

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