System integration of micromachined ultrasonic transducer arrays for wearable and implantable applications

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iMIST
Integrated Microsystems for
Imaging, Sensing, and Therapy

Ömer Oralkan is an inventor on patents related to CMUT fabrication on glass substrates and a co-founder of ClearSens, Inc., Morrisville, NC, USA, which has licensed some of these patents.

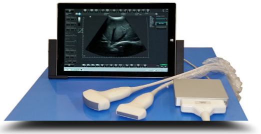
ULTRASONC

Outline

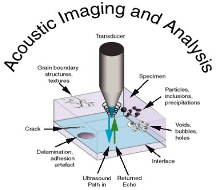
- Ultrasound and capacitive micromachined ultrasonic transducer (CMUT) overview
- Technology
  - Fabrication of vacuum-sealed CMUTs using anodic bonding
  - Integration of CMUT arrays with supporting electronics
  - 2D CMUT arrays with through-glass-via interconnects
- Select applications
  - Untethered systems for focused ultrasound neural stimulation
  - Ultrasound-enabled implants
  - Chem/bio sensors

Ultrasound Applications

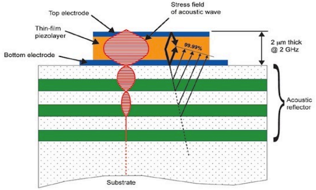
Ultrasound refers to a sound wave with a frequency > 20 kHz, which is above human hearing range



Ultrasound imaging

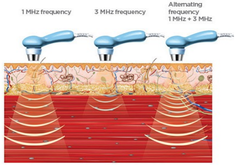


Acoustic microscopy



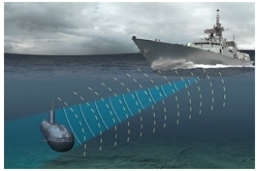
BAW

Parking aid sensor

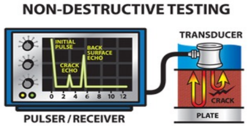


Ultrasound therapy

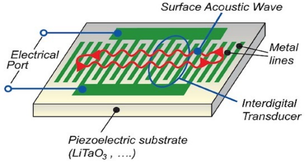
Small animal imaging



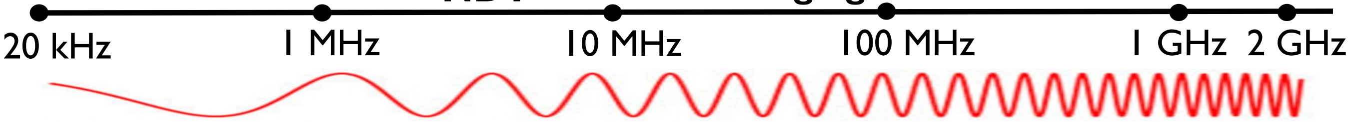
Sonar



NDT



SAW



20 kHz

1 MHz

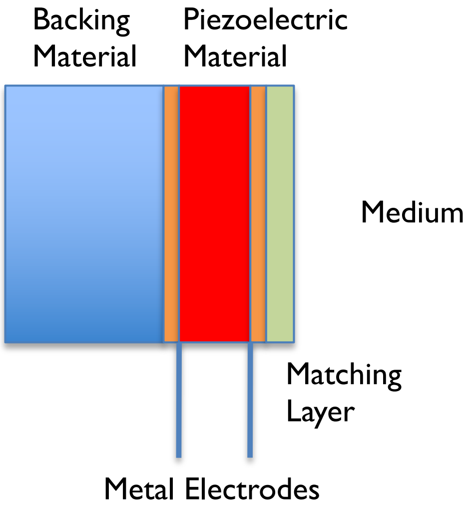
10 MHz

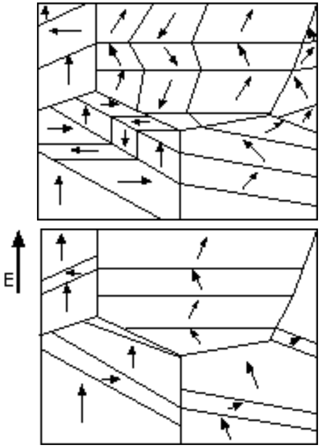
100 MHz

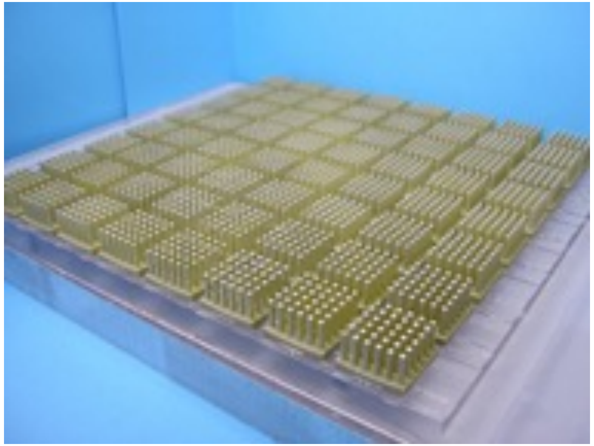
1 GHz

2 GHz

Piezoelectric materials have long dominated the ultrasound transducers field







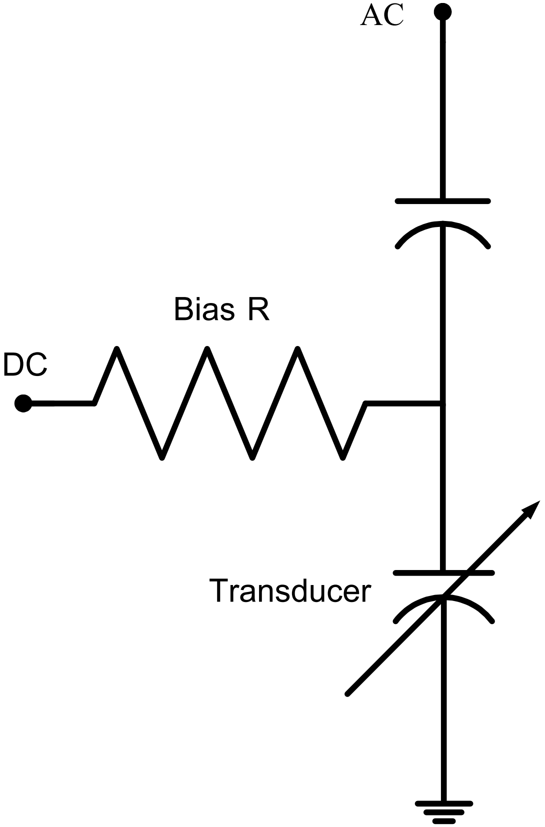
- Electric field and mechanical stress
- Quartz, lead zirconate titanate (PZT), lithium niobate ($LiNbO_3$), polyvinylidene fluoride (PVDF)
- Efficiency is set by the material properties
- Meticulous labor-intensive manufacturing process
- Difficult to make miniaturized transducer arrays

A parallel-plate capacitor with a movable plate can also generate and detect ultrasound

Transmitter: A thin plate is pulled down with DC bias. An AC bias vibrates the thin plate around the DC bias position.

Receiver: An incident vibration on the thin movable plate induces an AC current due to applied DC bias.

What will make a capacitor transducer competitive with a piezoelectric?



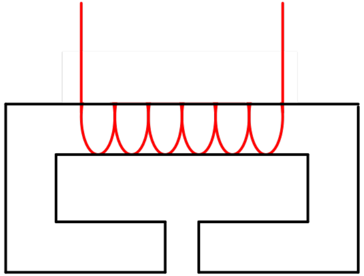
The idea of capacitive (electrostatic) ultrasonic transducer is as old as piezoelectrics

"After a month of careful study, during which both magnetostriction and piezoelectricity were considered and then rejected, **Langevin decided that it would be safer to fall back on the "singing condenser"**… (March 1915). Numerical estimates indicated that, if electric field strengths of the order of a million volts per centimeter (10^8 Volt per meter or 100 V per micron) could be maintained, electrostatic forces as large as a kilogram per square centimeter would (theoretically) come into play…"

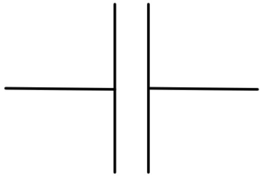
Paul Langevin
1872-1946

Hunt, "*Electroacoustics – The analysis of transduction and its historical background*", AIP, 1982.

$$\boxed{\frac{F}{A}=\frac{1}{2}\frac{B^2}{\mu_0}}$$



μ_0 , B



ε_0 , E

$$\boxed{\frac{F}{A}=\frac{1}{2}\varepsilon_0 E^2}$$

For E = 300 V per micron, the electrostatic force is equal to what B = 1 Tesla can create !
(Large hadron collider at CERN, Geneva, uses up to B = 8.3 Tesla)

Microfabrication has enabled CMUT

1880
The discovery of piezoelectricity
by Curie Brothers

1917
The ultrasonic submarine detector
by P. Langevin

1940s
Piezoelectric ceramics

1969
A piezoelectric polymer: PVDF

1980s
Piezocomposites

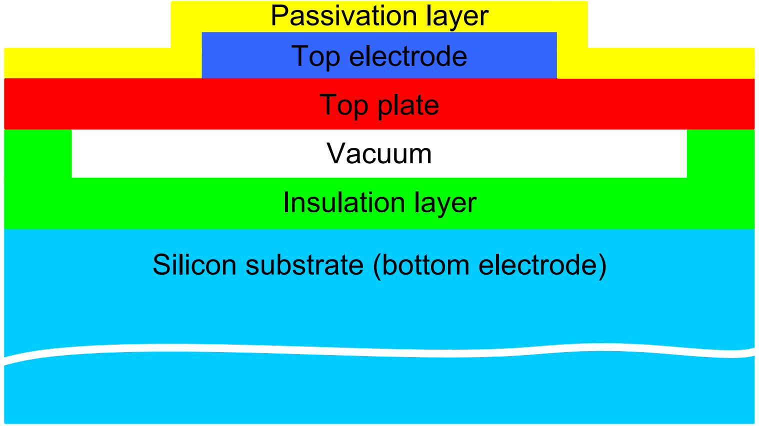
2000s
Single crystals

1915
Electrostatic transducers considered for
the ultrasonic submarine detector
by P. Langevin

1970s-1990s
Advances in microelectronics

1994
Micromachined electrostatic transducers
by M. Haller and B. T. Khuri-Yakub

The modern electrostatic transducer: CMUT



Some typical numbers …

Top plate diameter: 20-40 μm
Top plate thickness: 0.5-2 μm
Insulator thickness: 100-300 nm
Vacuum cavity: 100-200 nm

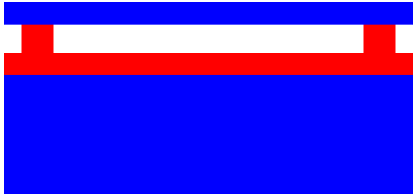
- Standard IC fabrication process
- Submicron gap → High E-field intensity → Improved sensitivity
- Broad operating frequency
- Wide bandwidth

Broad operating frequency and wide bandwidth → Improved resolution

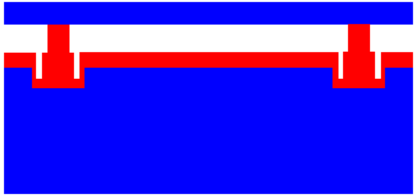
- Potential for integration with electronic circuits
- Patterning by simple lithography → Easy fabrication of 1-D & 2-D arrays

Many variations in structure and fabrication

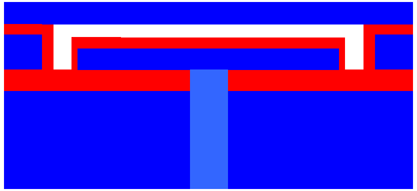
Silicon nitride plate realized using the sacrificial release process (Vertical dimensions and material properties not easy to control)



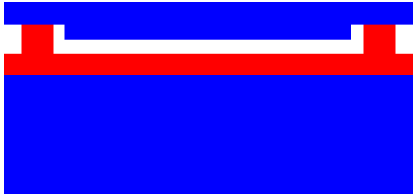
Single crystal silicon plate realized using SOI wafer bonding (Good control in dimensions and material properties, but vulnerable to breakdown)



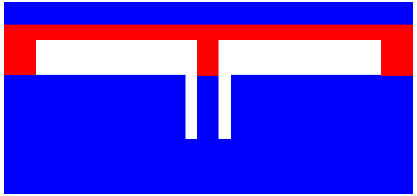
Extended dielectric posts realized by LOCOS process improve reliability and decrease the parasitic capacitance (limits minimum lateral dimensions)



Completely isolated bottom electrode (limits minimum lateral dimensions)



Added mass on the plate decouples mass and spring for design (piston-like motion)



Compliant post structure achieves piston-like motion

🟦 Silicon

🟩 Silicon nitride

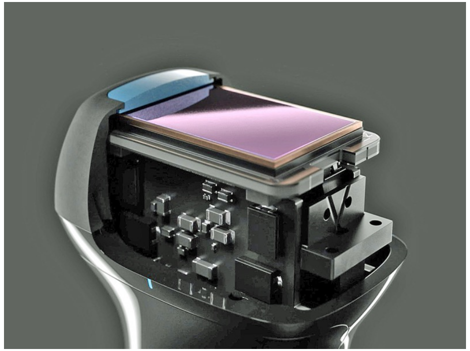
🟪 Aluminum

🟥 Silicon dioxide

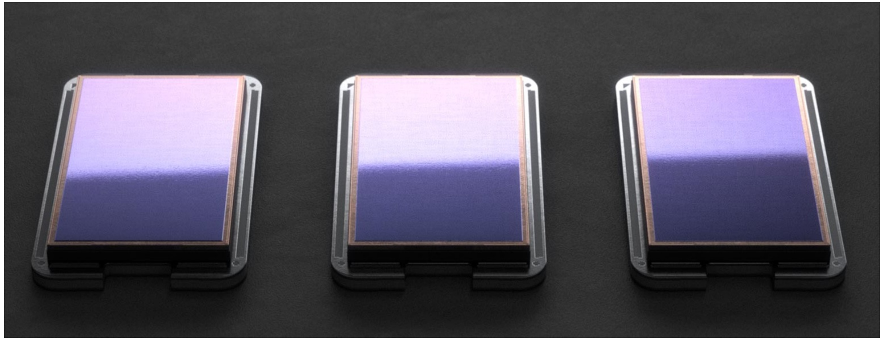
🟦 Polysilicon

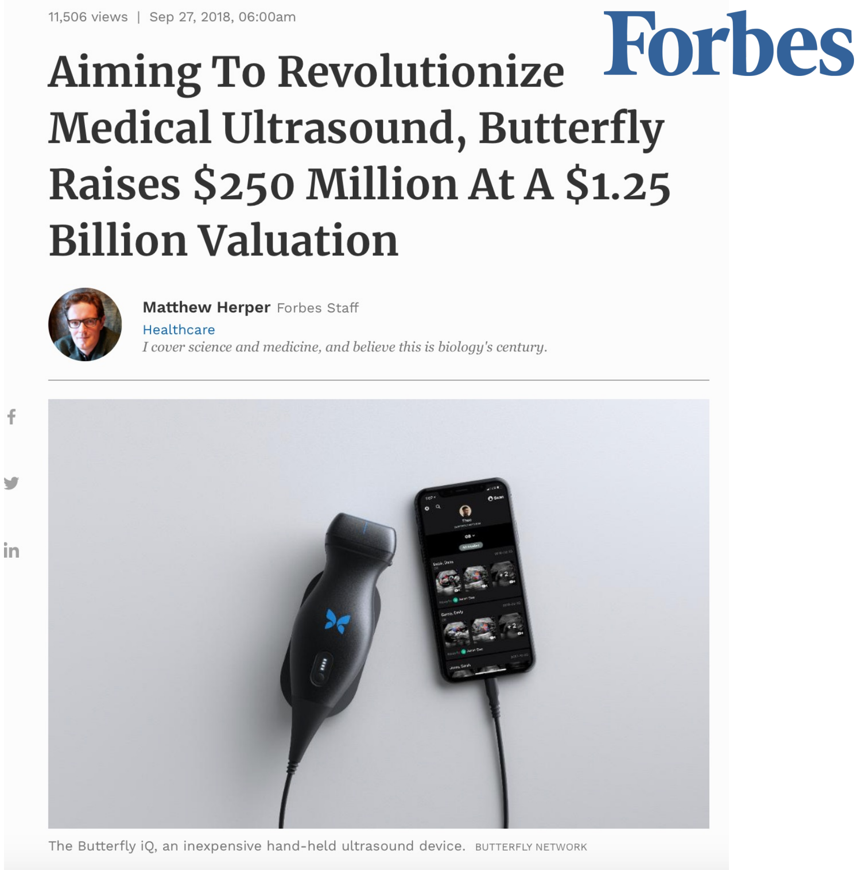
B. T. Khuri-Yakub and Ö. Oralkan, "Capacitive micromachined ultrasonic transducers for medical imaging and therapy," *J. Micromech. Microeng.*, vol. 21, no. 5, 054004, May 2011.

CMUTs recently hit the market!



Butterfly





11,506 views | Sep 27, 2018, 06:00am

Forbes

Aiming To Revolutionize Medical Ultrasound, Butterfly Raises $250 Million At A $1.25 Billion Valuation

Matthew Herper Forbes Staff

Healthcare

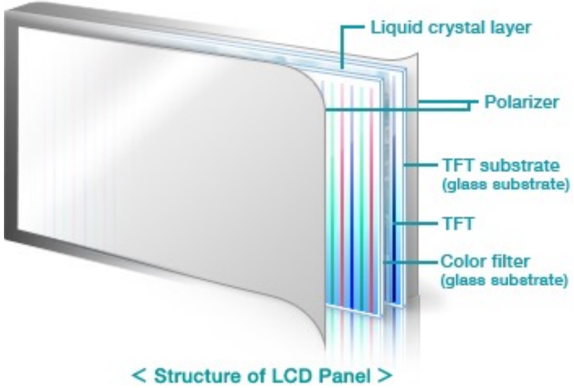
I cover science and medicine, and believe this is biology's century.

The Butterfly iQ, an inexpensive hand-held ultrasound device. BUTTERFLY NETWORK

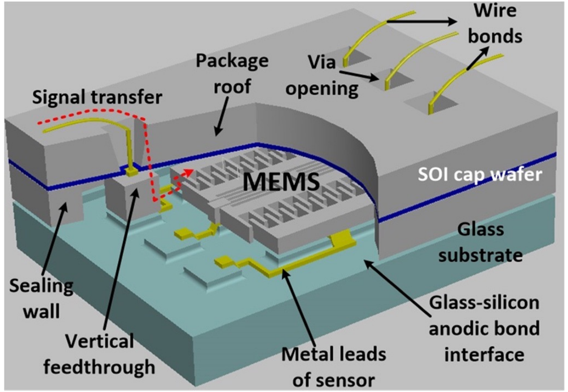
Glass: the other substrate – insulating, transparent…

Applications

- Microfluidic devices
- IR cut filter for CIS technology
- Some actuators and sensors
- Fanout wafer-level packaging
- Wafer-level capping
- RF applications
- Display

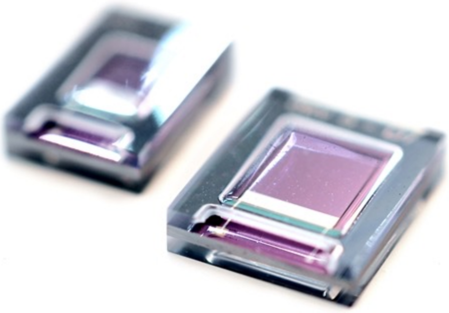


http://www.avanstrate.com/english/product/about.html



M. M. Torunbalci et al., Sens. and Act. A 224 (2015) 169–176

http://www.glass-solutions.com/microfluidic-chips.html



https://phys.org/news/2011-12-imec-mems-energy-harvester-suitable.html

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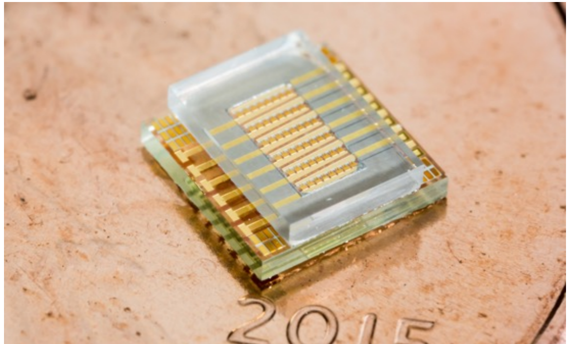
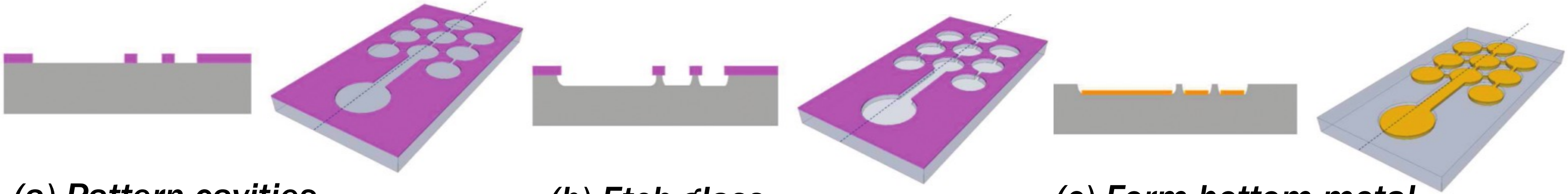


https://www.mwrf.com/components/mems-switches-shrink-glass-substrates

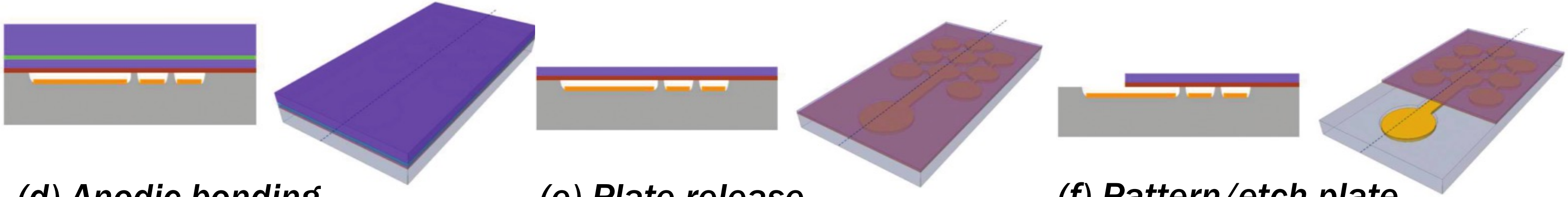
Base process: A three-mask process



(a) Pattern cavities

(b) Etch glass.

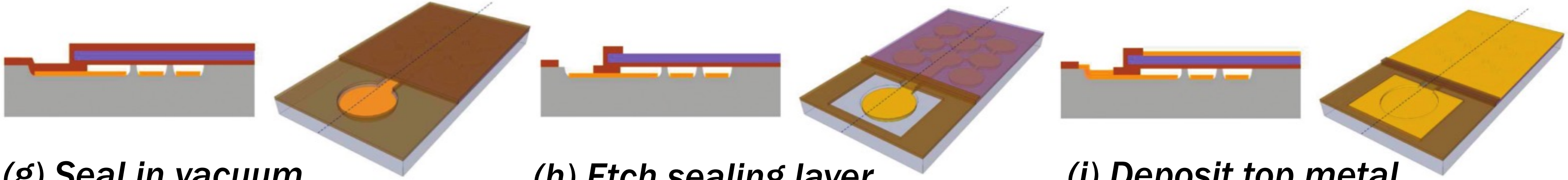
(c) Form bottom metal



(d) Anodic bonding

(e) Plate release

(f) Pattern/etch plate



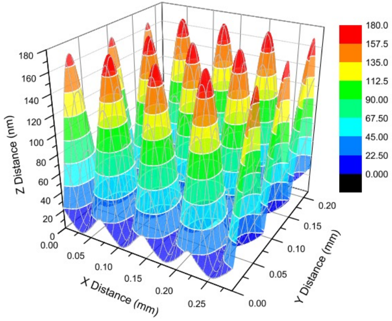
(g) Seal in vacuum

(h) Etch sealing layer

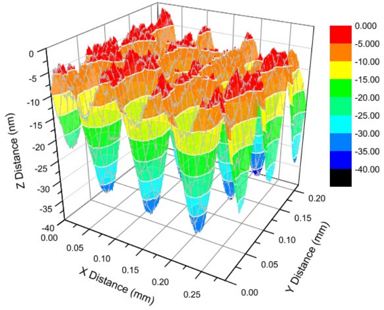
(i) Deposit top metal

F.Y. Yamaner, X. Zhang, and Ö. Oralkan, "A three-mask process for fabricating vacuum sealed capacitive micromachined ultrasonic transducers using anodic bonding," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 62, no. 5, pp. 972-982, May 2015

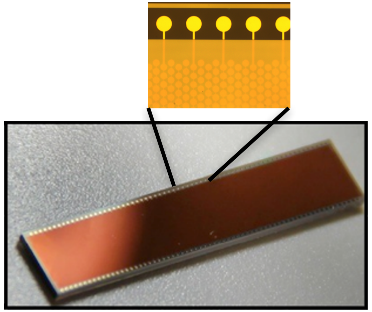
Achieved vacuum sealed cavities with anodic bonding



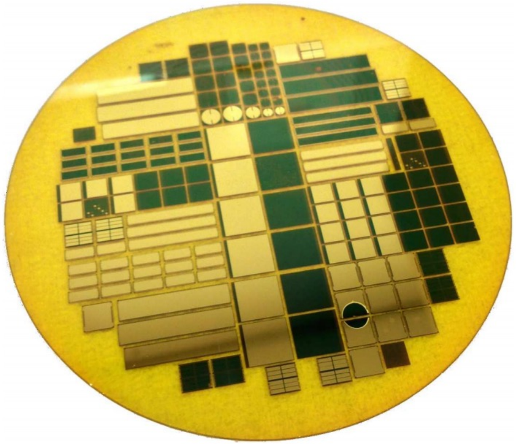
Before evacuating the gas



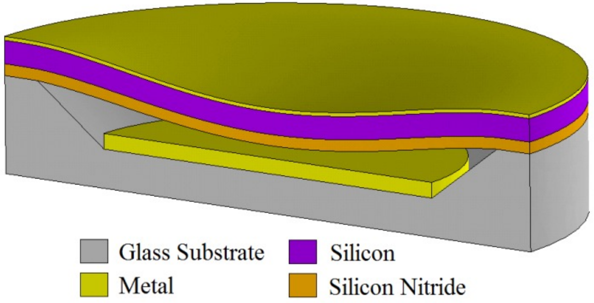
After vacuum sealing

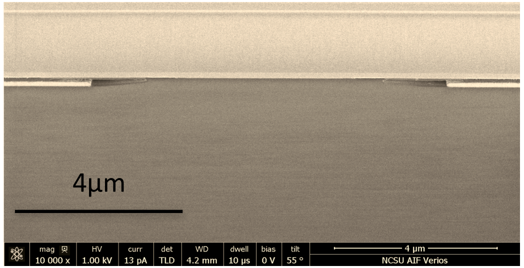


1D array



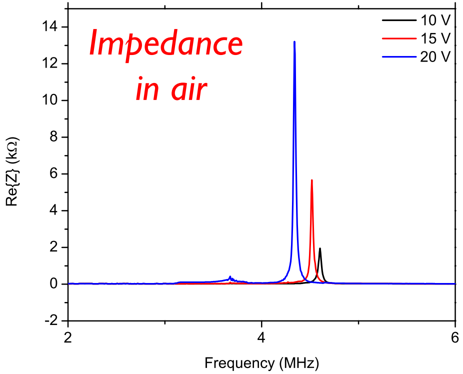
Completed CMUT wafer with single transducers and 1D arrays



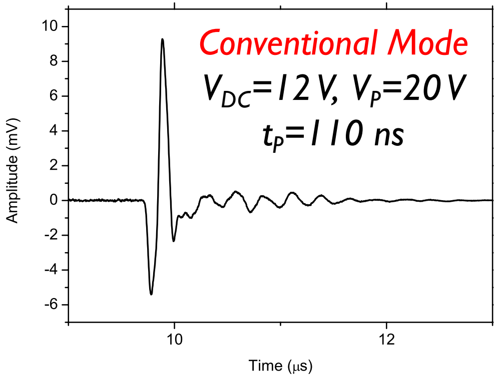


F.Y. Yamaner, X. Zhang, and Ö. Oralkan, "A three-mask process for fabricating vacuum sealed capacitive micromachined ultrasonic transducers using anodic bonding," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 62, no. 5, pp. 972-982, May 2015

All the expected behavior from a Si-CMUT and more …



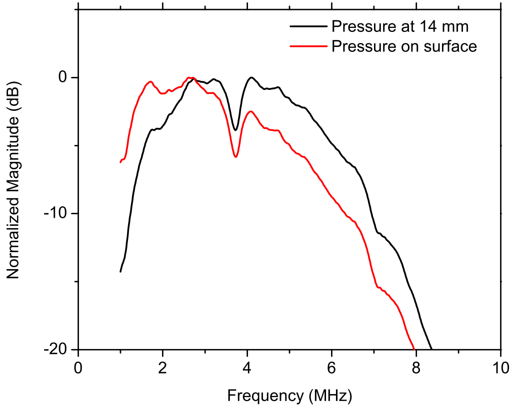
Impedance in air



Conventional Mode

V_{DC}=12 V, V_P=20 V

t_P=110 ns

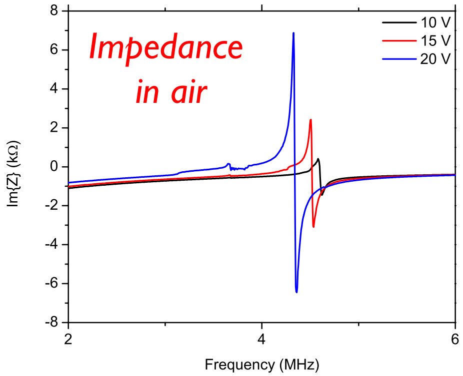


On the surface:

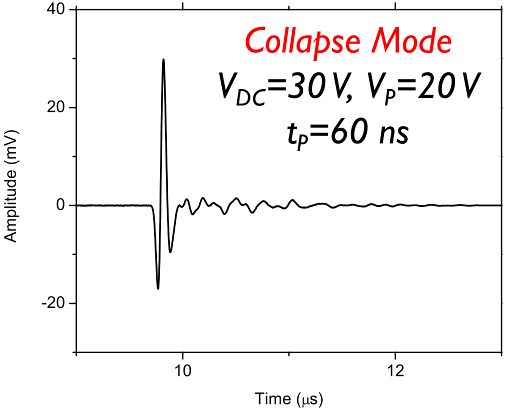
f_c=2.76 MHz

FBW=107%

S_{tx}=11.3 kPa/V



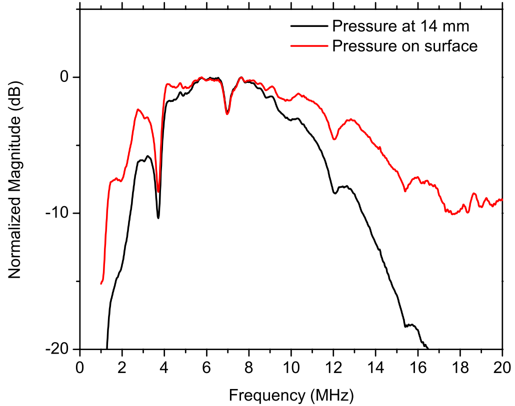
Impedance in air



Collapse Mode

V_{DC}=30 V, V_P=20 V

t_P=60 ns



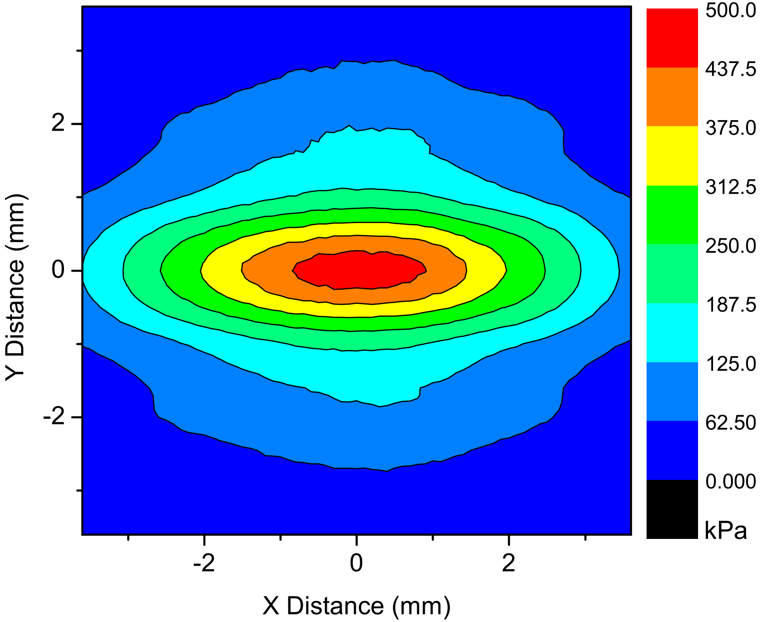
On the surface:

f_c=7.15 MHz

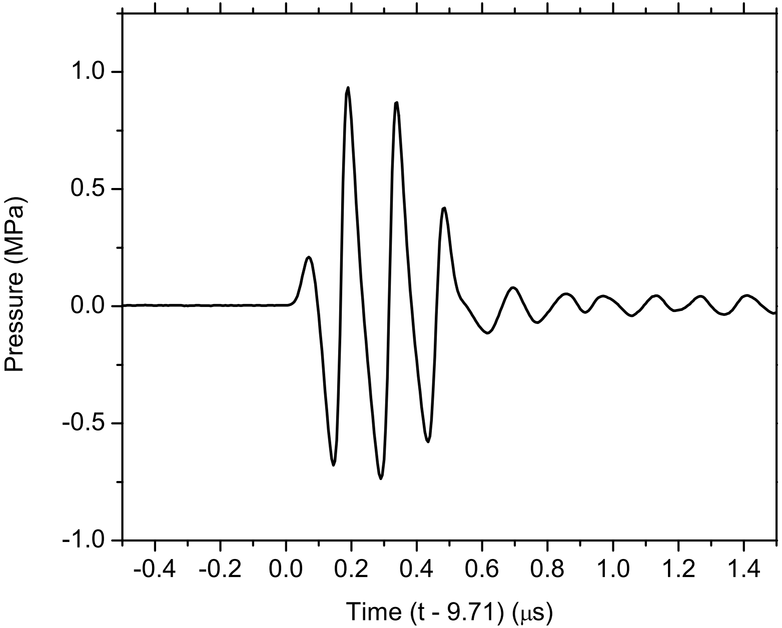
FBW=126%

S_{tx}=28.4 kPa/V

All the expected behavior from a Si-CMUT and more …

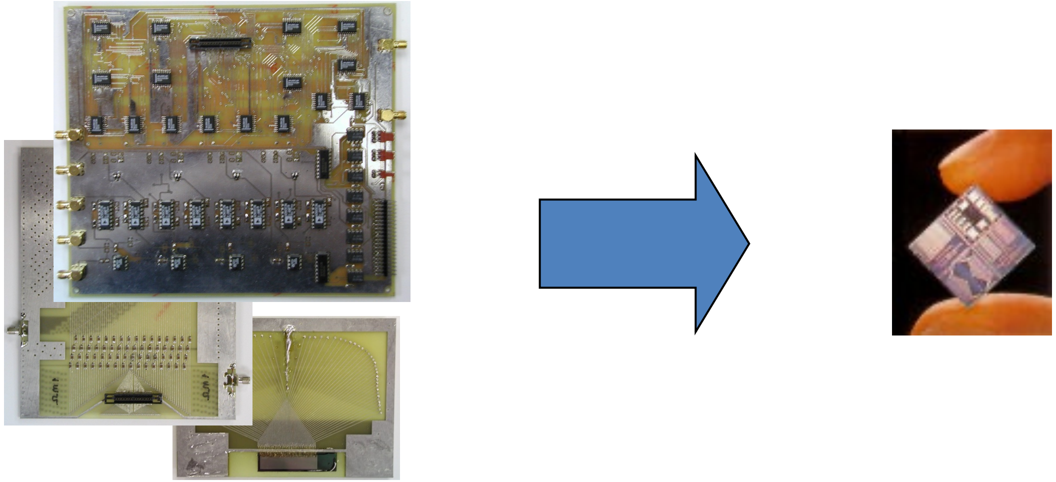


Pressure field measured at 14-mm distance from the transducer surface



Pressure on the surface calculated by compensating the on-axis pressure measurement at 14 mm for attenuation and diffraction loss

Why integrate transducers and electronics?



- Reduced complexity and cost.
- Reduced parasitics: Improved sensitivity, preserved bandwidth.
- Reduced number of external interconnects through multiplexing: Important for systems with large channel counts such as 2-D arrays.
- Compactness: Necessary for applications such as intravascular imaging, image guided surgery and implantable/wearable devices.

How to integrate transducers and electronics?

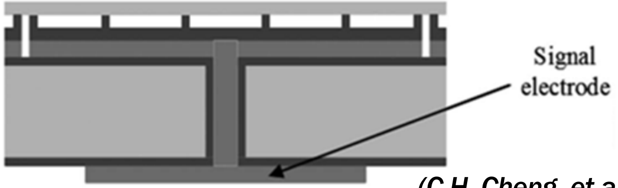
Monolithic or Multi-chip ?

	Monolithic?	**Area Utilization**	**Design Flexibility**	**Cost**
CMOS or BiCMOS (modified) *(Eccardt et al.)*	✓	✗ (lines & circuits)	✗ (obey foundry rules)	$
Postprocessing on top of standard CMOS *(Noble et al.)*	✓	✓ (3rd dimension)	✗ (thermal budget)	$ $ $ (low yield, nonuniform)
Flip-chip bonding	✗ ≥ 2 chips	✓ (3rd dimension)	✓	$ $ (good yield, quick)

Through-silicon interconnects for 2D arrays

Through-silicon-vias (TSVs)

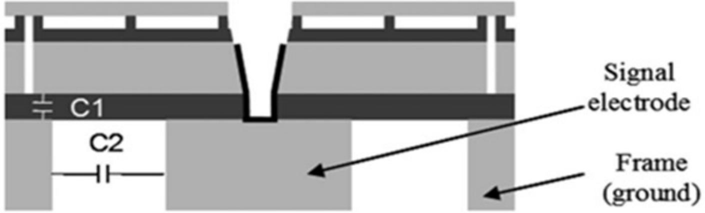
- Form through-wafer holes by DRIE.
- Coat insulation layer, such as silicon oxide, on the hole sidewall to isolate the hot electrodes from substrate.
- Deposit through-hole conductor (typically doped poly-Si).
- Reverse bias the PN or MIS junction to minimize parasitics.
- Limited mainly to surface micromachining CMUT process.



(C.H. Cheng, et al. 2004)

Trench-isolated interconnections

- Eliminate the complex process to make through-silicon vias.
- A smooth surface is required for fusion bonding.
- Reliability is an issue (shorting of hot electrode to top electrode on the front surface, mechanical stability of Si pillars).
- Introduce parasitics C1 and C2.



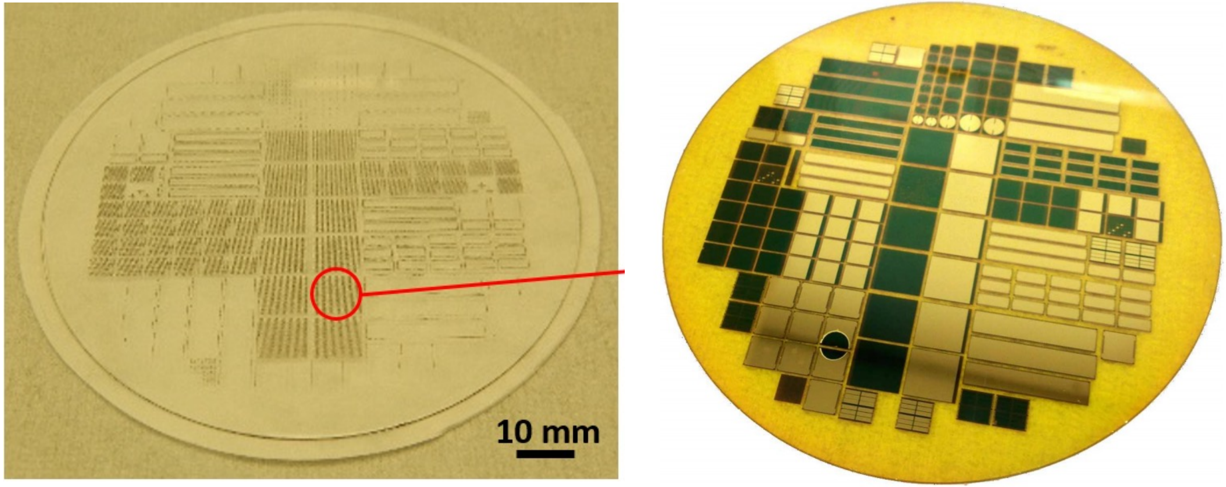
C_1: Overlapping area of the CMUTs and supporting frame.

C_2: Trench isolation capacitance.

(X. Zhuang, et al. 2005)

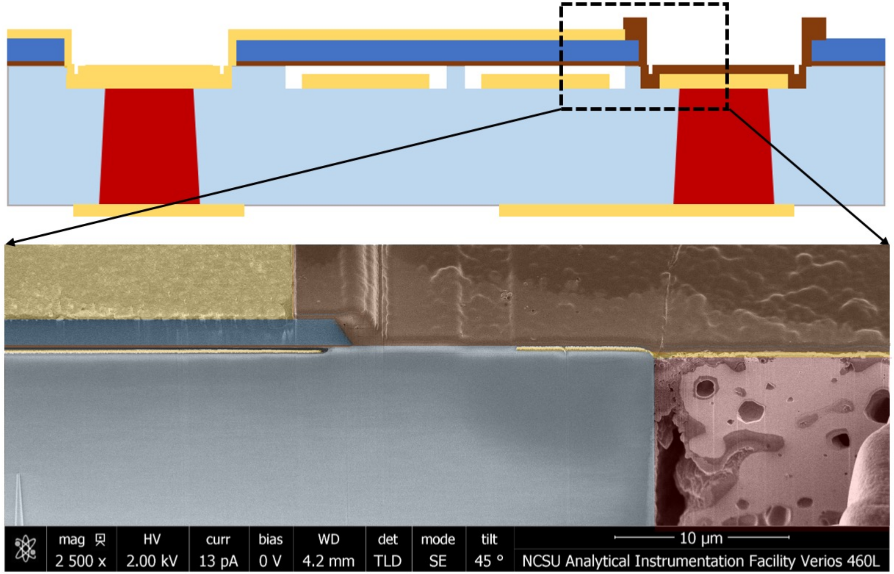
Through-glass-via (TGV) interconnects

- TGVs have been widely used in the interposer technology.
- Simplify the fabrication process by eliminating the isolation steps.
- Reduce parasitic capacitance and resistance.
- Compatible with anodic bonding.

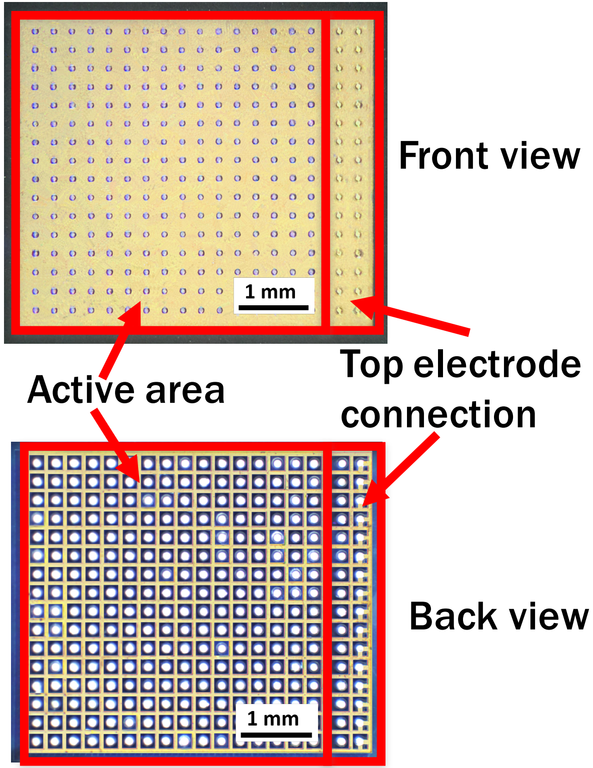


Patterned 4-inch glass substrate with pre-formed TGVs

Anodically bonded 2D arrays with TGV interconnects



🟦 **Glass** 🟫 **Silicon Nitride** 🟨 **Cr/Au**
🟦 **Silicon** 🟥 **Cu paste**

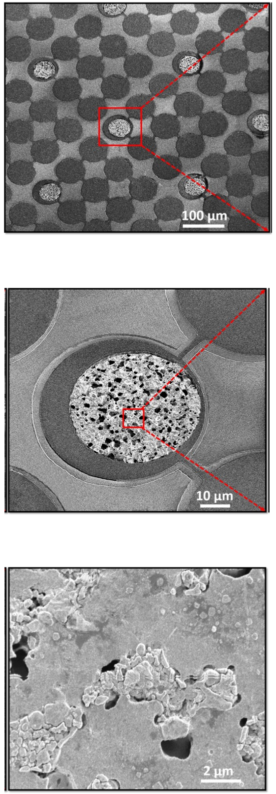


Front view

Active area

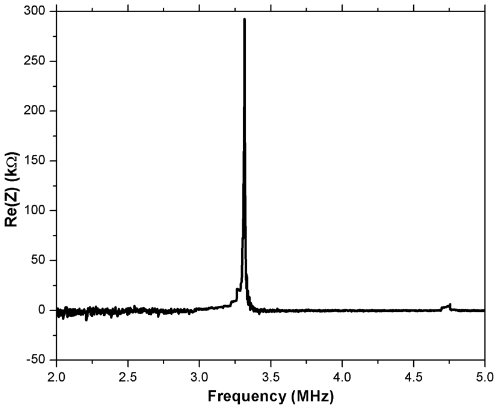
Top electrode connection

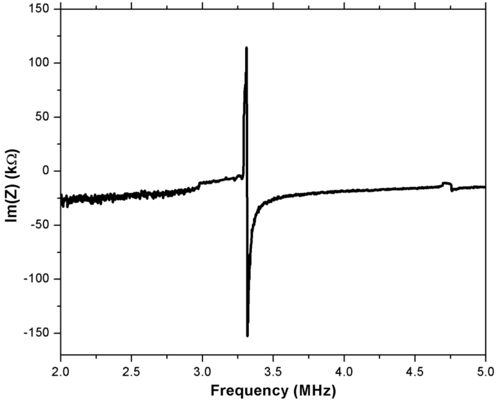
Back view

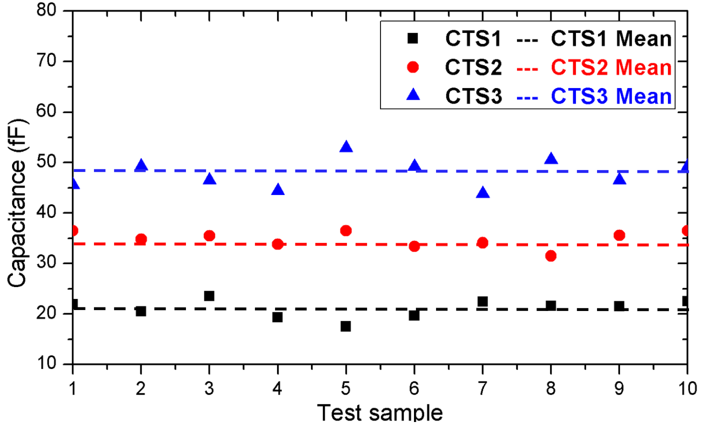


X. Zhang, F.Y. Yamaner, and Ö. Oralkan, "Fabrication of vacuum-sealed capacitive micromachined ultrasonic transducers with through-glass-via interconnects using anodic bonding," IEEE J. Microelectromech. Syst., vol. 26, no. 1, pp. 226-234, Feb. 2017.

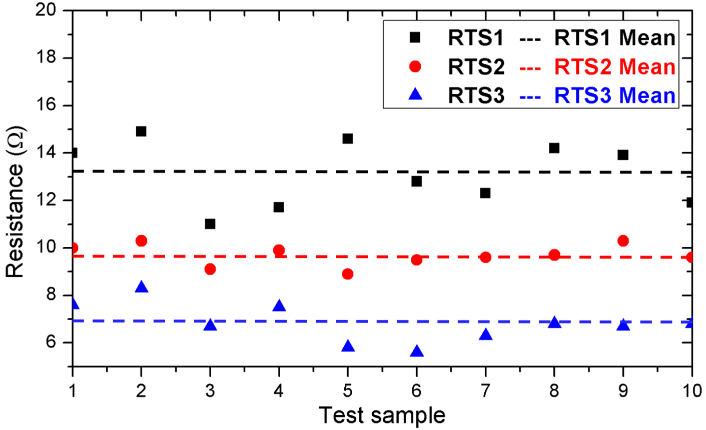
TGVs demonstrate lower parasitics than TSVs





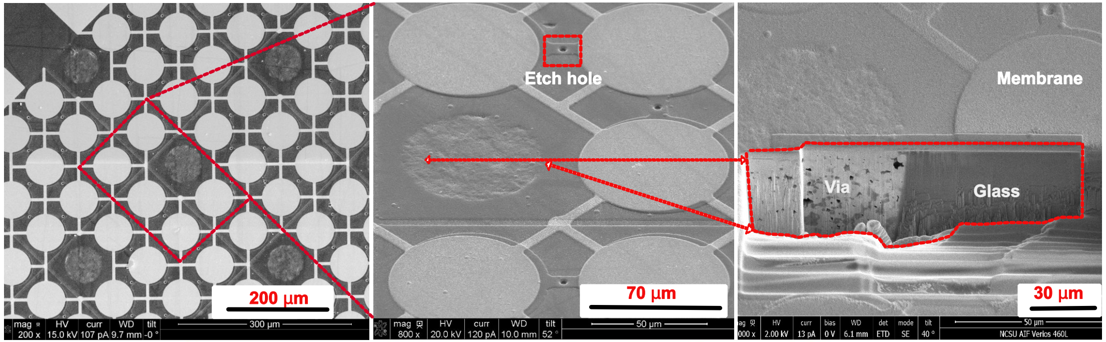


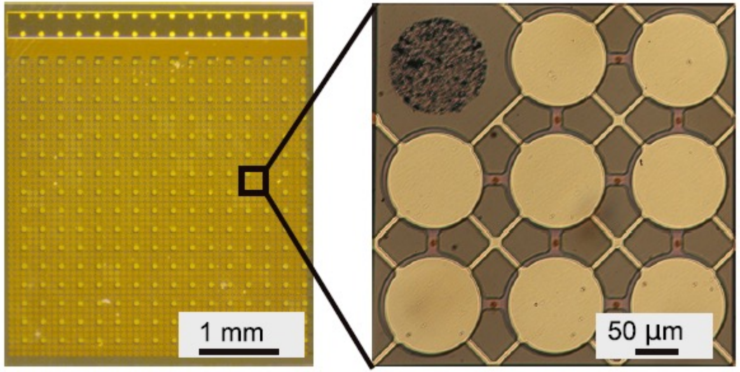
Resistance of a single via including the contact resistance is ~2 Ω

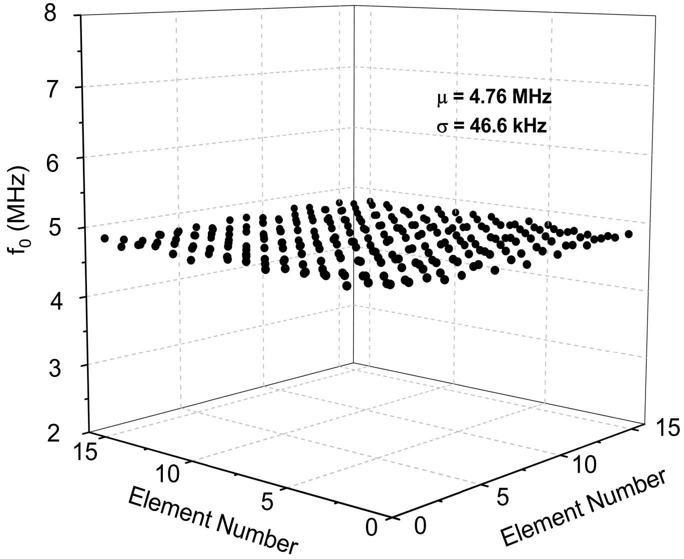


Via-to-via capacitance for a via pitch of 250-μm is 21 fF.

Surface micromachined 2D arrays with TGV interconnects



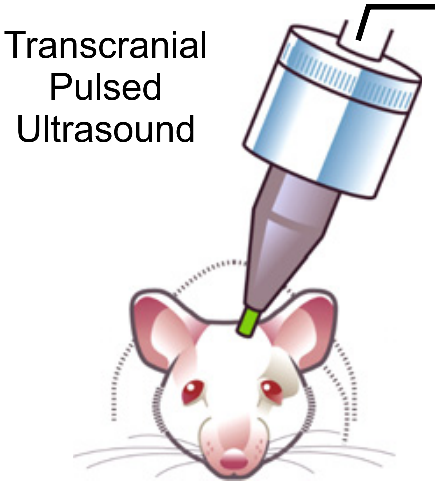




Resonant frequency variation is <1% of the mean

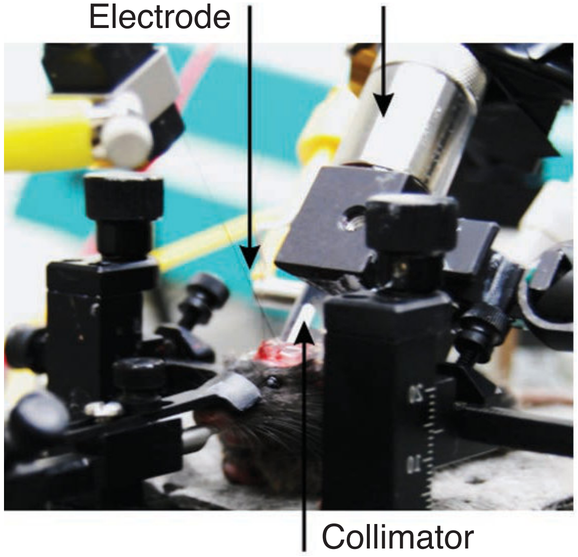
O. J. Adelegan, Z. A. Coutant, X. Zhang, F. Y. Yamaner, and Ö. Oralkan, "Fabrication of 2D capacitive micromachined ultrasonic transducer (CMUT) arrays on alkali-free glass substrates with through-glass-via interconnects using sacrificial release process," *IEEE J. Microelectromech. Syst.*, vol. 29, no. 4, pp. 553-561, Aug. 2020.

Ultrasound is a promising noninvasive technique to stimulate neural activity, and transducers are a key part of the technology



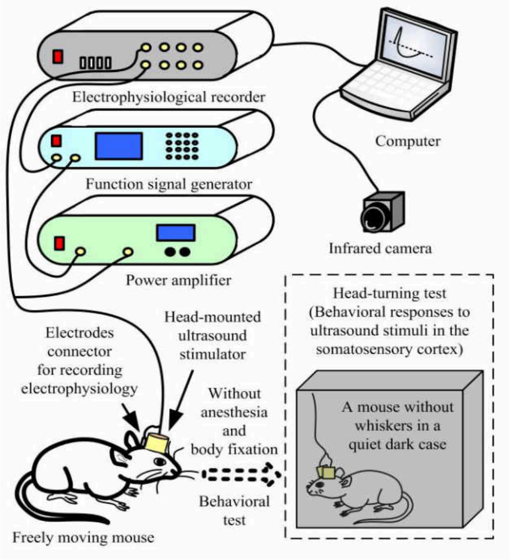
Y. Tufail et al., 2008

Bulky single transducer with fixed focus



Y. Tufail et al., 2011

Experimental animal fixed to a frame and anesthetized



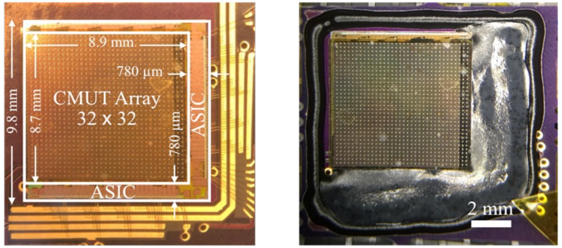
Li et al., 2018

Tethered to external equipment

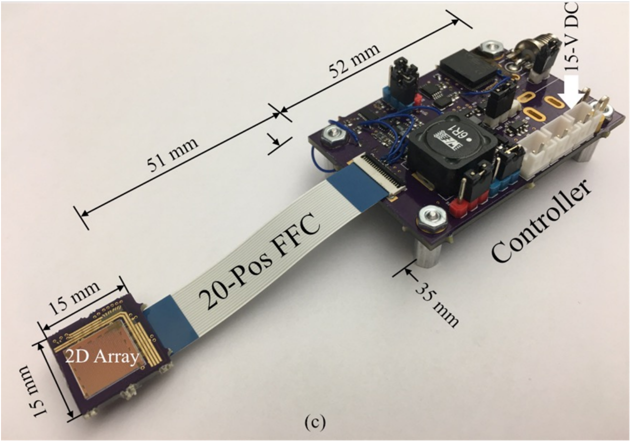
Our proposed system: a wearable, wireless, and dynamically controllable ultrasonic neural stimulator

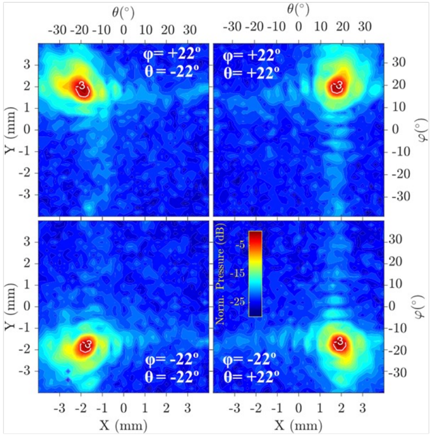
A wearable wireless neural stimulation system

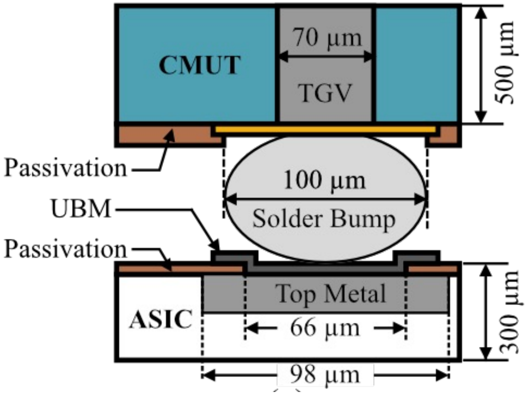
- **Head unit** (light and small): an ultrasonic transducer array on a flexible PCB
- **Backpack unit** (heavier and larger): supporting electronics + a battery on a rigid PCB



(a) (b)



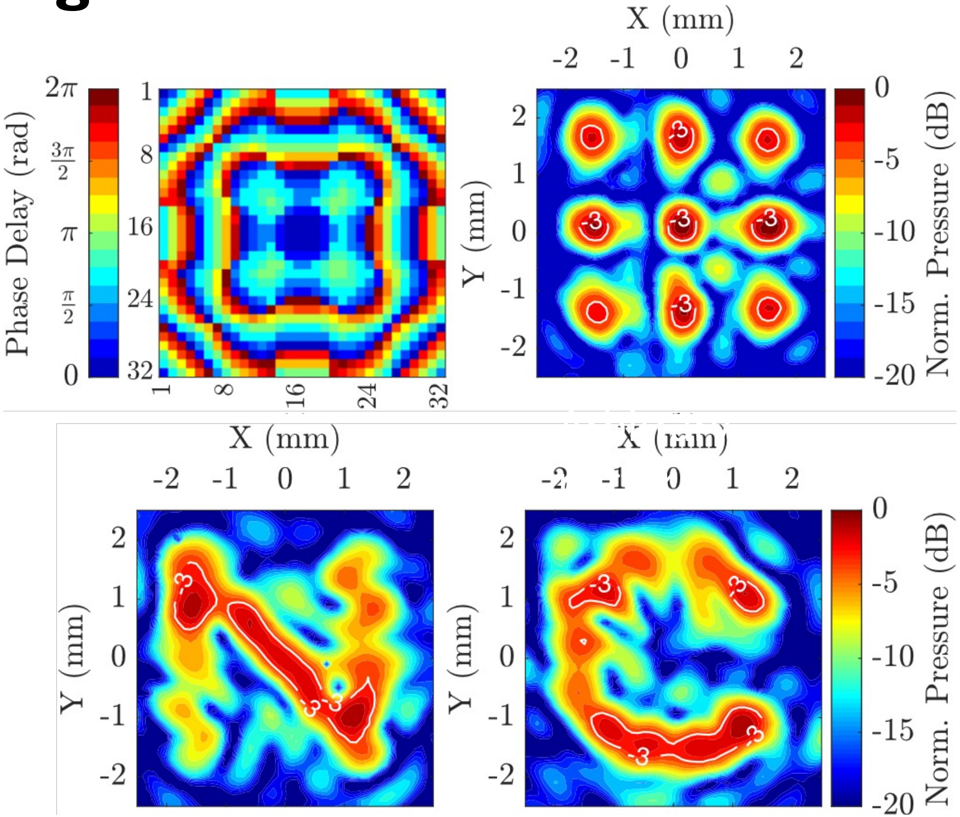




C. Seok, O. J. Adelegan, A. Ö. Biliroglu, F. Y. Yamaner, and Ö. Oralkan, “A wearable ultrasonic neurostimulator – part II: a 2D CMUT phased array system with a flip-ship bonded ASIC,” *IEEE Trans. Biomed. Circuits Syst.*, vol. 15, no. 4, pp. 705-718, Aug. 2021.

2D arrays enable multi-foci projection and arbitrary pattern generation

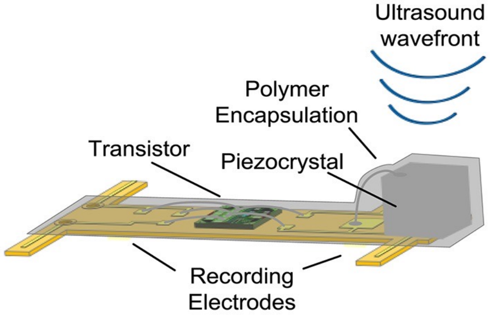
- Weighted Gerchberg–Saxton (GSW) algorithm was used to generate a phase delay pattern
- Projection plane: 5 mm x 5 mm @ Z = 5 mm
- Pixel size is set to 32 x 32 for the sake of simplicity



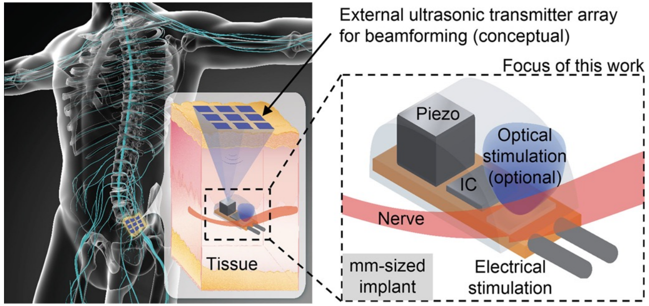
Ultrasound Power Transfer:
Safe, Efficient, Powerful, and Compact

- Ultrasound (e.g., >1 MHz) delivers power to mm-scale devices deep in tissue
- Ultrasonic power for diagnostic purposes has an FDA limit of 7.2 mW/mm^2
- Competing power technologies – radio frequency and inductive coupling have issues with device size, delivery range and/or power density that make them less desirable

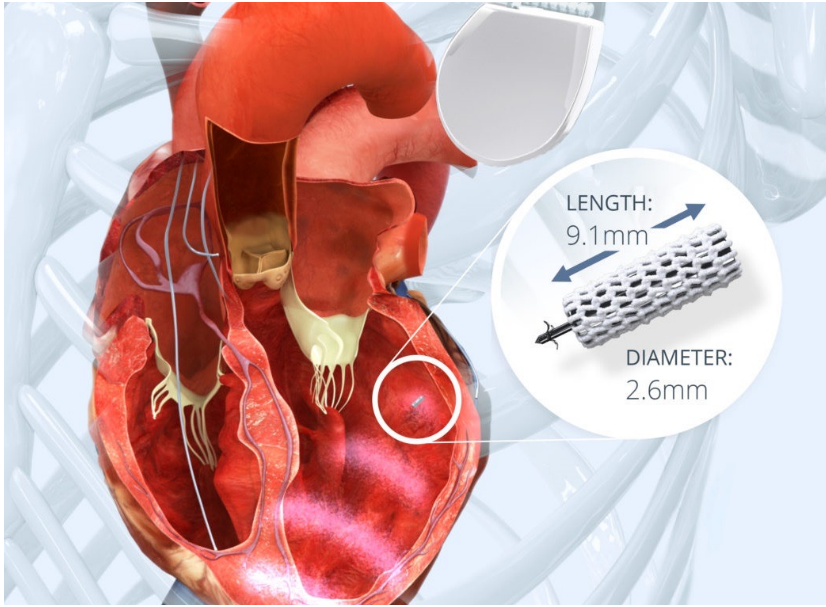
Ultrasonic powered implantables have recently emerged for neural and cardiac applications



D. Seo, "PhD Thesis - Design of Ultrasonic Power Link for Neural Dust,"

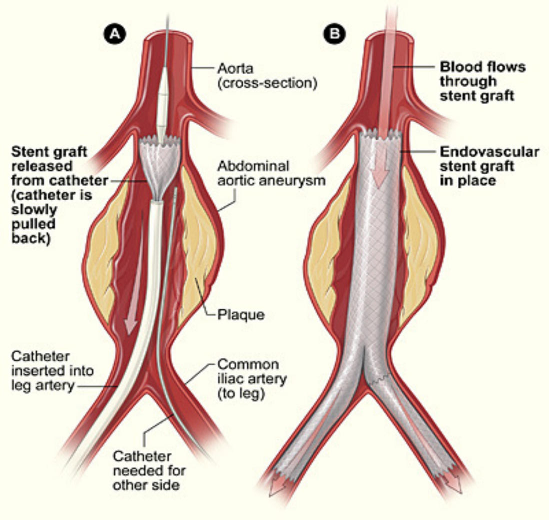


J. Charthad et al.,"A mm-Sized Wireless Implantable Device for Electrical Stimulation of Peripheral Nerves," IEEE T-BioCAS, Apr. 2018.



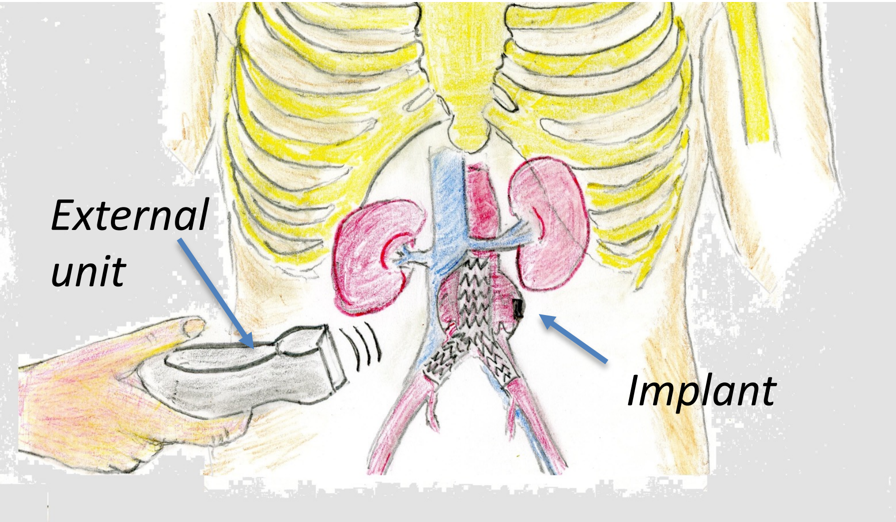
Source: https://cardiacrhythmnews.com/case-report-the-wise-crt-technology-%E2%80%92-a-feasible-and-effective-alternative-to-conventional-crt/

Intravascular monitoring of EVAR using a wireless implantable device could simplify diagnostic procedures & reduce costs for follow-up



EVAR Procedure showing insertion of stent

Source: https://surgery.ucsf.edu/conditions--procedures/endovascular-aneurysm-repair.aspx

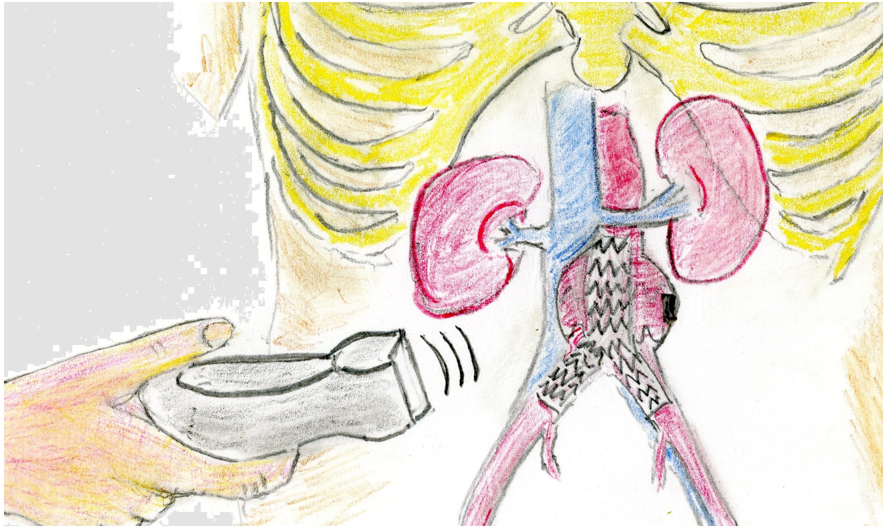


External unit applied to abdomen transmits power to and receives data from the implanted device

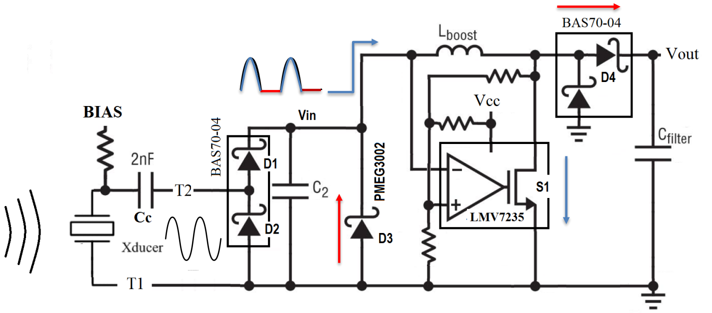
The conventional follow-up diagnostic methods require catheterization and injection of contrast dye while capturing fluoroscopic images to show (continued) perfusion of the aneurysm sack

An ultrasound-enabled implantable device integrated with the EVAR graft for postoperative monitoring

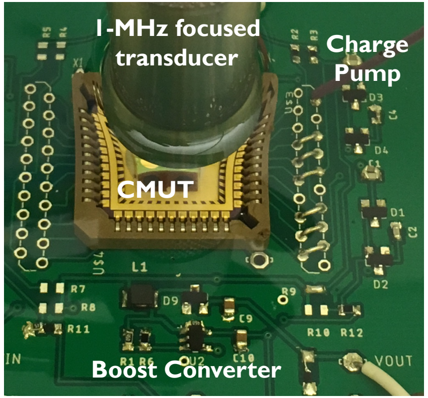
- External unit for power transmission and data reception
- Acoustic power receiver
- Pulse-echo distance measurement and data encoding
- Biphasic acoustic pulsed communication
- Ultra low power operation
- Designed for integration with the EVAR graft



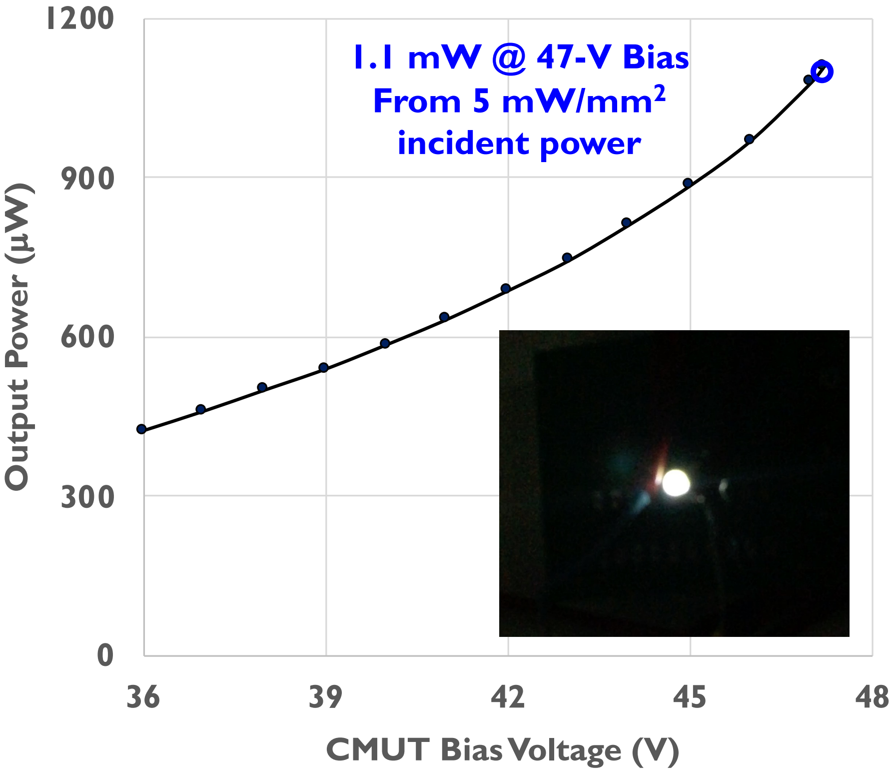
We demonstrated CMUT as a power receiver using a circuit with discrete components



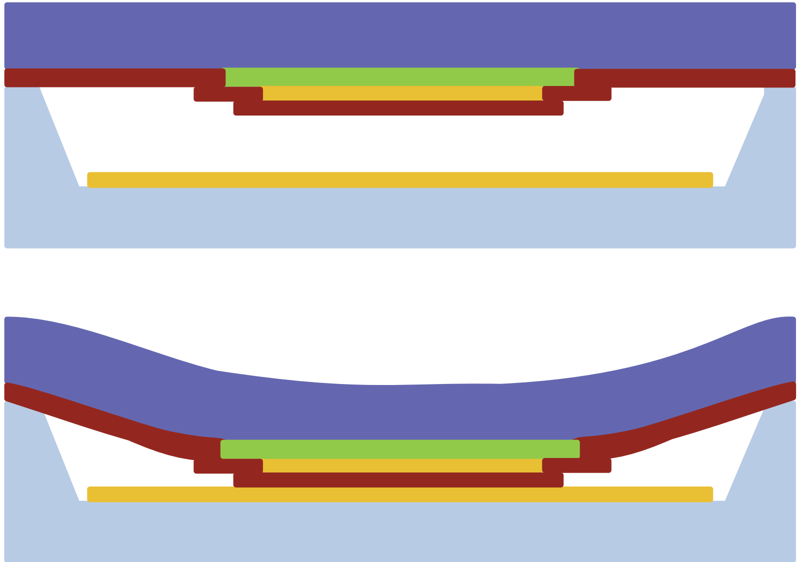
CMUT Device → Charge-Pump Rectifier → Inductive Boost Converter



E. S. Young, F. Y. Yamaner, and Ö. Oralkan, "Ultrasound-based post-endovascular aneurysm repair (EVAR) monitoring device," in *Proc. IEEE Ultrason. Symp.*, 2019.

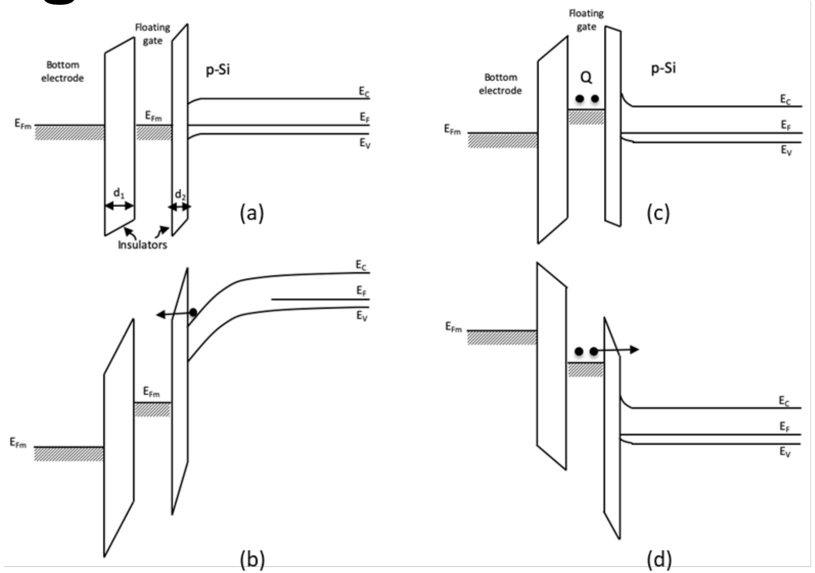


CMUT can be operated in constant-charge mode instead of constant-voltage mode



Pre-Charged CMUTs with release mode and collapse mode

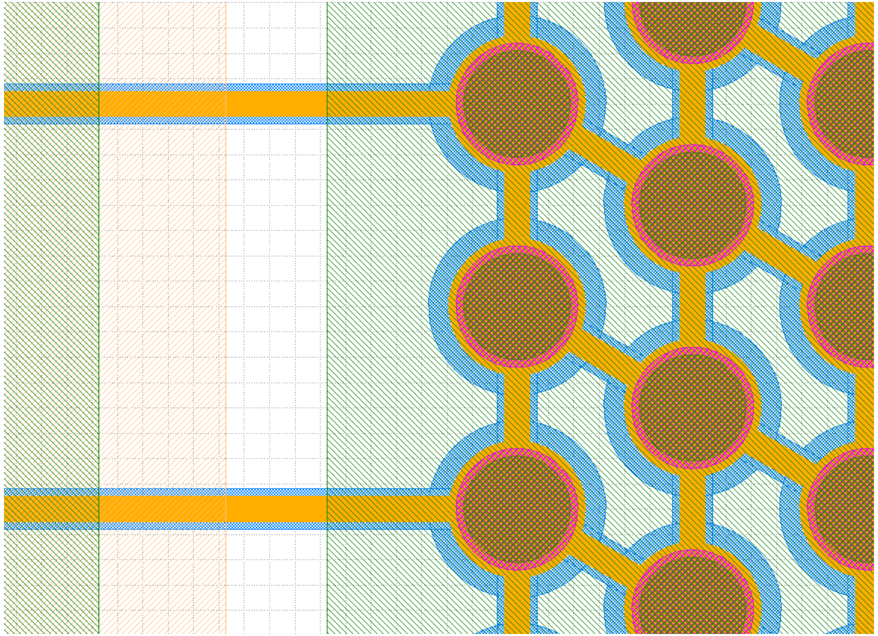
Silicon 🟦
Silicon dioxide 🟩
Chromium/Gold 🟨
Silicon nitride 🟥
Borosilicate Glass ▭

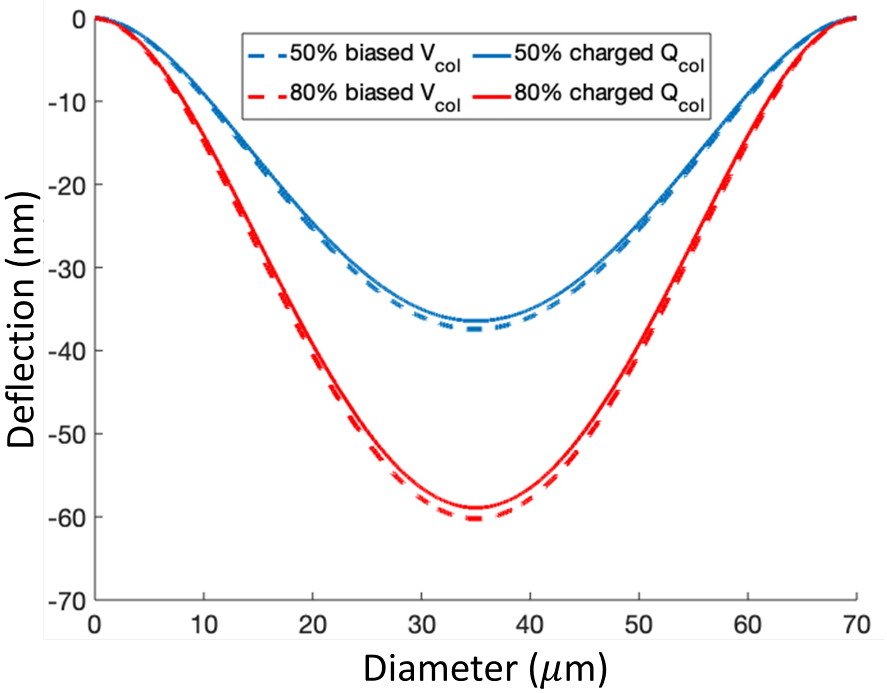


Energy-band diagrams for a CMUTs with metal floating-gate at different stages of charging. (a) Initial stage. (b) Charging by electron tunneling. (c) After charging, the floating-gate having charge Q (negative) is at higher potential (d) Erasing (removing) charges by electron tunneling.

M. Annayev, O. J. Adelegan, F.Y. Yamaner, and Ö. Oralkan, "Design of pre-charged CMUTs with a metal floating gate," in *Proc. IEEE Ultrason. Symp.*, 2021.

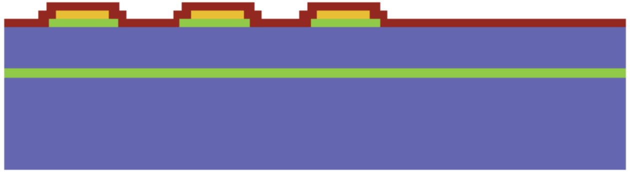
CMUT can be operated in constant-charge mode instead of constant-voltage mode



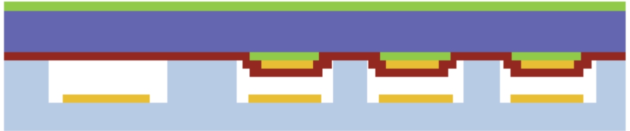


Pre-charged CMUT can be fabricated using the anodic bonding-based process

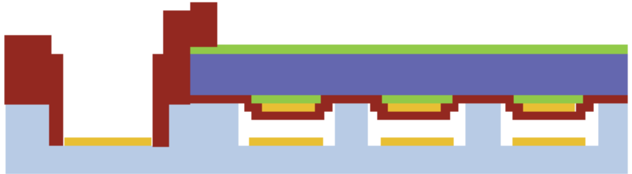
Glass substrate with Cr/Au electrode



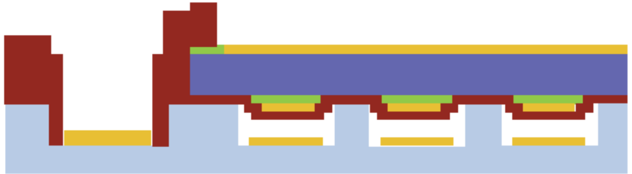
SOI wafer with Cr/Au floating gate



After anodic bonding and handle wafer removal



After opening the pads to reach bottom electrode and sealing with PECVD nitride



After BOX layer removal and deposited top electrode

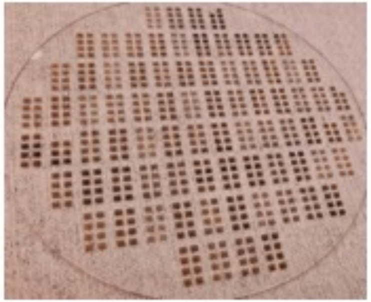
🟦 Silicon

🟩 Silicon dioxide

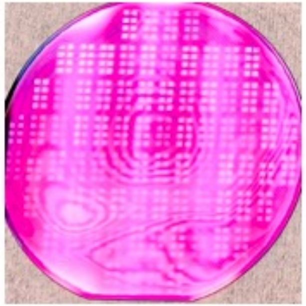
🟨 Chromium/Gold

🟥 Silicon nitride

🟦 Borosilicate glass

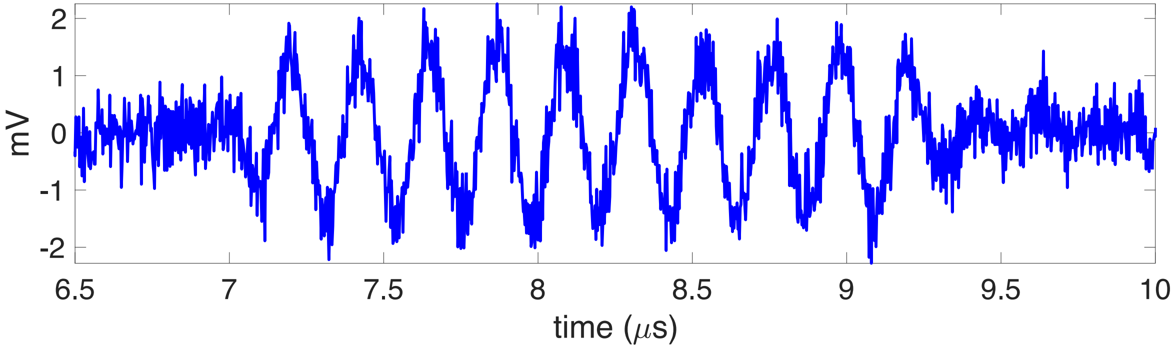


Cavities and bottom electrodes defined on glass

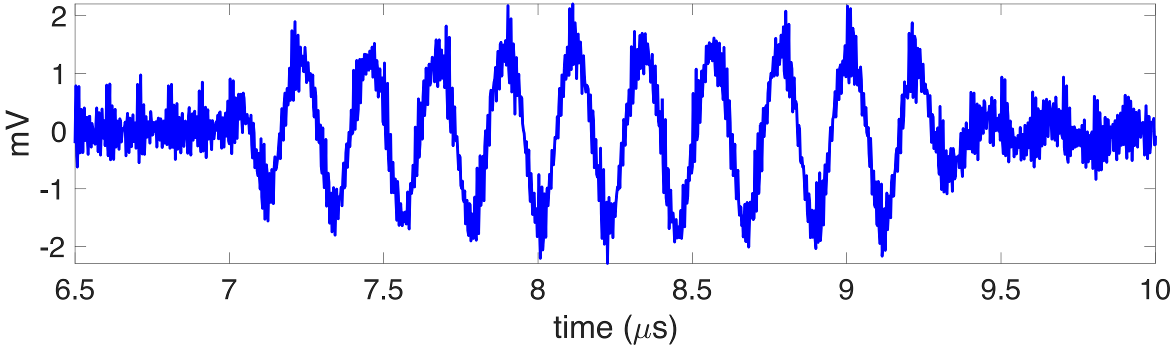


SOI with floating electrodes aligned and bonded on glass

Initial results demonstrate change can be tunneled to the floating electrode



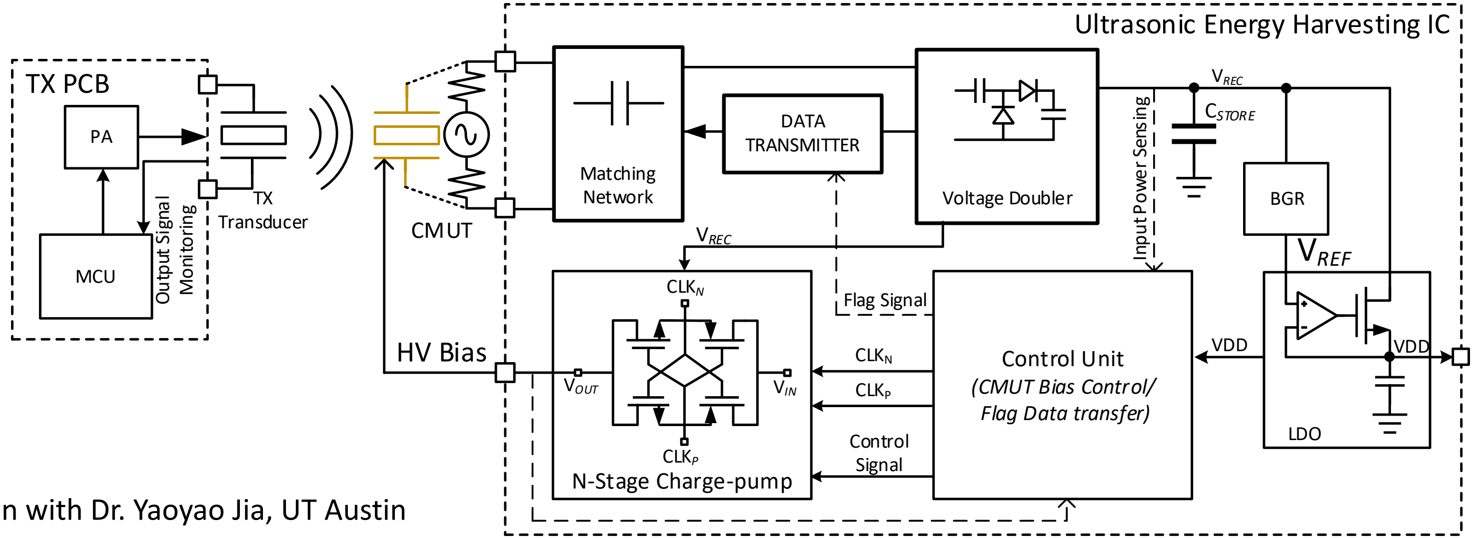
Pulse-Echo biased 25% of collapse voltage



Pulse-Echo Charged (no bias VDC)

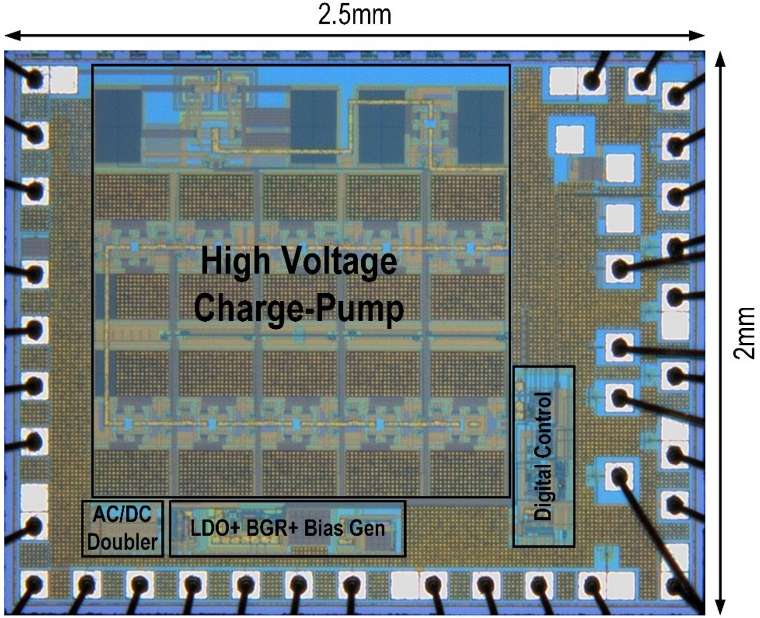
A custom power harvesting interface IC is needed to implement an implantable device

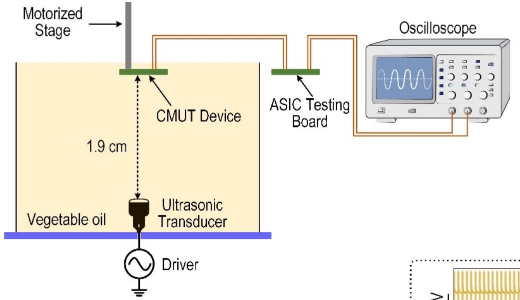
- Block diagram of ultrasonic energy harvesting chip
- Interface with CMUT: harvesting energy and biasing CMUT
- Main circuits: matching circuit, voltage doubler, bandgap, regulator, 12-stage charge pump, control unit
- Output DC bias voltage: 24 V – 60 V

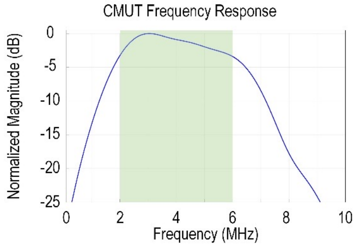


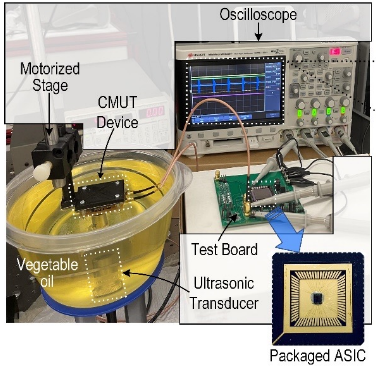
In collaboration with Dr. Yaoyao Jia, UT Austin

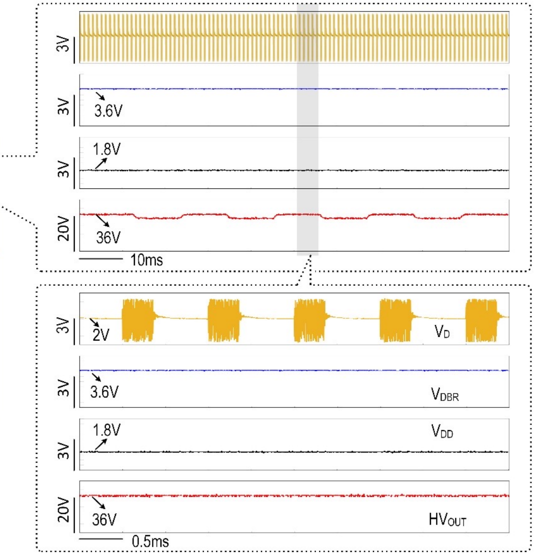
The custom IC is designed and fabricated for interfacing a CMUT for receiving power







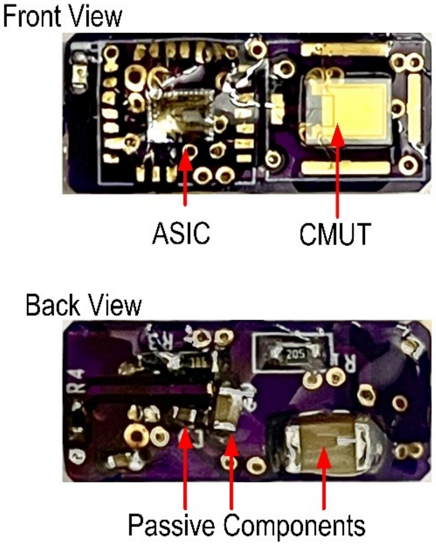


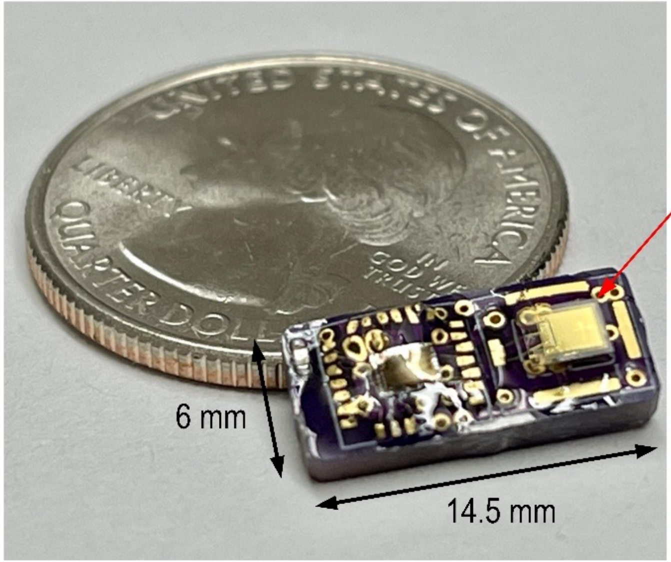


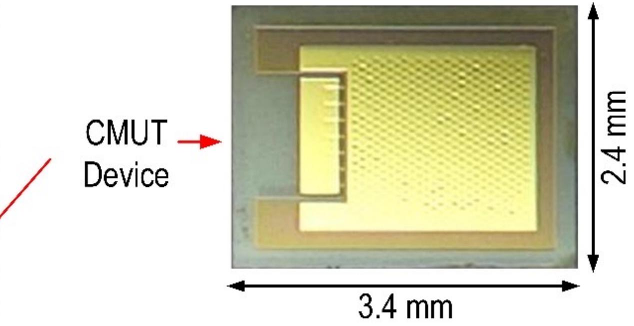
- Chip fabrication process: TSMC 180 nm HV BCD process

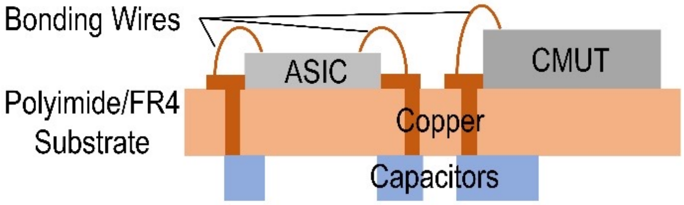
In collaboration with Dr. Yaoyao Jia, UT Austin

A miniaturized integrated prototype is designed





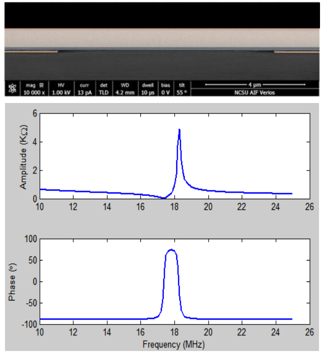




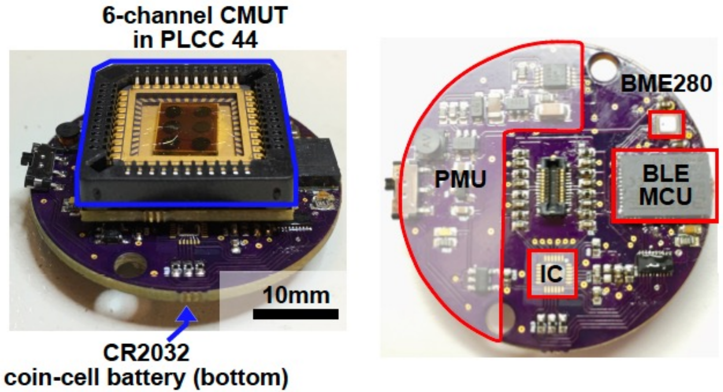
In collaboration with Dr. Yaoyao Jia, UT Austin

Gravitmetric sensing with CMUTs enable wearable low-power environmental sensors

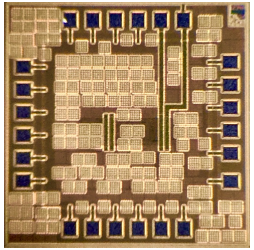
$$\frac{\Delta f}{f} \propto \frac{\Delta m}{m}$$



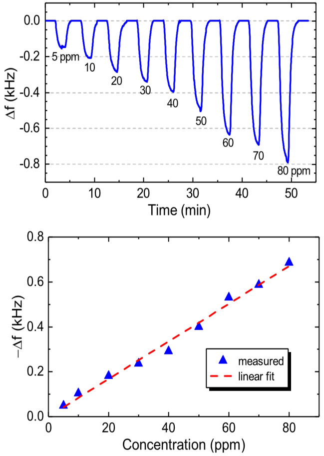
CMUT as a mechanical resonator



Battery-powered wireless sensor unit

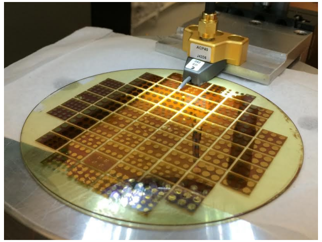


Custom-designed low-power (10-µW) IC

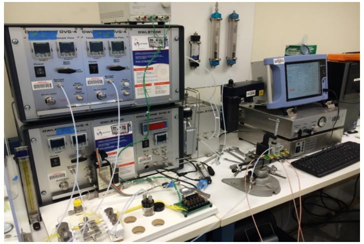


Sensing Ethanol

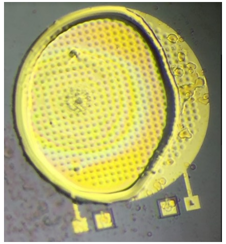
120 ppb/Hz sensitivity
120 ppb LOD for 500-ms gate time



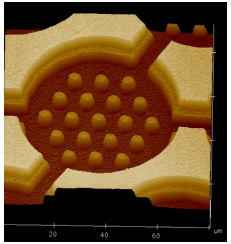
Wafer fabrication



Lab testing



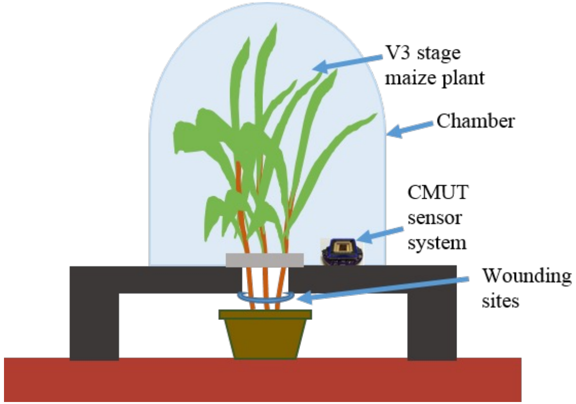
Polymer

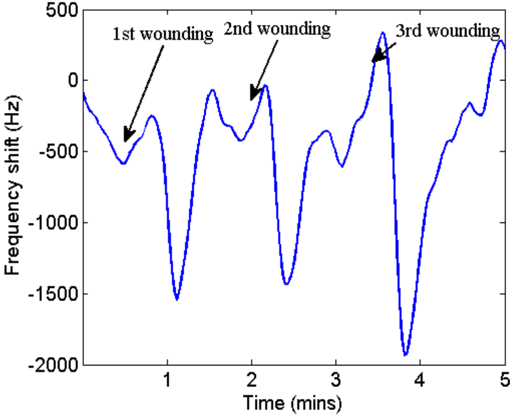


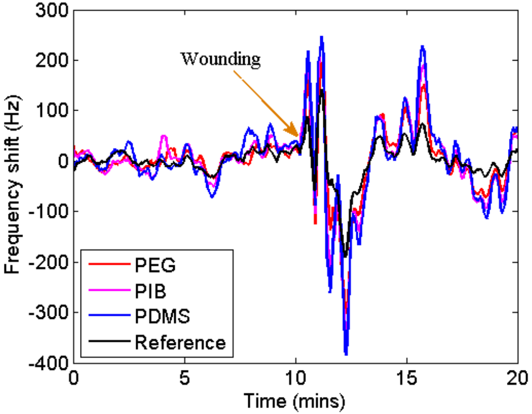
Improved device

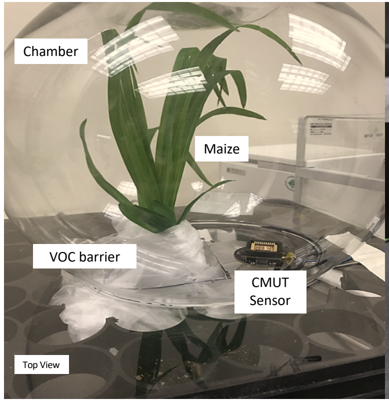
C. Seok, M. M. Mahmud, M. Kumar, O. J. Adelegan, F. Y. Yamaner, and Ö. Oralkan, "A low-power wireless multichannel gas sensing system based on a capacitive micromachined ultrasonic transducer (CMUT) array," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 831 - 843, Feb. 2019.

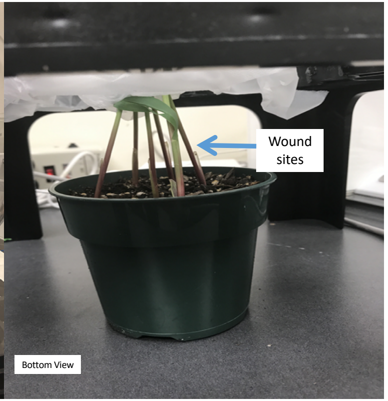
Can this sensor help us communicate with plants?



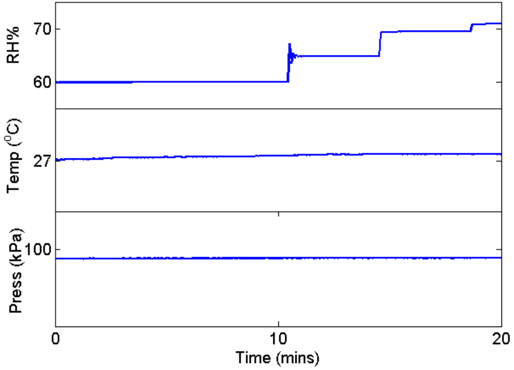




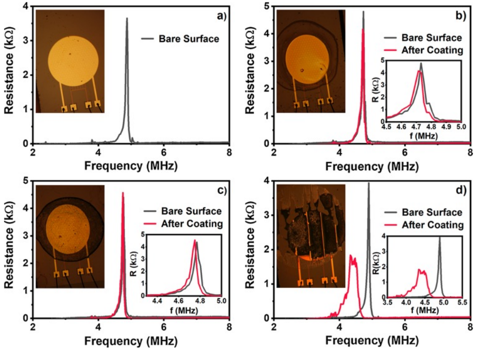


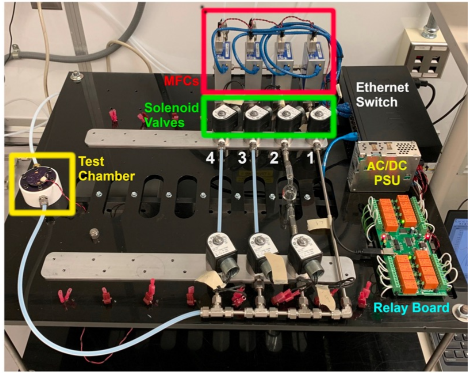


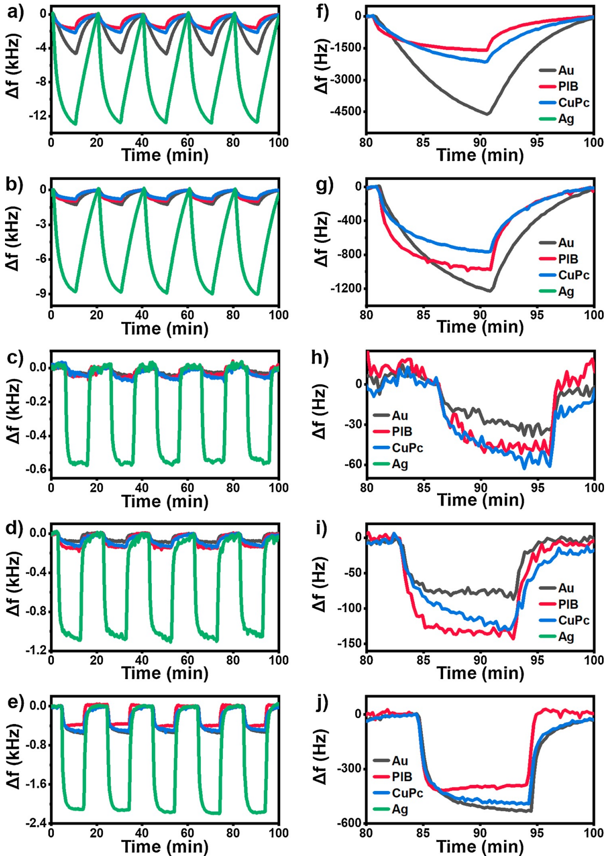
NC State Research Students Help Uncover Sensor Technology

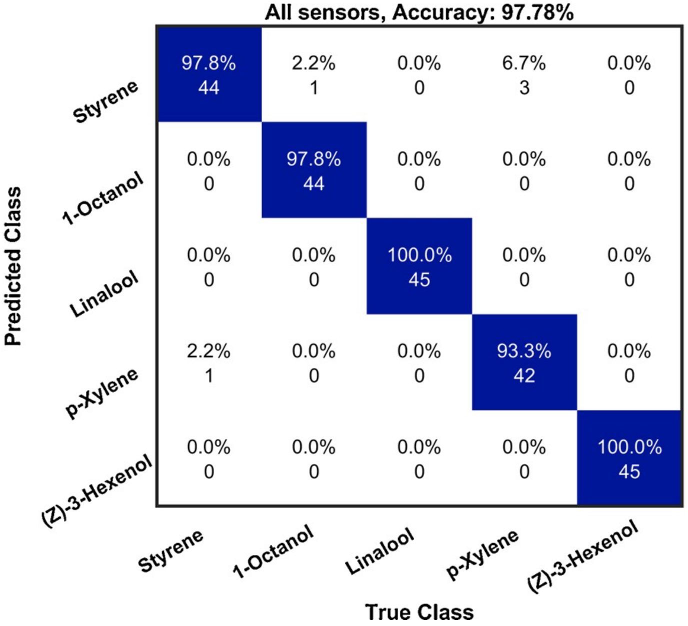


Can this sensor help us communicate with plants?









All sensors, Accuracy: 97.78%

Predicted Class \ True Class	Styrene	1-Octanol	Linalool	p-Xylene	(Z)-3-Hexenol
Styrene	97.8% 44	2.2% 1	0.0% 0	6.7% 3	0.0% 0
1-Octanol	0.0% 0	97.8% 44	0.0% 0	0.0% 0	0.0% 0
Linalool	0.0% 0	0.0% 0	100.0% 45	0.0% 0	0.0% 0
p-Xylene	2.2% 1	0.0% 0	0.0% 0	93.3% 42	0.0% 0
(Z)-3-Hexenol	0.0% 0	0.0% 0	0.0% 0	0.0% 0	100.0% 45

E. Sennik, F. Erden, N. Constantino, Y. Oh, R. A. Dean, and Ö. Oralkan, "Electronic nose system based on a functionalized capacitive micromachined ultrasonic transducer (CMUT) array for selective detection of plant volatiles," *Sens. Actu. B: Chemical*, vol. 341, 130001, 15 Aug. 2021.

Conclusions

- Glass substrate enables CMUTs with reduced parasitics, improved optical transparency, and reduced process complexity.
- Hybrid integration of CMUT arrays with supporting electronic circuits enable ultrasonic microsystems for novel applications.
- These ultrasonic microsystems in implanted, wearable, or distributed settings need energy harvesting.
- Ultrasound is an attractive modality to power up electronics in implantable devices.