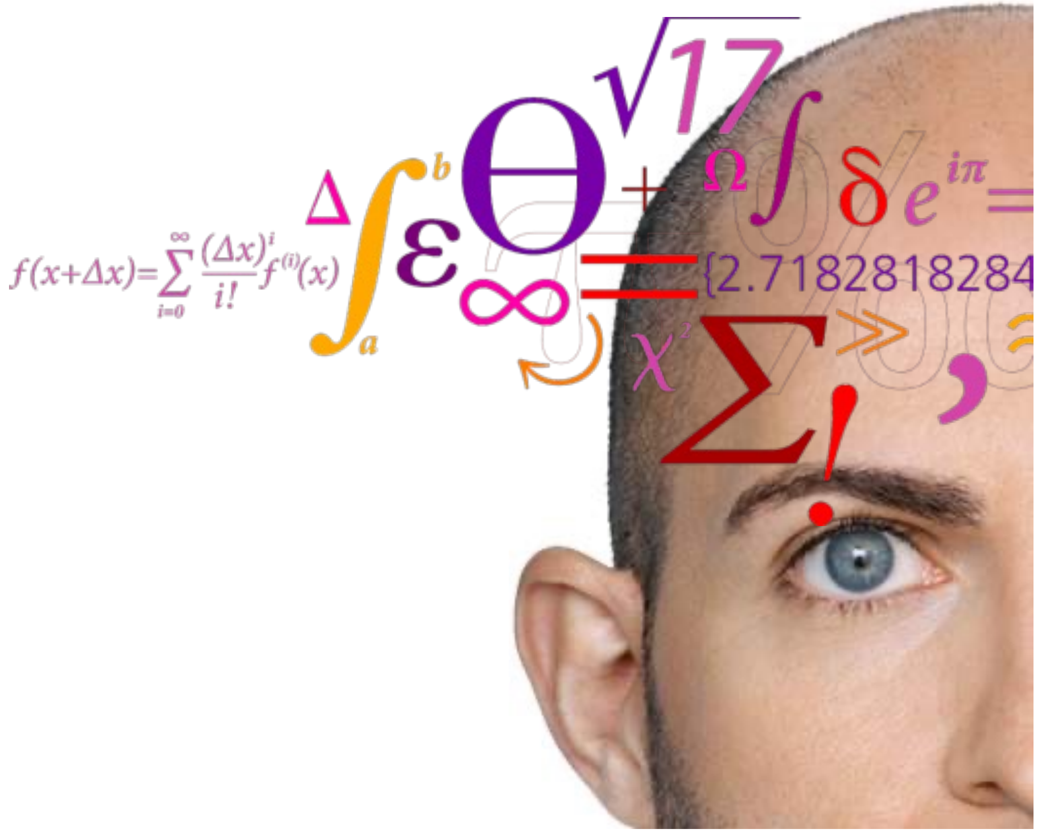
Transducers for Medical Imaging

Erik V. Thomsen



Agenda

- The probe
- The PZT transducer
- The CMUT transducer
  - Introduction
  - Design
  - Fabrication
  - Use
- Conclusions
- Problem solving: Design your transducer!

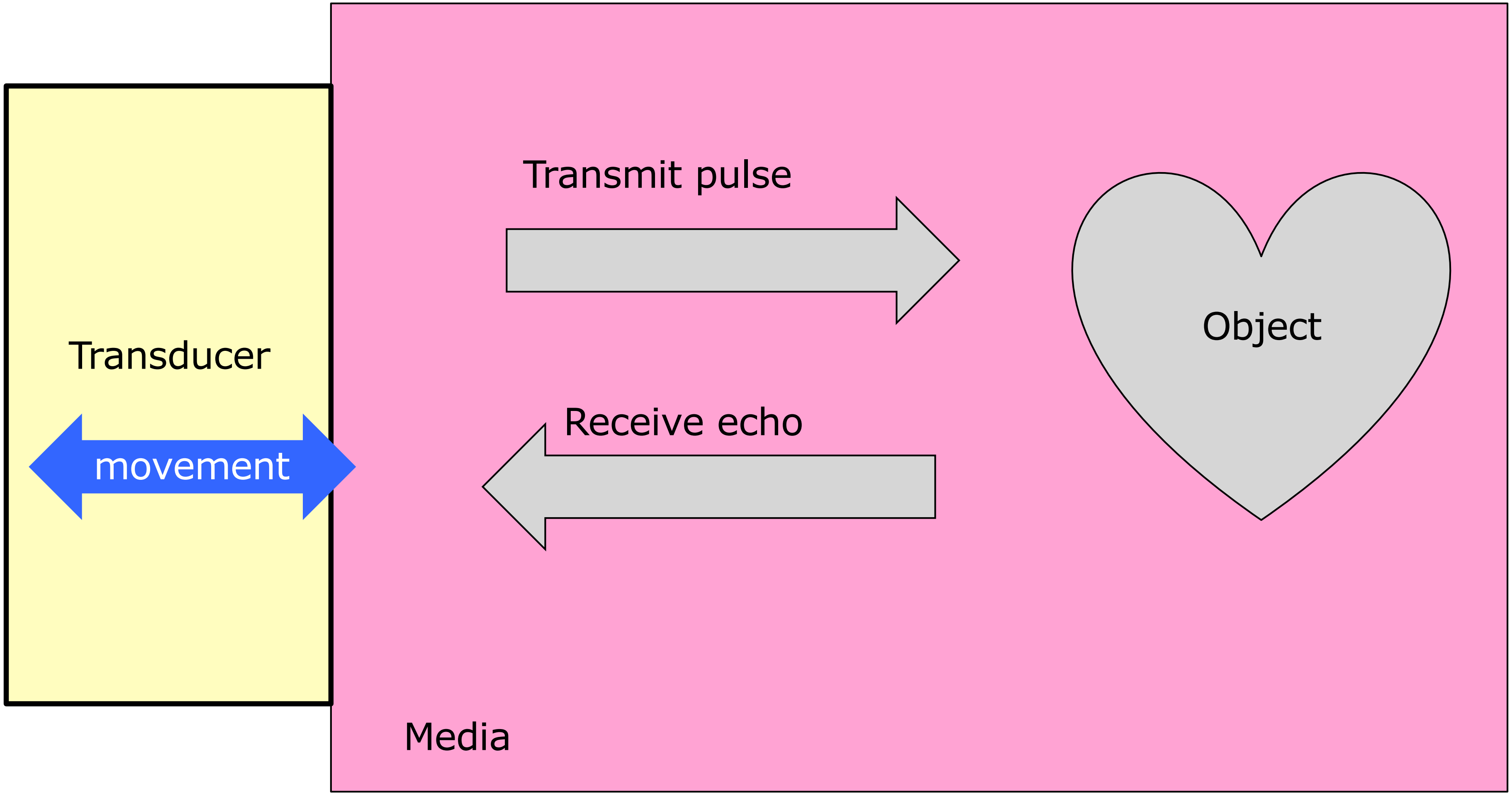
How does the probe work?

1D PZT probe

2D CMUT probe

Transduction

Transmit and receive with the same transducer



Transduction

Transmit → Electrical signal → Mechanical displacement → Presure in media → Pulse

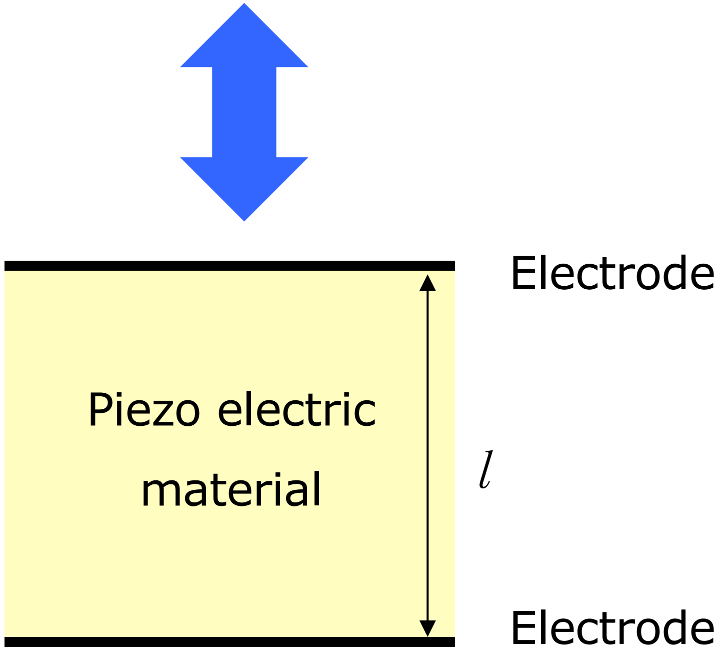
How can we create mechanical movement?

Receive ← Electrical signal ← Mechanical displacement ← Pressure in media ← Echo

Transducer principles: PZT & CMUT

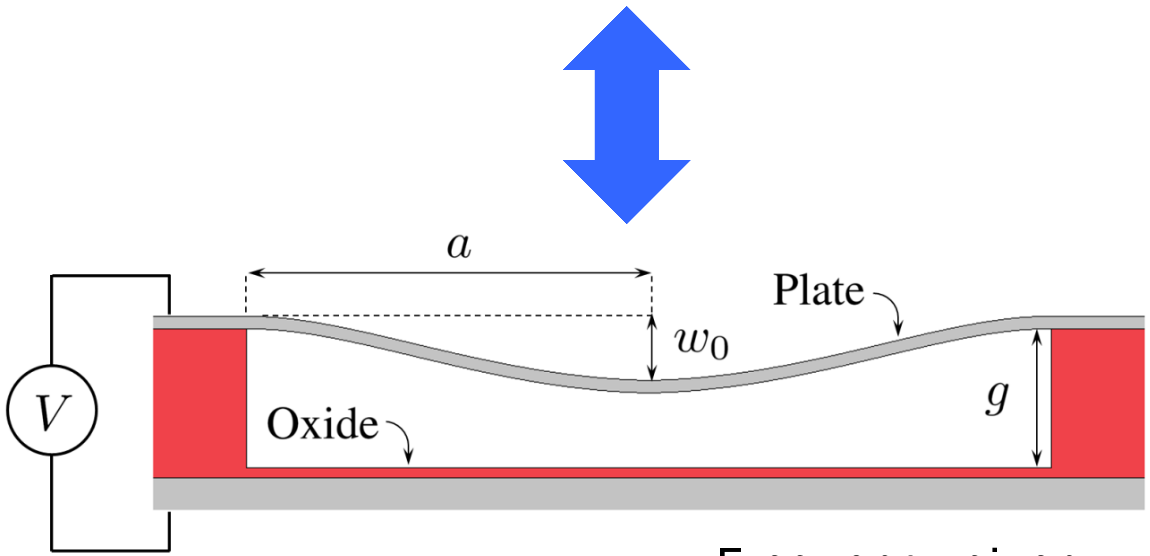
How can we create mechanical movement?

Same transducer for send & receive!



Piezo electric

Frequency given by thickness, l, (and boundary conditions)



CMUT: Capacitive

Micromachined Ultrasonic Transducers

Frequency given by thickness and radius

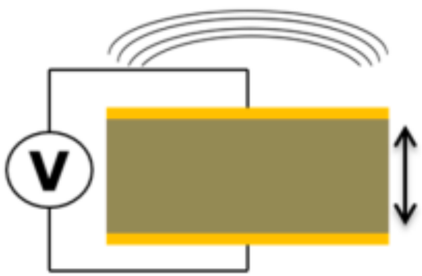
CMUT's: Pros and cons

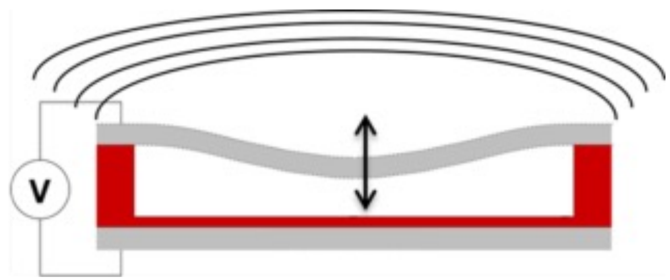
Piezoelectric transducers

- Conventional technology – well known
- Elements defined mechanically
  - Limited design flexibility
  - Size limitation 20 µm
- High mechanical impedance
  - $Z_{media.} < Z_{mech.}$
  - Need impedance matching layers
- Narrow bandwidth, <100%
- High pressure
- Difficult direct integration with CMOS
- Contains lead

CMUTs

- New technology – not as mature
- Elements defined by photolithography
  - Large design flexibility (different elements in TX & RX, lateral flexibility)
  - Size limitation 1 µm
- Very low plate mechanical impedance
  - $Z_{media.} \gg Z_{mech.}$
  - No need for impedance matching
- Wide bandwidth, >100% ➔ Improved axial resolution
- Pressure-bandwidth trade off
- Integration capability with silicon CMOS
- Lead free
- Potential for low cost (& high yield)
- Do not heat up -> coded excitation





CMUT's have been promising for 30 years

Still - few products on the marked

The PZT transducer rules the game

(today)

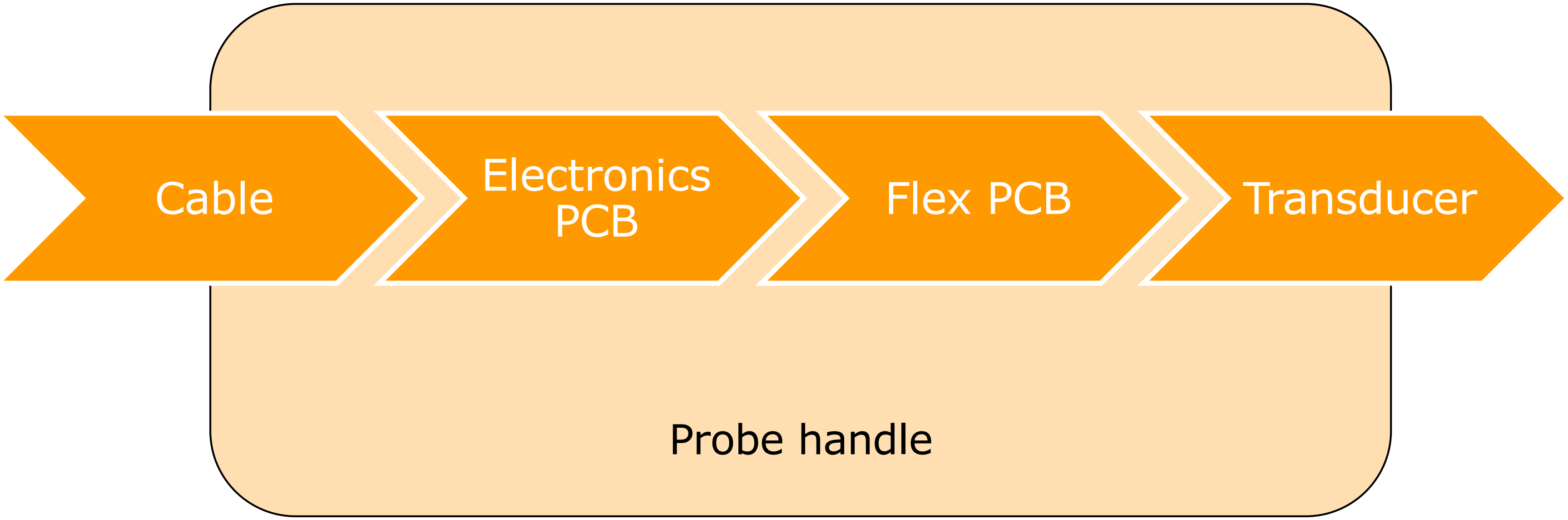
might change

(tomorrow?)

What's inside a probe?

Example: 2D CMUT probe

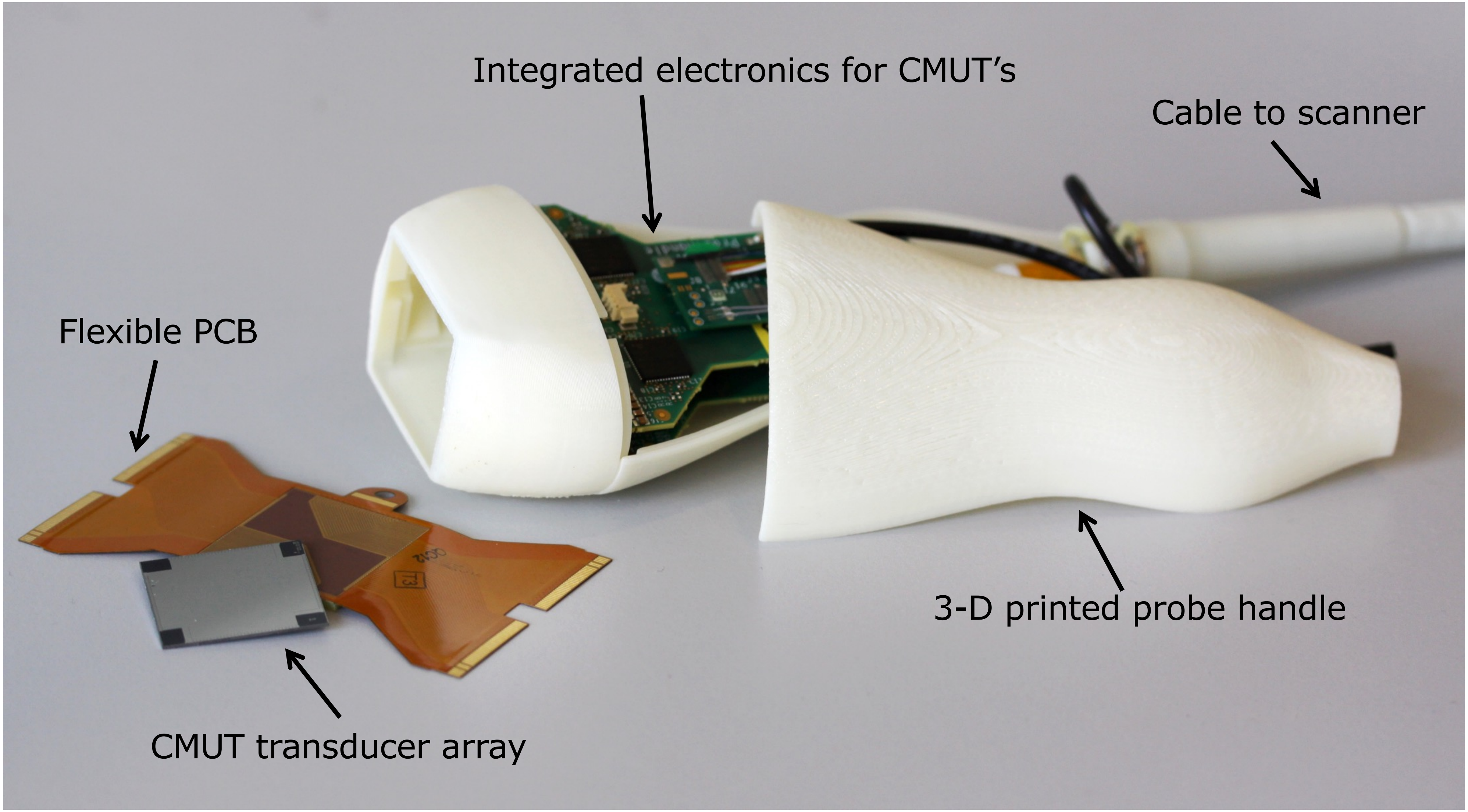
Assembly principle



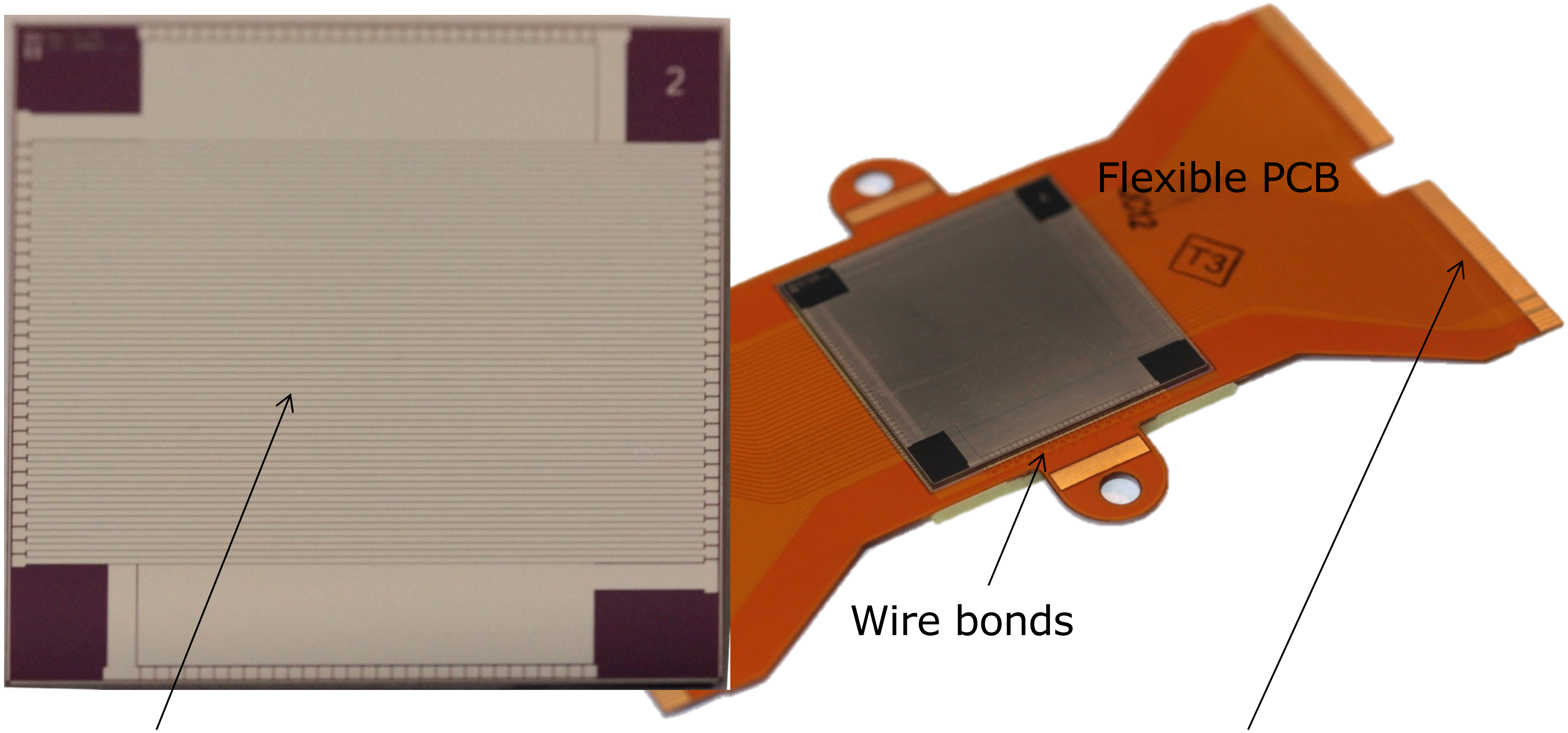
PCB = Printed Circuit Board

Flex: Flexible

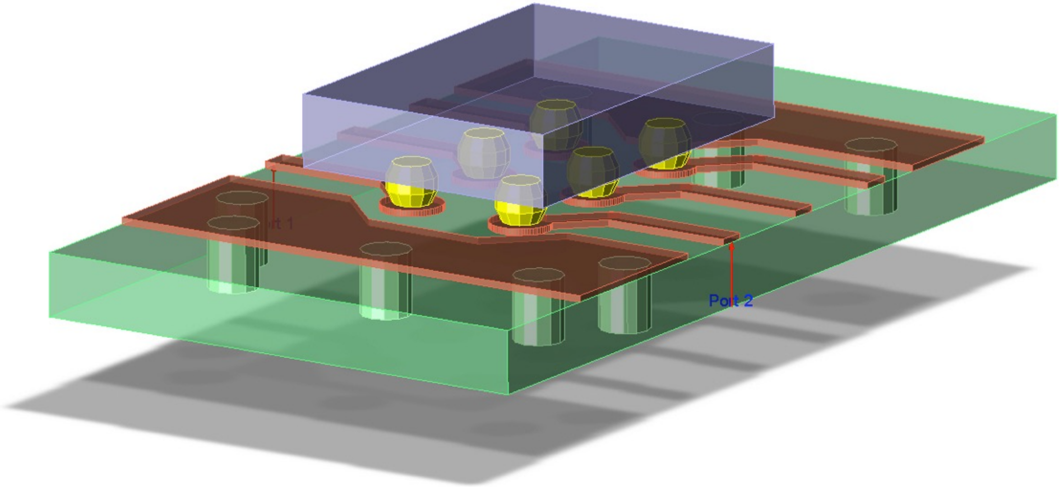
Example: 2D CMUT Probe assembly

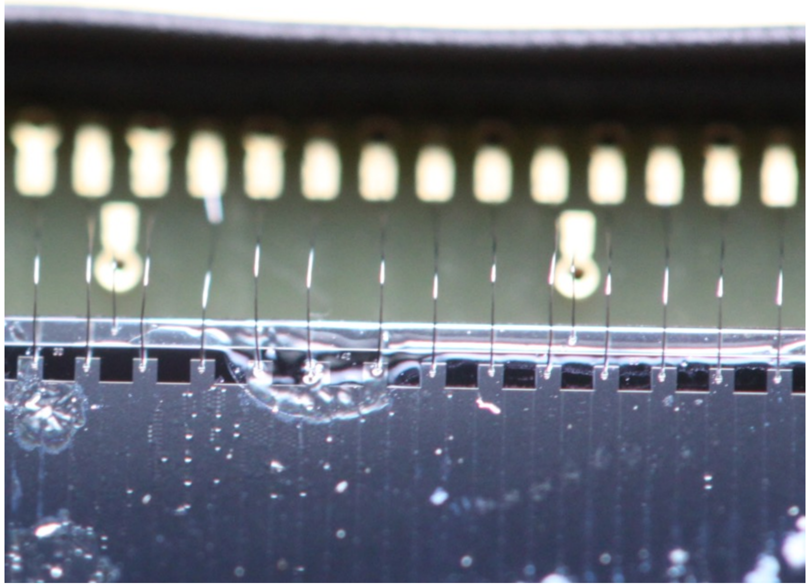


Probe Assembly – Flexible PCB



Interconnect technology





Flip-chip:

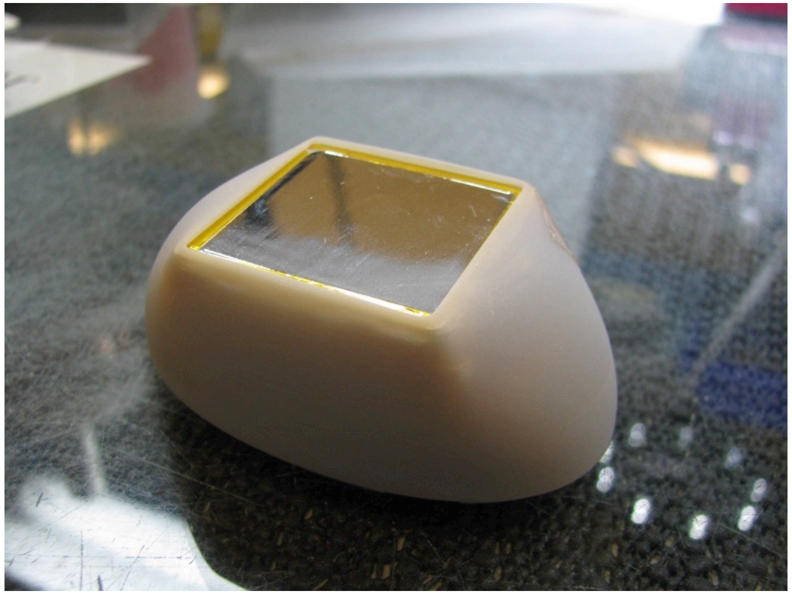
Transducer mounted to PCB using solder bumps

Wire bonding:

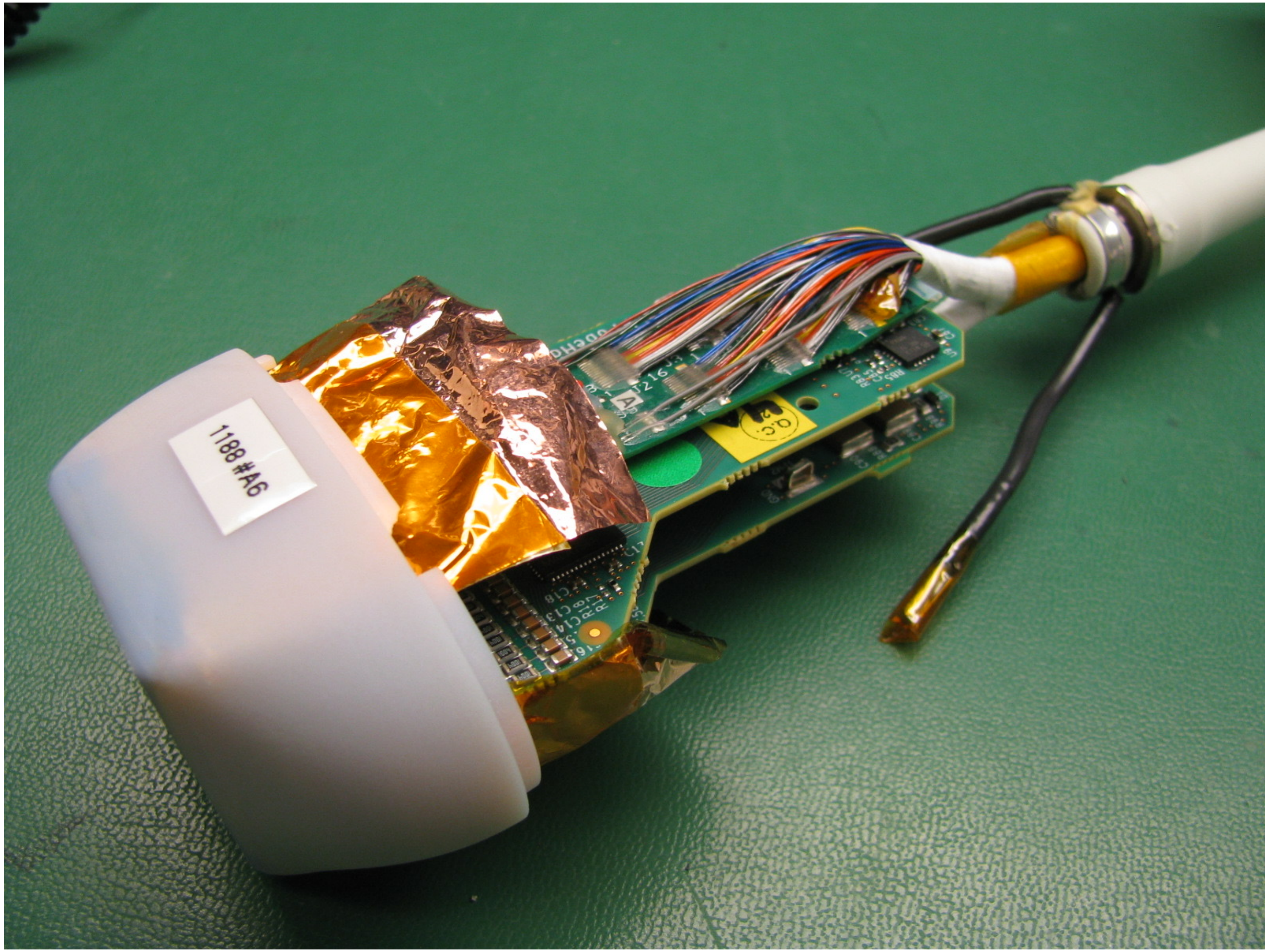
Transducer mounted to PCB using thin (ø20 µm) wires

Probe Assembly – Nose piece

- Transducer array mounted in nose piece with grounded shielding layer
- Polymer coating for physical and electrical insulation

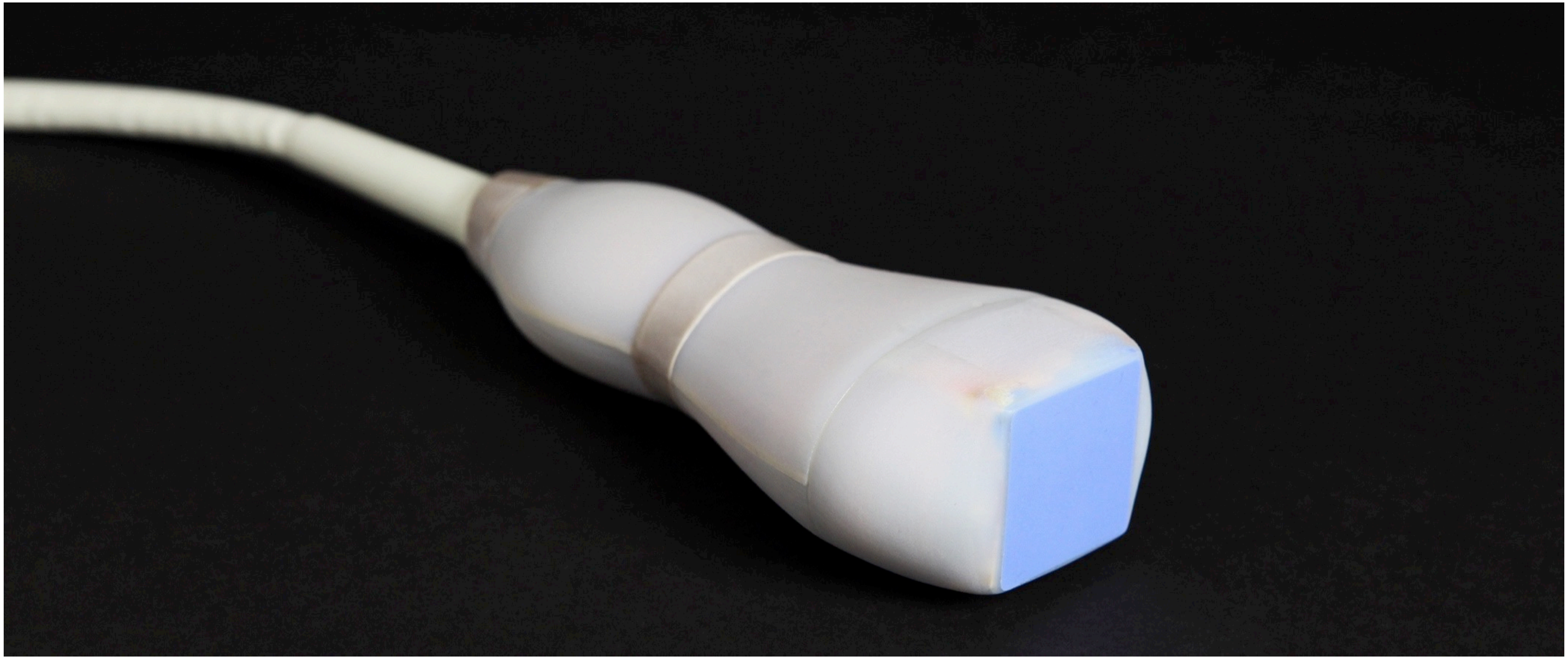


Probe Assembly –
Attach to electronics and cable

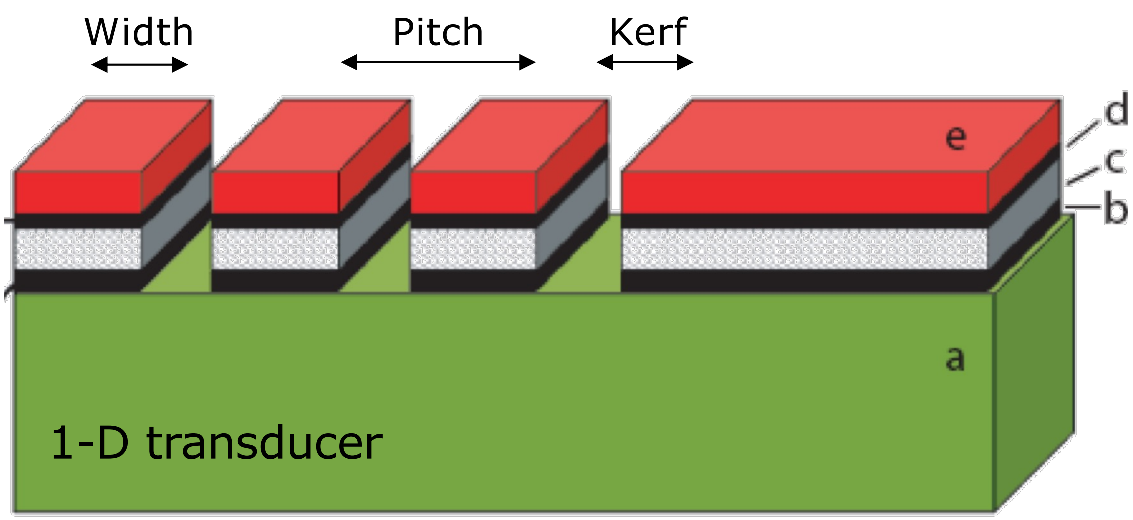


Probe Assembly – PCB shielding

Probe Assembly – Finished Probe

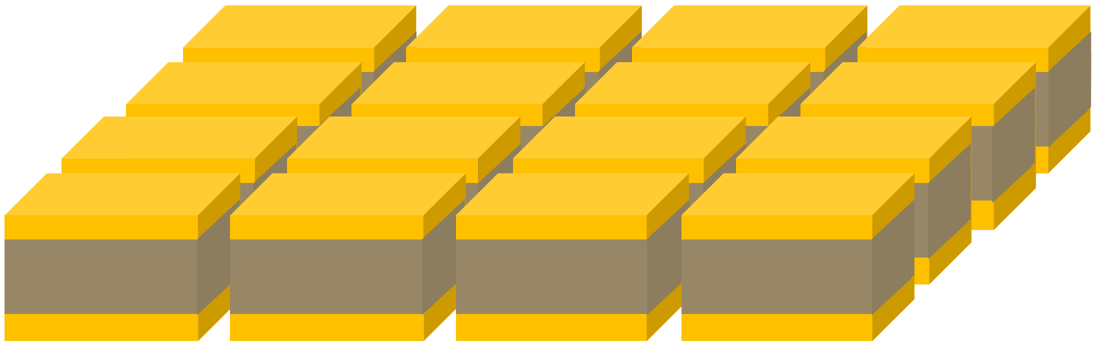


Array based transducers



Width = pitch – kerf

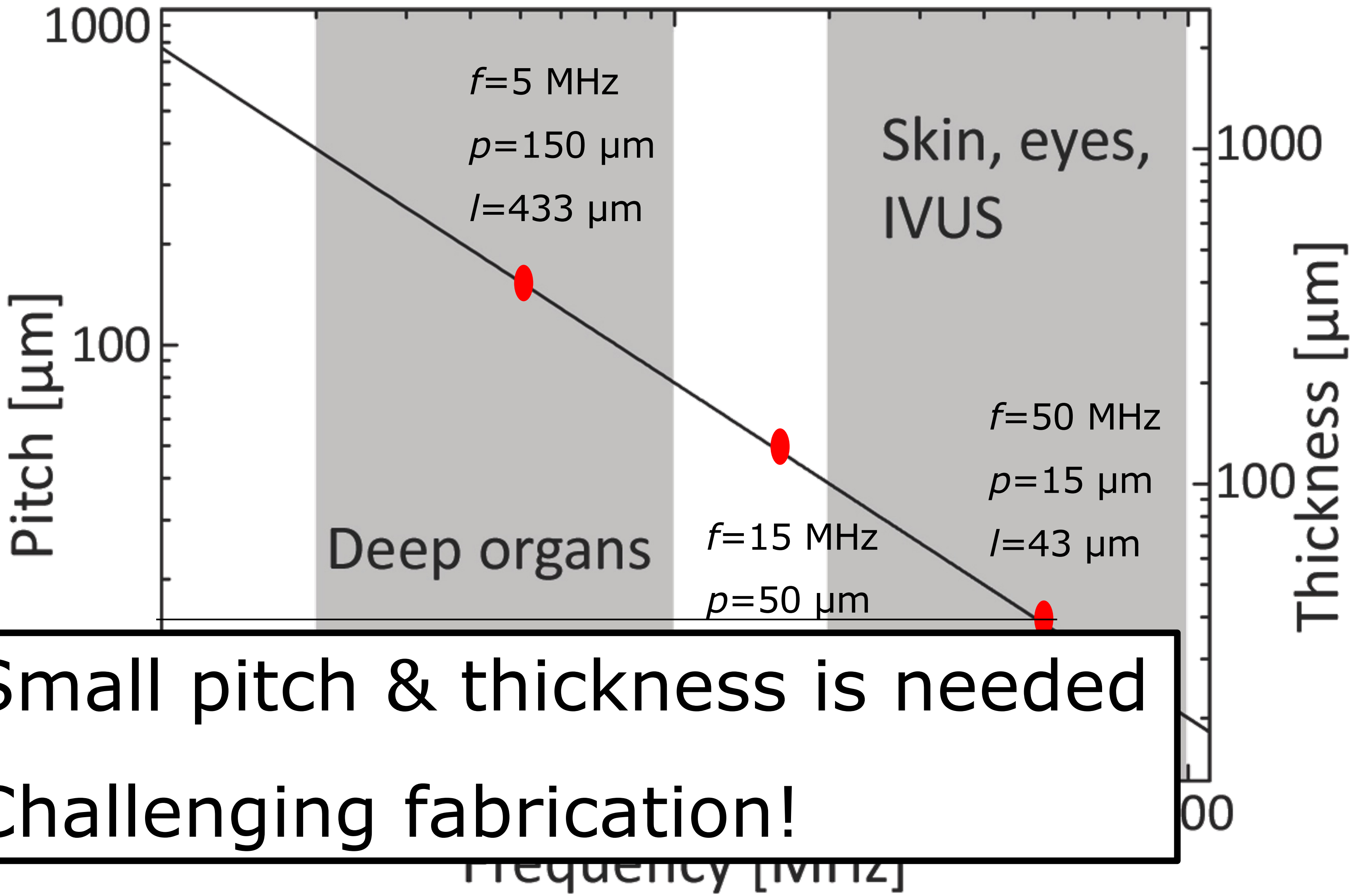
Fill factor = width/pitch



2-D transducer

PZT transducer dimensions

For arrays: Pitch must be λ/2 to avoid grating lobes!



Small pitch & thickness is needed

Challenging fabrication!

Fabrication technologies

How to pattern ***lateral*** structures in the micrometer range?

- Fine mechanics > 25 μm
- Micro mechanics > 1 μm
- Nano technology < 1 μm

Mechanical shaping:

Grinding, dicing & polishing

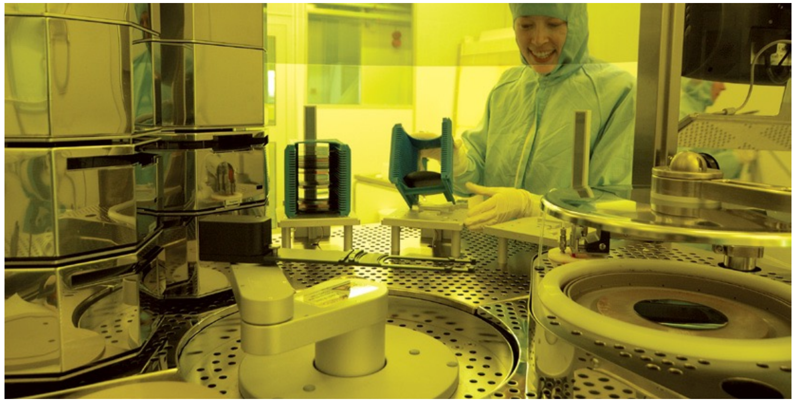
Silicon based

micro fabrication:

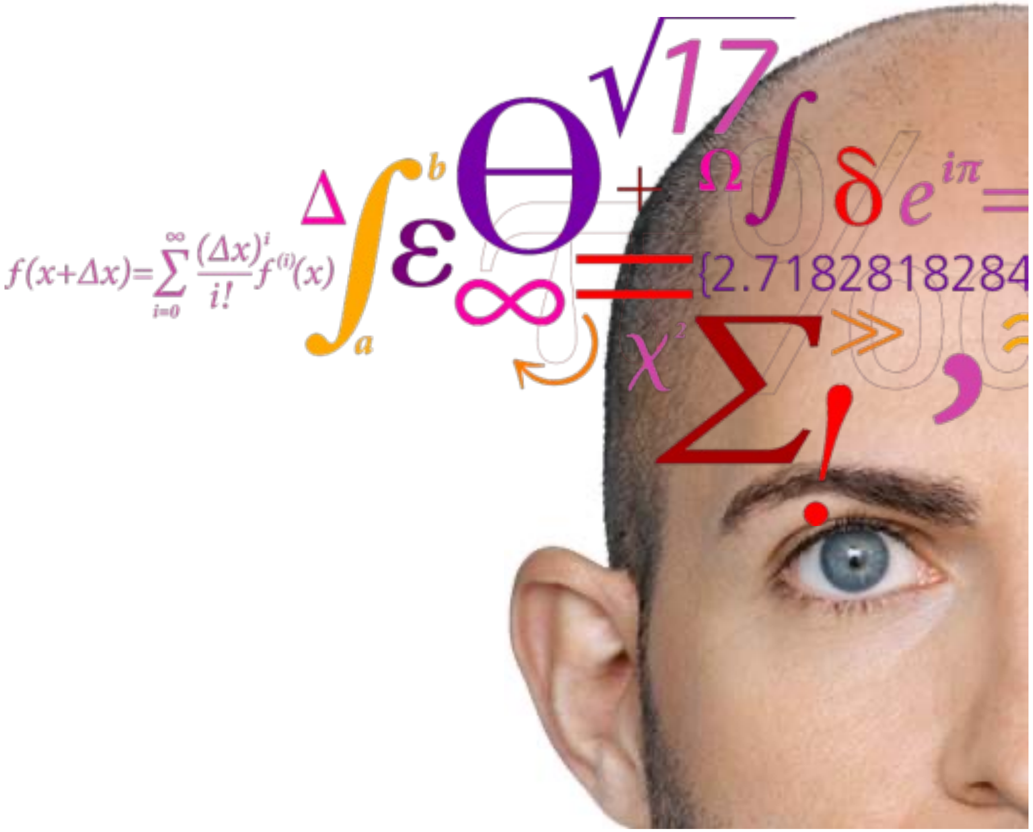
Lithography

Deposition

Etching



The PZT transducer



Conventional 1D PZT transducer array

a) Backing layer (reduce ringing)
b) Bottom electrode
c) Each element is a piezoelectric block
d) Top electrode
e) Matching layers (high to low acoustic impedance)

Thickness mode

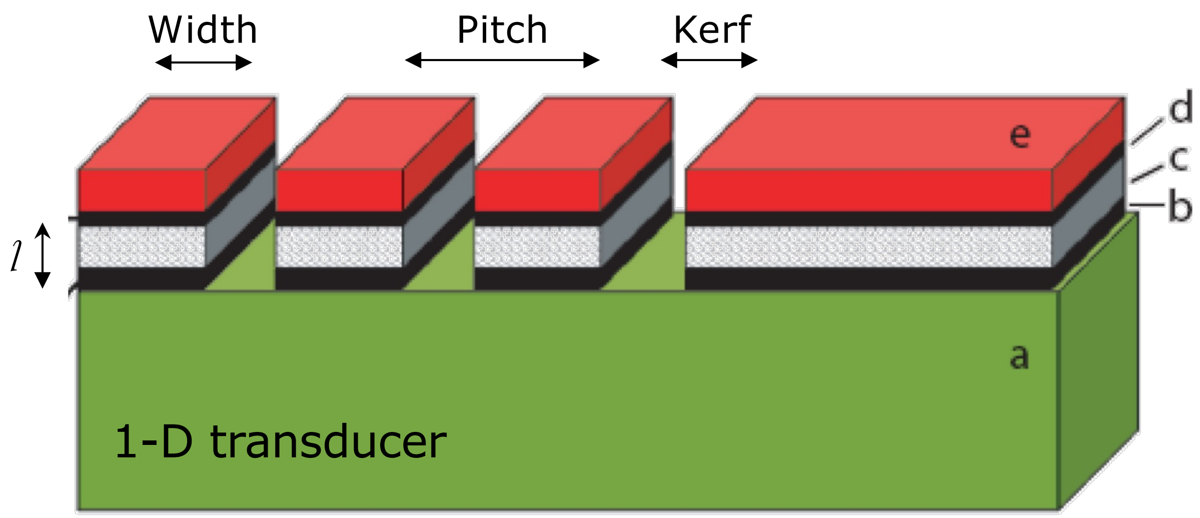
Frequency: $f = \frac{c_{piezo}}{2l}$

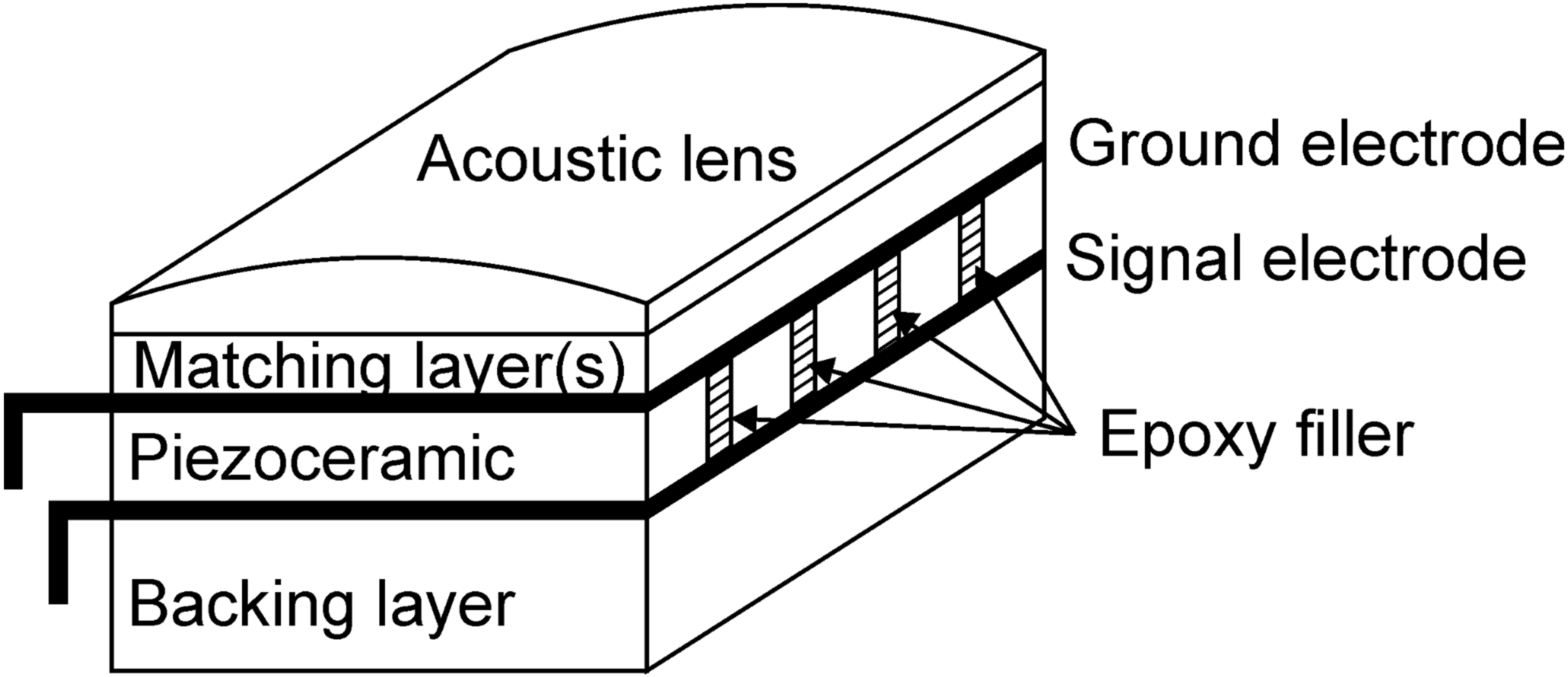
c_{piezo} is sound velocity in PZT (4330 m/s)

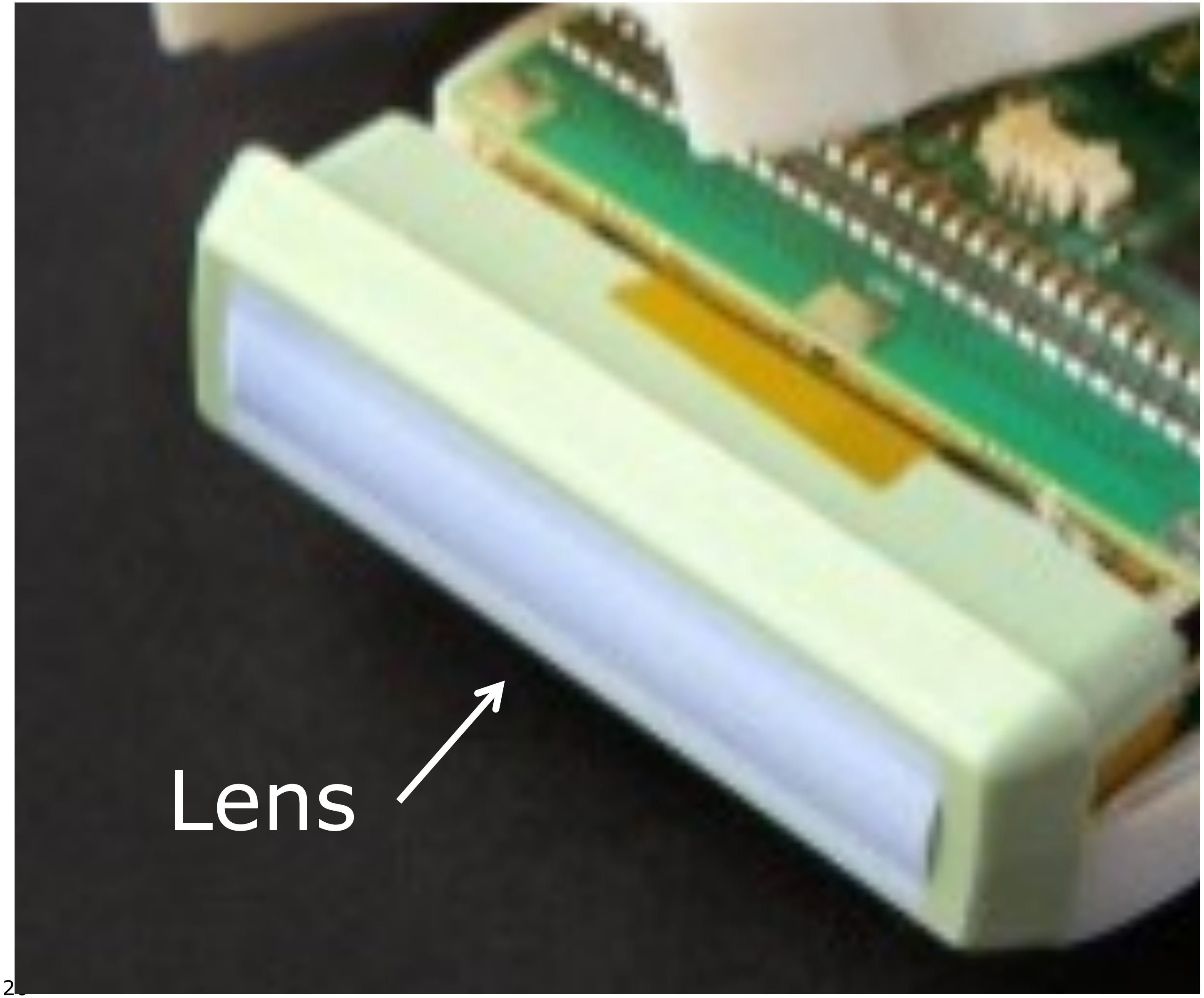
l is piezo element thickness

Width = pitch – kerf

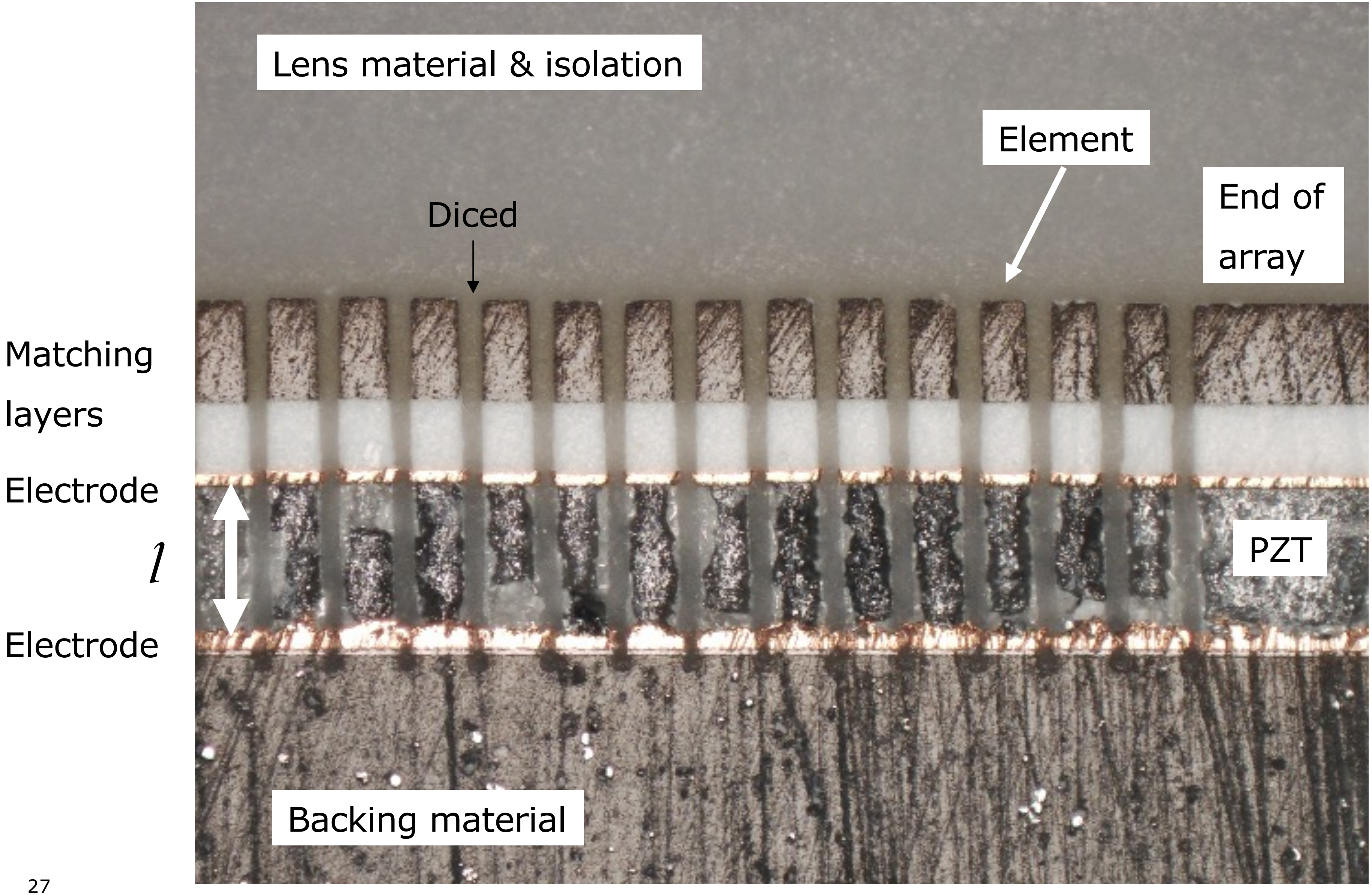
Fill factor = width/pitch




Acoustic lens
Ground electrode
Signal electrode
Matching layer(s)
Piezoceramic
Epoxy filler
Backing layer

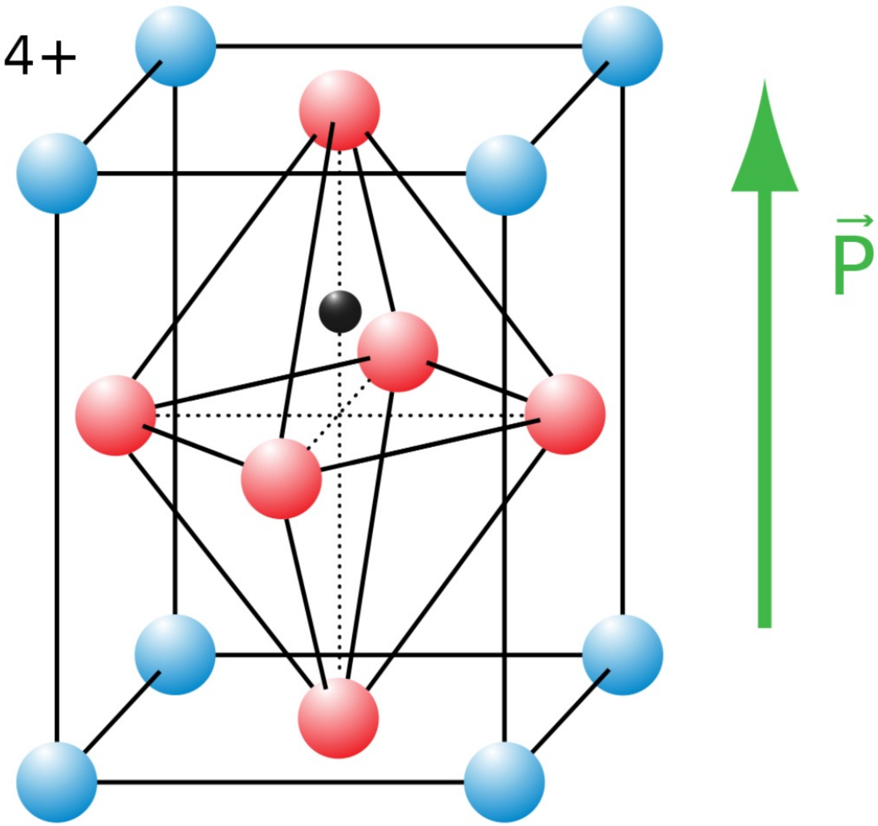

Lens

A PZT transducer: Cross-section



Structure of PZT

Pb^{2+} O^{2-} Ti^{4+}; Zr^{4+}

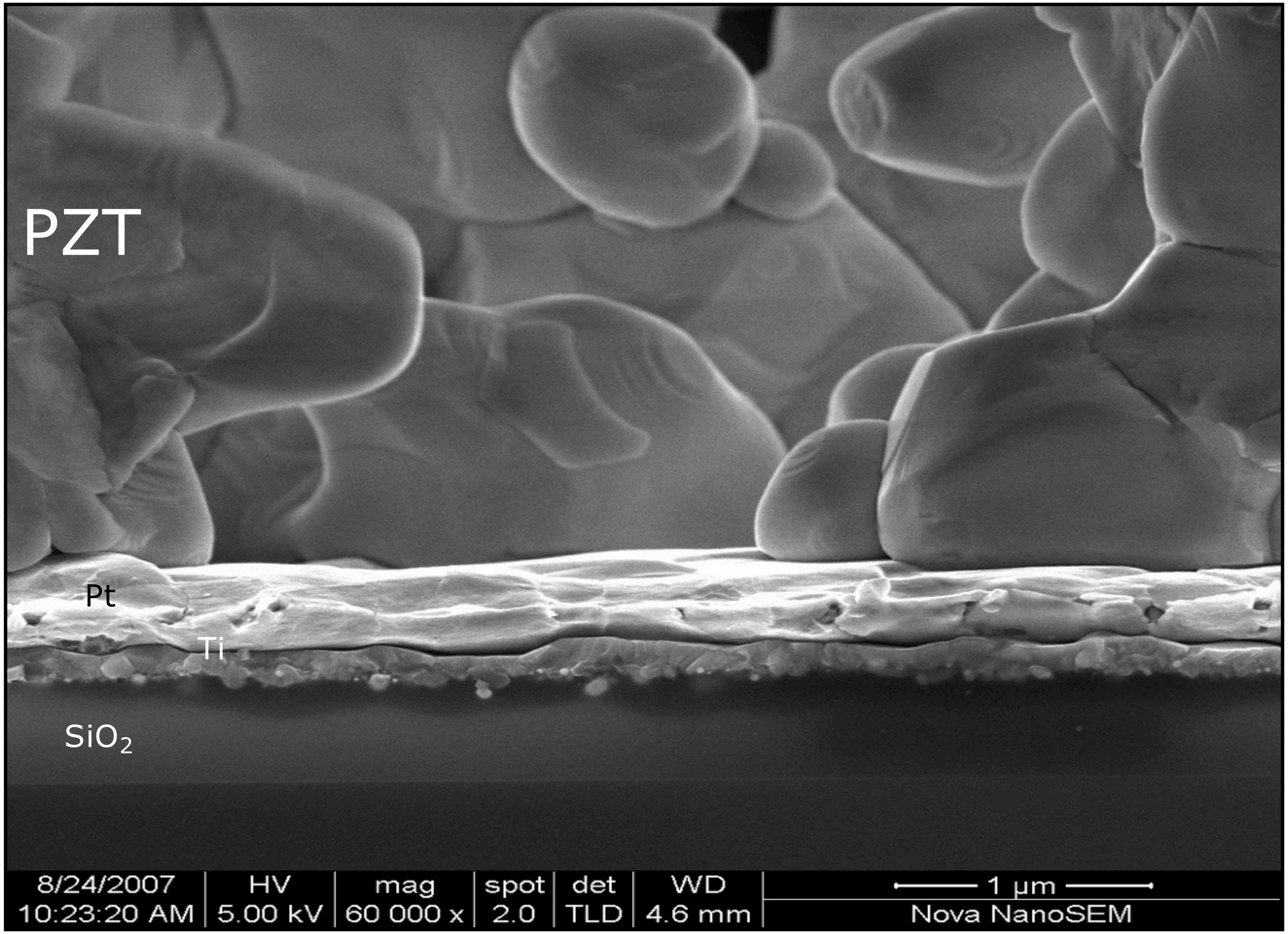


Lead atoms at the corners

Oxygen atoms at the faces

Ti,Zr closer to center

Inside PZT …

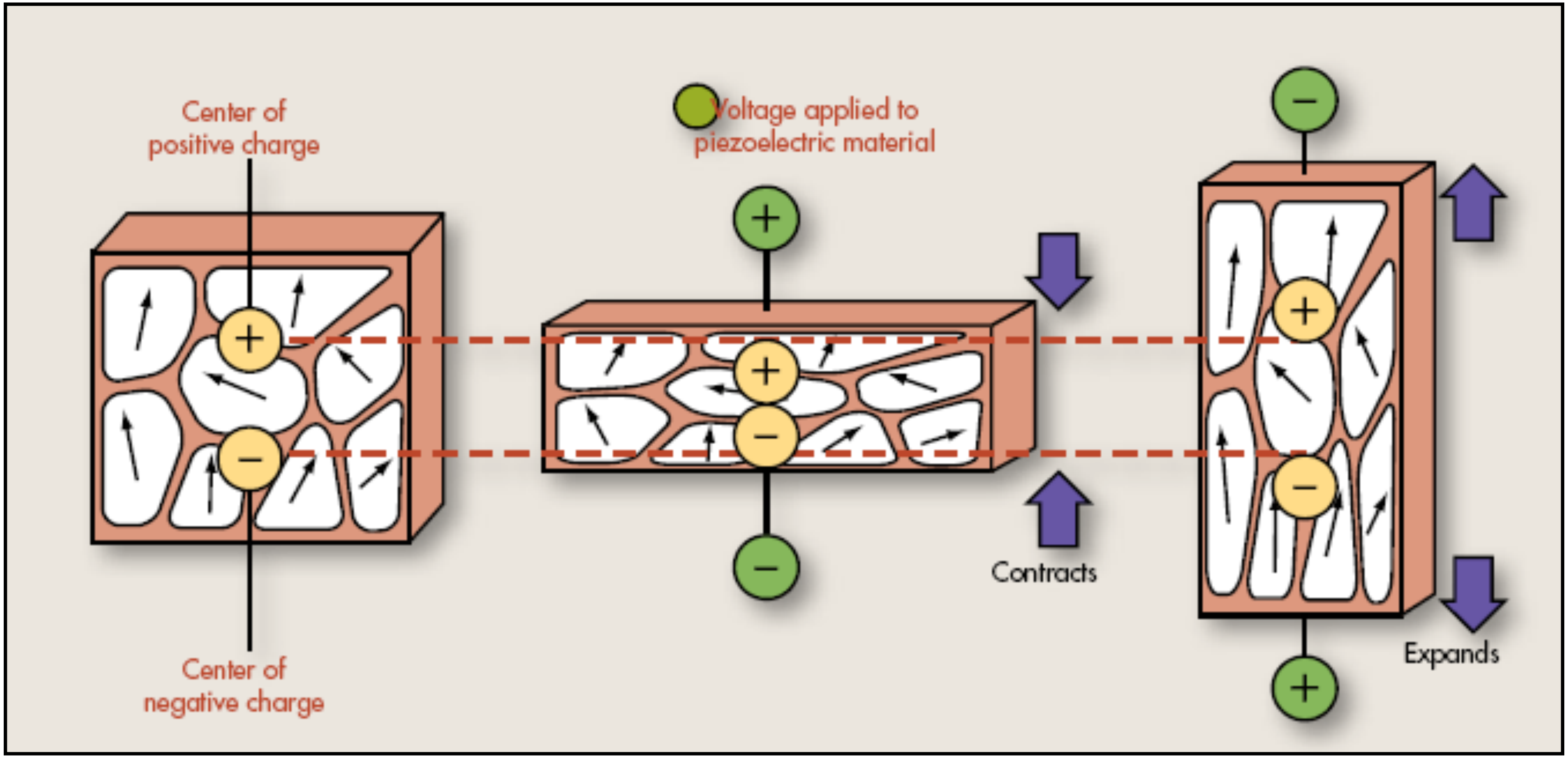


PZT
Pt
Ti
SiO_2
8/24/2007 10:23:20 AM
HV 5.00 kV
mag 60 000 x
spot 2.0
det TLD
WD 4.6 mm
1 µm
Nova NanoSEM

Working principle

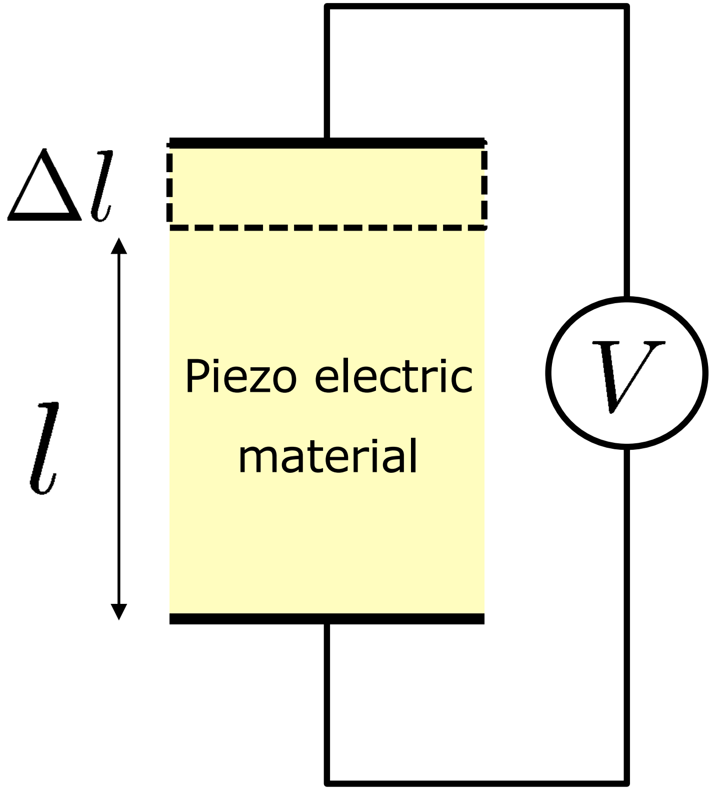
The PZT transducer is based on the piezoelectric transducer principle:

- Direct effect: Stress => Charge build up
- Converse effect: Applied charge (voltage) => Strain



Source: http://electronicdesign.com/

Working principle in 1D: Converse effect



Piezo electric coefficient:

Unit: C/N=m/V

$$S = \frac{\Delta l}{l} = dE = d\frac{V}{l}$$

Mechanical strain

Electric Field (V/m)

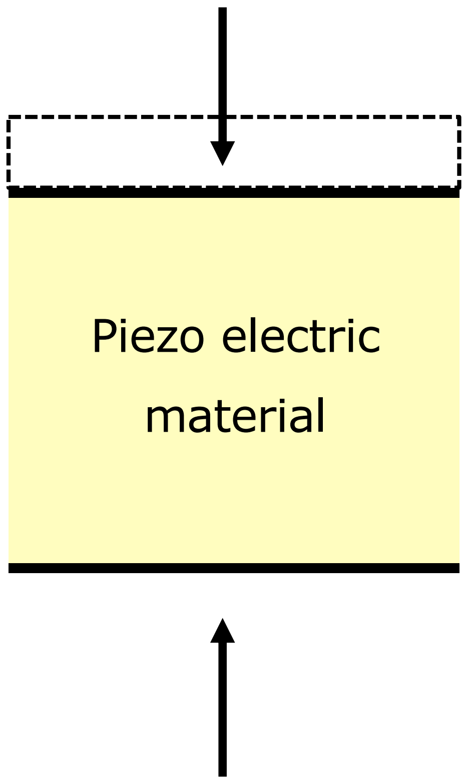
$$\Delta l = dV$$

Used in transmit

Working principle in 1D: Direct effect

stress=force/area

T=F/A



Used in receive

Piezo electric coefficient:

Unit: C/N=m/V

$$P = dT = d\frac{F}{A}$$

Electrical polarization

Mechanical stress

Electric displacement

Electric field

$$D = \varepsilon E + P$$

Permittivity

Receive – in 1D

Electrical polarization

T=force/area=F/A=pressure=p

$$P = dT = d\frac{F}{A} = dp$$

T: Mechanical stress

d: Piezo electric coefficient

Electric displacement

$$D = \varepsilon E + P = \varepsilon \frac{V}{l} + dp = 0$$

Permittivity   Electric field

E= Electric field=Voltage/distance=*V/l*

Receive voltage

$$V = \frac{dl}{\varepsilon} p$$

Working principle in 3D: Coupled equations

Direct effect (receive):

Stress

Electric field

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Electrical displacement

direct piezoelectric effect

Permittivity

Converse effect (transmit):

converse piezoelectric effect

Strain

Compliance

Stress

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Electric field

Properties of PZT (5-H)

Compliance

$$\mathbf{s_E} = \begin{bmatrix} 16.5 & -4.78 & -8.45 & 0 & 0 & 0 \\ -4.78 & 16.5 & -8.45 & 0 & 0 & 0 \\ -8.45 & -8.45 & 20.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 43.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 43.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 42.6 \end{bmatrix} *10^{-12} \frac{\mathrm{m}^2}{\mathrm{N}}$$

Piezoelectric Coupling

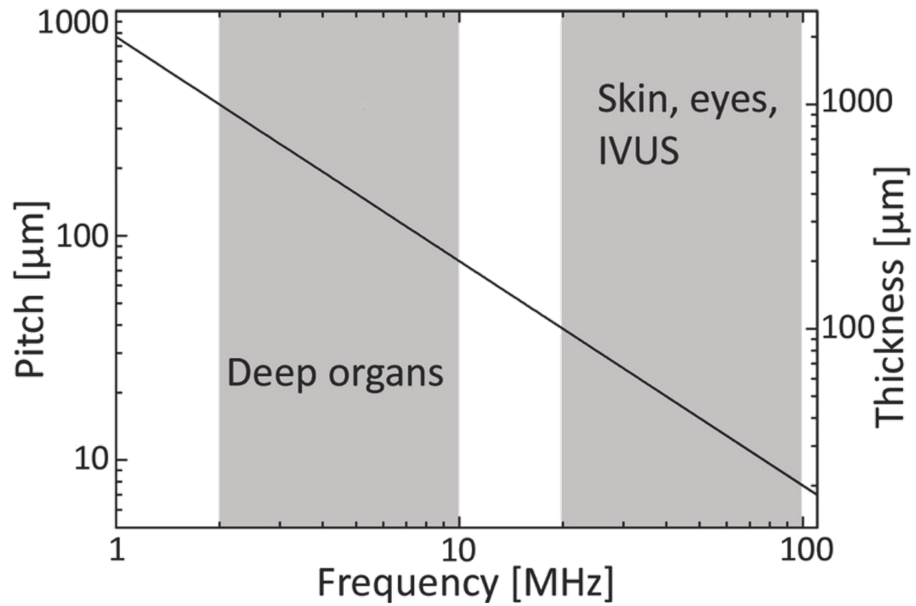
$$\mathbf{d} = \begin{bmatrix} 0 & 0 & 0 & 0 & 741 & 0 \\ 0 & 0 & 0 & 741 & 0 & 0 \\ -274 & -274 & 593 & 0 & 0 & 0 \end{bmatrix} *10^{-12} \frac{\mathrm{C}}{\mathrm{N}}$$

Relative Permittivity

$$\frac{\boldsymbol{\varepsilon}_\mathbf{T}}{\varepsilon_0} = \begin{bmatrix} 3130 & 0 & 0 \\ 0 & 3130 & 0 \\ 0 & 0 & 3400 \end{bmatrix}, \quad \varepsilon_0 = 8.854 *10^{-12} \frac{\mathrm{F}}{\mathrm{m}}$$

Characteristics of piezoelectric transducer

- Thickness mode
  - Frequency $f = \frac{c_{piezo}}{2l}$
  - c_{piezo} is sound velocity in PZT (4330 m/s)
  - l is element thickness
- Element pitch = 0.5 λ_{media}
- Width = pitch-kerf



3 MHz:
$\lambda_{media} \approx$ 500 µm
Pitch ≈ 250 µm
Thickness ≈ 722 µm
Width ≈ 220 µm

20 MHz:
$\lambda_{media} \approx$ 75
Pitch
108µm
≈ 7µm

Not feasible

Advanced PZT transducer design

Some tools:

- PZCAD
- COMSOL
- KLM modeling
- OnScale

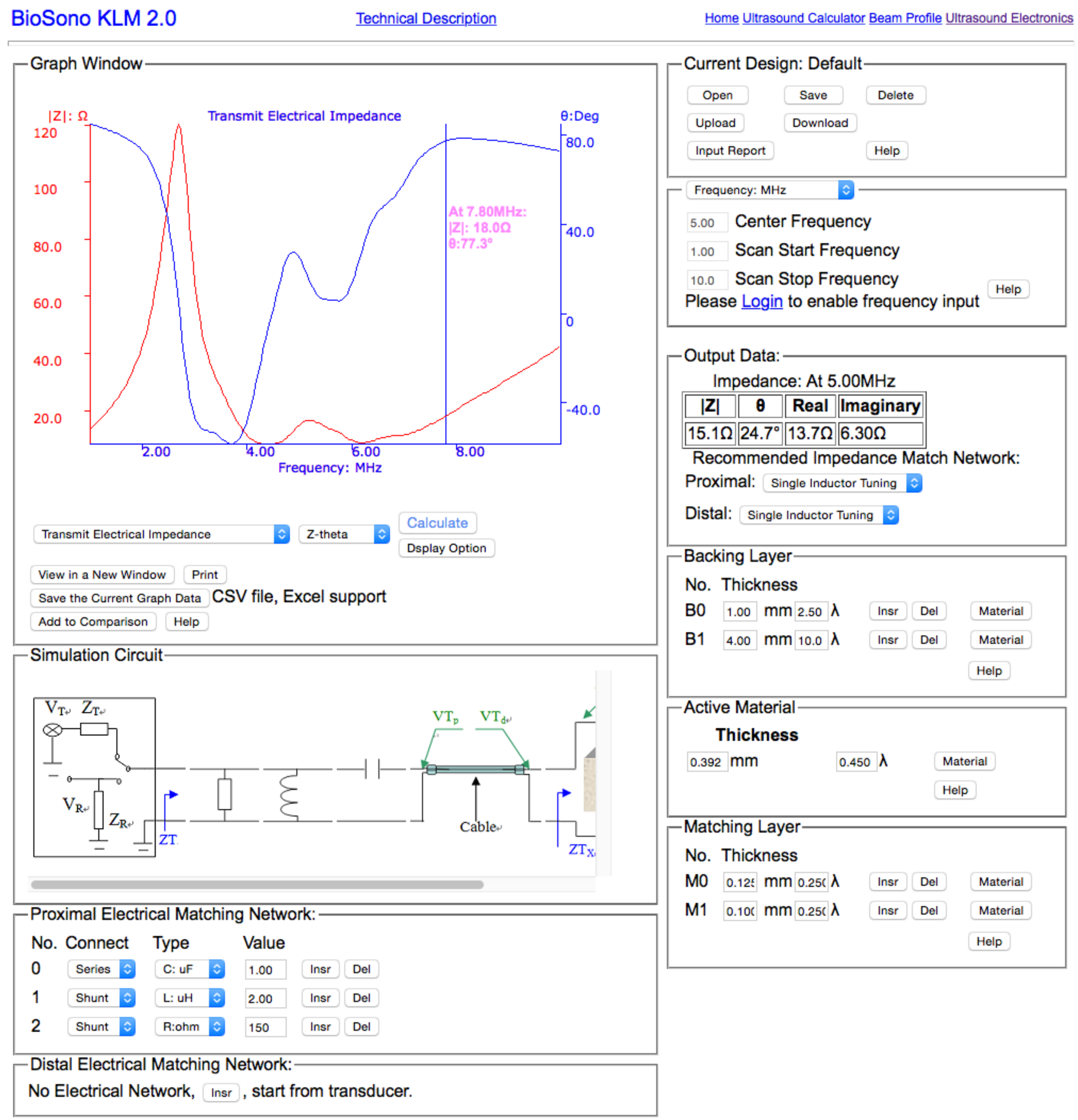
On-line KLM tool:

https://www.biosono.com/

(https://biosono.com/?page_id=91)

Onscale has a 10 core hour/month free account

https://onscale.com



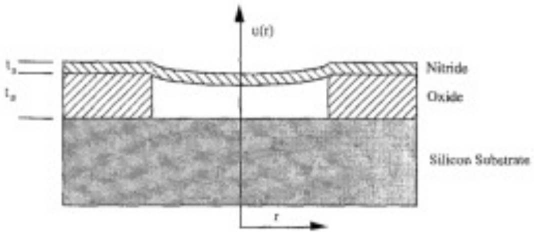
BREAK

THE CMUT TRANSDUCER

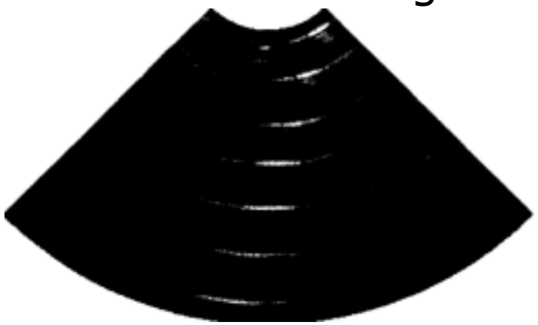
Capacitive Micro-machined Ultrasonic Transducers

CMUT: History

1994: 1st CMUTs made at Stanford

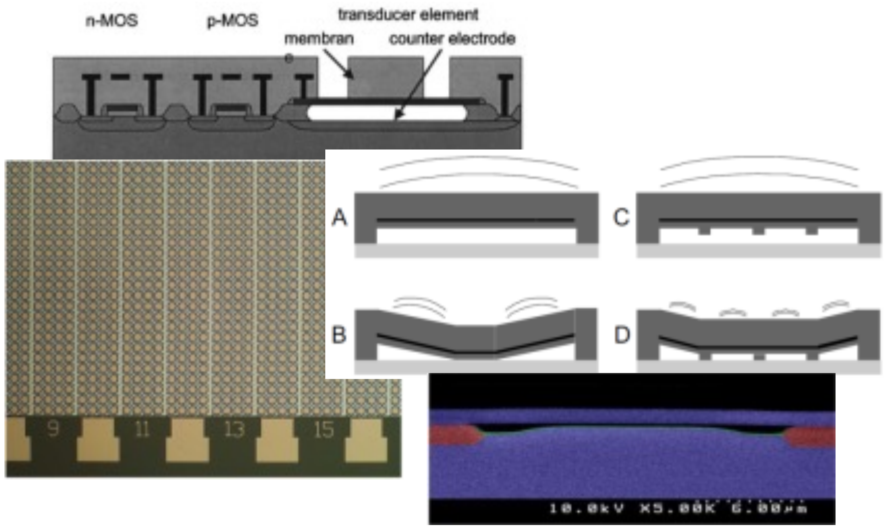


2000: First CMUT ultrasound images



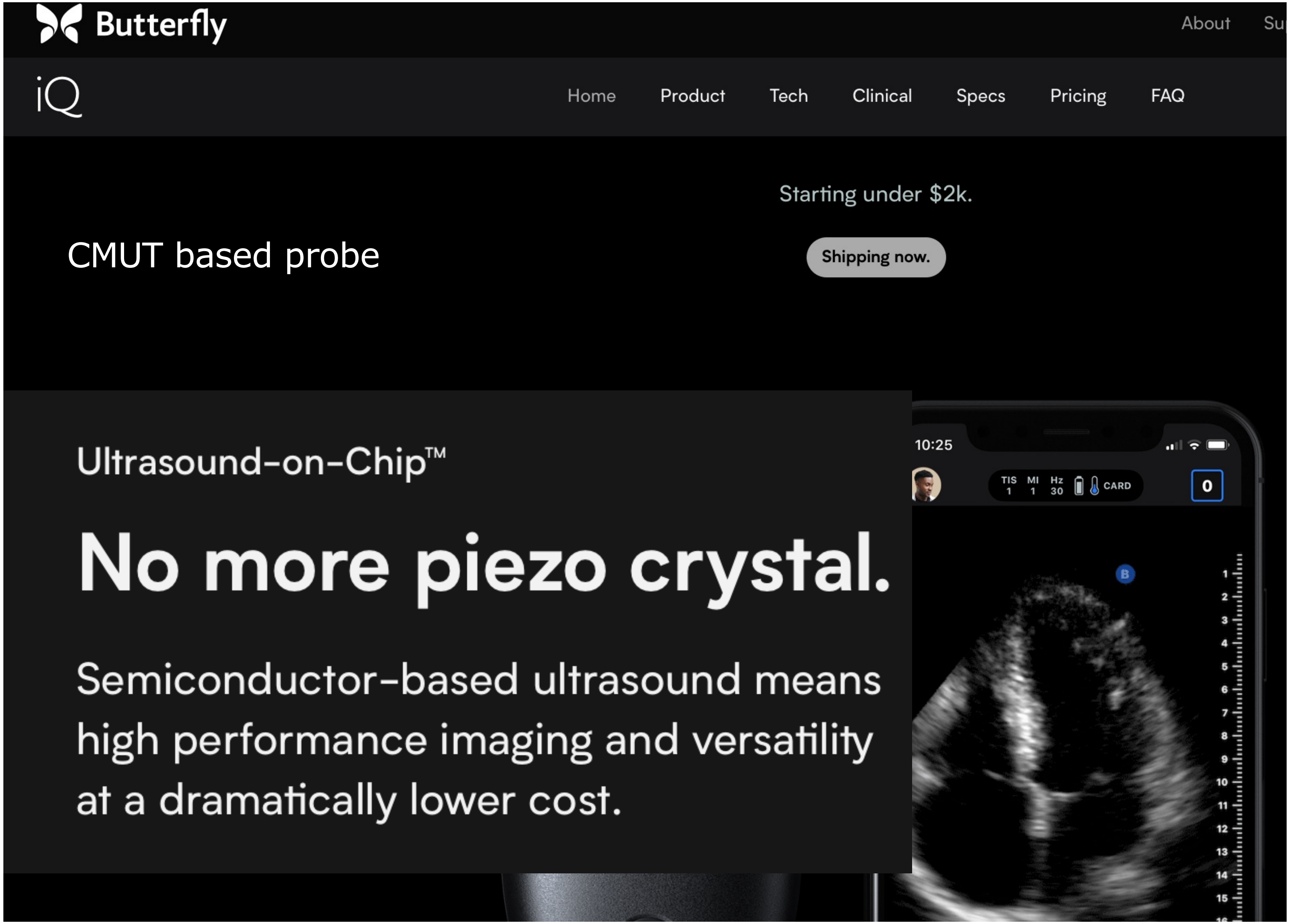
2012: Roma Tre

1994-now: Different CMUT versions



2004-now: GE, Stanford, Vermon, DTU, Kolo, Butterfly (2018)

Butterfly – 2018 – portable ultrasound




C Submode
Capture
Off
Advanced
3D
Documentation
Measure and Mark
Image
bk5000
analogic
DTU_1302
Save buffers: Freeze, CTRL+ALT+SHIFT+2

The CMUT building block: Capacitor

The CMUT is a capacitive device:

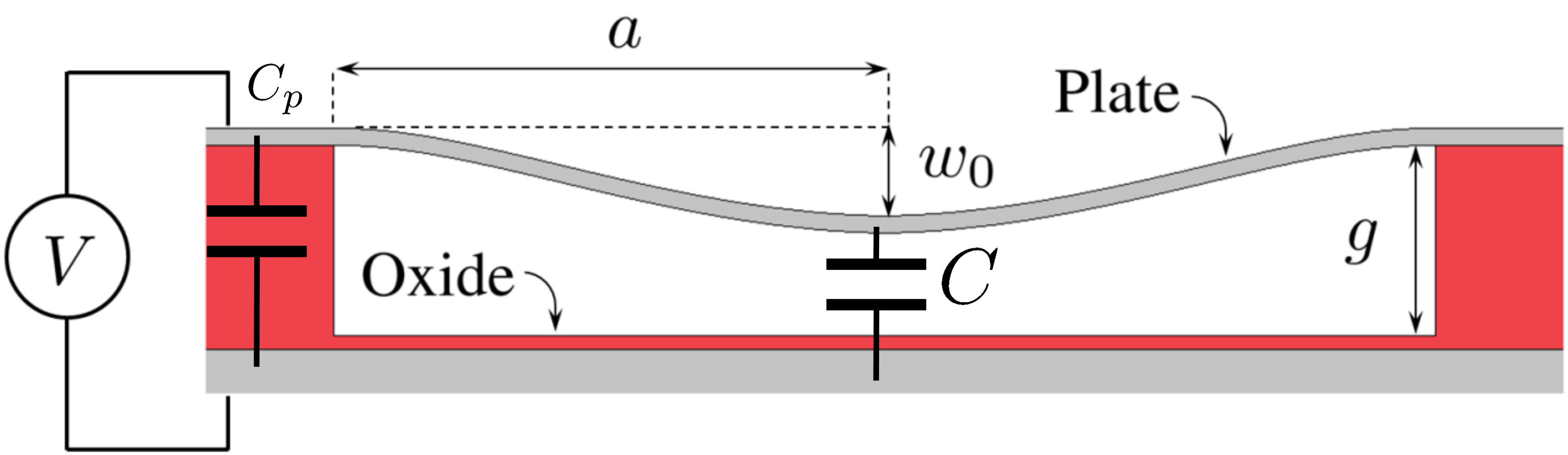
$$C_{\text{tot}} = C + C_p$$

Transmit:

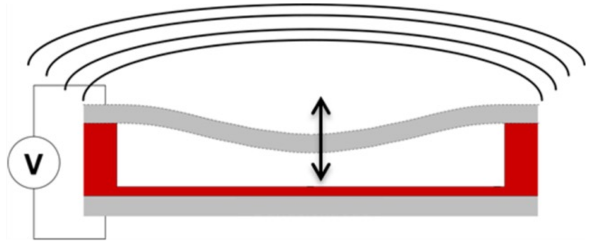
Use DC voltage to increase coupling coefficient

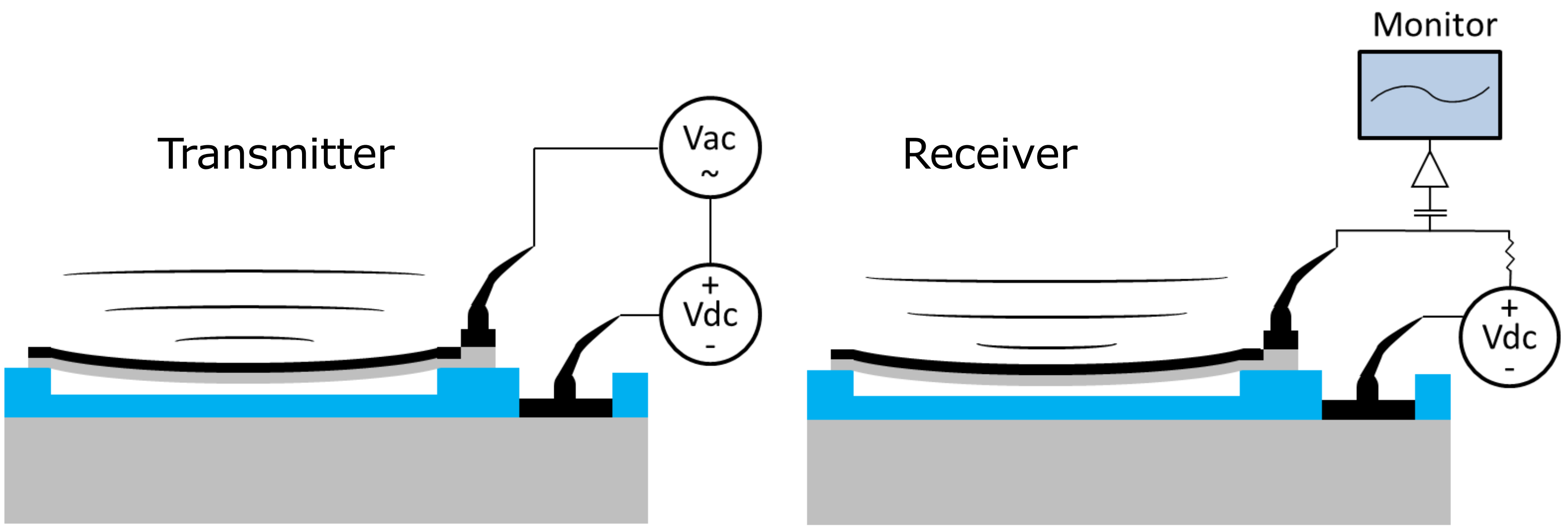
Actuation is performed by varying the voltage

Receive: Change in capacitance is detected

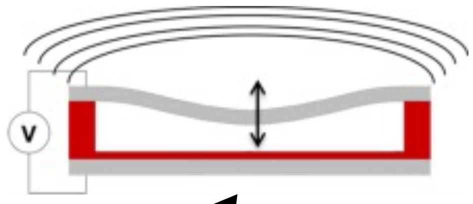


Operating the CMUT

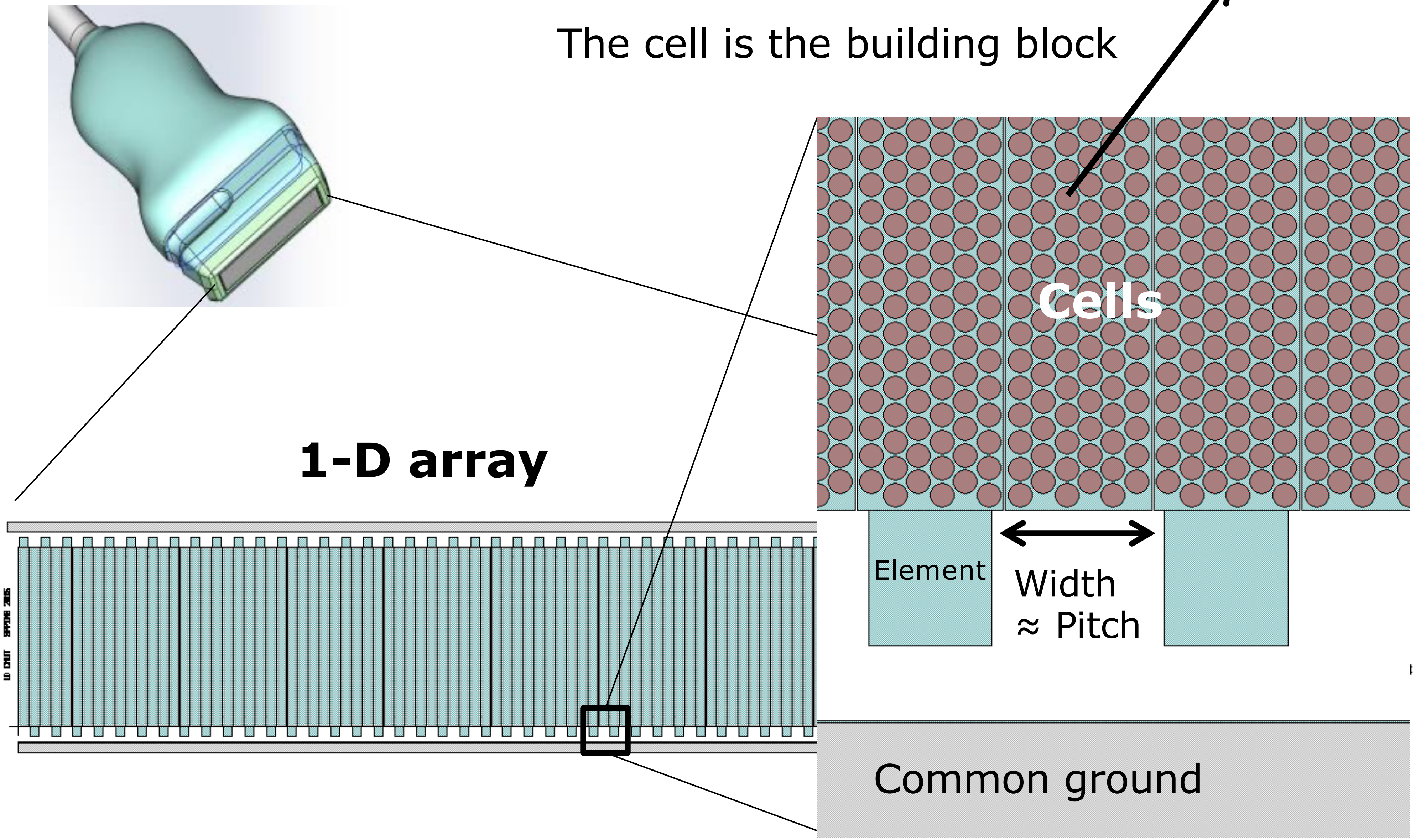




CMUT Design - Array



The cell is the building block



UNDERSTANDING CAPACITIVE TRANSDUCERS

What is pull-in and spring softening?

Basic principle: Sensing & Actuation

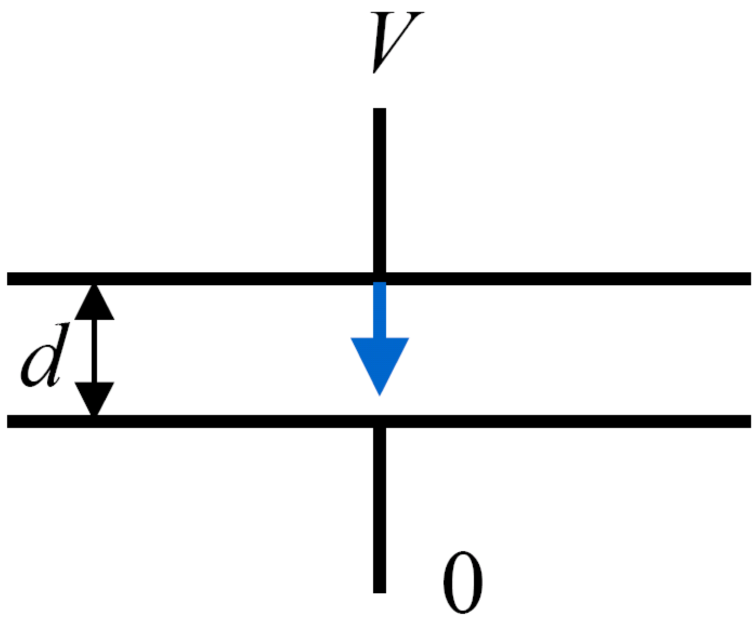
Capacitance (sensing):

$$C = \frac{\epsilon S}{d}$$

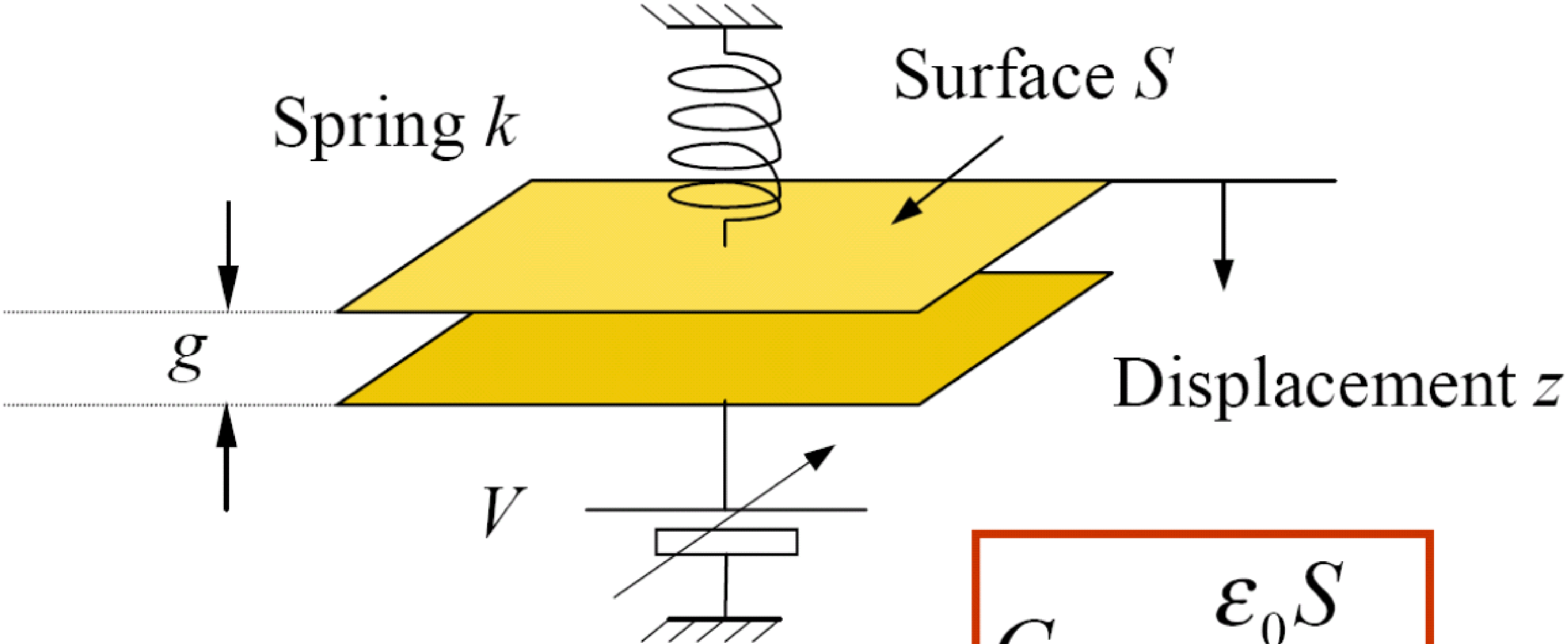
S: Plate area
d: Plate distance

Attractive
force between the plates
(actuation):

$$F = \frac{1}{2}\frac{\epsilon S}{d^2}V^2$$

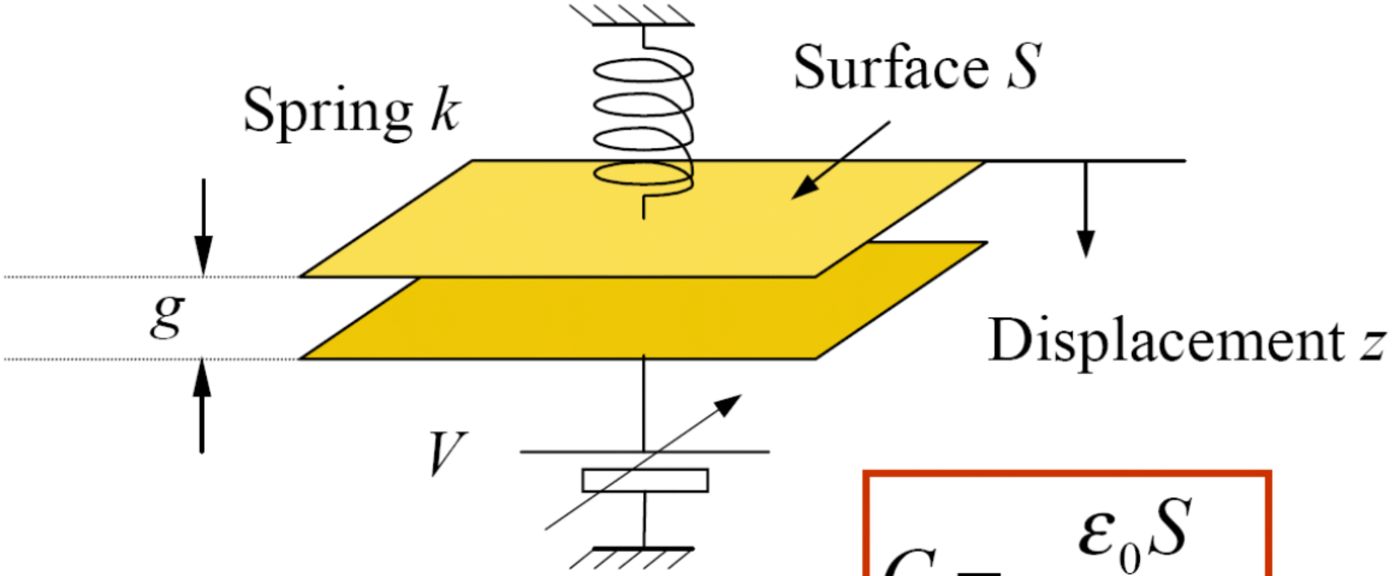


Model for capacitive device



$$C = \frac{\varepsilon_0 S}{(g - z)}$$

Force & potential energy



$$C = \frac{\varepsilon_0 S}{(g - z)}$$

- Which forces act on the movable plate?
- How does force/energy depend on *z* and *V*?
- Calculate the force as function of *z* and *V*

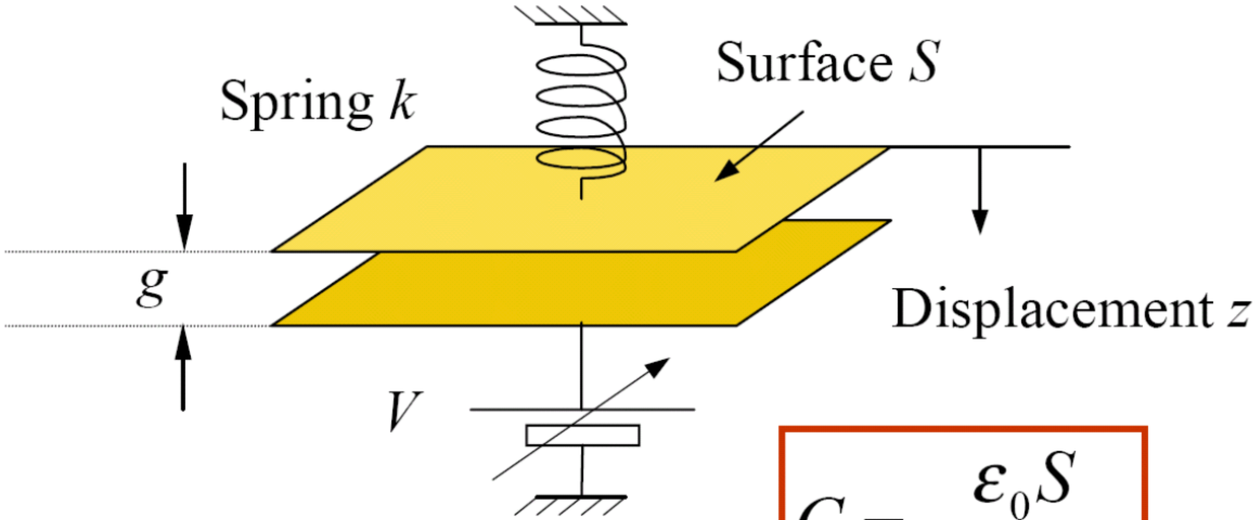
Potential energy:

$$U = -\frac{1}{2}CV^2 + \frac{1}{2}kz^2$$

Force:

$$F = -\frac{\partial U}{\partial z}$$

Forces



$$C = \frac{\varepsilon_0 S}{(g - z)}$$

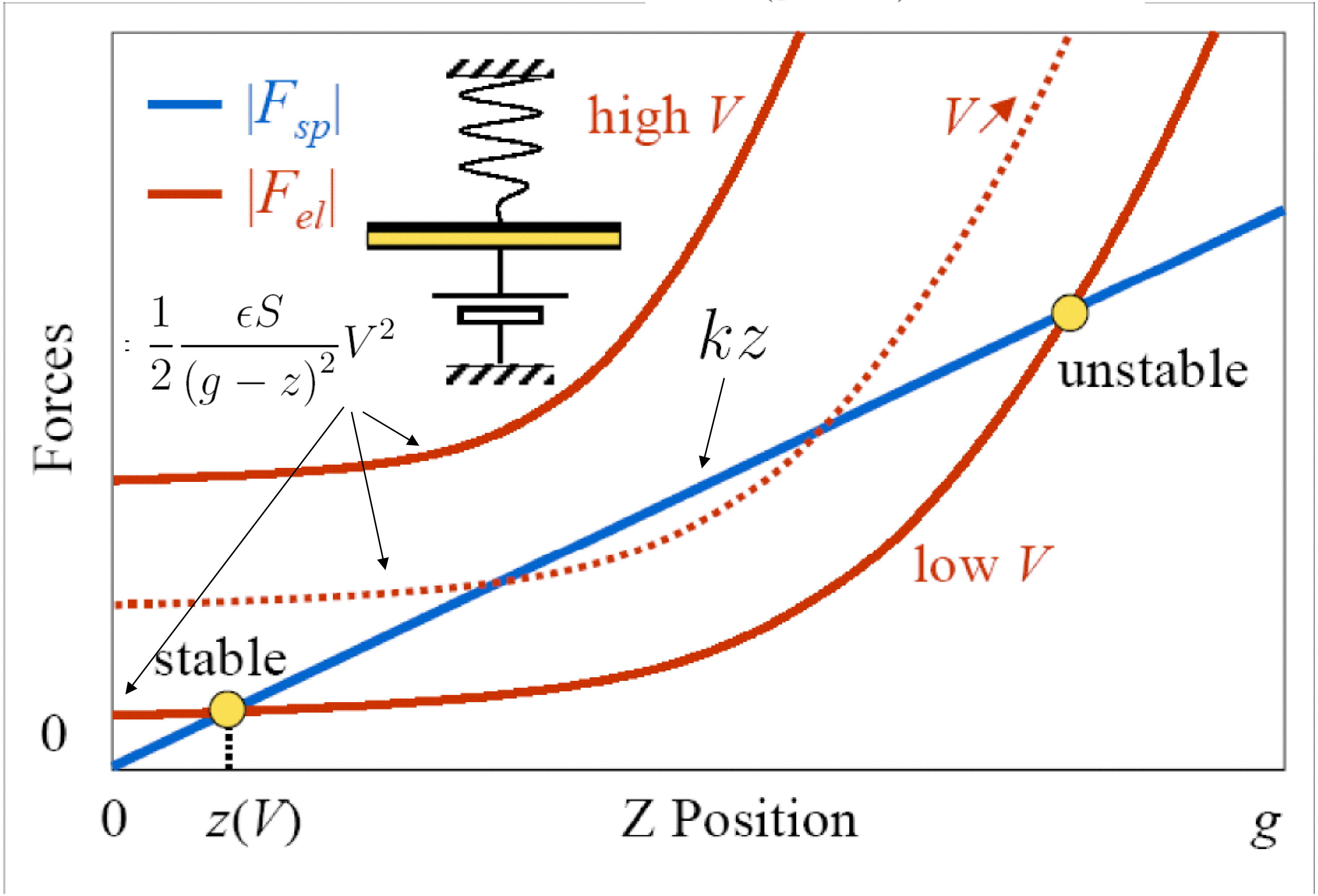
$$U = -\frac{1}{2}CV^2 + \frac{1}{2}kz^2 = -\frac{1}{2}\frac{\epsilon S}{g - z}V^2 + \frac{1}{2}kz^2$$

$$F = -\frac{\partial U}{\partial z} = \frac{1}{2}\frac{\epsilon S}{(g - z)^2}V^2 - kz$$

Mechanical (spring)

Electrostatic

Force balance $\mathrm{F} = \frac{1}{2}\frac{\epsilon S}{(g-z)^2}V^2 - kz = 0$



Stable equilibrium

- Condition 1: Total force = 0
- Condition 2: Small movement lowers force

(i.e. minimum in potential energy)

$$U = -\frac{1}{2}CV^2 + \frac{1}{2}kz^2 = -\frac{1}{2}\frac{\epsilon S}{g-z}V^2 + \frac{1}{2}kz^2$$

$$F = -\frac{\partial U}{\partial z} = \frac{1}{2}\frac{\epsilon S}{(g-z)^2}V^2 - kz$$

$$\delta F = \left.\frac{\partial F}{\partial z}\right|_V \delta z$$

Must be negative!

Stable equilibrium

$$\left.\frac{\partial F}{\partial z}\right|_V = \frac{\epsilon S}{(g-z)^3} V^2 - k$$

1 - Stable position:

$$\frac{\epsilon S}{(g-z)^3} V^2 - k < 0$$

2 – Pull-in voltage:

$$\frac{\epsilon S}{(g-z)^3} V_{pi}^2 = k$$

Pull-in voltage

At pull in the electrostatic & the spring force are equal:

1 $$\frac{1}{2}\frac{\epsilon S}{(g-z)^2}V_{pi}^2 = kz$$

Pull in voltage:

2 $$\frac{\epsilon S}{(g-z)^3}V_{pi}^2 = k$$

Combining:

$$\frac{\epsilon S}{(g-z)^3}V_{pi}^2 = \frac{1}{2}\frac{1}{z}\frac{\epsilon S}{(g-z)^2}V_{pi}^2$$

What is *z* at pull in?

$$z = \frac{1}{3}g$$

Pull-in distance & voltage

Pull-in distance:

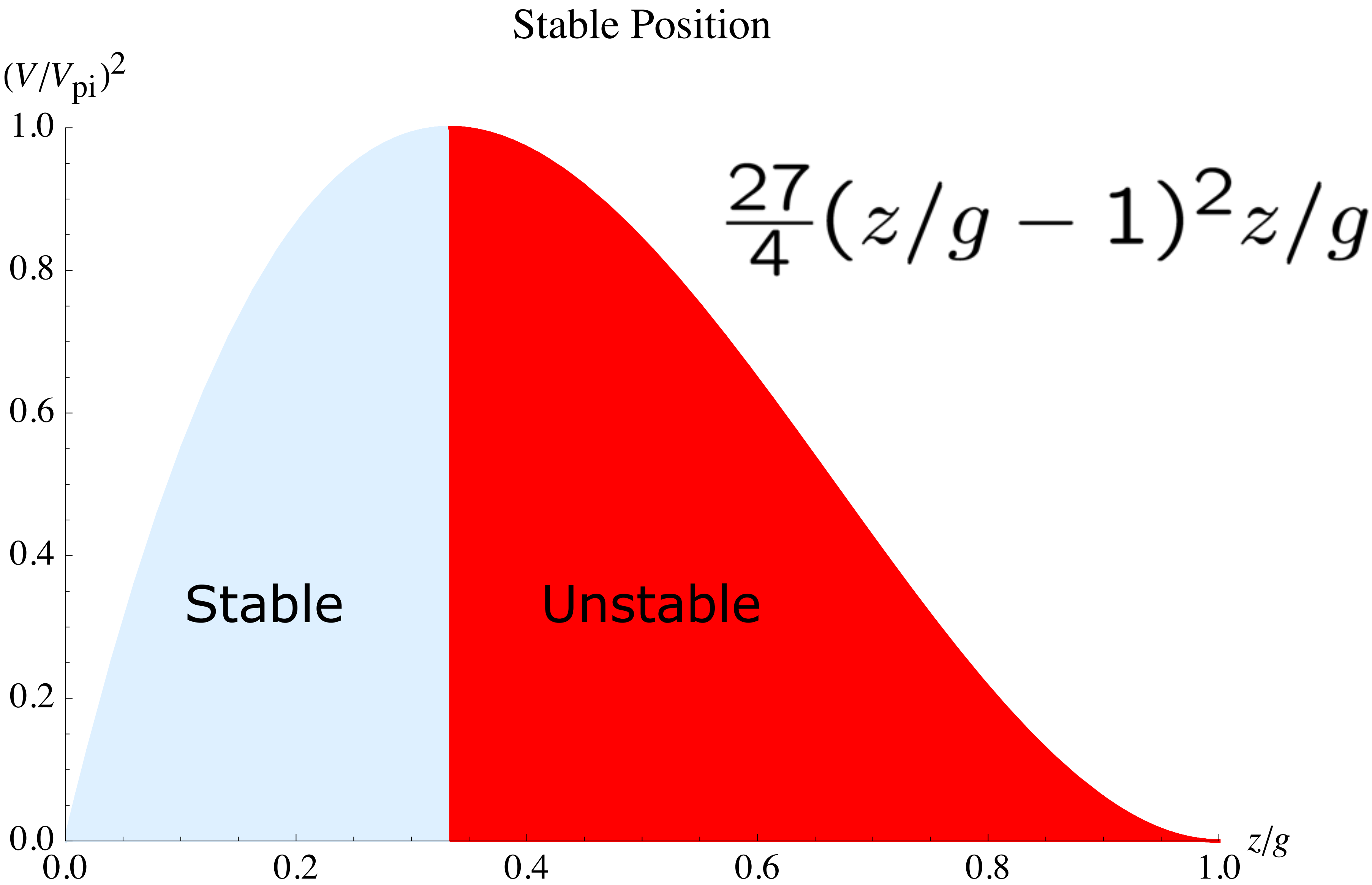
$$z = \frac{1}{3}g$$

Thus,

Pull-in voltage:

$$V_{pi} = \sqrt{\frac{2\left(g-z\right)^2}{\epsilon S}kz} = \sqrt{\frac{2\left(g-\frac{1}{3}g\right)^2}{\epsilon S}k\frac{1}{3}g} = \sqrt{\frac{8}{27}\frac{kg^3}{\epsilon S}}$$

Depends on $g^{3/2}$!


Stable Position
$(V/V_{pi})^2$
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
z/g
$\frac{27}{4}(z/g-1)^2 z/g$
Stable
Unstable

Details at pull-in

At pull-in the two plates touch each other!

$$C = \frac{\epsilon_{ox} S}{t_{ox}}$$

Pull-out voltage

At pull-in the moving plate touches fixed plate
Plate distance is the thickness of the insulating layer

Force between plates:

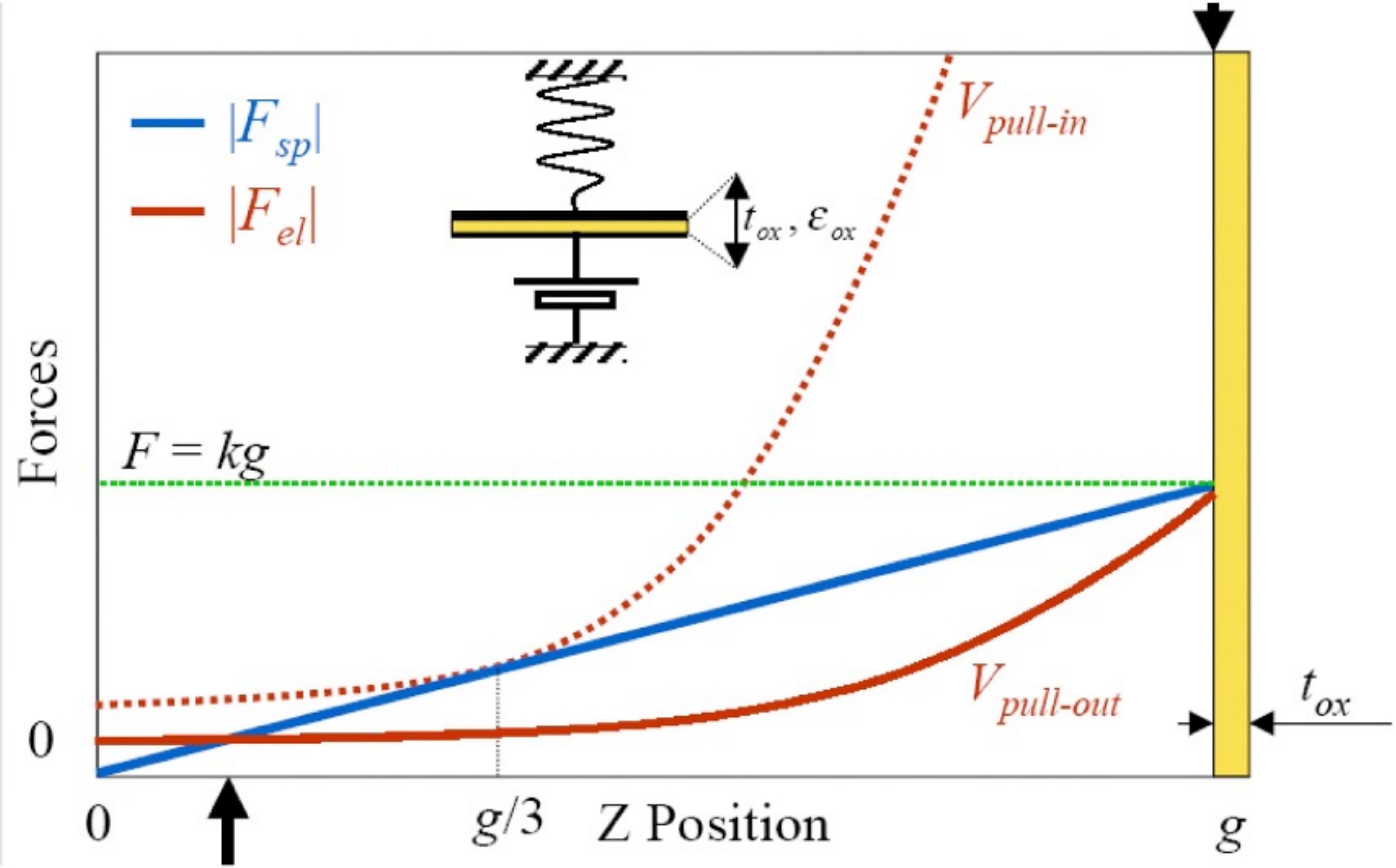
$$C = \frac{\epsilon_{ox} S}{t_{ox}}$$

$$F = \frac{1}{2} \frac{\epsilon_{ox} S}{t_{ox}^2} V^2$$

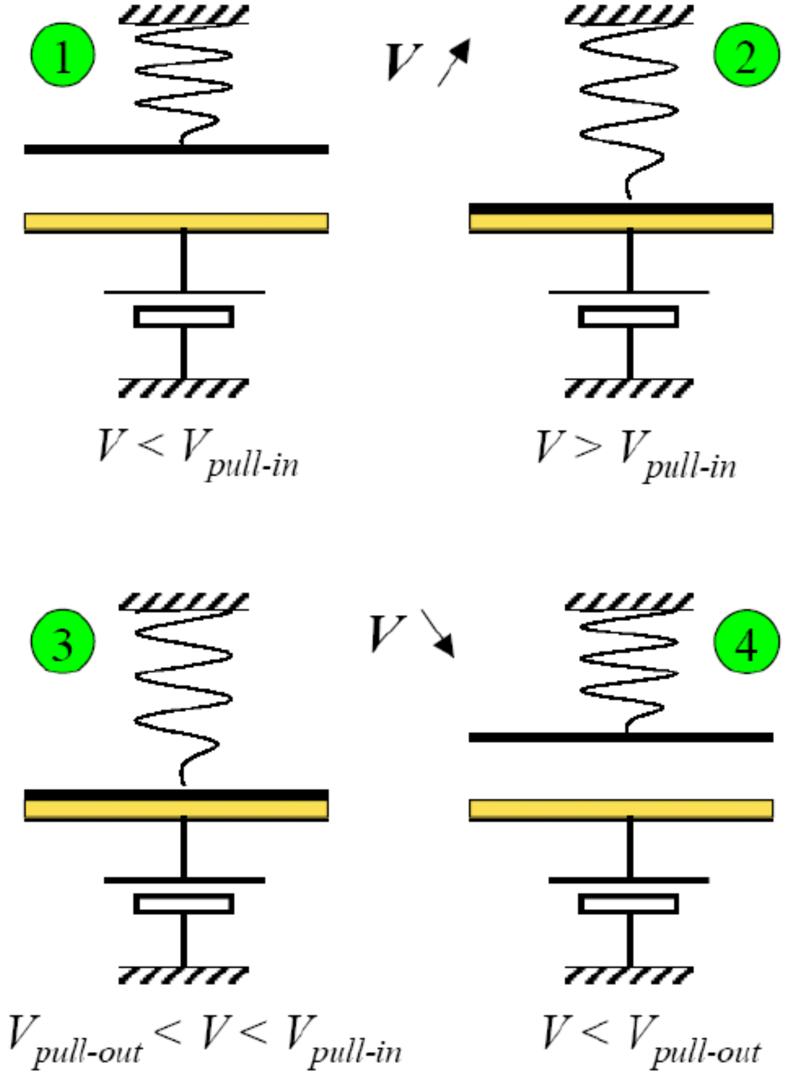
Force balance leads to pull-out condition:

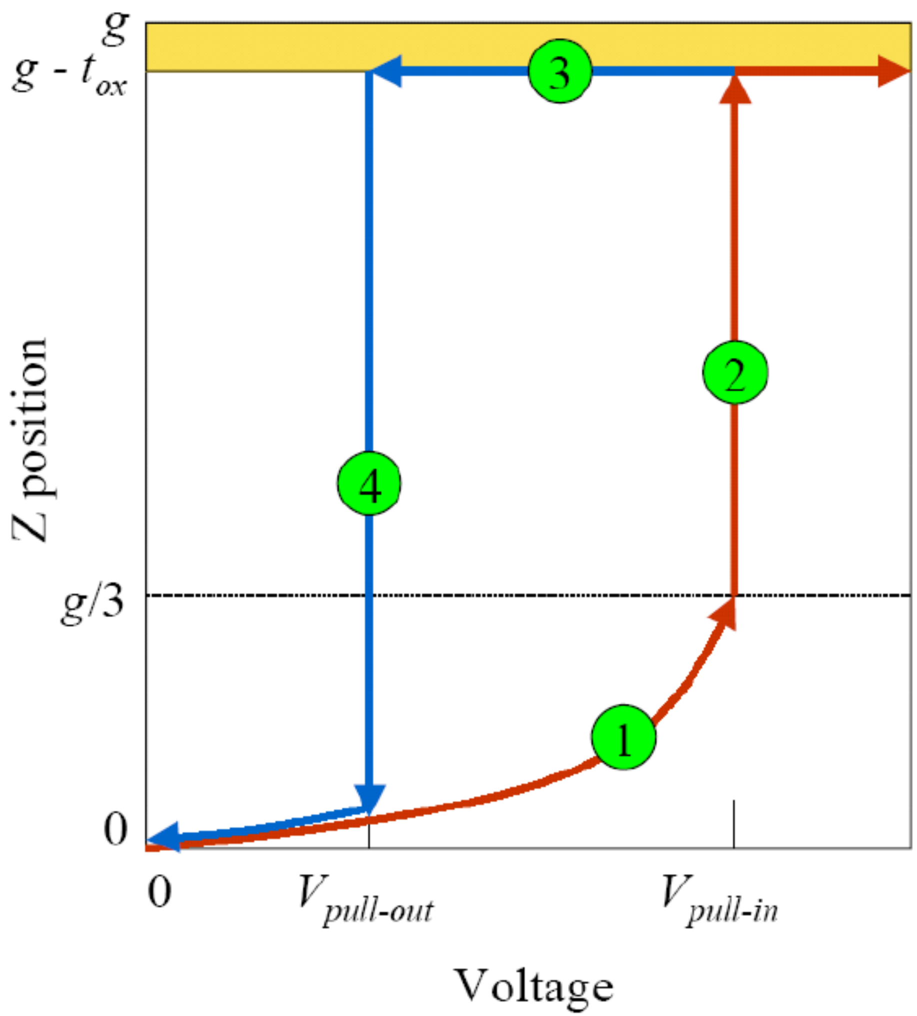
$$\frac{1}{2} \frac{\epsilon_{ox} S}{t_{ox}^2} V_{pu}^2 = kg \qquad V_{pu} = \sqrt{\frac{2kg}{\epsilon_{ox} S}} t_{ox}$$

Pull-out – force balance

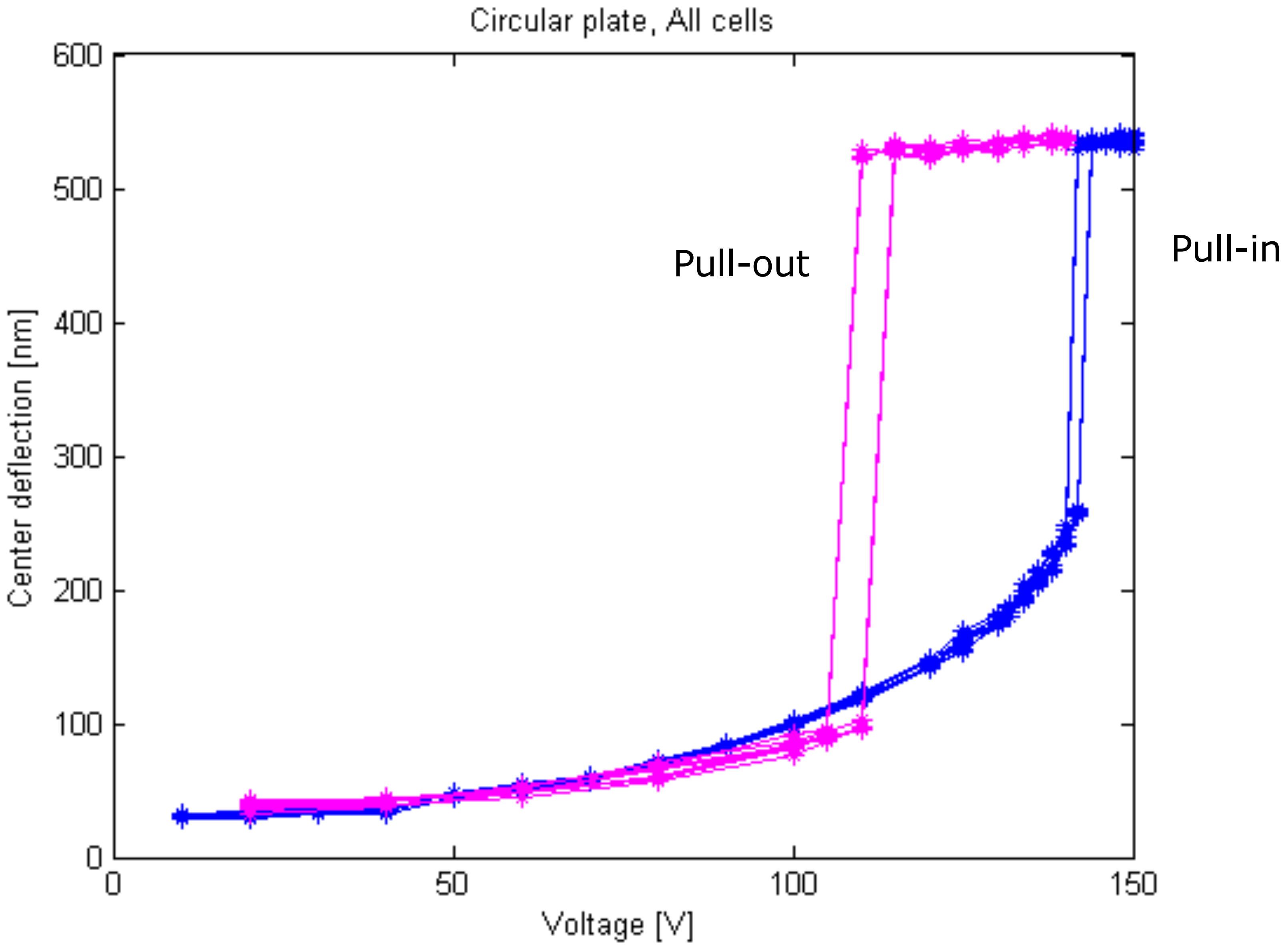


Hysteresis


1
V ↗
2
V < V pull-in
V > V pull-in
3
V ↘
4
V pull-out < V < V pull-in
V < V pull-out

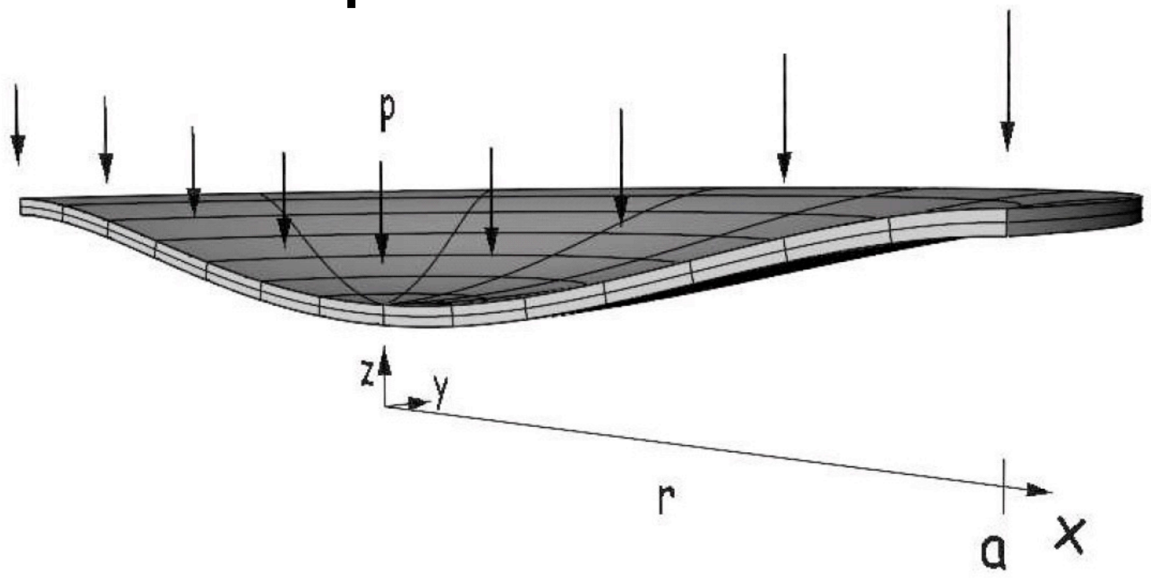

g
g - t ox
g/3
0
Z position
3
2
4
1
0
V pull-out
V pull-in
Voltage

Measured hysteresis



The CMUT is not a parallel plate capacitor – what do we do?

CMUT capacitance of circular device



$$z_0 = \frac{pa^4}{64D}$$

$$D = \frac{Et^3}{12(1-\nu^2)}$$

Deflection comes from structural mechanics

$$z(r) = z_0\left(1-\left(\frac{r}{a}\right)^2\right)^2 = \frac{p}{64D}(a^2-r^2)^2$$

$$C = \epsilon_r\epsilon_0\int_0^{2\pi}\int_0^a \frac{r}{d-z(r,\theta)}\mathrm{d}r\mathrm{d}\theta$$

CMUT – capacitance of circular device

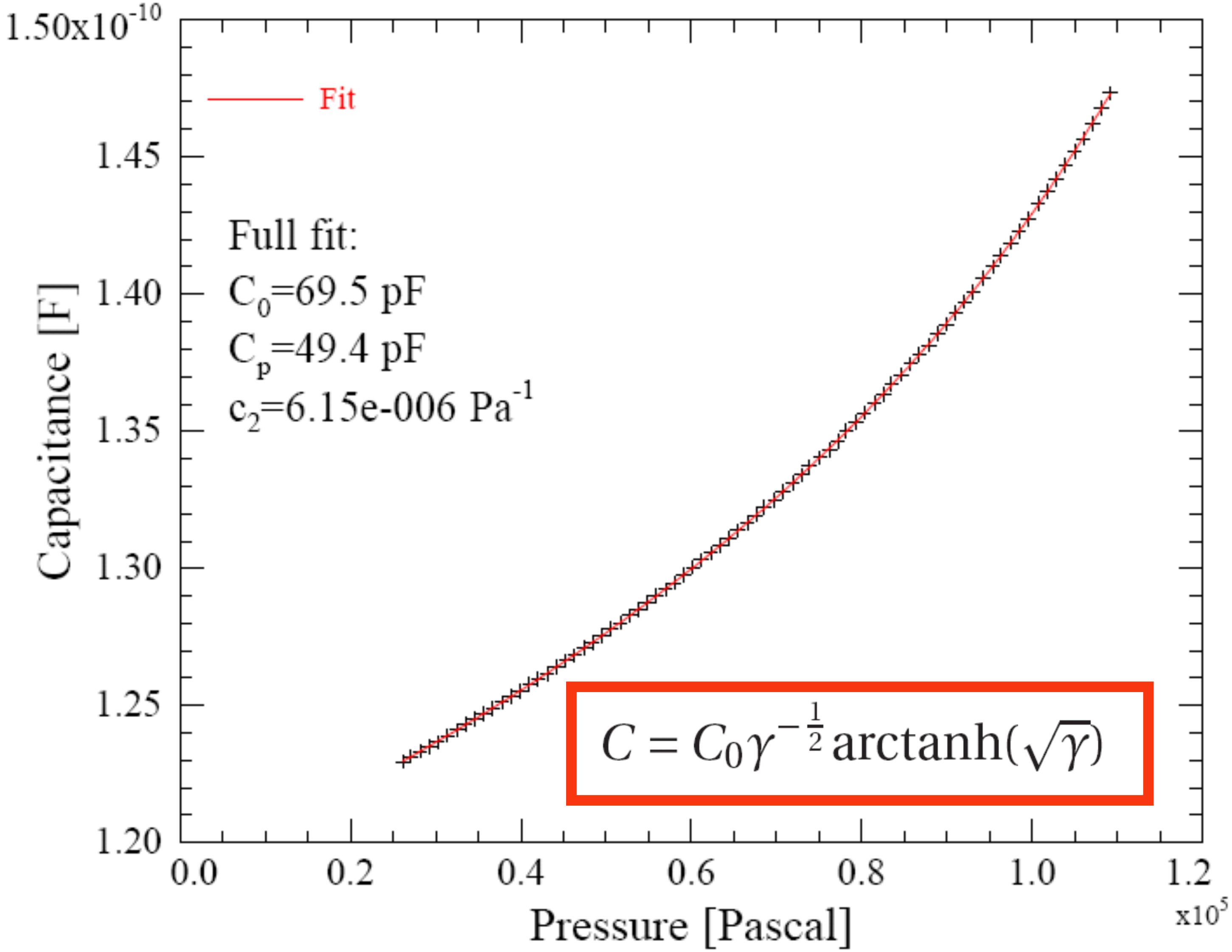
$$C = 2\pi\epsilon_r\epsilon_0 \int_0^a \frac{r}{d - z(r)} \mathrm{d}r \qquad C = 2\pi\epsilon_r\epsilon_0 \int_0^a \frac{r}{d - z_0\left(1-\left(\frac{r}{a}\right)^2\right)^2} \mathrm{d}r$$

$$\gamma = \frac{z_0}{d} \qquad x = \sqrt{\gamma}\left(1-\left(\frac{r}{a}\right)^2\right)^2$$

$$C = \epsilon_r\epsilon_0 \frac{\pi a^2}{d} \gamma^{-\frac{1}{2}} \int_0^{\sqrt{\gamma}} \frac{1}{1-x^2} \mathrm{d}x$$

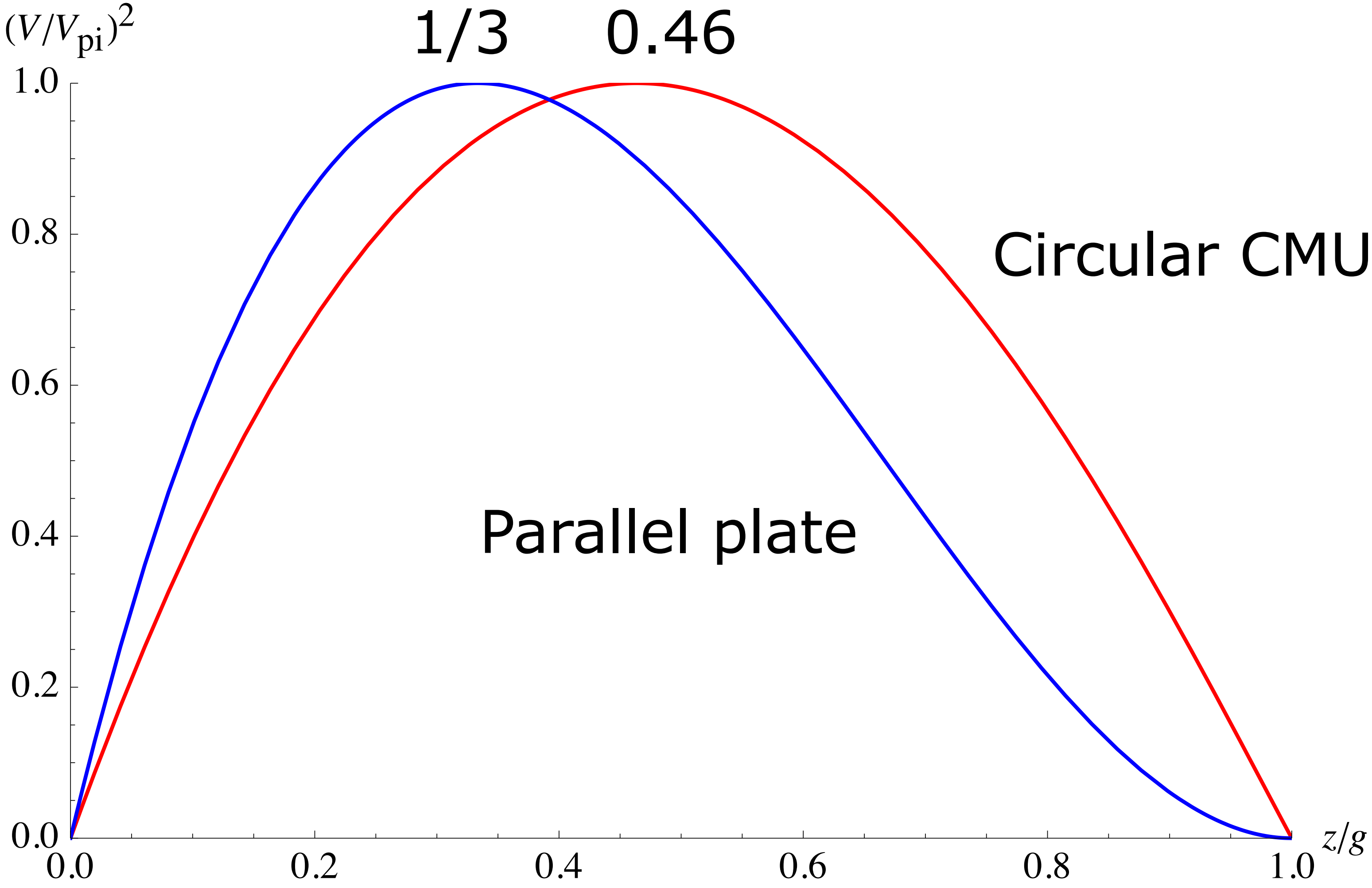
$$C = C_0 \gamma^{-\frac{1}{2}} \operatorname{arctanh}(\sqrt{\gamma})$$

Comparison: Theory - Experiment



$$C = C_0 \gamma^{-\frac{1}{2}} \operatorname{arctanh}(\sqrt{\gamma})$$

Stable position



Pull-in parameters

For the circular plate:

Pull-in distance:

$$x = \frac{w_0}{g} = 0.463\,26$$

Pull-in voltage:

$$V_{\mathrm{pi}} = \sqrt{\frac{2.373 g^3 h^3 Y}{a^4 (1-\nu^2)\epsilon}}$$

g = gap

h = plate thickness

a = radius

Y = Young's modulus, ~148 GPa

ν = Poisson's ratio, ~ 0.17

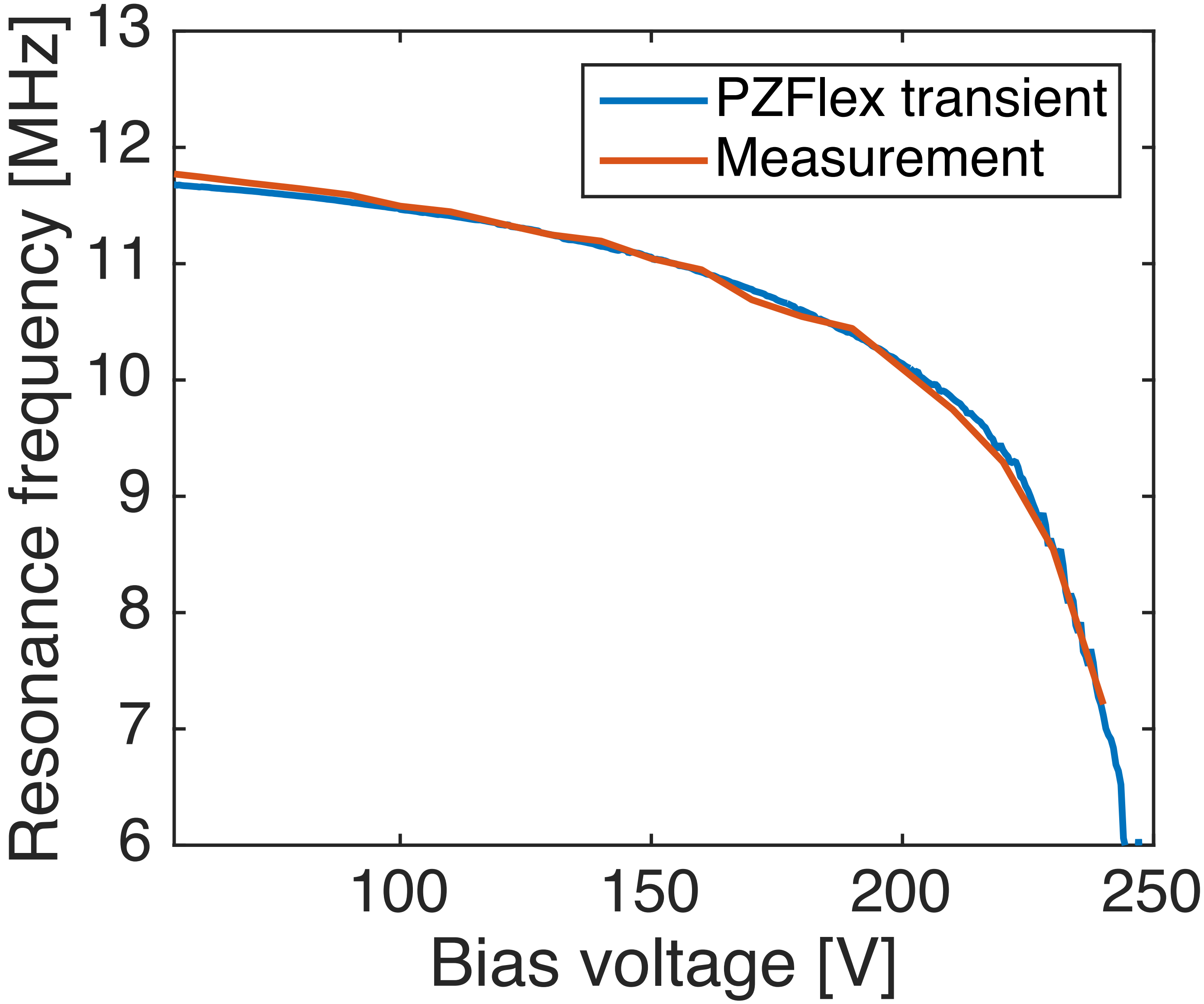
ε = Vacuum permittivity

Spring softning

Spring constant decreases with voltage!

$$
\begin{aligned}
k_{\text{eff}} &= -\frac{\partial F}{\partial z} = -\frac{\partial}{\partial z}\left(-\frac{\partial U}{\partial z}\right) = \frac{\partial^2 U}{\partial z^2} \\
&= -\frac{\partial}{\partial z}\left(\frac{1}{2}\frac{\epsilon S}{(g-z)^2}V^2 - kz\right) \\
&= -\frac{\partial}{\partial z}\left(\frac{1}{2}\frac{\epsilon S}{(g-z)^2}V^2\right) - \frac{\partial}{\partial z}(-kz) \\
&= k - \frac{\epsilon S}{(g-z)^3}V^2
\end{aligned}
$$

Spring softning: Measured



Mini conclusion

- Capacitive sensors have high sensitivity!
- Can be used for actuation & sensing
- Pull–in <> pull–out
- Hysteresis

CMUT DESIGN

From specifications to design parameters

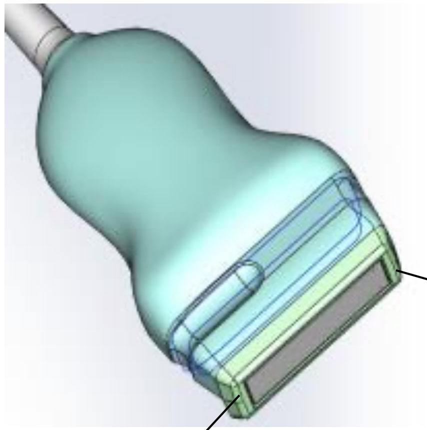
Probe requirements – one example

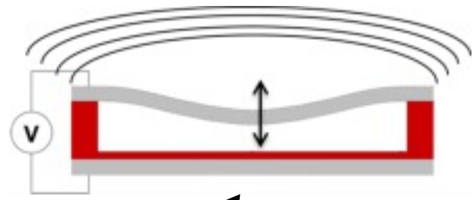
Medical imaging:
- 128-element linear array
- 5 MHz center frequency
- λ-pitch

Assembly and electronics:
- Compatible with commercial BK ultrasound scanner
- Up to 190 V DC bias is available
- Up to +/- 75 V AC transmit voltage

All CMUT designs begin with a set of specifications

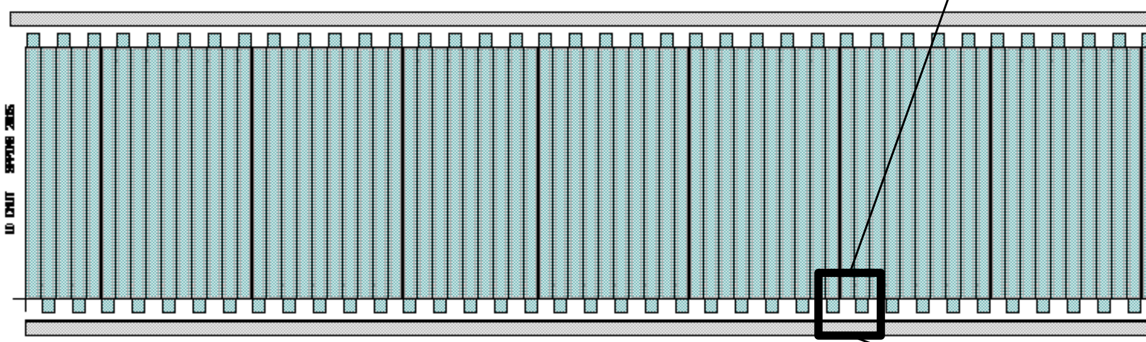
CMUT Design - Array

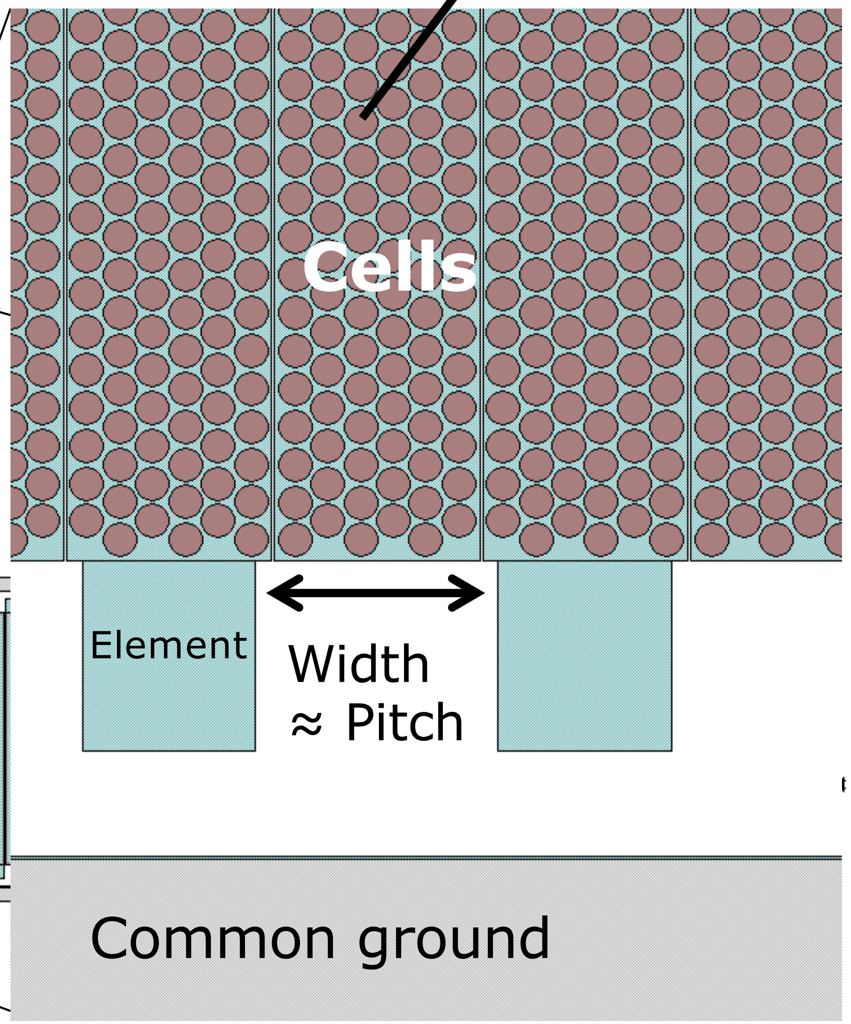




The cell is the building block

1-D array





CMUT design questions

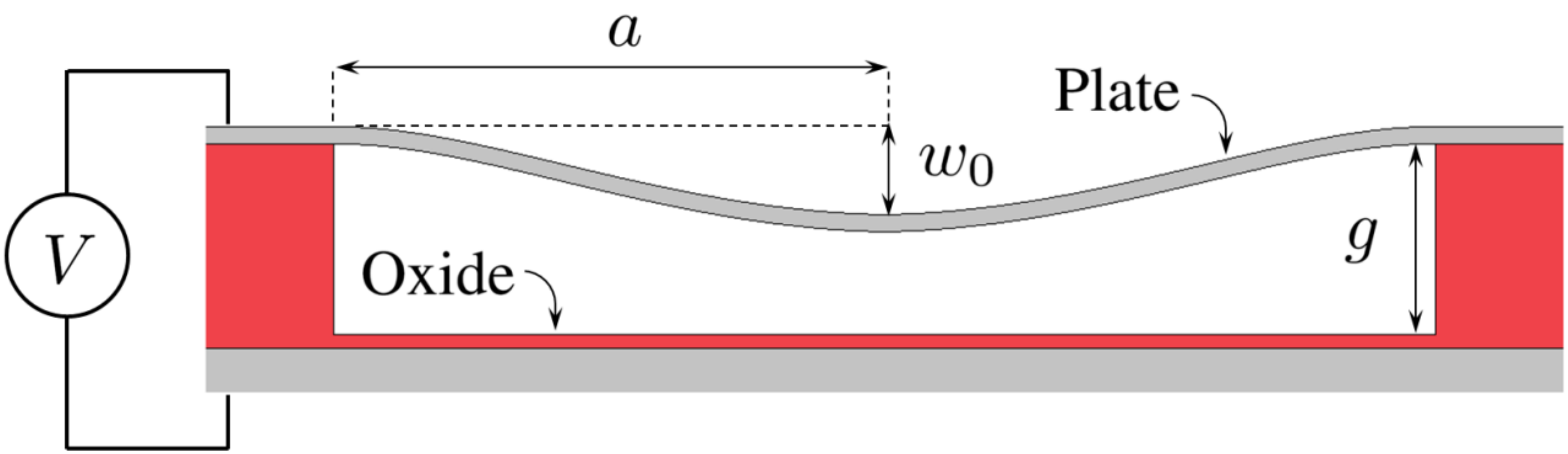
The CMUT designer must choose dimensions and fabrication technology.

Given:

- Array type (linear, row-column, …)
- Center frequency in water, f_{water}
- Pitch (λ or λ/2 or …) , *p*
- DC and AC voltages

One must find:

- How to layout the cells
- Plate radius, *a*
- Plate thickness, *h*
- Vacuum gap, *g*



Basic CMUT cell design equations

Circular plate
vacuum resonant frequency:

$$f_r = \frac{10.2158}{2\pi}\sqrt{\frac{h^2 Y}{12(a^4(1-\nu^2)\rho)}}$$

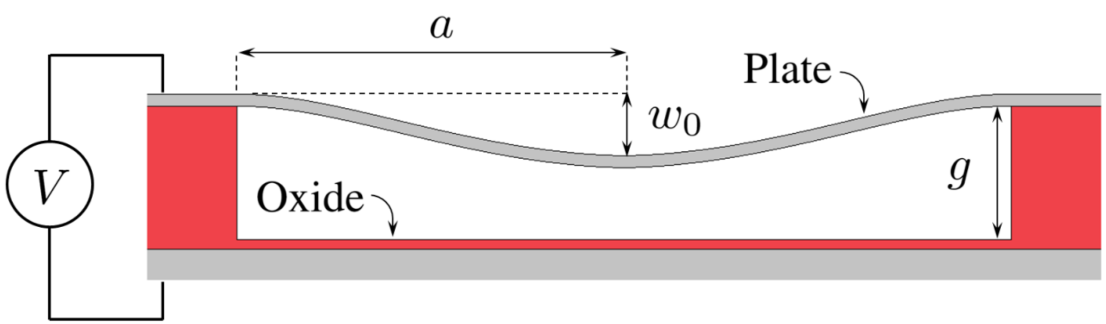
Circular plate
resonant frequency in water:
(Lamb 1920)

$$\frac{f_{water}}{f_r} = \frac{1}{\sqrt{\frac{a}{h}\frac{\rho_{water}}{\rho_{plate}}\Gamma + 1}}$$

Ratio is around ½, i.e., the resonant frequency is water is half that in vacuum

Circular plate
pull-in voltage:

$$V_{pi} = \sqrt{\frac{2.373 g^3 h^3 Y}{a^4(1-\nu^2)\epsilon}}$$



g = gap

h = plate thickness

a = radius

Y = Young's modulus, ~148 GPa

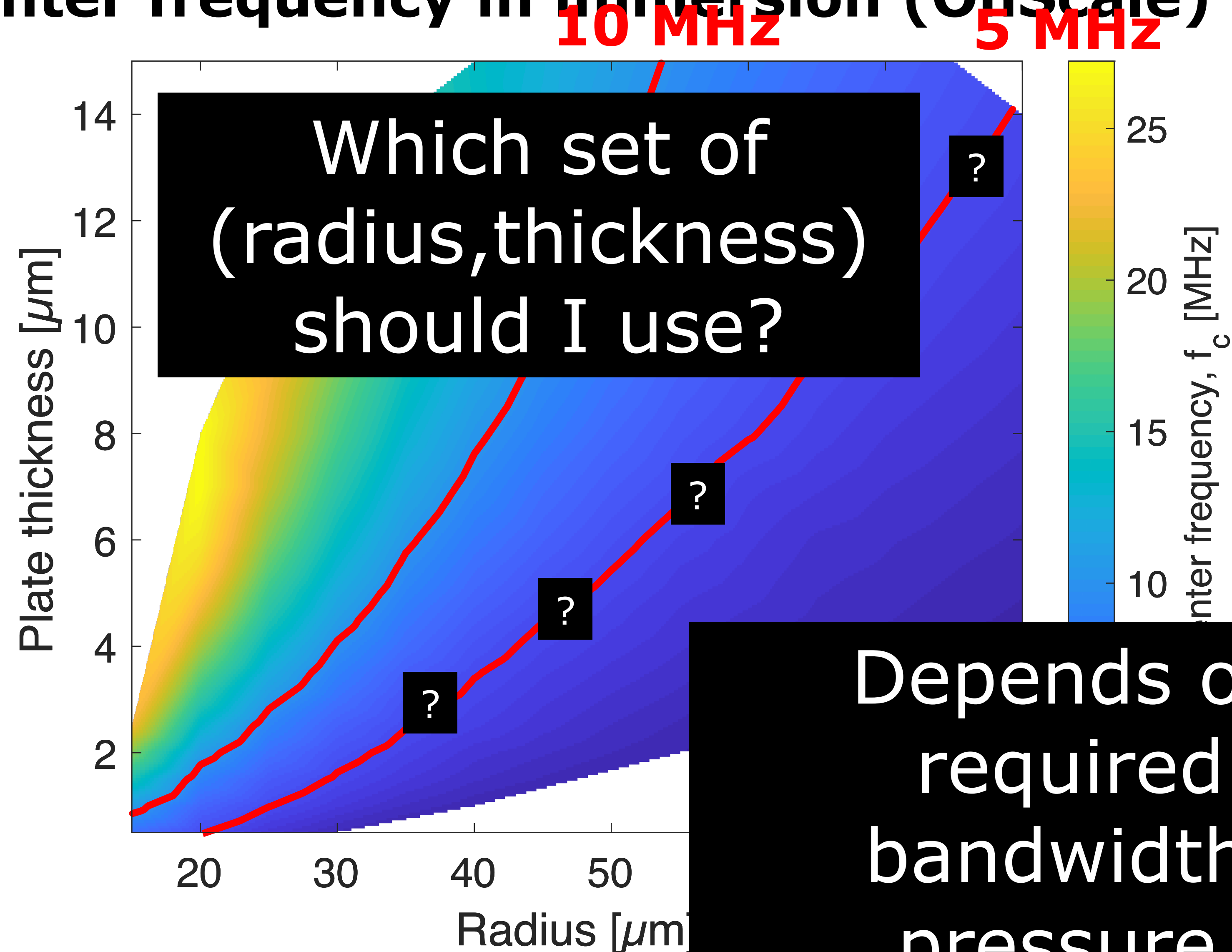
ν = Poisson's ratio, ~ 0.17

ρ = Plate density, ~ 2.33 g/cm^3

ε = Vacuum permittivity

Γ = 0.6689

Center frequency in immersion (OnScale)



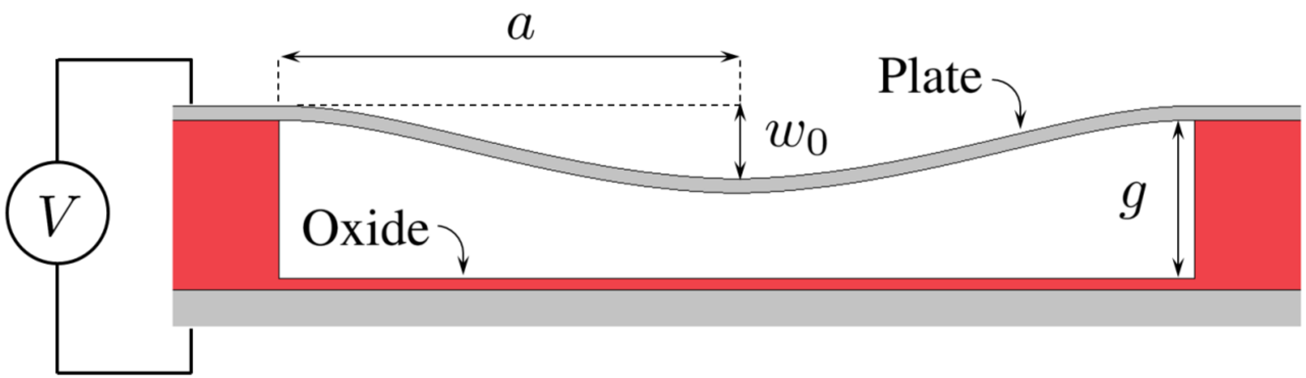
Which set of (radius,thickness) should I use?

Depends on required bandwidth, pressure, sensitivity

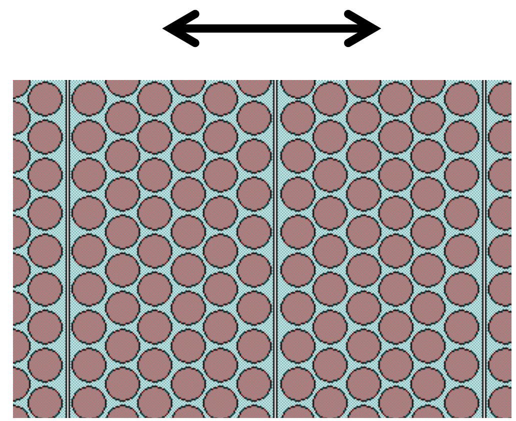
Center frequency depends both on radius an

Basic CMUT design methodology

1) Calculate pitch (λ or λ/2 or …) from wavelength in the media
2) Calculate element width (kerf almost zero or even negative)
3) Choose 2D cell layout (cell pitch, circles, squares, hexagonal …)
4) Fit circles into the element and determine radius, *a*
5) Find the plate thickness, *h*, to match immersion frequency
6) Select pull-in voltage ≈ 1.25 × V_{DC}
7) Adjust gap, *g*, to reach pull-in voltage
8) Check performance (bandwidth, pressure, PE sensitivity)
9) Check for substrate ringing and array effects ("Bragg" frequency)
10) If (performance < specs) goto 3
11) Check design with a full Finite Element model



Width ≈ Pitch = λ/2



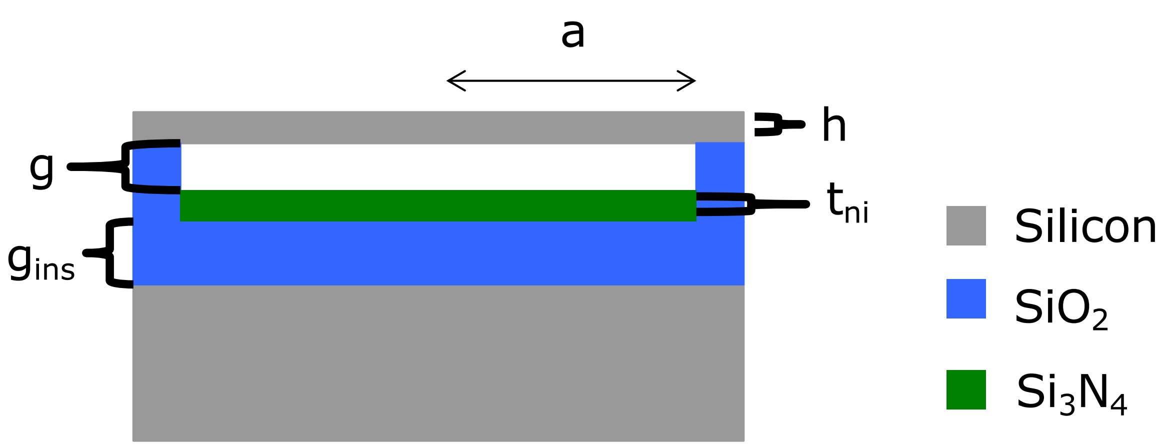
CMUT Design Example - Dimensions

- Available plate thickness, h = 2.2 +/- 0.5 μm
- Center frequency = 5 MHz

→ Circular plate size, a = 24.3 μm

- Desired pull-in voltage = 240 V

→ Vacuum gap height, g = 260 nm
→ Insulating oxide thickness, g_{ins} = 380 nm
→ Nitride layer, t_{ni} = 50 nm



Complication:

Cells interact!

(Array effects)

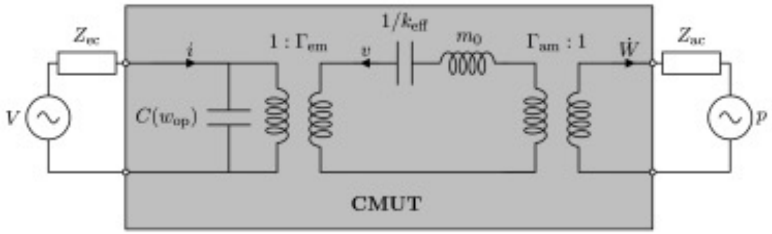
Advanced modelling needed

FEM simulations – PZFLEX/OnScale/COMSOL models

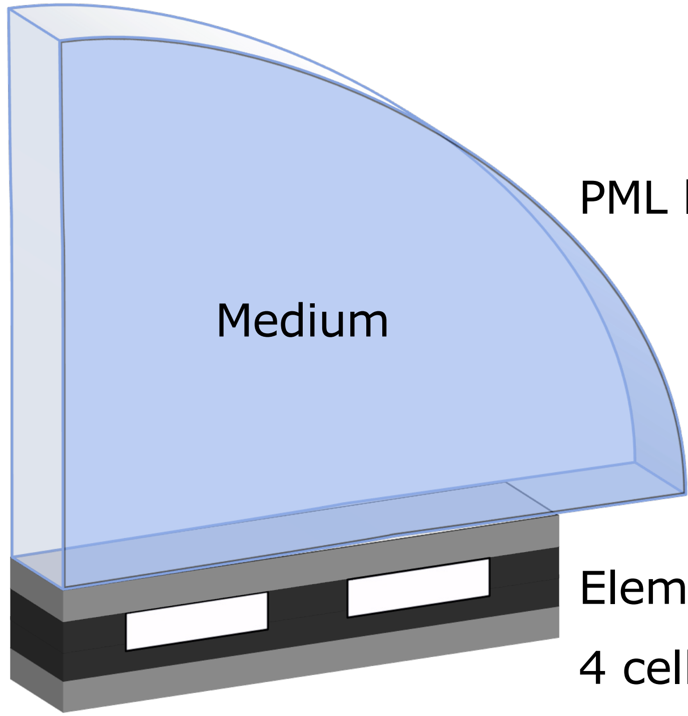
Physics: Electrostatic, mechanical and acoustical

Solvers: Frequency domain and transient

Aim: Frequency spectrum and transient response



Lumped element modeling



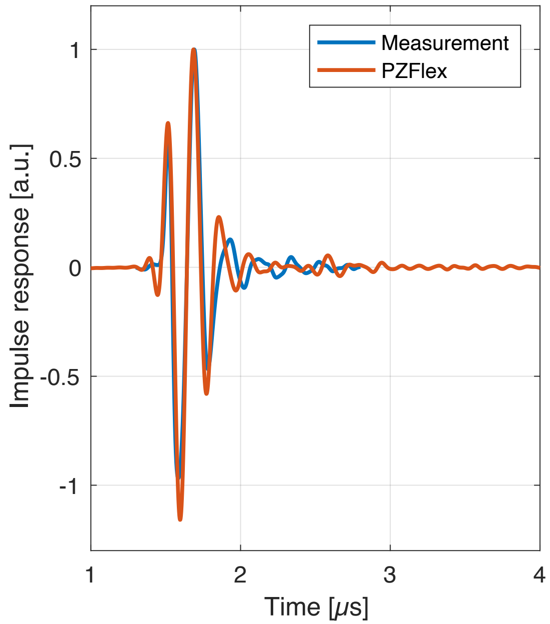
PML layer

Element with

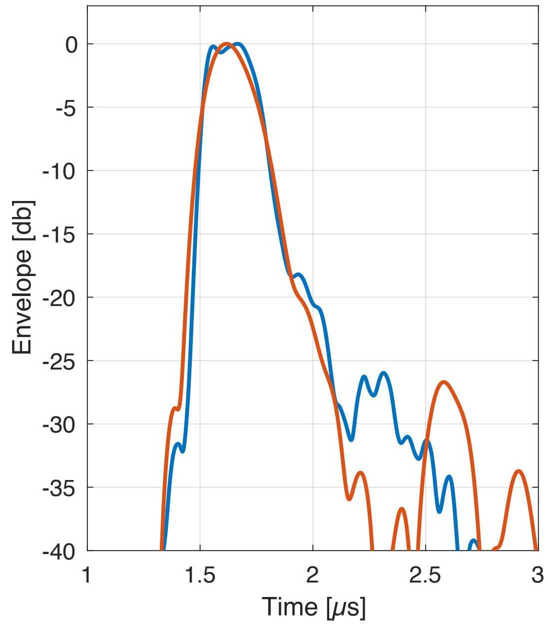
4 cells in width

Simulation & experiment fit well

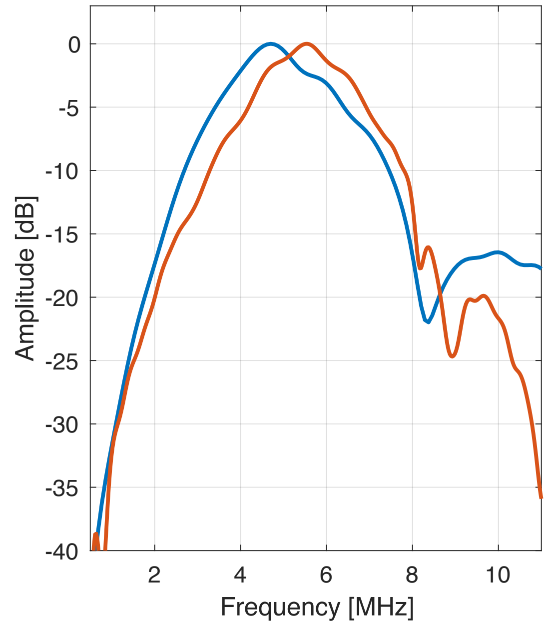
Impulse response signal



Envelope

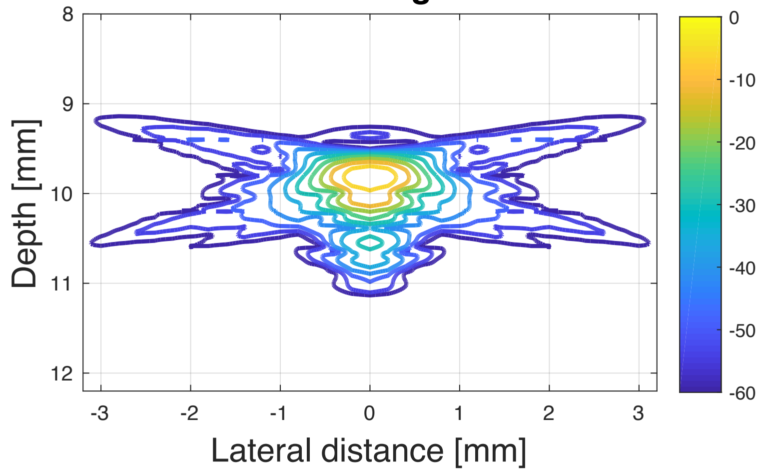


Frequency spectrum



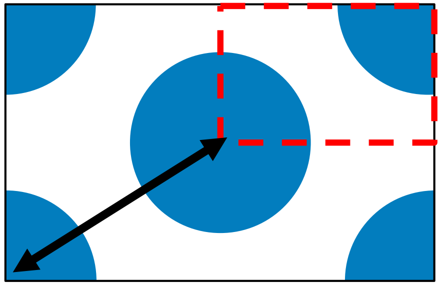
→ Field II

Point target



Optimization of a CMUT device

- Model
  - Infinite array
  - Circular cells placed in a hexagonal grid
  - Simulating one unit cell



Cell pitch

- Results
  - Impulse response
    - Transmit
    - Receive
  - Sensitivity
  - Plate velocity at center
  - Pressure
  - Acoustic impedance

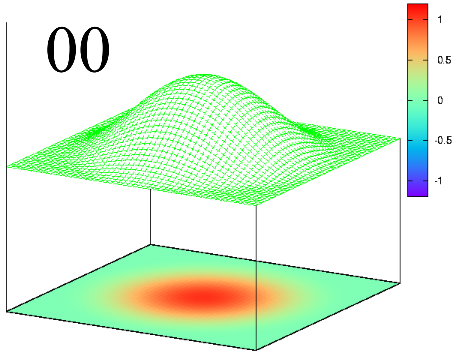
Three cell and array effects

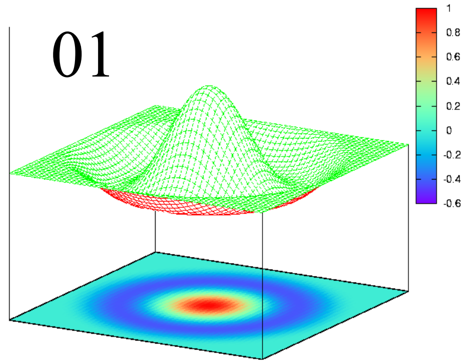
1) Plate vibration modes

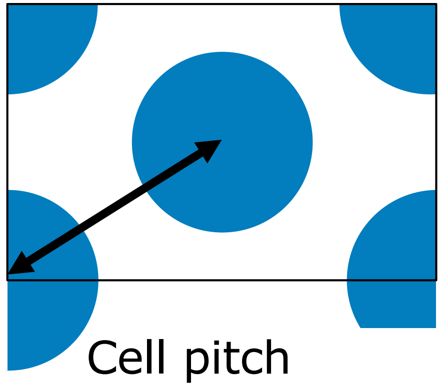
2) Mutual couplings: “Bragg frequency”,
f_b= (Speed of sound) / (cell pitch)

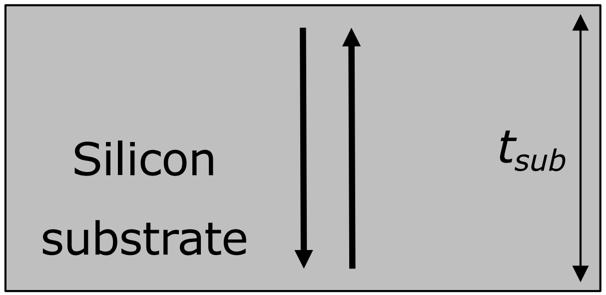
3) Substrate ringing

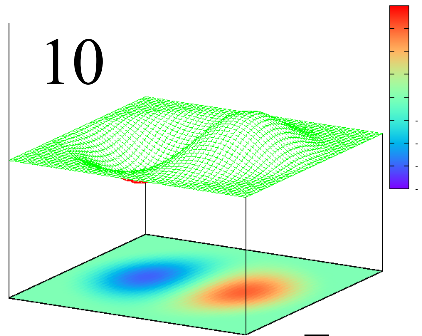
f_s= (Si Speed of sound) / (2 t_{sub})

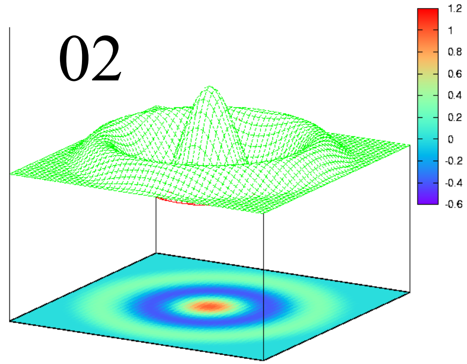










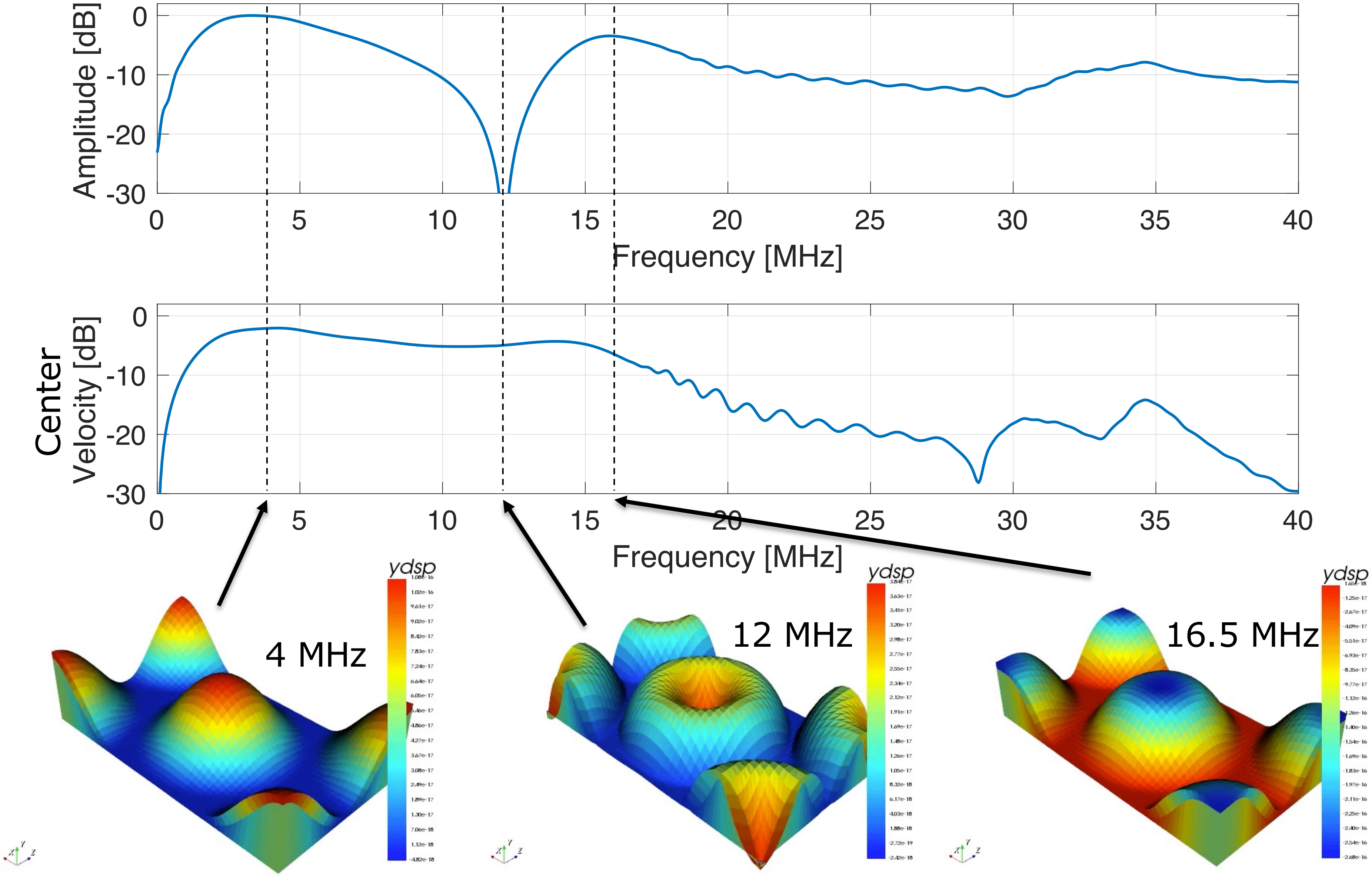


Zero pressure

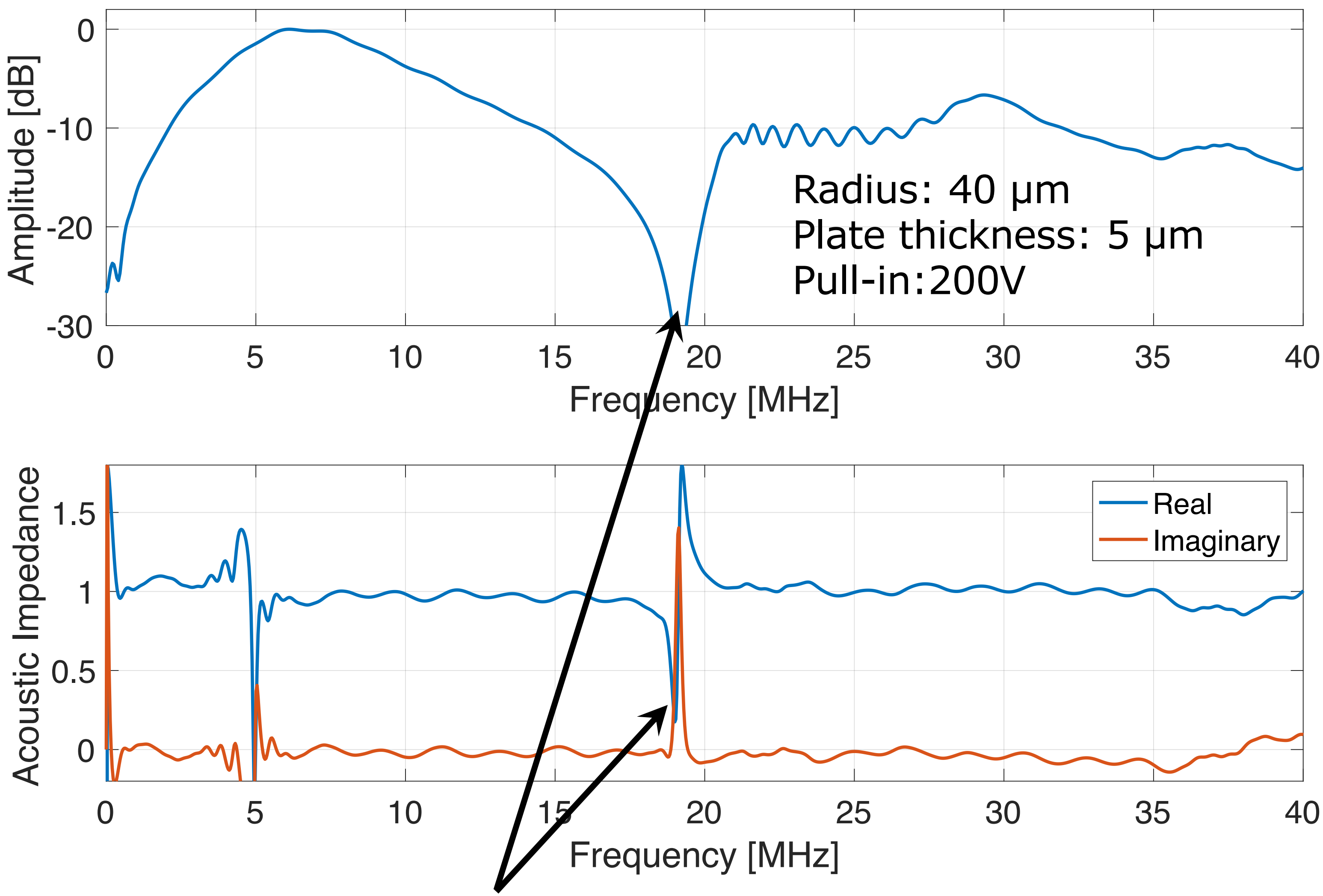
Mode shapes

Radius: 50 μm

Plate thickness: 4 μm



Output of <u>One Transmit</u> Simulation



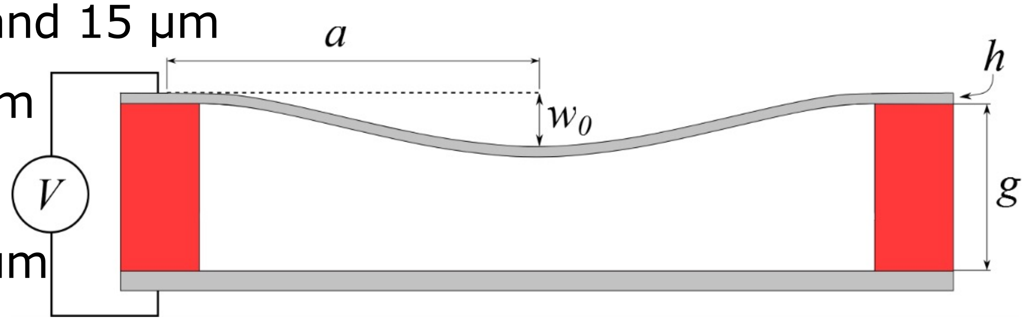
Frequency dip = (Speed of sound) / (cell pitch) =~18 MHz

*Meynier, Cyril, Franck Teston, and Dominique Certon. "A multiscale model for array of capacitive micromachined ultrasonic transducers." *The Journal of the Acoustical Society of America* 128.5 (2010): 2549-2561.

Parametric Sweep

Parameters

- Plate thickness between 0.5μm and 15 μm
- Radius between 10 μm and 80 μm
- Fixed pull-in voltage at 200 V
- Fixed distance between cells, 5 μm
- Constant electrode area, 1 cm^2
- Both transmit and receive



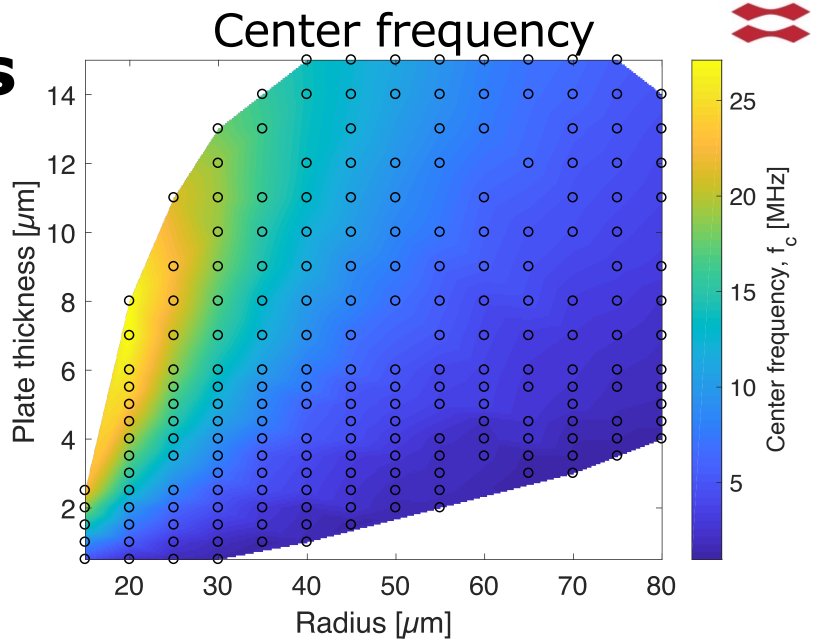
Total of 567 simulations

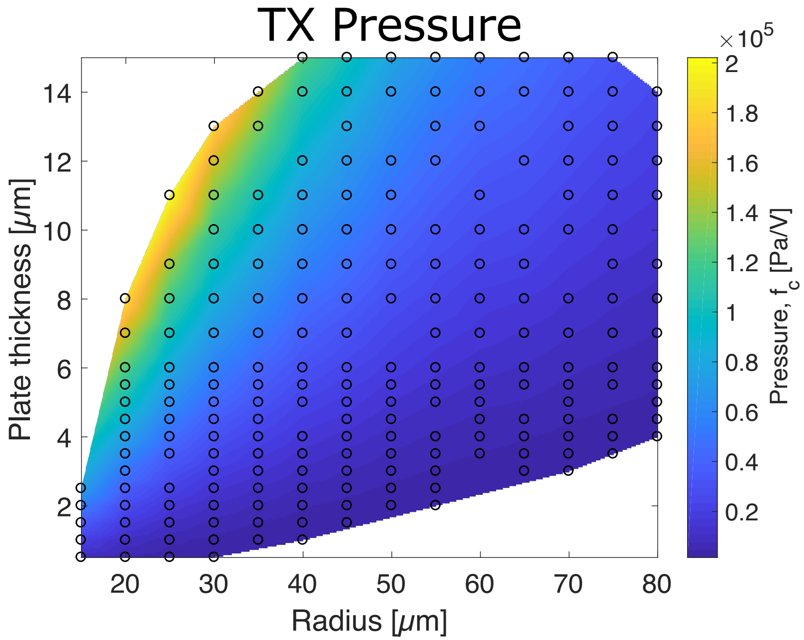
Simulation time

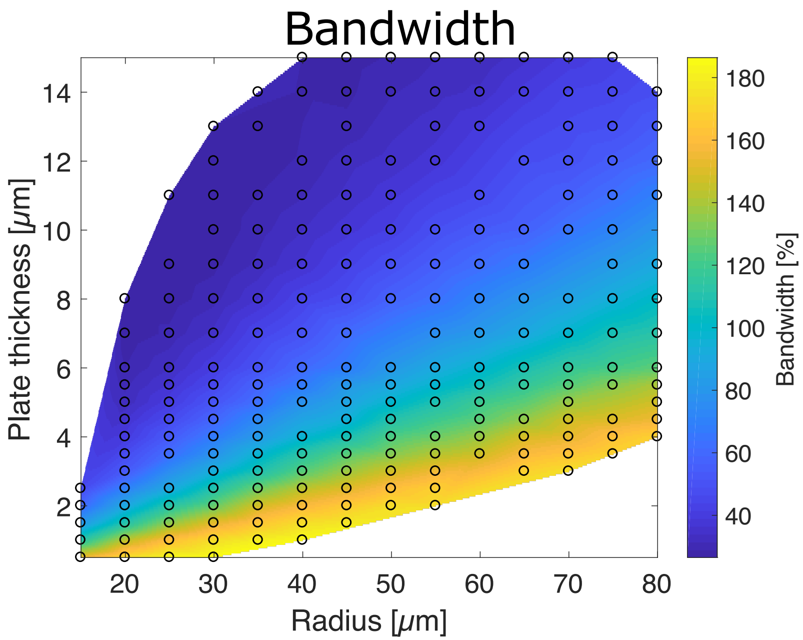
- Personal computer (8 cores, 64GB ram) : >1 week
- In the cloud: <2 hours (2 cores per simulation, parallel, ~600 core hours)

Parametric Sweep Results

- Center frequency
- Pressure
- Bandwidth





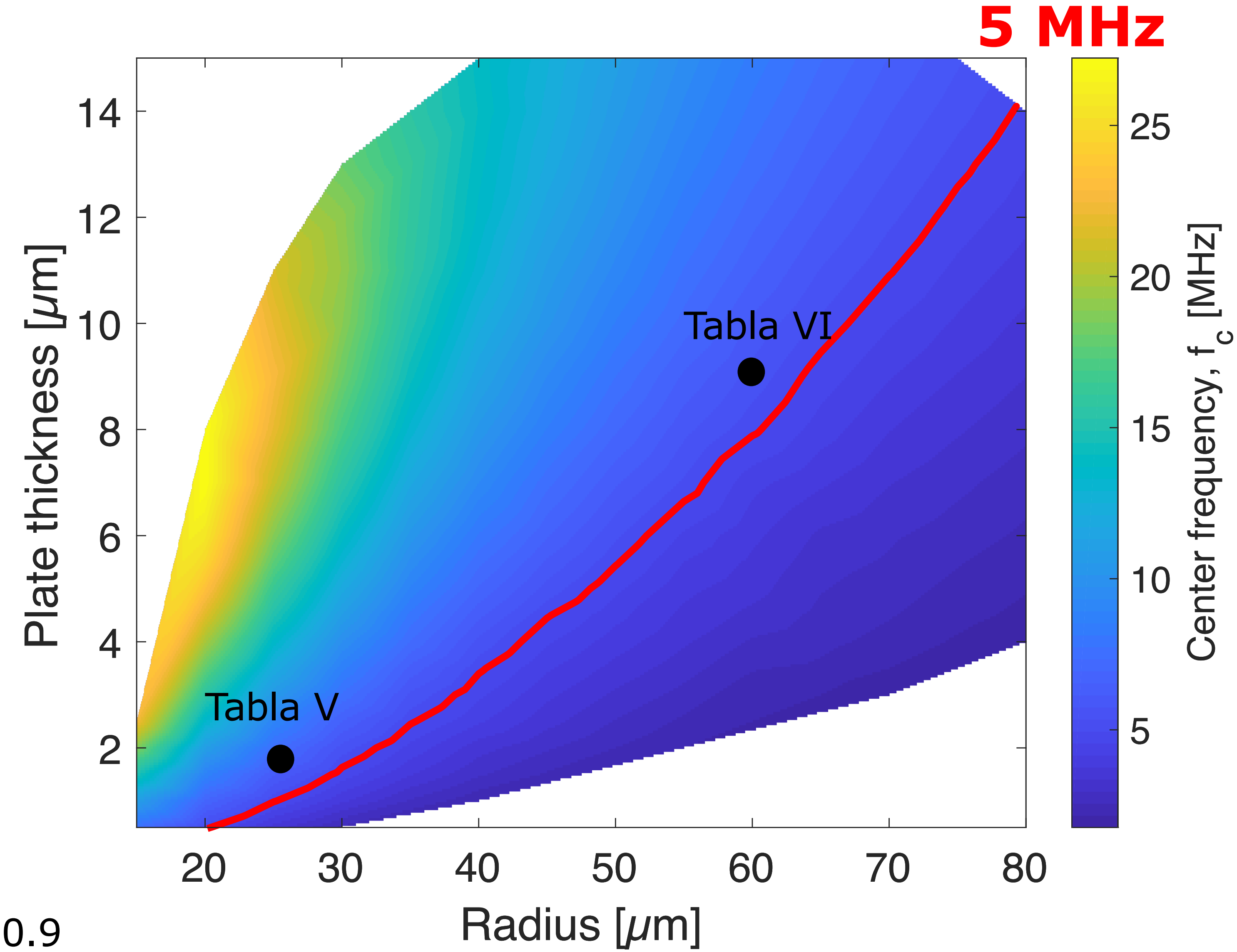


Design of a 5 MHz transducer (like Tabla V & VI)

- Optimal parameters
- Trade-offs

- Evaluate
  - Sensitivity
  - Bandwidth
  - Frequency dip
- In
  - Transmit mode
  - Receive mode
  - Pulse-echo

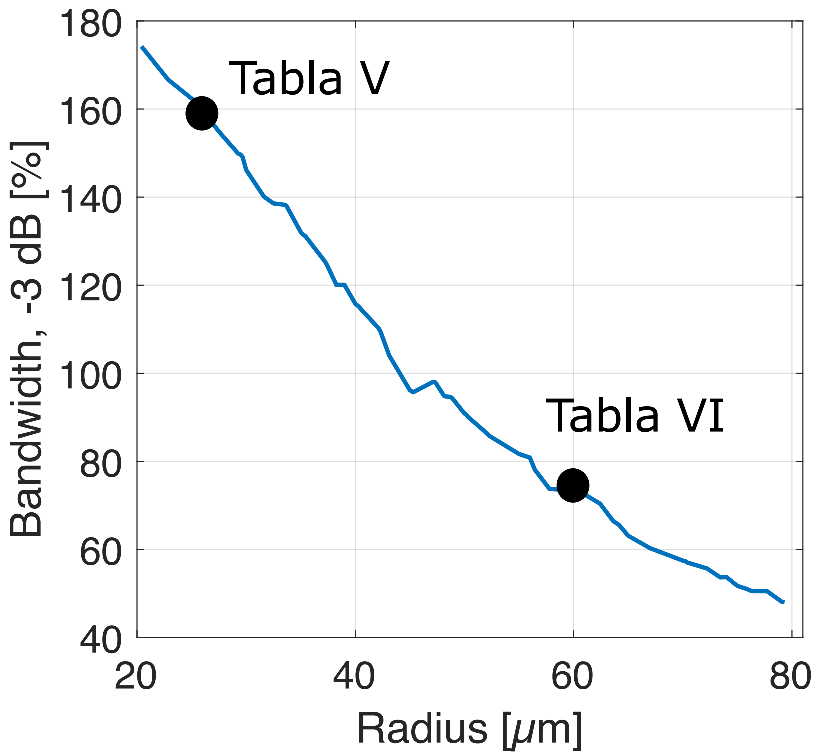
Optimize a 5 MHz transducer: Dimensions

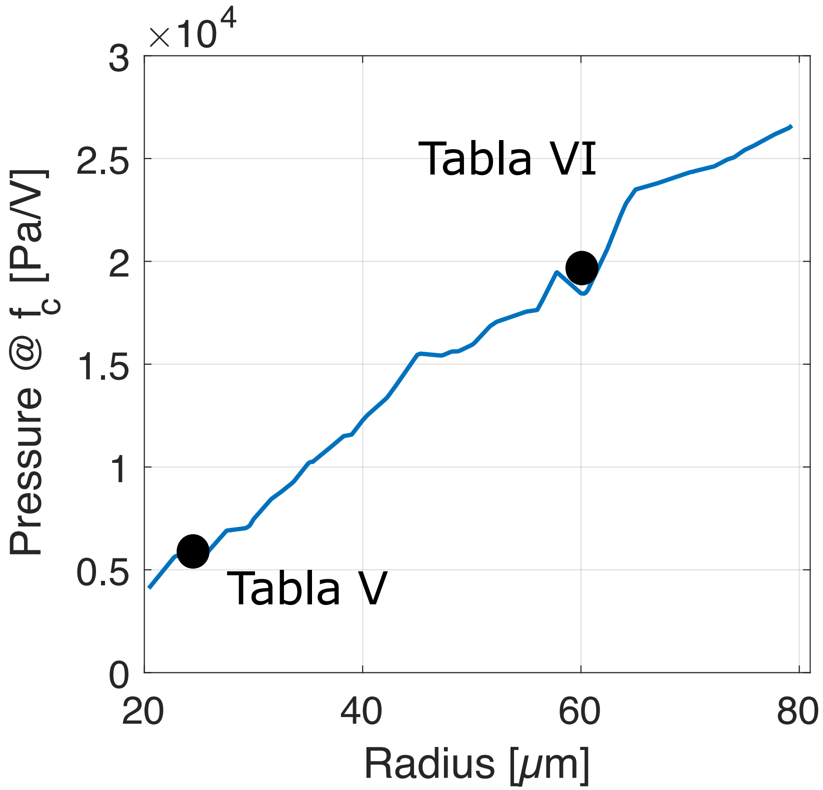


V_{pi} = 200

V_{DC}/V_{pi} = 0.9

Transmit Mode





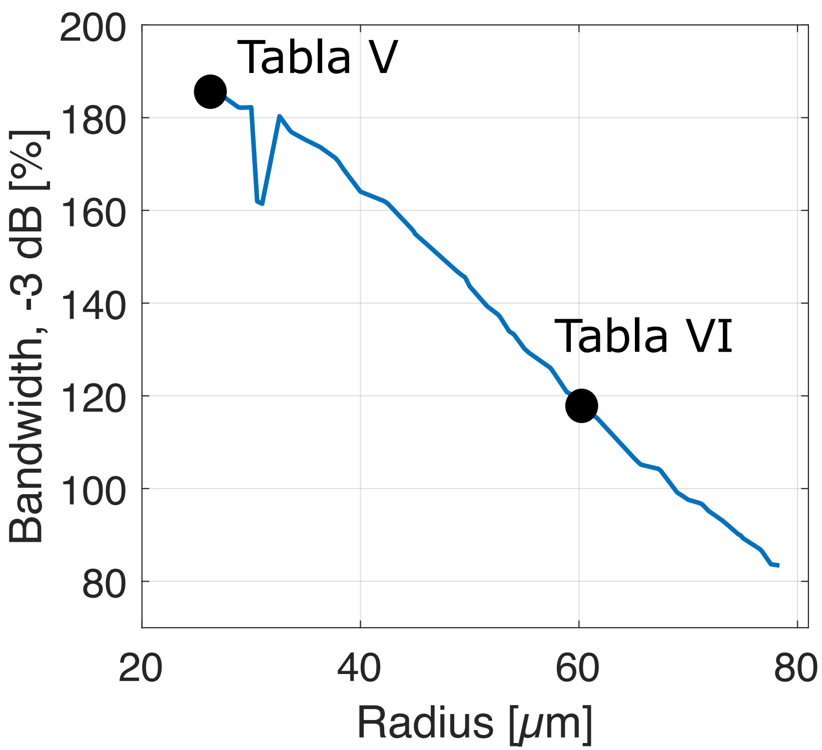
V_{pi} = 200

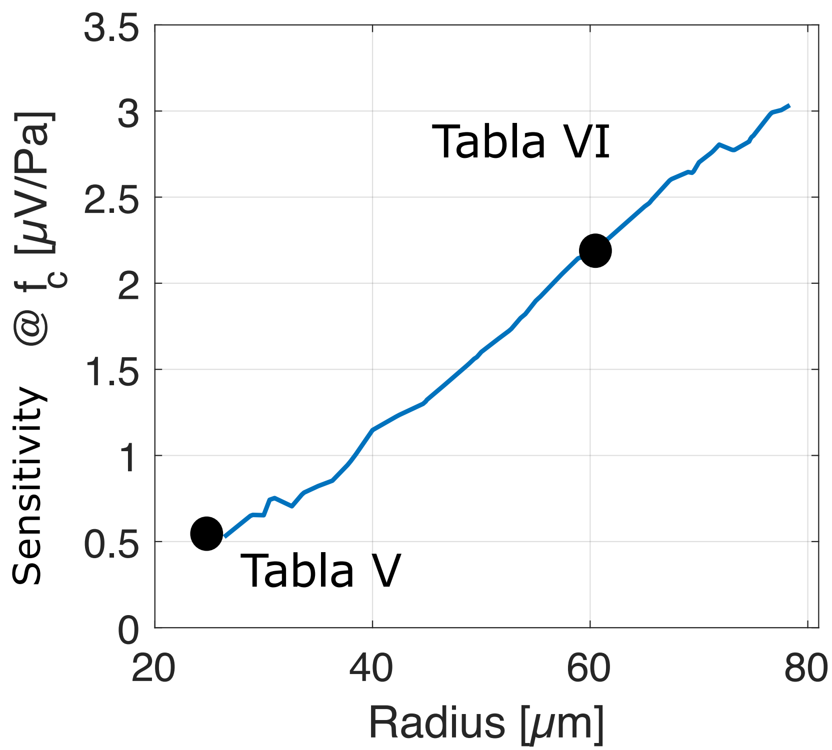
V_{DC}/V_{pi} = 0.9

f_c = 5MHz

Pressure or Bandwidth!

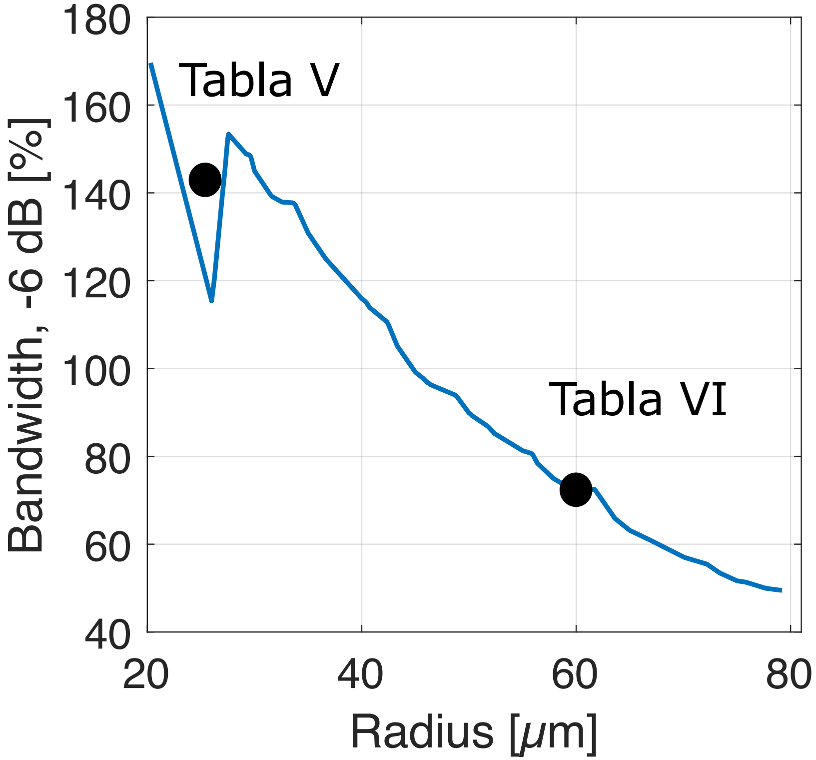
Receive Mode

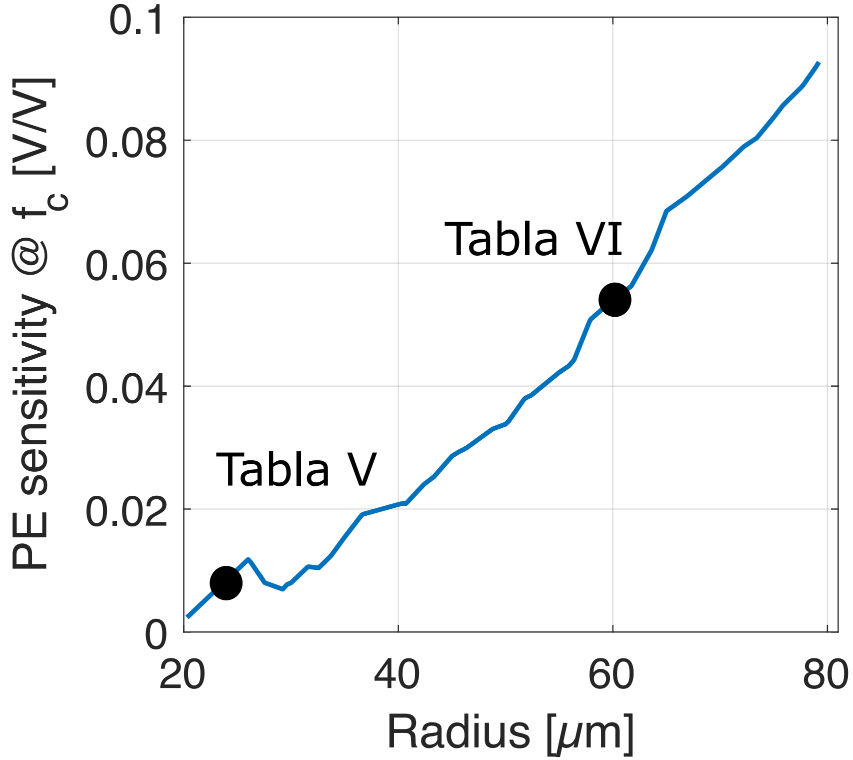




Sensitivity or Bandwidth!

Pulse-echo





<u>To summarize:</u>

Pressure, sensitivity, and PE sensitivity can be improved at the expense of bandwidth

Tabla VI

CMUT dimensions:

Cell type: Circular, Ø 120

Cell separation: 7 µm

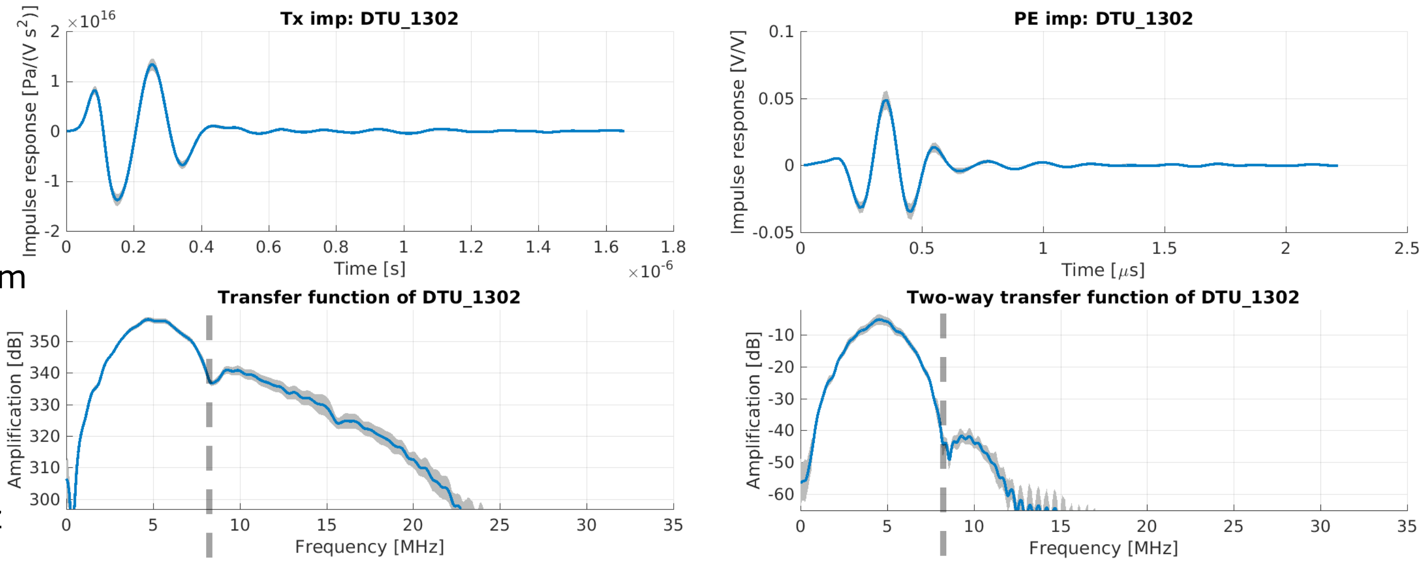
Plate thickness: 9.3 µm

Substrate thickness: 500 µm

Characterisistics:

Substrate ringing: 8.1 MHz

Bragg frequency: 11.7 MHz



Substrate ringing

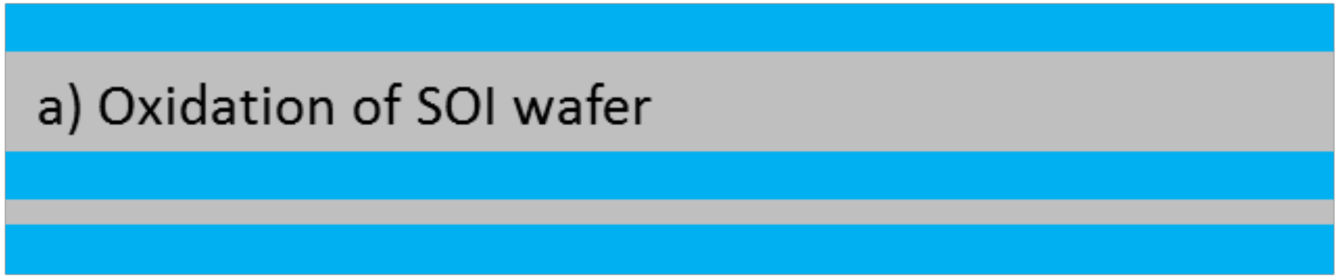
Substrate ringing

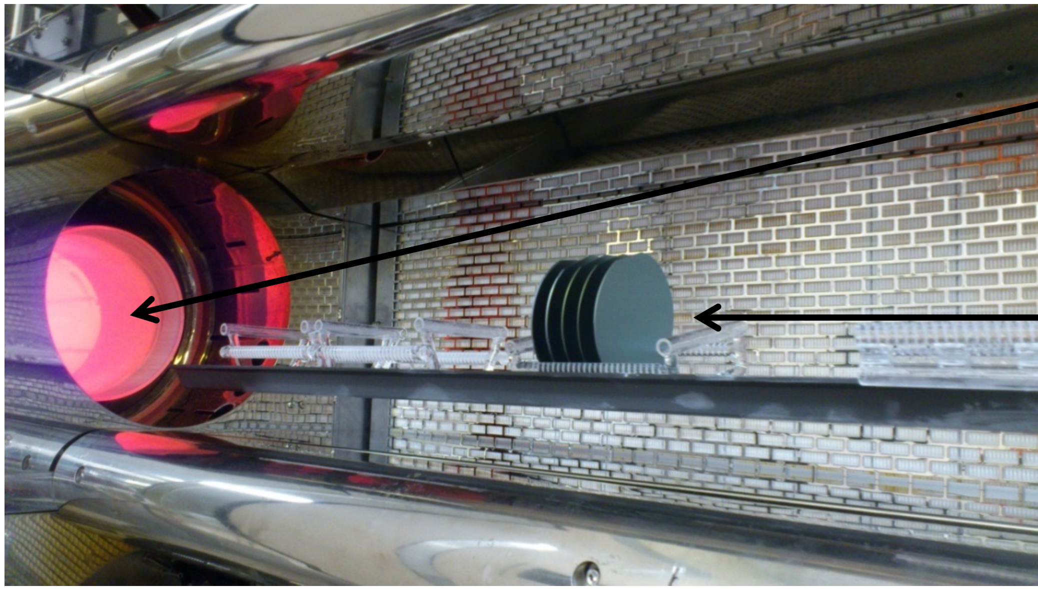
Sub - conclusion

- High performance cloud computing and OnScale enables huge parametric FEA studies
- CMUT can be optimized with respect to output pressure and receive sensitivity, but at the expense of bandwidth.
- Mutual acoustic impedance effects are captured explaining dips in frequency spectra
  - can limit bandwidth and performance if not designed properly

CMUT FABRICATION

CMUT fabrication – baseline process

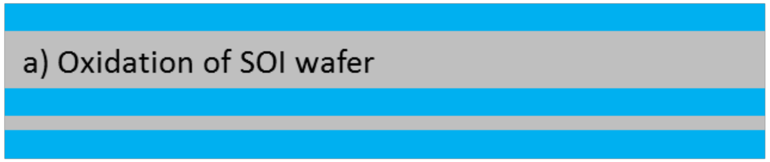


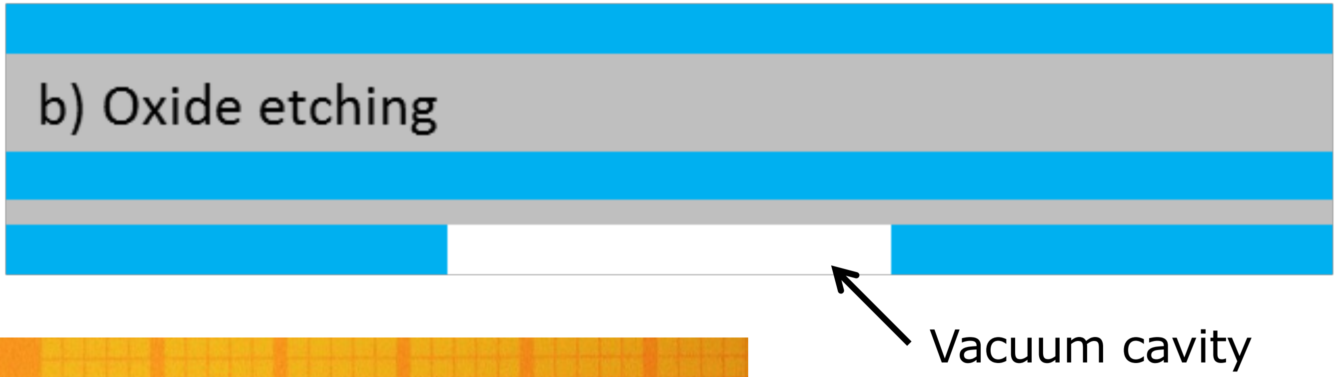


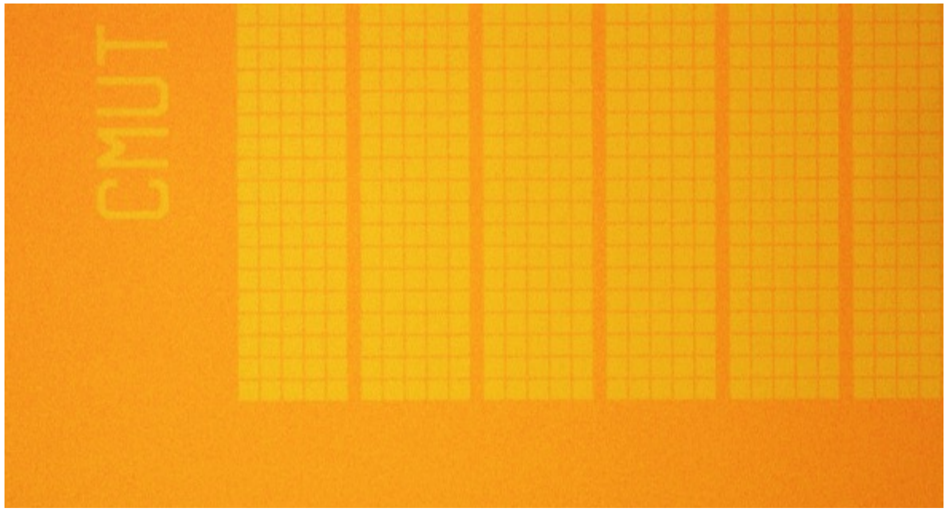
Furnace, idle temp. 800° C

Wafers

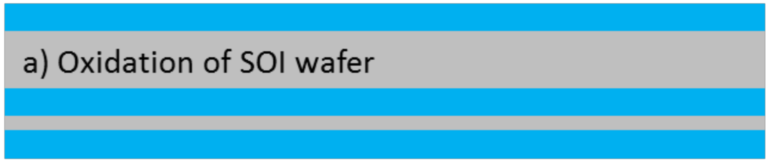
CMUT fabrication





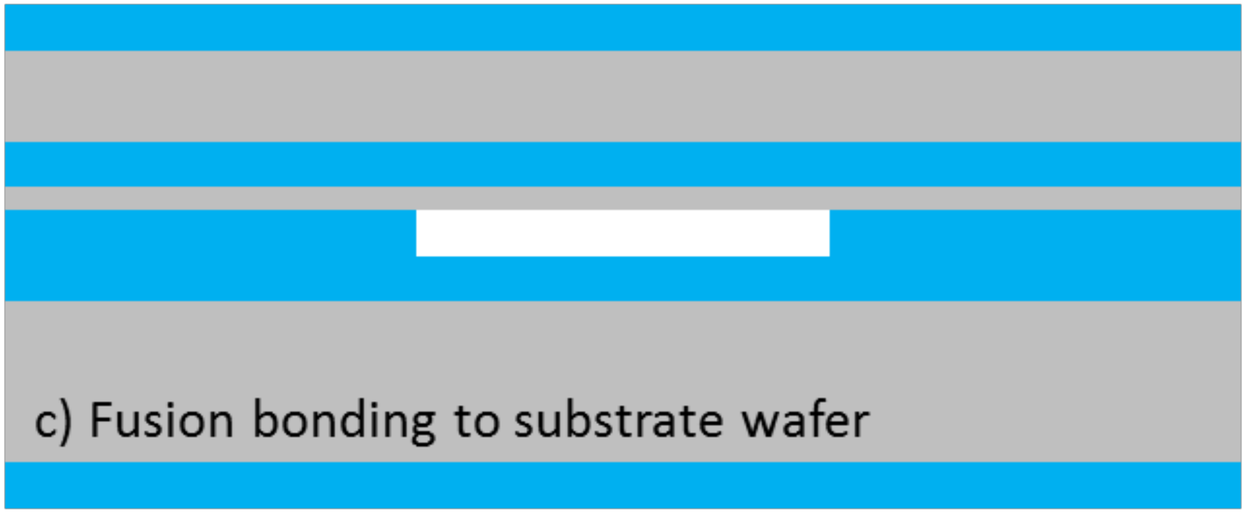


CMUT fabrication

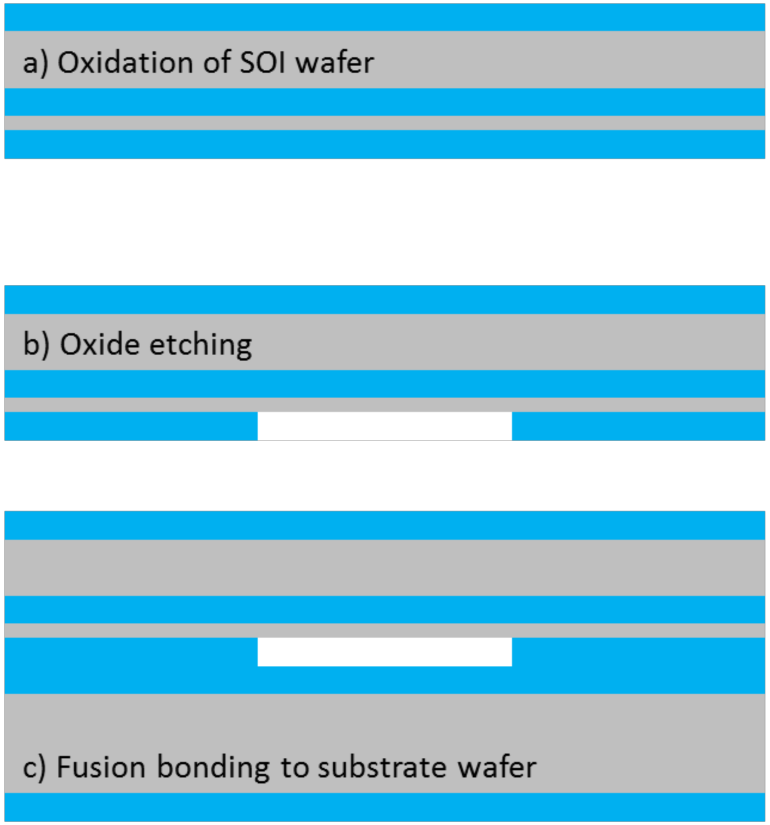


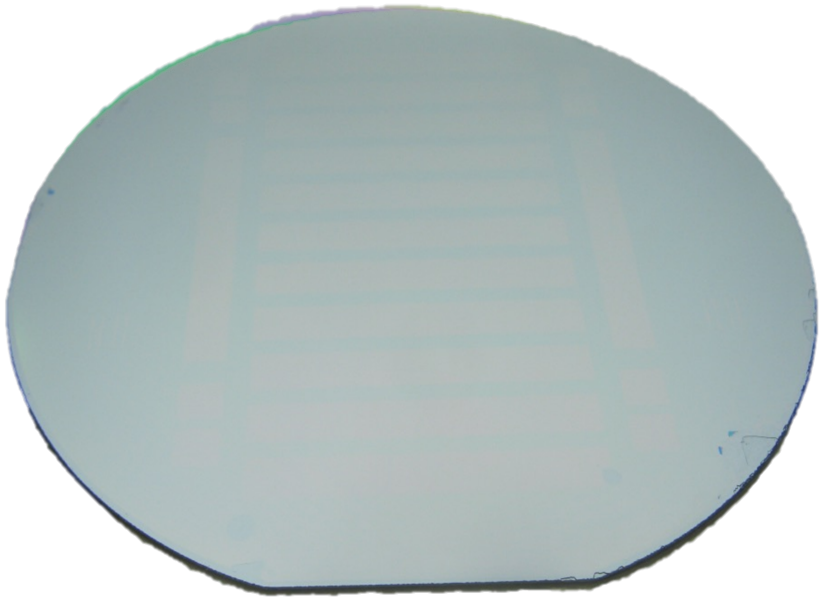
EVG 520HE at DTU: NIL & Fusion bonding

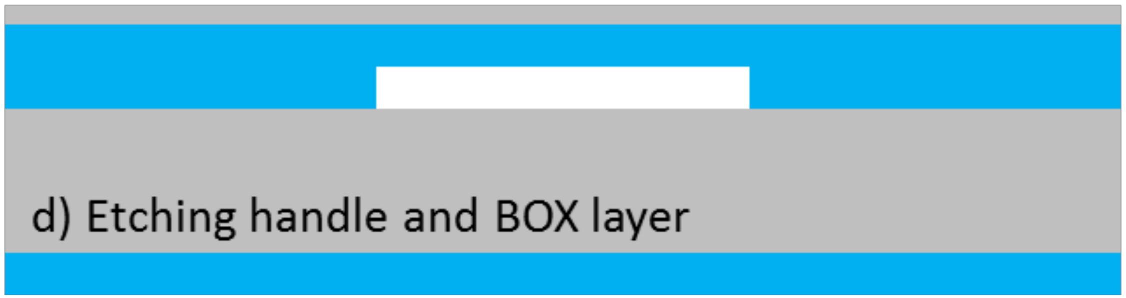
RCA cleaning before bonding



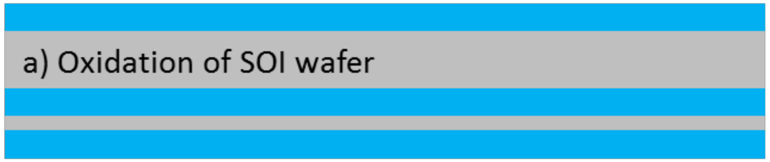
CMUT fabrication

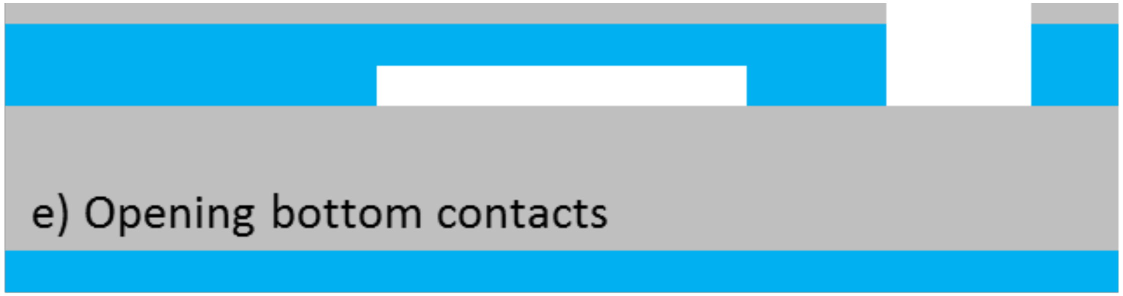


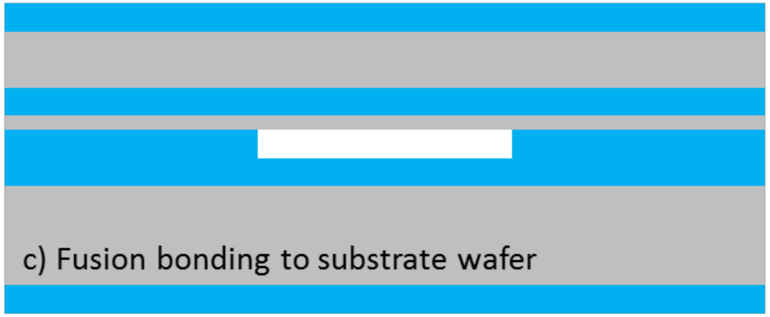


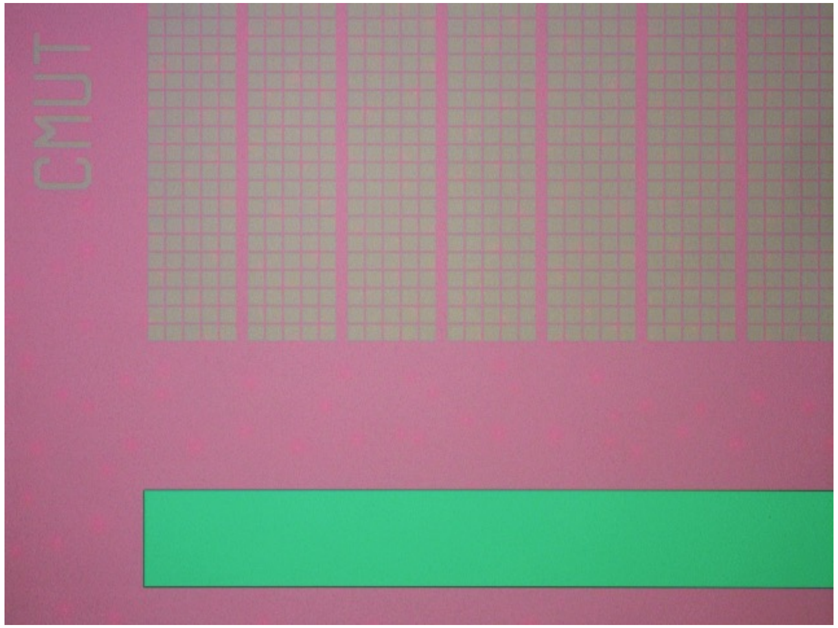


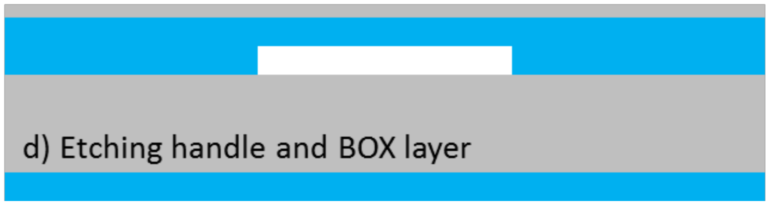
CMUT fabrication











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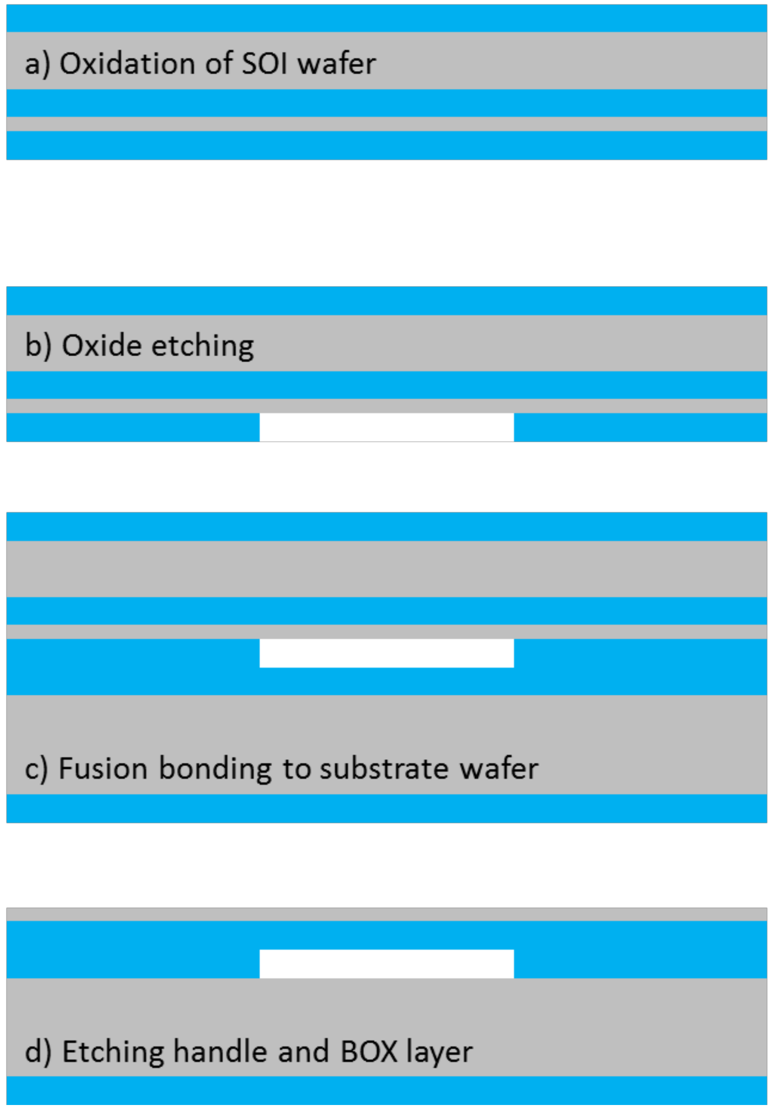
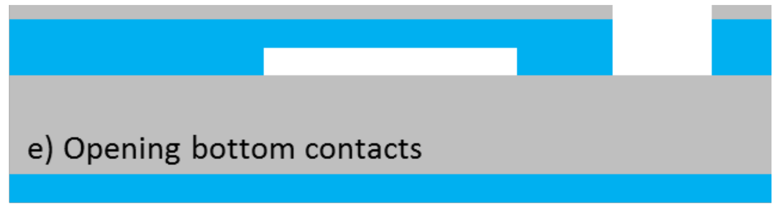
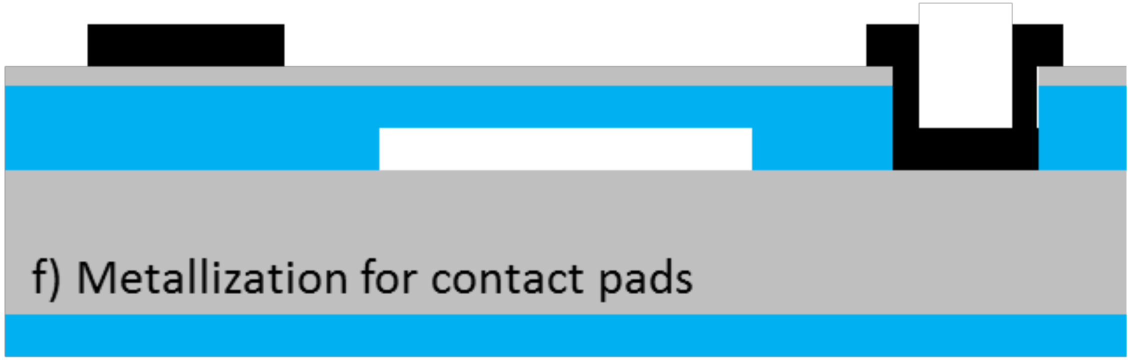
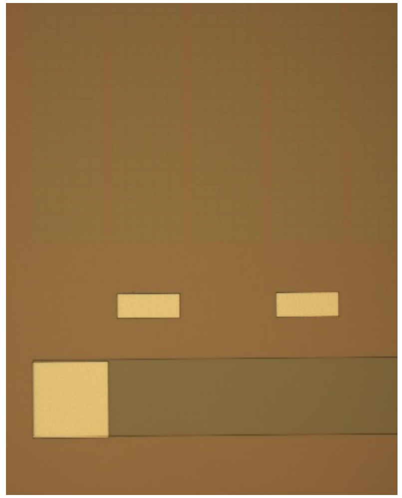
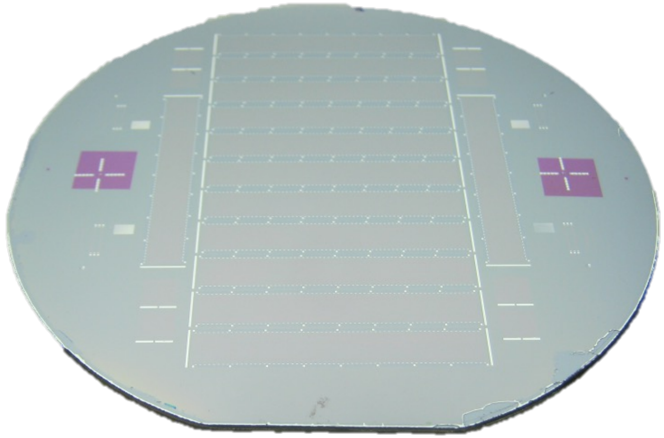


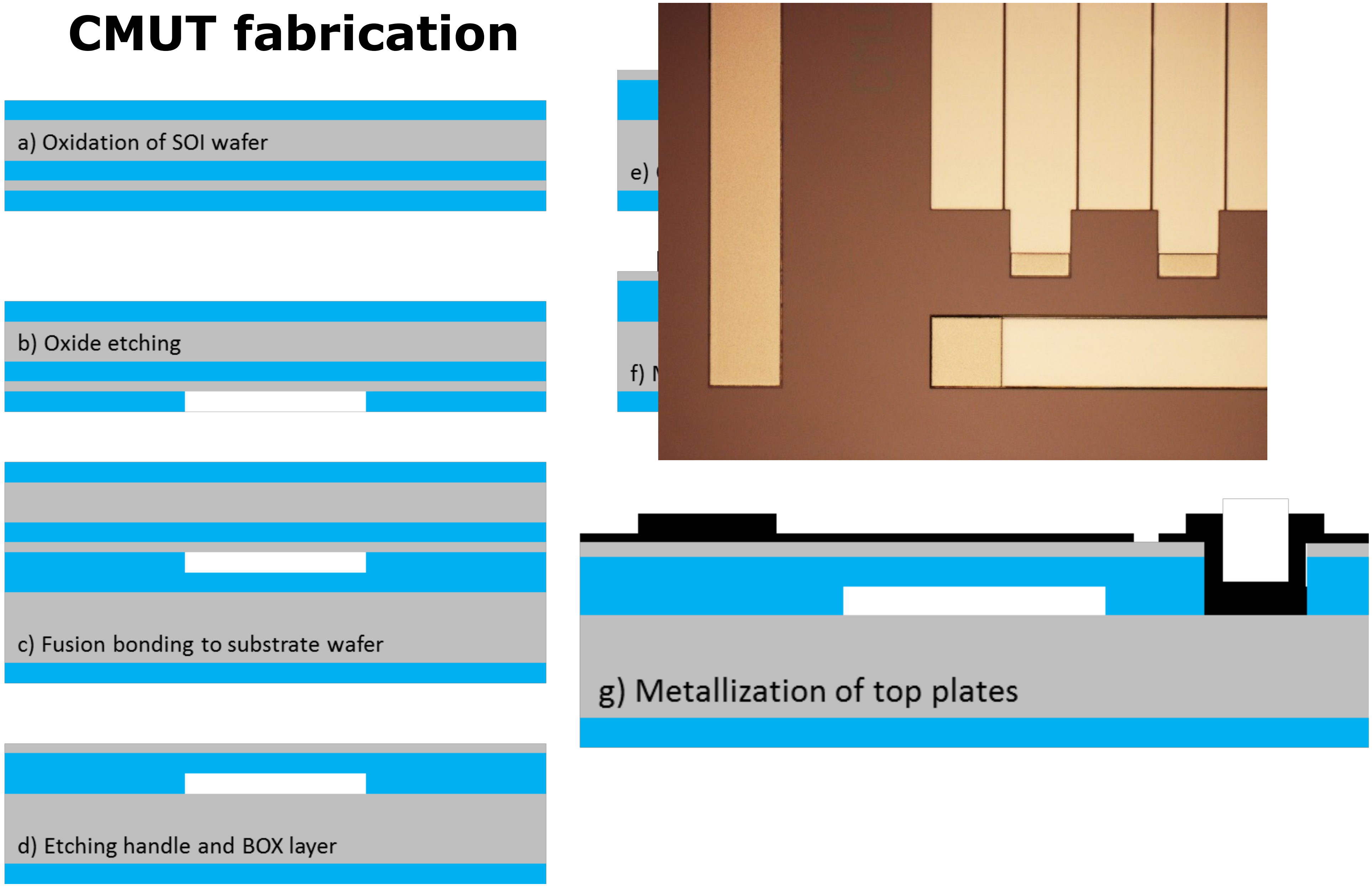




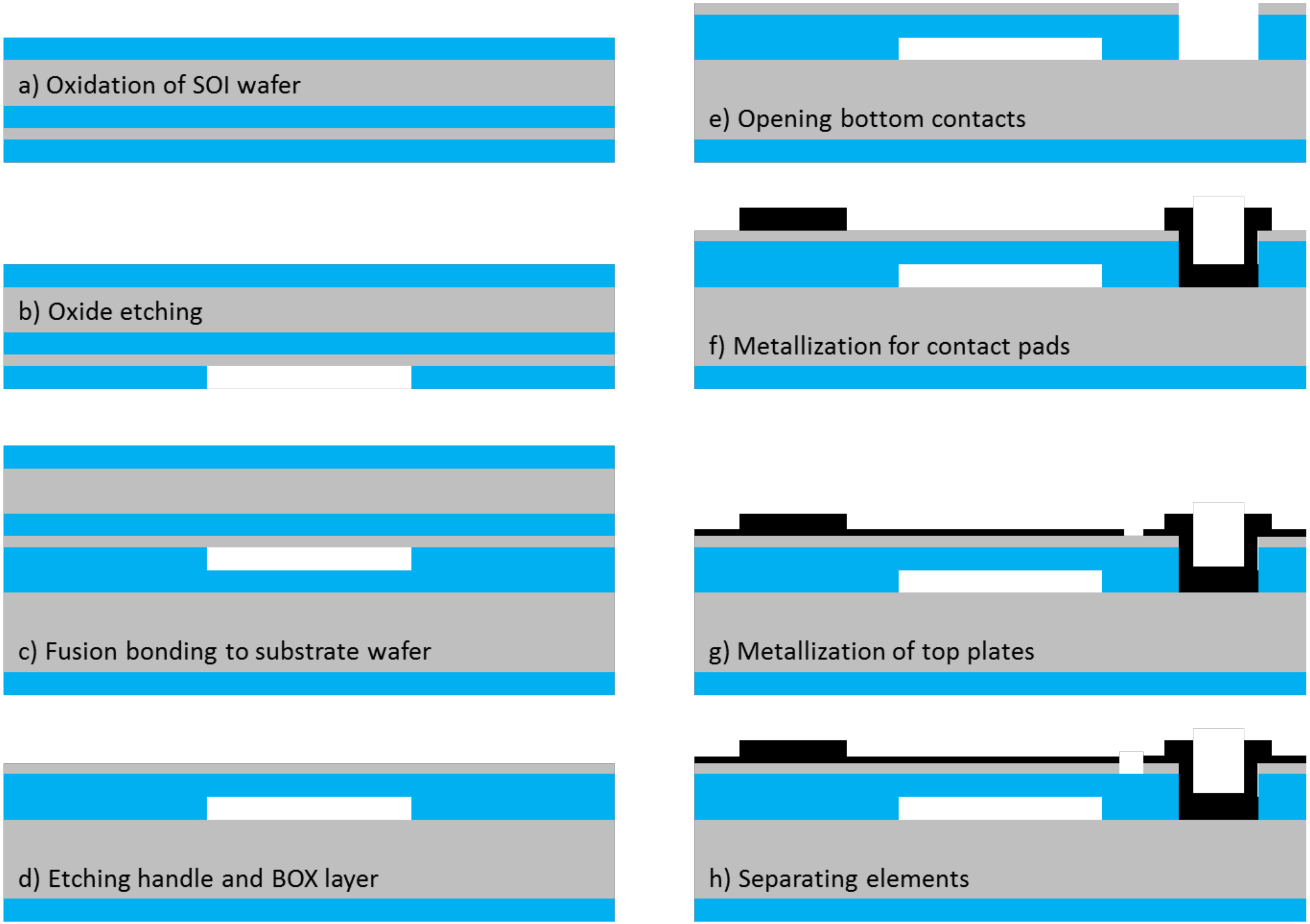




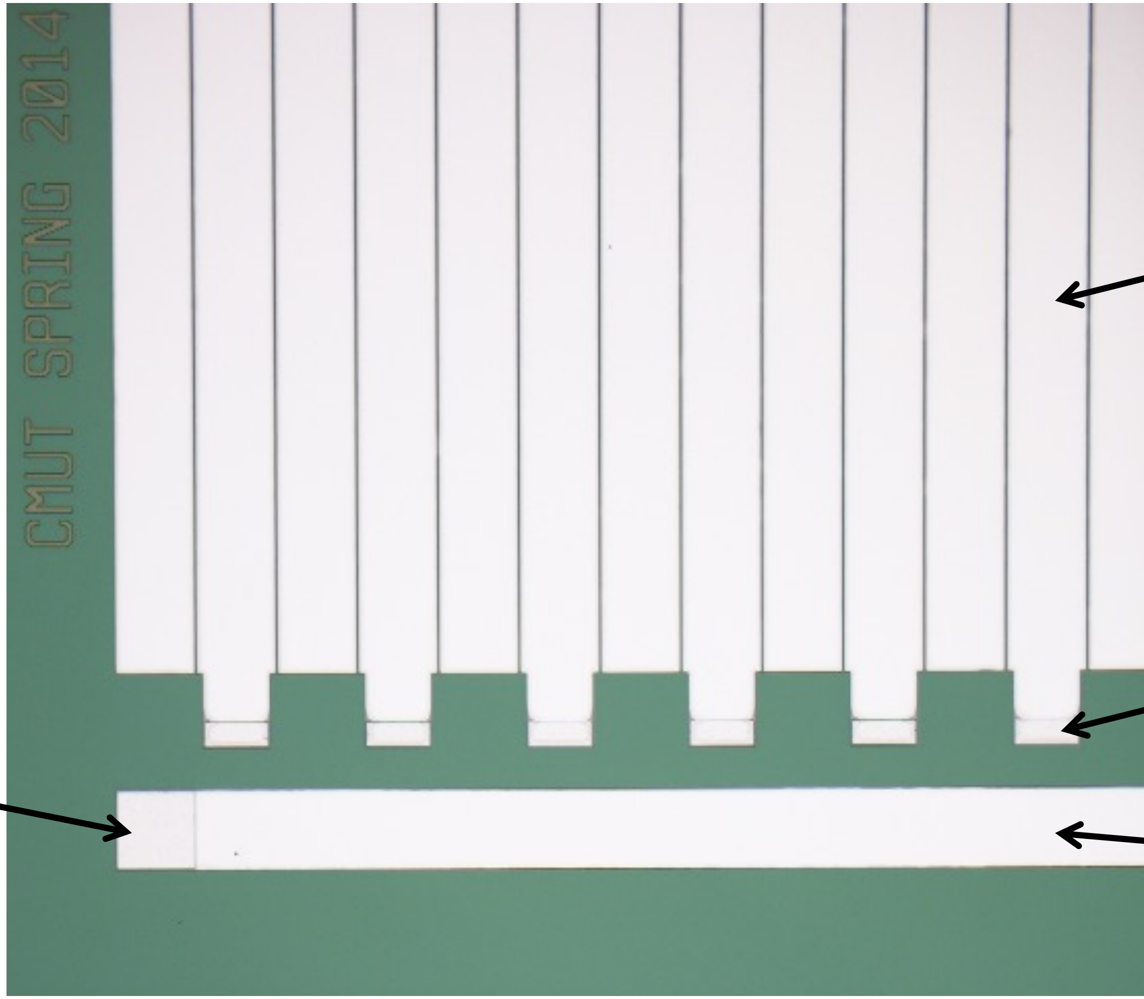
CMUT fabrication



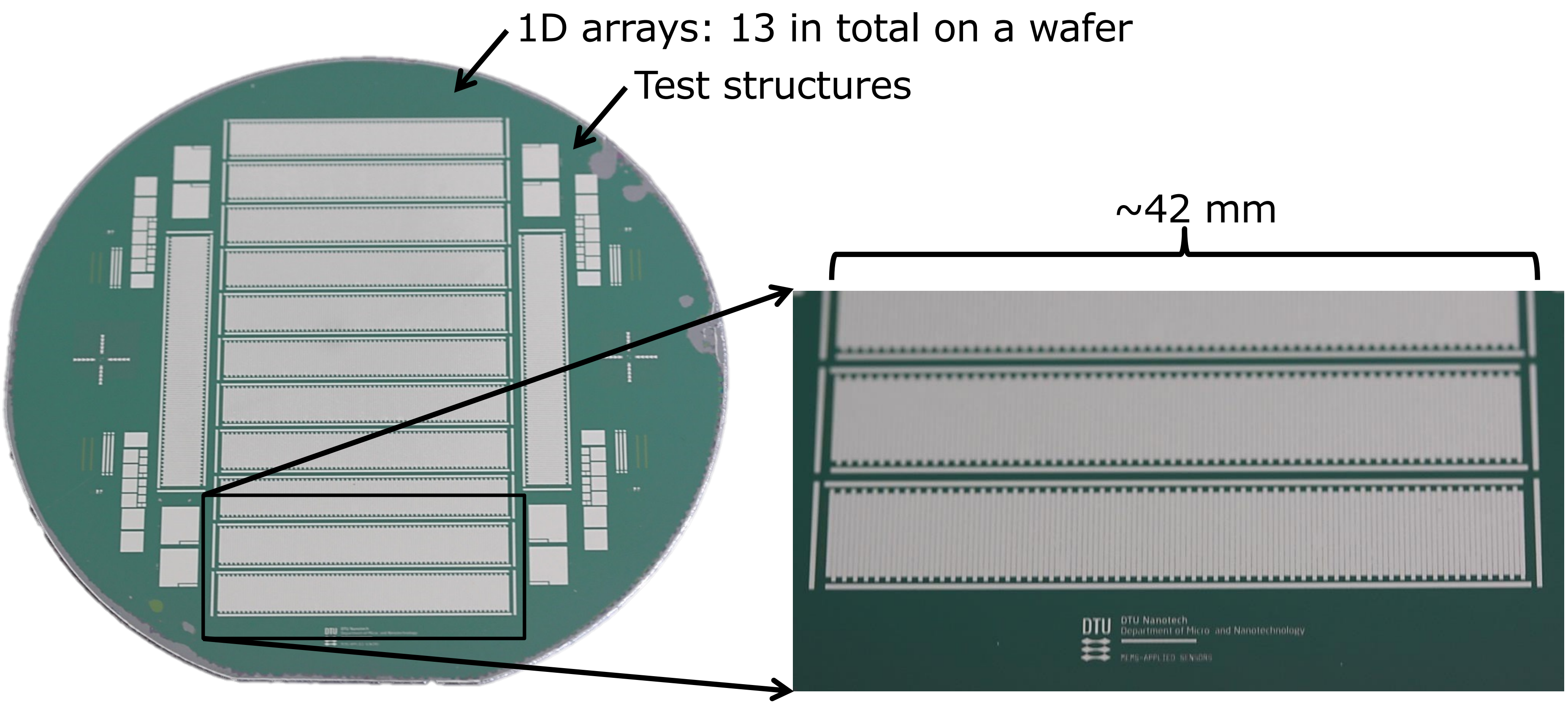
CMUT fabrication



Finished array

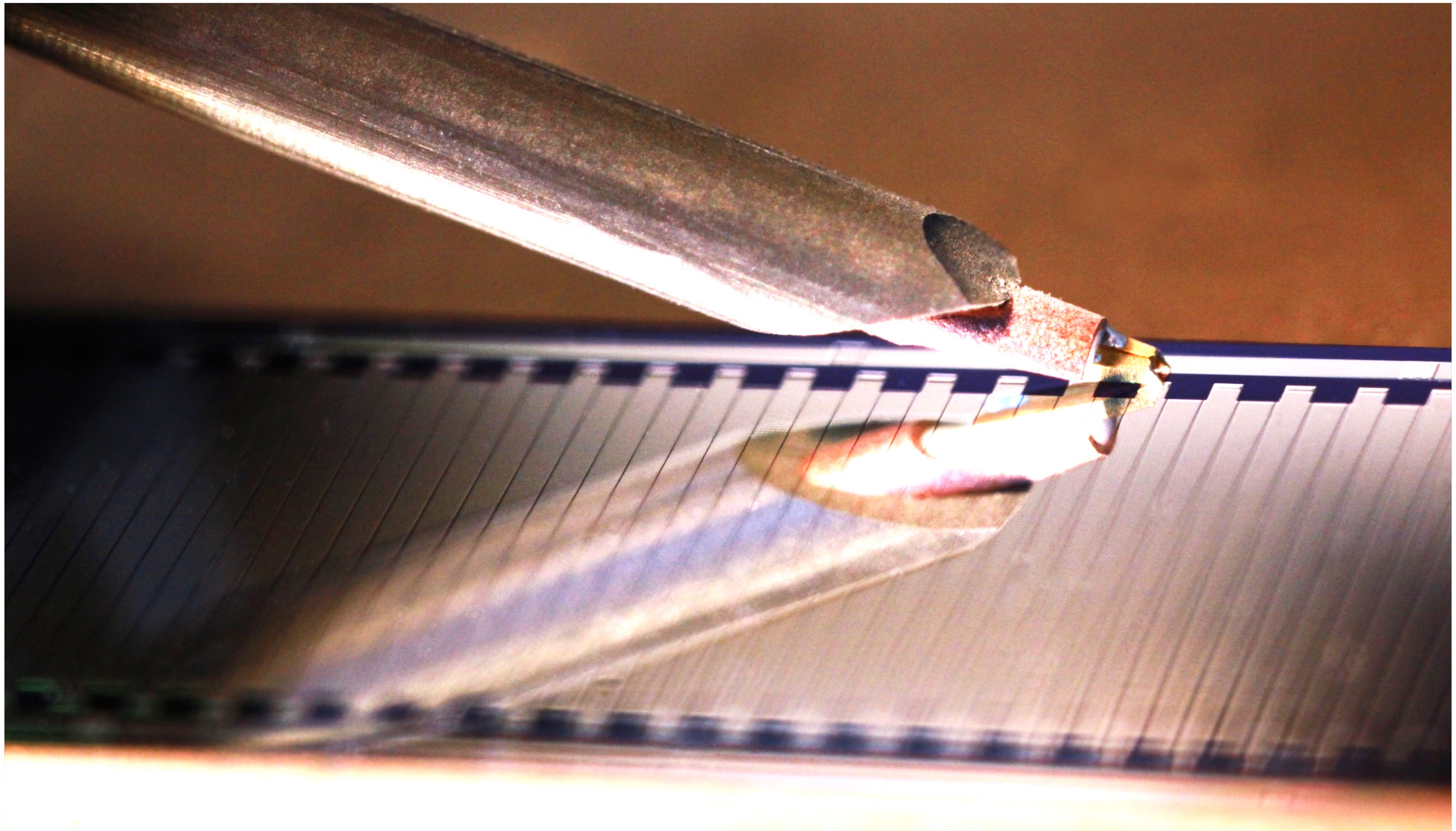


More than 90% yield

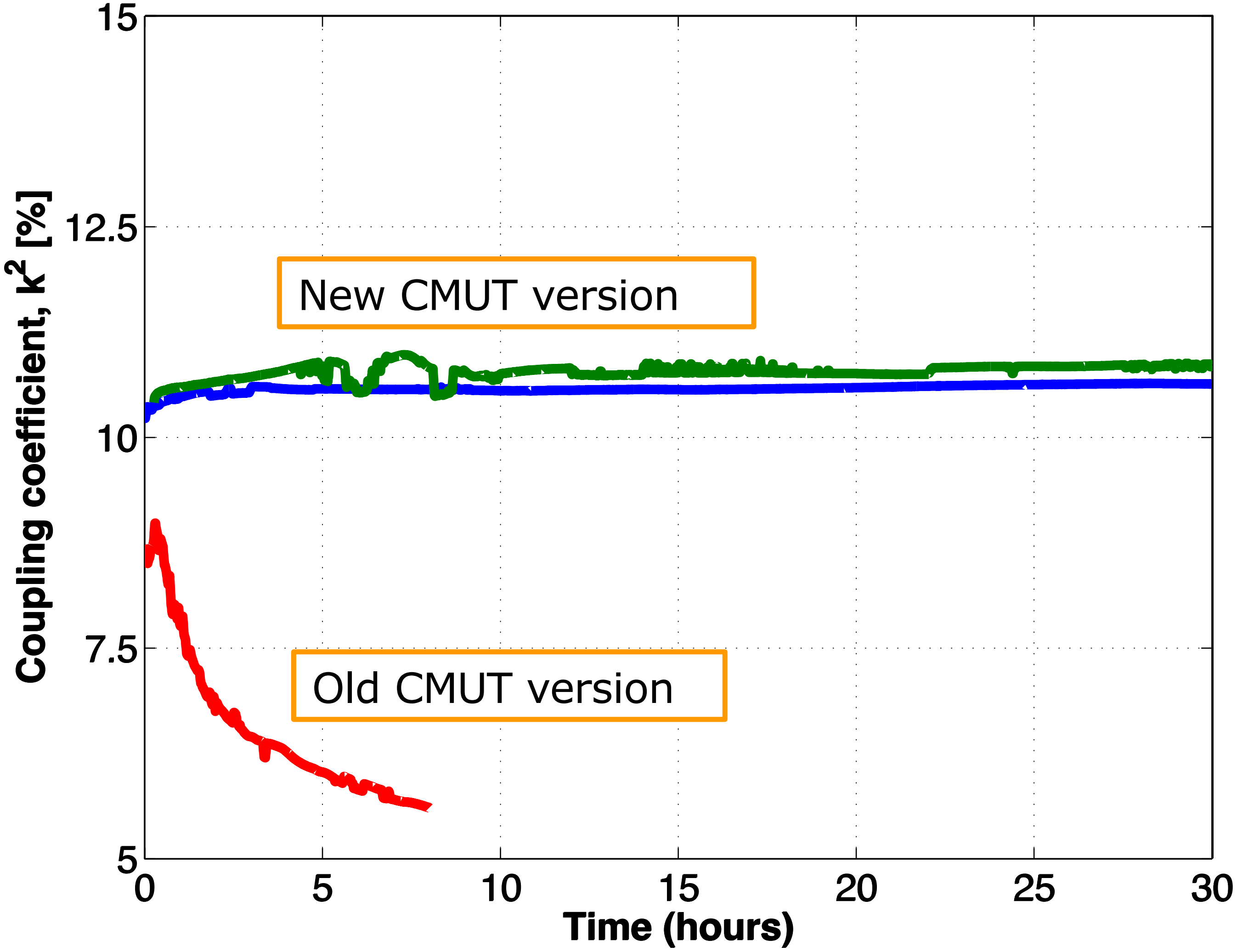


Characterization

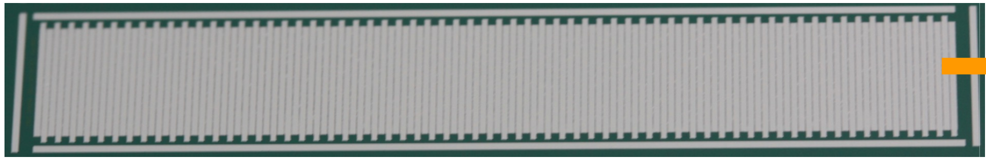
Impedance measurements in air to quantify the electromechanical coupling

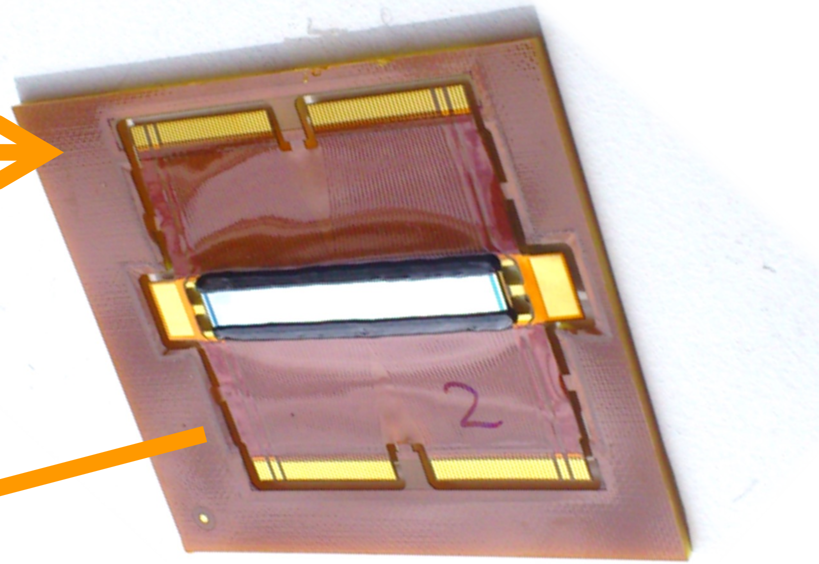


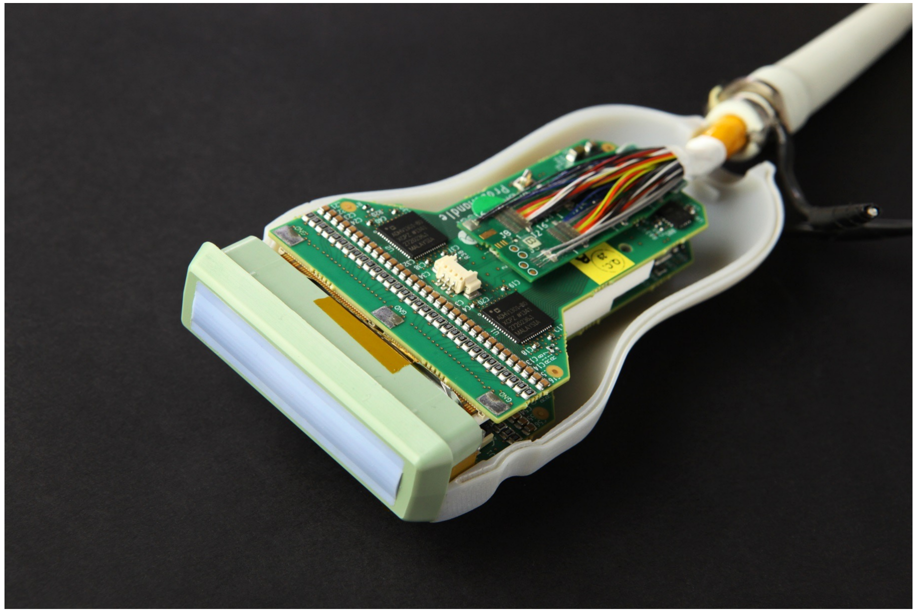
Stability assesment



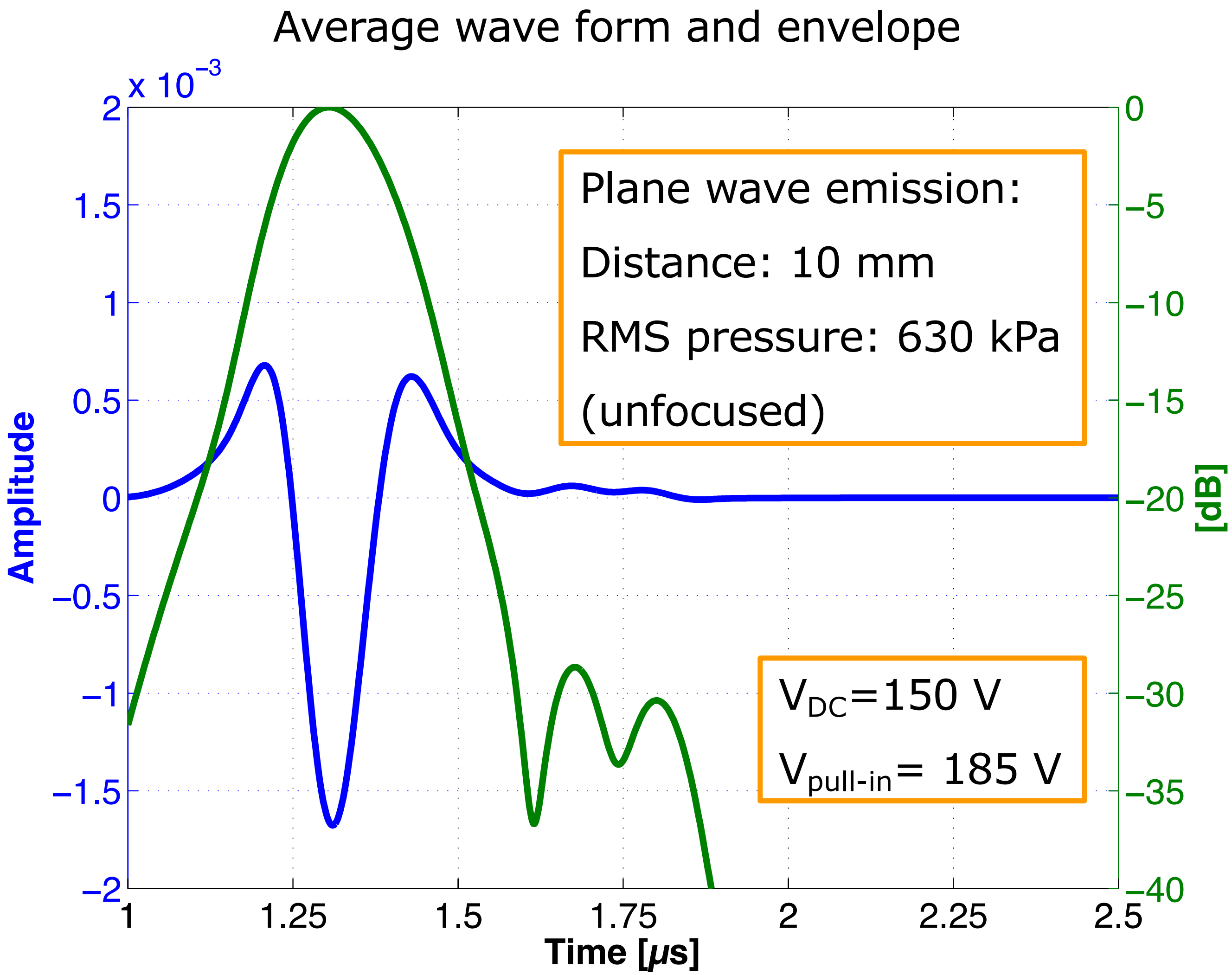
Probe assembly



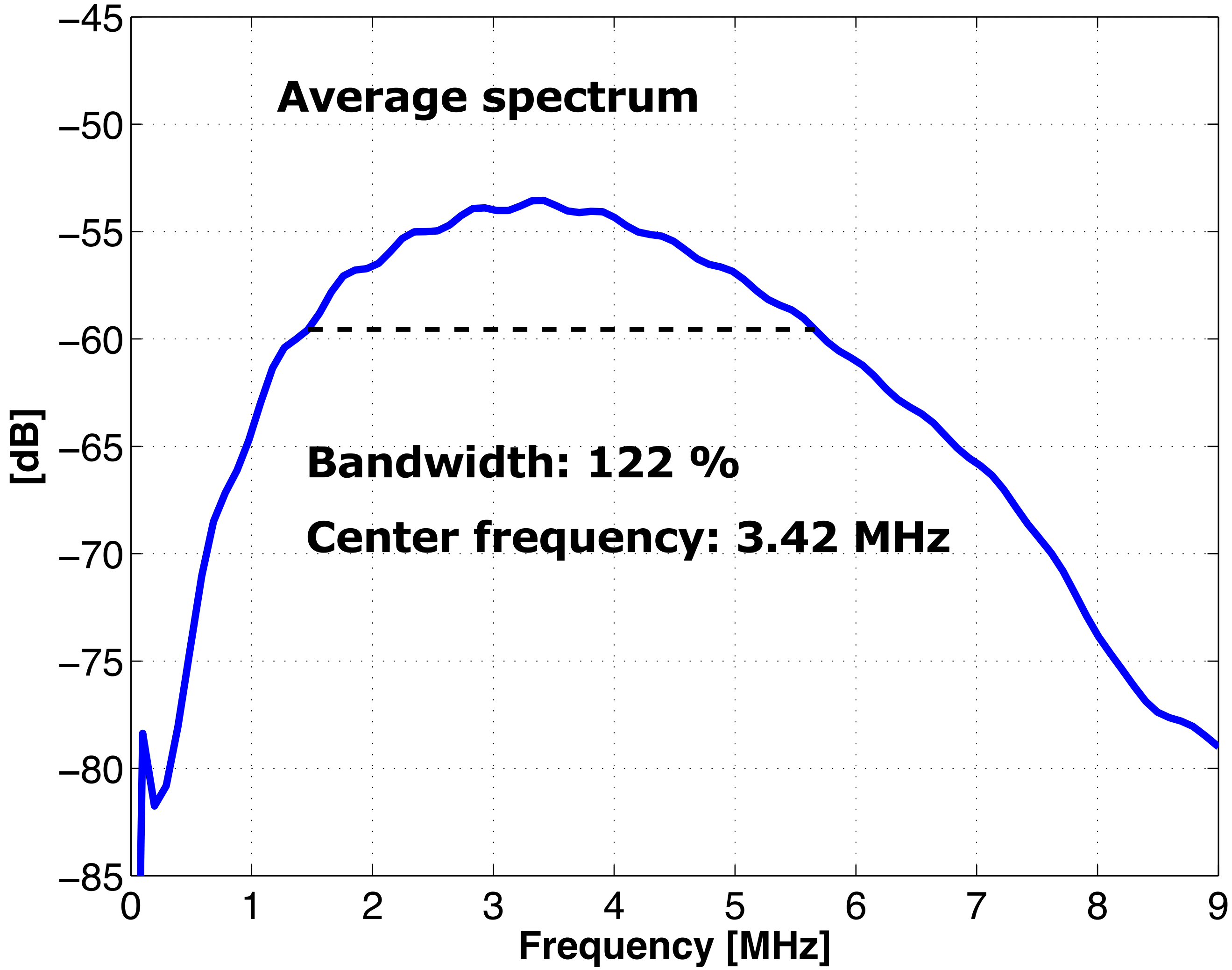




Fully assembled probe
– Pulse-echo

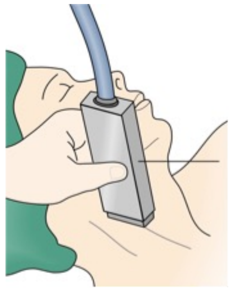


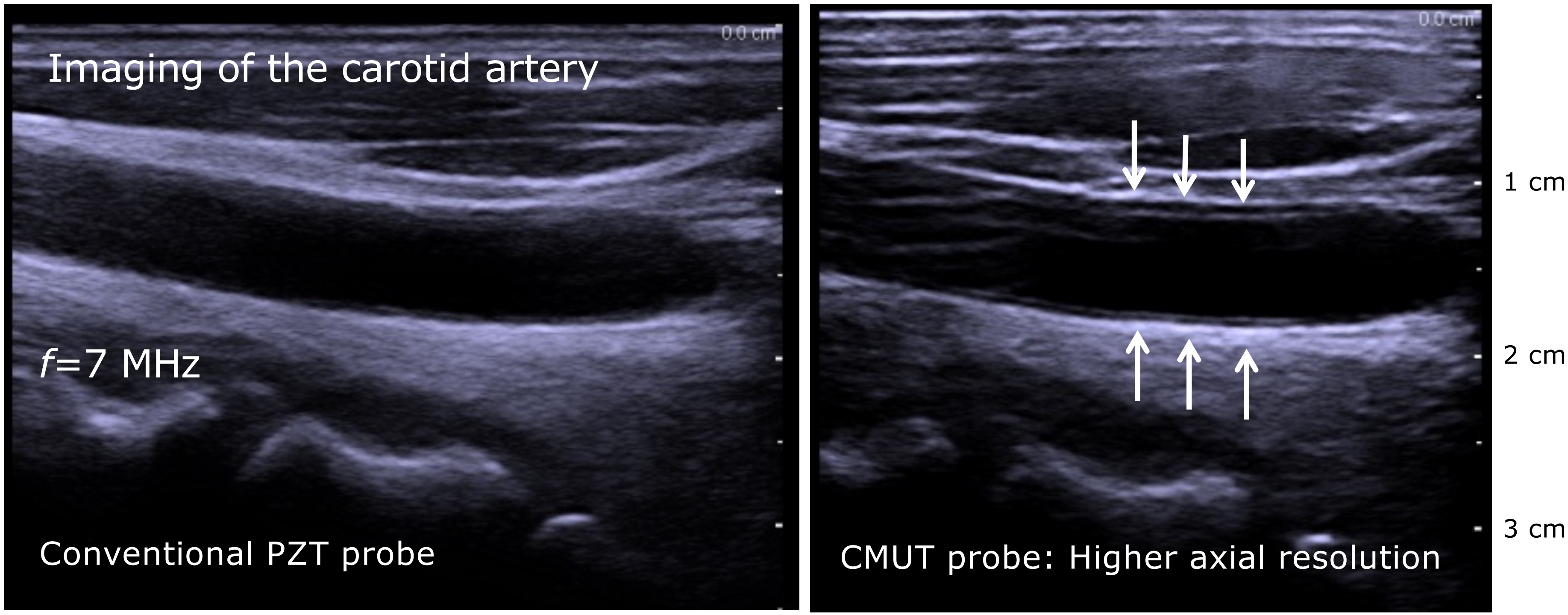
Fully assembled probe
- Pulse-echo sensitivity



1-D TABLA probe

- MEMS ➔ small mass
- High bandwidth
- High axial resolution
- Improved image quality





la Cour et al., IEEE Trans. Ultrason., Ferroelect., Freq. Control (62), 1563-1579, 2015; Lei et al. Proc. IEEE IUS 2015; Christiansen et al., ECS J. Solid State Sci. Technol. (3), 63-68, 2014; Christiansen et al., J. Acoust. Soc. Am. (135), 2523-2533; la Cour et al. Proc. IEEE IUS, 2584-2587, 2014; Lei et al. Proc. IEEE IUS,2595-2598, 2014; Thomsen et al., Sensors and Actuators A (220), 347-364, 2014; Engholm et al. Proc. IEEE IUS, 2603 - 2606 , 2014; la Cour et al. Proc. IEEE IUS, 2187-2190, 2013; Christiansen et al. Proc. IEEE IUS1737-1740, 2013; ; la Cour et al. Proc. IEEE IUS, 588-591, 2012

Conclusion

- PZT technology dominates the transducer market
- CMUT is an emerging technology
  - Compatibility with silicon fabrication
  - Excellent dimensional control (≈1 μm)
  - No need for impedance matching layers
  - Large bandwidth (>100%)
  - Low price – if many are made
  - Lead free
- All major players investigate CMUT technology

CMUT's could change the game – when full potential is realized

Thank you for your attention!

Time for problem solving

Problems

Design of PZT and CMUT transducers

Design of PZT thickness mode transducers

We investigate the design of PZT transducers. The transducer has 128 elements, and it has a pitch of $\lambda/2$. The dicing saw has a blade width of 20 μm.

Find the:

- thickness of the PZT
- pitch
- element width
- fill factor

for the following center frequencies:

- 3 MHz
- 8 MHz
- 15 MHz

Design of CMUTs

We now investigate the design of CMUTs. The transducer has 128 elements, and it has a pitch of $\lambda/2$. The transducers operates at a DC voltage of 200 V.

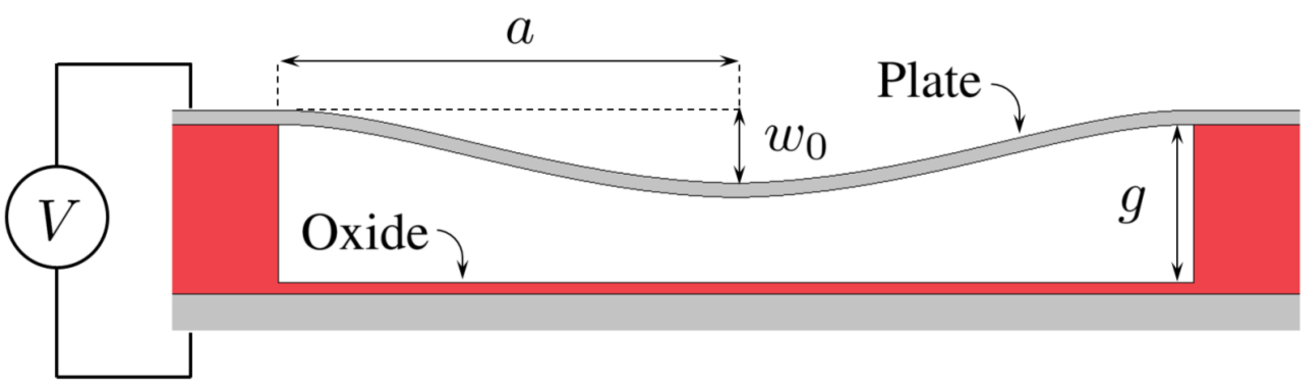
We will do our calculations for the following center frequencies:

- 3 MHz
- 8 MHz
- 15 MHz

Follow the CMUT design guidelines (see next page) and calculate the parameters mentioned in the guidelines.

Basic CMUT design methodology

1) Calculate pitch (λ or λ/2 or …) from wavelength in the media
2) Calculate element width (kerf almost zero or even negative)
3) Choose 2D cell layout (cell pitch, circles, squares, hexagonal …)
4) Fit circles into the element and determine radius, *a*
5) Find the plate thickness, *h*, to match immersion frequency
6) Select pull-in voltage ≈ $1.25 \times V_{DC}$
7) Adjust gap, *g*, to reach pull-in voltage
8) Check performance (bandwidth, pressure, PE sensitivity)
9) Check for substrate ringing and array effects (“Bragg” frequency)
10) If (performance < specs) goto 3
11) Check design with a full Finite Element model



Width ≈ Pitch = λ/2