# DYNAMIC FEM ANALYSIS OF MULTIPLE CMUT CELLS IN IMMERSION

Baris Bayram, Goksen G. Yaralioglu,
Arif Sanli Ergun, Ömer Oralkan, and
Butrus T. Khuri-Yakub

***Ginzton Laboratory, Stanford University, CA***

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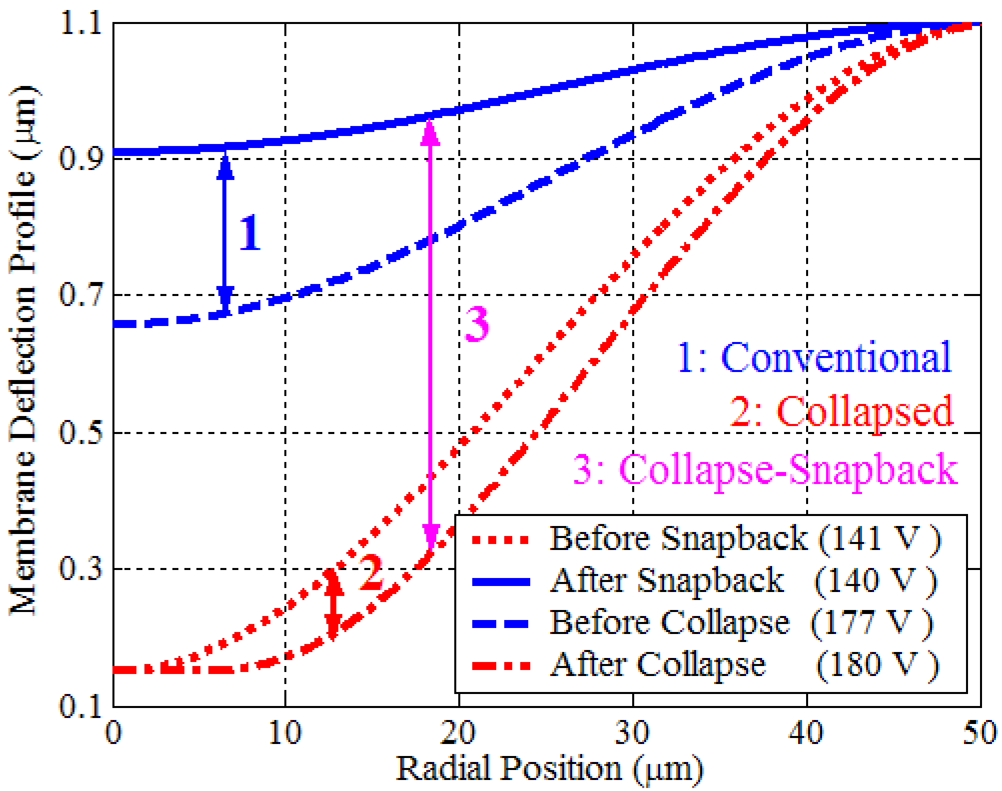
# Outline

- Motivation
- FEM model of an infinite CMUT
- Dynamic FEM analysis
- FEM and experimental results
- Conclusion

# Motivation

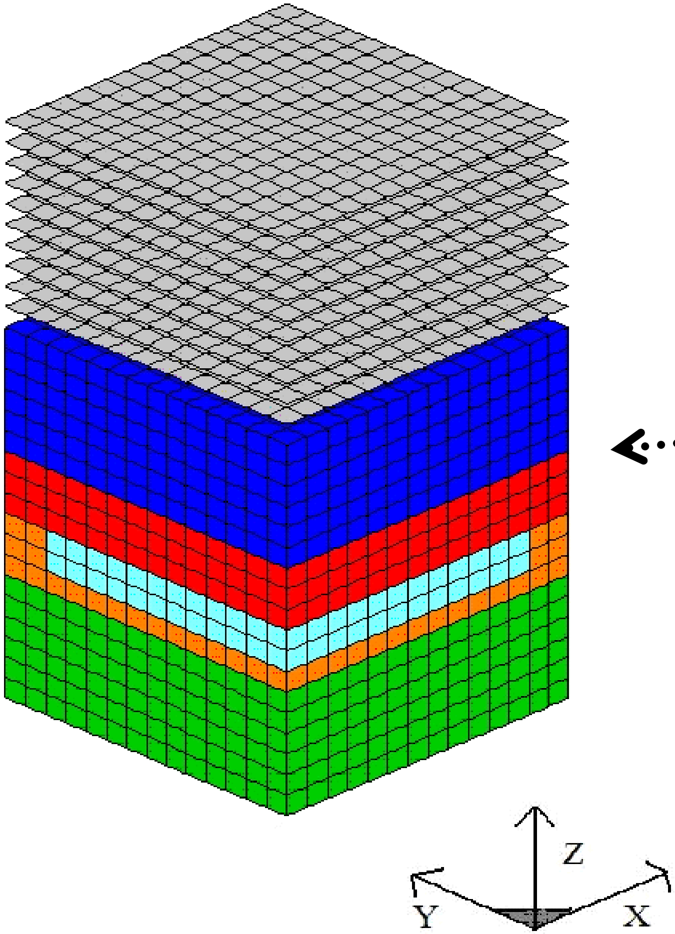
- Goal: To accurately model the cMUT dynamics in “linear” and nonlinear operation regimes using time-domain, finite element method (FEM)
- Test: Operate in different regimes:
  - Conventional (no contact)
  - Collapsed (always in contact)
  - Collapse-snapback (intermittent contact)

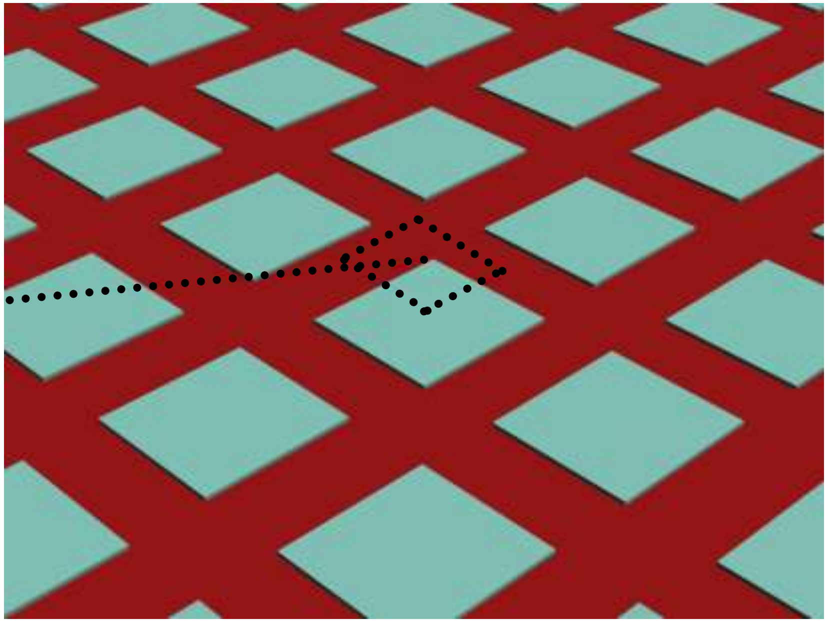
# Different Operation Regimes




Conventional, Collapsed and Collapse-Snapback Operations

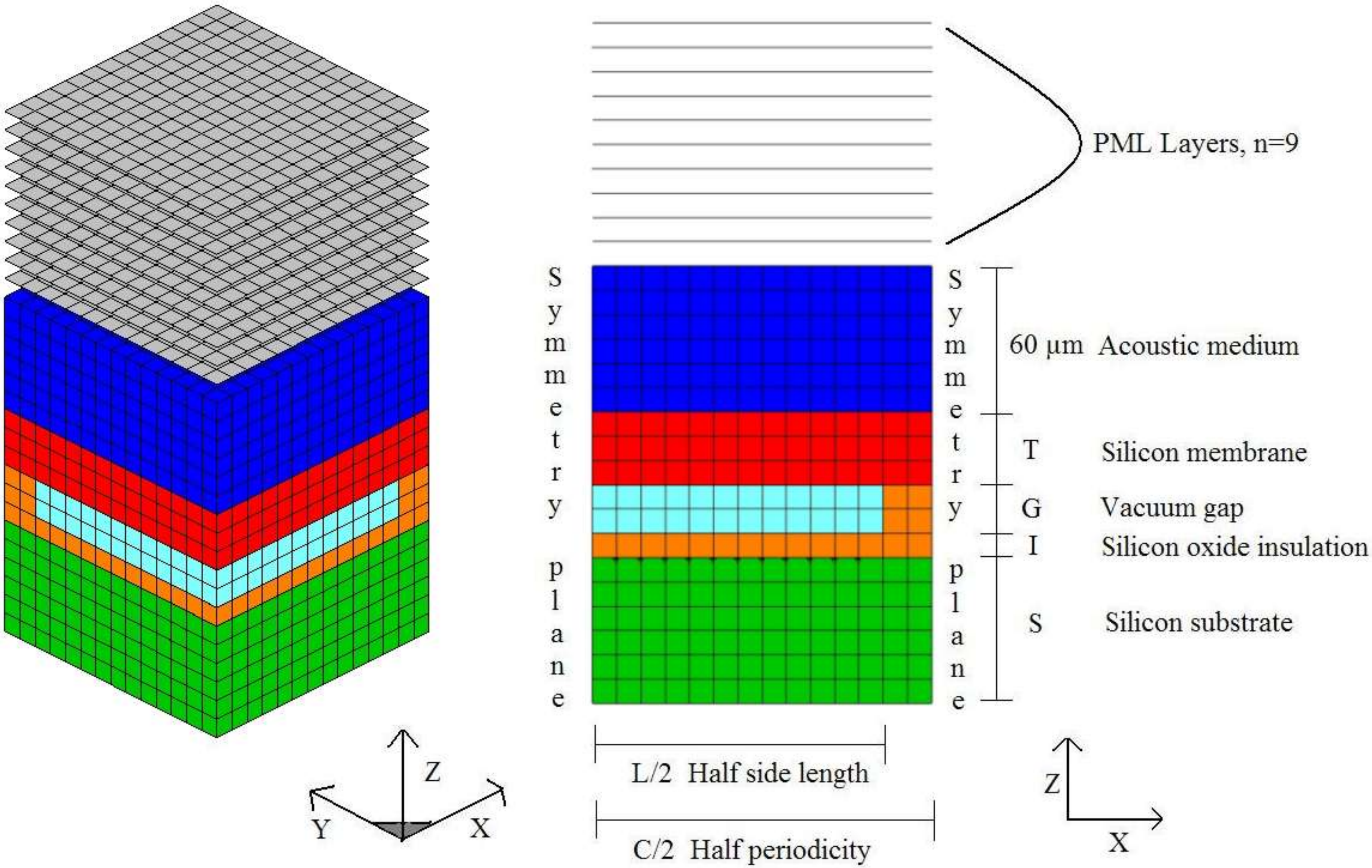
# FEM model of an infinite CMUT



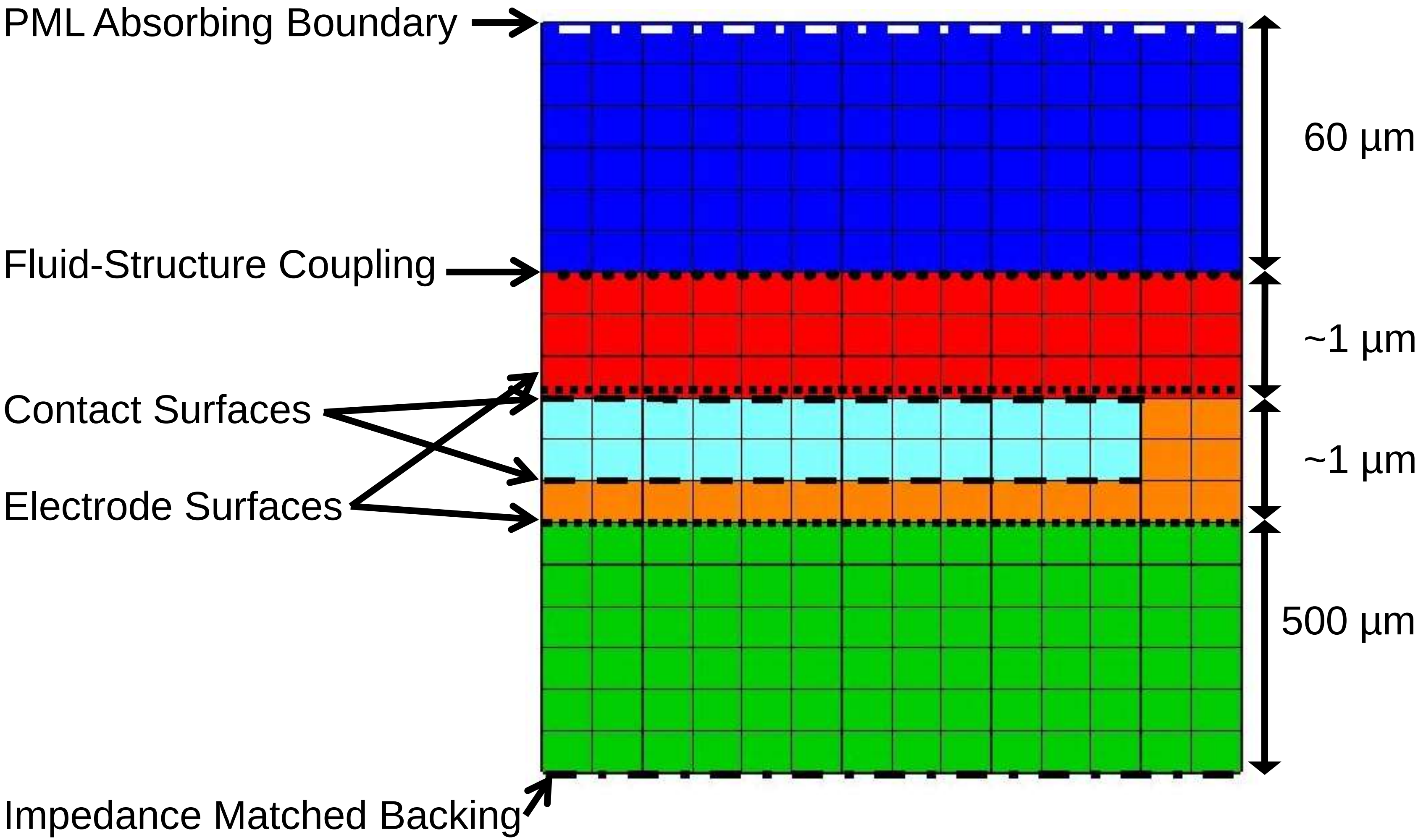



¼ of a square cMUT cell. ← Infinite cMUT

# FEM model of an infinite CMUT



# FEM model of an infinite CMUT



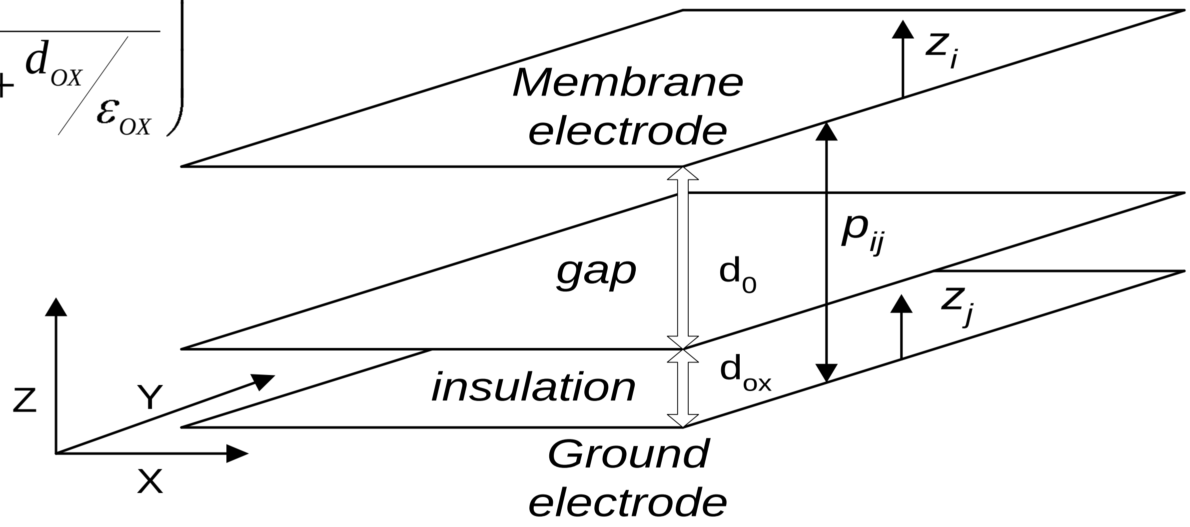
# Dynamic FEM Analysis

- Commercially available software (***LS-DYNA 970***)
  - Explicit, time-domain solver
- LS-DYNA built-in features
  - Fluid-structure coupling
  - Contact capability
- LS-DYNA user-defined features
  - Electrostatic-structural coupling
  - Berenger's Perfectly Matched Layer (PML) absorbing boundary
- Large Signal Characterization
  - Biasing + Pulse excitation
  - Acoustic Output Pressure

# LS-DYNA User-defined Features

– Electrostatic-structural coupling

$$p_{ij} = \frac{1}{2}\varepsilon_0 \left( \frac{V}{d_0 + (z_i - z_j) + d_{OX}/\varepsilon_{OX}} \right)^2$$




| Operation Regime | Bias voltage (Volt) | Average Deflection (Å) using ANSYS | LS-DYNA | Percentage Difference |
|---|---|---|---|---|
| Conventional | 83 | -148 | -145 | 2.1 % |
| Collapsed | 83 | -649 | -632 | 2.6 % |
| Collapsed | 101 | -755 | -752 | 0.4 % |

# LS-DYNA User-defined Features

– Berenger's Perfectly Matched Layer (PML)

Attenuation profile:

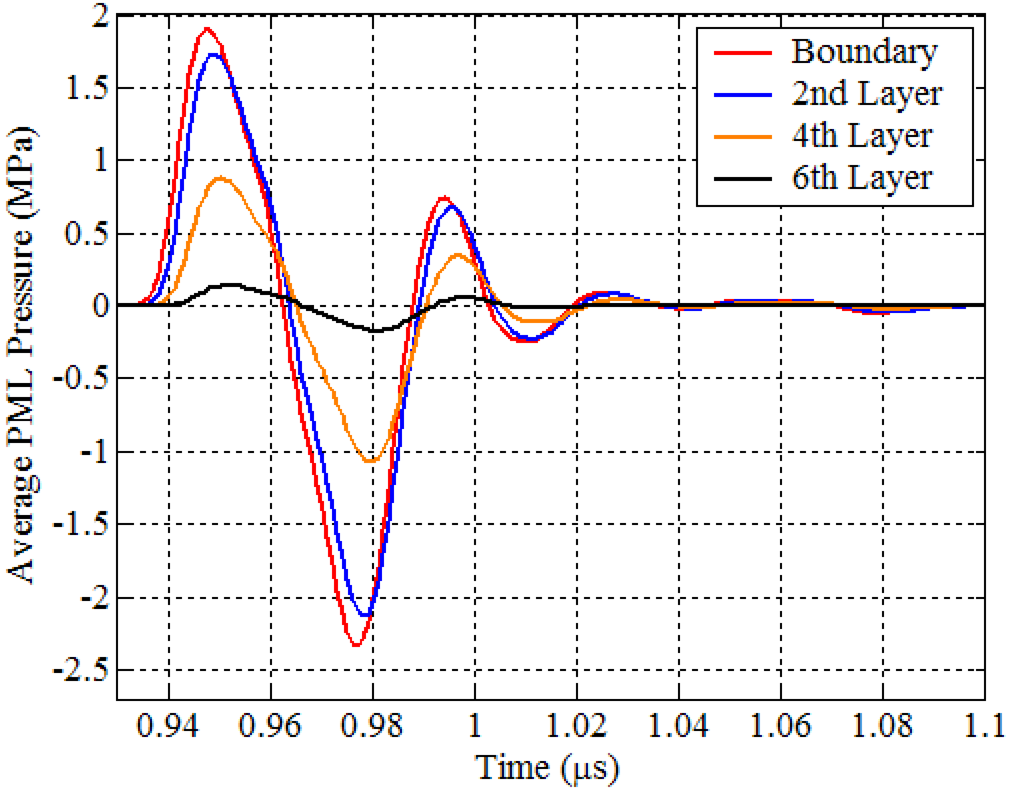
$$\alpha_{Zi} = \alpha_{Z\max} \times \left(\frac{n-i}{n}\right)^2 ; n = 9$$

Reflection (dB):

-40 dB

Stability (# of $t_{STEP}$):

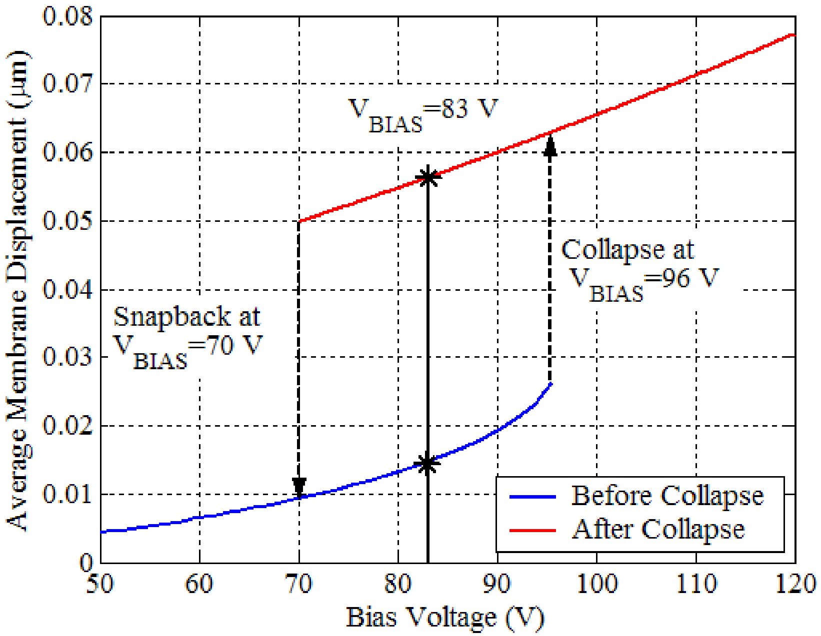
300,000



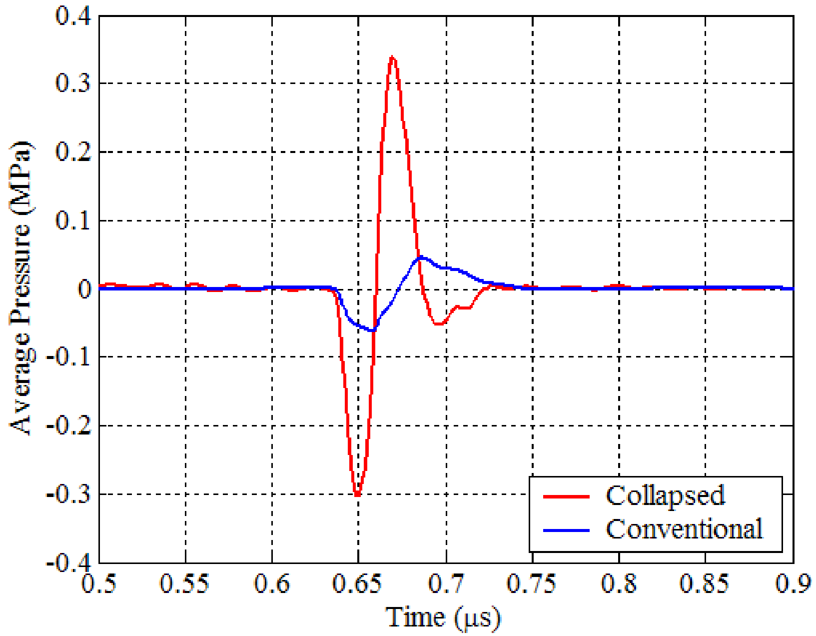
# Static FEM Results

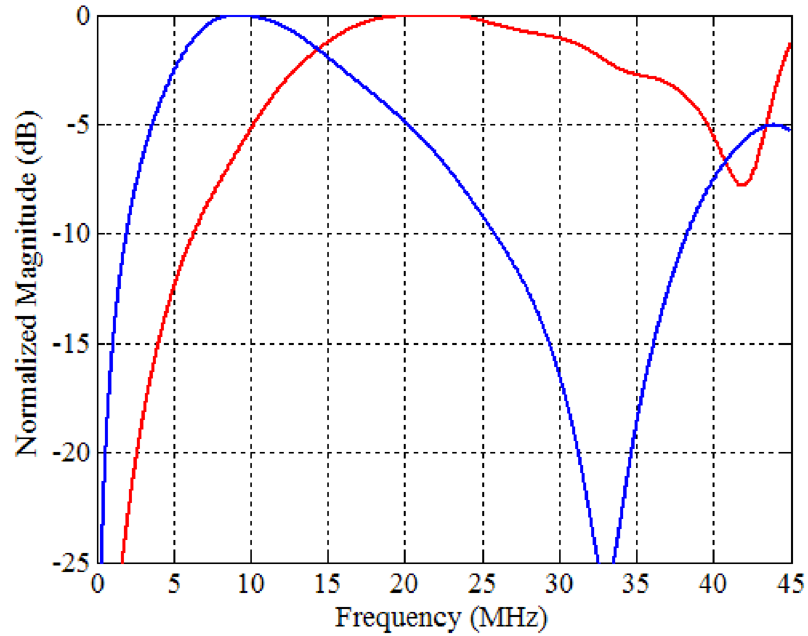
- **CMUT Dimensions**

| | |
|---|---|
| Side length (L) (μm) | **30** |
| Membrane thickness (T) (μm) | **1.2** |
| Gap thickness (G) (μm) | **0.18** |
| Insulating layer thickness (I) (μm) | **0.10** |
| Cell periodicity (C) (μm) | **35** |
| Substrate (S) (μm) | **500** |



# Dynamic FEM Results



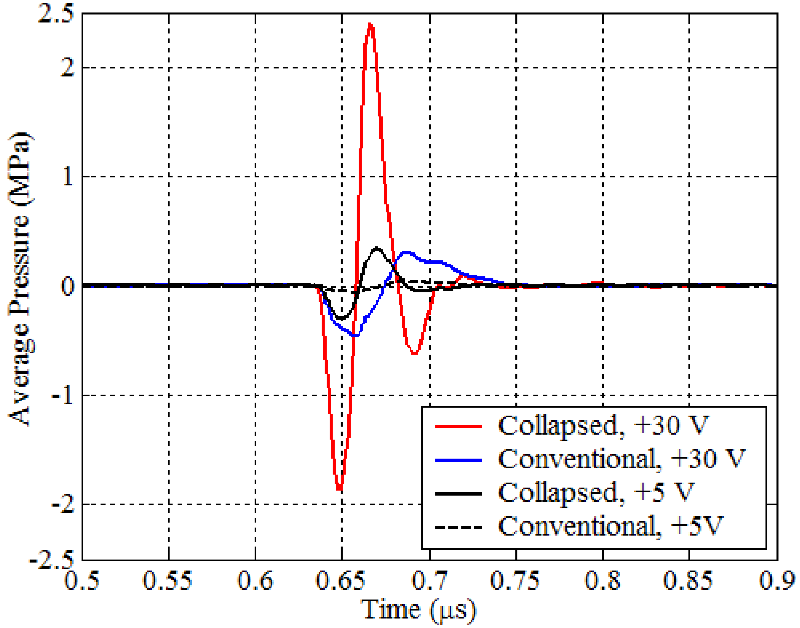



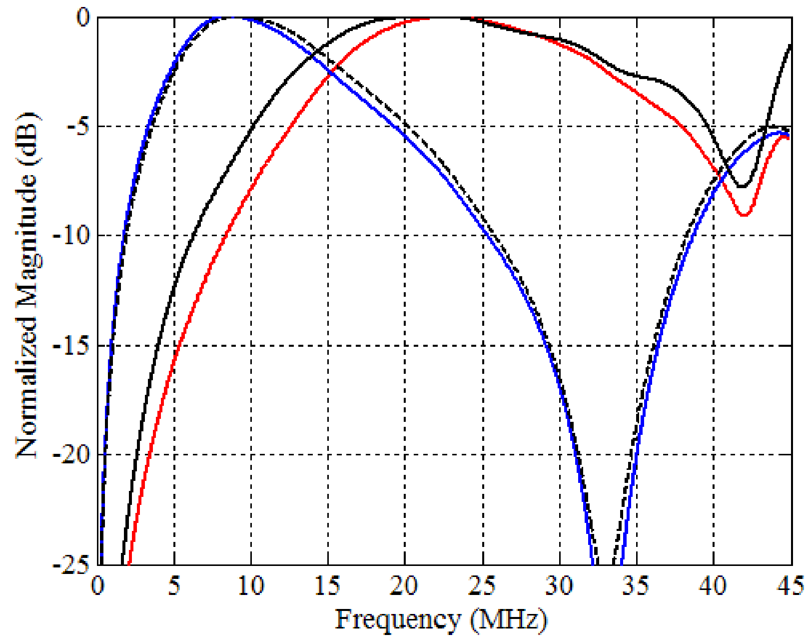

| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(ns) |
|---|---|---|
| 83 | +5 | 20 |

| | |
|---|---|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

| | Conventional | Collapsed |
|---|---|---|
| Pressure (p-p) | 107 kPa (21 kPa/V) | **641 kPa (128 kPa/V)** |
| $f_{CENTER}$, BW (%) | 9.2 MHz, 130 % | **21.6 MHz, 108 %** |

# Dynamic FEM Results



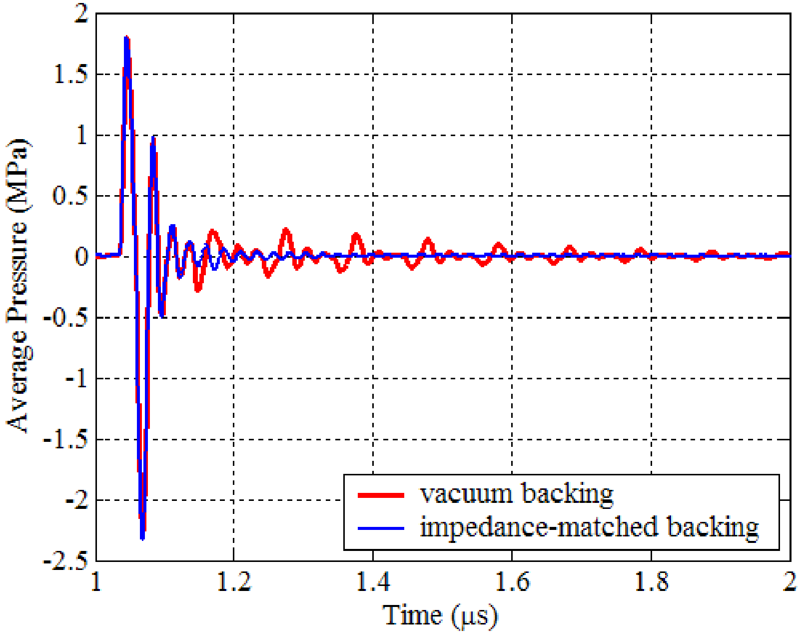



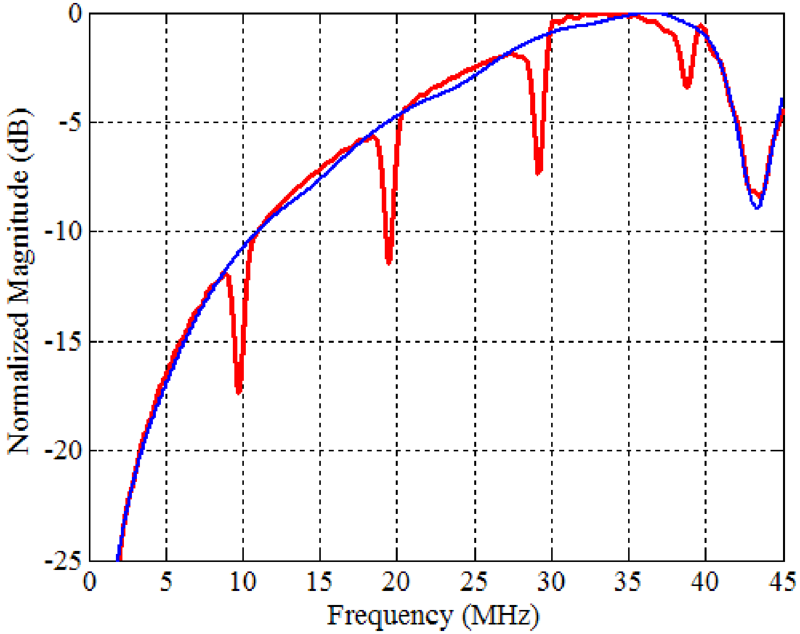

| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(ns) |
|---|---|---|
| 83 | +30 | 20 |

| | |
|---|---|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

| | Conventional | Collapsed |
|---|---|---|
| Pressure (p-p) | 770 kPa (25 kPa/V) | **4260 kPa (142 kPa/V)** |
| $f_{CENTER}$, BW (%) | 8.6 MHz, 132 % | **22.7 MHz, 84 %** |

# Dynamic FEM Results




| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(ns) |
|---|---|---|
| 120 | -30 | 20 |

| | |
|---|---|
| Collapse Voltage (V) | 96 |
| Snapback Voltage (V) | 70 |

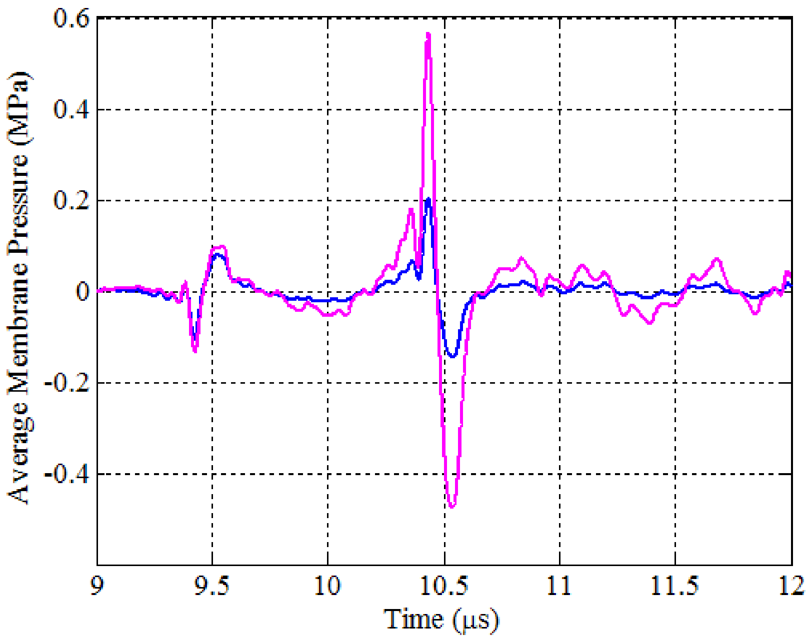
- Vacuum backing causes reflections from the bottom of the substrate.

# Conventional vs. Collapse-snapback

## CMUT Parameters

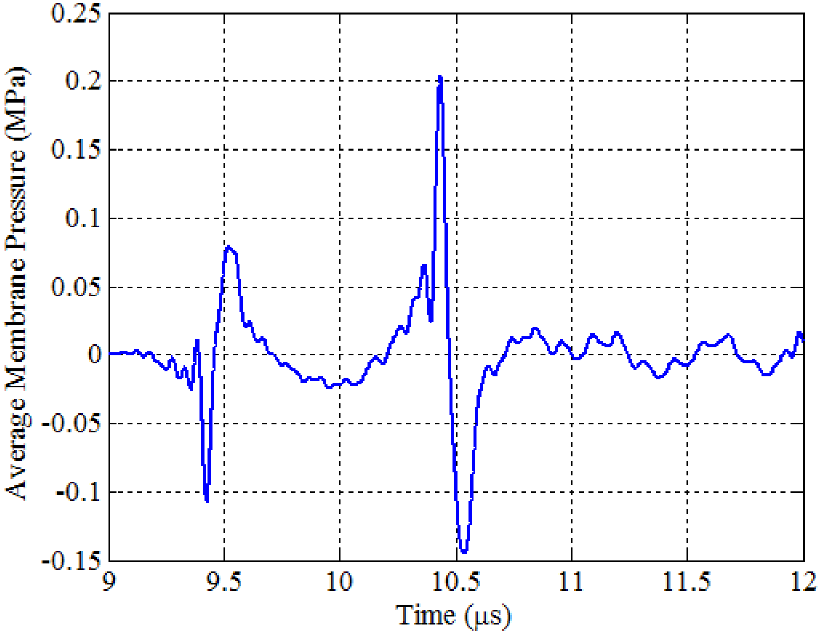
| | |
|---|---|
| Length of the transducer, $\mu m$ | 1180 |
| Width of the transducer, $\mu m$ | 280 |
| Number of cells per element | 4 x 52 |
| Cell Shape Factor | Hexagon |
| Cell radius ($r_{cell}$), $\mu m$ | 16 |
| Electrode radius ($r_{el}$), $\mu m$ | 8 |
| Electrode thickness ($t_{el}$), $\mu m$ | 0.3 |
| Membrane thickness ($t_m$), $\mu m$ | 1.06 |
| Gap thickness ($t_g$), $\mu m$ | 0.22 |
| Insulating layer thickness ($t_i$), $\mu m$ | 0.3 |
| Silicon substrate thickness, $\mu m$ | 500 |
| Collapse voltage, $V$ | 130 |
| Snapback voltage, $V$ | 110 |

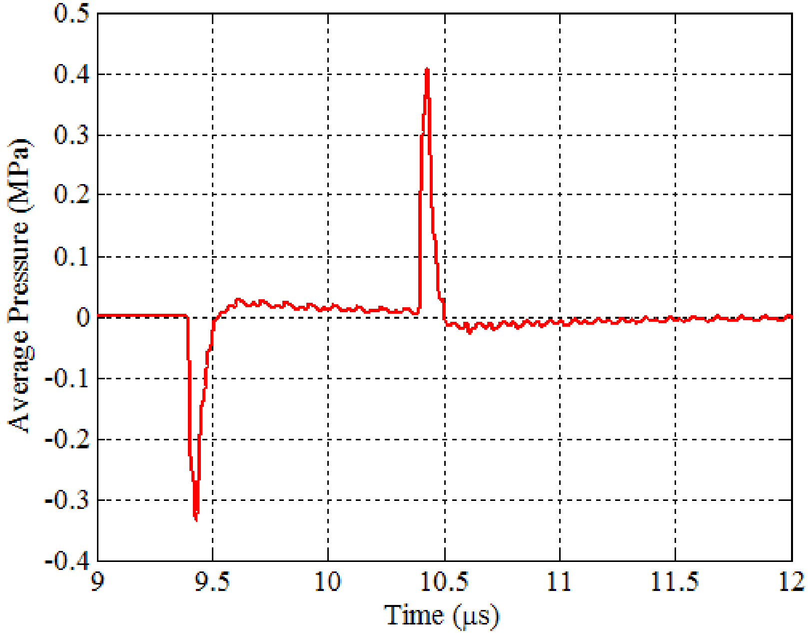
## Experimental Results




| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(µs) |
|---|---|---|
| 50 | +70 | 1 |
| 50 | +90 | 1 |

# Experimental and FEM Results



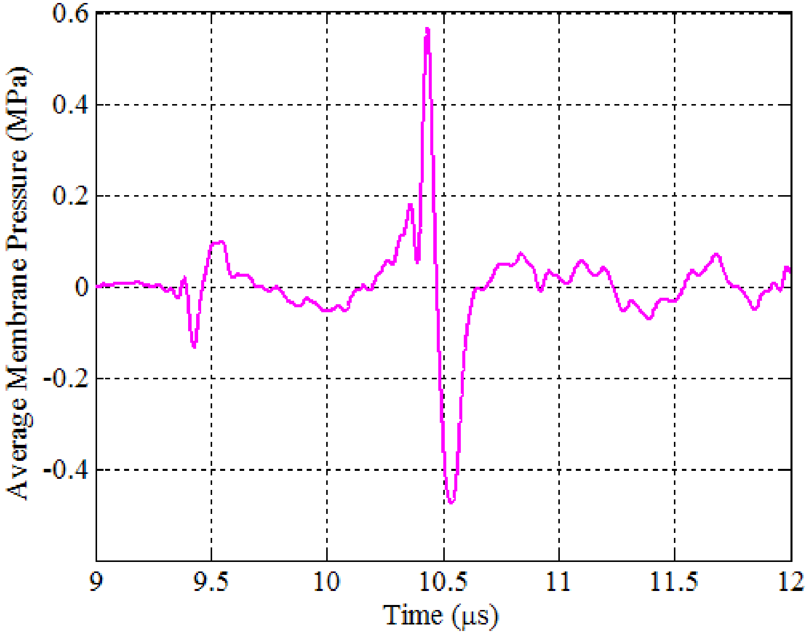



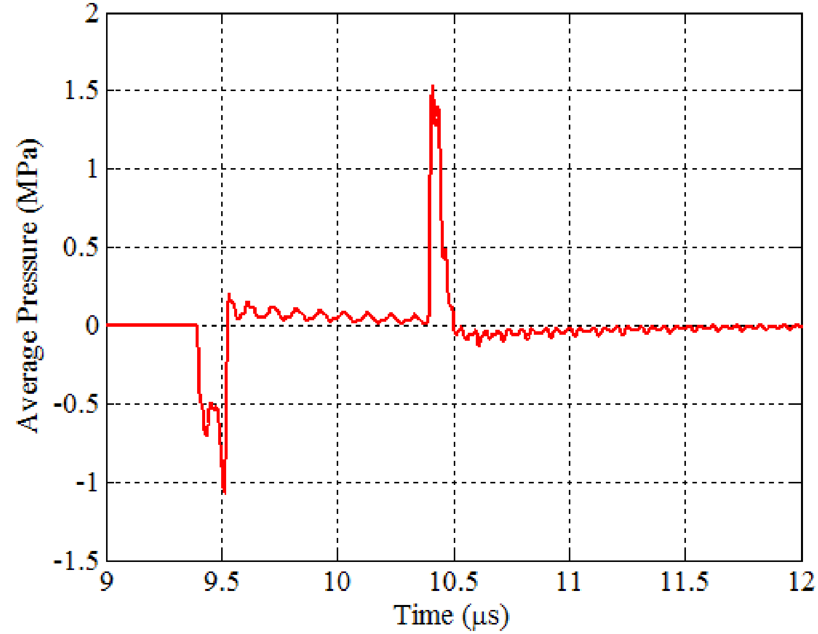

| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(μs) |
|---|---|---|
| 50 | +70 | 1 |

| | |
|---|---|
| Collapse Voltage (V) | 130 |
| Snapback Voltage (V) | 110 |

| Conventional | Experimental | FEM |
|---|---|---|
| Pressure (p-p) | Rising, Falling<br>185 kPa, 348 kPa | **Rising, Falling**<br>**366 kPa, 422 kPa** |

# Experimental and FEM Results



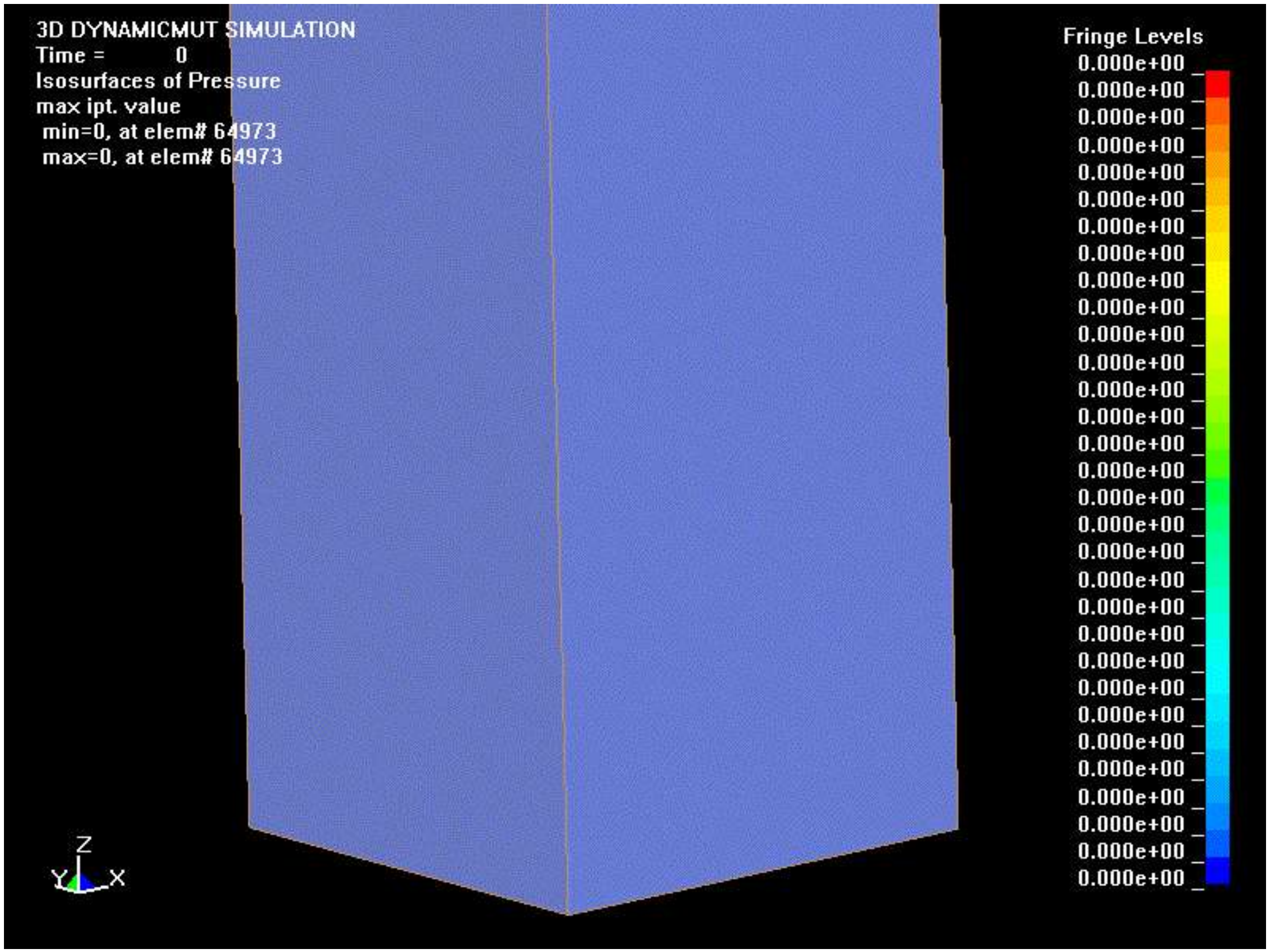




| $V_{BIAS}$(V) | $V_{PULSE}$(V) | $t_{PULSE}$(µs) |
|---|---|---|
| 50 | +90 | 1 |

| | |
|---|---|
| Collapse Voltage (V) | 130 |
| Snapback Voltage (V) | 110 |

| Collapse-Snapback | Experimental | FEM |
|---|---|---|
| Pressure (p-p) | Collapse, Snapback<br>234 kPa, 1040 kPa | **Collapse, Snapback**<br>**1270 kPa, 1580 kPa** |

# Animation




90 V step voltage on 500 um substrate: Pressure isometric animation

# More Results

- U3-D-4 High-Frequency CMUT Arrays for High-Resolution Medical Imaging: Preliminary Results.

- U3-D-5 CMUT Ring Arrays for Forward-looking Intravascular Imaging: Preliminary Results.

# Conclusion

- The cMUT dynamics modeled with time-domain, nonlinear, finite element method (FEM) using LS-DYNA explicit solver.
- Tested in linear (conventional) and nonlinear (collapsed and collapse-snapback) operation regimes.
- Good agreement between experimental and FEM results observed.
- High acoustic output pressure produced in nonlinear regimes.