Residual stress in Silicon membranes of circular CMUT

A. T. Galisultanov, P. Le Moal, V. Walter, G. Bourbon
Department of Applied Mechanics
FEMTO-ST institute, Besançon, France

E-mail: ayrat.galisultanov@femto-st.fr

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Outline

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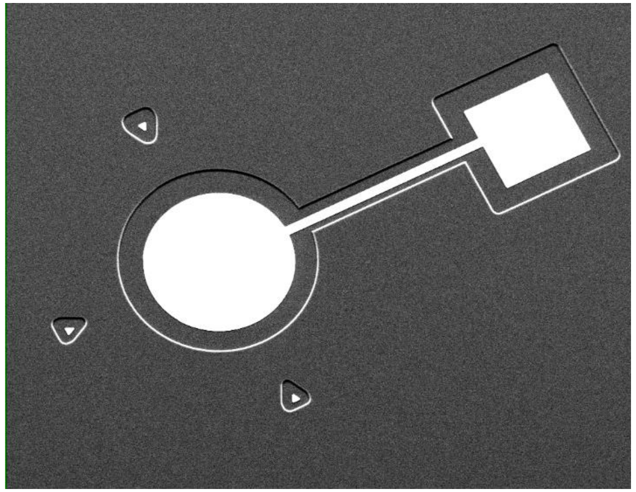


SEM image of cavity and bottom electrode of a single CMUT

Introduction

What is CMUT?

Capacitive Micromachined Ultrasound Transducer

Energy converters from electrical to mechanical domain and vice versa

Why CMUT?

Wide bandwidth

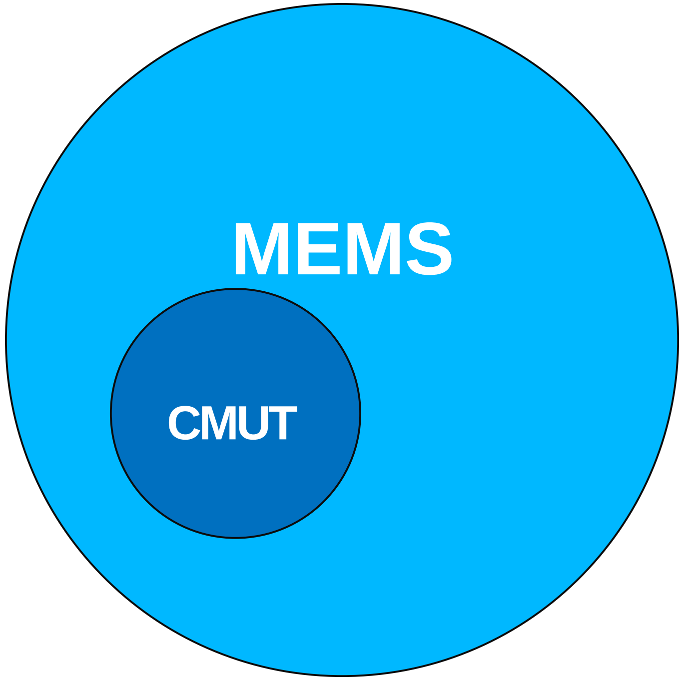
Compatibility with standard CMOS processes

Application

Ultrasound Imaging System (liquid, tissue)

Flow sensors (air)

Structural Health Monitoring (solid)



Key parameters

Electrostatic force

$$F_E = \frac{1}{2}\frac{C(x)}{d_{eff}-x}V^2,\ C(x) = \frac{\varepsilon\varepsilon_0 S}{d_{eff}-x},\ V = V_{DC} + V_{AC};$$

Electrostatic softening effect: elastic restoring force

$$k = k_m + k_e = k_m - \frac{C(x)}{(d_{eff}-x)^2}V^2$$

Pull-In Voltage

$$V_{PI}:\ k_m + k_e = 0$$

Electromechanical coupling

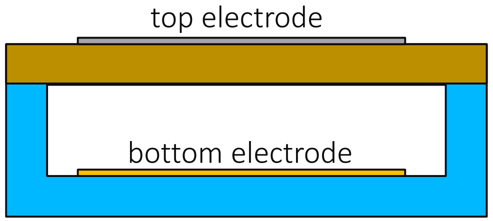
$$k_T^2 = \frac{2x}{d_{eff}-x+(d_{eff}-3x)\frac{C_p}{C(x)}}$$

Eigenfrequency

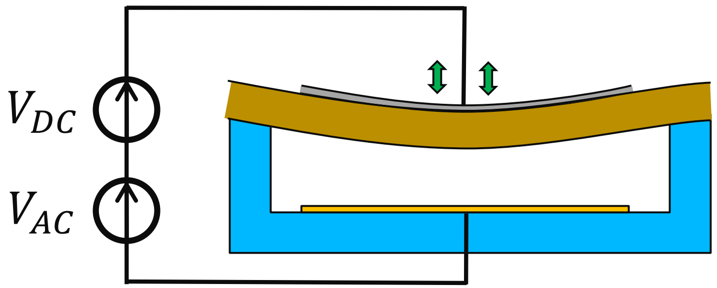
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_m+k_e}{m}}$$

Bandwidth

$$\frac{\Delta f}{f_0} = \frac{f_2-f_1}{f_0}$$



Schematic cross-section of CMUT structure



Fabrication of CMUT

Fabrication approach:

- **Sacrificial release process**
- **<u>Wafer bonding technique</u>**

Radius of CMUT R: **50**, **70**, **100**, **150** um

Radius of the bottom electrode: **0,8*R**

Gap: **1,1** um

Thickness of Silicon, (100) plane : **1,5** um;

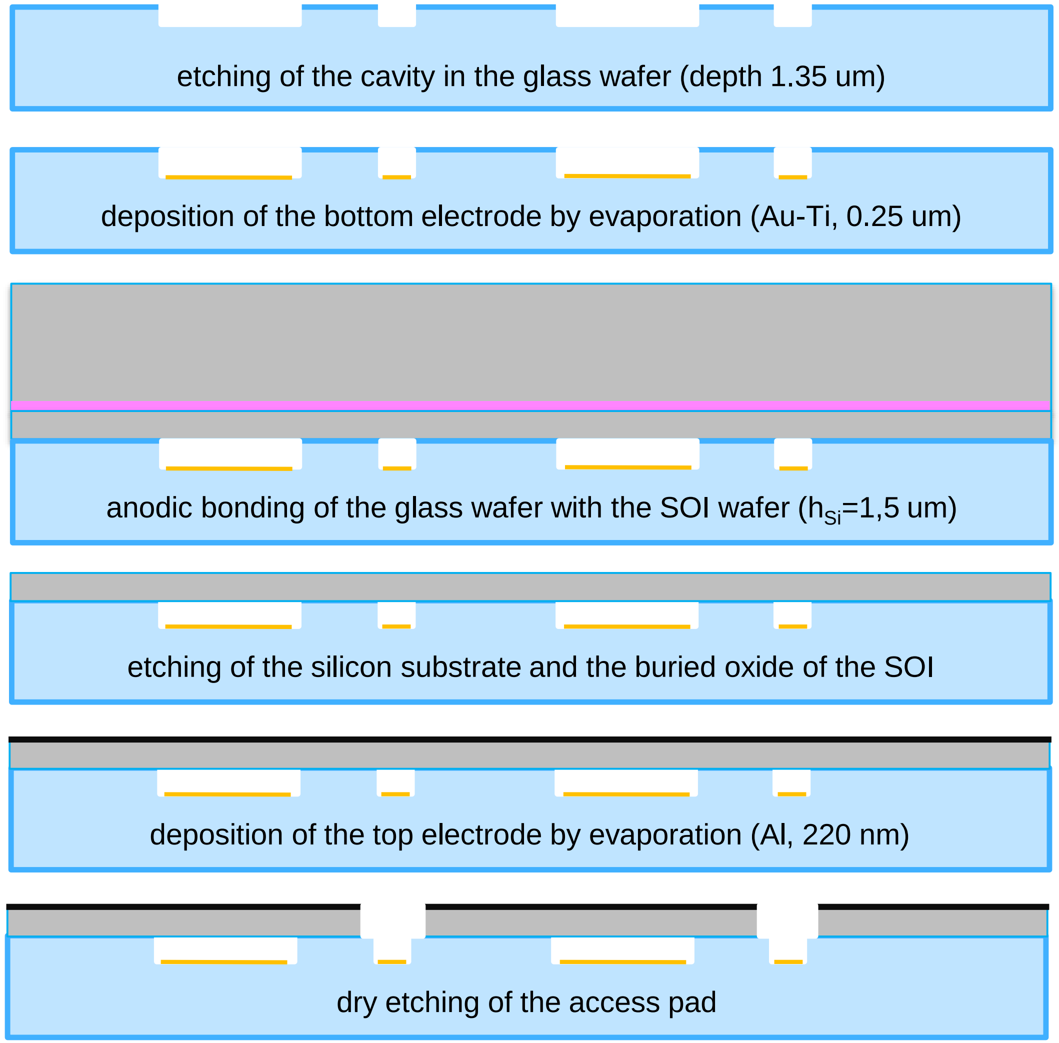
Thickness of Al: **0,22** um;

Residual stress appears due to fabrication steps process:

- SOI wafer with prestressed Si layer;

- anodic wafer bonding;

- Al deposition.



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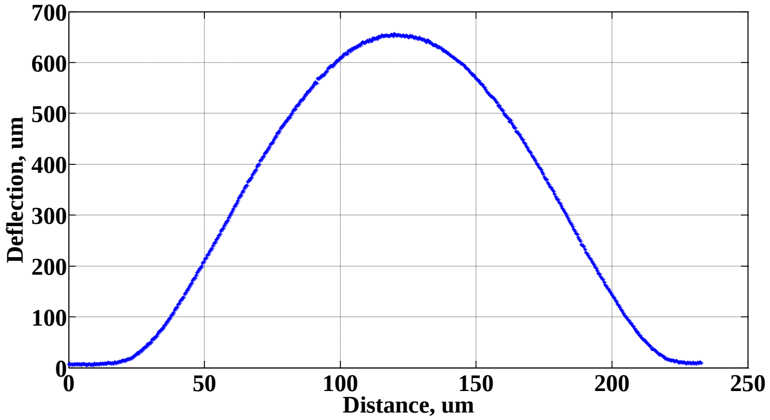
Experimental results

Radius, um	Maximum static deflection, nm	Eigenfrequency, MHz (FEM)	Eigenfrequency*, MHz (exp.)
50	142	2,28	2,3
70	360	1,18	1,26
100	650	0,58	0,82
150	1500	0,26	0,6

*in air



Typical static deflection after fabrication (R=100 um)

Static deflection

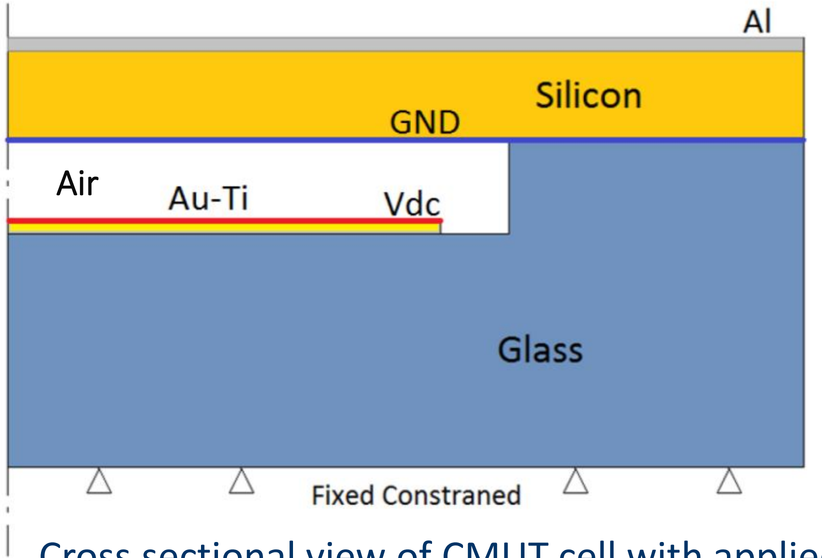
residual stress

Eigenfrequency

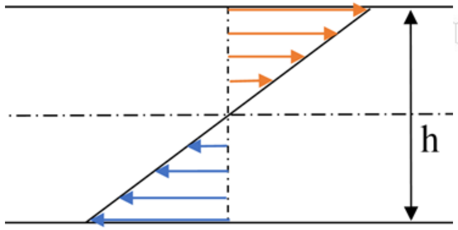
residual stress

air spring effect

Comsol model



Cross sectional view of CMUT cell with applied mechanical and electrical boundary conditions



Bending stress distribution in Silicon

$$S_r = S_0 \frac{z}{(h/2)}$$

Types of studies:

-Stationary study (deflection, pull-in voltage)

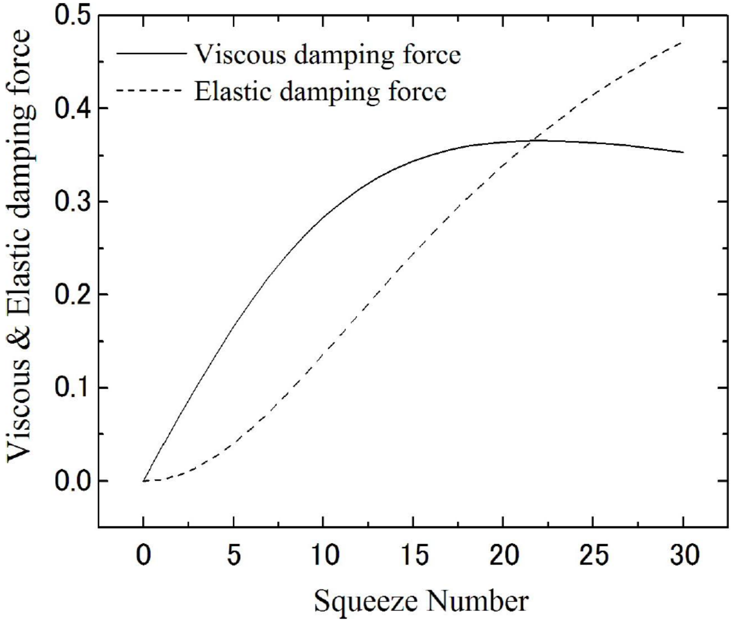
-The Prestressed Analysis, Eigenfrequency study (deflection, eigenfrequency)

-The Prestressed Analysis, Frequency Domain (deflection, bandwidth, coupling)

Air spring effect

$$m\ddot{y} + c_d\dot{y} + (k_0 + k_e)y = F_0 \sin(\omega t)$$

k_e - the coefficient of viscous damping force,
c_d - the coefficient of elastic damping force



Dependences of the viscous and the elastic damping forces of CMUTs on the squeeze number. The membrane plate is assumed to be a square.*

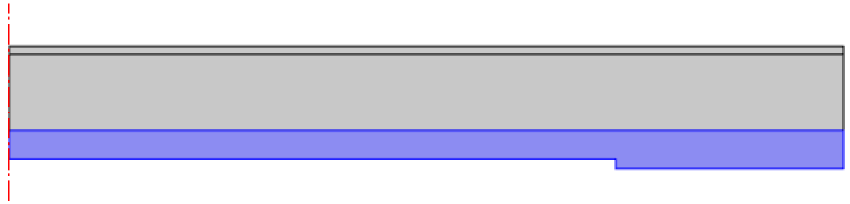
$\sigma = \frac{12\mu\omega R^2}{P_a h_0^2}$ - squeeze number

$$\sigma = 36{,}2$$

$$\sigma \gg \sigma_c: \quad k_e = \frac{P_a A}{h_0},\ c_d \cong 0$$

$\omega_0 = \sqrt{\frac{k_0}{m}} \rightarrow \omega_e = \sqrt{\frac{k_0 + k_e}{m}}$ – air spring effect

FEM model

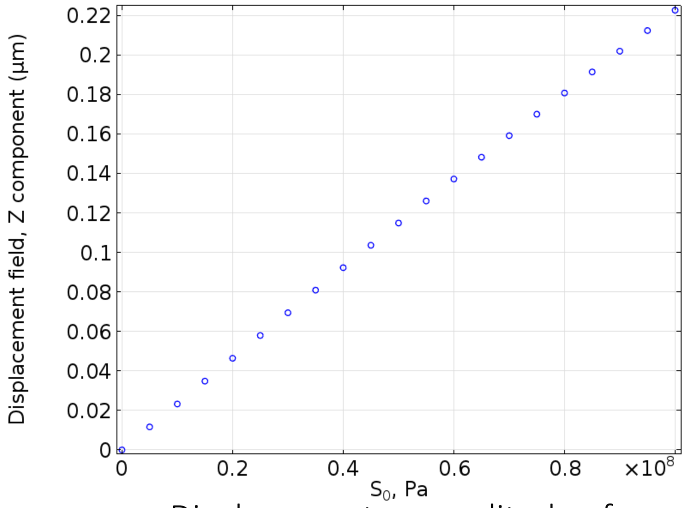


Grey area - Solid Mechanics
Blue area - Pressure Acoustics,
Linear elastic fluid model ($k_e = \frac{P_a A}{h_0}$, $c_d = 0$)

*Lee, S. M., Cha, B. S., & Okuyama, M. (2011). Viscous Damping Effect on the CMUT Device in Air. JOURNAL OF THE KOREAN PHYSICAL SOCIETY, 58(4), 747-755.

Residual stress calculation

Radius, um	Maximal static deflection, nm
50	142
70	360
100	650
150	1500



Displacement vs amplitude of bending stress (R=50um)

R, um	S_0, MPa (defl)	Eigenfrequency, MHz (FEM)	Eigenfrequency[1], MHz (FEM)	Eigenfrequency, MHz (exp.)
50	63,5	2,28	2,31	2,3
70	86,0	1,18	1,29	1,26
100	76,5	0,58	0,88	0,82
150	78,7	0,26	0,65	0,6

[1] with considering air spring effect and geometric nonlinearity

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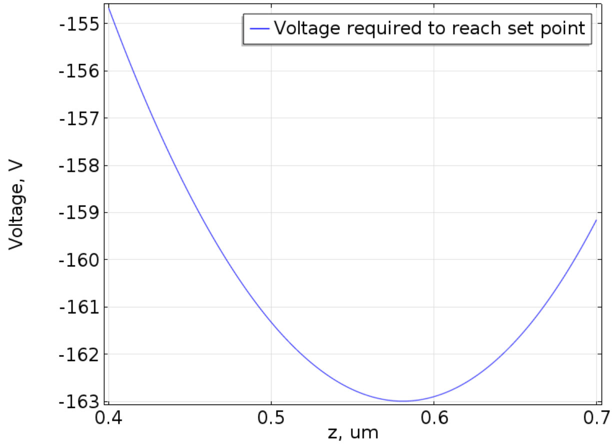
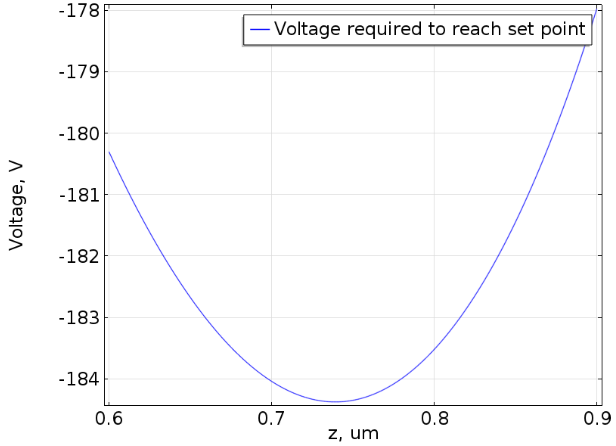
Results

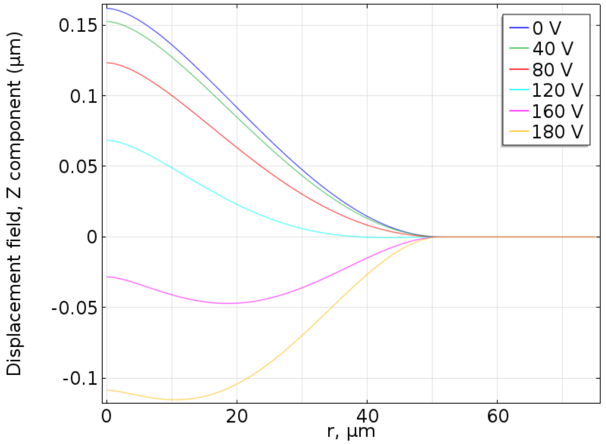
Pull In Voltage calculation



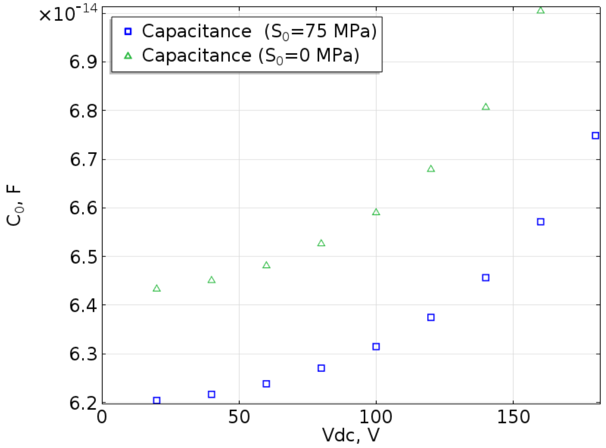
V_{PI}=163 V (S_0=0 MPa, R=50um)



V_{PI}=184,4V (S_0=75 MPa, R=50um)
exp. V_{PI}=180 V, σ=19,8 V



Vertical displacement of CMUT membrane for different dc bias voltage (S_0=75MPa, R=50um)



Capacitance vs dc bias voltage with and without stress (R=50um)

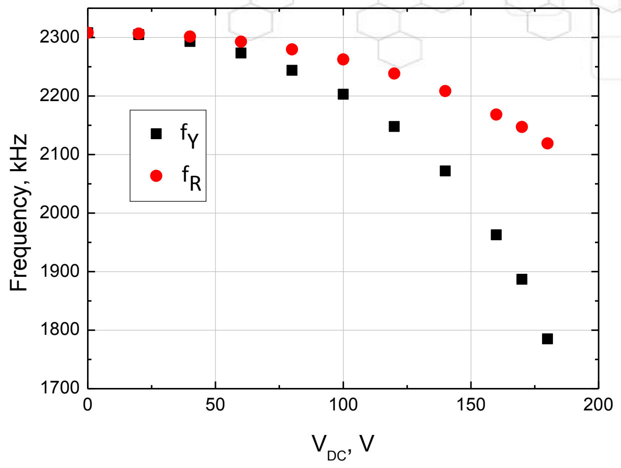
Results

Coupling factor

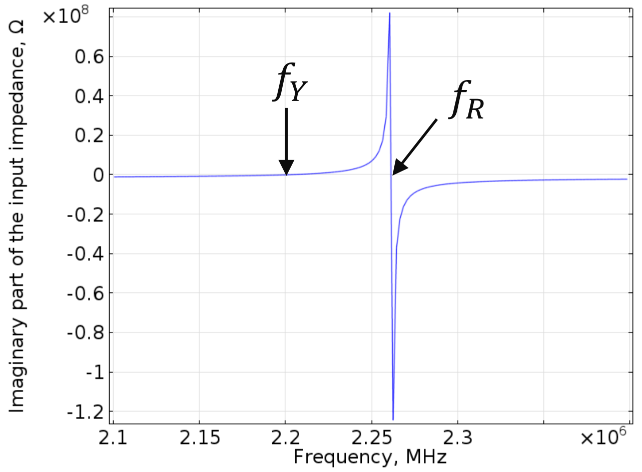
$$k_T^2 = 1 - \left(\frac{f_Y}{f_R}\right)^2$$

f_Y - resonance frequency

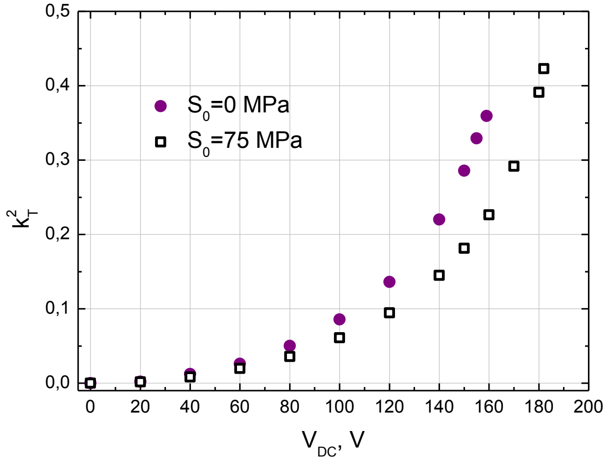
f_R - antiresonance frequency



Resonance and antiresonance frequencies vs biased voltage (S_0=75MPa, R=50um)



Imaginary part of the input impedance of the CMUT (V_{DC}=100 V, S_0=75MPa, R=50um)



Coupling factor vs dc bias voltage with and without stress

Conclusions

- We used COMSOL Multiphysics MEMS module to obtain the value of bending stress with parametric sweep. The average value of amplitude of bending stress is 75 MPa
- COMSOL provides better understanding of static and dynamic behavior of CMUT (air spring effect, pull in voltage, capacitance, coupling)
- The calculated results are in a good agreement with experimental data

Future plans and final goal

- Test of CMUTs in vacuum chamber
- Developing approach for application of CMUT in structural health monitoring

Thank you!

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