MEMS resonator

Presentation by

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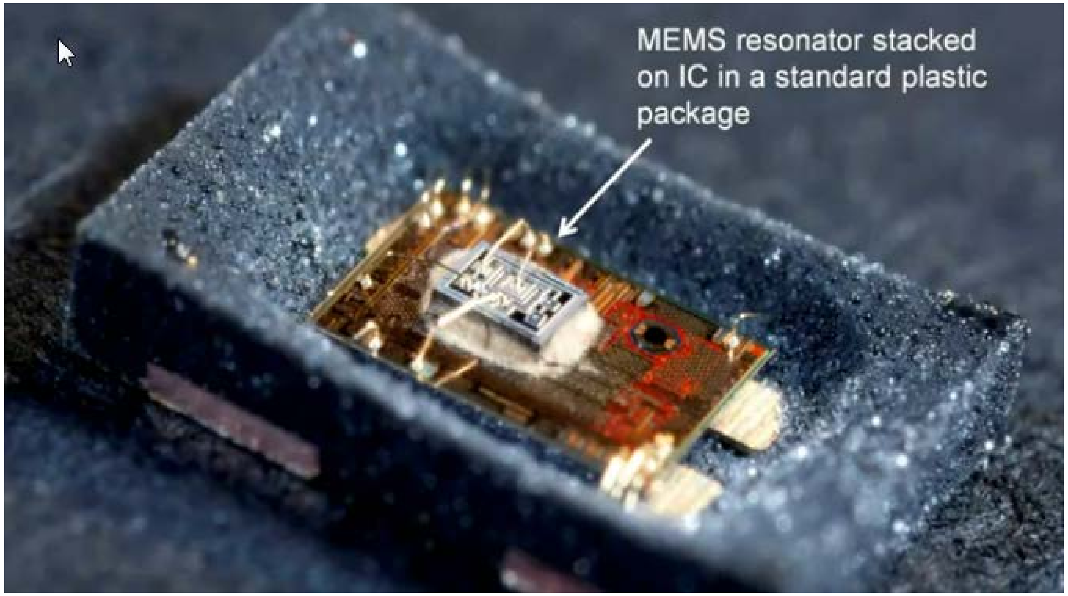
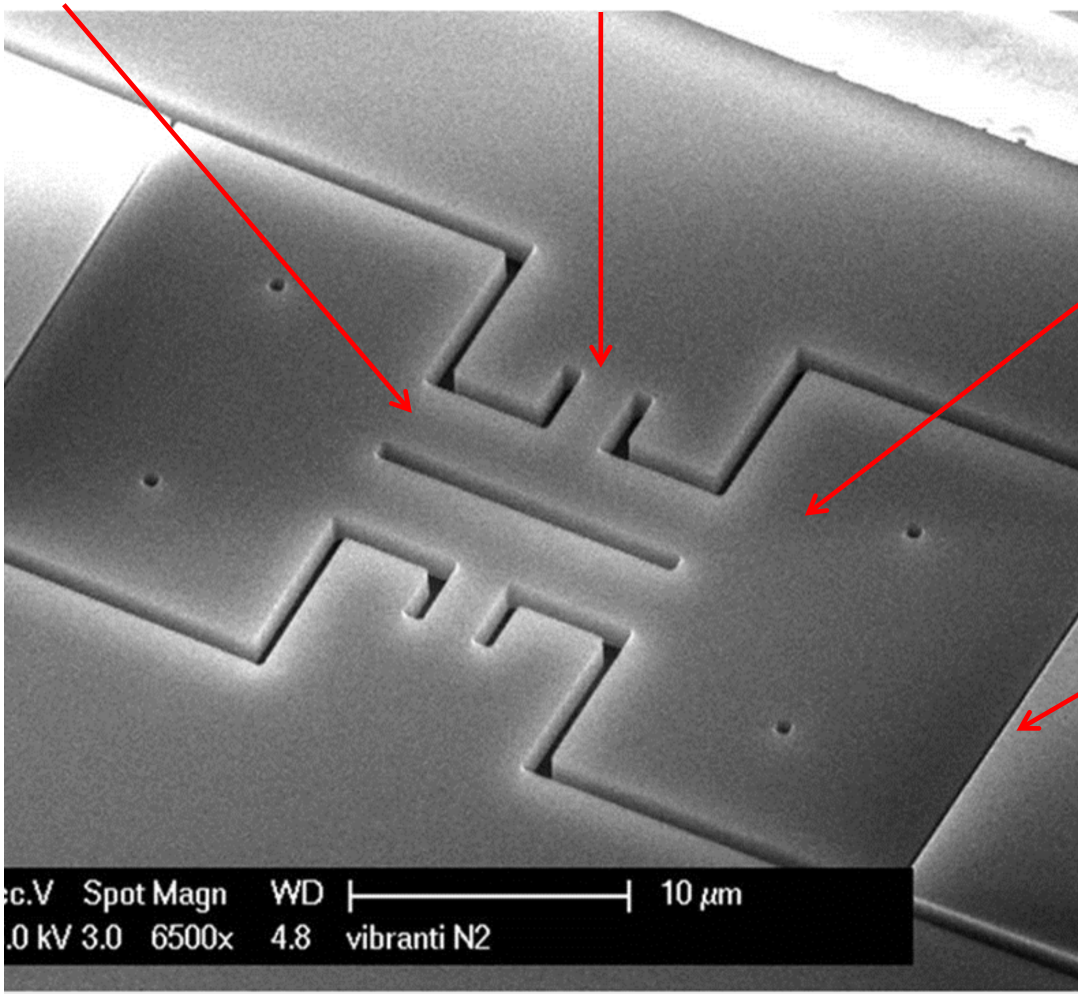
Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan

MEMS resonator overview package

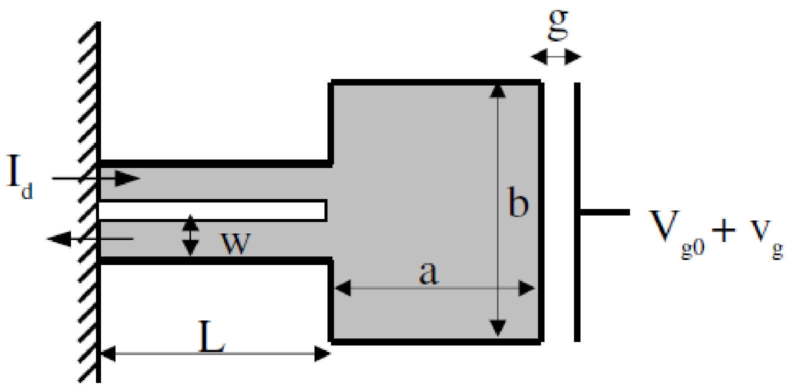


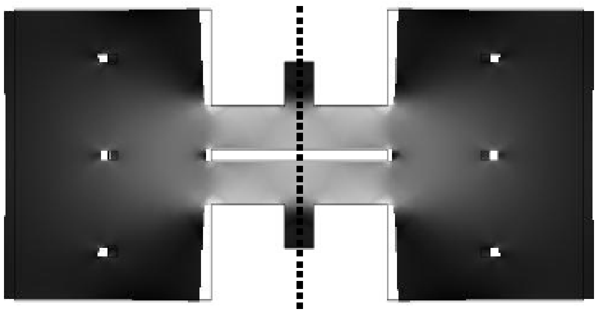
- Resonator size 500 x 700 x 150 micron
- Single silicon on CMOS technology
- High frequency stability, low time jitter, low temperature drift.
- Low motion damping ➔ Q-factor > 40000 (≈ 50 MHz)

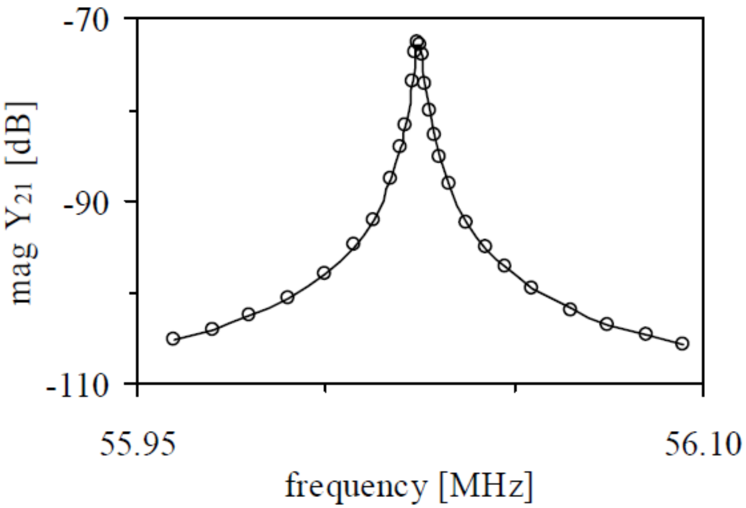
Overview of dogbone resonator



Schematic of dogbone resonator



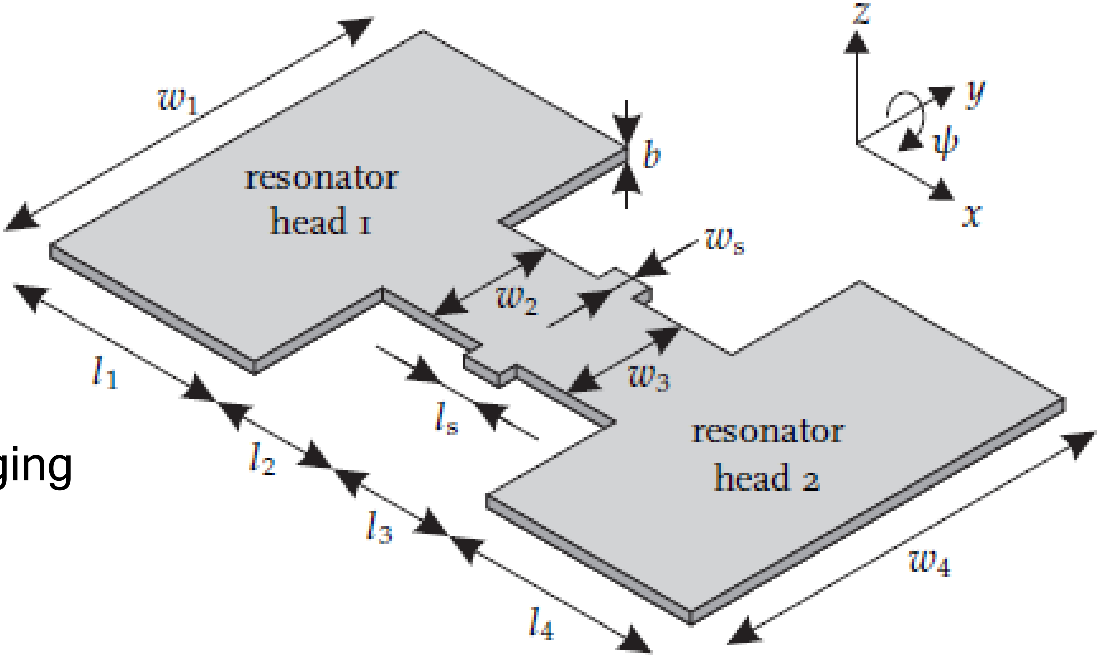




Some parameters studied in COMSOL

- During production in waferfab all dimensions variations can influence the performance
- Q-factor, resonance stability

1. Dimensions resonator head
2. Anchor loss
3. Thickness Si
4. Oxidation layer
5. Air pressure (vacuum)\
6. Thermal losses.
7. Viscous Drag
8. Electrostatic actuation+fringing
9. Mode coupling.

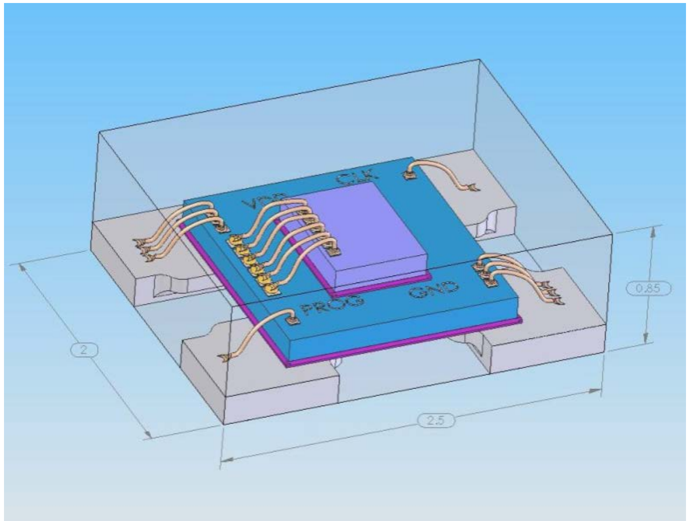


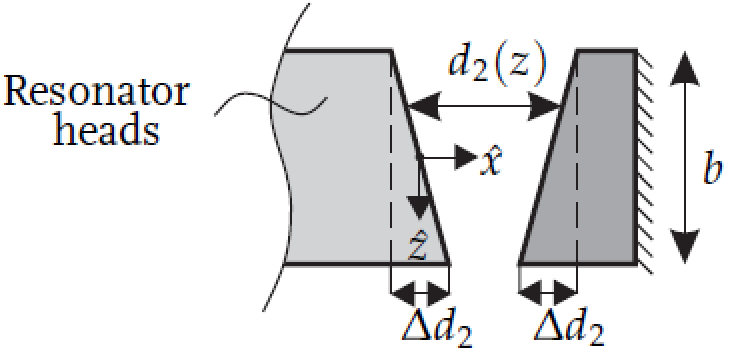
Non linear resonance frequency

- Resonance frequency

$$F_{el} = \eta V_{AC}\sin(\omega t) + \frac{V_{DC}\eta x}{g}$$

$$f_{res} = \sqrt{\frac{k}{m} - \frac{V_{DC}^{2}\varepsilon_0 wh}{mg^3}}$$





1. k spring constant
2. m mass system
3. V driving voltage
4. w width
5. h height
6. g gap

Q-factor estimation

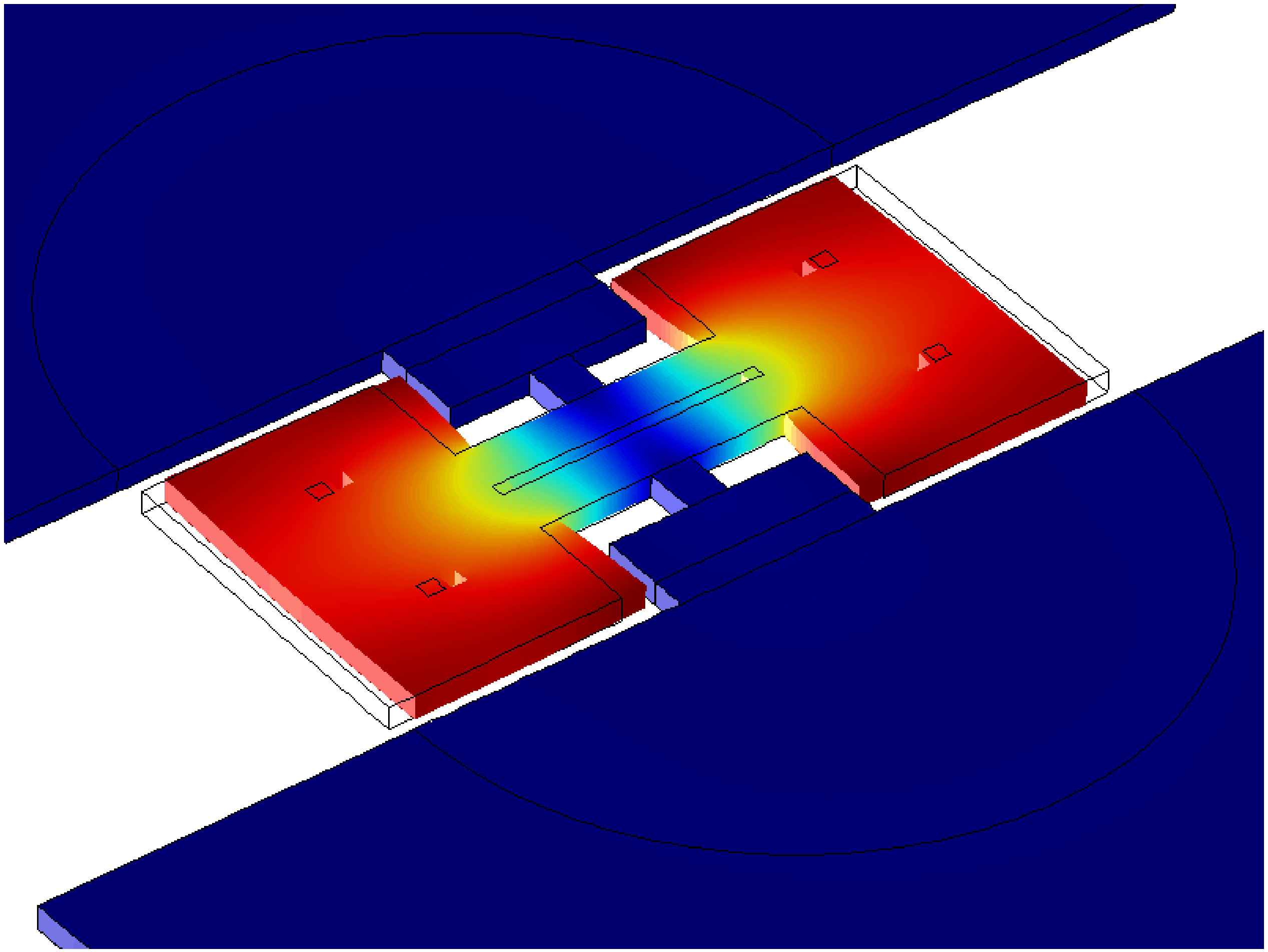
- Reciprocal addition.

$$\frac{1}{Q_{tot}} = \sum_{i=1}^{N} \frac{1}{Q_i}$$

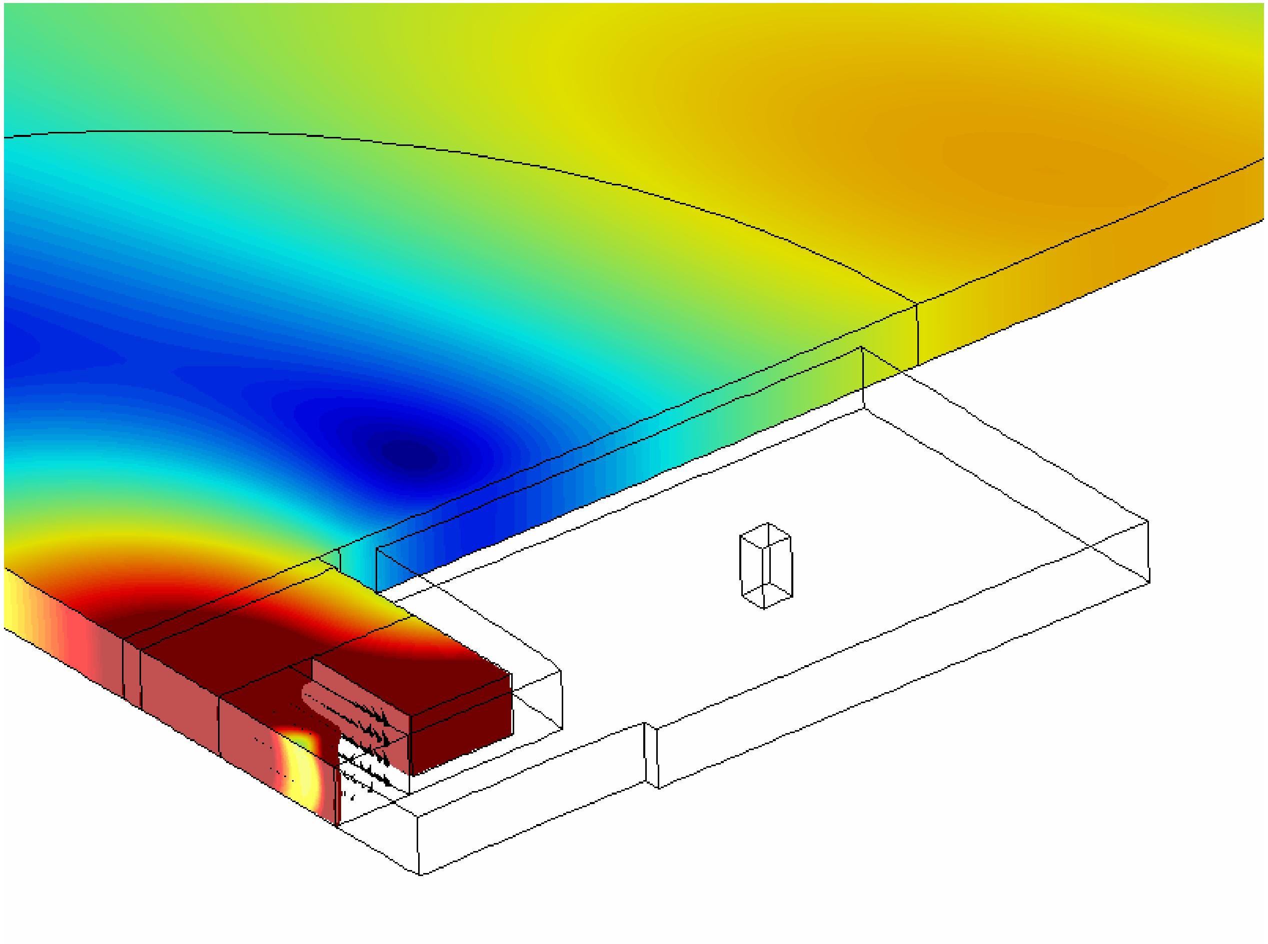
- Anchor loss : $Q_{anchor} \approx 10^4 - 10^7$ dimension
- Thermo-elastic loss $Q_{te} \approx 10^4 - 10^6$ material
- Surface loss: $Q_{sur} \approx 10^6 - 10^8$ debris or cracks
- Air damping: $Q_{air} \approx 10^2 - 10^7$ vacuum quality, leakage
- Viscous drag $Q_{drag} \approx 10^5 - 10^7$ vacuum quality

- All seperate Q factors are estimated with COMSOL.

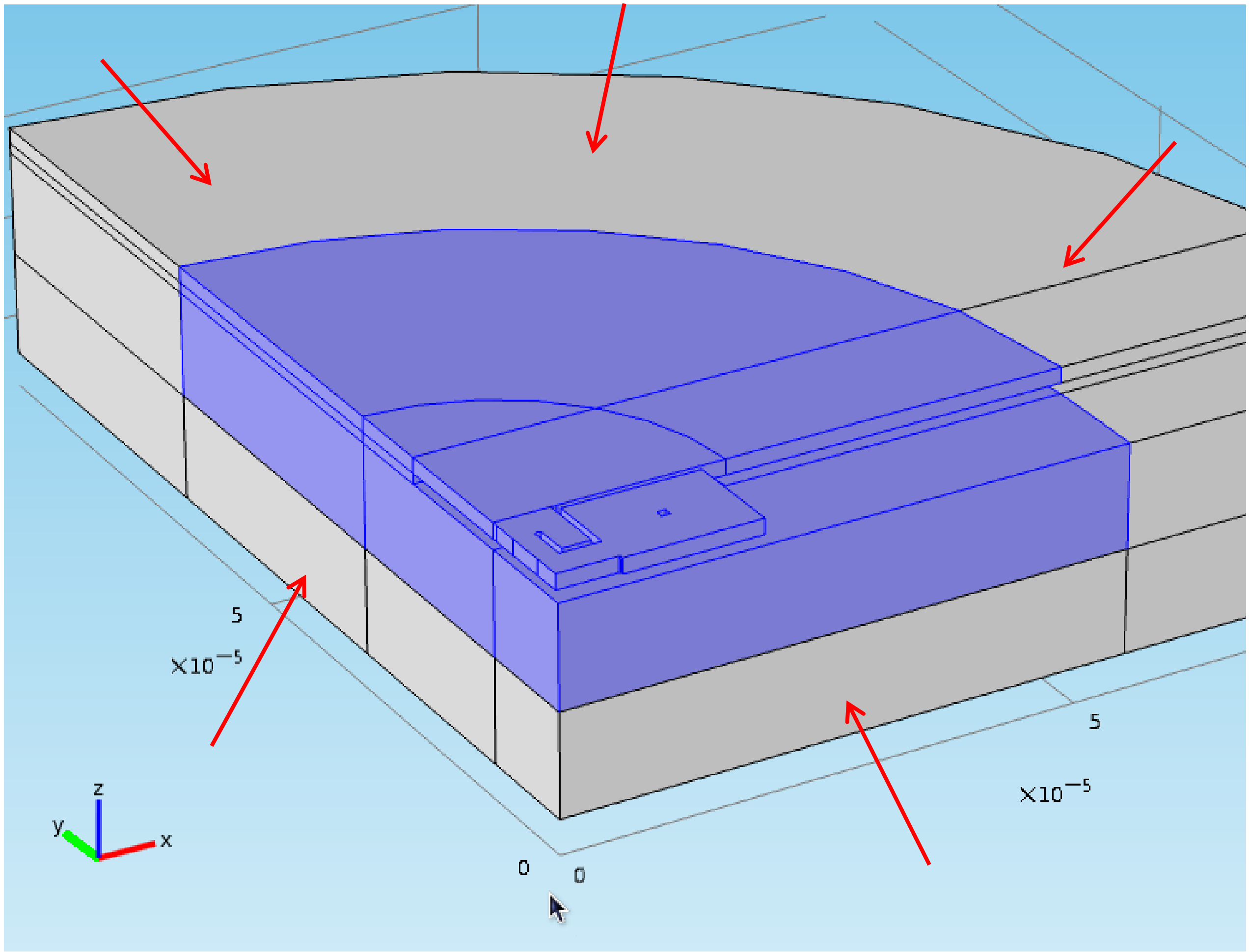
Overview resonance mode at 56 MHz



Acoustic loss at anchor.

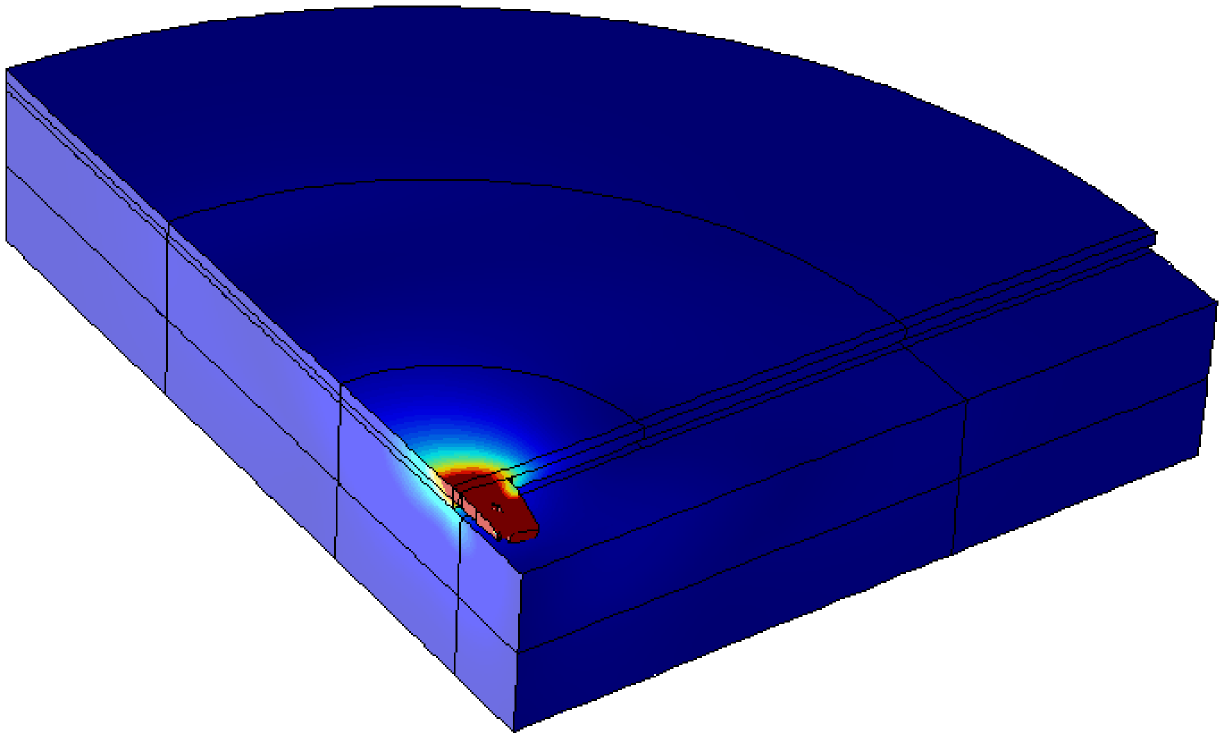


Acoustic loss: Gray domains, PML



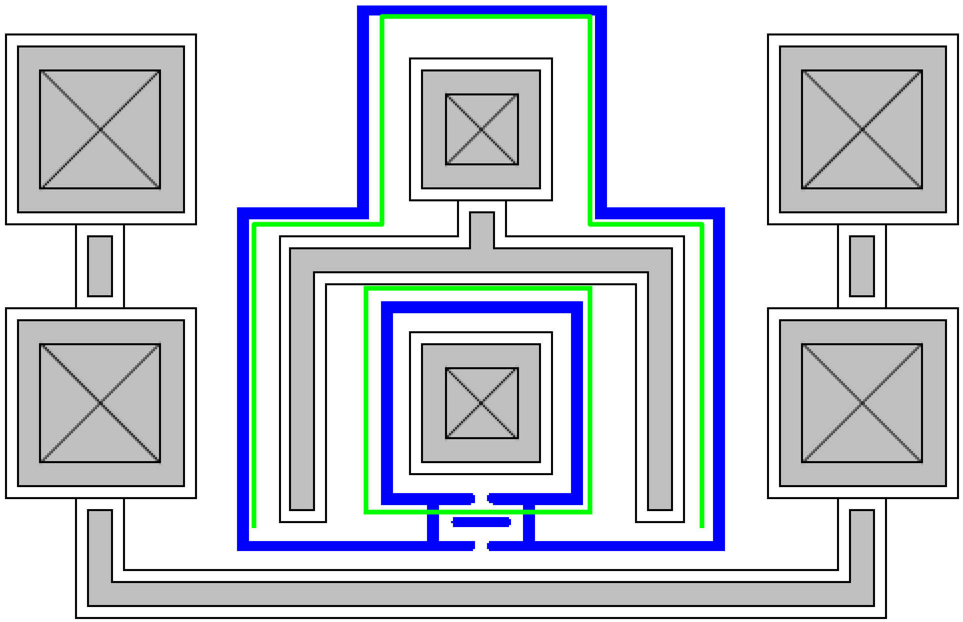
- Red arrows indicate PML-layers.
- In PML complete acoustic absorption.
- Blue domains represent normal material properties.
- Eigenfrequency analyses.

Acoustic loss: dimensional variations in the structure.

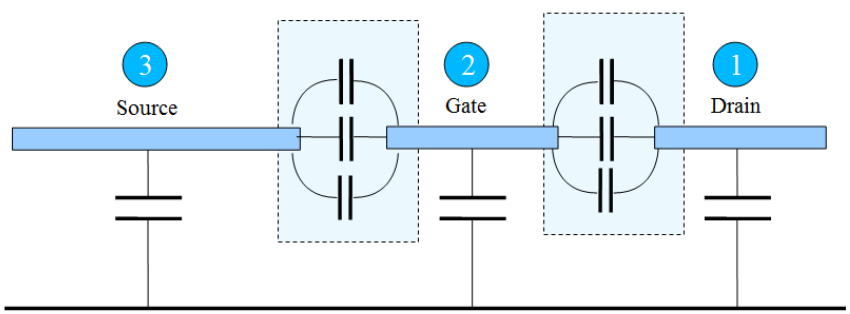


Capacitances

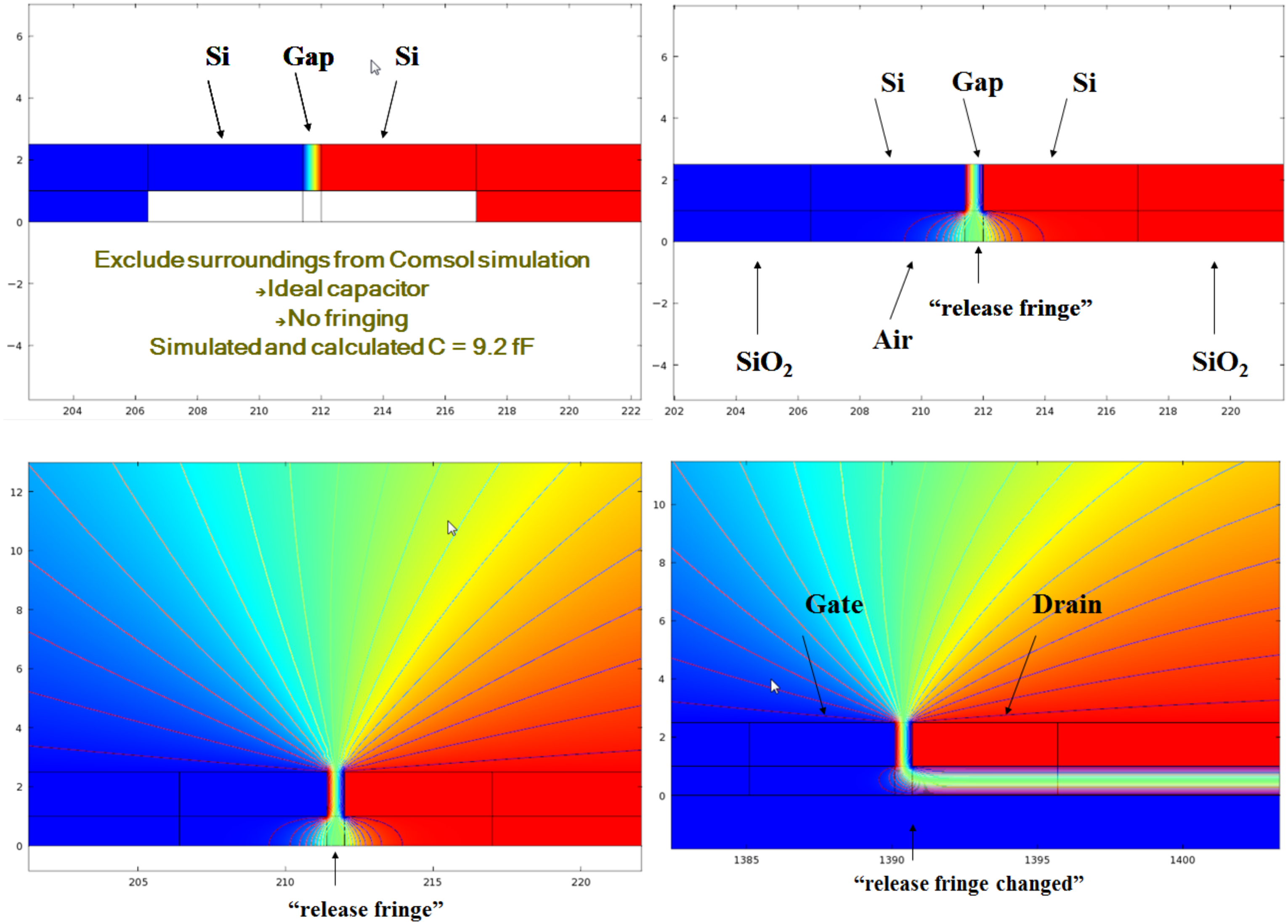
Present design



•Area of gate within green lines is 41(



Fringe effects, from simple to real system

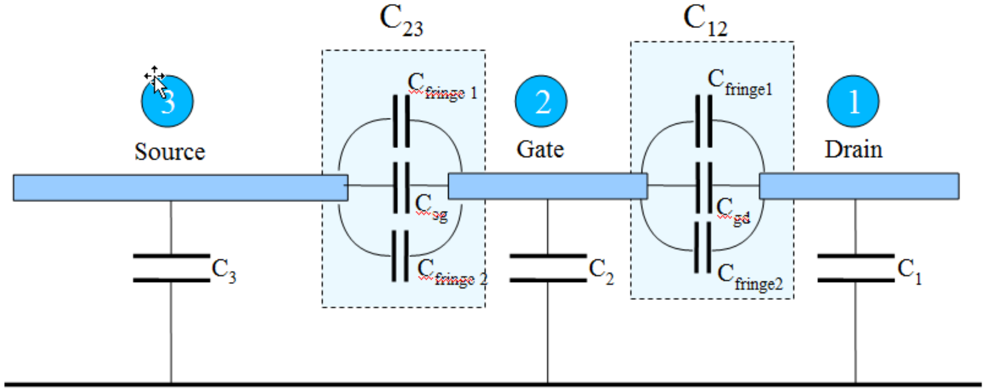


- Simulated Cap = 338 fF
- Dominated by drain bottom capacitance

Calculation + Simulation Gate Capacitance

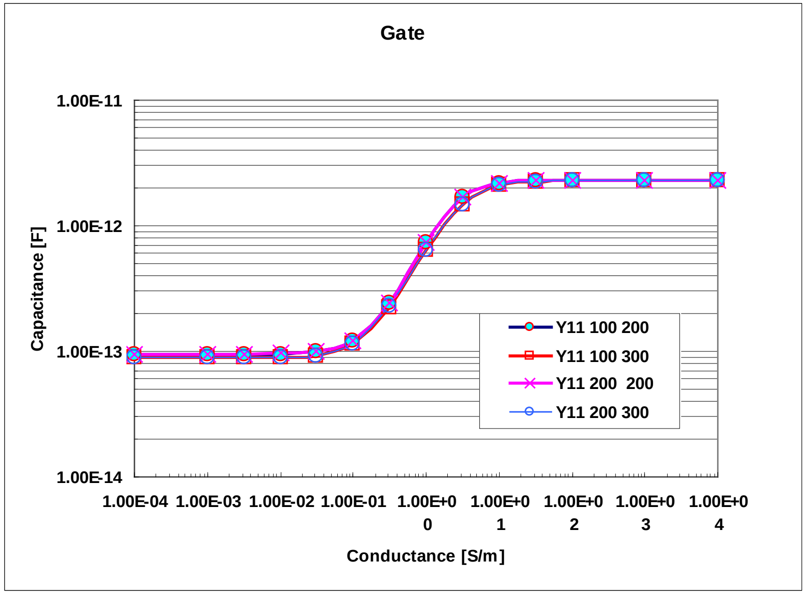
1. Simple hand calculation Drain C_1 = 322 fF
2. Gate C_2 = 1270 fF and Source C_3 = 18700 fF
3. Capacitance C_{12}=22.5 fF and C_{23}=51 fF
4. Using mathematical formula

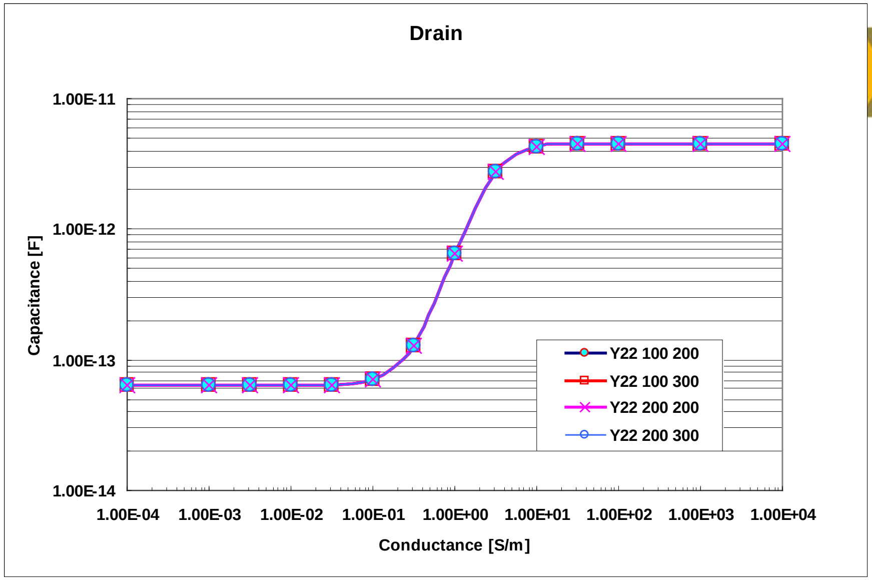
$$C_{gate} = C_{12} + C_{23} + \frac{1}{\frac{1}{C_2} + \frac{1}{C_1 + C_3}}$$

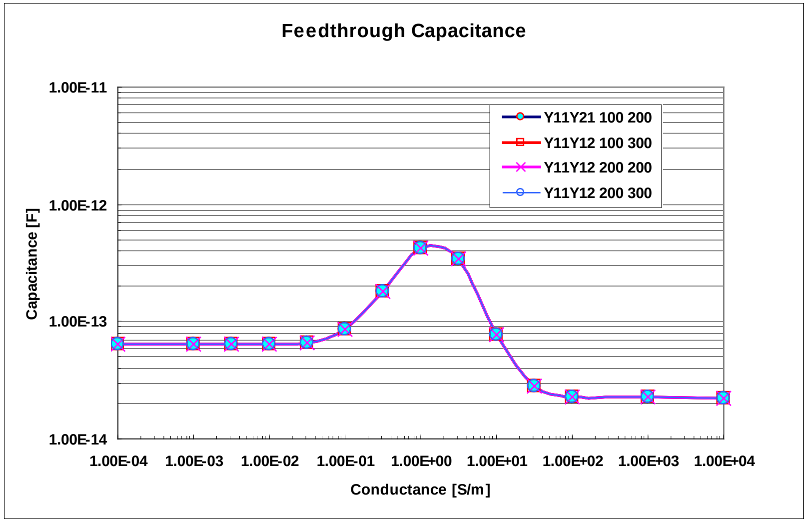


5. C_{gate} = 1264 fF
6. Comsol result is $C_{gate\ Comsol}$= 1266 fF → OK
7. C_{source} and C_{drain} have similar accuracies.

Capacitance as function of resistivity

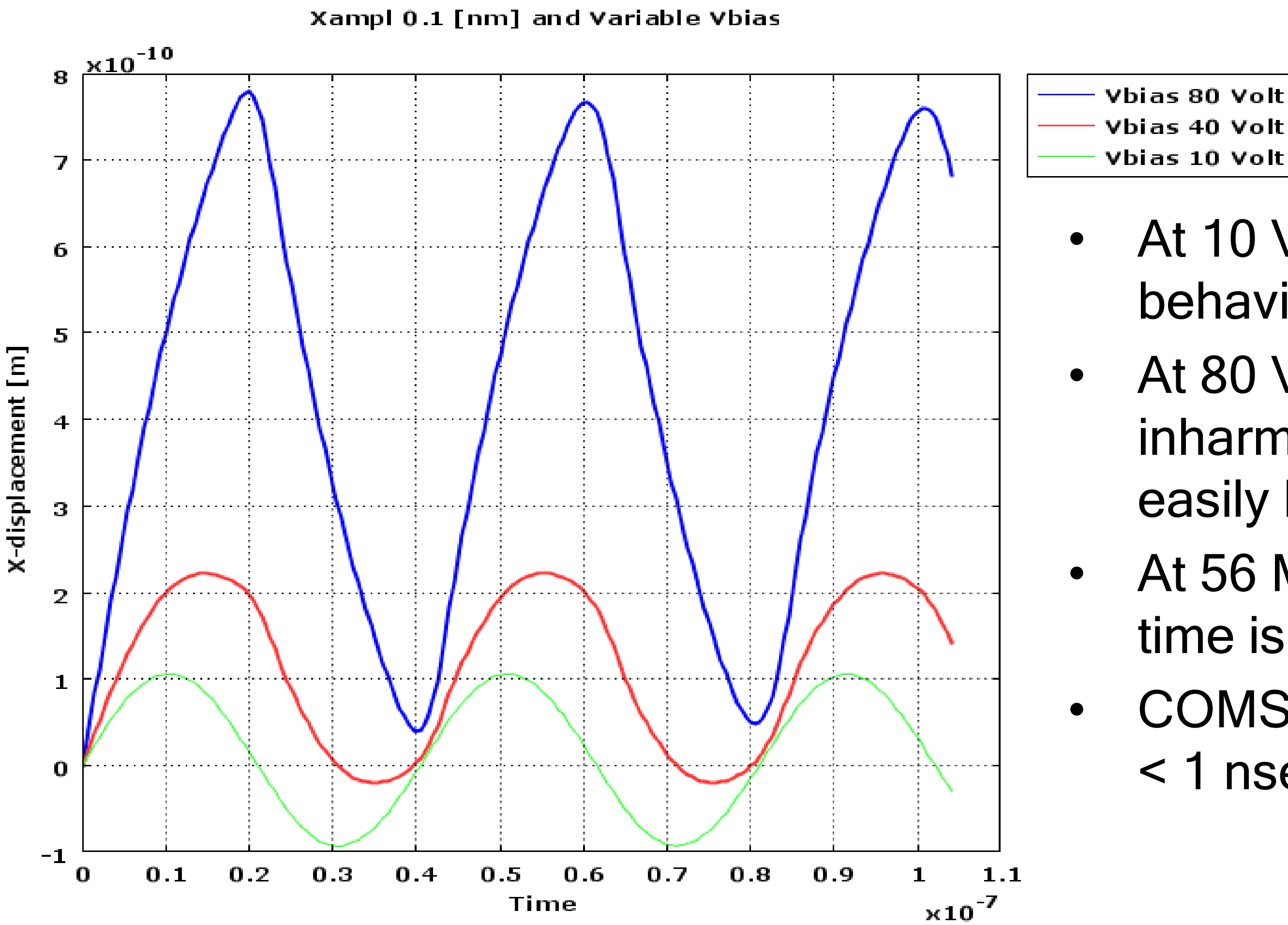






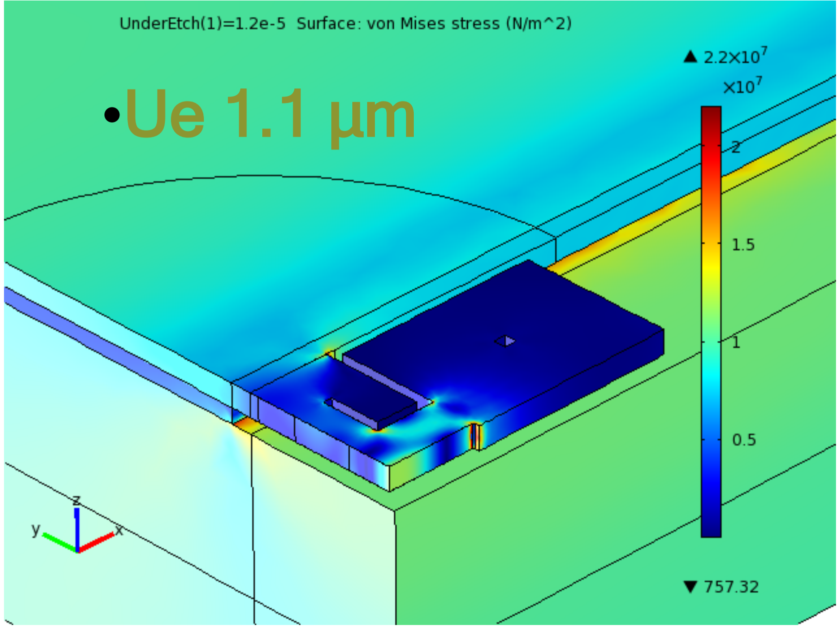
1. Results from Comsol
2. Including effects like air height and substrates thickness
3. Resonator operates at 0.3 – 1.2 Ωcm (equivalent to 80 - 330 S/m)
4. Capacitance variation is < 2% in resistivity range
5. All simulations are performed with 56 MHz

Asymmetric amplitude under electrical load (V bias)

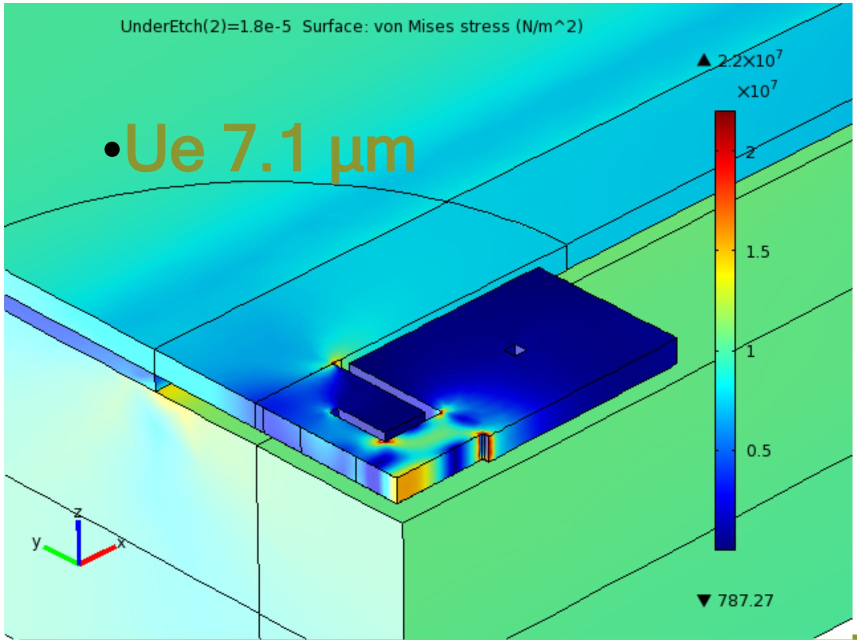


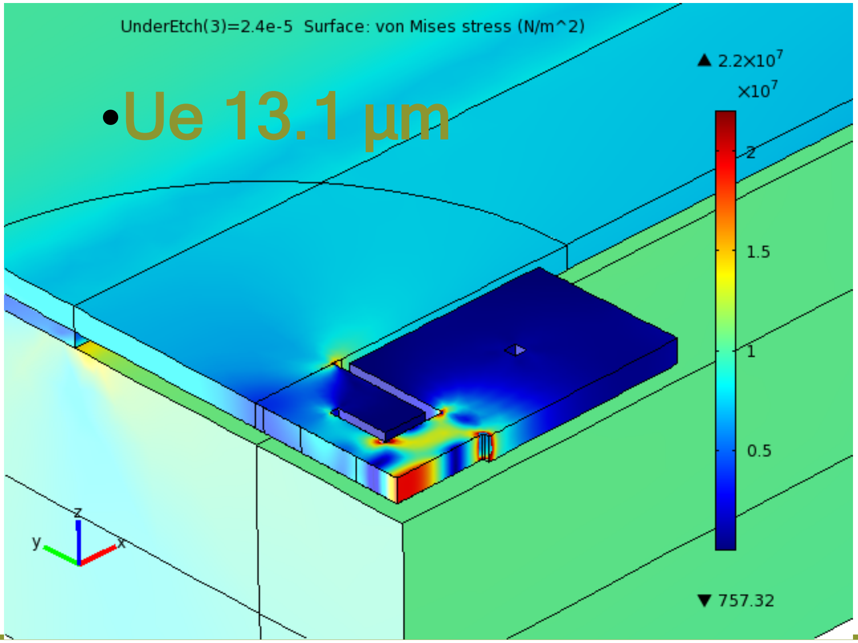
- At 10 Volt, a harmonic behavior.
- At 80 Volt bias an inharmonic term can easily be seen.
- At 56 MHz, oscillation time is 40 nsec.
- COMSOL time step < 1 nsec

Static stress due to process cycles

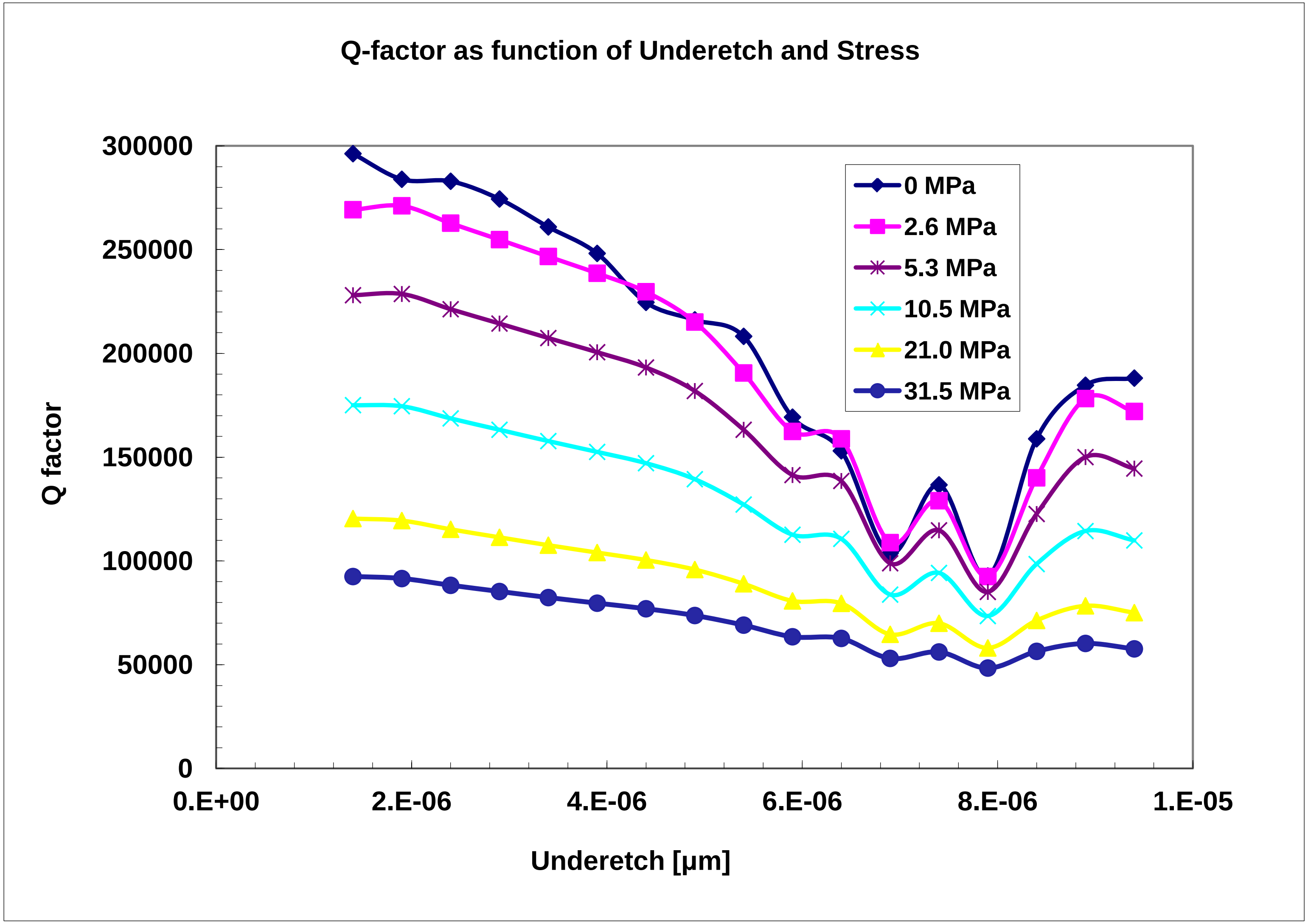


- Static stress at perifery due to curing procedures at various process conditions
- Stress concentrations in resonator legs.





Q-factor of resonator under Stress



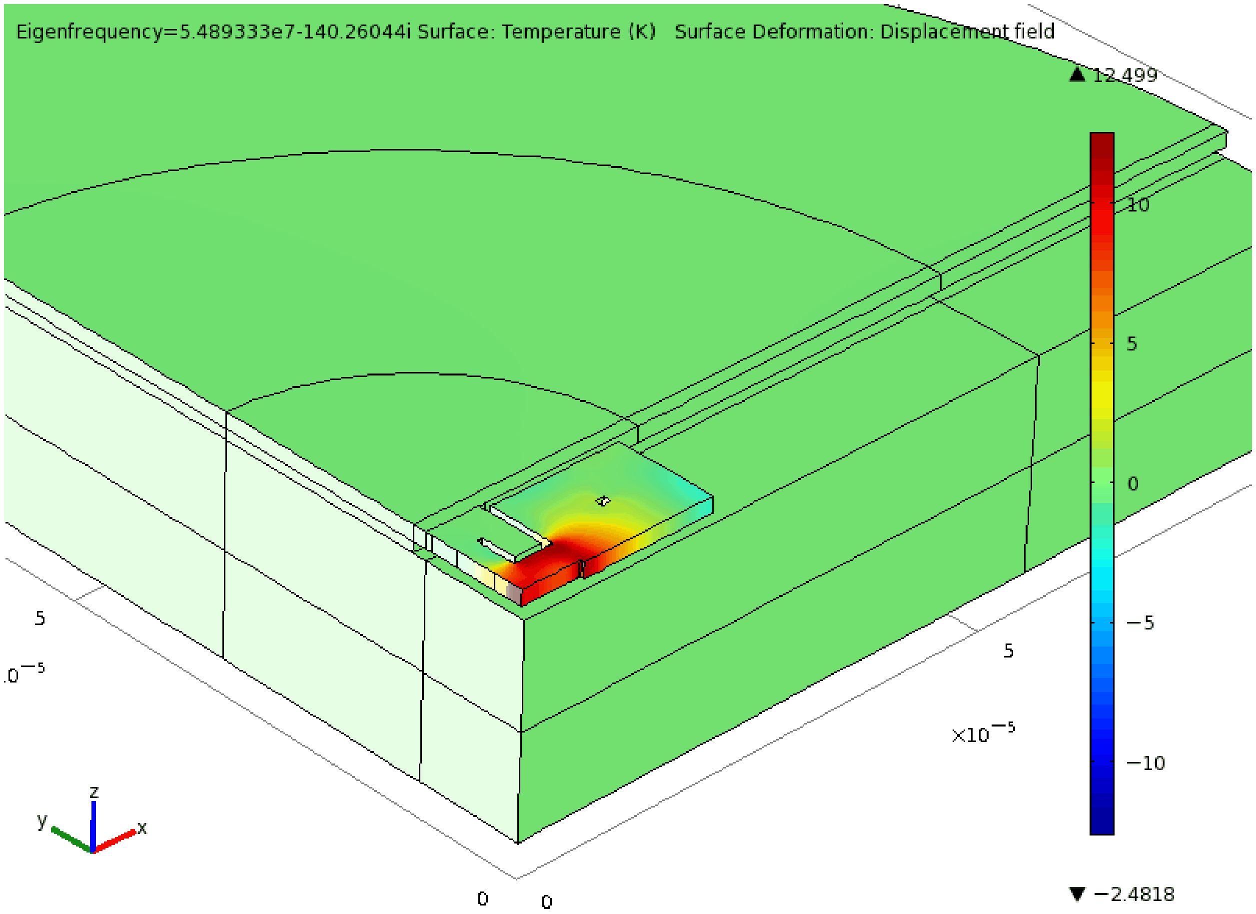
Thermal losses in resonator

- Q-factor can be written as:

$$\frac{1}{Q_{therm}} = \frac{E\alpha^2 T_o}{\rho C_p} \frac{\omega\tau}{1+(\omega\tau)^2}$$

- E = Youngs Modulus [Pa]
- α = expansioncoefficient [1/m]
- T_o = ambient temperature [K]
- ρ = density [kg/m^3]
- ω = frequency [rad/s]
- τ = thermal relaxation [s]

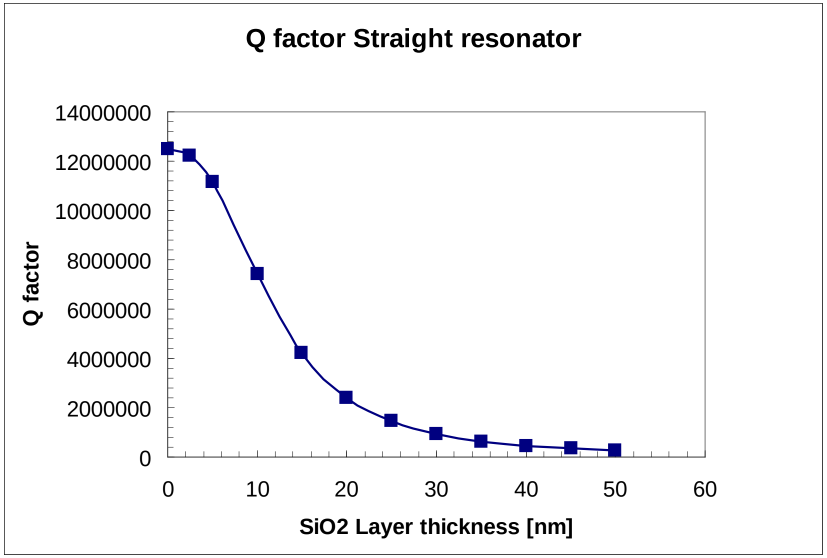
Thermal losses in resonator

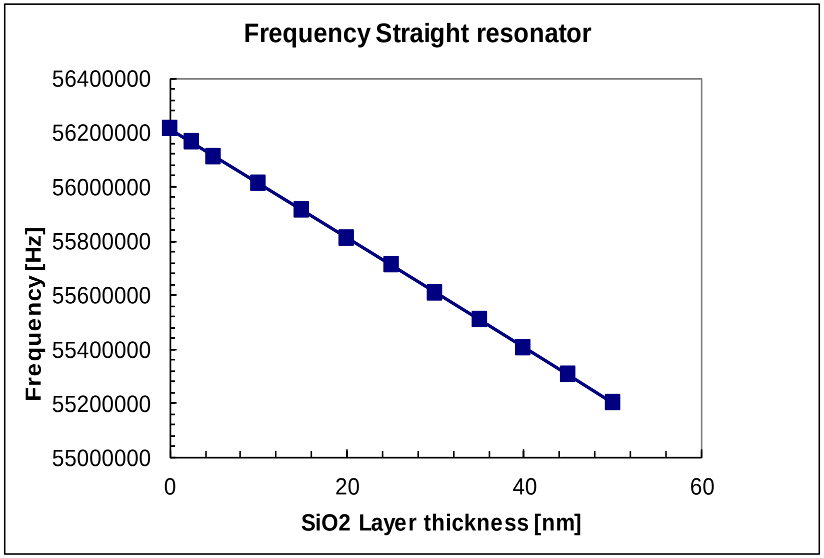


Temperature fluctuations of about ±10^0C, at 56 MHz.

This mechanism is due to material properties.

Thickness Oxidation: Q factor and frequency shift

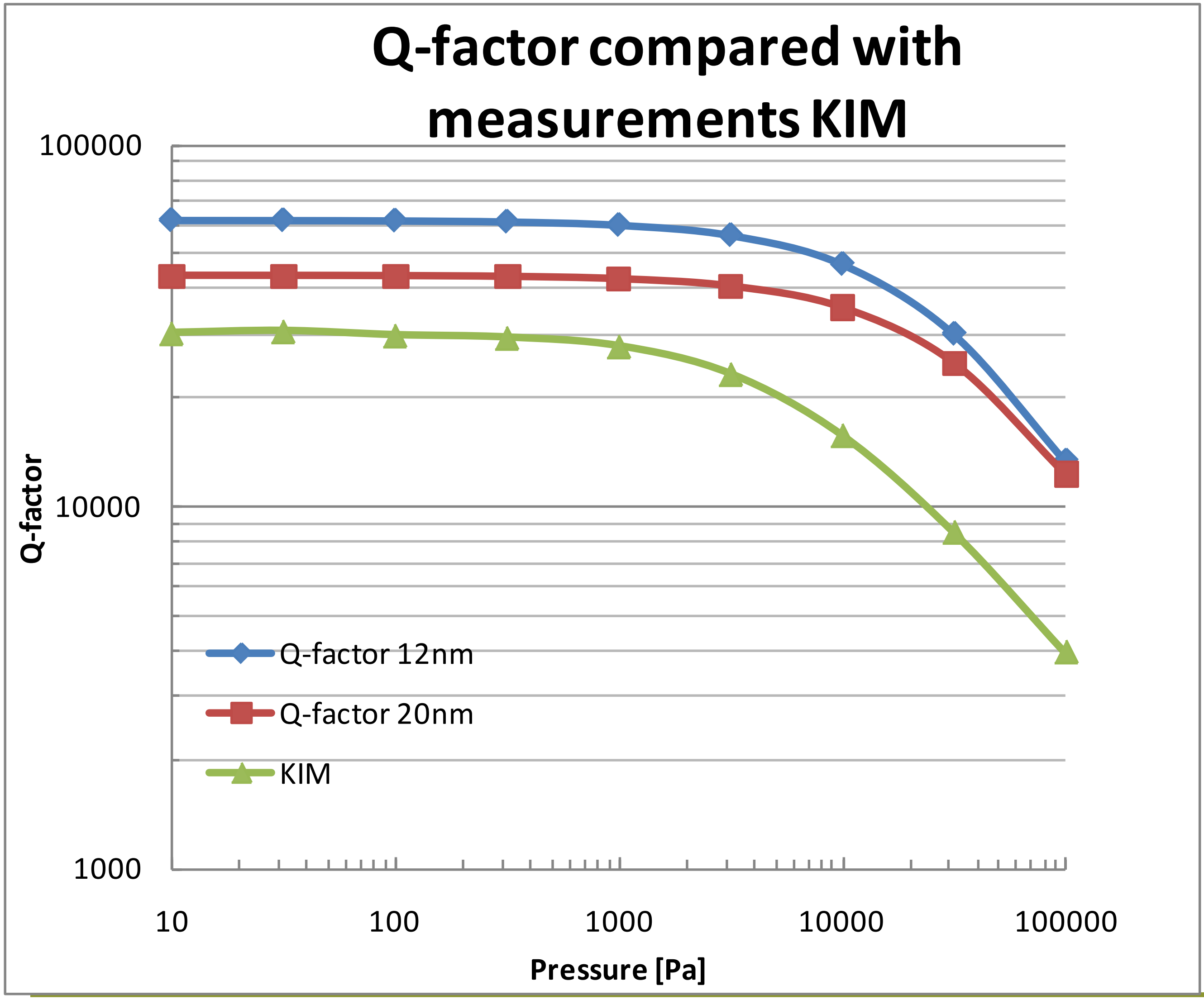




- Simulation with single layer.
- Mesh is adapted at layers lower than 20 nm.
- Minimum layer thickness 2.5 nm.

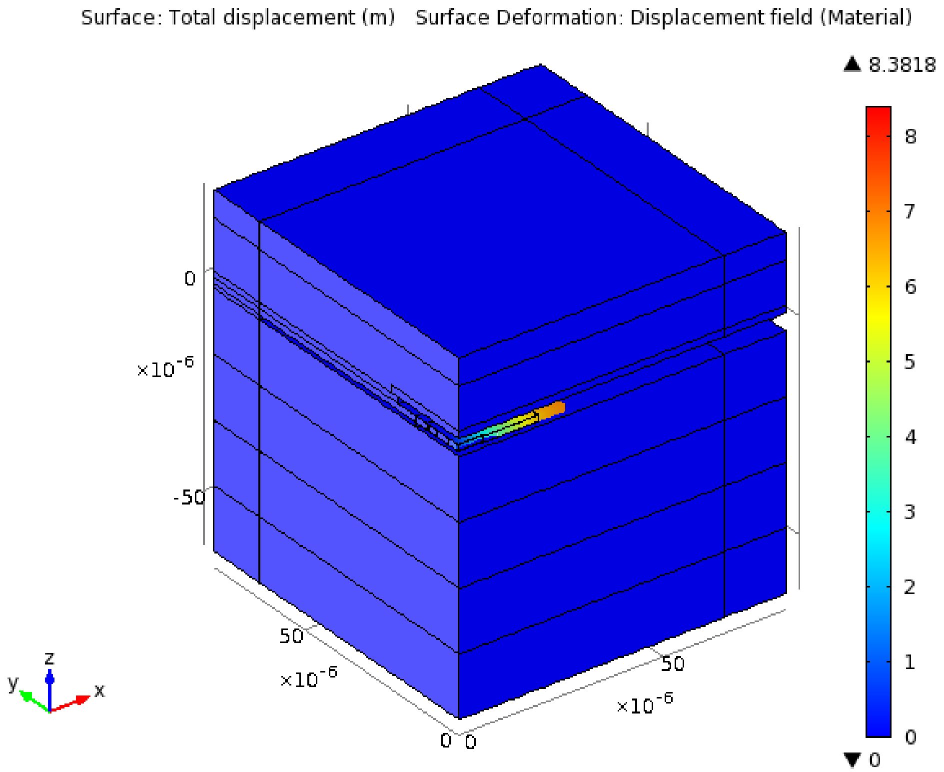
- In Comsol, Solid mechanics and shells are combined.

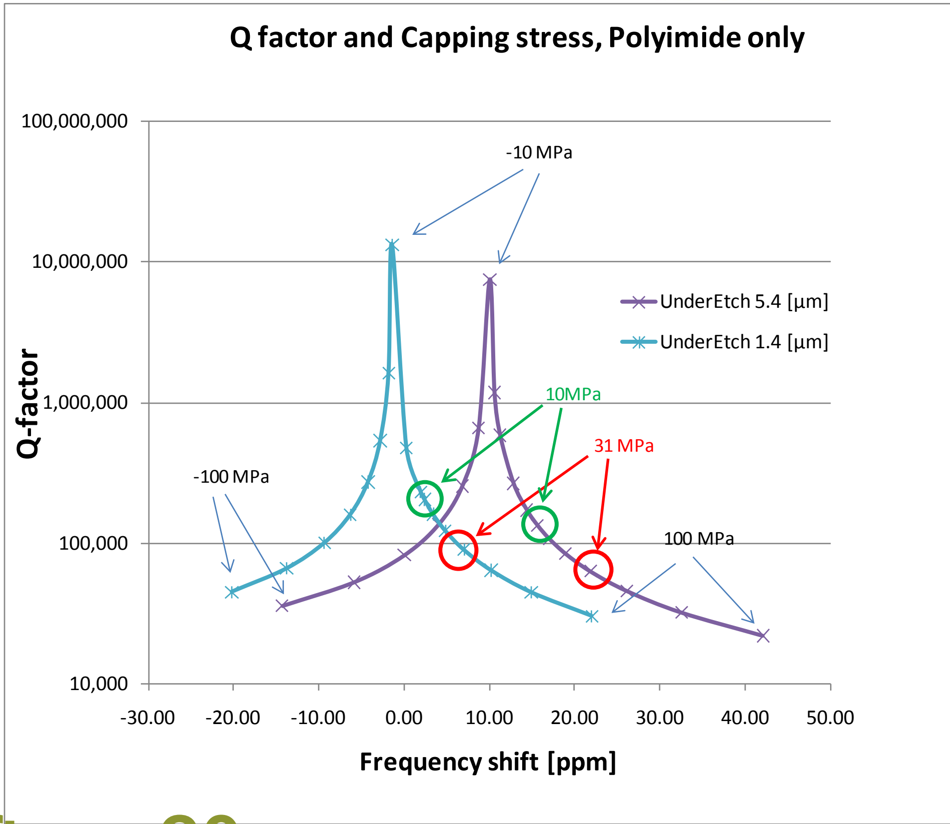
Squeezed film effect including stress



- Q > 40000 at appropriate conditions
- Sliding effect on large surface negligable
- Q-factor is slightly dependant on mesh size of the surface where the film damping is applied.

Overview: Influence of Polyamide Capping above resonator





Permanent frequency shifts: ≈ 20 ppm

Well within specs.

Conclusion

- Production steps in CMOS technlogy have their own influence on the performance of the resonator.
- COMSOL paved the way to better understanding to control specs in production. (Q-factor, dimensions, stress and material loss factors)
- MEMS module was used together with the mechanical module.
  - Prestressed Analysis, eigenfrequency
  - Prestressed Analysis, frequency domain.
  - Heat module, Squeezed film and much more.

- Thanks to Dr. H van de Vlist (NXP, Nijmegen)
  Dr. J. van Beek (NXP, Eindhoven)