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Simulation Methods for Electrostatic MEMS Switches and Resonators

Peter Steeneken

Jaap Ruigrok, Shuo Kang, Joost van Beek, Hilco Suy, Martijn Goossens, Joep Bontemps and Jan-Jaap Koning

NXP Semiconductors, The Netherlands

NXP Semiconductors

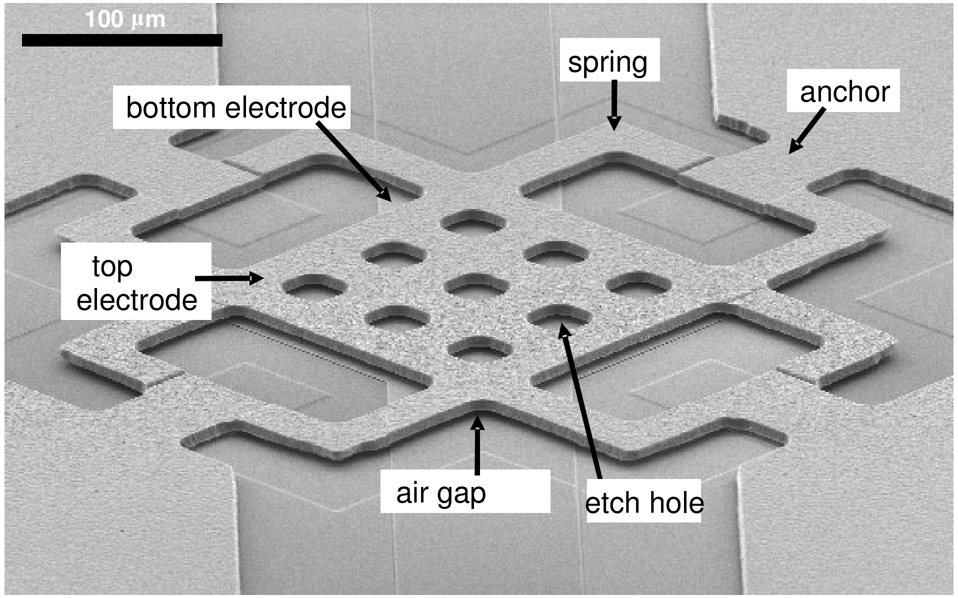
- Established in September 2006 (formerly a division of Philips)
- ~38,000 employees
- Headquarters: Eindhoven, The Netherlands
- Main product: transistors on Silicon
- But also other electronic devices on Silicon…

Outline

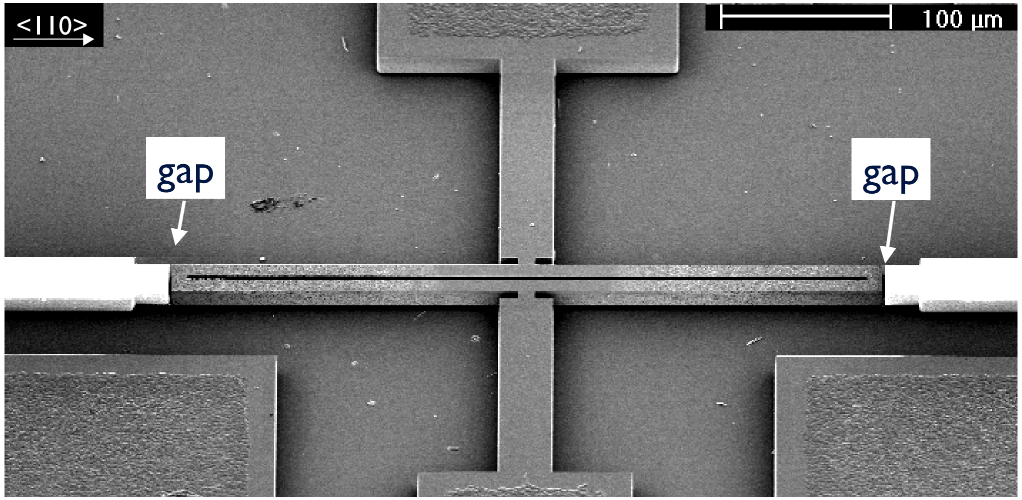
MEMS: Micro Electrical Mechanical Systems

- RF MEMS switches
  - Calculation of the C-V curve using Comsol
- MEMS resonators
  - Equivalent parameters m, k and Q of a MEMS resonator using Comsol

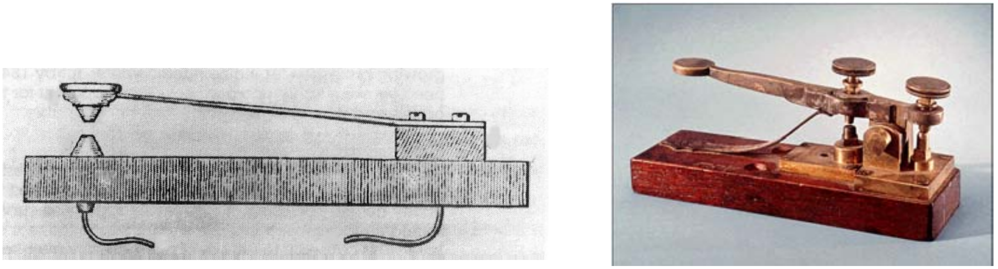
RF MEMS capacitive switch



MEMS resonator

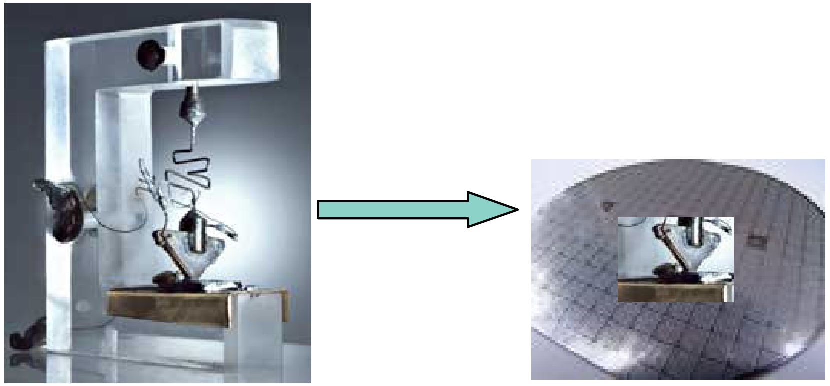


Electrical switches



Morse telegraph key (1844)
Mechanical switch

Advantages
- Low loss/resistance
- High linearity
- High power handling



Transistor (1947)
Semiconductor switch

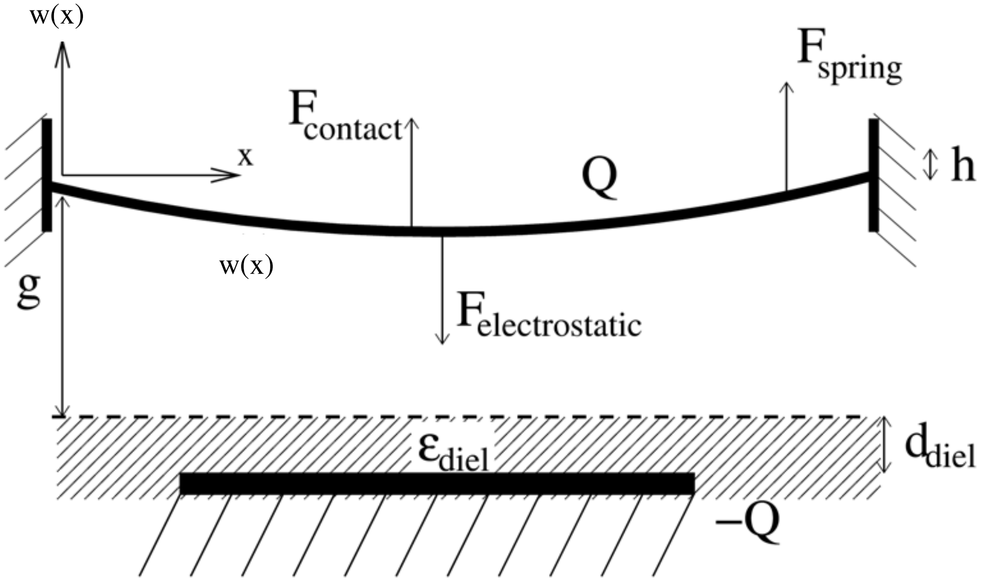
Advantages:
- Very small size
- High switching speed
- Low cost

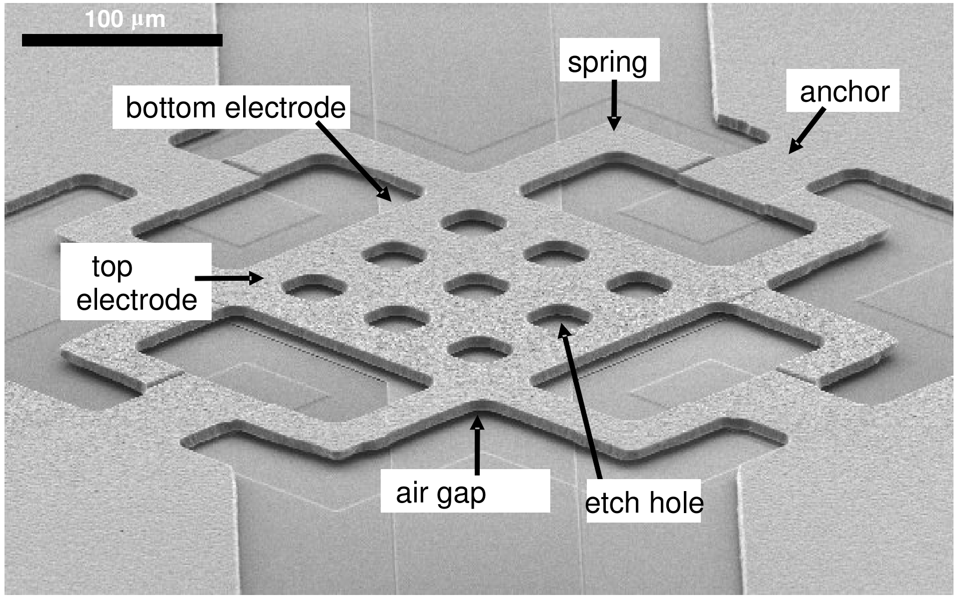
Radio Frequency MicroElectroMechanical Switch (RF MEMS)

Best of both worlds: Mechanical switch on semiconductor substrate.
- Low loss
- High linearity
- High RF power handling
- Intermediate size
- Intermediate switching speed
- Intermediate cost

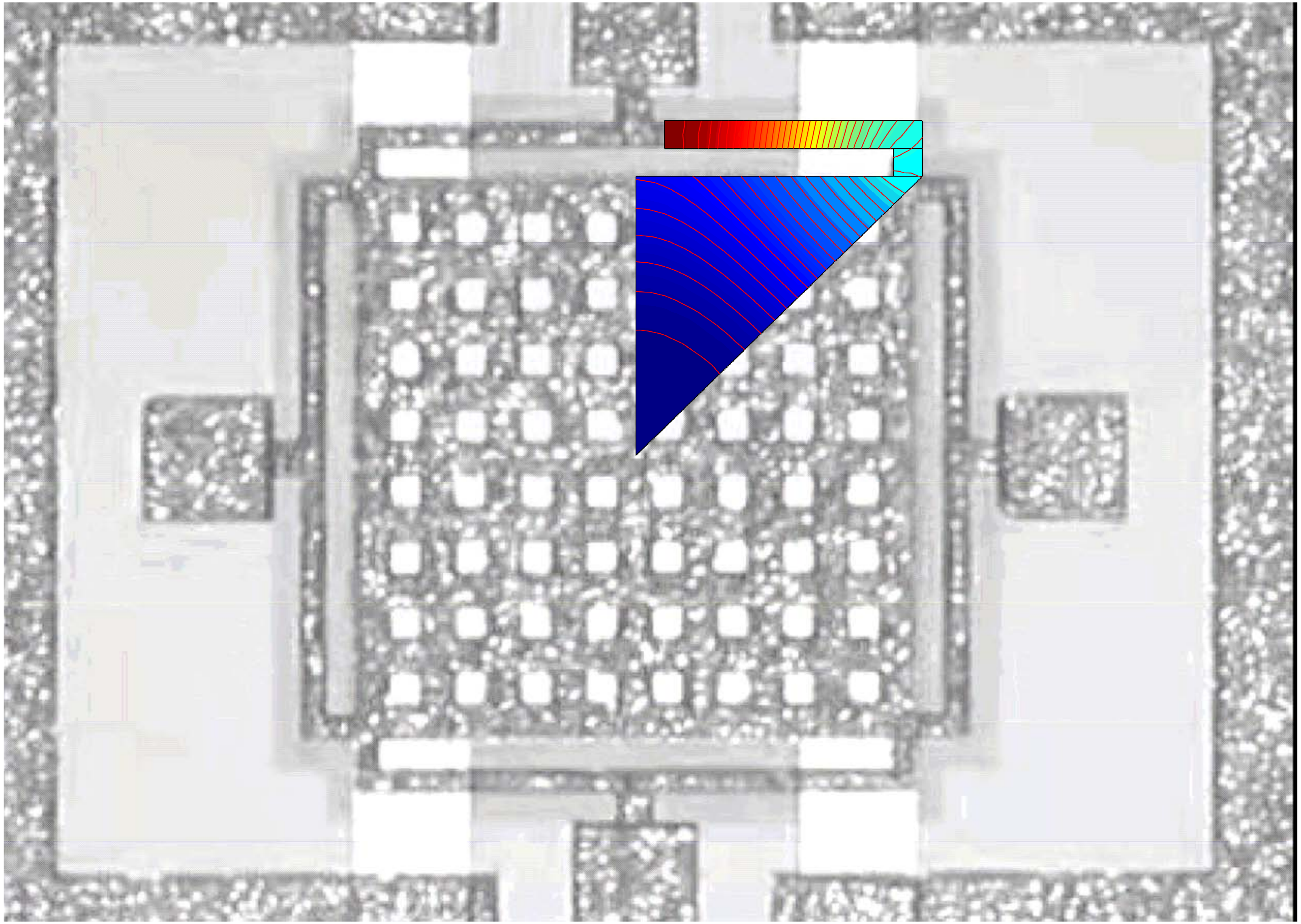
RF MEMS switch physics

- Forces
- Static
  - Spring forces
  - Electrostatic force
  - Contact force
- Dynamics
  - Gas damping force
  - Inertial forces





MEMS switch under study

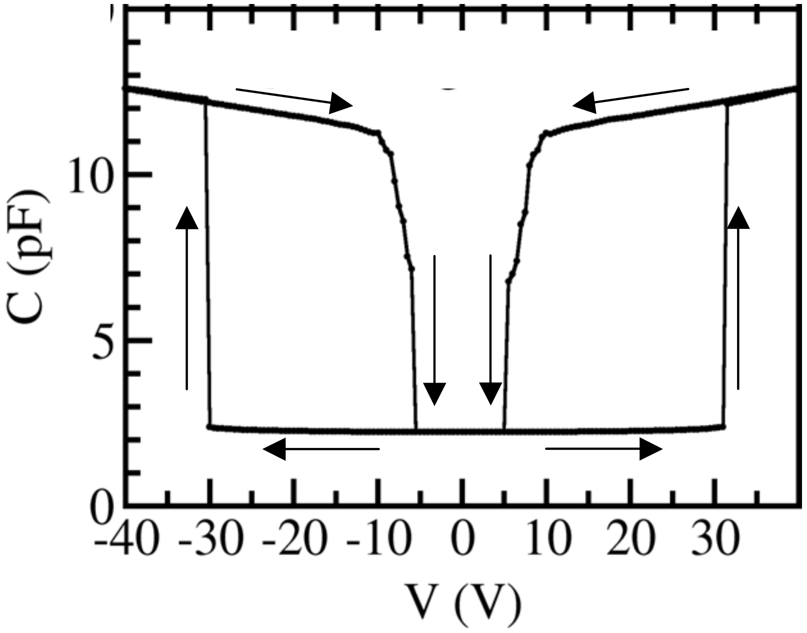


MEMS Capacitance-Voltage curve in Comsol

- Approximations:
  - Electrostatic parallel plate approximation.
  - Use Mindlin elements for mechanical domain.
  - Hard contact.
- Simulation in Comsol structural mechanics domain
  - Implement electrostatic and contact forces as pressures on the structure.

Parametric solver

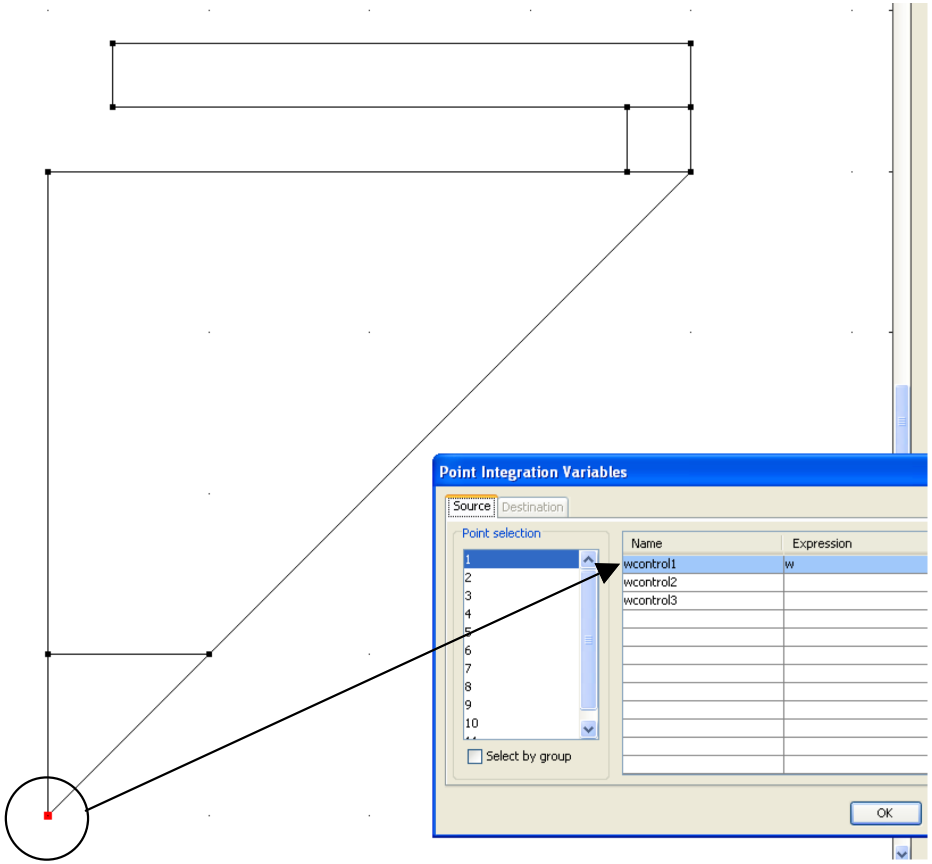
- How to get C(V)?
- Problem with voltage control:
  - Multiple solutions for 1 voltage.
  - Discontinuities in the shape at pull-in and release voltage.
  - Convergence problems.



- Solution:
  - Position control of control node.
  - Determine C and V at each position.

Implementation of position control in Comsol

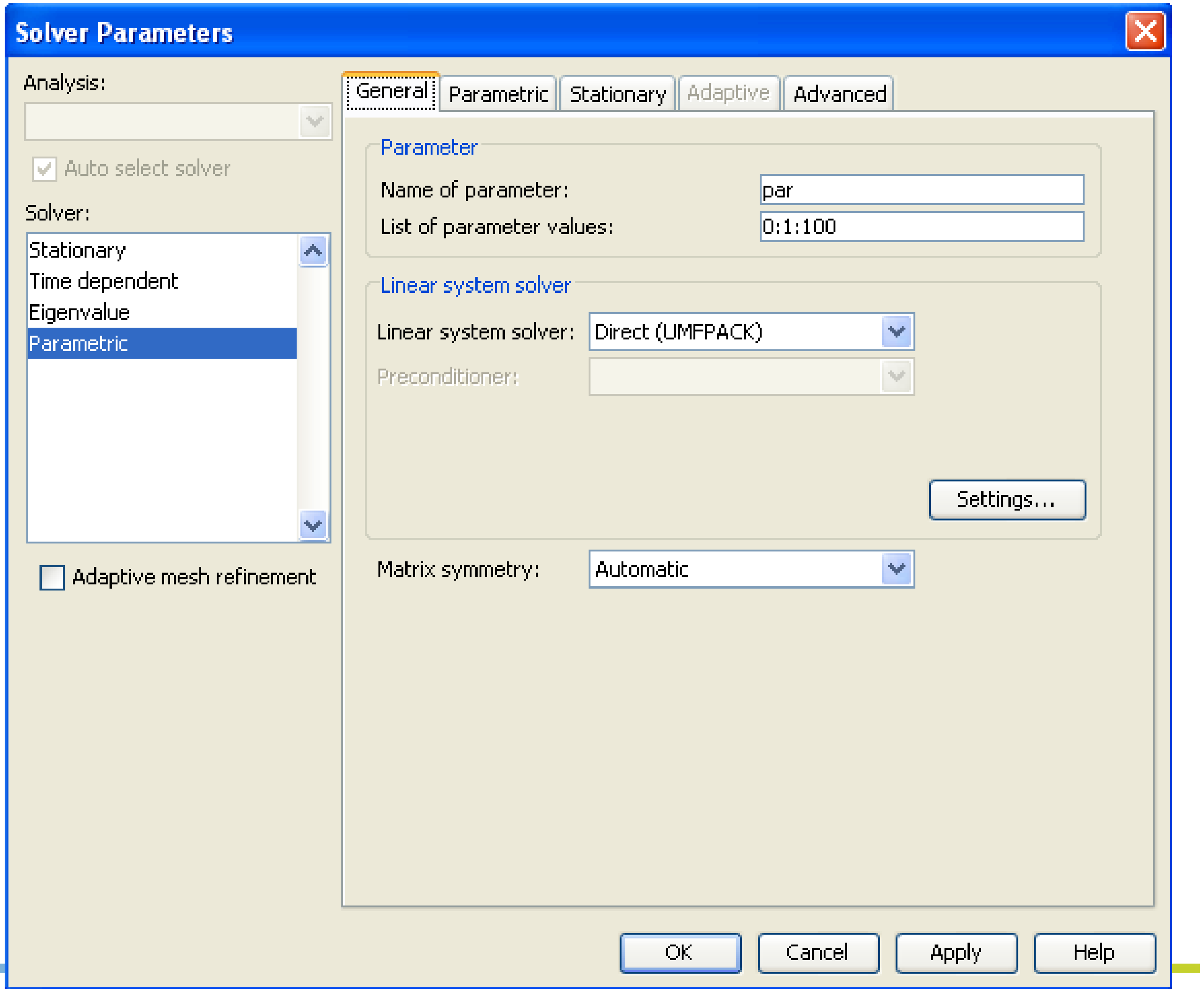
- Define point integration variable wcontrol1 on control node.



Name	Expression
wcontrol1	w
wcontrol2	
wcontrol3	

Parametric solver

- Parameter par goes from 0-100.
- wset=-g*par/100.



Solver Parameters

Analysis:

☑ Auto select solver

Solver:
- Stationary
- Time dependent
- Eigenvalue
- Parametric

☐ Adaptive mesh refinement

Parameter

Name of parameter: par

List of parameter values: 0:1:100

Linear system solver

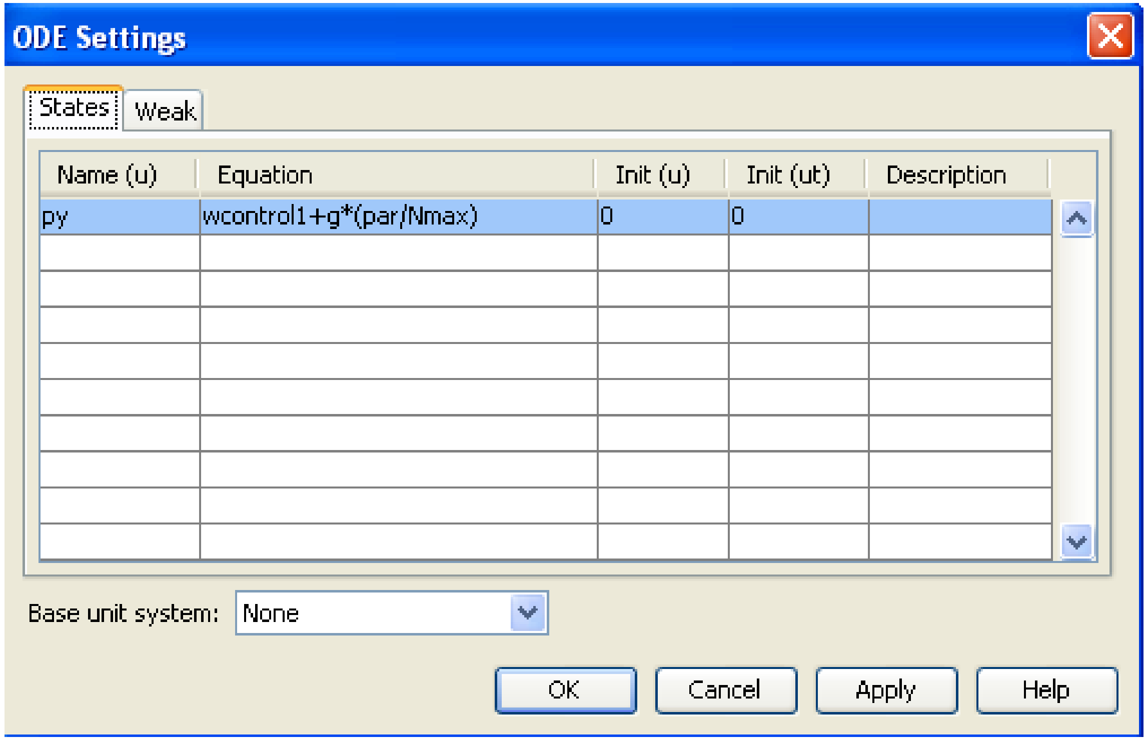
Linear system solver: Direct (UMFPACK)

Preconditioner:

Matrix symmetry: Automatic

Define extra degree of freedom py

- ODE will vary py until: *wcontrol1=wset* *(wset=-g*par/100)*
- This will ensure that the control node is moved from open to closed position.

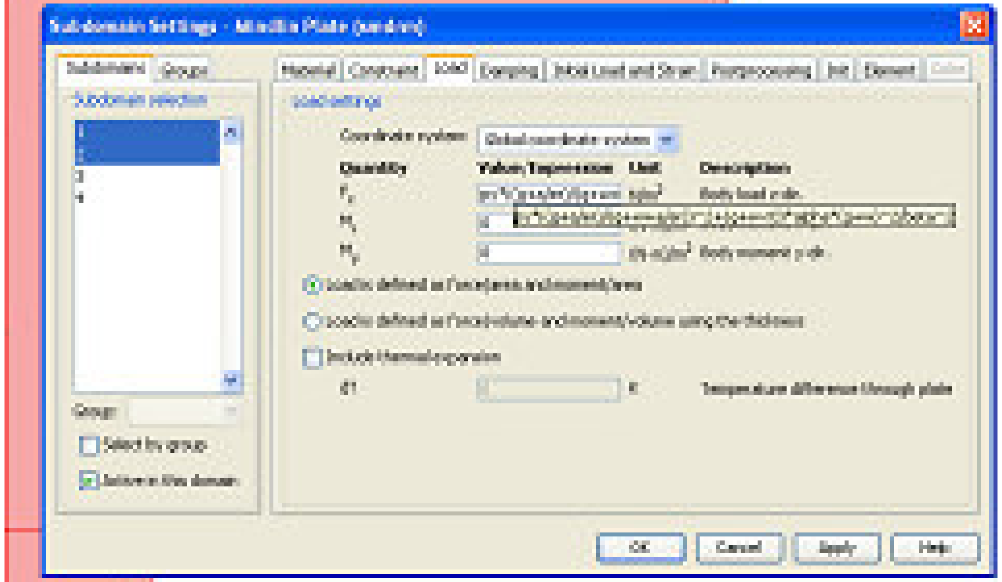


Name (u)	Equation	Init (u)	Init (ut)	Description
py	wcontrol1+g*(par/Nmax)	0	0	

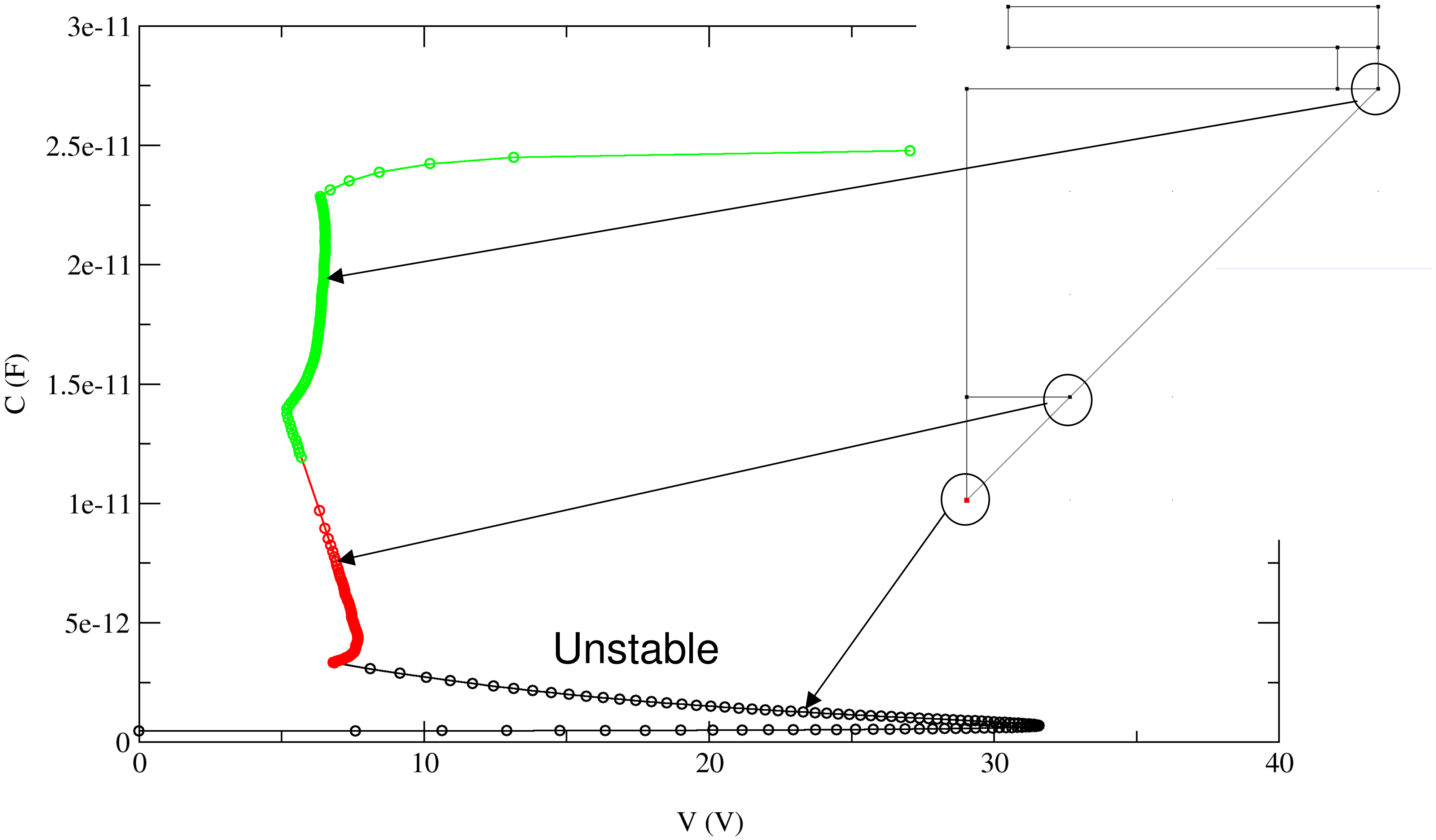
Base unit system: None

Apply adaptive electrostatic and contact force

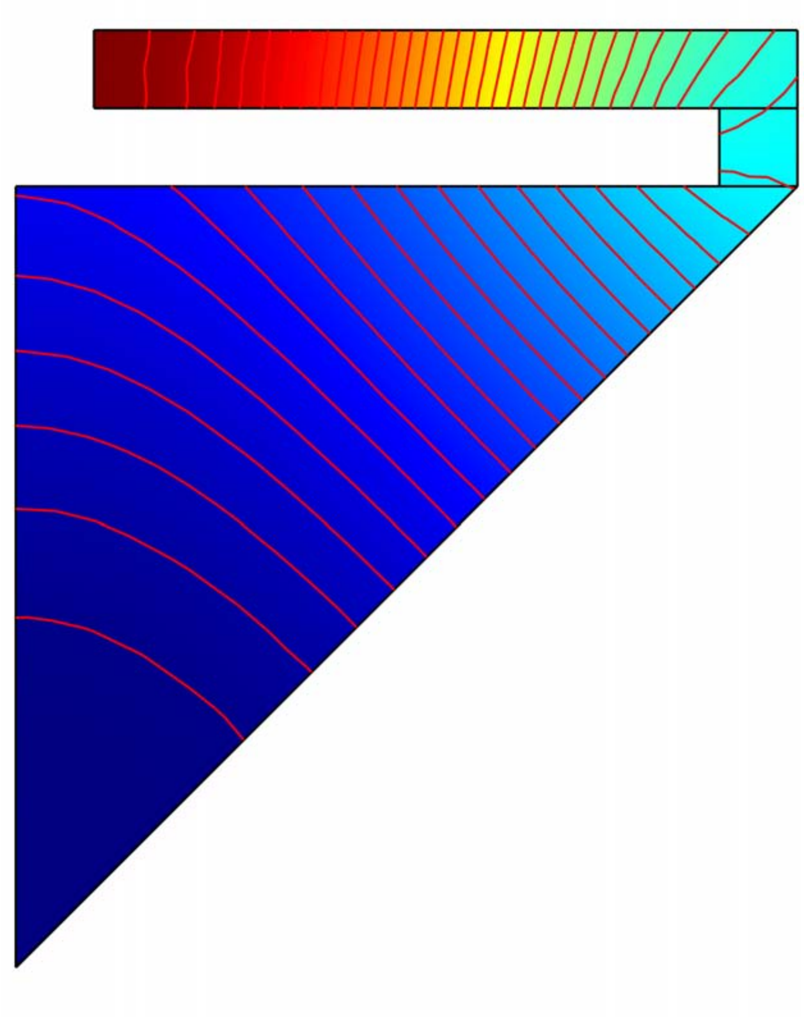
- In Comsol a pressure $P_e=py^*(g+a/\varepsilon_r)^2/(g+w+a/\varepsilon_r)^2=V^2/2\varepsilon_0(g+w+a/\varepsilon_r)^2$ is applied.
- Extra degree of freedom $py \propto V^2$
- The ODE finds V^2 such that wcontrol1=wset!
- C is obtained from subdomain integration: $C=\int dA\varepsilon_0/(g+w+a/\varepsilon_r)$.
- Contact pressure is modelled by a steep parabola if $(g+w<0)$.
- C(V) curve is obtained.

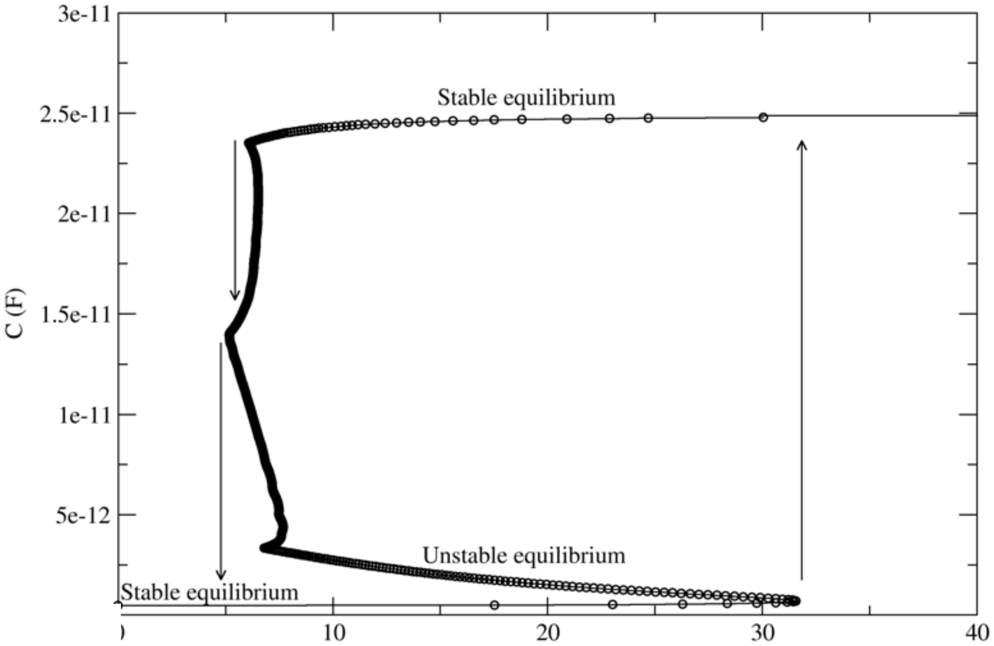


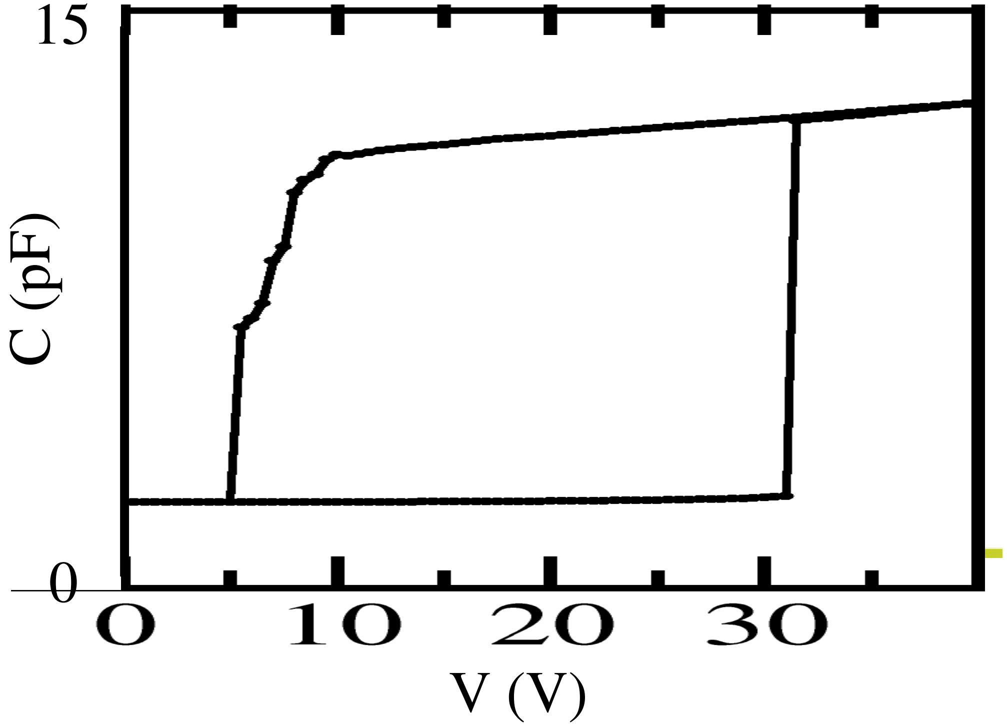
Calculated CV curve

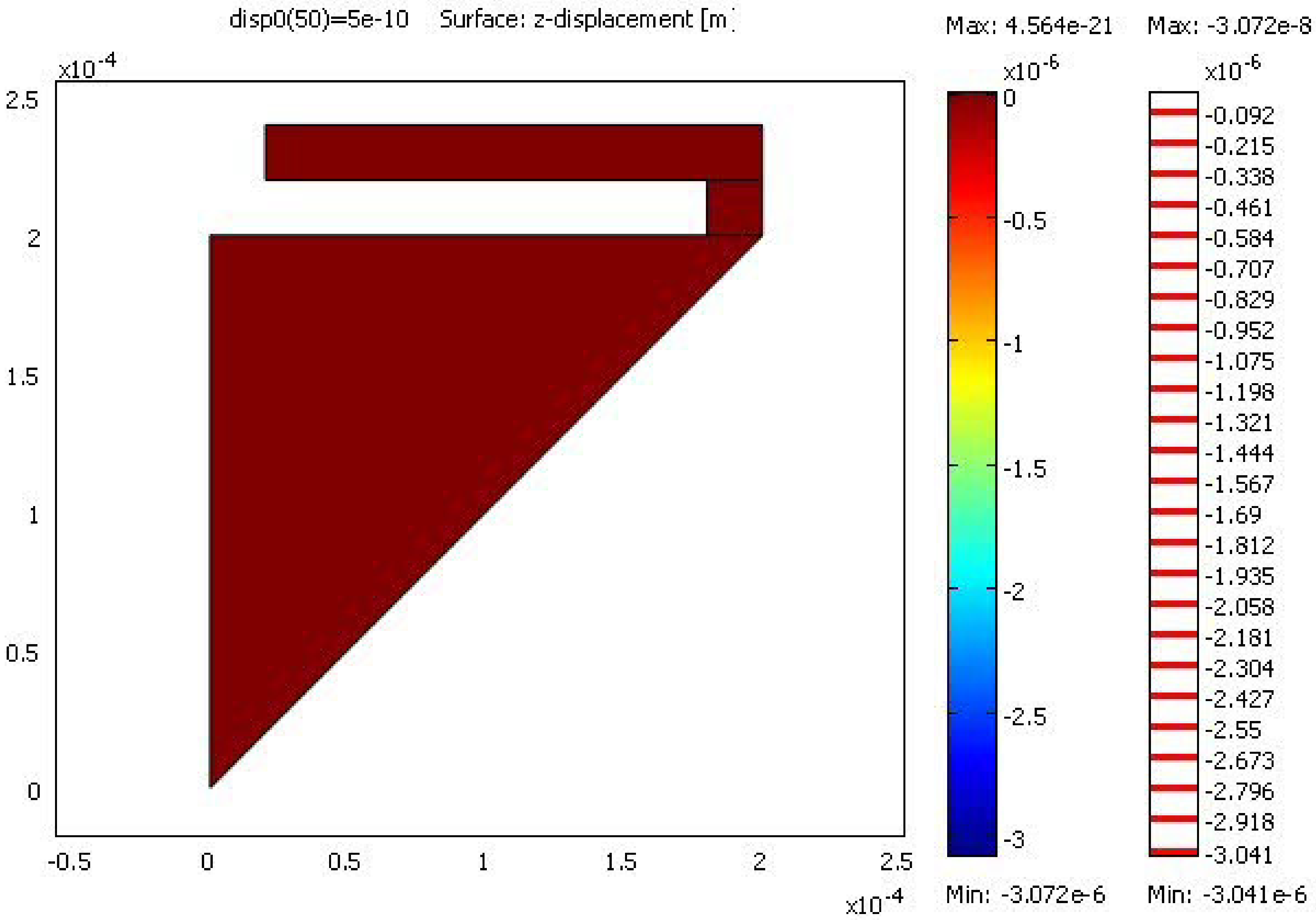


Simulation and measurement



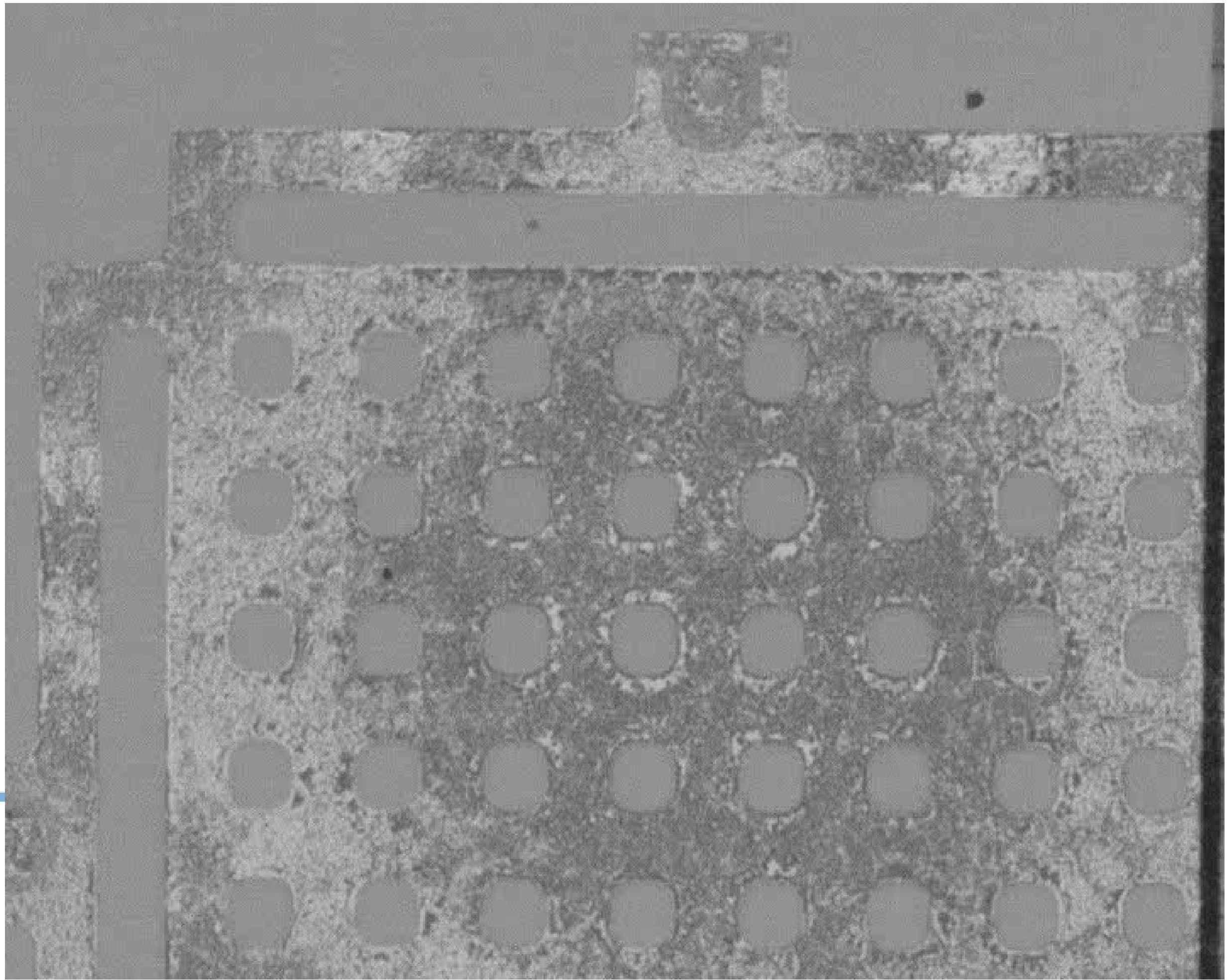




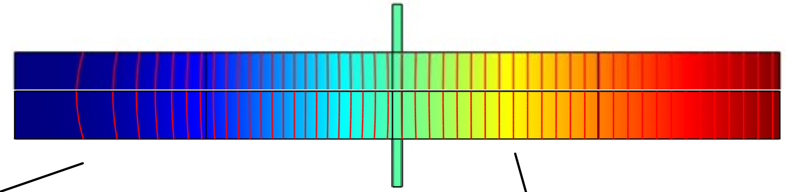

disp0(50)=5e-10 Surface: z-displacement [m]
Max: 4.564e-21
Max: -3.072e-8
x10^-4
2.5
2
1.5
1
0.5
0
-0.5
0
0.5
1
1.5
2
2.5
x10^-4
x10^-6
0
-0.5
-1
-1.5
-2
-2.5
-3
x10^-6
-0.092
-0.215
-0.338
-0.461
-0.584
-0.707
-0.829
-0.952
-1.075
-1.198
-1.321
-1.444
-1.567
-1.69
-1.812
-1.935
-2.058
-2.181
-2.304
-2.427
-2.55
-2.673
-2.796
-2.918
-3.041
Min: -3.072e-6
Min: -3.041e-6

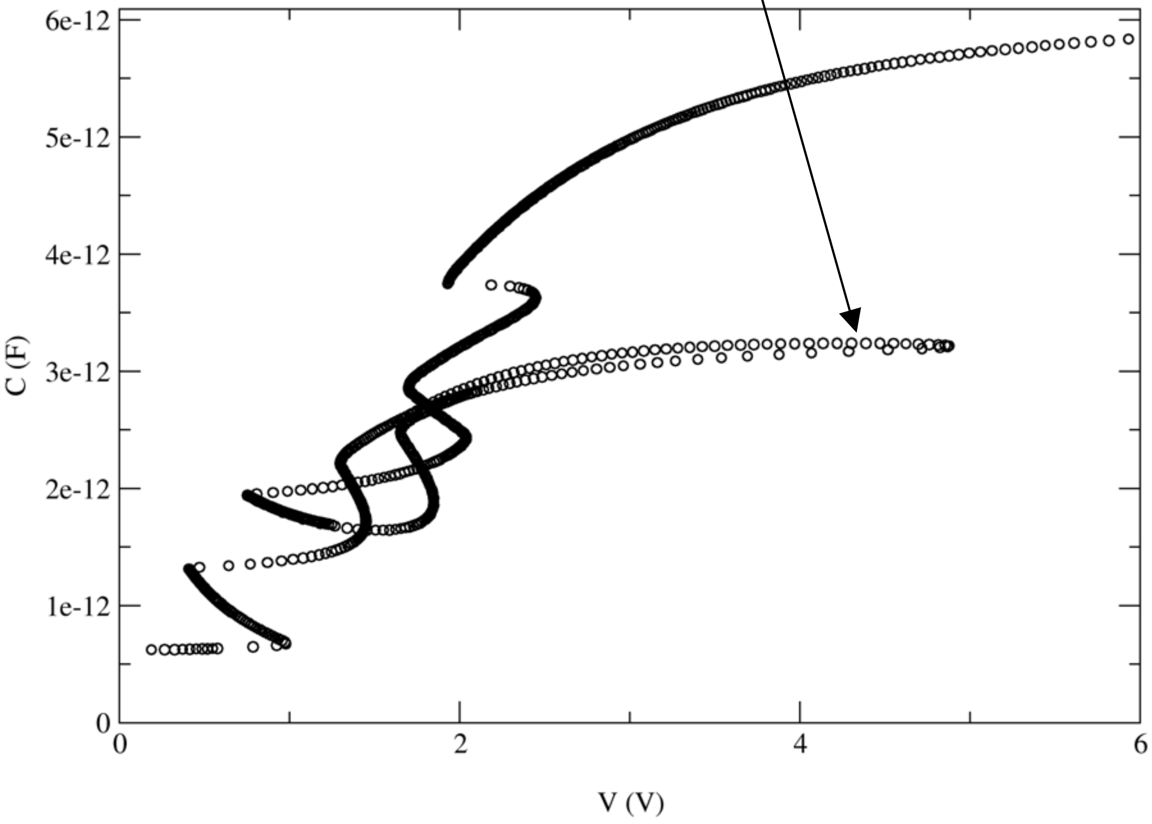
Outlook: dynamics

- Each second in the interferometric slow-motion movie is about 2 µs in reality
- If we would play a 1 hour movie recording of the switch at this slow-motion rate, we would not be able to see the end of the movie within our lifetime.
- Therefore I only show 50 µs.



More complications
Electrostatic see-saw structure

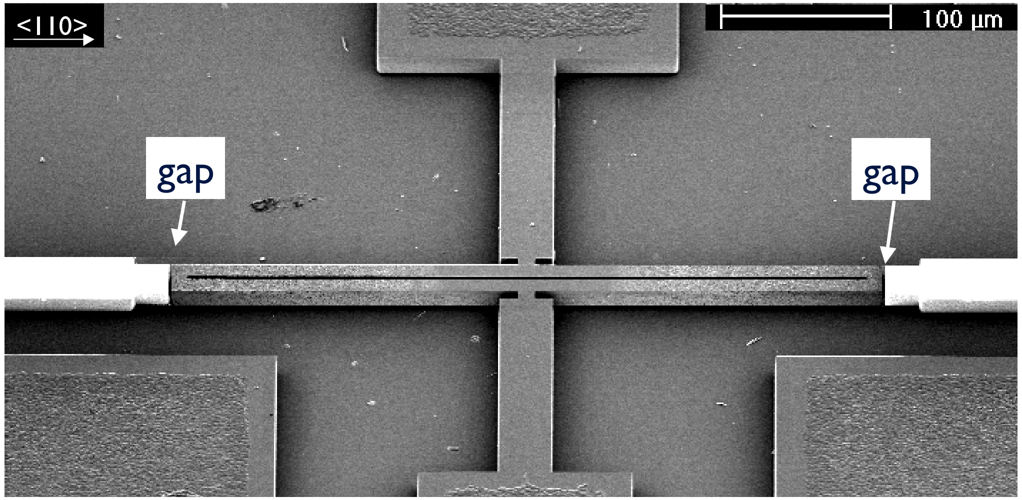


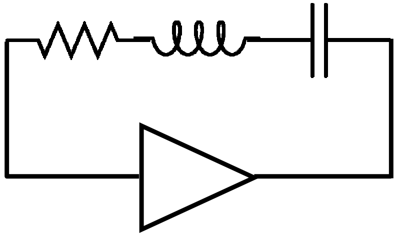


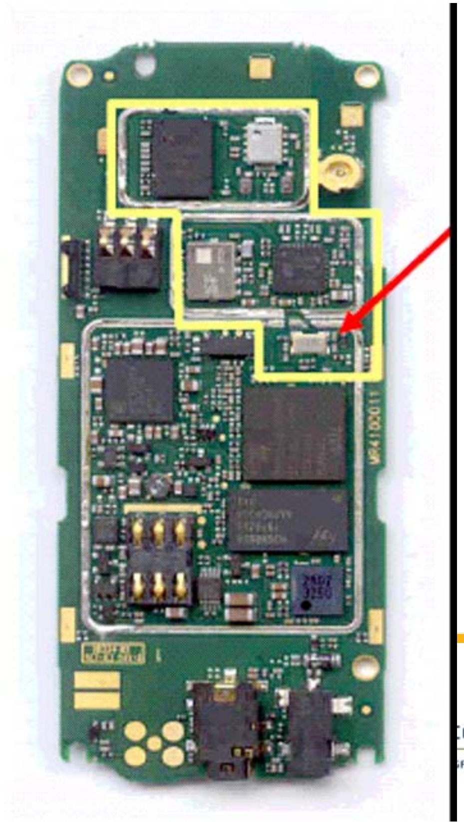
MEMS resonators

- Application:
  - Oscillator (clock)

MEMS resonator







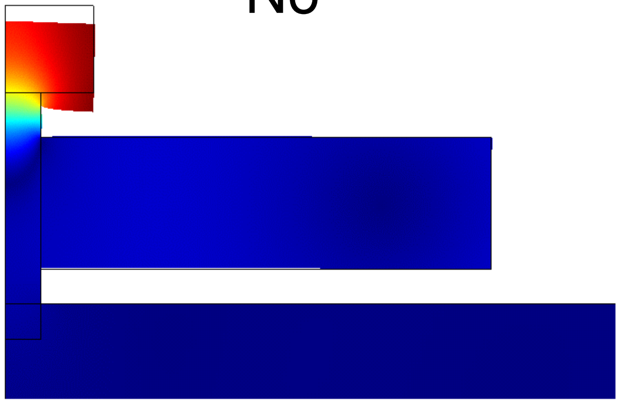
Quartz resonator is large and expensive

Goal: replace Quartz crystal by Silicon crystal

J.T.M. van Beek, P.G. Steeneken and Ben Giesbers, '*A 10 MHz Piezoresistive MEMS Resonator with High-Q*'. Proceedings International Frequency Control Symposium 2006 (Miami).

Simulating MEMS resonators

- Simplistic way to analyze MEMS resonators with Comsol:
  - Put geometry and material parameters in Comsol.
  - Run eigenfrequency analysis.
  - Select required mode shape by hand.
  - Examine frequency.
- How can we get more information from this simulation?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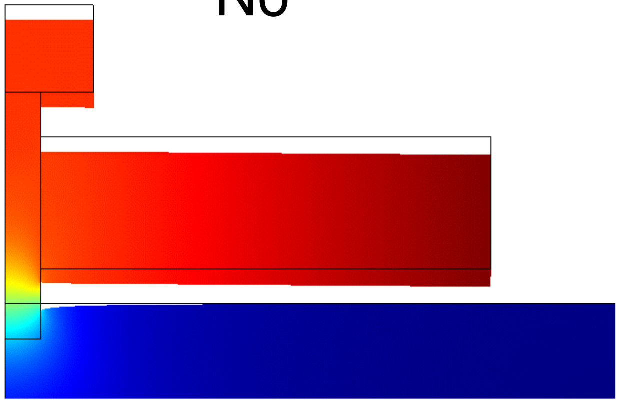
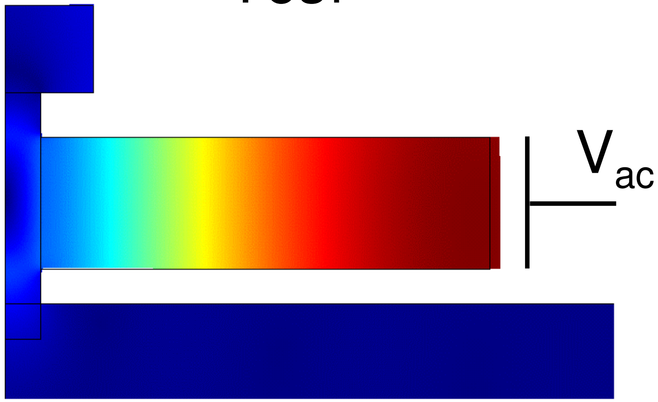
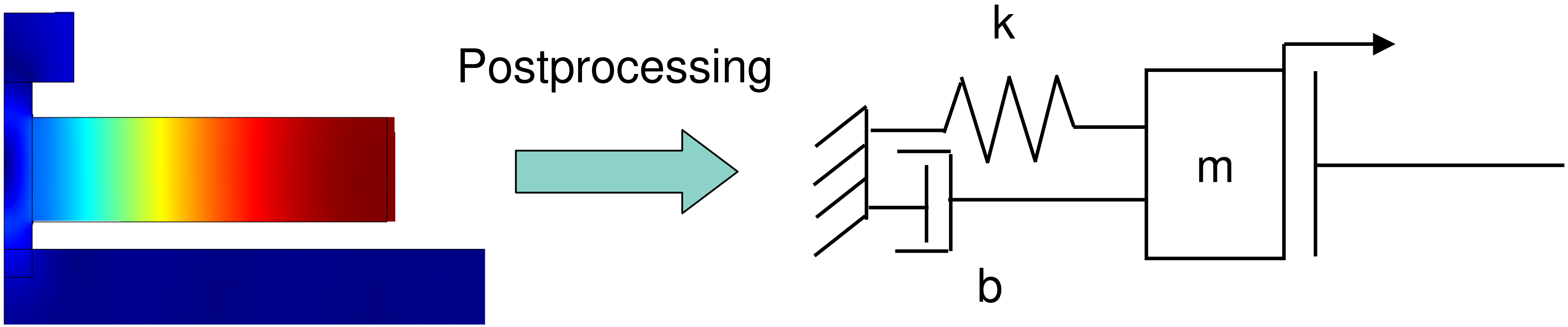

No


Yes!

Parameter extraction

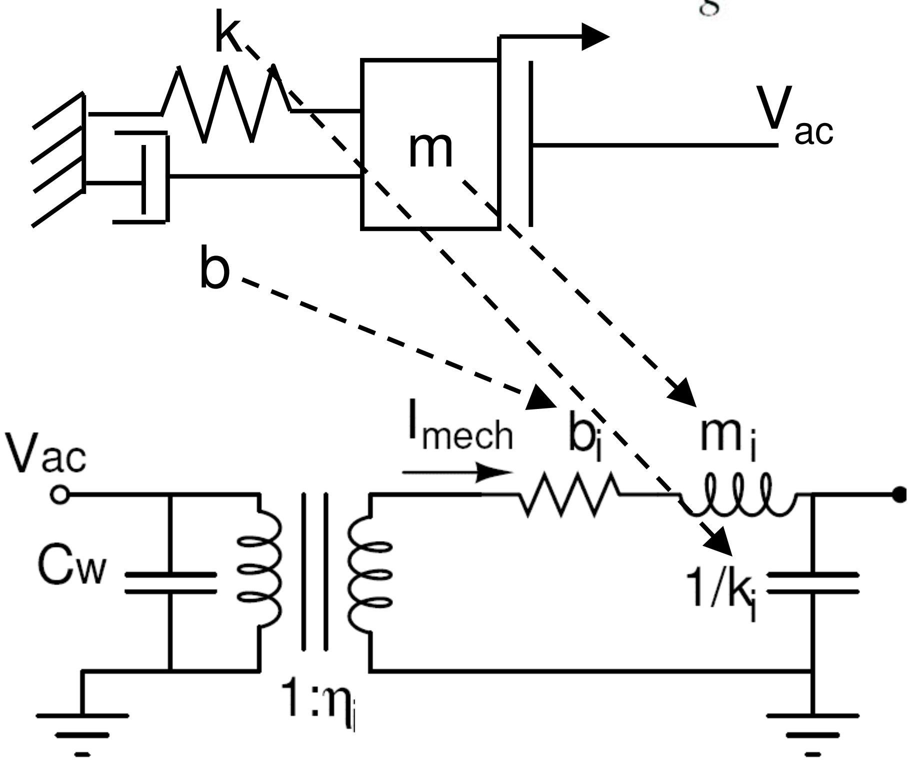
- Method to extract the 3 mechanical parameters by postprocessing of the eigenmode.



Equivalent circuit

$$F_{ac} = \frac{A_{act}\varepsilon_0 V_{dc}}{g^2} V_{ac} = \eta V_{ac}$$

- Assume everything is linear.
- Electrical admittance Y can be determined if k_i,m_i and b_i are known for all eigenmodes.



$$Y = \frac{i_{ac}}{V_{ac}} = j\omega C_w + \eta^2 \sum_{i=1}^{N} \left(j\omega m_i + b_i + \frac{k_i}{j\omega} \right)^{-1}$$

Determining m and k by postprocessing of eigenmodes

$$E_{tot} = E_{el,\max} = \frac{1}{2} k_i |x_i|^2 = \left| \int_V W_s \, dV \right|$$

Max. elastic energy

$$E_{tot} = E_{kin,\max} = \frac{1}{2} m_i |\omega_i x_i|^2 = \frac{1}{2} \left| \int_V \rho \omega_i \mathbf{u}_i{}^2 \, dV \right|$$

Max. kinetic energy

Therefore:

$$k_i = \frac{2}{|x_i|^2} \left| \int_V W_s \, dV \right|$$

$$m_i = \frac{k_i}{|\omega_i|^2} = \frac{1}{|x_i|^2} \left| \int_V \rho \mathbf{u}_i{}^2 \, dV \right|$$

Determining the damping coefficient b

- Damping in our resonators seems to be dominated by support losses:
  - Energy in traveling waves disappears via the anchors to the substrate.
- Substrate is very large. How to model the traveling waves?
  - Absorb them using an artificial boundary layer in the substrate.
  - Artificial material should have the following properties:
    - No reflection (matched layer).
    - Energy of traveling waves needs to be absorbed to prevent wave from coming back.
- Comsol 3.3: Perfectly Matched Layer(PML) in Structural Mechanics Module
  - Only available in frequency response analysis mode.
  - PMLs will be implemented in eigenfrequency analysis in future Comsol version.
  - Eigenfrequency analysis mode is much faster.

Matched layer (artificial material E’, ρ’,v’)

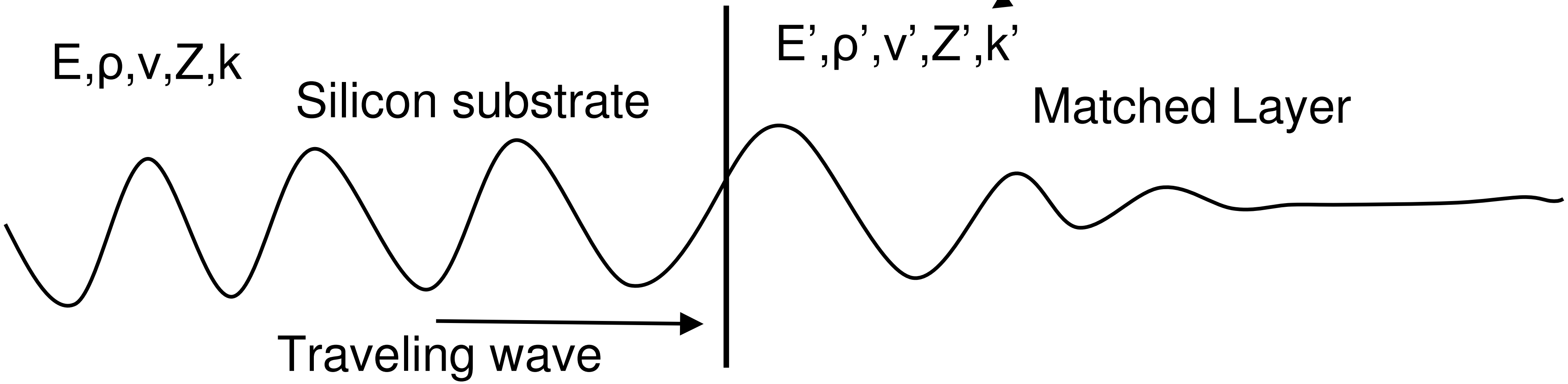
- Zero reflection: Z=Z’
- Wave absorption: Im ρ’<0

$$E' = jE/\alpha$$

$$\rho' = -j\alpha\rho$$

$$\nu' = \nu$$

- Only perfectly matched for normal incidence.



E,ρ,v,Z,k

Silicon substrate

E’,ρ’,v’,Z’,k’

Matched Layer

Traveling wave

Determining b

- Complex material parameters of Matched Layer
- Therefore: Complex eigenfrequencies ω.

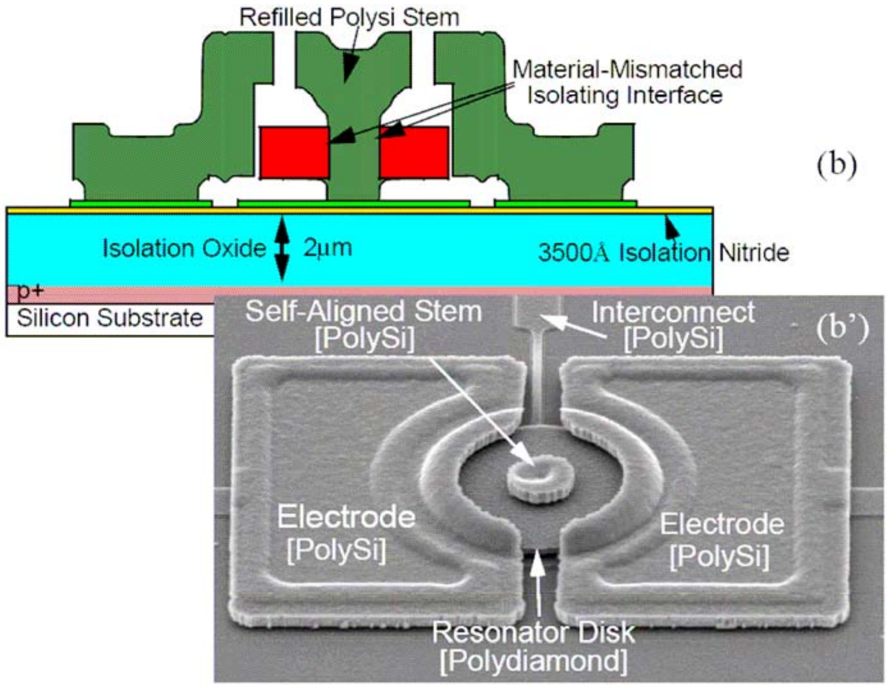
$$Q_i = \frac{\operatorname{Re}\omega_i}{2\operatorname{Im}\omega_i}$$

- Damping coefficient b_i is obtained using:

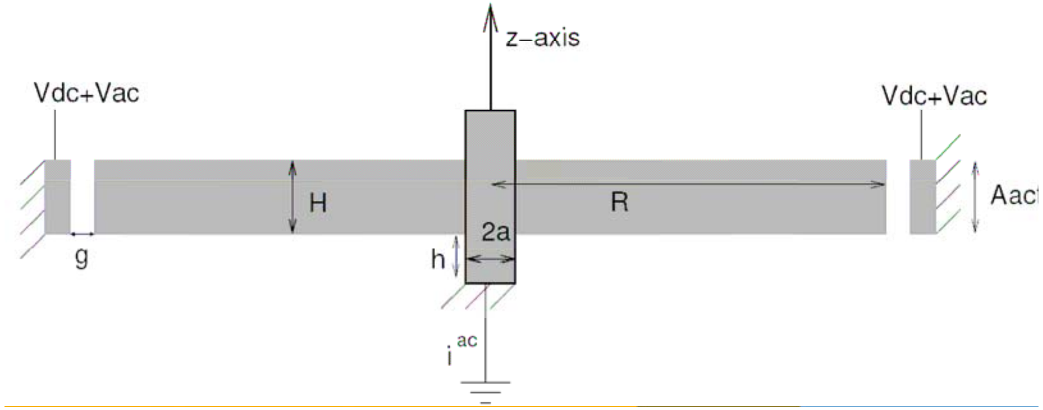
$$b_i = \frac{\sqrt{k_i m_i}}{Q_i}$$

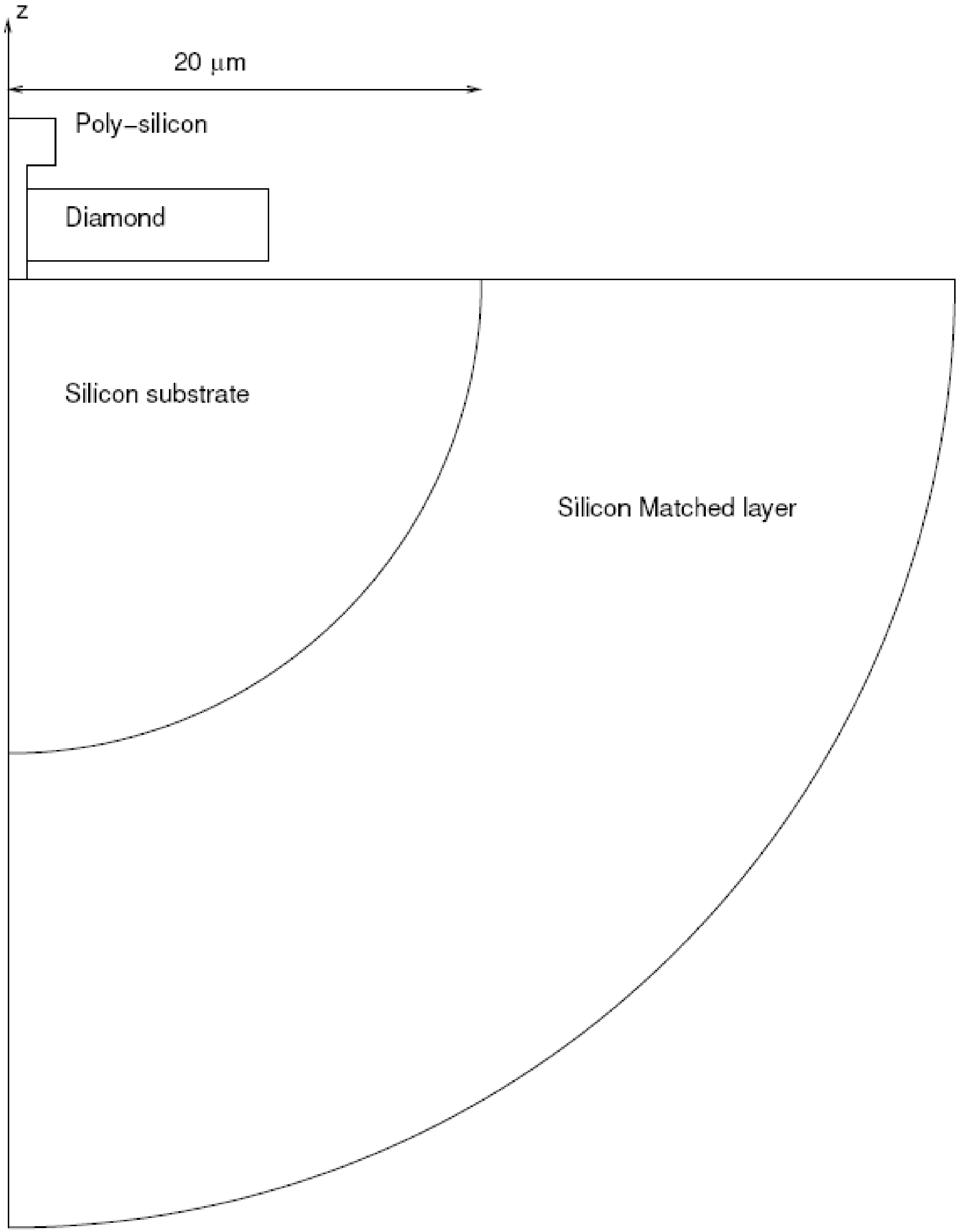
Example: MEMS disk resonator

- Check method on diamond disk resonator
  - J. Wang et al., 1.51-GHz Nanocrystalline Diamond Micromechanical Disk Resonator With Material-Mismatched Isolating Support, *Proc. MEMS 2004*, pp. 641-644.
- Analytically verified:
  - Z. Hao and F. Ayazi, Support loss in the radial bulk-mode vibrations of center-supported micromechanical disk resonators, *Sensors and Actuators A*, **134**, p. 582-593 (2007)



Geometry (cylindrical symmetry)



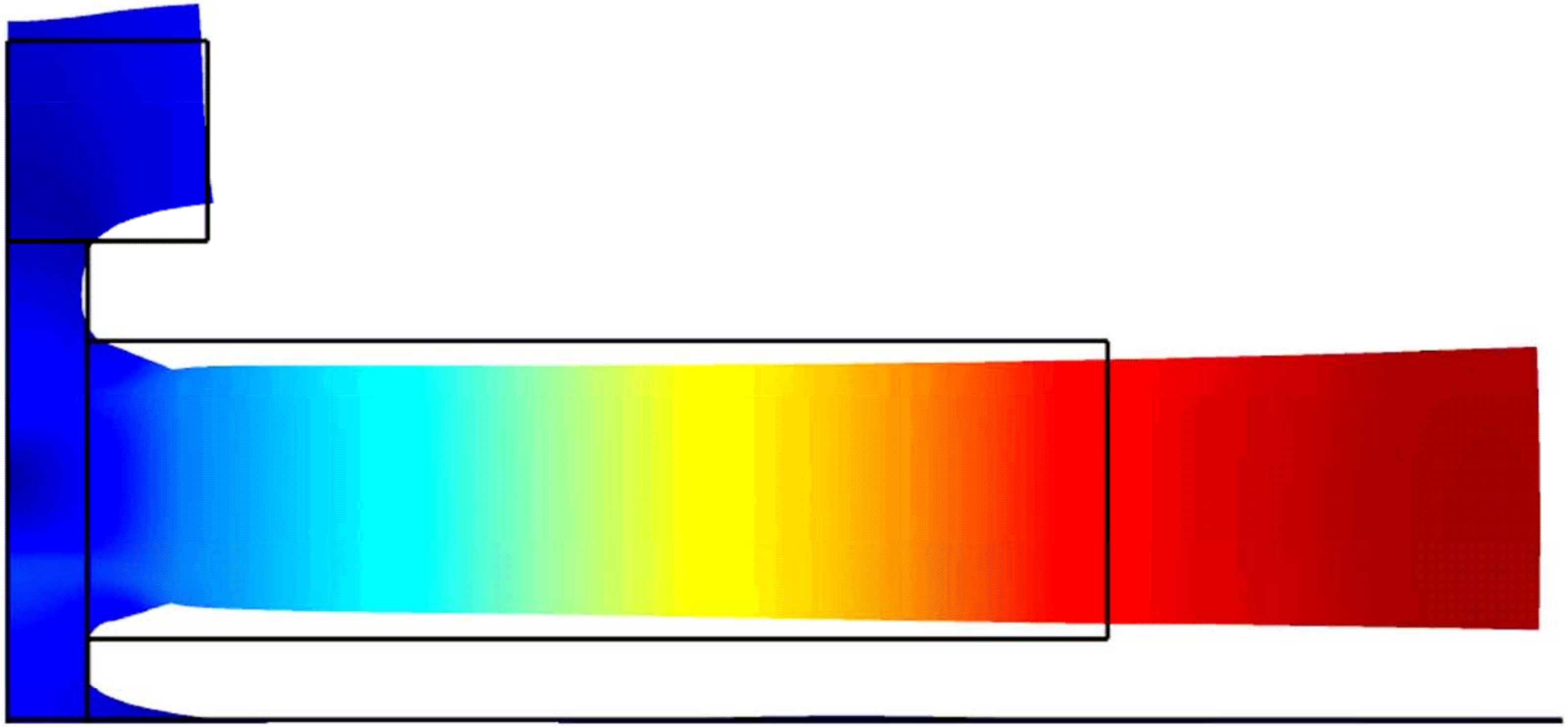


Script to analyze all eigenmodes

- Analyze all eigenmodes up to 700 MHz.
- Select modes with Q>10.
- Dominant mode is selected using script.

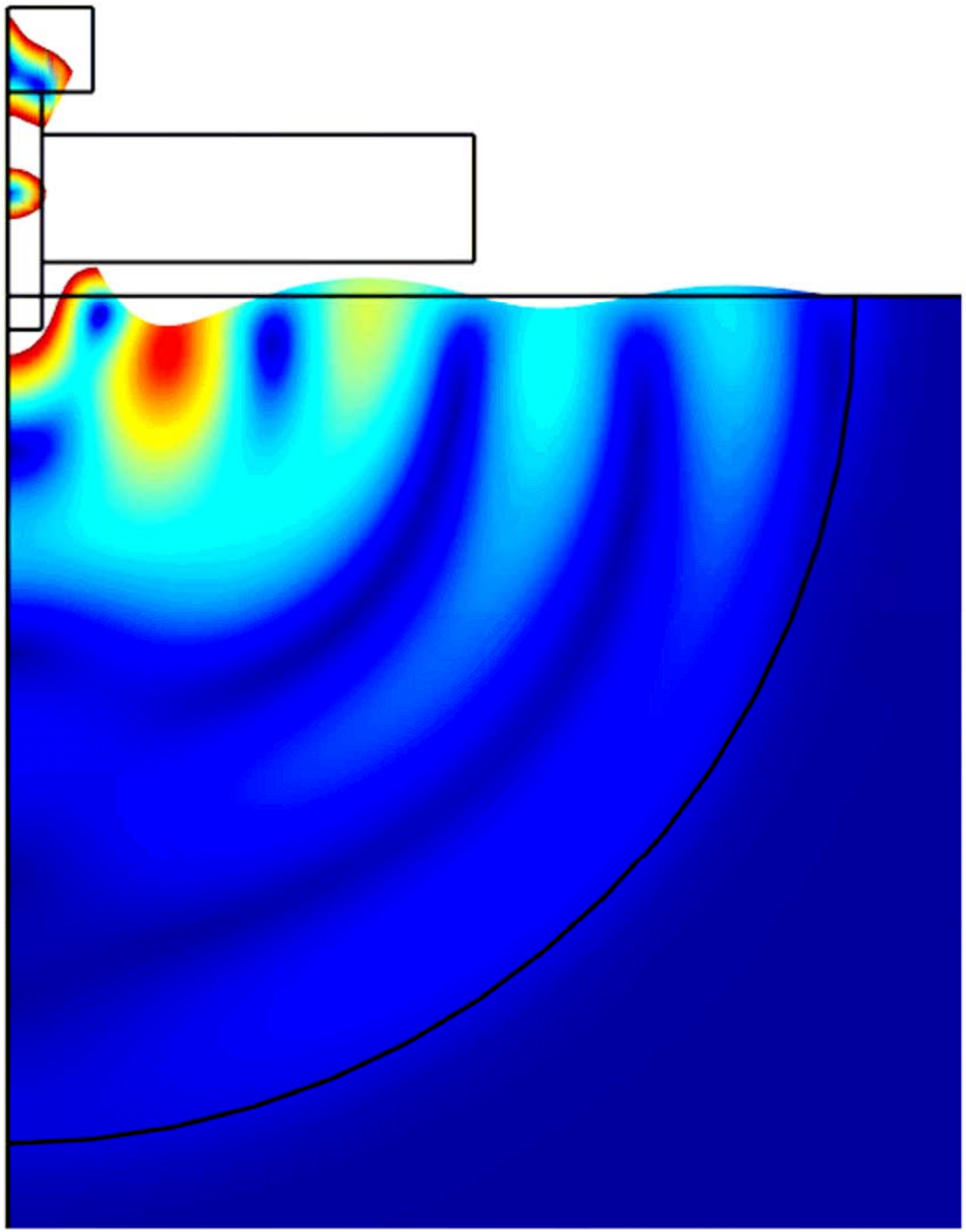
fres (MHz)	k (N/m)	m(kg)	b (kg/s)	Q	Ymax (1/Ohm)
26.34	4.41E+11	1.61E-05	77.1466	34.5267	1.12E-15
158.25	9.55E+11	9.66E-07	6.08278	157.914	1.42E-14
258.78	1.72E+11	6.50E-08	0.0307684	3433.51	2.80E-12
489.28	2.76E+07	2.92E-12	2.99E-07	30068.4	2.89E-07
579.70	4.76E+12	3.58E-07	7.46487	174.922	1.15E-14
630.49	3.15E+12	2.00E-07	78.2594	10.1447	1.10E-15

1st Disk mode

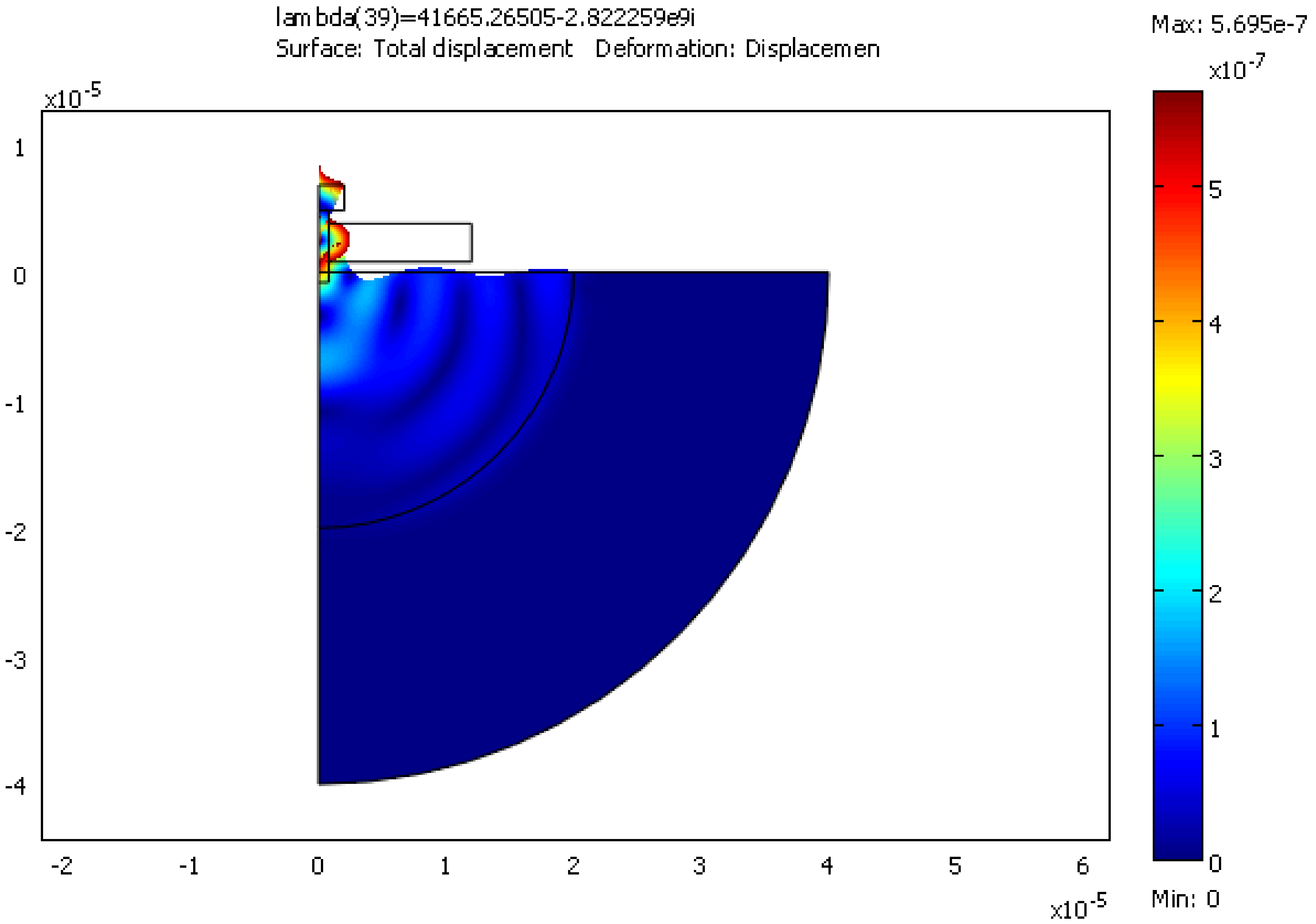


Total displacement in the first radial bulk-mode of the disk resonator at 489.27 MHz.

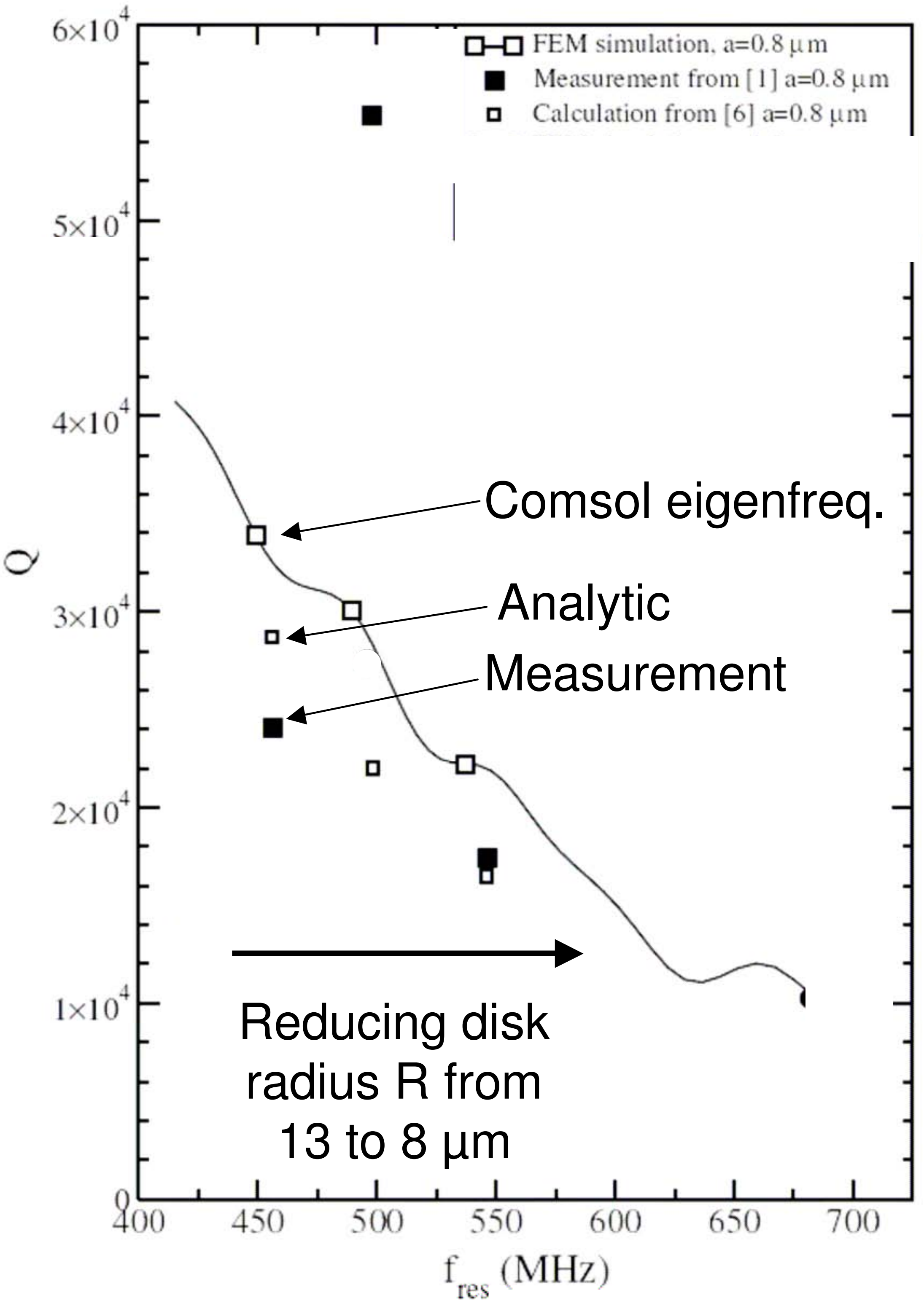
Acoustic waves traveling in the substrate



Acoustic waves traveling in the substrate



Measurement comparison



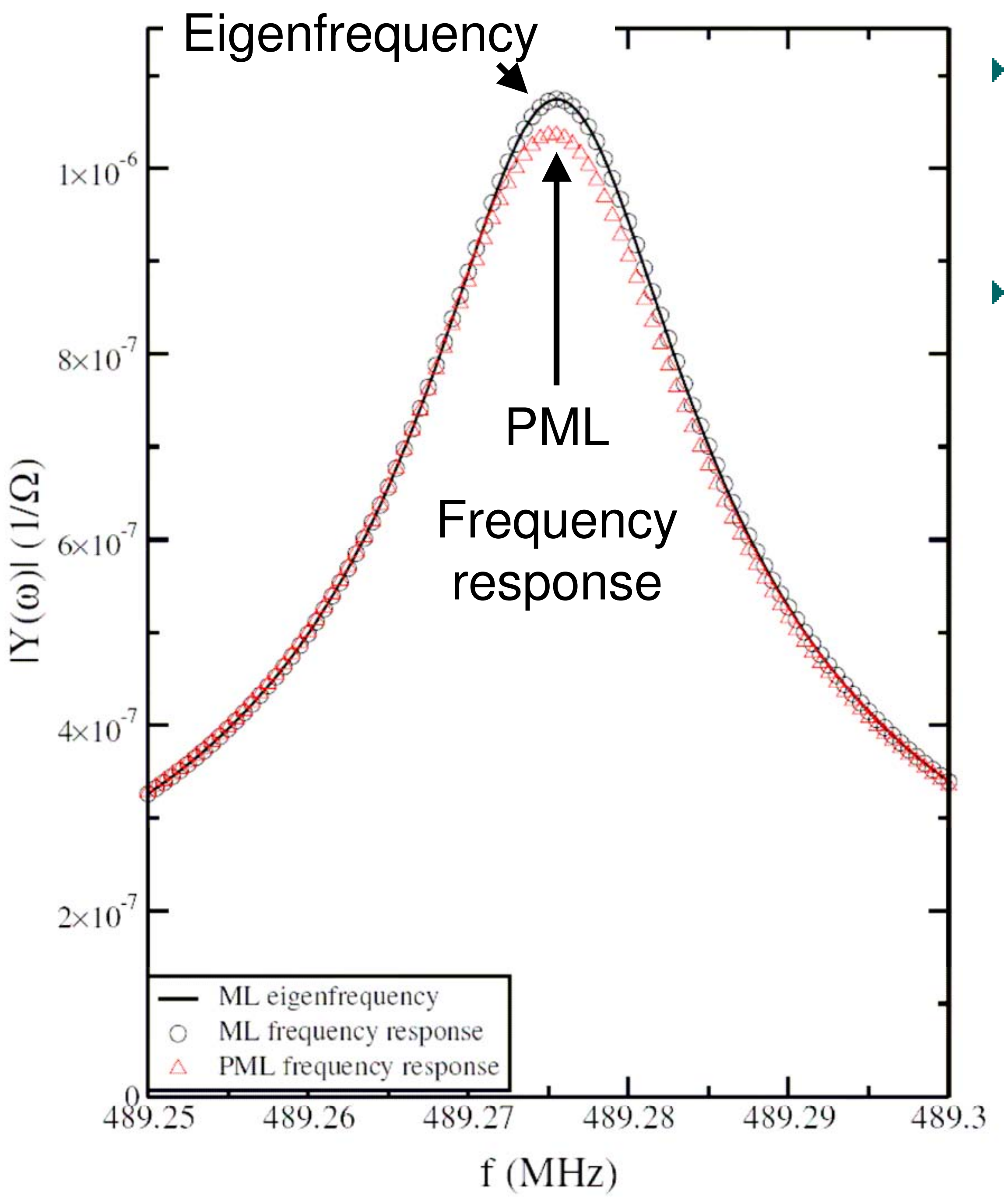
Comsol eigenfreq.

Analytic

Measurement

Reducing disk radius R from 13 to 8 µm

Comparison with frequency response and PML



- Eigenfrequency analysis 60x faster than frequency response.
- ML in good agreement with PML result.

Conclusions

- Simulation methods for electrostatic MEMS devices:
  - Static C-V curve of capacitive RF MEMS switches.
    - Position control efficiently implemented using Comsol ODE.

    Reference article: J. Bielen and J. Stulemeijer, Proc. Eurosime 2007.
  - Admittance calculation of MEMS resonators
    - Support losses implemented using matched layer material model.
    - Equivalent parameter k,m and b extracted by postprocessing of eigenmodes.
    - Script to analyze all mode shapes.
    - See my Comsol 2007 proceedings article for more details.