Coventor platform for MEMS design, – from device design and process development to system optimization

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Overview of Coventor

Founded in 1996 with a focus on software for MEMS Design

- Management team from MEMS and EDA
- Validated tools and library across a broad range of designs and applications

Initial products for MEMS ‘experts’

- Device design, modeling, simulation
- Process development

Established proven track record with MEMS market leaders

- Top tier MEMS device makers and specialized manufacturers
- 11 of top 15 MEMS companies* use Coventor

*Source: Yole Development (Feb. 2010): Top 15 MEMS companies = 80% of MEMS market

Coventor’s Mission

Enable Our Customers to Grow Their MEMS Business

- **Providing Essential Design Automation Software**
- **Setting the Standards for MEMS Design Methodology**
- **Partnering for Success**

COVENTOR

A Diversity of Customers

Foundries

- tsmc
- XFAB MIXED-SIGNAL FOUNDRY EXPERTS
- tronics mems inc.
- MEMSCAP The Power of a Small World™
- DALSA
- IBM
- QinetiQ

IDMs

- Pioneer
- Honeywell
- ANALOG DEVICES
- GE
- OMRON
- SONY
- infineon
- EPCOS
- DLP TEXAS INSTRUMENTS
- Lucent Technologies Bell Labs Innovations
- DENSO
- wolfson microelectronics
- PHILIPS
- SHARP
- COLIBRYS
- HITACHI
- Canon
- intel
- SAMSUNG
- freescale semiconductor
- hp
- ST
- Seagate
- IDT
- WD
- NXP
- LEXMARK
- MEGGITT smart engineering for extreme environments

Fabless Companies

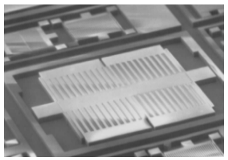
- wiSpry Dynamically Tunable RF
- MIRADIA
- QUALCOMM
- SILICON CLOCKS
- Medtronic
- PERICOM Semiconductor Corporation
- Intersema a measurement specialties company
- neosens Pure Sensor Solutions
- Continental
- RFMD
- MEMtronics
- Schlumberger
- Theon sensors
- BOSTON MICROMACHINES CORPORATION SHAPING LIGHT
- Raytheon
- BLOCK ENGINEERING

R&D Institutes

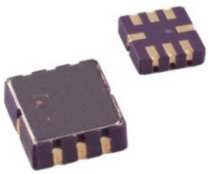
- imec
- NIST
- NASA
- Fraunhofer
- Holst Centre Open Innovation by IMEC and TNO
- A*STAR Institute of Microelectronics

Simulation of Complete Product

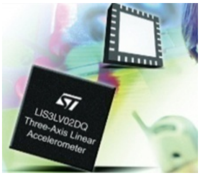
MEMS-based products are becoming more integrated



1-axis accel.



2-axis accel.



3-axis accel.

IMU: 3-axis accel. + 3-axis gyro

Increasing integration requires more verification by simulation

- More difficult or impossible to test individual components
- More chance of design errors in interconnect
- More likelihood of undesirable coupling between components
- More sensitive to signal integrity and parasitics

Simulations must include more of the system

It is no longer sufficient to simulate individual system blocks

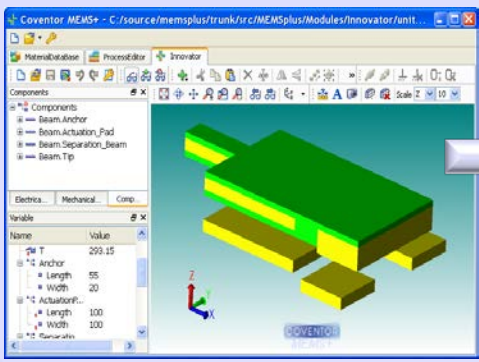
Overview of CoventorTools

Material Properties Database and Process Editor

SEMulator3D Virtual prototyping

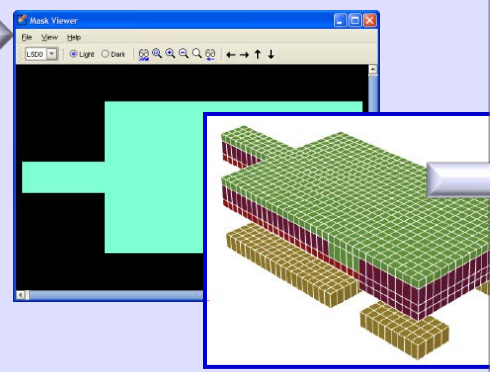
MEMS+

- MEMS behavioral modeling environment



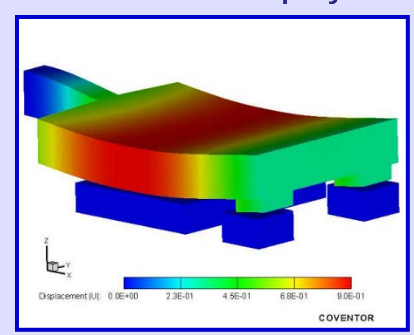
DESIGNER

- 2D Layout Editor
- Solid Modeler (2D to 3D)
- Preprocessor for FEA



ANALYZER

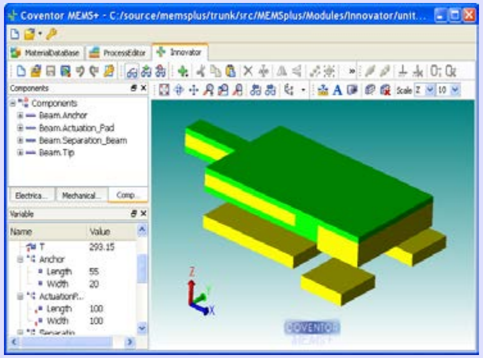
- Suite of field solvers, hybrid FEM & BEM
- Comprehensive coverage for MEMS multi-physics



Material Properties Database and Process Editor

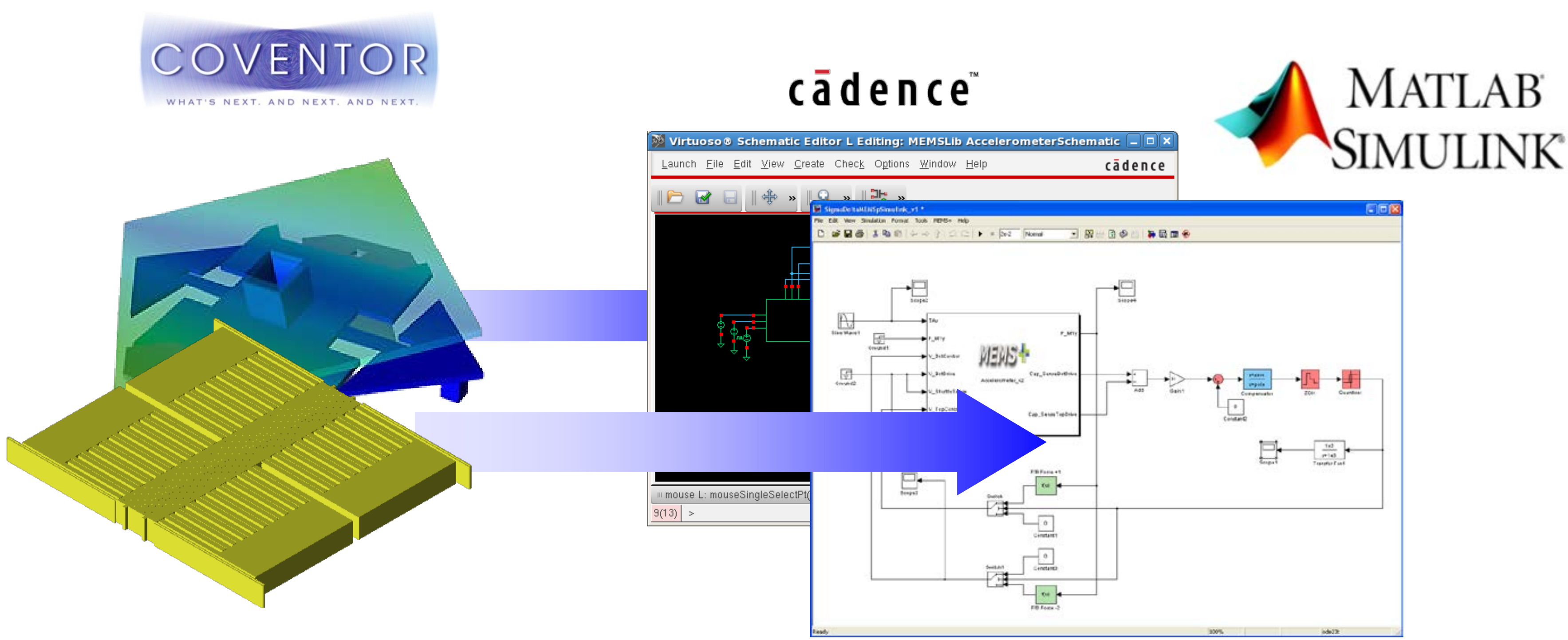
MEMS+

- MEMS behavioral modeling environment



MEMS+System & IC Challenge

- System, IC and layout designers require a MEMS component for their design environment
- No standard, automated methodology across the industry
- Disconnect between MEMS, System and IC design flows leads to long development cycles and high costs and minimal design reuse

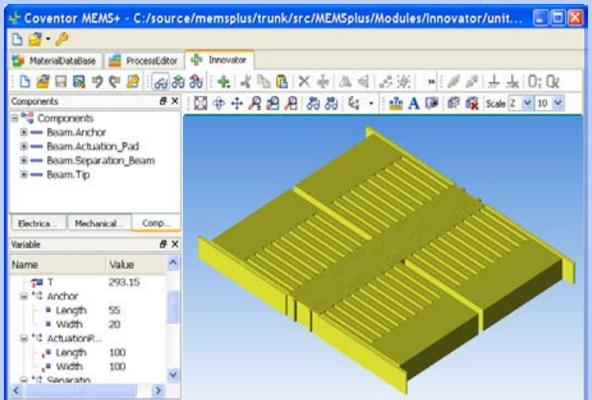


Coventor MEMS+ for Matlab Simulink

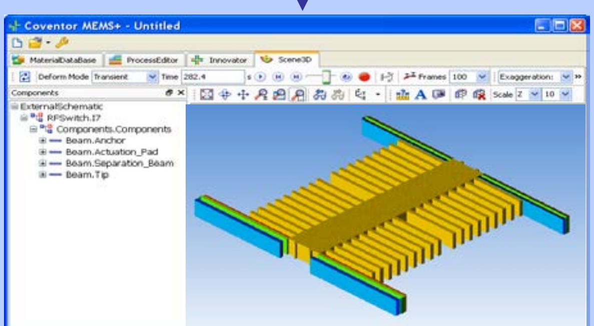
COVENTOR

Coventor *MEMS*+

1 Assemble design in 3-D



Parameterized MEMS Component Library (.lib)



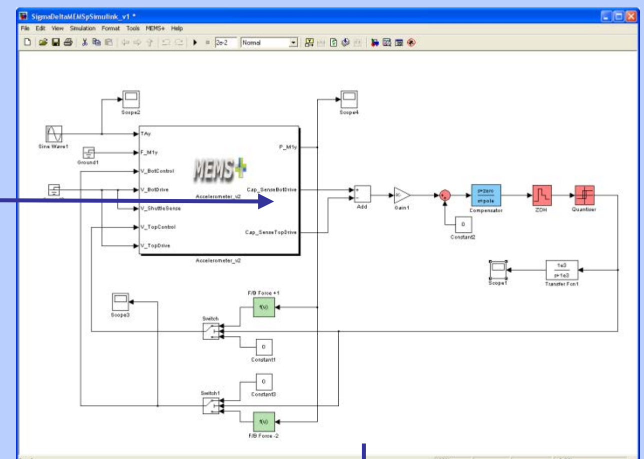
6 Visualize simulations in 3-D

2 Import MEMS Model

MATLAB SIMULINK

Symbol

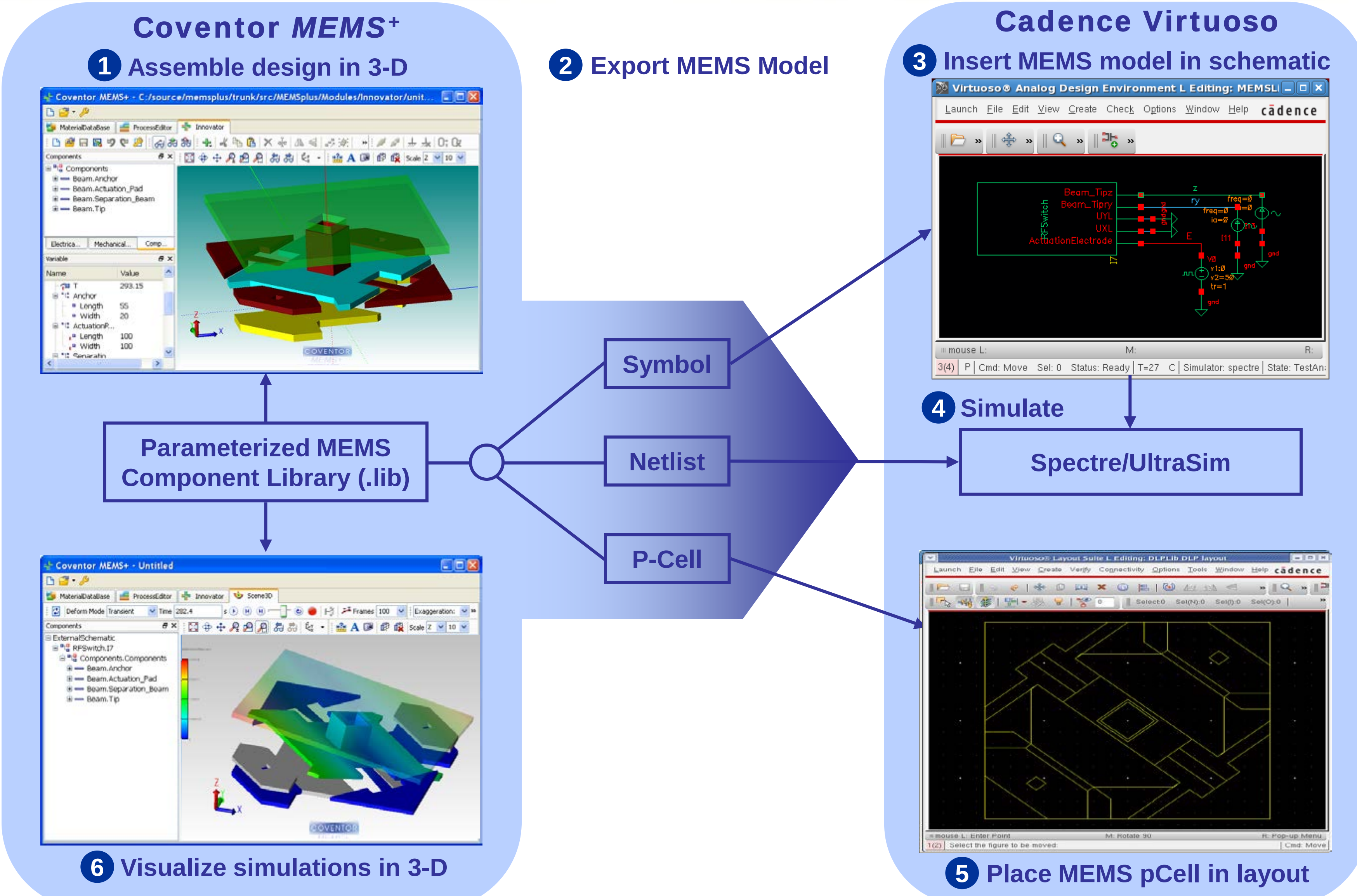
3 Insert MEMS model in schematic



4 Simulate

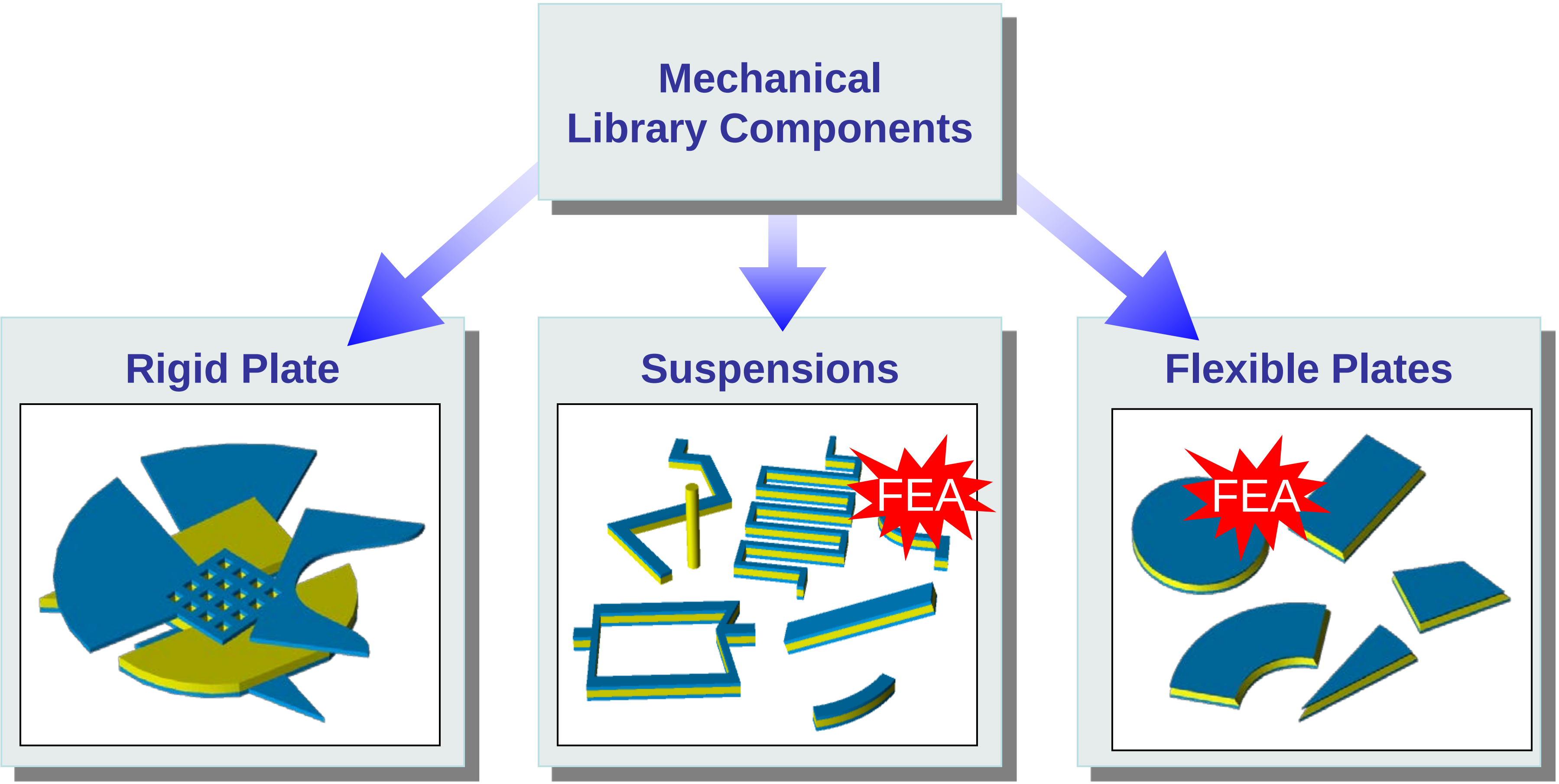
S-Function Interface

Coventor MEMS+ for Cadence Virtuoso

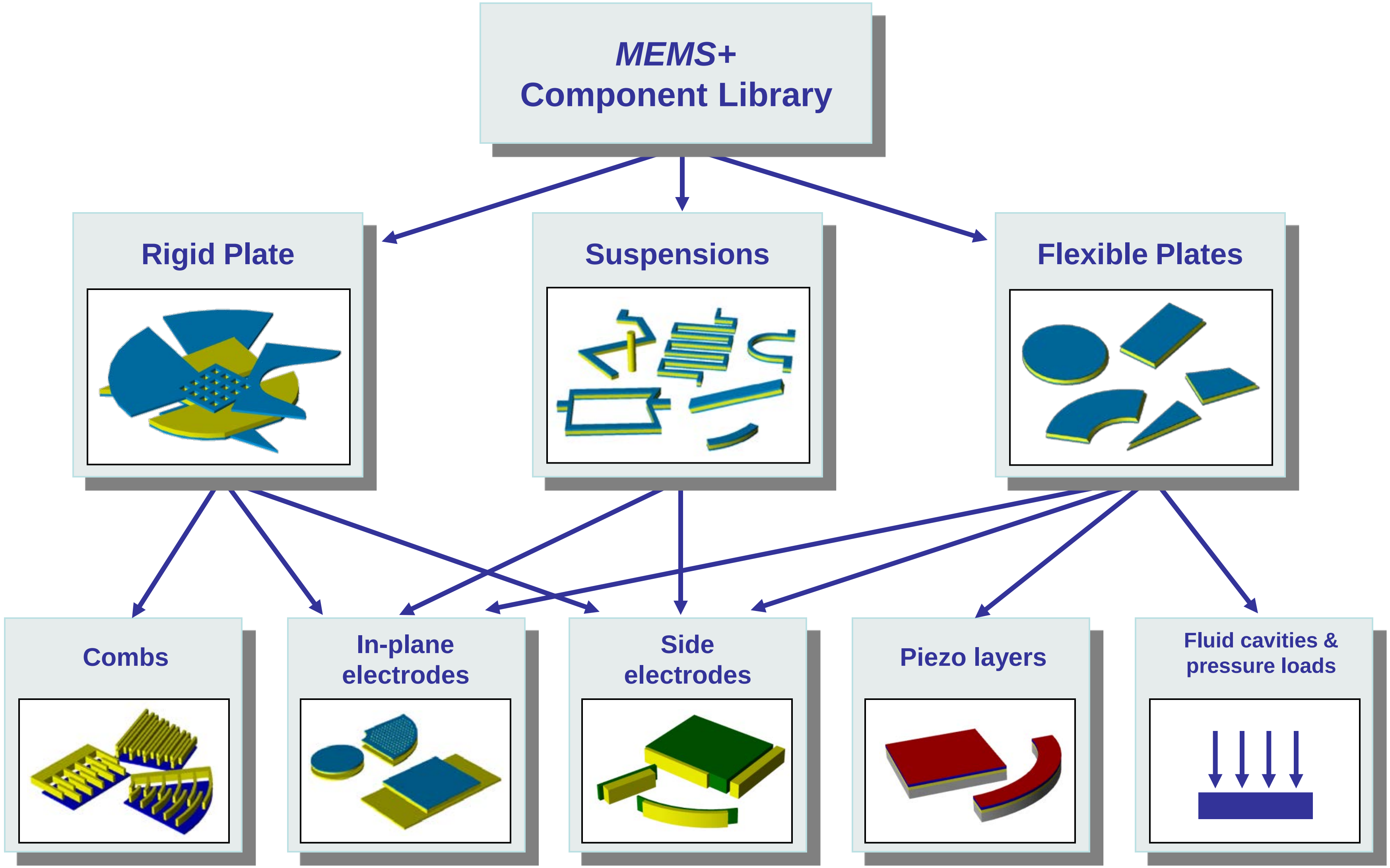


Mechanical Library Components

- The MEMS+ component library is build on top of three different mechanical model families



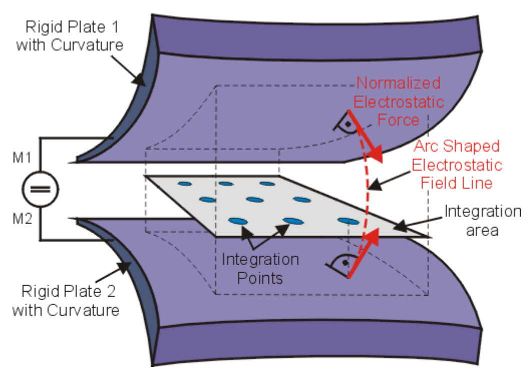
Add-on Models

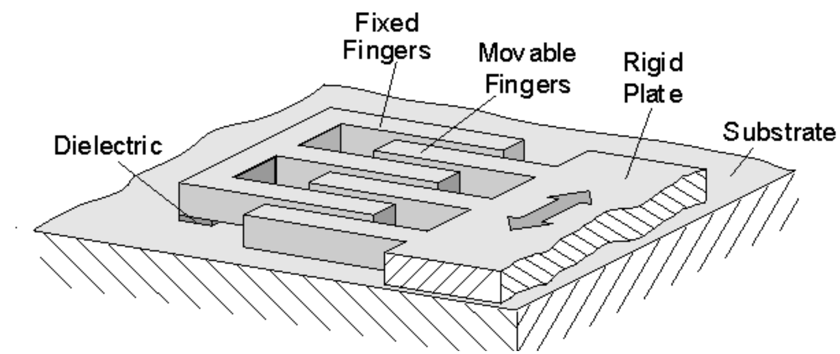


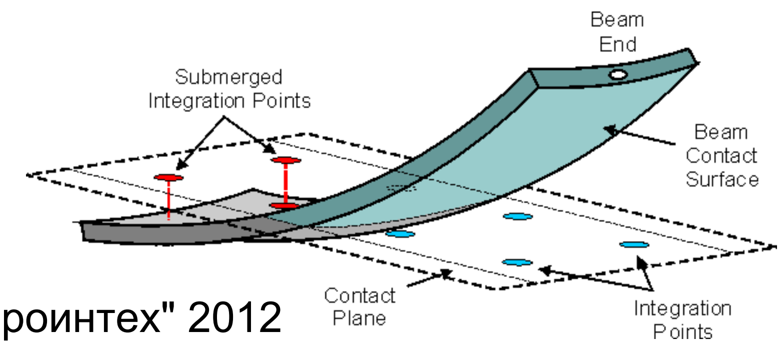
MEMS Behavioral Model Library

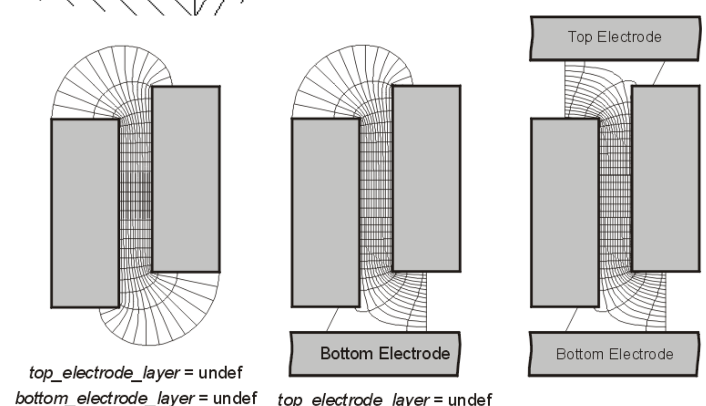
MEMS+ is built on a comprehensive model library

- Beams & Suspensions (**FEA Elements** Bernoulli Beam Theory)
- Plates (**FEA Elements** Flexible MITC Plate Theory)
- Sensing Electrodes, (Conformal Mapping Theory)
- Comb Finger Drives (Conformal Mapping Theory)



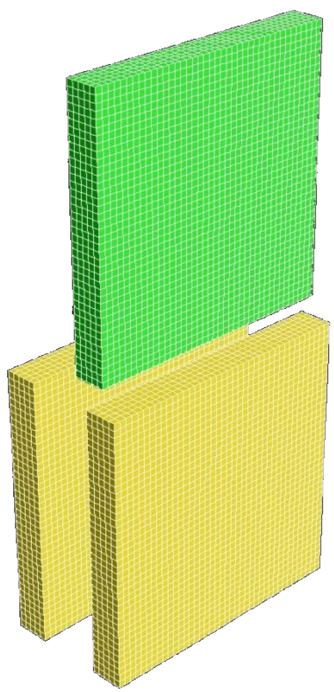




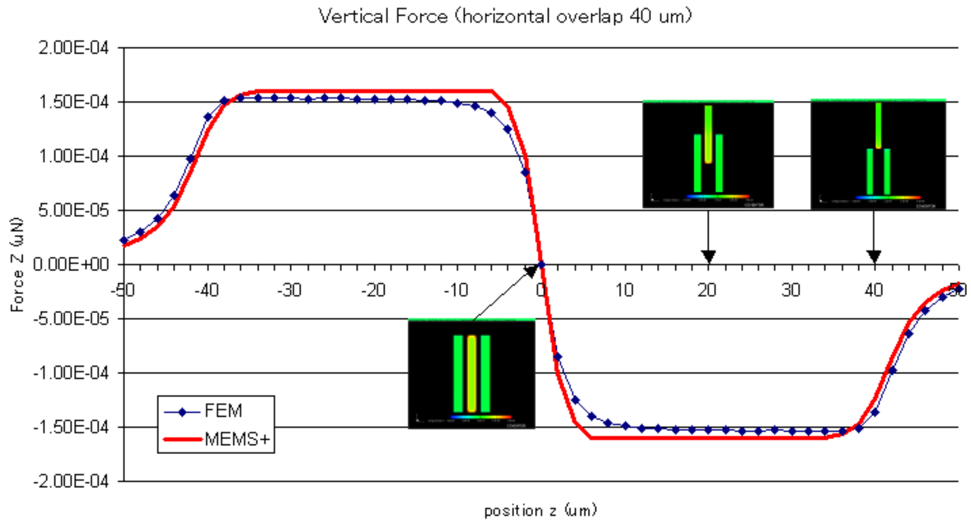


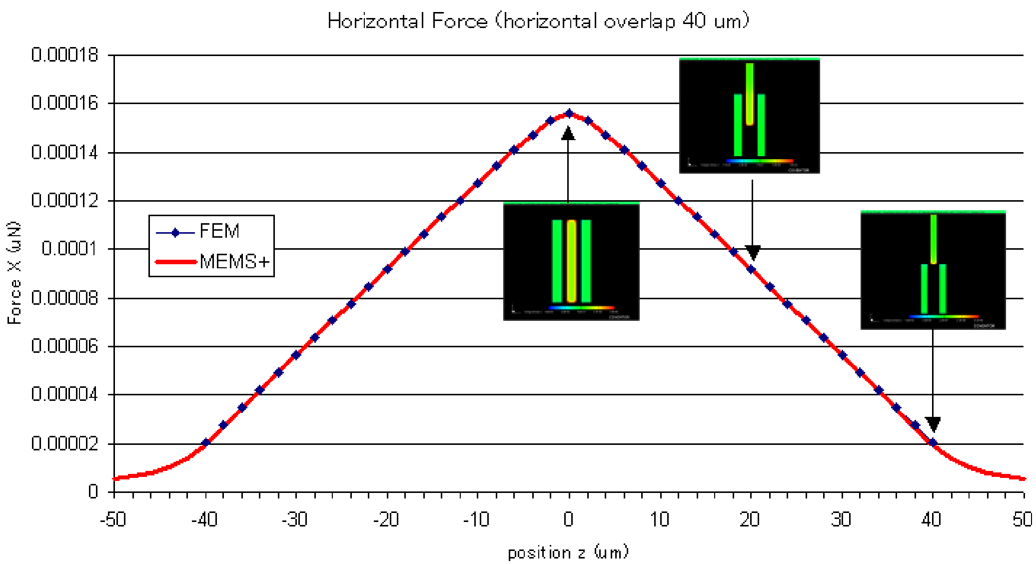
Model Verification Example

- All our electrostatic models are carefully verified against our BEM solver



BEM mesh model used as reference

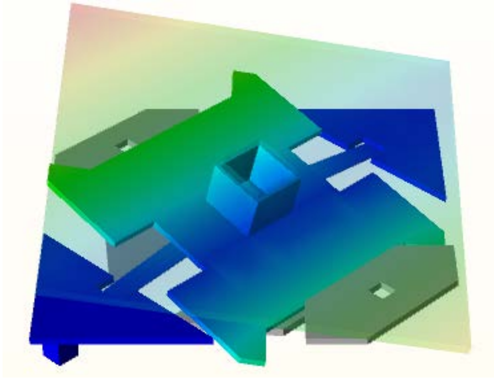




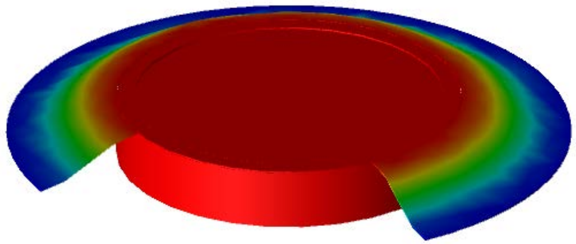
MEMS+ Design Examples 1

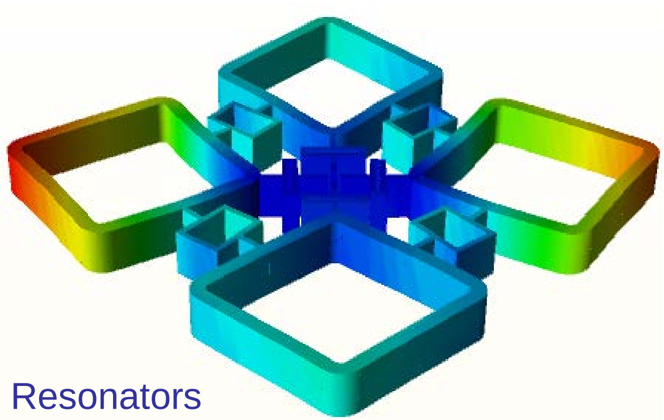
- ***MEMS+*** builds on Coventor’s parametric model library which has been proven on real-world designs…

Display Devices

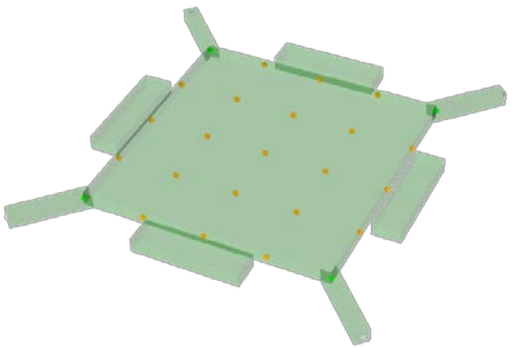


PZE Actuated Mirror





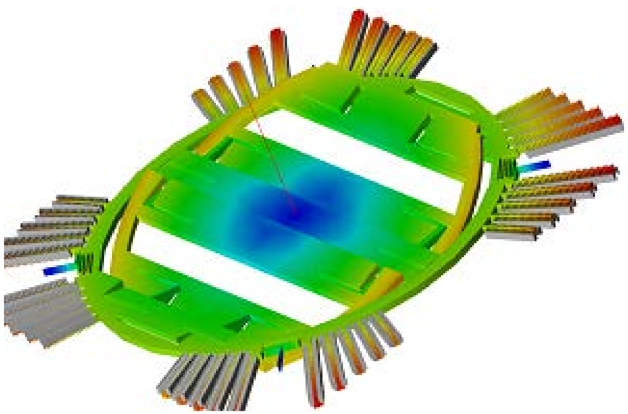
Resonators

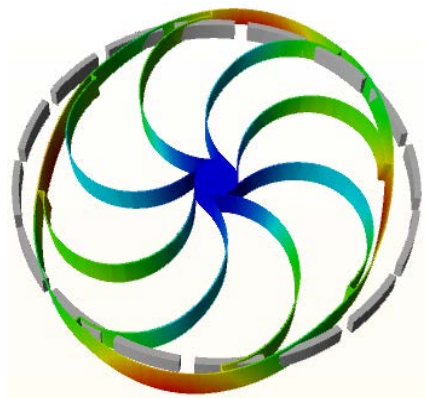


MEMS+ Design Examples 2

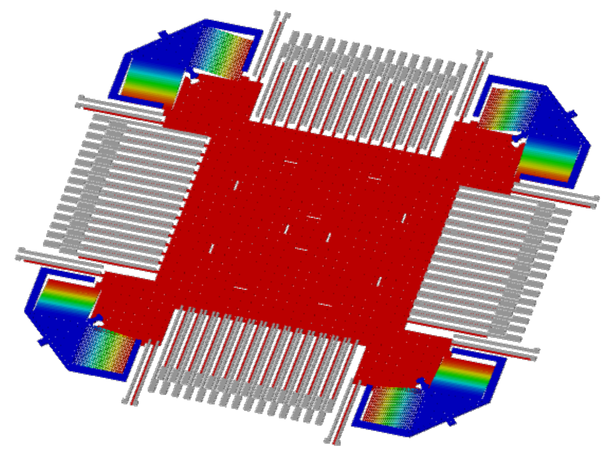
- ***MEMS+*** builds on Coventor’s parametric model library which has been proven on real-world designs…

Gyros (Angular Rate Sensors)

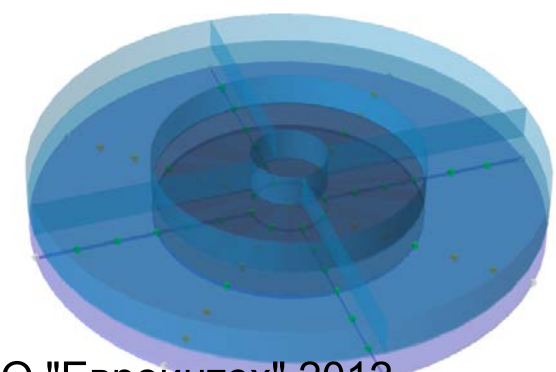


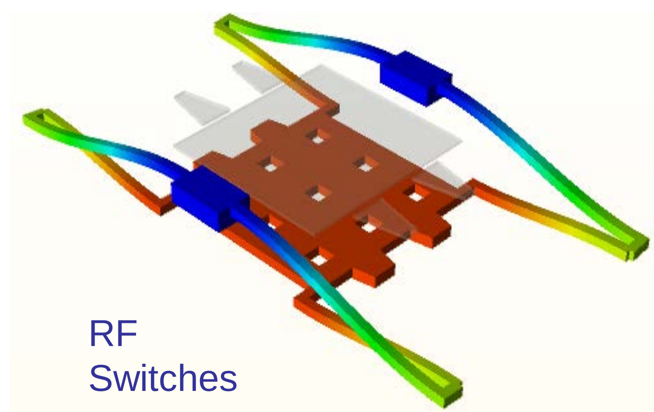


Accelerometers

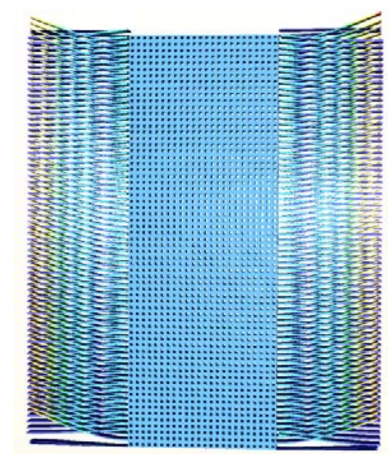


Capactive/PZE Microphone





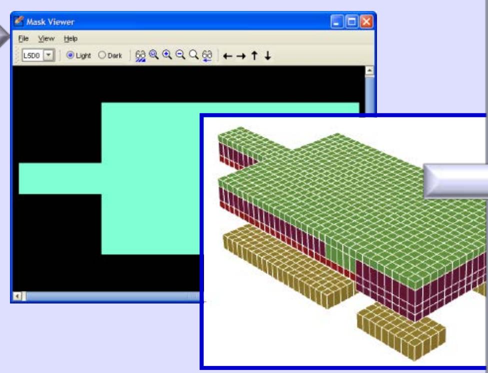
RF
Switches



Material Properties Database and Process Editor

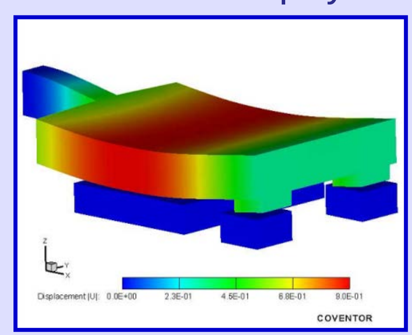
DESIGNER

- 2D Layout Editor
- Solid Modeler (2D to 3D)
- Preprocessor for FEA



ANALYZER

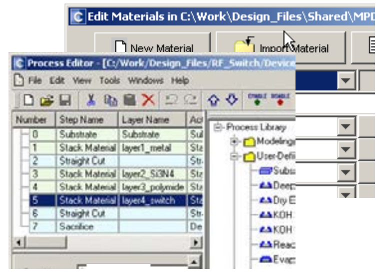
- Suite of field solvers, hybrid FEM & BEM
- Comprehensive coverage for MEMS multi-physics



Overview of DESIGNER

Materials & Process

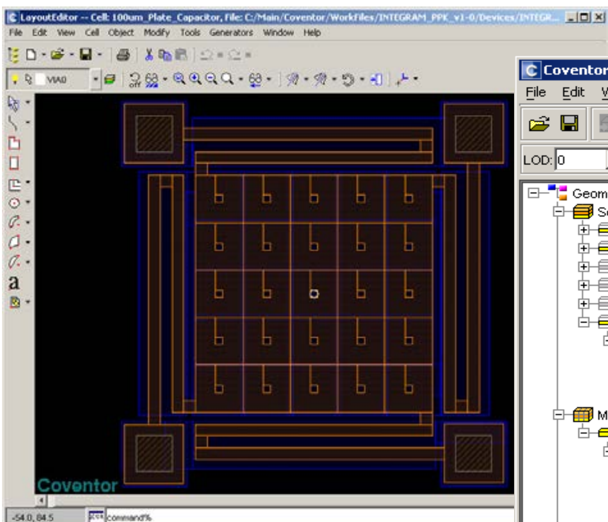
Customizable for any MEMS process



Integrated with Architect and Analyzer

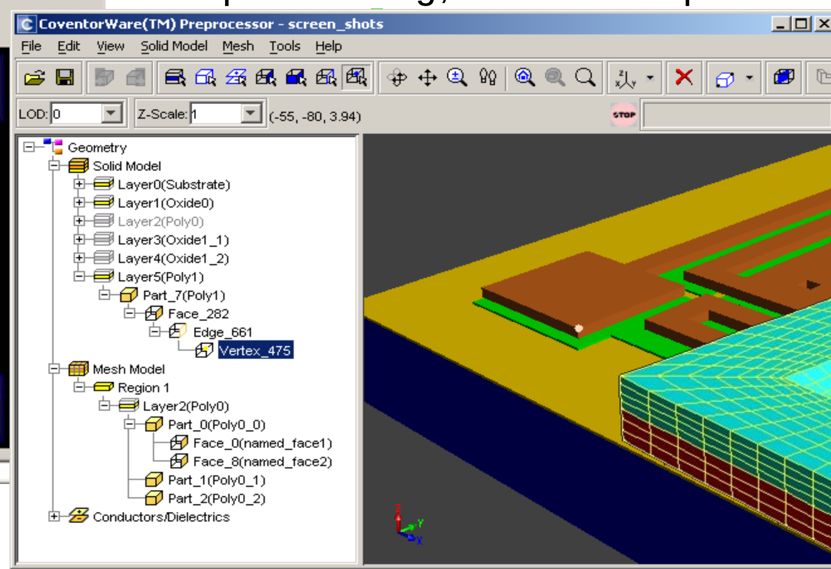
2D Layout Editor

with MEMS-specific features



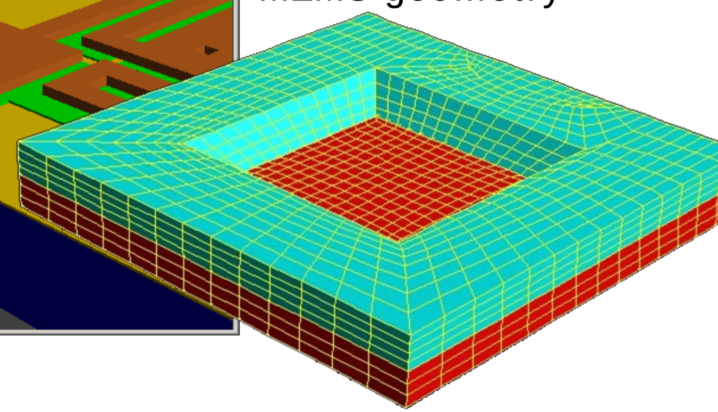
Preprocessor

with partitioning, transform operations,...



Automatic Meshing

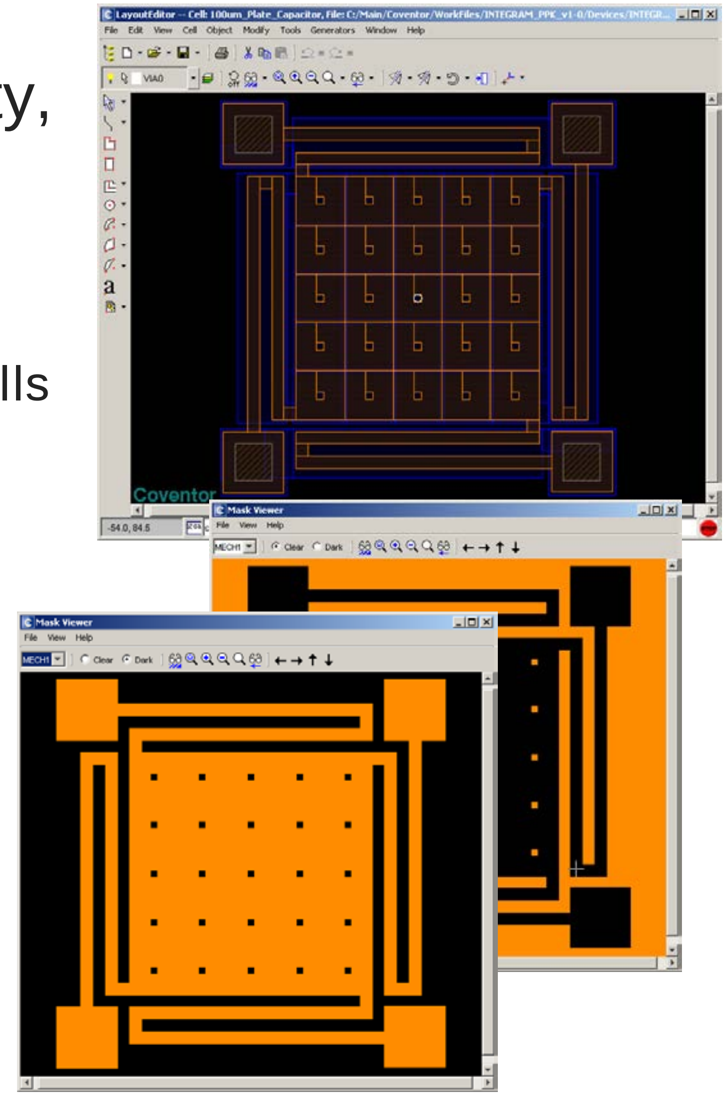
6 meshers, optimized for MEMS geometry



DESIGNER™ Layout Editor

Has standard layout editor functionality, plus MEMS-specific features

- Enter true curves (arcs, circles, splines) for efficient 3D solid modeling
- Save time by using hierarchical layout cells
- Parametric MEMS layout cell generators
- Import standard layout formats (GDS2, DXF)



Verify design before tape out

- Layer browser shows layer-to-mask mapping
- Built-in design rule checks
- Mask Viewer allows users see the masks exactly as they will be manufactured

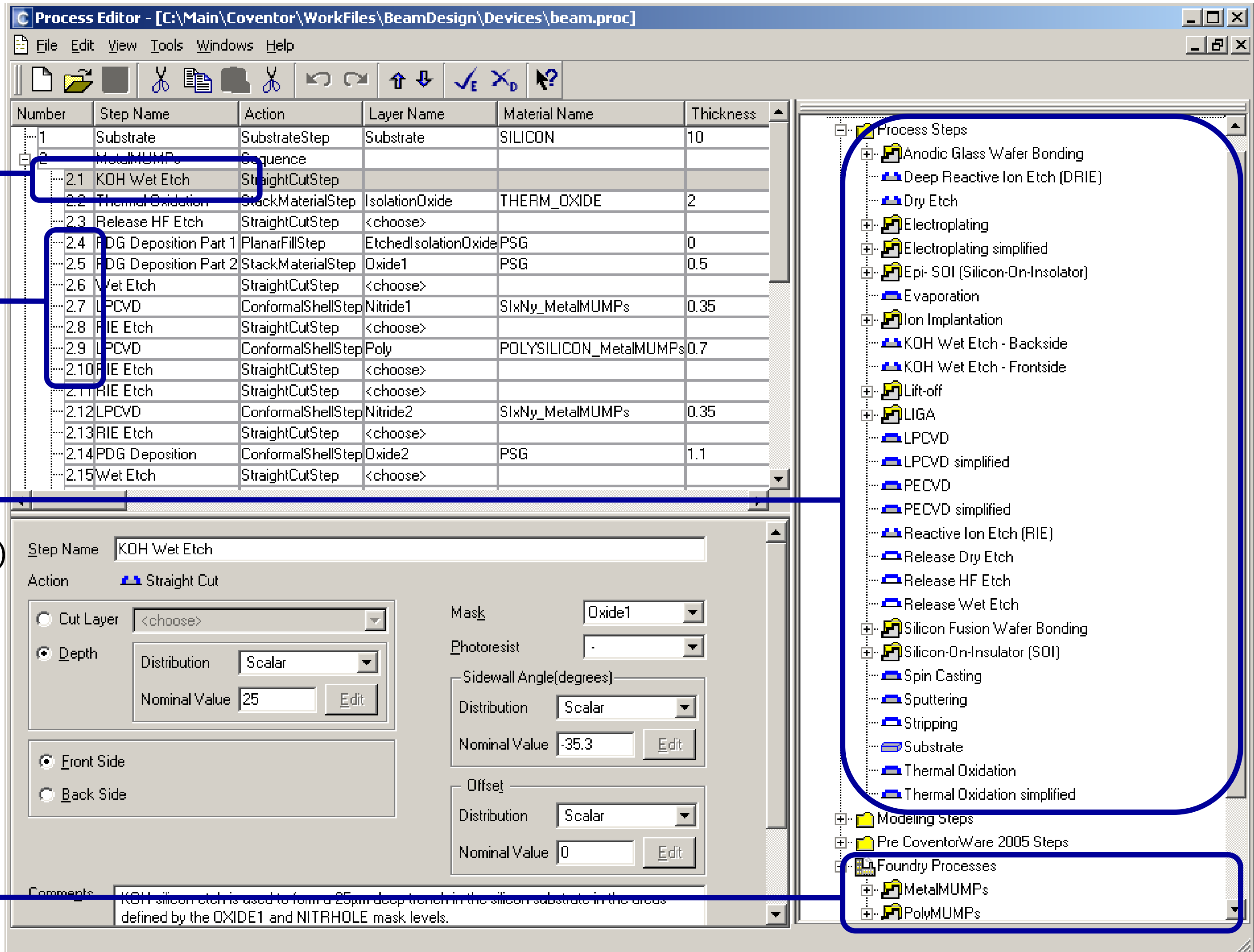
DESIGNER™ Process Editor

Descriptive step names

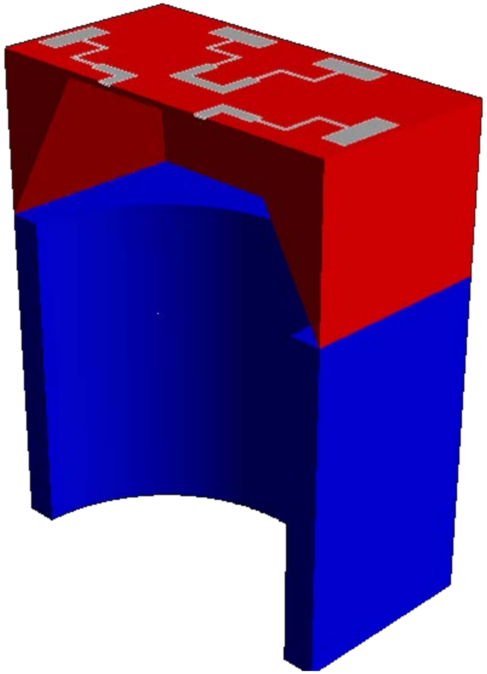
Customizable step hierarchy

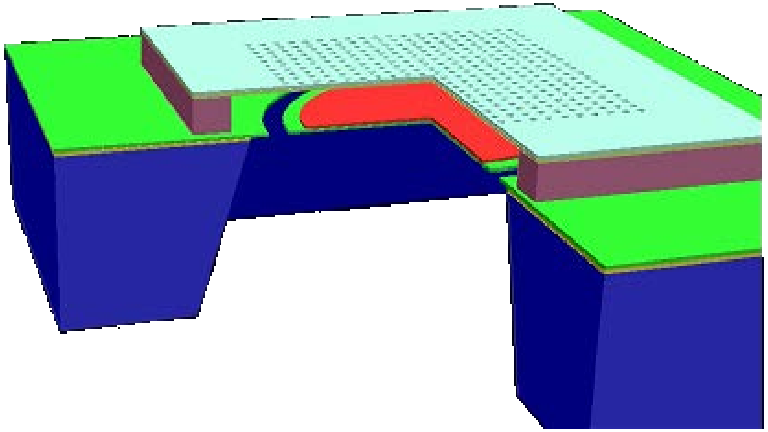
User customizable library of standard process steps (mapped to solid modeling steps)

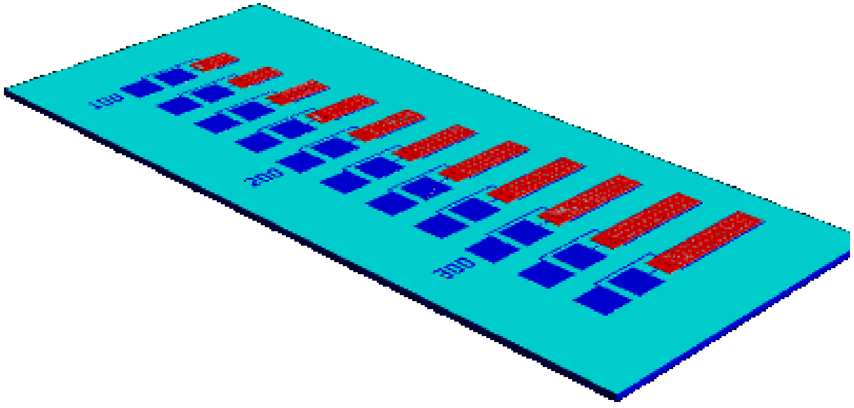
Access to standard foundry processes



- 3D Solid Model Builder
  - Employs the 2D layout and fabrication process description to automatically build 3D models (ACIS SAT format)
  - Emulates real foundry steps, such as etching through multiple layers or partial backside etching





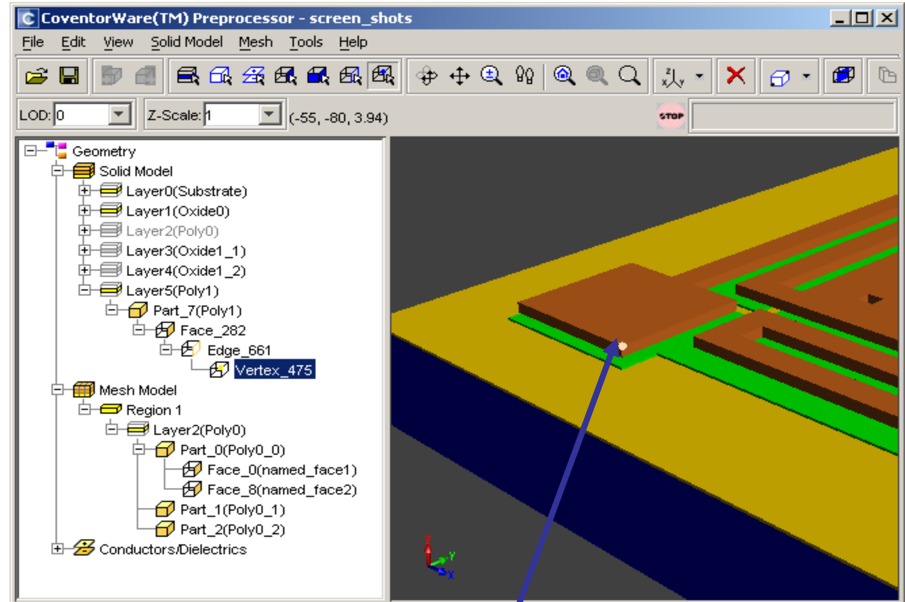


DESIGNER™ Preprocessor

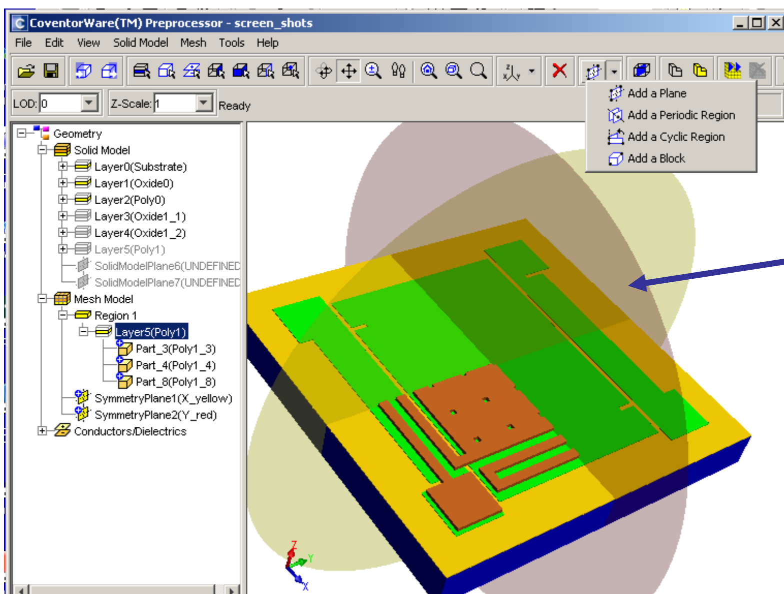
Optimized for MEMs layers

Features include

- Cross-section planes
- Solid model partitioning & transforms
- Automatic layer merging to assure conformal meshes
- Part and face labeling for BCs
- Mesh generation
- Mesh quality checks



Tree expands to show only named
or highlighted entities



Same plane can be used as x-section, partition or symmetry.

DESIGNER™ Meshing

Choose from 5 optimized mesh generators that are ideal for MEMS solid models

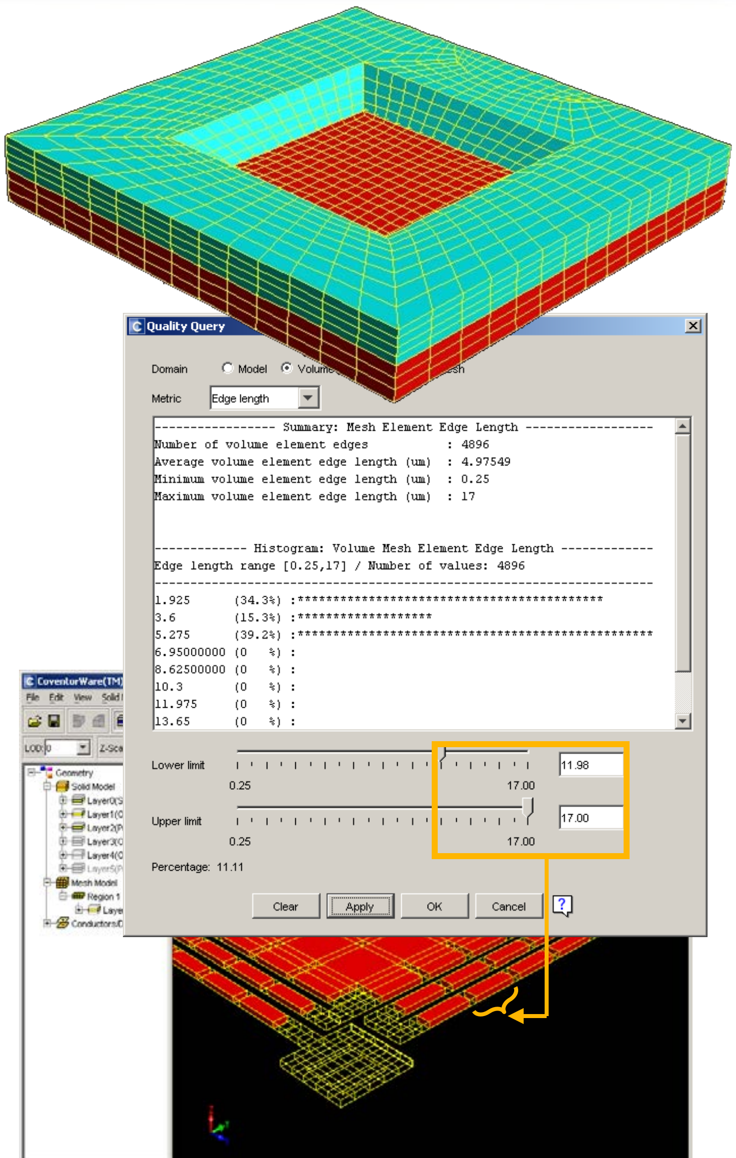
1. Manhattan bricks (hexes) for near orthogonal geometry
2. Extruded bricks for multi-layered non-orthogonal geometry (choose from 3 algorithms)
3. Mapped meshing for 6-sided volumes
4. Tetrahedrals meshing for arbitrary shapes
5. Surface meshing (triangles and quadrilaterals) for BEM

Local refinement controls on all model entities (layers, parts, faces, edges, vertices)

Mesh quality checks

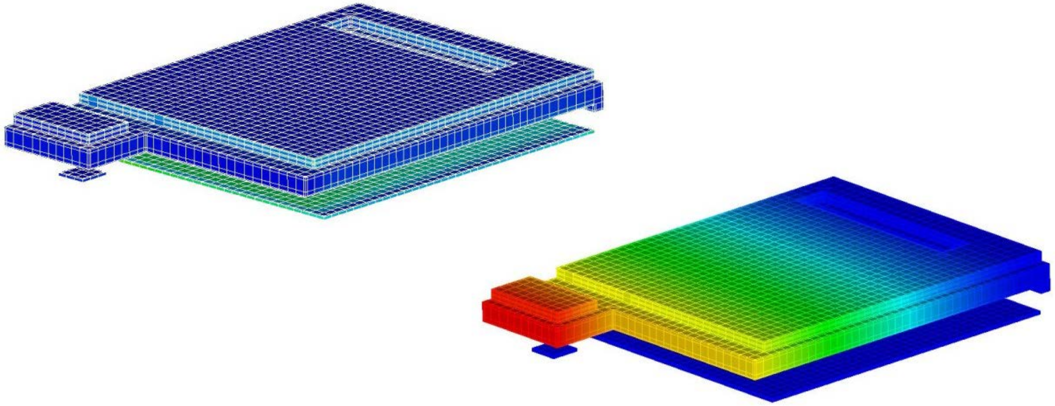
- Easy to read reports
- Highlighted display of “bad” elements

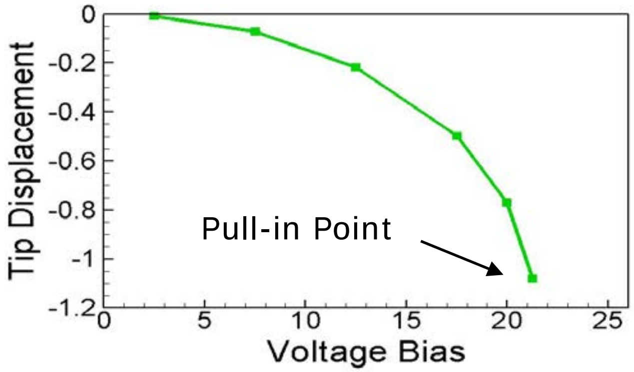
Import/export ANSYS meshes



Overview of ANALYZER™

- Comprehensive suite of 3D field solvers for MEMS
- Coventor solvers for thermo-mechanics, electrostatics, damping, piezo-resistance, piezoelectric effect
  - Hybrid FEM/BEM approach to coupled electromechanics
  - Gas damping, Anchor Damping, TED
- Simulation management
- Versatile results visualization

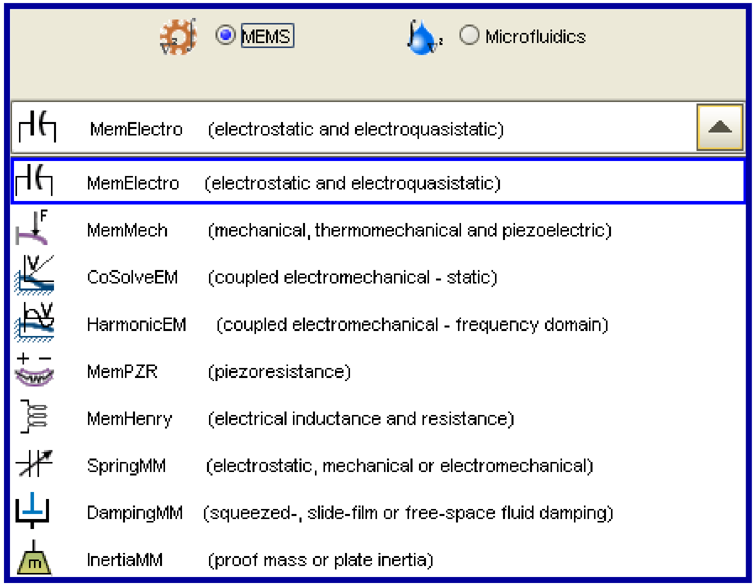




Overview of ANALYZER™

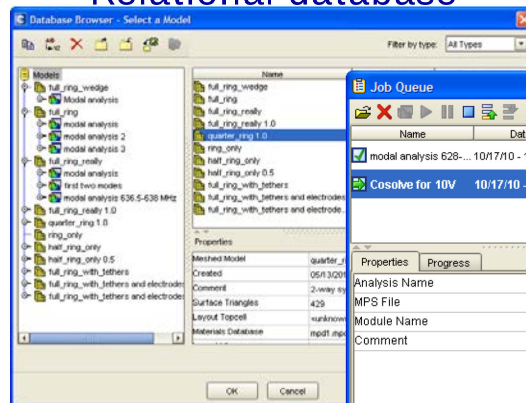
1. Comprehensive suite of 3D field solvers

Multi-physics with multi-core and 64-bit support

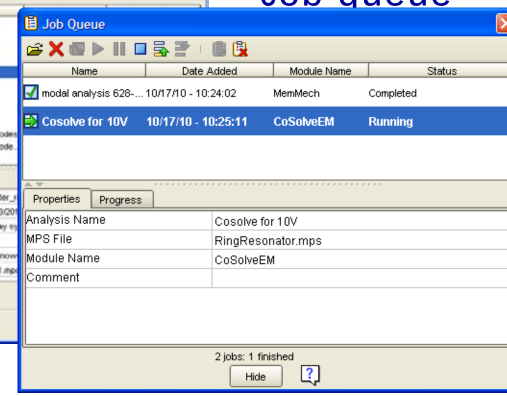


2. Simulation management

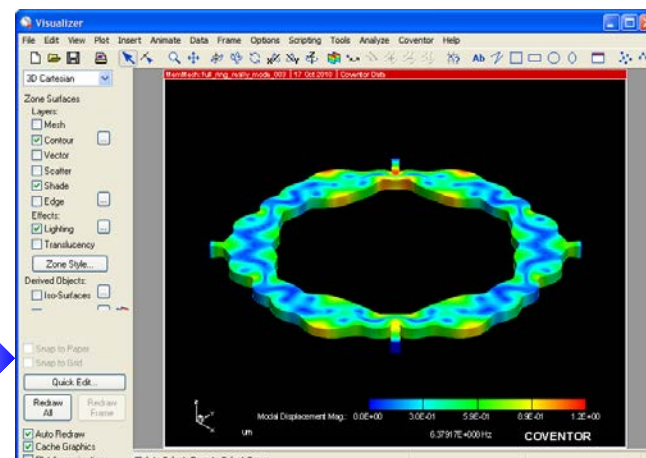
Relational database



Job queue

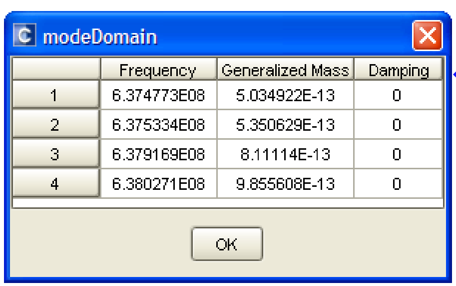


Visualizer



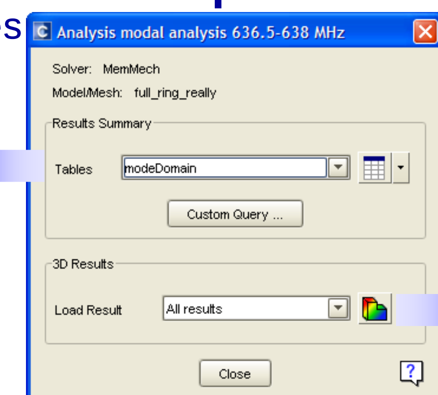
3. Postprocessing

Convenient pre-defined tables and custom queries

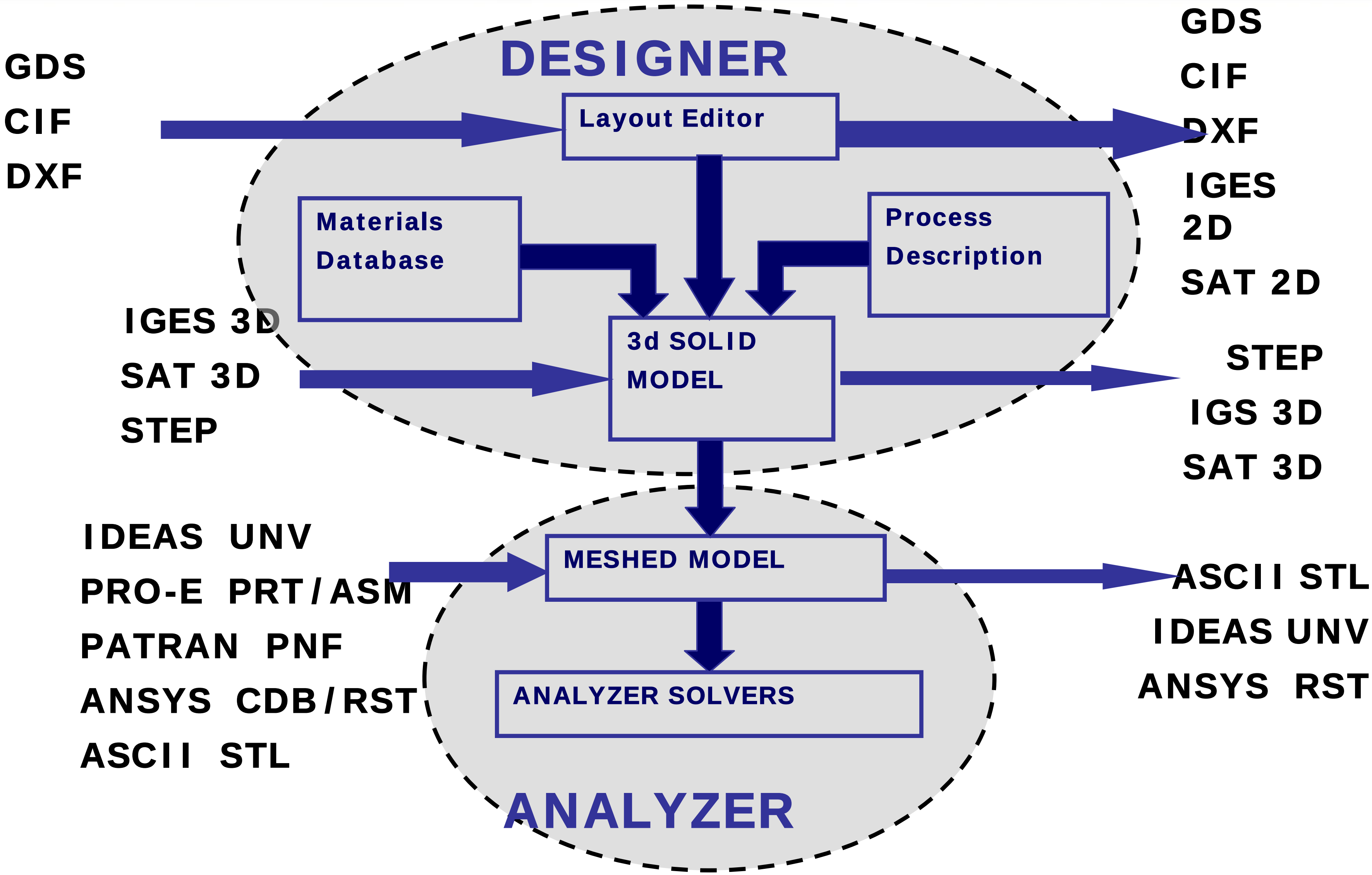

modeDomain

	Frequency	Generalized Mass	Damping
1	6.374773E08	5.034922E-13	0
2	6.375334E08	5.350629E-13	0
3	6.379169E08	8.11114E-13	0
4	6.380271E08	9.855608E-13	0

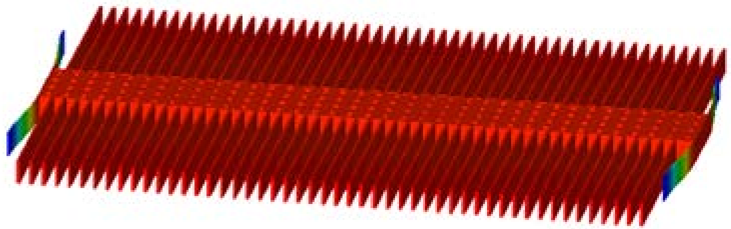
OK



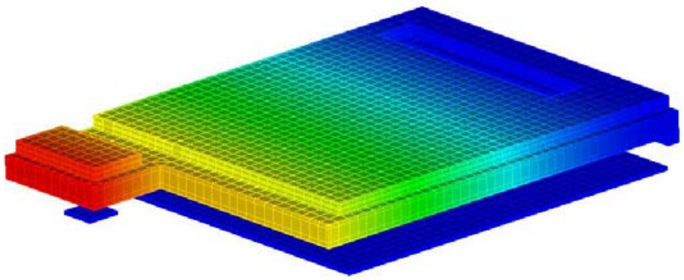
CoventorWare Compatibility



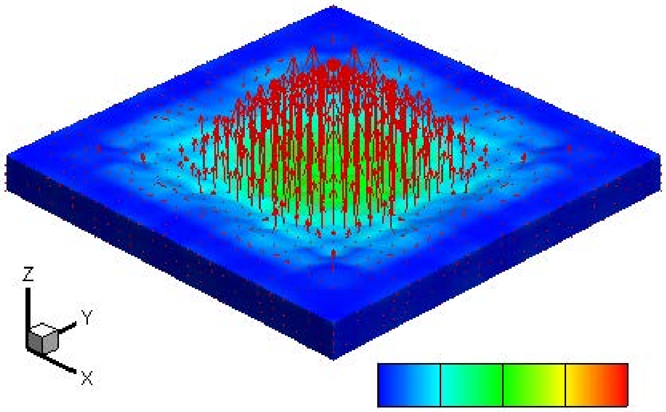
MEMS Examples in ANALYZER™



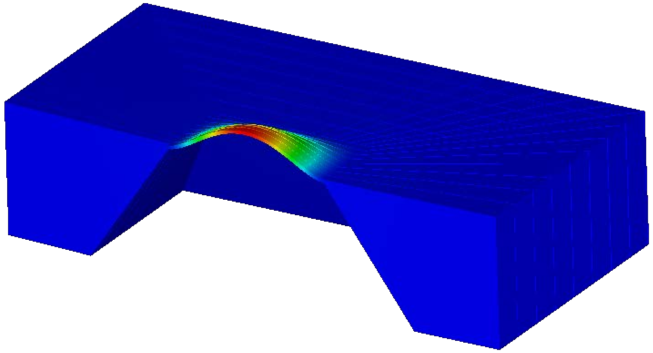
Accelerometer
(Coupled Electro-Mechanics, Gas Damping)



RF Switch
(Coupled Electro-Mechanics, Gas Damping)

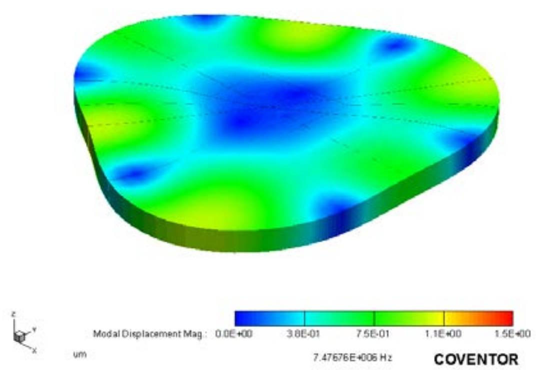


FBAR
(Piezoelectric and Mechanical Effects)

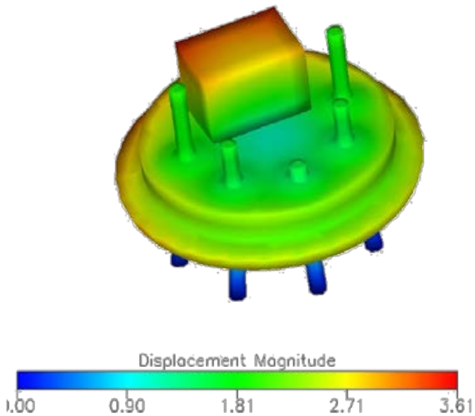


Pressure Sensor
(Mechanics, Piezo-Resistive Sensing

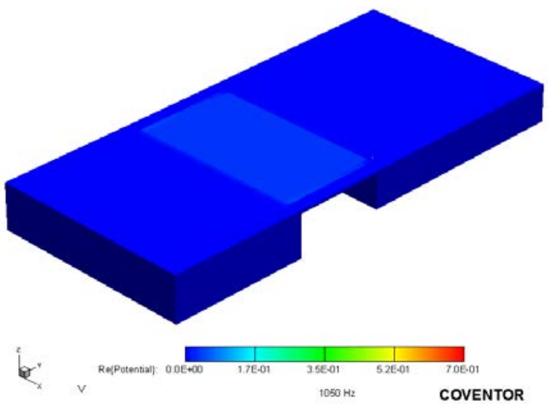
ANALYZER™ Examples MEMS



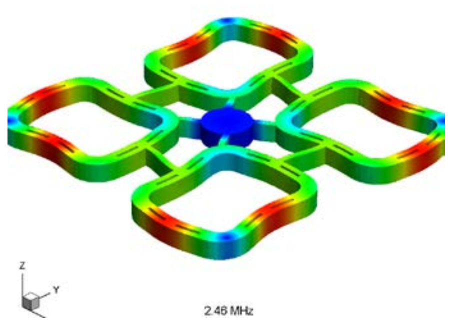
Disk gyro



Displacement inside package at -40^0 C



Energy Scavenger



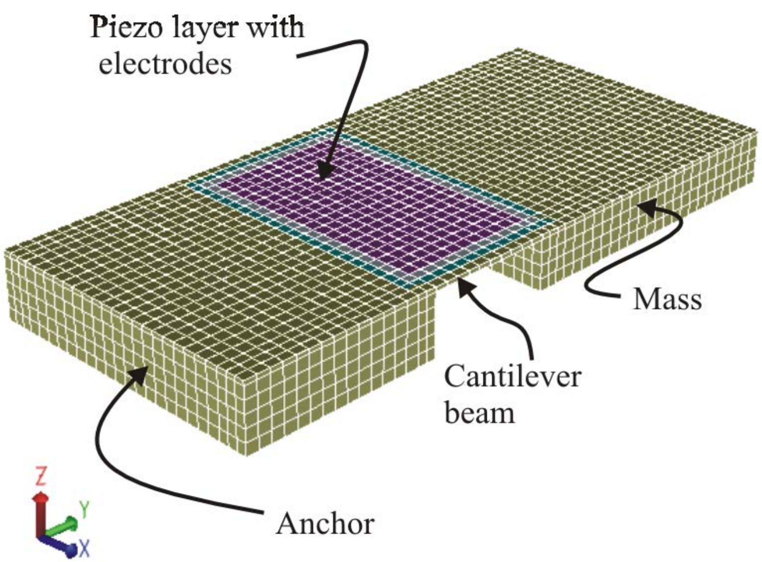
Resonator, TED, Anchor Loss, Stress Relief.

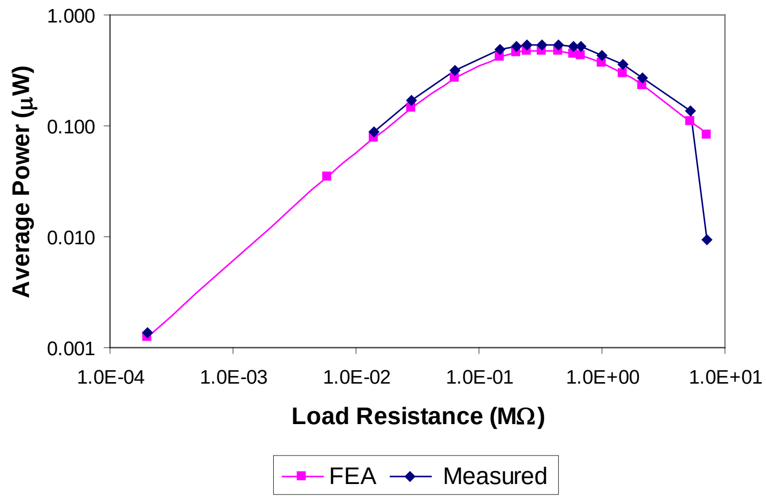
Experimental Validation of Aluminum Nitride Energy Harvester Model with Power Transfer Circuit

S. Matova1, D. Hohlfeld1, R. van Schaijk1, C. J. Welham2, S. Rouvillois2

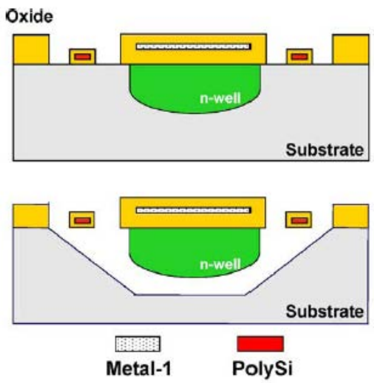
1 IMEC / Holst Centre, The Netherlands,

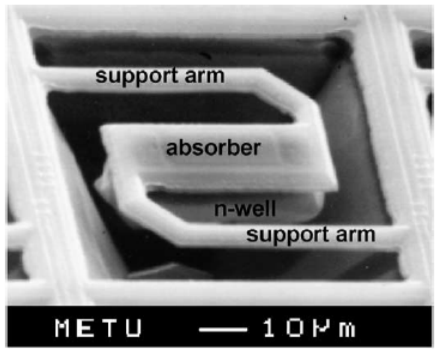
2Coventor, France

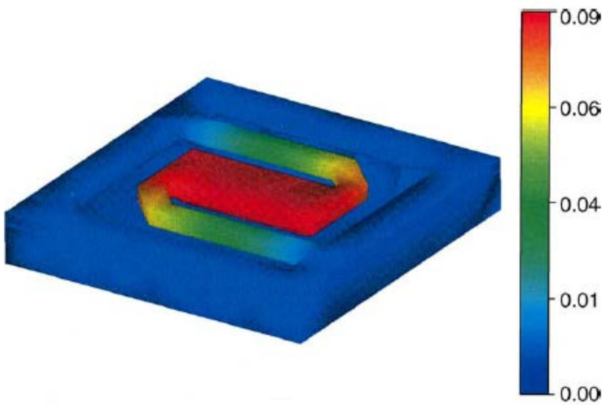




Resistive Bolometer

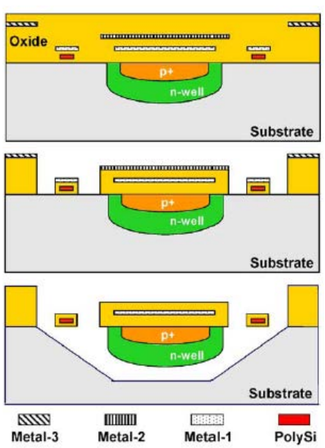


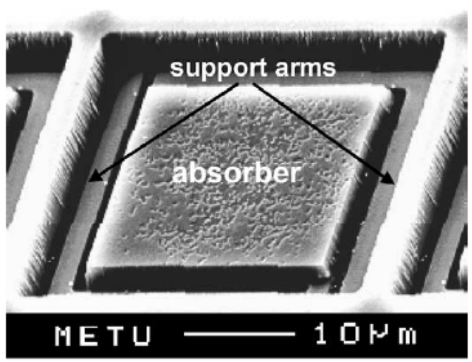


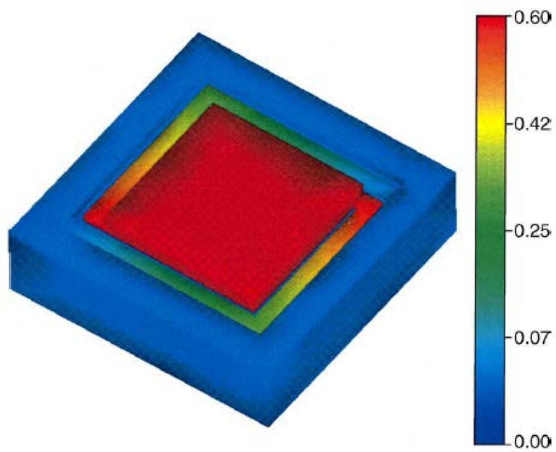


100nW power absorbed by the detector: temperature gradient in the pixel is simulated in vacuum at temperature of 300 K

Diode Bolometer







Low-cost uncooled infrared detectors in CMOS process

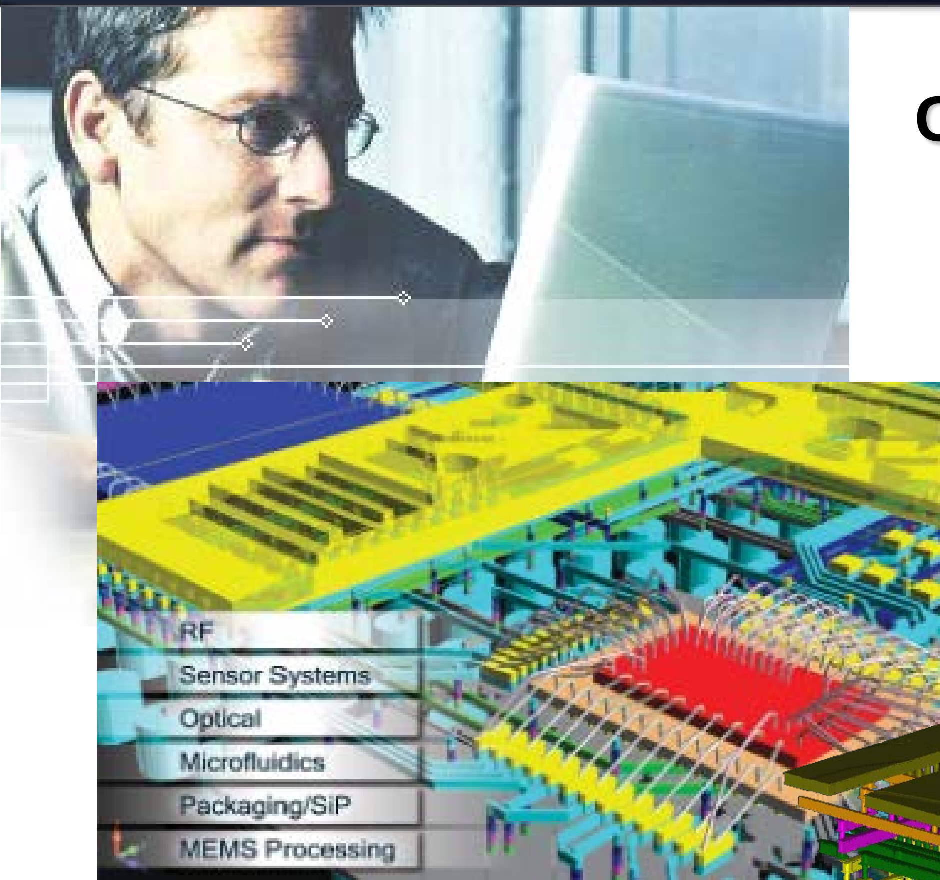
Selim Eminoglu, Deniz Sabuncuoglu Tezcan, M. Yusuf Tanrikulu, Tayfun Akin*
Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara 06531, Turkey

Overview of CoventorTools

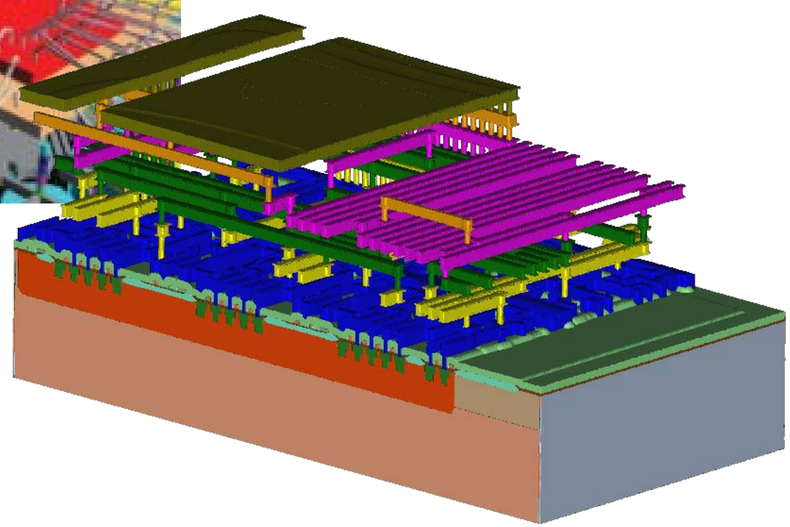
Material Properties Database and Process Editor

SEMulator3D Virtual prototyping

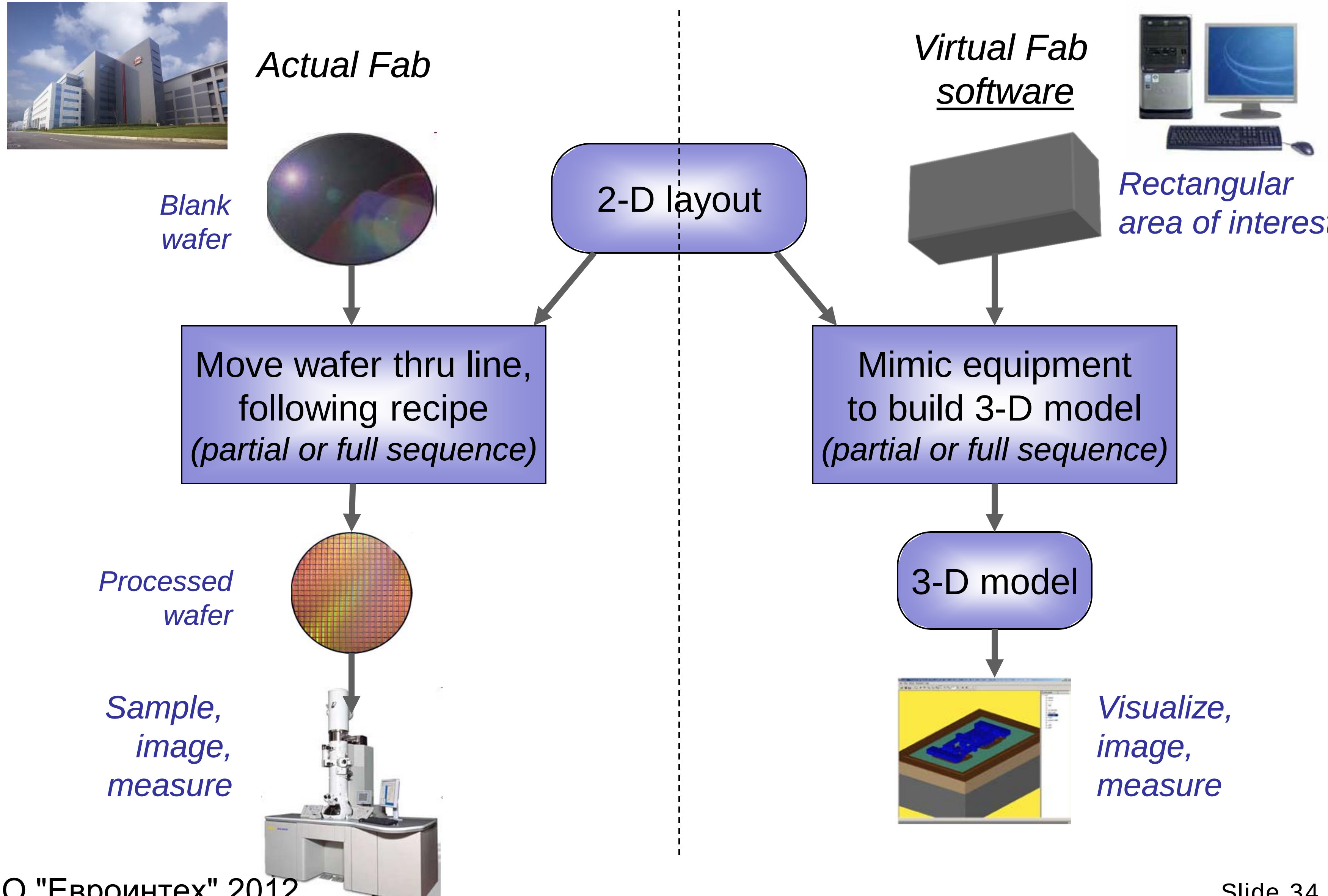
Coventor is the leader in MEMS design automation software



Applying our technology to modeling MEMS and semiconductor processes in 3-D



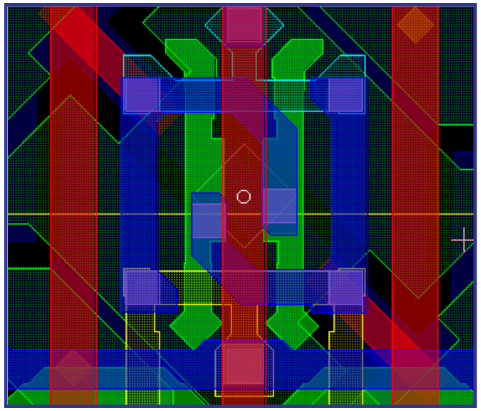
What is Virtual Fabrication?



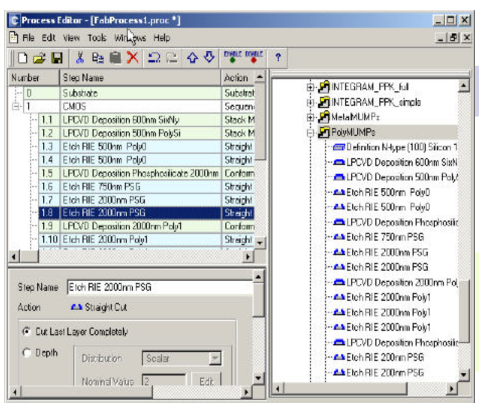
What is SEMulator3D

A modeling tool used by leading MEMS and semiconductor fabs

GDSII Layout

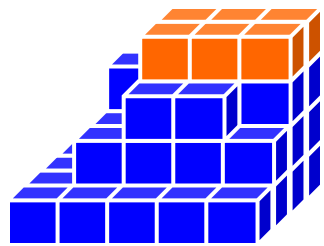


Process Description



3D Modeling Engine

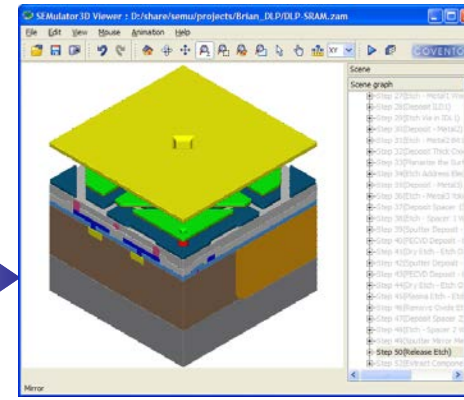
builds voxel models by applying a sequence of primitive operations



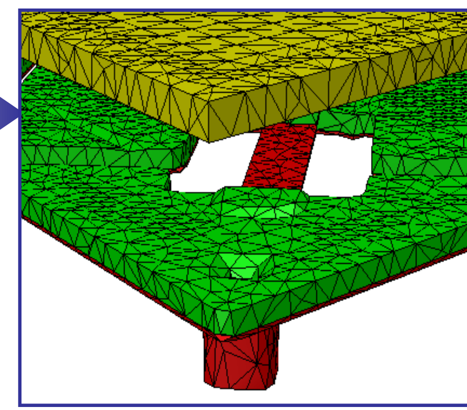
Voxels are 3D pixels

Customizable to <u>any</u> process technology

Visualization



Simulation Mesh

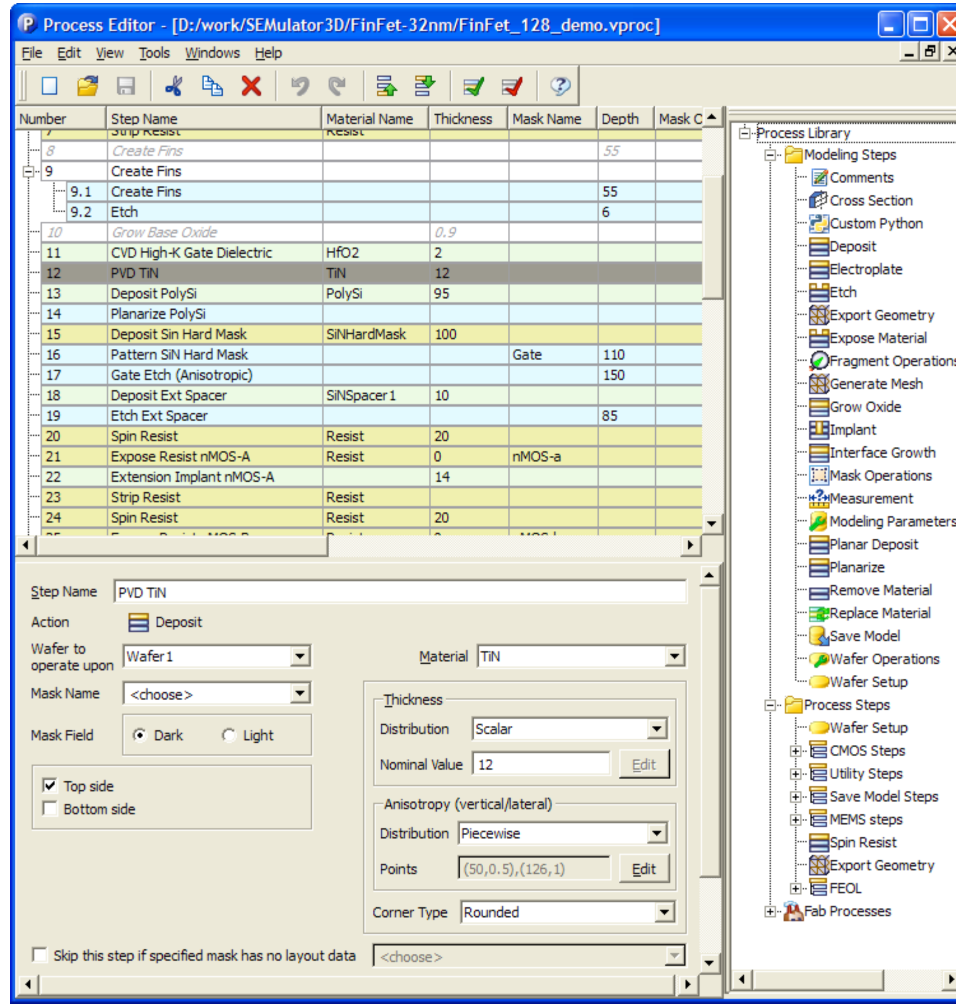


SEMulator3D Process Recipe

SEMulator3D follows a process “recipe” to emulate the fabrication sequence step-by-step:

- Process recipe is composed of primitives from a standard library
- Primitive steps can be configured (calibrated) to match fab
- Input is *parameterized*
- Parameters are *geometric*; process setup is easy and fast

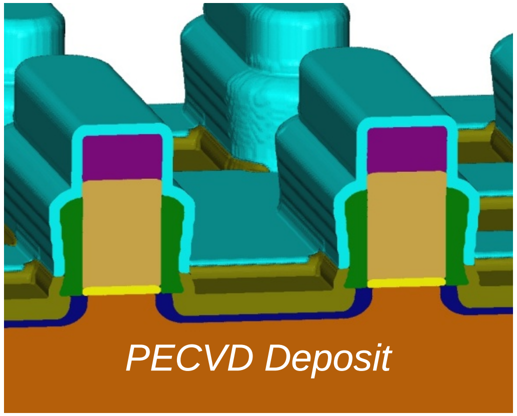
SEMulator3D can model ***any*** process technology.

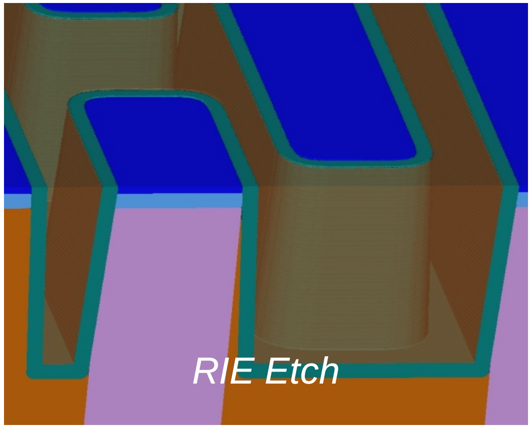


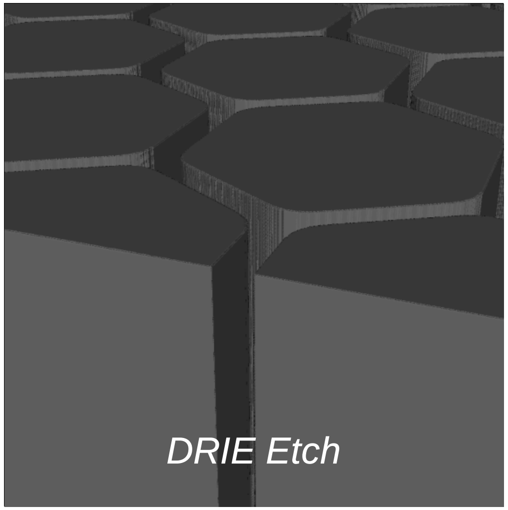
SEMulator3D Process Editor

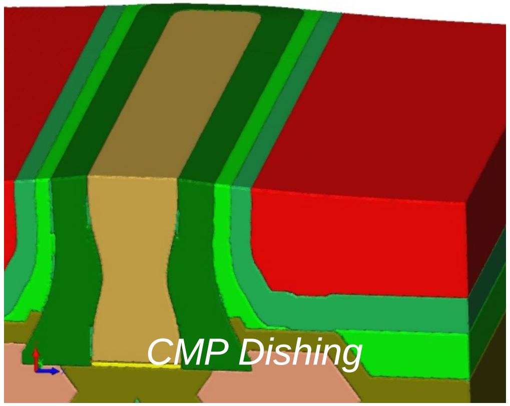
SEMulator3D Library of Standard Process Steps

- ✓ Conformal deposits
  - CVD, PECVD, HDPCVD, etc
- ✓ Directional deposits
  - Evaporation, sputtering
- ✓ Wet etches
  - Including selectivity
- ✓ Dry etches
  - Plasma-based etches, RIE, DRIE, etc
- ✓ Growth
  - Oxide growth
  - Epitaxy (some)
  - Salicide
  - Electroplate
- ✓ Miscellaneous
  - CMP
  - Lift-Off
  - Implant + Diffusion


PECVD Deposit

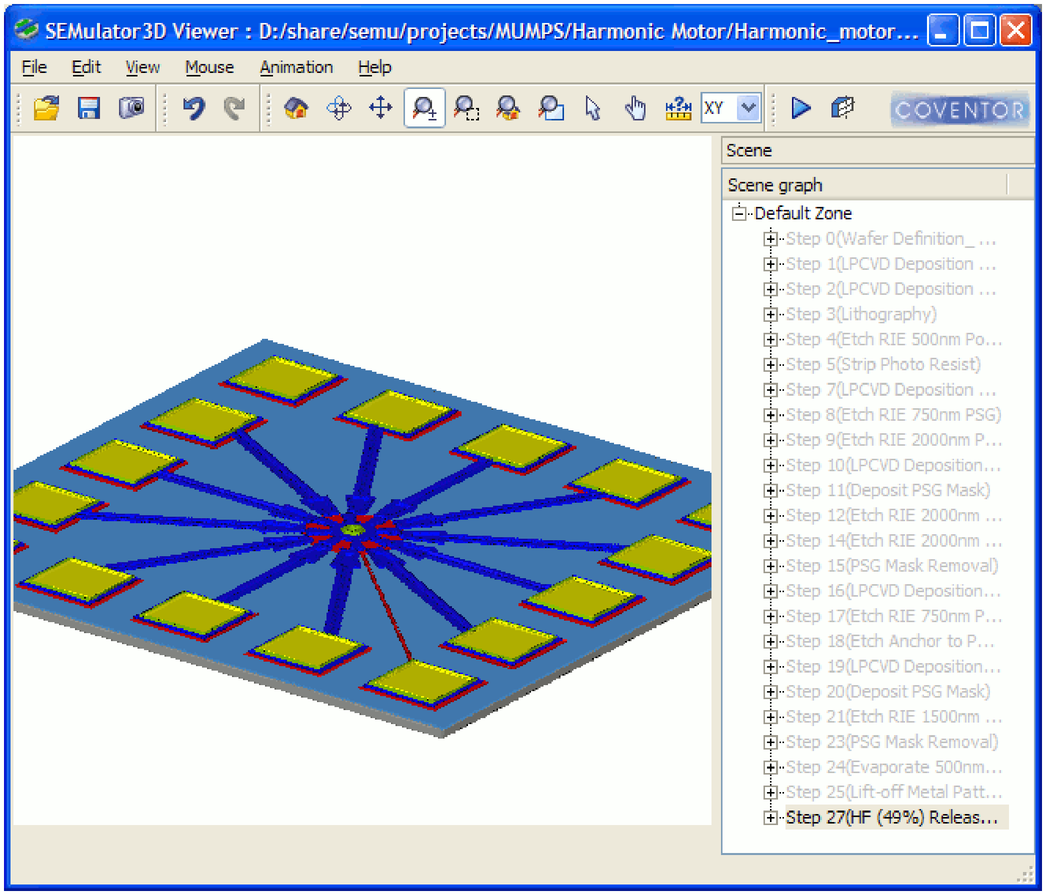

RIE Etch


DRIE Etch


CMP Dishing

Powerful 3D Visualization

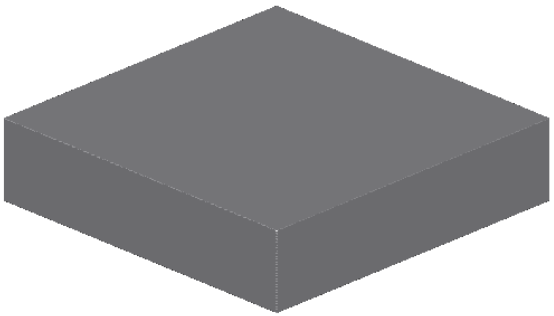
With the SEMulator3D Visualizer, you can



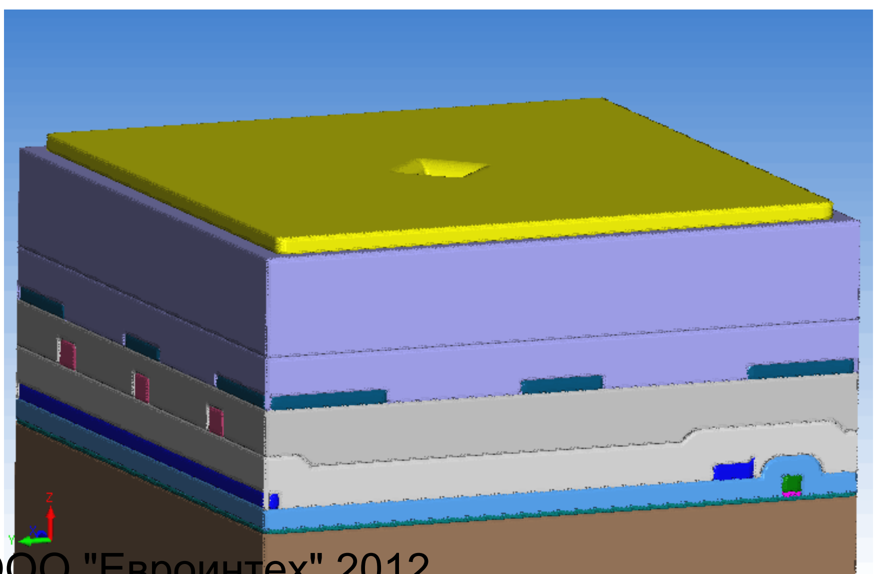
MEMS Motor using Metal MUMPS process

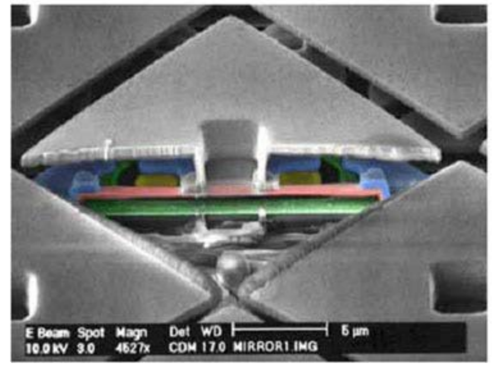
- Interact with a 3-D view
- Create and animate <u>dimensionally accurate</u> cross sections
- Color by material or by electrical connectivity
- Hide/show materials or electrical nets
- Take measurements
- Exaggerate scale in x,y or z
- Capture 3-D images
- Animate the fabrication steps

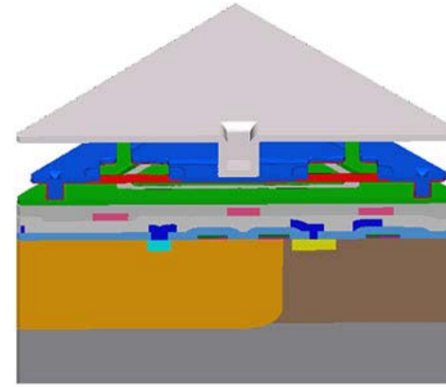
Example: MEMS DLP Mirror

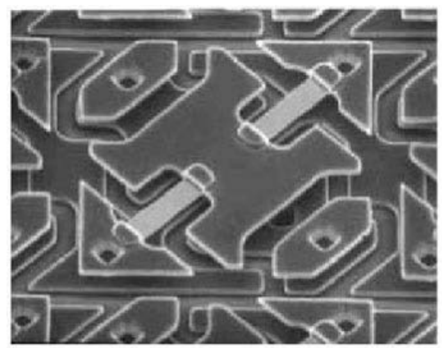


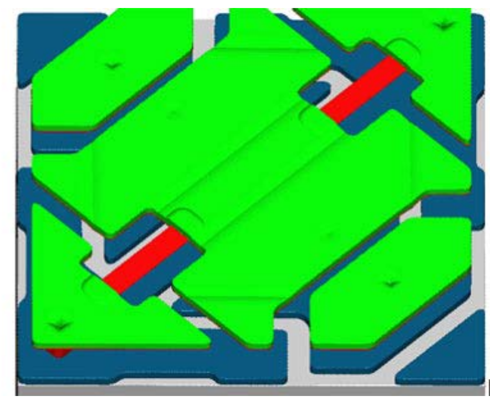
DLP Process Sequence (above) and release etch (below).





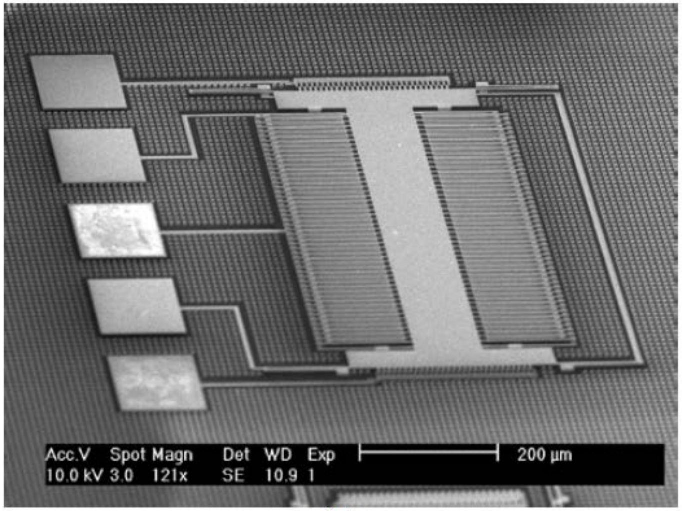




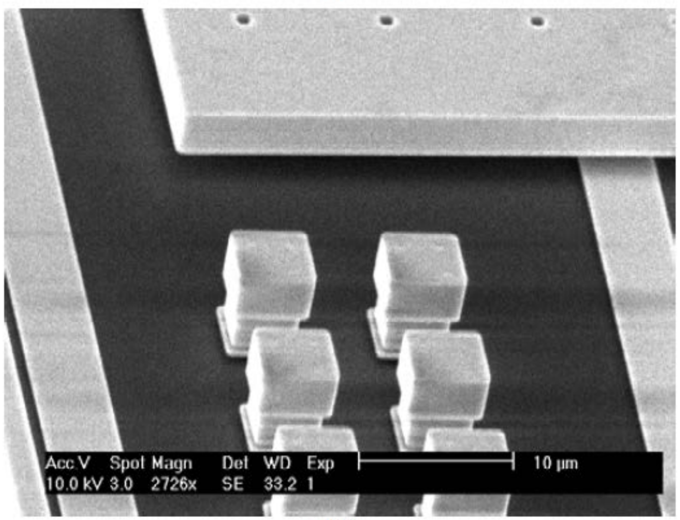


DLP mirror based on a design by Texas Instruments. Note accurate representation of tether attachments!

Example: SiGe Accelerometer

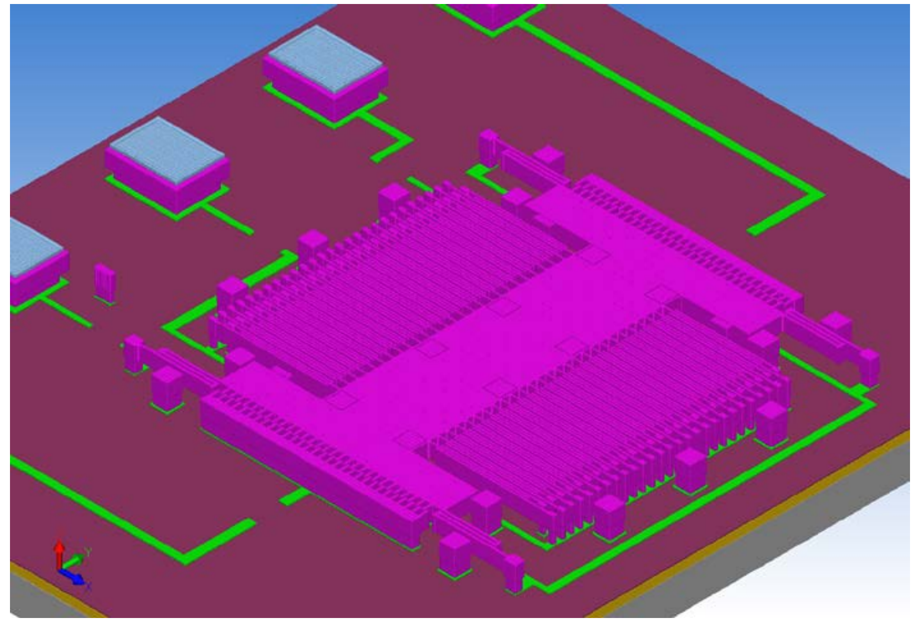


(a)



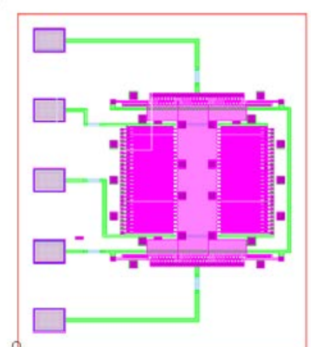
(b)

Figure 3: *SEM view of the fabricated poly-SiGe lateral capacitive accelerometer*



A COMB BASED IN-PLANE SIGE CAPACITIVE ACCELEROMETER FOR ABOVE-IC INTEGRATION

L. Wen[1], K. Wouters[1], L. Haspeslagh[2], A. Witvrouw[2], R. Puers[1]
[1]*ESAT-MICAS, Katholieke Universiteit Leuven, Leuven, Belgium*
[2]*IMEC, Kapeldreef 75, Leuven, Belgium*



Stopper
for SiGe Accelerometer

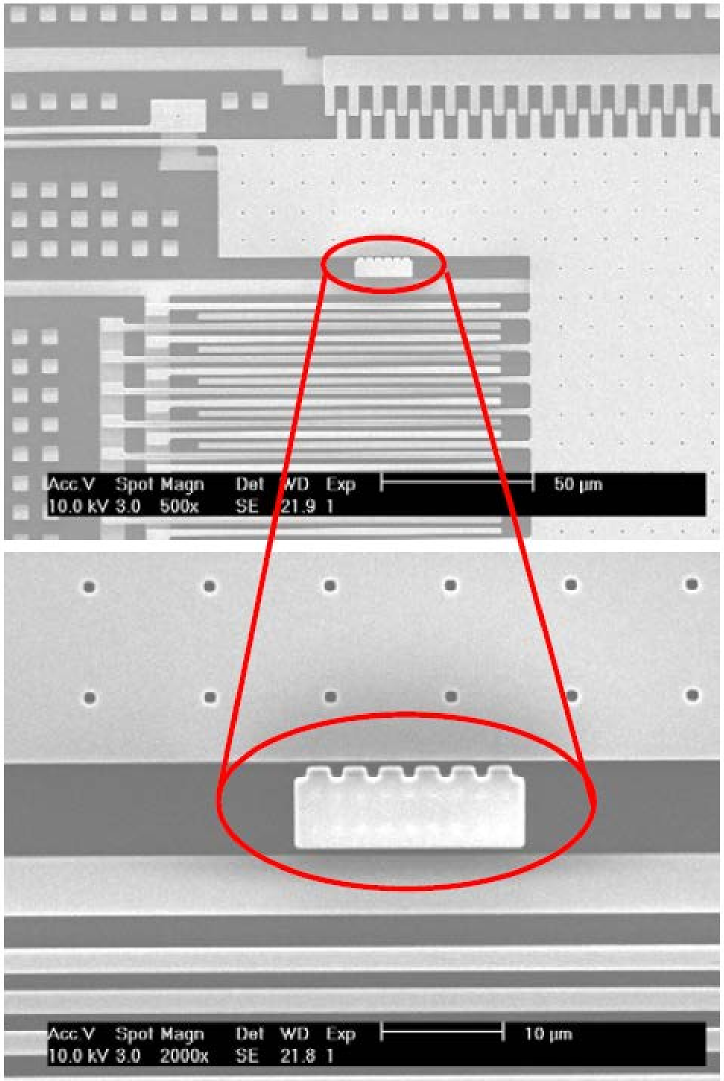
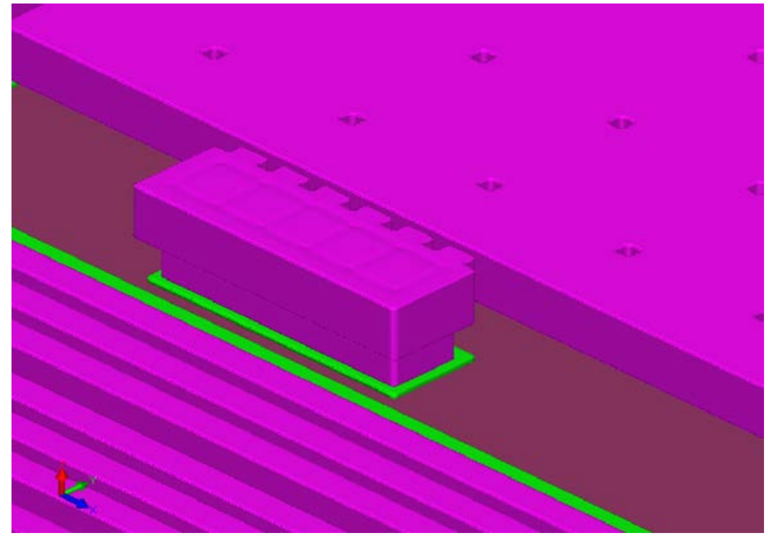
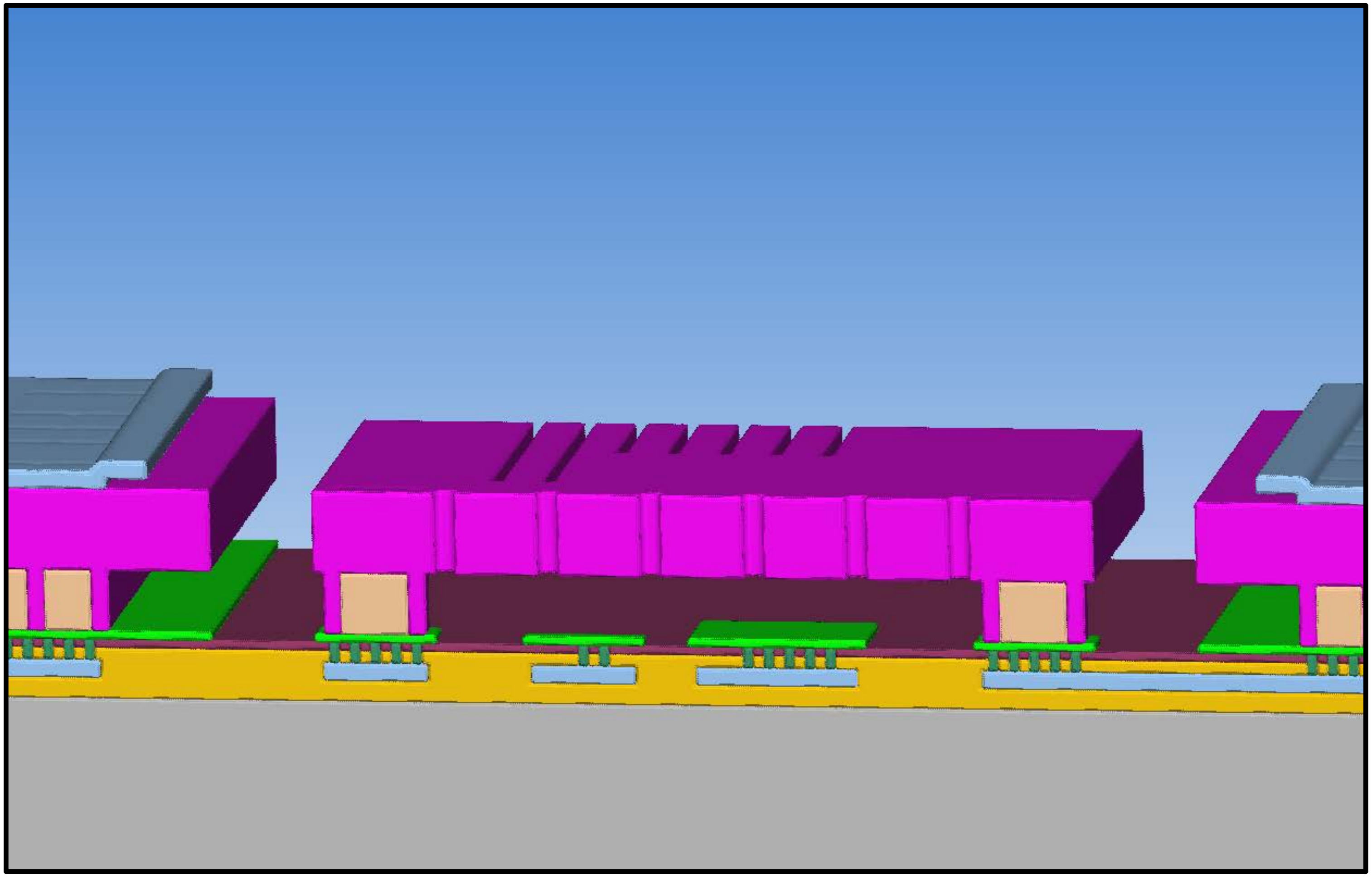


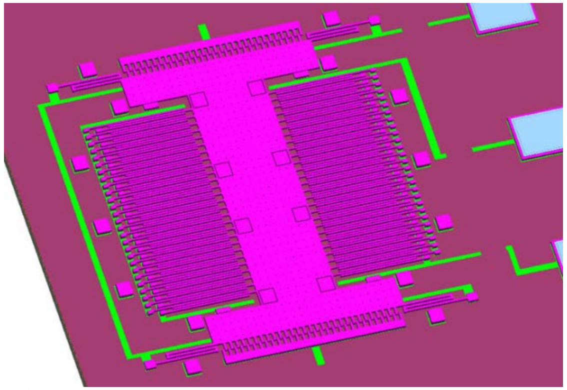
Figure 6: *SEM view over the positioning of the shock protectors of the fabricated poly-SiGe lateral capacitive accelerometer*

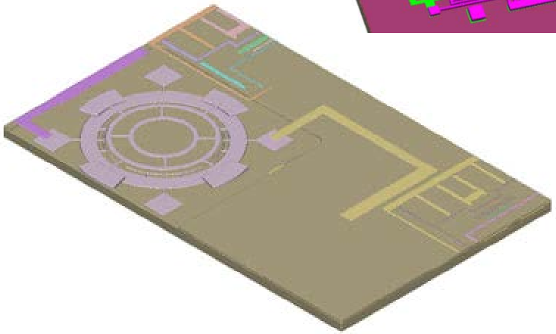


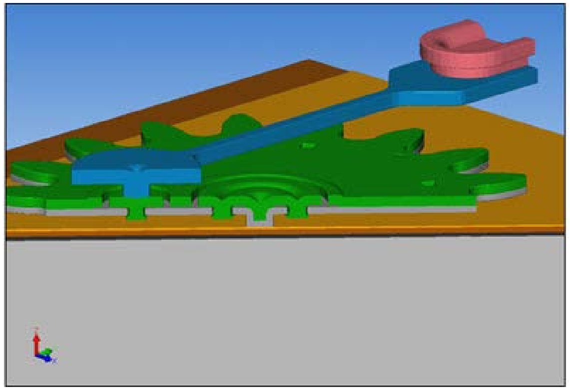
Demo IMEC's SiGe



Who needs Virtual Fabrication







Process Development

- Model the full fabrication sequence
- *Prototype* process changes before implementing them
- *Predict* process problems
- Save wafers ($$$) and time

Foundry Services

- *MEMS Design validation* before fabrication
- *Communication* with customers

MEMS Designers

- Test manufacturability before tape-out
- Silicon-accurate models for FEM simulation
- *Communication* with fab

Process Documentation & Training

- Add realistic 3D graphics for more effective documentation

Design Validation

Foundry Service companies use SEMulator3D to:

- Communicate design and process information with customers.
- Validate designs before fabrication.
- Efficiently model any design changes.
- Analyze and improve yield.
- Allow customers to build 3D models with SEMulator3D via PDK.

TELEDYNE DALSA Everywhereyoulook™

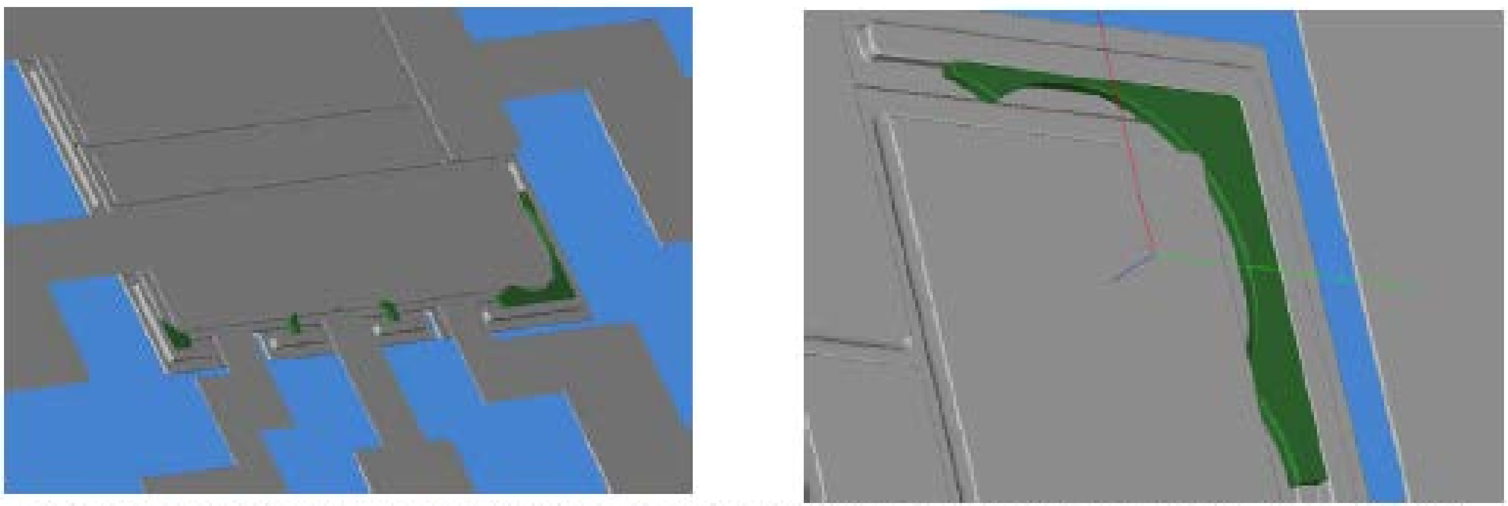
“Emulation also gives engineers the ability to do virtual test runs to verify that a device design is compatible with the manufacturing process, and that the 3D result is as expected. Moreover, design mistakes and shortcomings can be identified, even if they are compatible with 2D layout rules.”

XFAB MIXED-SIGNAL FOUNDRY EXPERTS

“The benefits of visualizing accurate 3-D virtual MEMS prototypes include increased probability of achieving first-time success by minimizing analysis errors, increased design efficiency by identifying process errors early, avoiding undesired effects that would have reduced yield, and more efficient communication between design engineers and outside groups.”

Baolab – Design review for PolyMUMPS with SEMulator3D

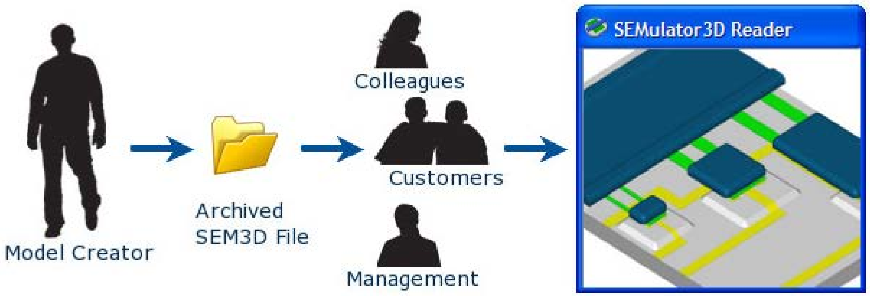
“We have now established a strict submission procedure within Baolab for all the foundry runs, and one imperative step is to simulate the whole die micromachining process using SEMulator3D and to visualize the 3D result using the mechanical coloring scheme, and this must be included in the final report.”



Green indicates Oxide not removed despite non-violation of design rules

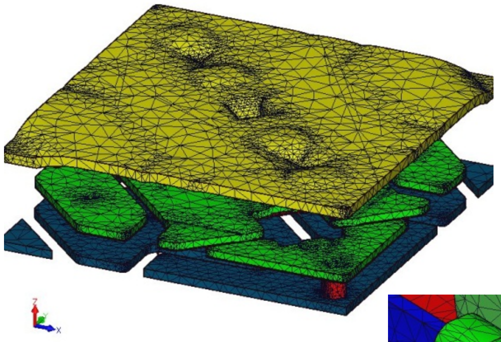
SEMulator3D Reader

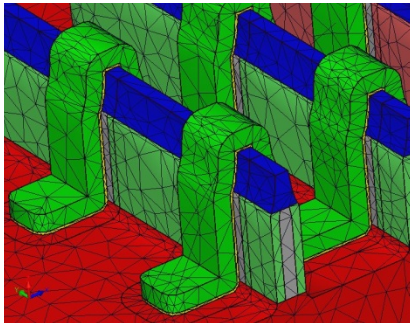
- An open version of SEMulator3D Viewer that anyone can download from Coventor's website
- SEMulator3D users can distribute 3D models to anyone.
- Encourage your prospects to try it out!



Mesh Generation

- SEMulator3D Meshing creates accurate surface and volume meshes for simulation:
  - Thermal
  - Mechanical stress/strain
  - Diffusion
  - Electrical parasitics
  - Multi-Physics (MEMS)
- SEMulator3D meshes can be used with CoventorWare Analyzer and 3rd-party solvers

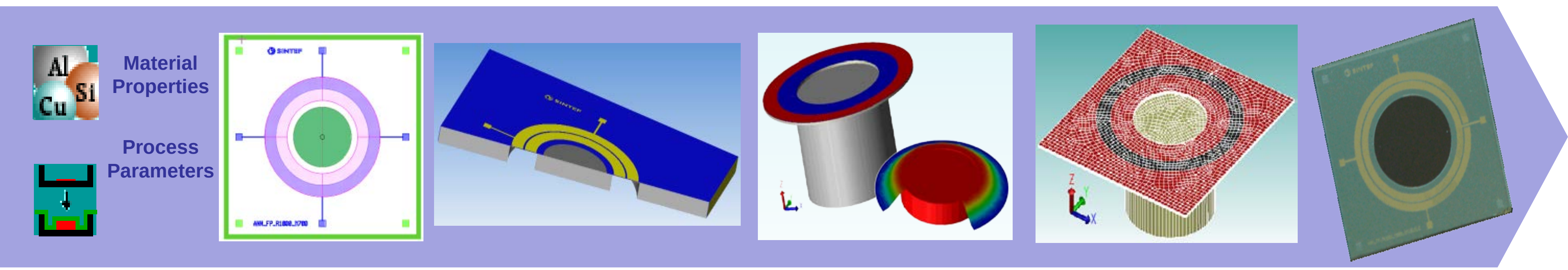




Design Kits

Design your MEMS in stable well-known manufacturing processes using CoventorWare development platform

- Data available:
  - Specific material property databases
  - Library of foundry specific process emulation files
  - Layout template file incl. DRC
  - Case studies and tutorials



Technology **DESIGNER™** **SEMULATOR3D ™** **MEMS+ ™** **ANALYZER™** **Fabrication run**

Library of Standard Foundry Processes

DALSA – post-processing on CMOS

IMEPKU – Polysilicon

PolyMUMPS – 3-Layer Polysilicon Surface

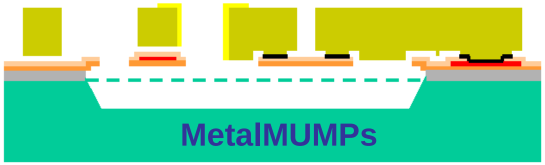
SOIMUMPS – SOI

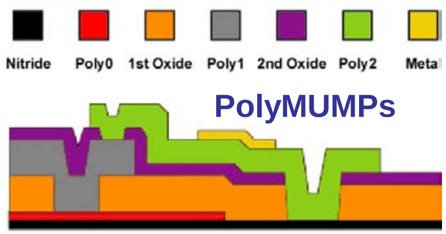
MetalMUMPS – Electroplating

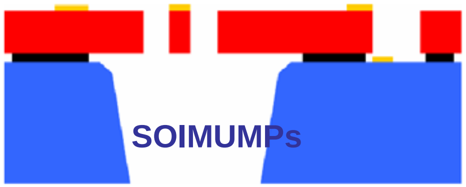
Tronics 60µm SOI-HARM – epitaxial SOI

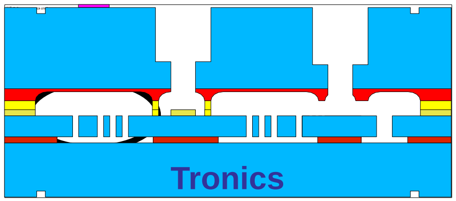
MultiMEMS – Piezoresistive Bulk

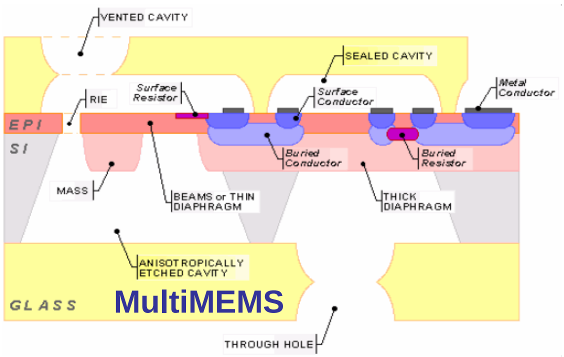
SINTEF – MOVEMEMS PZT (beta)

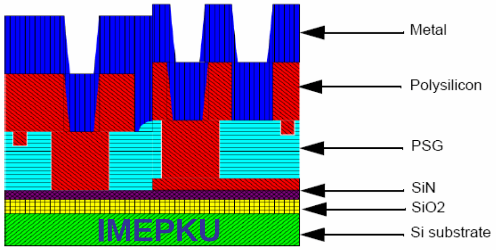










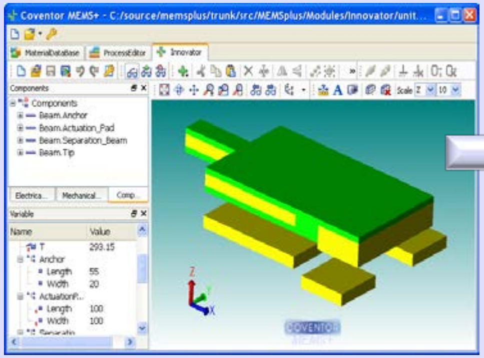


Overview of CoventorTools

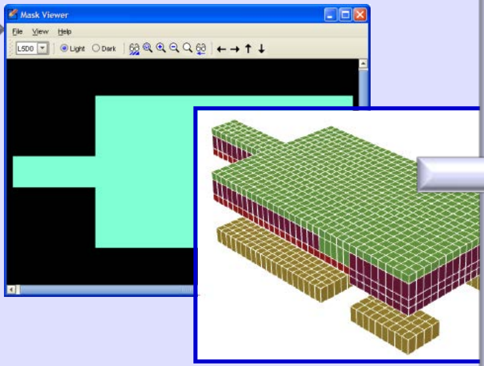
Material Properties Database and Process Editor

SEMulator3D Virtual prototyping

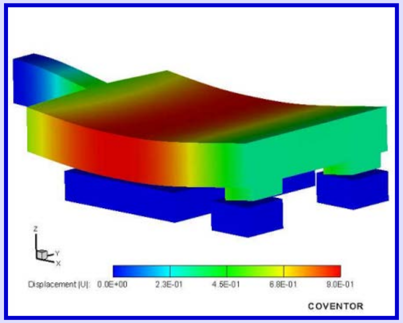
MEMS+
- MEMS behavioral modeling environment



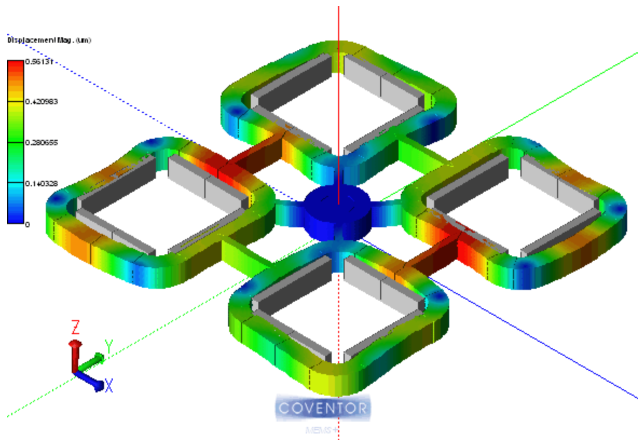
DESIGNER
- 2D Layout Editor
- Solid Modeler (2D to 3D)
- Preprocessor for FEA



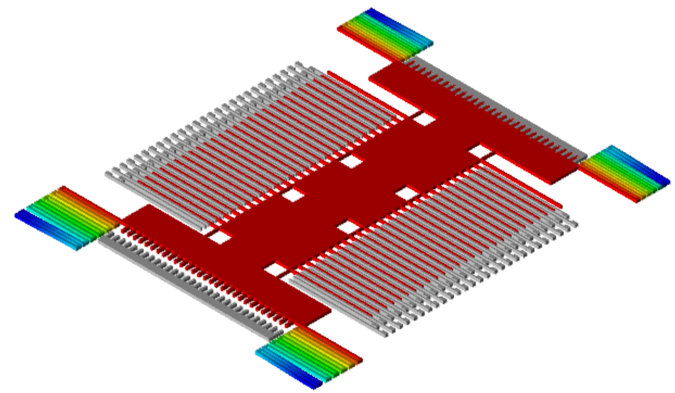
ANALYZER
- Suite of field solvers, hybrid FEM & BEM
- Comprehensive coverage for MEMS multi-physics



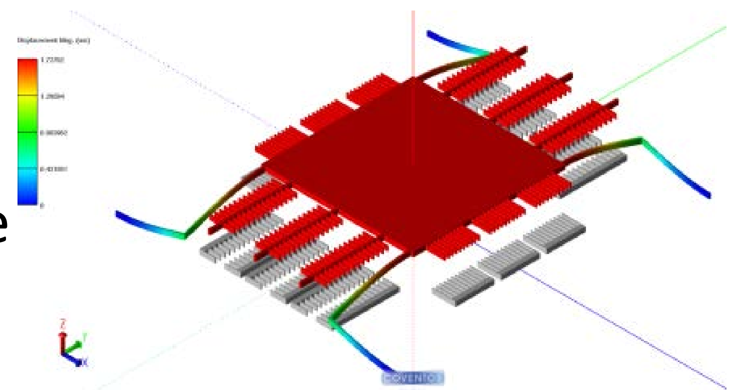
Resonator



Accelerometer



Gyroscope



Solution for MEMS Resonator Design and Integration

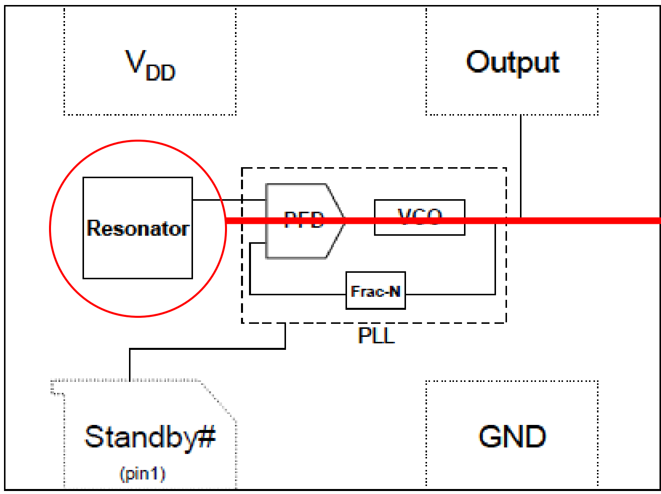
MEMS Resonators for quartz replacement or RF applications

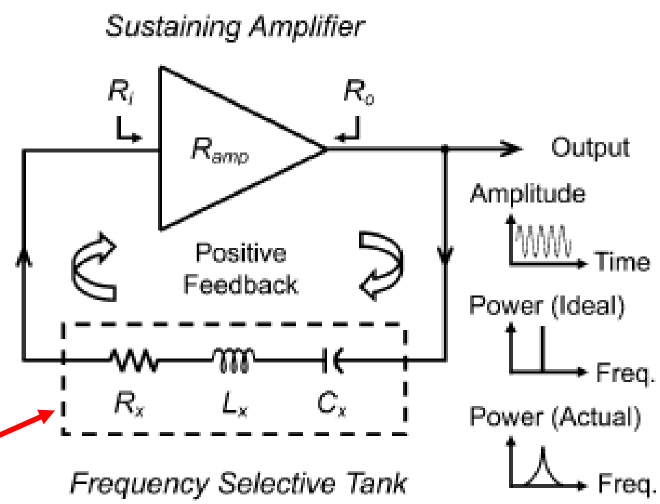
- Electromechanical
- Piezoelectric

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 39, NO. 12, DECEMBER 2004 2477

Series-Resonant VHF Micromechanical Resonator Reference Oscillators

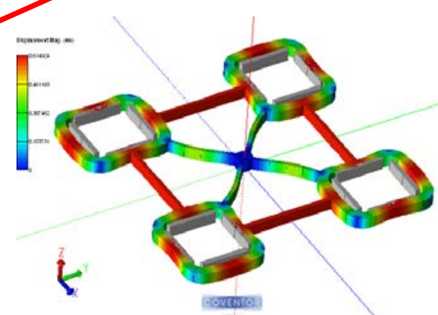
Yu-Wei Lin, *Student Member, IEEE*, Seungbae Lee, *Student Member, IEEE*, Sheng-Shian Li, *Student Member, IEEE*, Yuan Xie, *Student Member, IEEE*, Zeying Ren, *Member, IEEE*, and Clark T.-C. Nguyen, *Senior Member, IEEE*





series-resonant oscillator.

MEMS part



Specification Sheet

COVENTOR

Electrical Characteristics

Parameter	Symbol	Min.	Typ.	Max.	Unit	Condition
Output Frequency Range	f	1	–	110	MHz	
Frequency Stability	F_stab	-20	–	+20	PPM	Inclusive of: Initial stability, operating temperature, rated power, supply voltage change, load change, shock and vibration. **± 20 PPM available in extended commercial temperature only**
		-25	–	+25	PPM	
		-30	–	+30	PPM	
		-50	–	+50	PPM	
Aging	Ag	-1.0	–	1.0	PPM	1st year at 25°C
Operating Temperature Range	T_use	-20	–	+70	°C	Extended Commercial
		-40	–	+85	°C	Industrial
Supply Voltage	Vdd	1.71	1.8	1.89	V	
		2.25	2.5	2.75	V	
		2.52	2.8	3.08	V	
		2.97	3.3	3.63	V	
Current Consumption	Idd	–	6.7	7.5	mA	No load condition, f = 20 MHz, Vdd = 2.5 V, 2.8 V or 3.3 V
		–	6.1	6.7	mA	No load condition, f = 20 MHz, Vdd = 1.8 V
Standby Current	I_std	–	2.4	4.3	µA	$\overline{\text{ST}}$ = GND, Vdd = 3.3 V, Output is Weakly Pulled Down
		–	1.2	2.2	µA	$\overline{\text{ST}}$ = GND, Vdd = 2.5 or 2.8 V, Output is Weakly Pulled Down
		–	0.4	0.8	µA	$\overline{\text{ST}}$ = GND, Vdd = 1.8 V, Output is Weakly Pulled Down
Duty Cycle	DC	45	50	55	%	All Vdds. f <= 75 MHz
		40	50	60	%	All Vdds. f > 75 MHz
Rise/Fall Time	Tr, Tf	–	1	2	ns	20% - 80% Vdd=2.5V, 2.8V or 3.3V, 15pf load
		-	1.3	2.5	ns	20% - 80% Vdd=1.8V, 15pf load
Output Voltage High	VOH	90%	–	–	Vdd	IOH = -4 mA (Vdd = 3.3 V) IOH = -3 mA (Vdd = 2.8 V and Vdd = 2.5 V) IOH = -2 mA (Vdd = 1.8 V)
Output Voltage Low	VOL	–	–	10%	Vdd	IOL = 4 mA (Vdd = 3.3 V) IOL = 3 mA (Vdd = 2.8 V and Vdd = 2.5 V) IOL = 2 mA (Vdd = 1.8 V)
Output Load	Ld	–	–	15	pF	At maximum frequency and supply voltage. Contact SiTime for higher output load option
Input Voltage High	VIH	70%	–	–	Vdd	Pin 1, OE or $\overline{\text{ST}}$
Input Voltage Low	VIL	–	–	30%	Vdd	Pin 1, OE or $\overline{\text{ST}}$
Startup Time	T_osc	–	–	10	ms	Measured from the time Vdd reaches its rated minimum value
Resume Time	T_resume	–	3.0	4	ms	Measured from the time ST pin crosses 50% threshold
RMS Period Jitter	T_jitt	–	–	4.0	ps	f = 75 MHz, Vdd = 2.5 V, 2.8 V or 3.3 V
		–	–	6.5	ps	f = 75 MHz, Vdd = 1.8 V
RMS Phase Jitter (random)	T_phj	–	0.6	–	ps	f = 75 MHz, Integration bandwidth = 900 kHz to 7.5 MHz, VDD = 2.5 V, 2.8 V, or 3.3 V
		–	0.8	–	ps	f = 75 MHz, Integration bandwidth = 900 kHz to 7.5 MHz, VDD = 1.8 V

SiTime quartz replacement electromechanical oscillator

How do we design one?

General design:

- Find geometry that resonates at desired frequency
- Array devices so impedance (motional resistance) is low so it connects to circuits effectively (RF 50 ohm or good for sustaining amplifier)
- Drive and sense electrostatics
- Reliability: Stress relief
- Package effects

Frequency stability

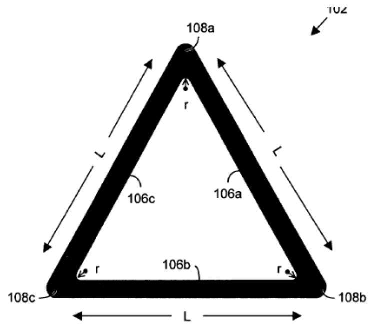
- Effect of temperature, stress, packaging(!) to make compensating circuit?

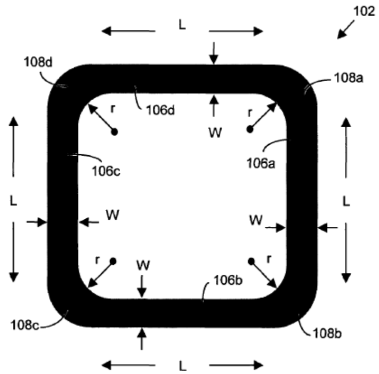
Phase noise reduction (most challenging for MEMS!):

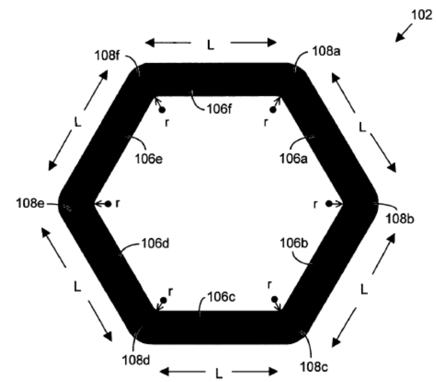
- High Q (low loss)
  - Vacuum sealed: Thermoelastic damping loss and anchor loss
- Power handling (how high a voltage can I drive it before it goes nonlinear?)

Initial design: What should the shape be?

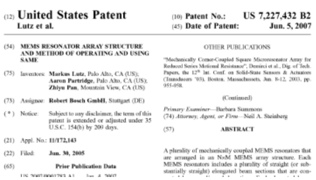
(From SiTime Patent 7227432)

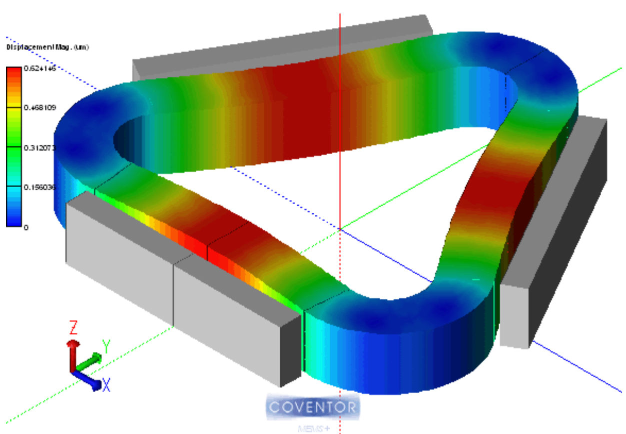




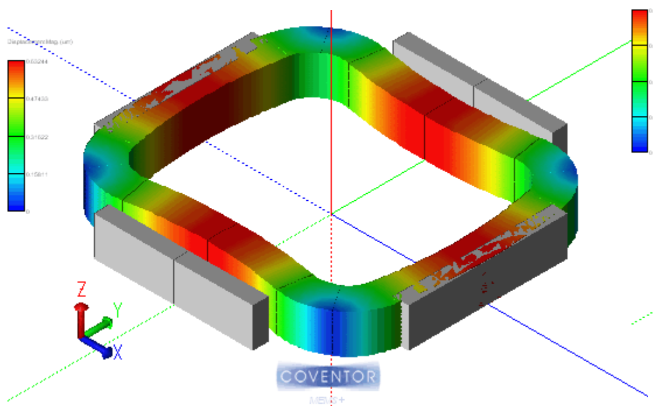


Coventor's MEMS+ for design tradeoffs, optimization, electrical-in, electrical-out, and frequency stability

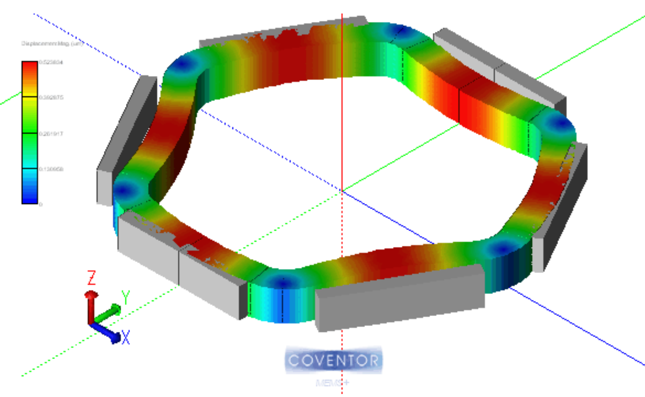

United States Patent
Lutz et al.
Patent No.: US 7,227,432 B2
Date of Patent: Jun. 5, 2007
MEMS RESONATOR ARRAY STRUCTURE AND METHOD OF OPERATING AND USING SAME
OTHER PUBLICATIONS
ABSTRACT



3.37MHz



2.40MHz



3.34MHz

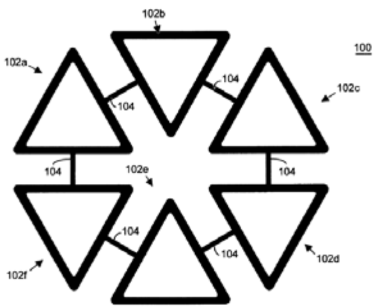
ООО "Евроинтех" 2012

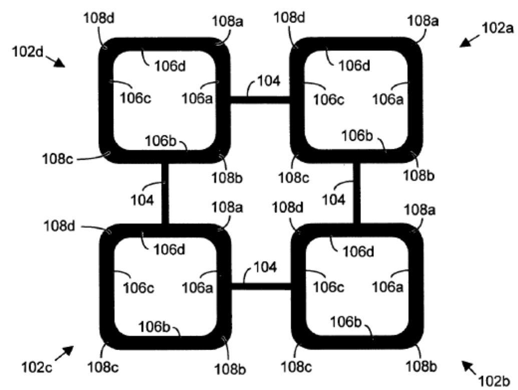
Resonator_Square.3dsch

And how will I array them?

For better power handling and lower impedance

All are possible with MEMS+





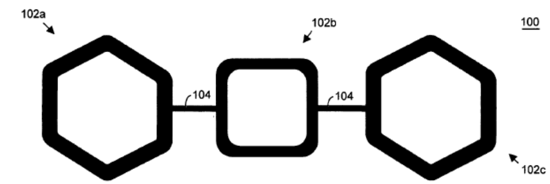
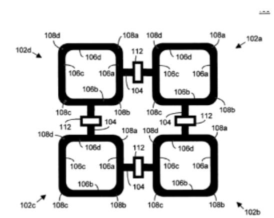
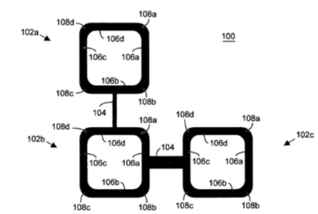
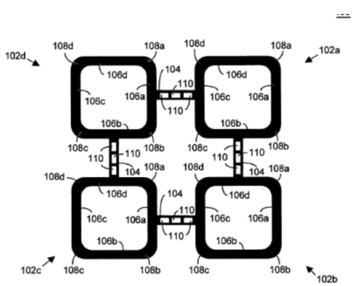
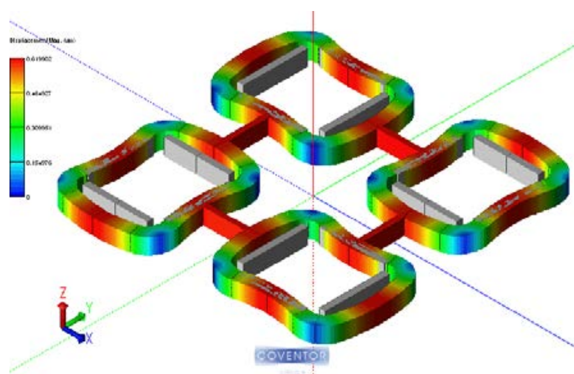


FIGURE 43D





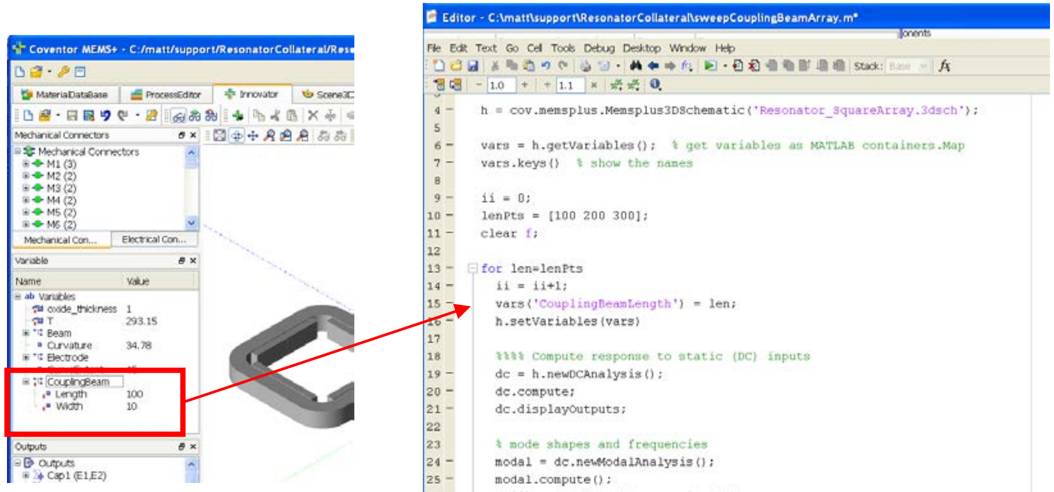




2.28MHz

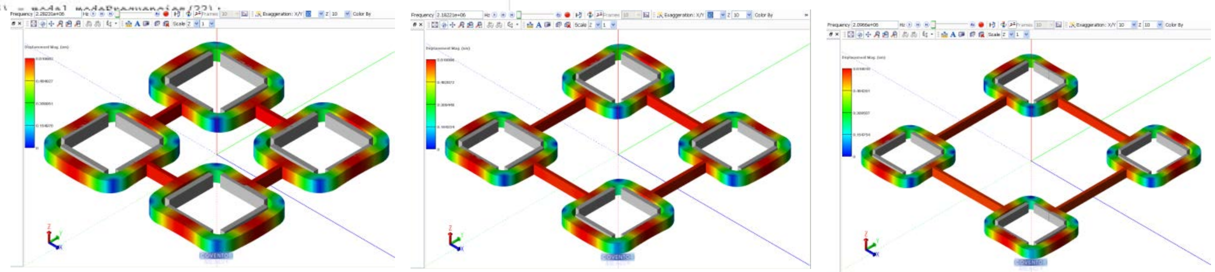
(added mass of coupling beams lowers resonance)

Coupling Beam Length impact on frequency



Use MEMS+ 2.1 with Matlab to sweep the Coupling Beam Length and compute the modal frequencies

Also view spurious mode dependency

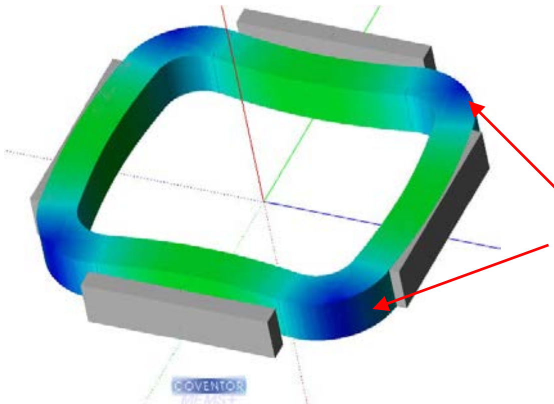


Coupling Beam Length	100 um	200 um	300 um
Frequency	2.28MHz	2.18MHz	2.10MHz

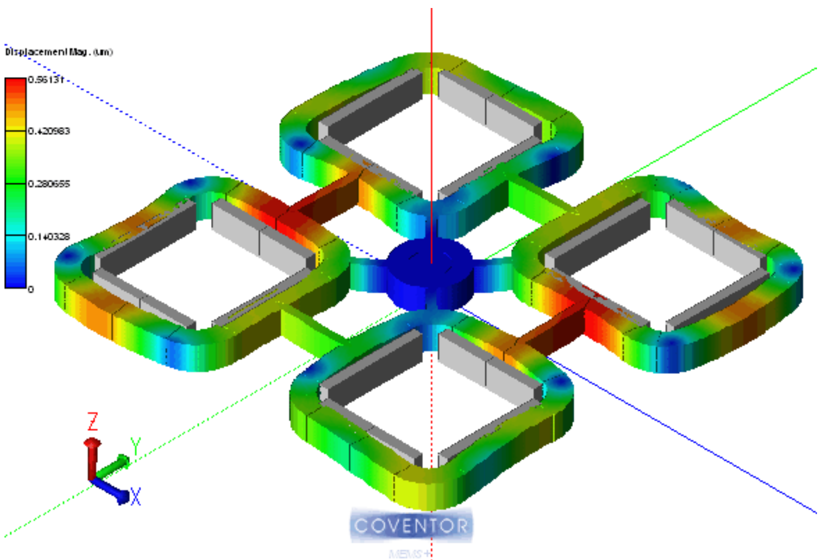
Resonator_SquareArray.sch

Added mass of coupling beams lowers resonance

Anchor Placement



Anchor where resonator doesn't move (nodal points). But it does rotate there.

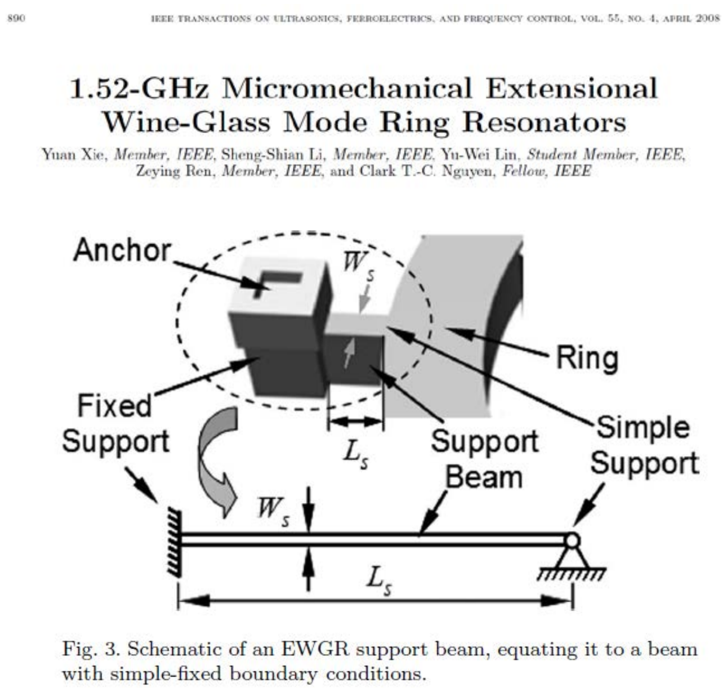


3.28MHz – much stiffer (was 2.28MHz) and the anchors interfere with the mode (squares are not moving symmetrically)

Anchor Design

A ‘zero impedance’ anchor: Choose support beam dimensions so the resonator frequency is its first mode of twist about z

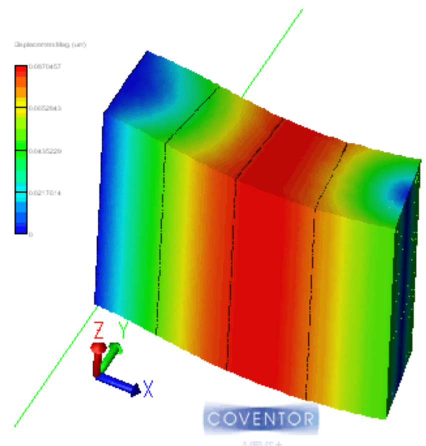
- Doesn’t interfere with desired resonator mode
- Reduces stress on anchor, and thus reduces anchor loss


890 IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 55, NO. 4, APRIL 2008

1.52-GHz Micromechanical Extensional Wine-Glass Mode Ring Resonators

Yuan Xie, *Member, IEEE*, Sheng-Shian Li, *Member, IEEE*, Yu-Wei Lin, *Student Member, IEEE*, Zeying Ren, *Member, IEEE*, and Clark T.-C. Nguyen, *Fellow, IEEE*

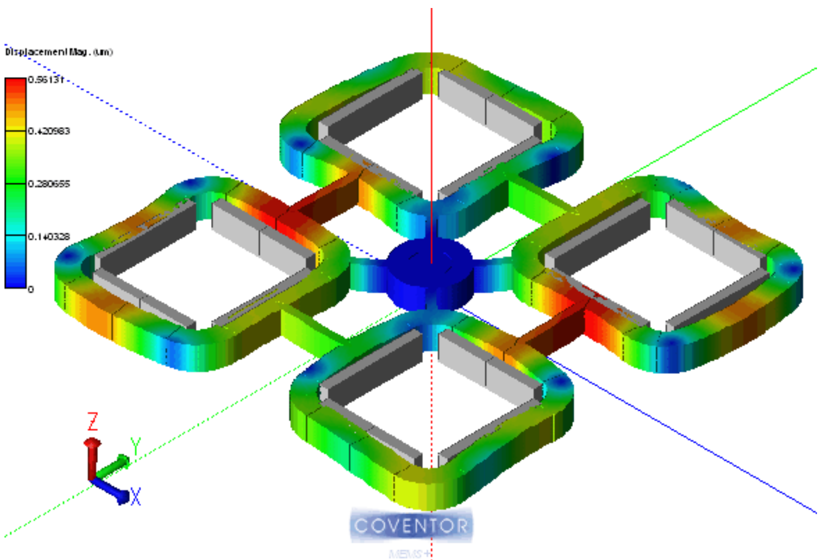
Fig. 3. Schematic of an EWGR support beam, equating it to a beam with simple-fixed boundary conditions.



51 MHz -– 25x too high for this 2MHz resonator

Optimum Support Beam

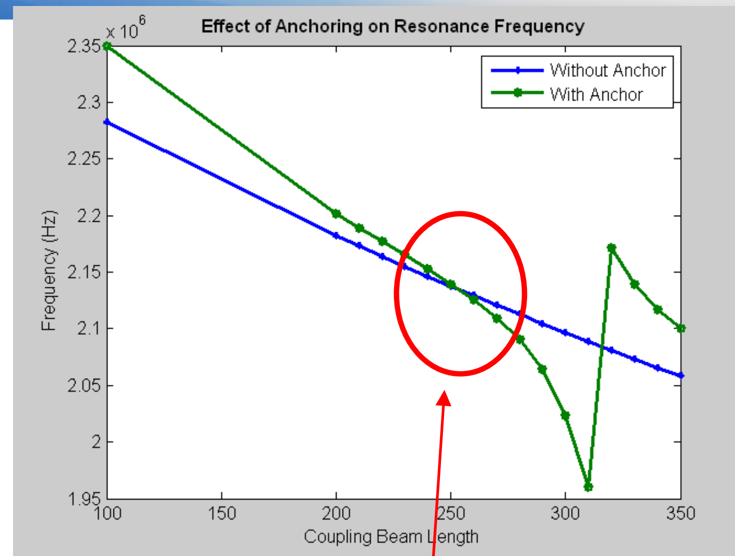
Quarter wavelength beam and resonance frequency both depend on coupling beam length. Where is optimal length to make the support beam ¼ wavelength of the array's resonance frequency?



Zero Impedance Anchor

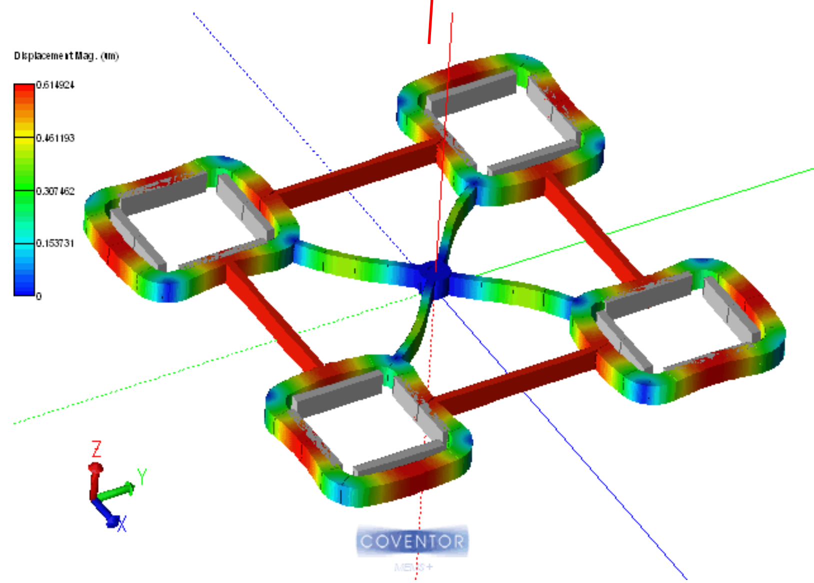
Run single MATLAB script to

- Specify mode ***shape*** of interest
- Sweep over Coupling Beam Lengths
- Automatically extract mode frequency for mode shape of interest (even if mode number changed)
- Plot



Choose 250um (or so) for minimal impact of anchor!!

compareSweeps.m



Resonator_SquareArrayFlexAnchor4.3dsch

Frequency Stability with Temperature

Thermal Expansion

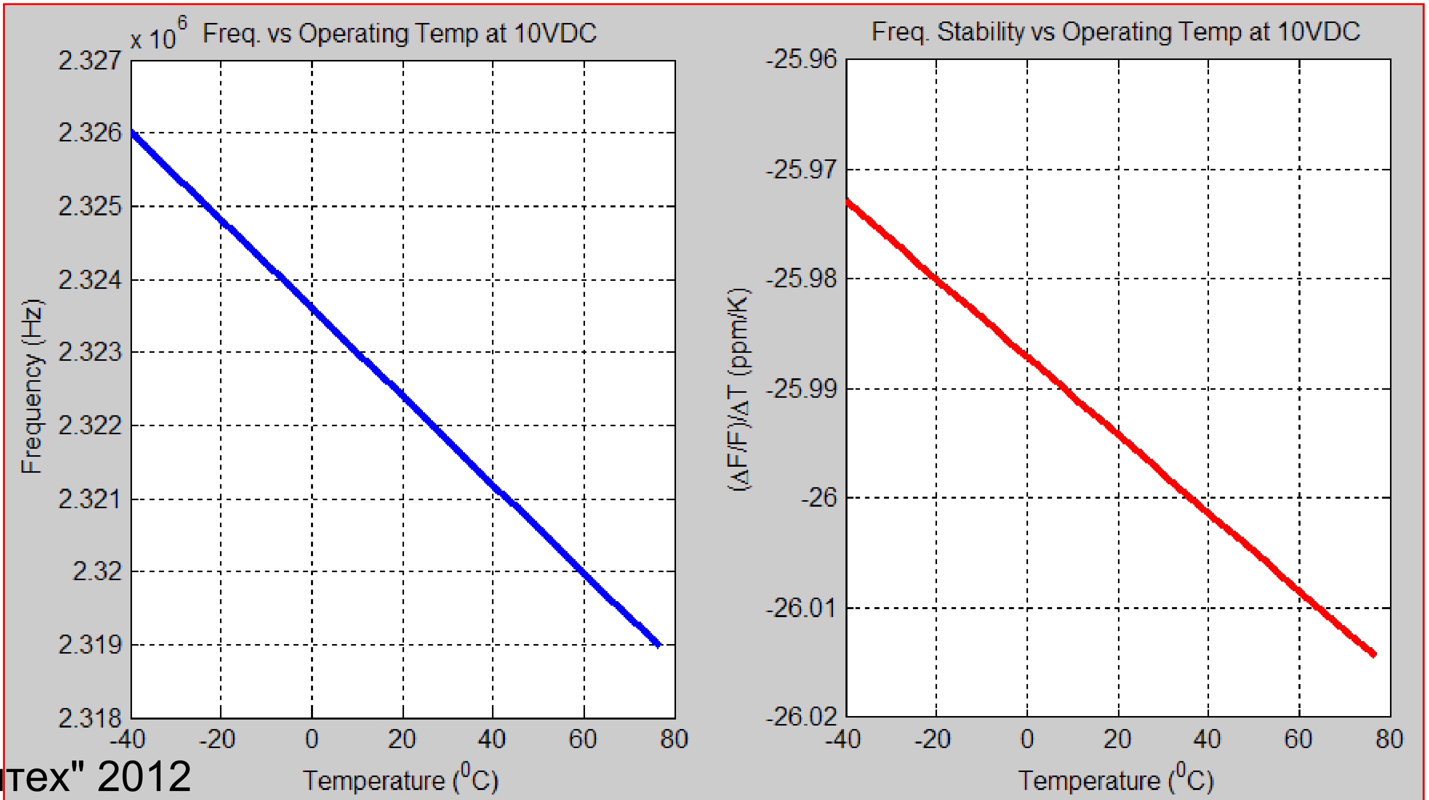
$$\alpha_{TCE} = \frac{1}{L}\frac{\partial L}{\partial T} = 2.5\times10^{-6}/K$$

Elastic Modulus temperature dependence

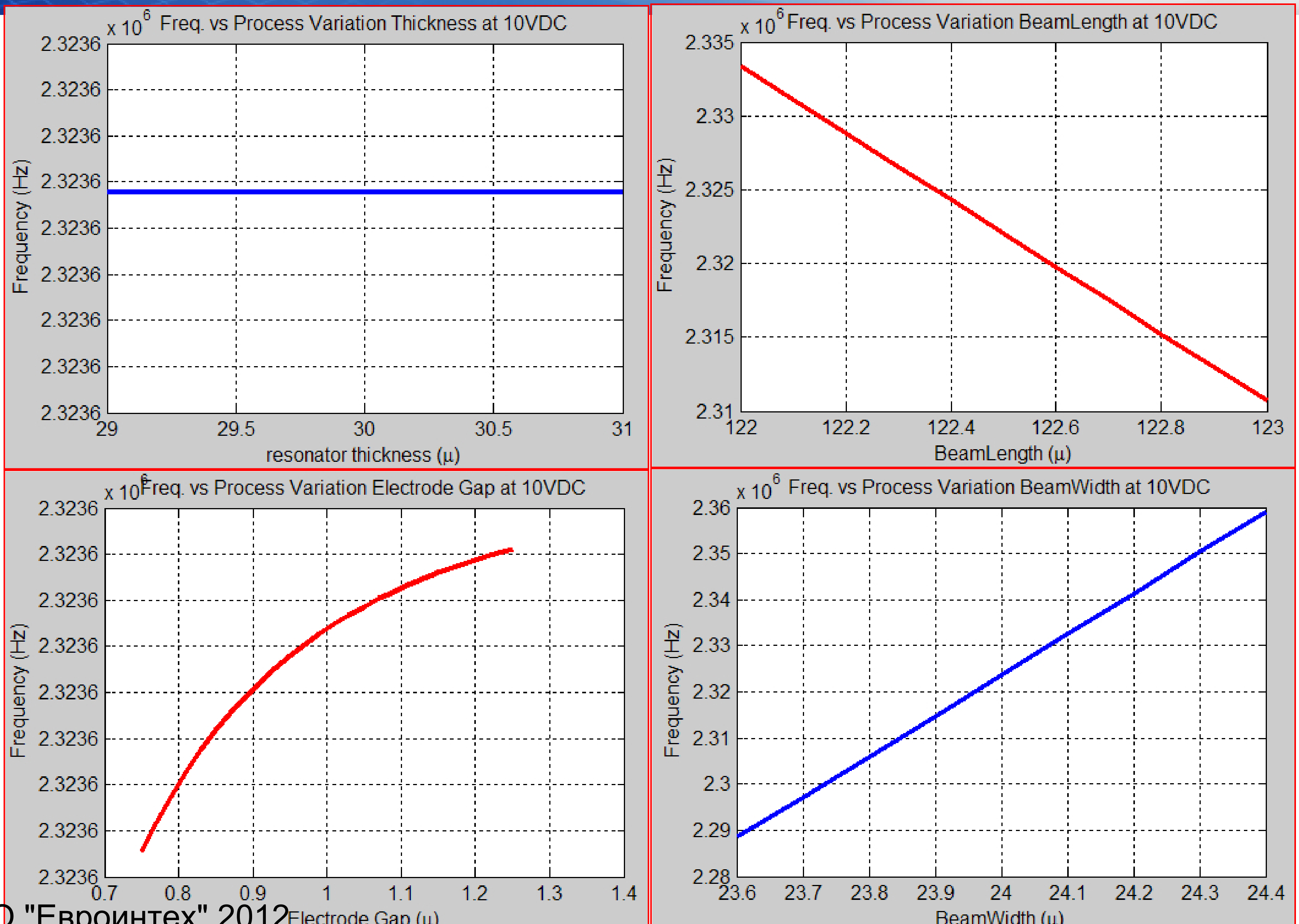
$$E = E_0(1+\alpha_{TCF}(T-T_0))$$

$$\alpha_{TCF} = \frac{1}{E}\frac{\partial E}{\partial T} = -52\times10^{-6}/K$$

Effect of both on frequency:



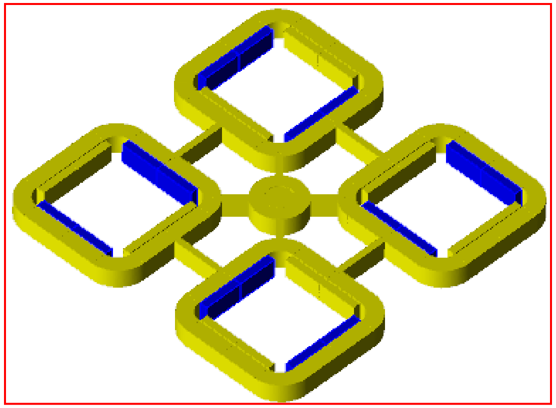
Process Variation Effects on Frequency

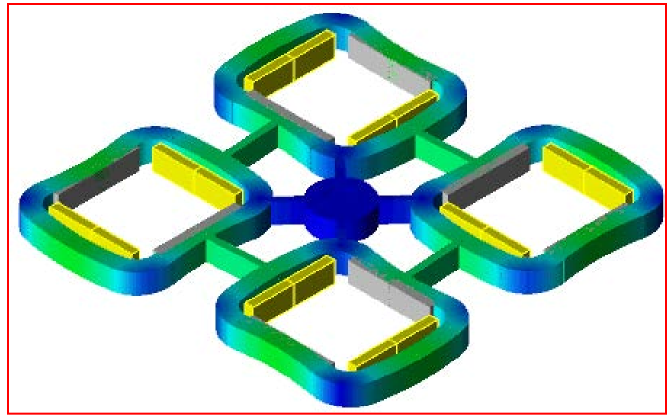


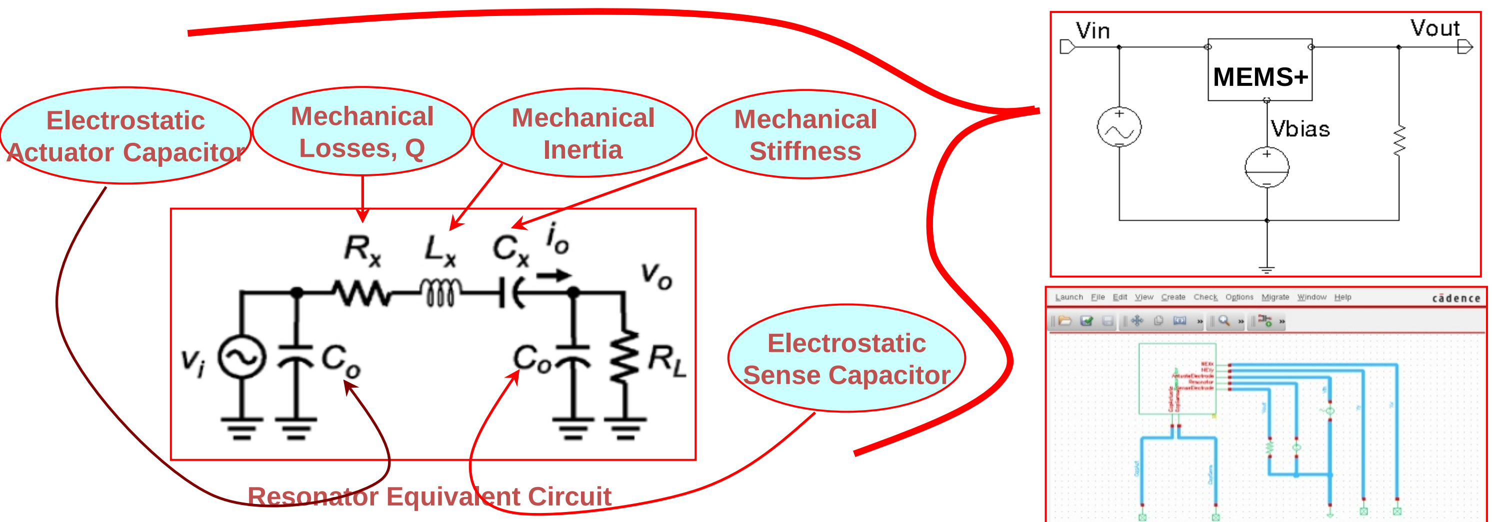
Coupled Mechanical, Electrical and IC

COVENTOR

Add electrode elements to electrically drive MEMS+ model







(simplified for illustration)

Model is immediately available in Cadence Virtuoso and Mathworks Simulink and MATLAB.

No extraction or equivalent circuits to create.

Captures multiple modes.

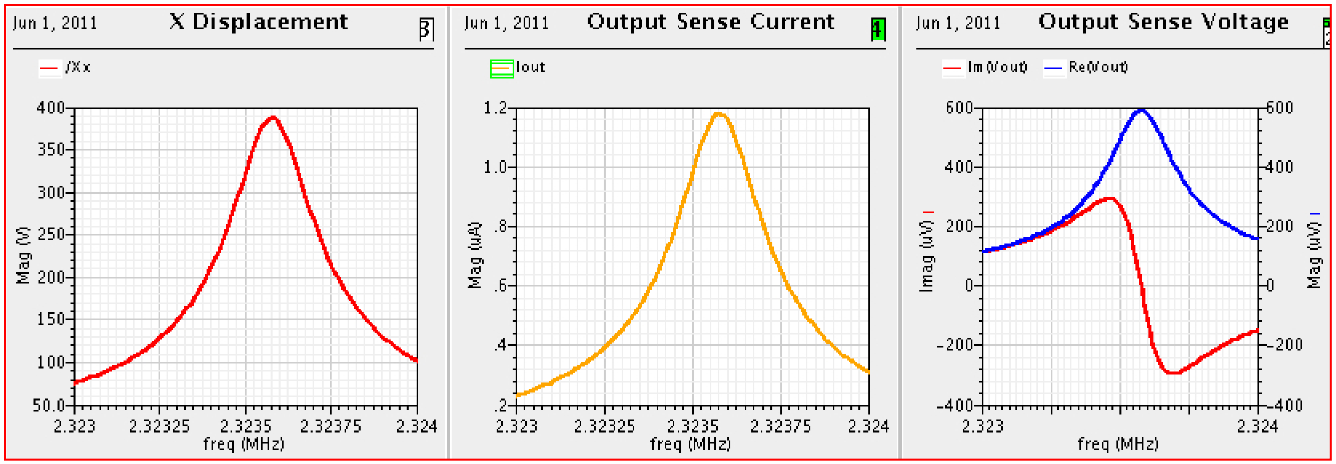
Parametric

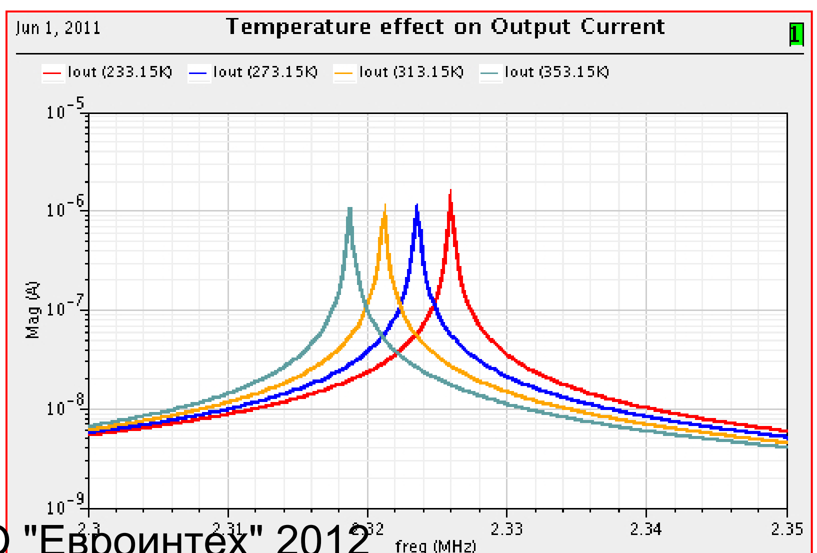
Fully nonlinear

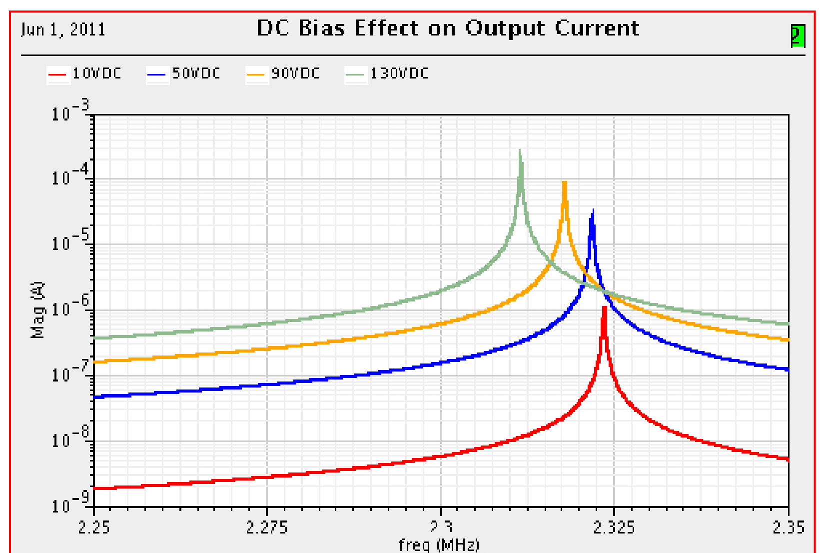
Electrostatic spring softenting

MEMS-IC Electronic Output

MEMS+ model is still fully parametric and can show output electrical response to input electrical stimulus. Below we see dependence on Temperature and DC Bias





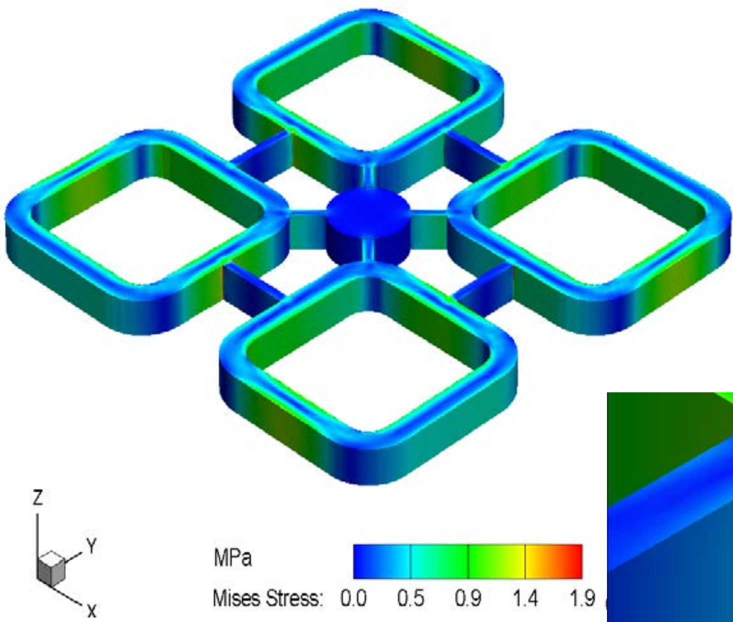


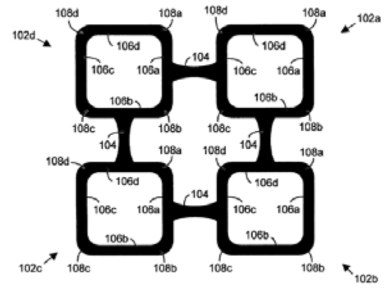
Production Design

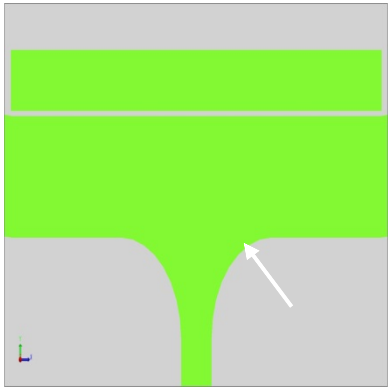
Coventor's Analyzer tool suite

- Stress Relief
- Loss mechanisms to improve Q
  - Thermoelastic Damping
  - Anchor Loss
- Package Effects

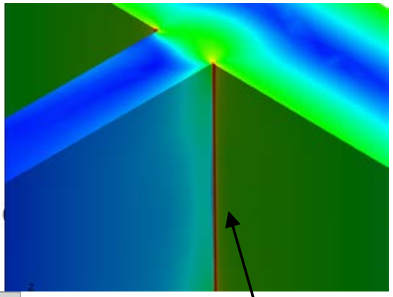
Exploring designs for Stress Relief

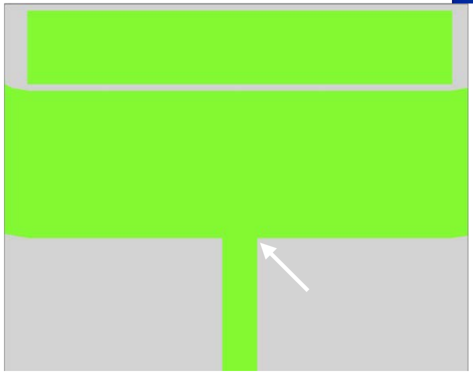




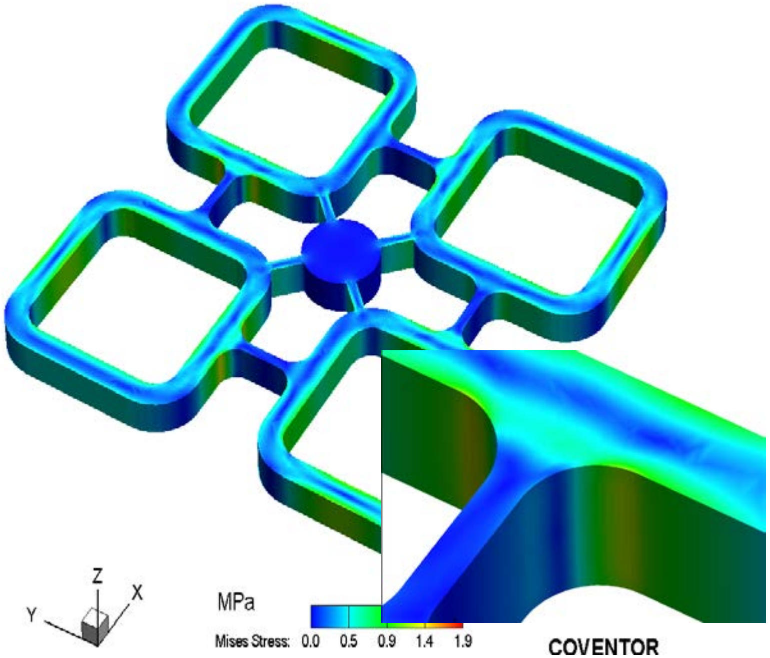


20u Fillet

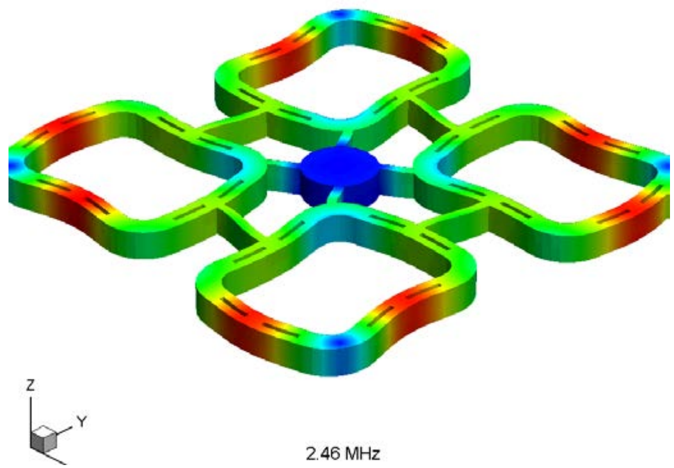


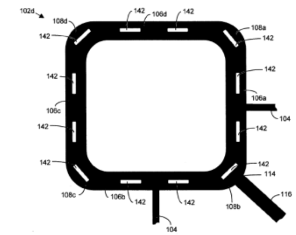


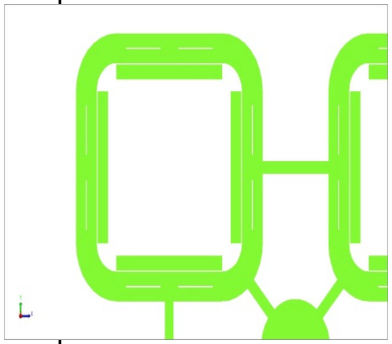
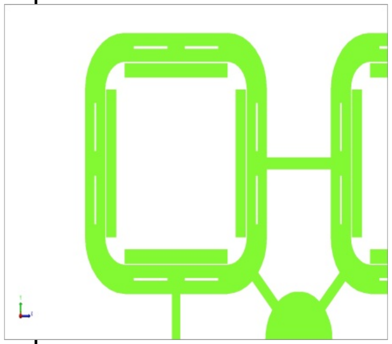
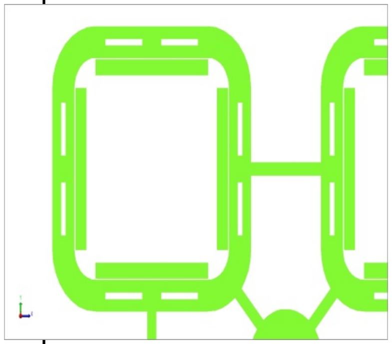
0.18u Fillet



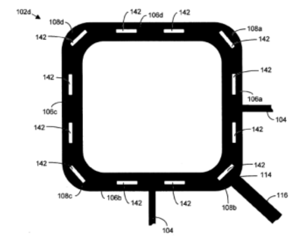
Effect of details on mechanics

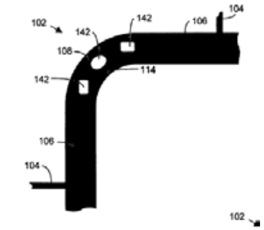


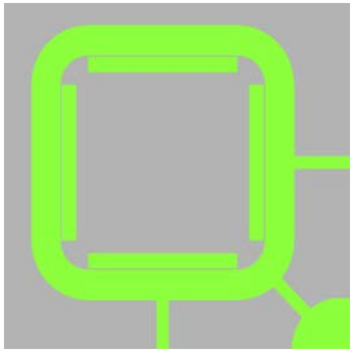
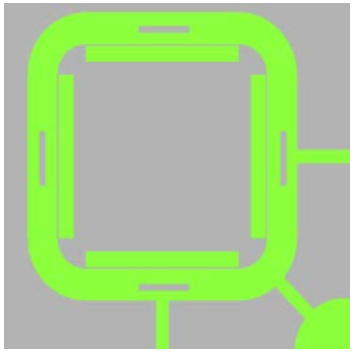
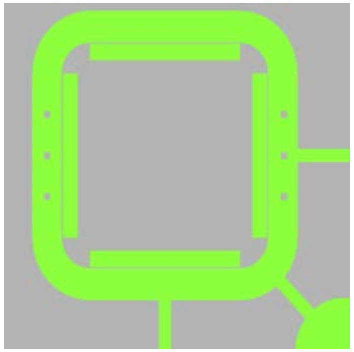


			
Perforations	1u X 40u slit	2u X 40u slit	5u X 40u slit
Frequency	2.4MHZ	2.41MHZ	2.46MHz

Exploring designs for Thermo-elastic Damping



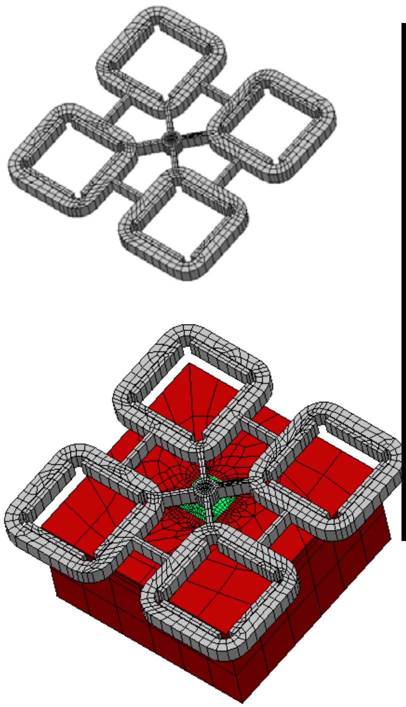


			
	No Perforations	5u X 40u@Center	3 uniformly distributed 5u Square holes
Q	26550	33083	26800
Frequency	2.41MHZ	2.48MHZ	2.42MHz

Anchoring the device

What does anchoring do to the mechanical response?

Small substrate added below resonator

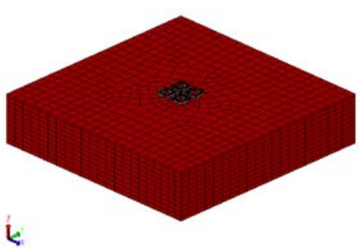


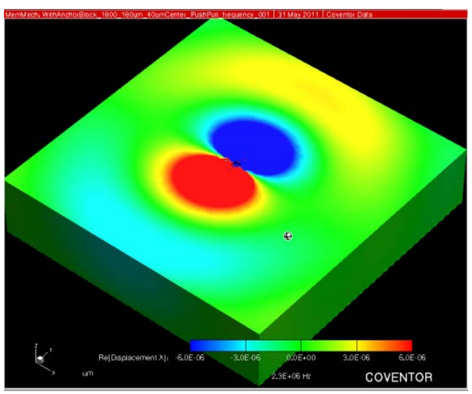
	Freq	Amplitude At 2.300MHz	Strain Energy Resonator	Strain Energy Substrate (green)	Strain Energy Substrate (red)
No Substrate	2.324MHz	0.265	9.32e5	0	0
Substrate	2.320MHz	0.308	12.9e6	63.1	0.39

Adding the substrate allows anchor to twist slightly which very slightly lowers the resonance frequency, but also allows a higher amplitude of oscillation which improves the strain energy. Note the twisting generates strain directly below the anchor (green block) and little elsewhere in the substrate

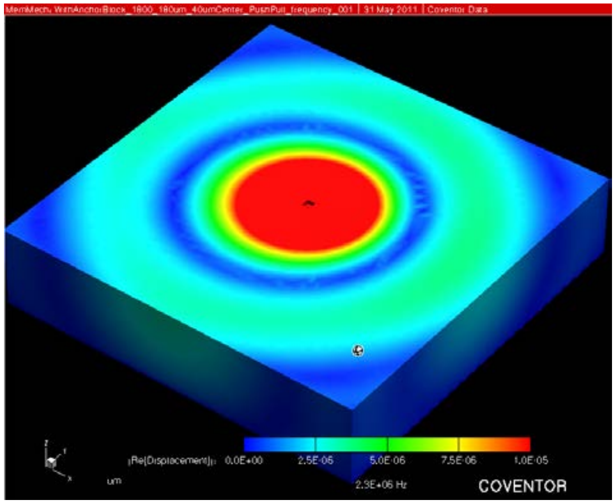
Anchor loss

The small energy present in the larger substrate is the origin of anchor loss





Shear wave
Re(displacement X)



Magnitude of displacement field in substrate showing outgoing acoustic wave

Use absorbing boundary conditions to treat substrate as infinite and compute lost energy

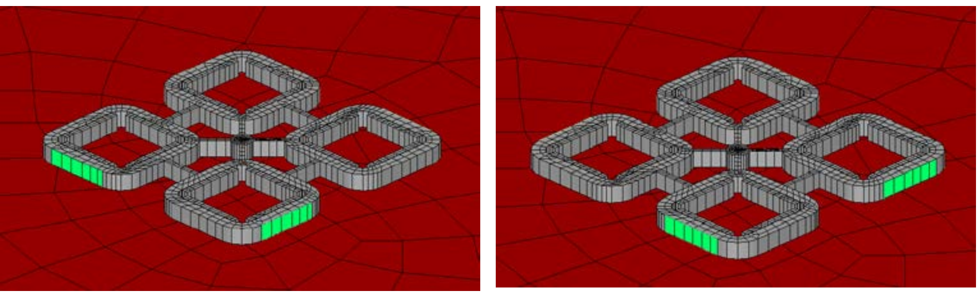
Q = 74e6 without thermoelastic damping

So thermoelastic damping of 26,000 on previous slides is the dominant damping mechanism!

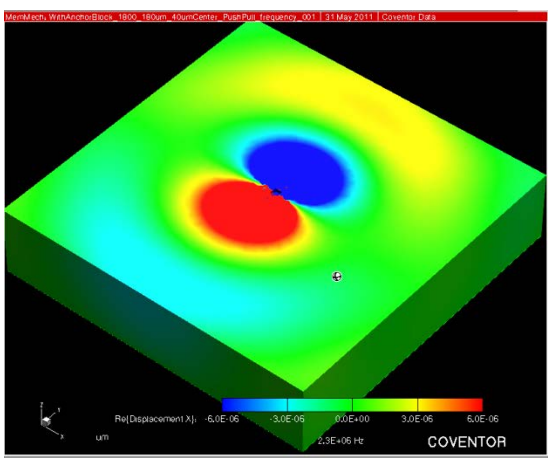
How do asymmetries affect anchor loss?

Any asymmetries from process or design won't perfectly "twist" the anchor. On the right, we drive it asymmetrically and generate both a compressive and shear wave which lowers Q

Symmetric drive

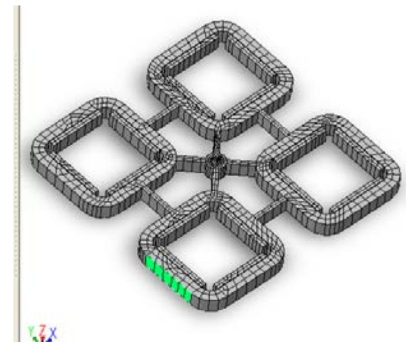


Pull and push each square

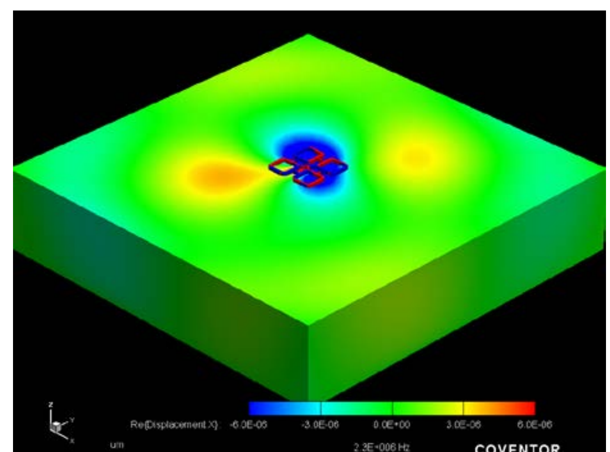


Q = 74,600,000

Asymmetric drive

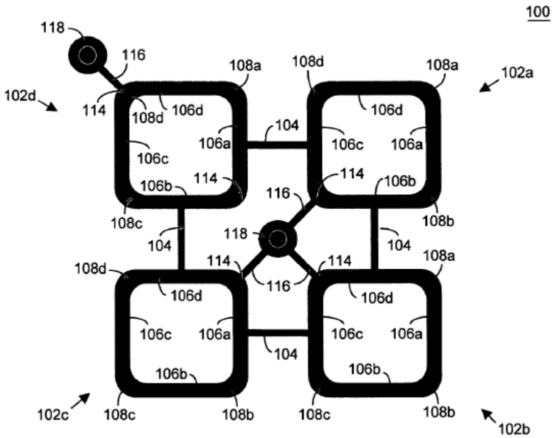


Push 1 side only



Q = 863,000

Package effects



When package warps with temperature, anchor points spread apart or come closer causing stress, which changes frequency (or offsets capacitances)

(Simulations not completed)

Conclusions

Coventor's MEMS+ and Analyzer tools work together to take resonators from initial design ideas to production.

General design:

- Find geometry that resonates at desired frequency
- Array devices so impedance (motional resistance) is low so it connects to circuits effectively (RF 50 ohm or good for sustaining amplifier)
- Drive and sense electrostatics
- Reliability: Stress relief
- Package effects (TO DO)

Frequency stability

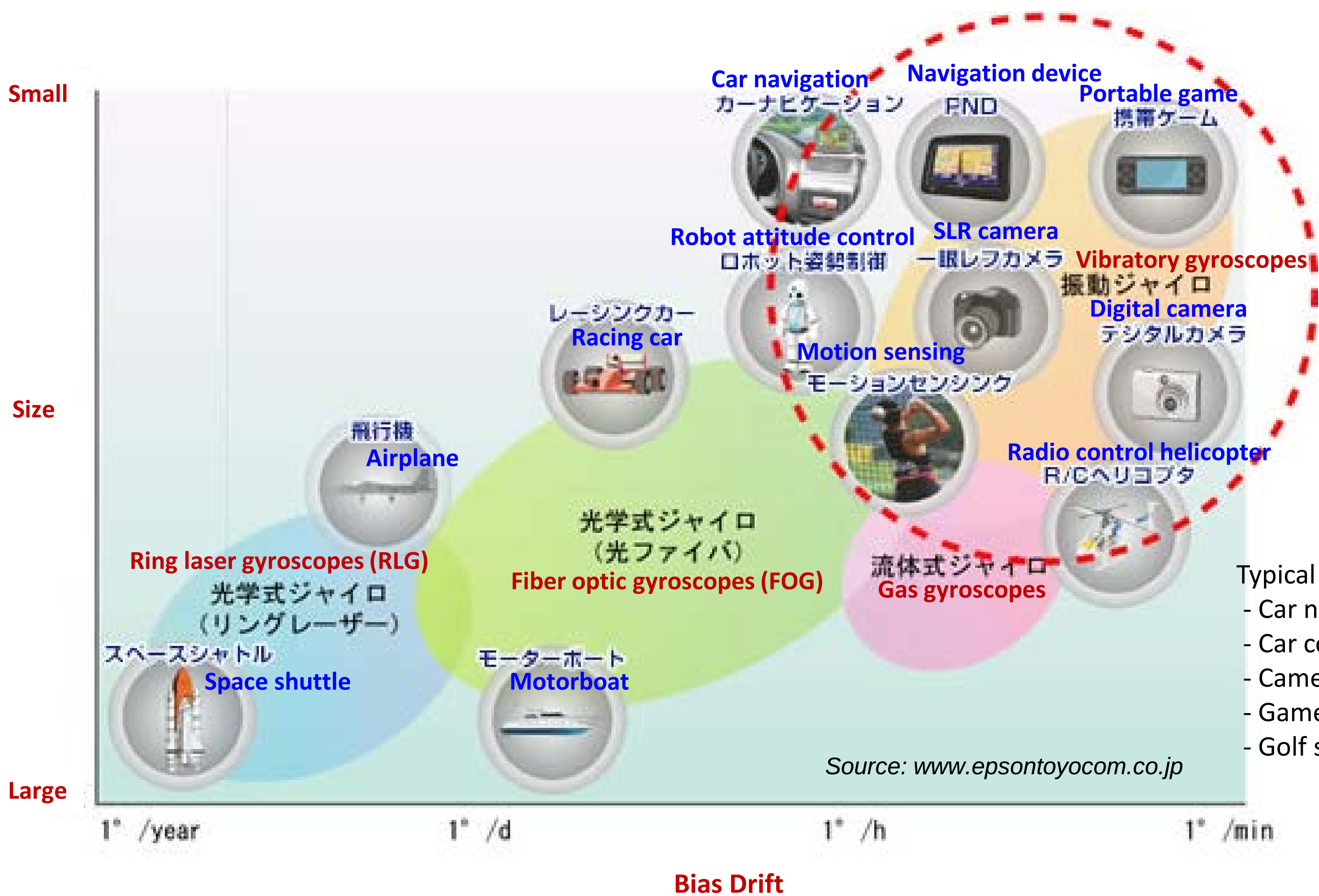
- Effect of temperature, stress, packaging(!) to make compensating circuit?

Phase noise reduction (most challenging for MEMS!):

- High Q (low loss)
  - Vacuum sealed: Thermoelastic damping loss and anchor loss
- Power handling (how high a voltage can I drive it before it goes nonlinear?) (TO DO)

Coventor Solutions for Vibratory Gyroscopes
Design and Integration

Applications of Gyroscopes



Typical angular rate for
- Car navigation system 10 °/sec
- Car control 30 °/sec
- Camera image stabilizer 100 °/sec
- Game controller 300 °/sec
- Golf swing detection 3000 °/sec

Overview

COVENTOR

Introduction

- Applications of MEMS vibratory gyroscopes
- Typical gyroscope specifications
- Coventor’s Value:
  - Design and integration challenges

An example showing use of Coventor’s tools – a single-axis gyroscope from the Univ. of British Columbia

- Frequency response and electrostatic spring softening for the matched-mode condition
- Simulation of sensitivity and cross-axis sensitivity
- Damping estimation

Conclusions

Spec sheet for commercial InvenSense IDG-650

Gyroscope specs that can be simulated with Coventor tools

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
SENSITIVITY						
Full-Scale Range	At X-OUT and Y-OUT			±2000		°/s
	At X4.5OUT and Y4.5OUT			±440		°/s
Sensitivity	At X-OUT and Y-OUT			0.5		mV/°/s
	At X4.5OUT and Y4.5OUT			2.27		mV/°/s
Initial Calibration Tolerance	At X-OUT and Y-OUT			±6		%
Calibration Drift Over Specified Temperature	At X-OUT and Y-OUT			±10		%
Nonlinearity	At X-OUT and Y-OUT, Best Fit Straight Line			<1		% of FS
Cross-axis Sensitivity				±1		%
ZERO-RATE OUTPUT (ZRO)						
Static Output (Bias)	Factory Set			1.35		V
Initial Calibration Tolerance	Relative to VREF	With Auto Zero		±20		mV
		Without Auto Zero		±150		mV
ZRO Drift Over Specified Temperature						
Power Supply Sensitivity	@ 50 Hz			10		°/sec/V
FREQUENCY RESPONSE						
High Frequency Cutoff	Internal LPF -90°			140		Hz
LPF Phase Delay	10Hz			-4.5		°
MECHANICAL FREQUENCIES						
X-Axis Resonant Frequency			20	24	28	kHz
Y-Axis Resonant Frequency			23	27	31	kHz
Frequency Separation	X and Y Gyroscopes			3		kHz
NOISE PERFORMANCE						
Total RMS Noise	Bandwidth 1Hz to 1kHz, At X-OUT and Y-OUT			0.3		mV rms
POWER ON-TIME						
Zero-rate Output	Settling to ±3°/s			50	200	ms

Highlighted parameters are shown in the following slides

Spec sheet for ADI ADXRS620

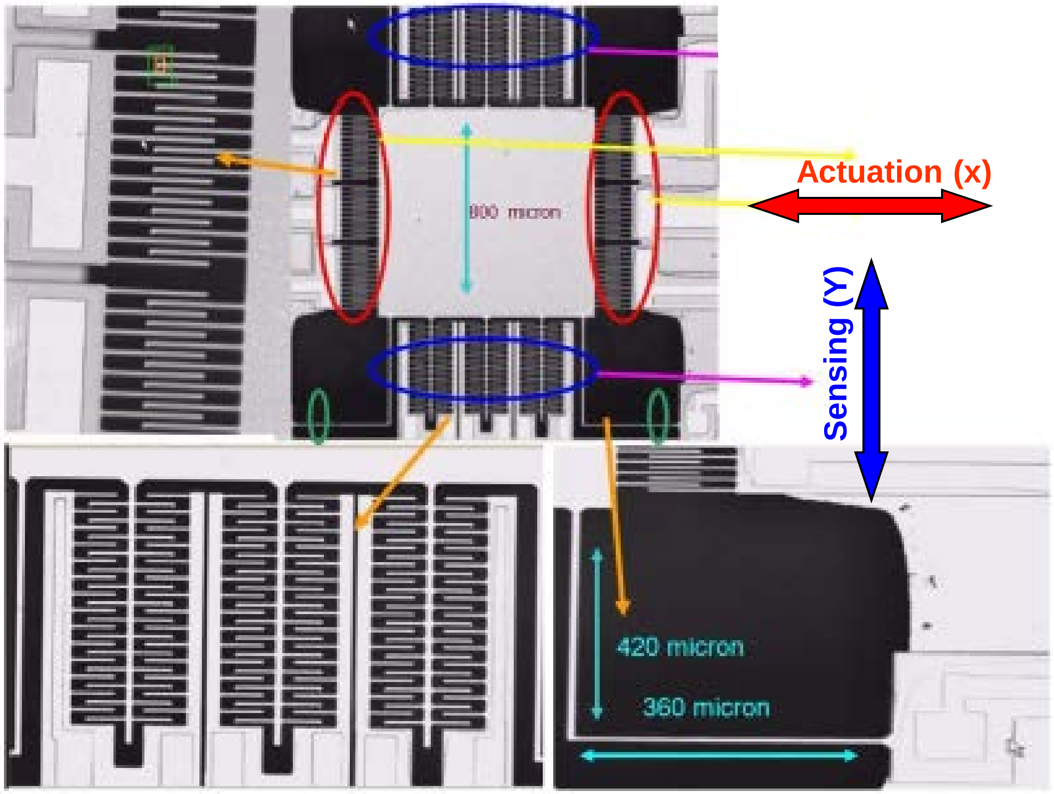
NULL[1]					
Null	−40°C to +105°C	2.2	2.5	2.8	V
Linear Acceleration Effect	Any axis		0.1		°/sec/g

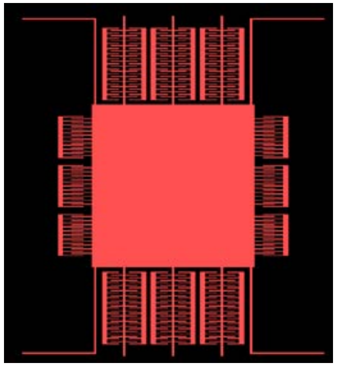
An Example:
A single-axis Gyroscope

Single proof mass gyroscope fabricated in SOIMUMPs technology

- Thickness: 25 μm, Minimum Gap size: 2 μm

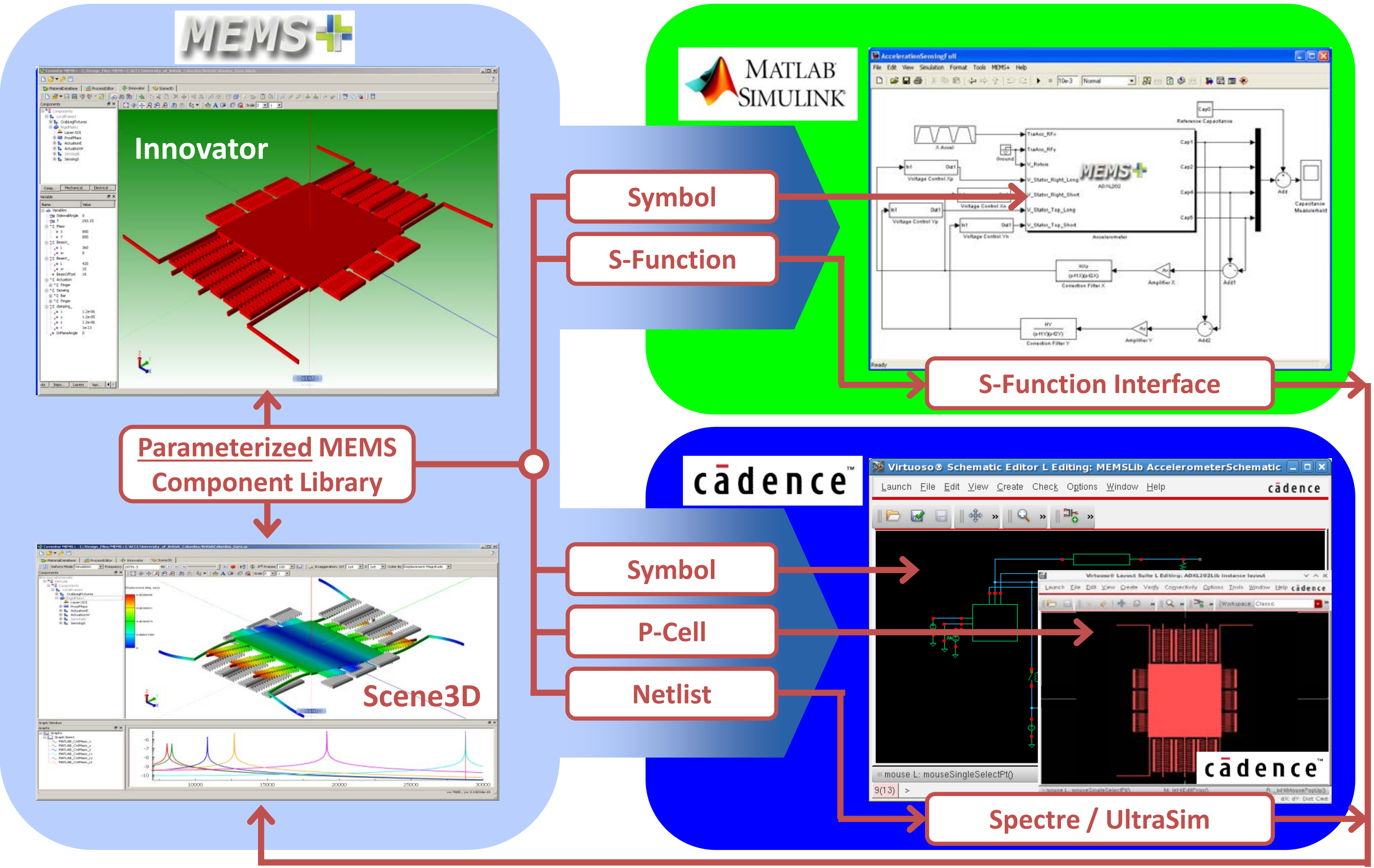
Measure Angular Rare around Z axis



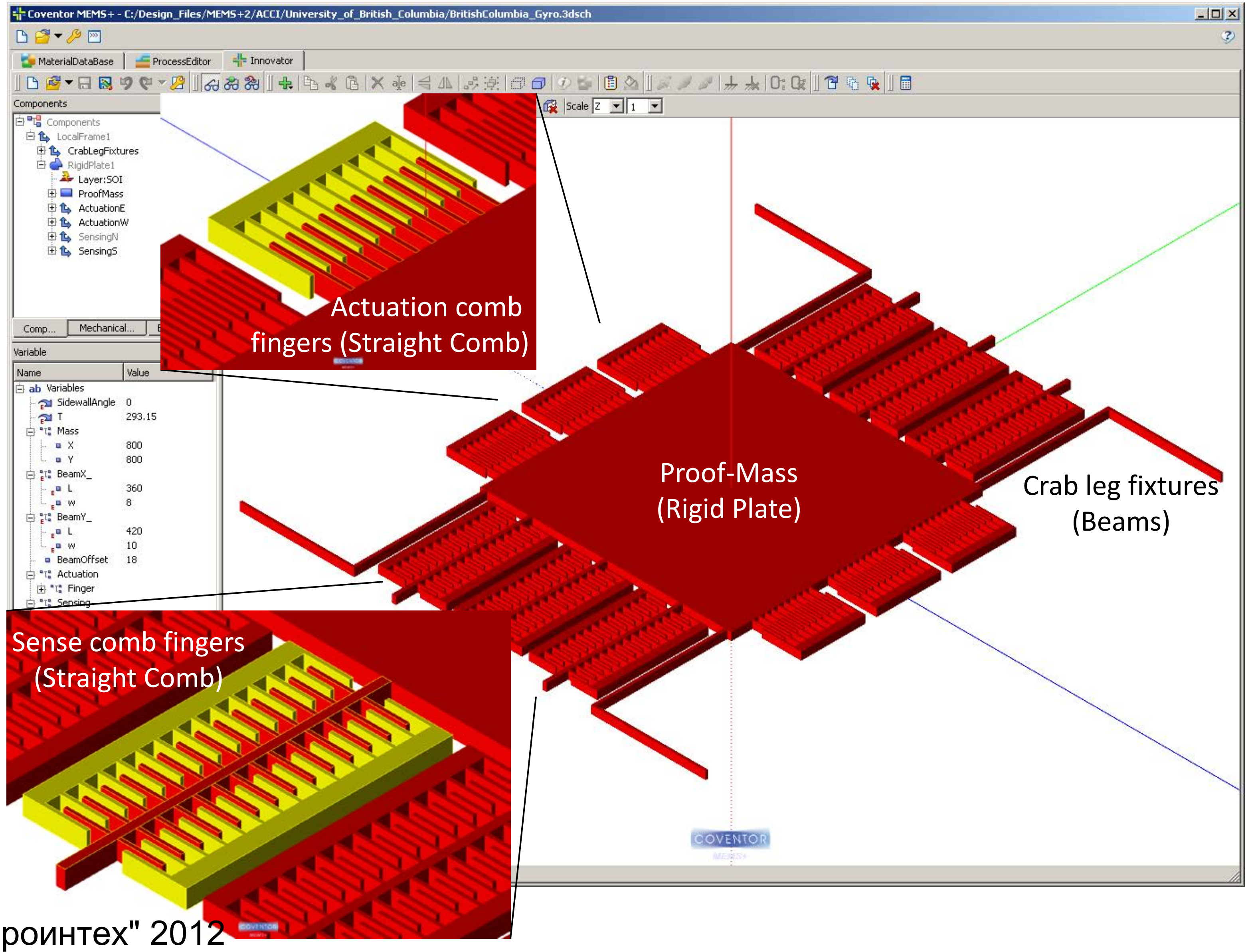


Reference: M.Sharma, E.H.Sarraf, E.Cretu (The Univ. of British Columbia), “Parametric Amplification/Damping in MEMS Gyroscopes”, MEMS 2011

Coventor MEMS+ for Matlab and Cadence



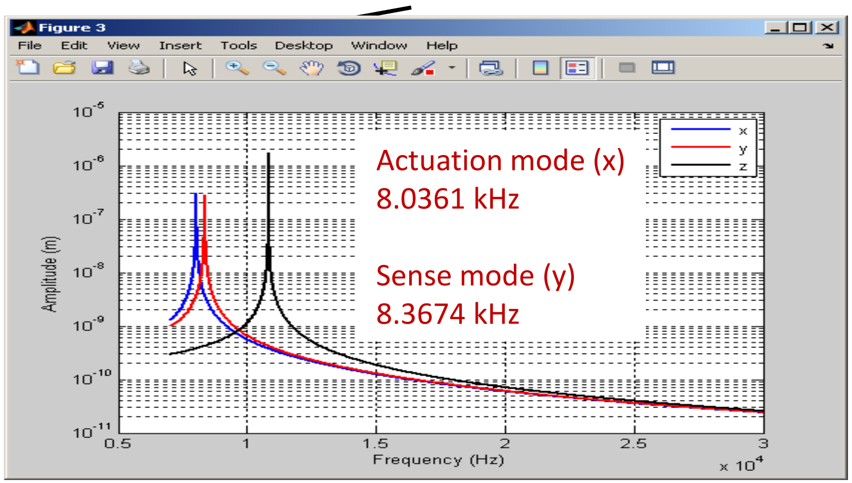
Electro-Mechanical Modeling in MEMS+

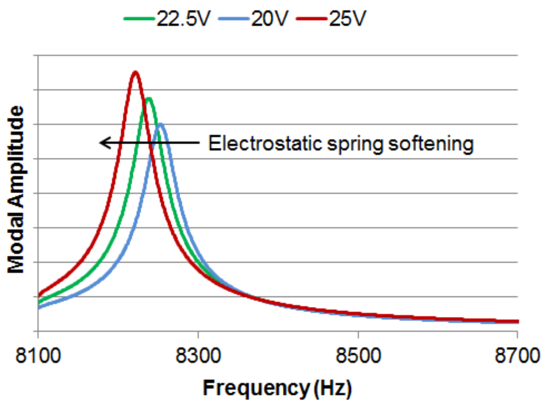


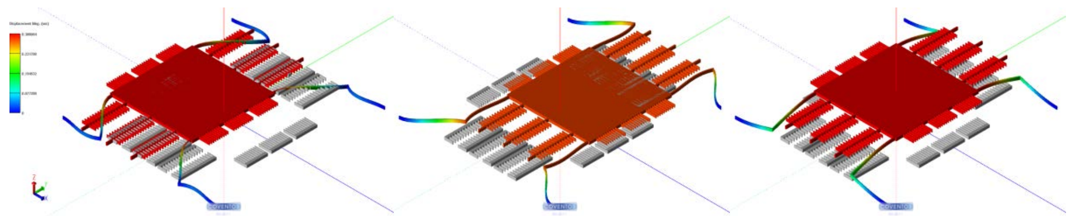
Mechanical Frequencies

Initial Design – Drive/Sense modes have a frequency split

- Drive and sense mode frequencies can be compensated by adjusting the DC bias voltage on the sensing or actuation comb drives







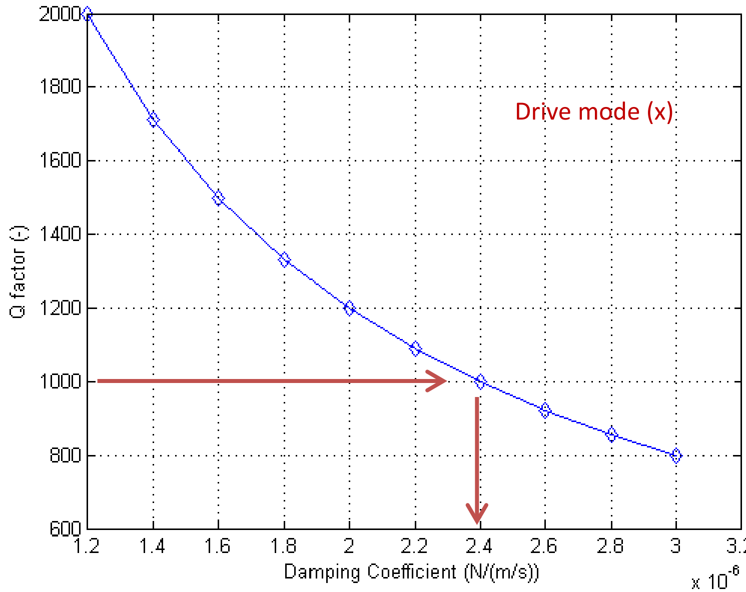
Drive mode (x)   Sense mode (y)   Z mode

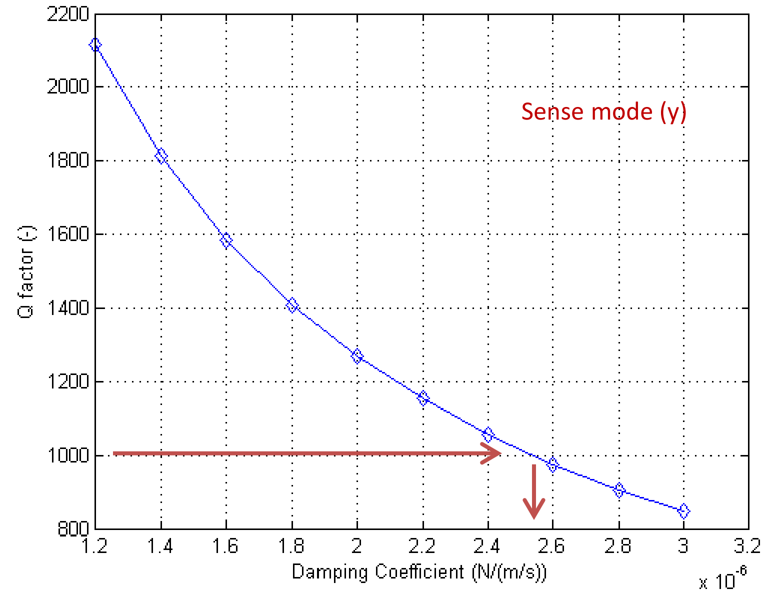
Deformed shapes are exaggerated accordingly

Parametric Study
Q factor vs. Damping Coefficient

Simulated in MATLAB

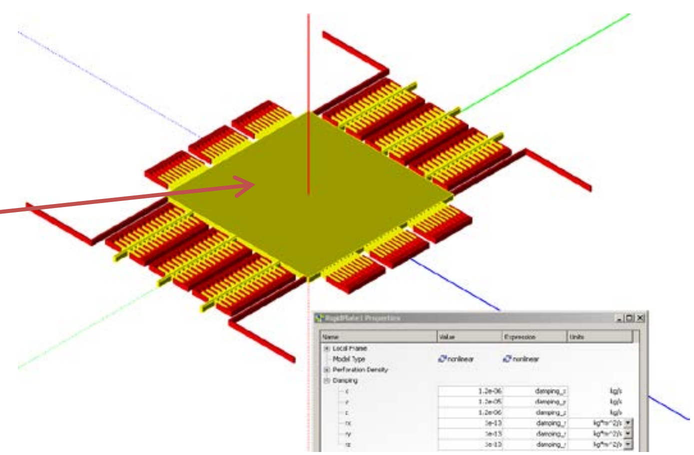
Vary Damping Coefficients to meet given Q factor (1000)





Q factors are measured as a ratio of AC to DC amplitudes

Damping Coefficients in actuation and sensing are estimated and assigned to rigid plate (Highlighted in yellow)



Parametric Study for mode-matched condition

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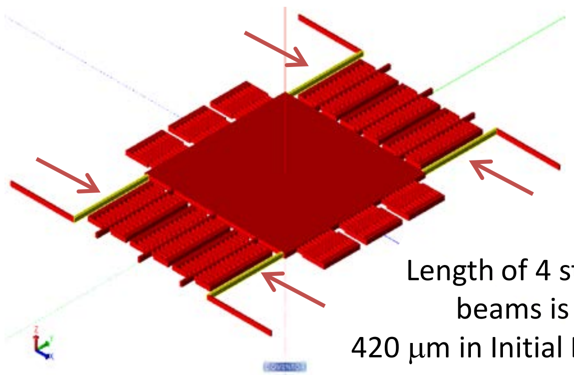
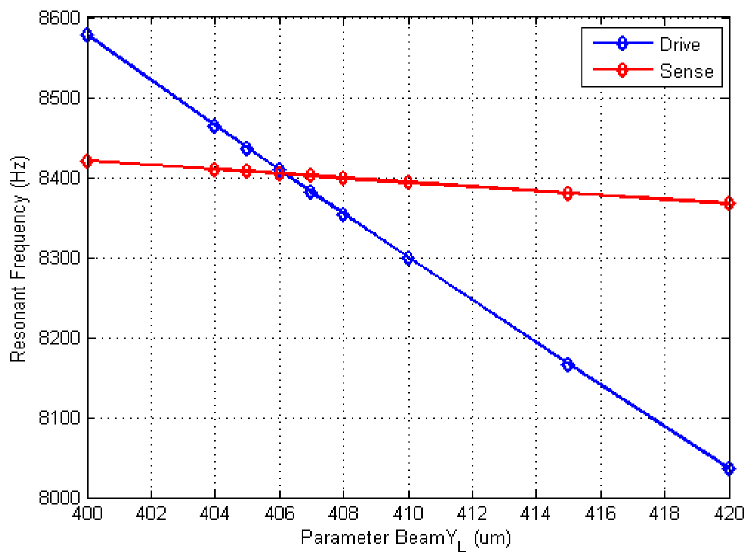
Vary a design parameter, Beam Length in Y, to measure resonant frequency change

Mechanical stimuli are applied

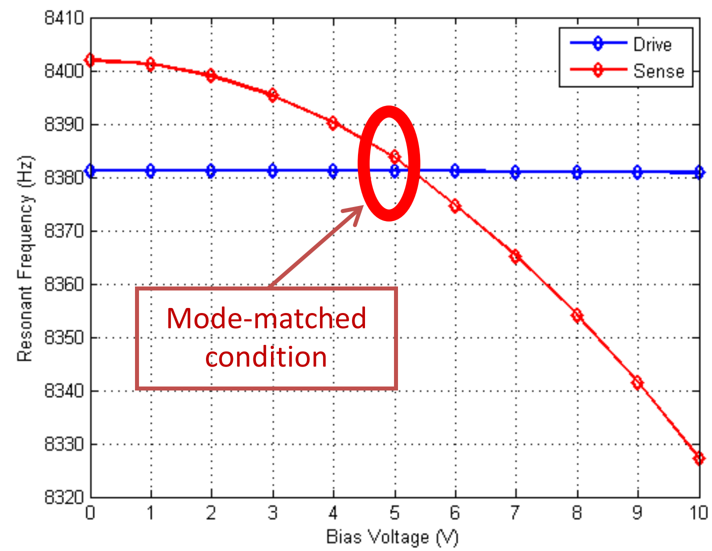


Length of 4 straight beams is varied
420 μm in Initial Design



Resonant Frequency change in Drive/Sense-Dir with Beam Length

Next, set the Beam Length = 407 μm, and vary Bias Voltage, measure resonant frequency shift



Resonant Frequency change in Drive/Sense-Dir with Bias Voltage

Sensitivity and Cross-Axis Sensitivity for Capacitive Sensing

Simulated in MATLAB

Vary sidewall angle in the process, measure Differential sense Capacitance

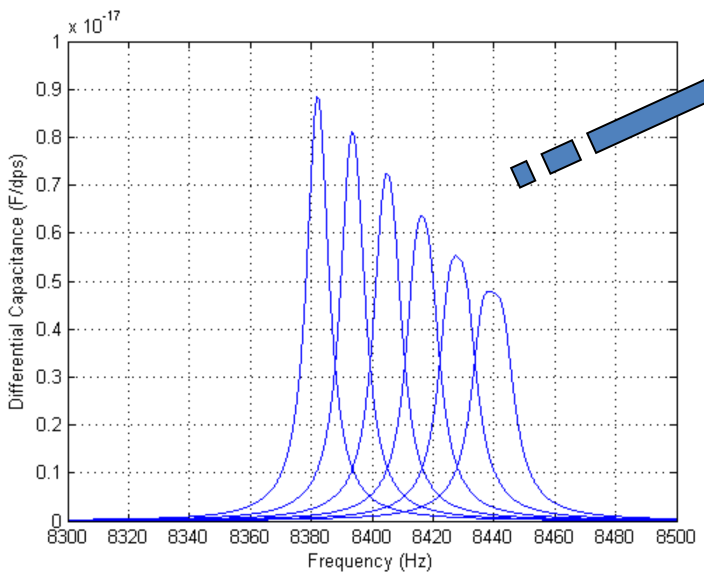
Matched Mode
- Beam Length = 407 μm,
- Damping Coefficients, X-dir 2.4e-6, Y-dir 2.55e-6 (N/(m/s))

Key simulation parameters

DC 5V to proof-mass

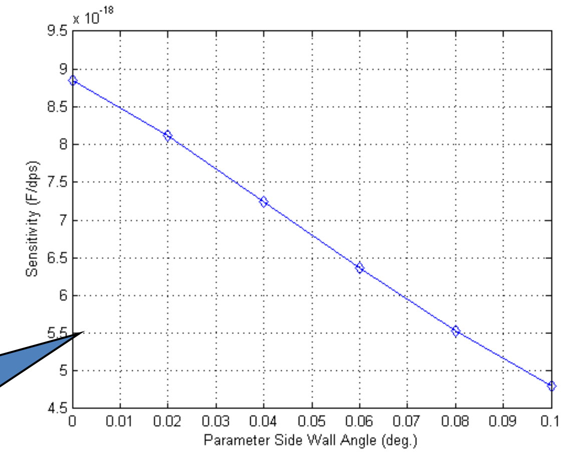
AC ±2V to actuation comb drives

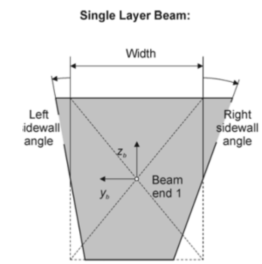
Apply angular rate 1 °/sec in Z-dir



Simulated Differential Capacitance

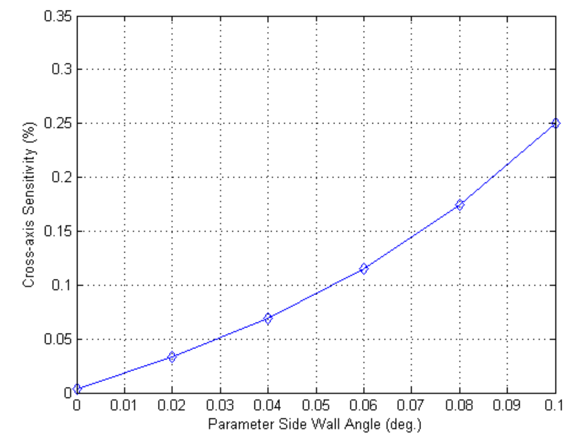
Apply angular rate 1 °/sec in Z-dir





Sensitivity vs. Sidewall Angle

Next, Apply angular rate 1 °/sec in X-dir



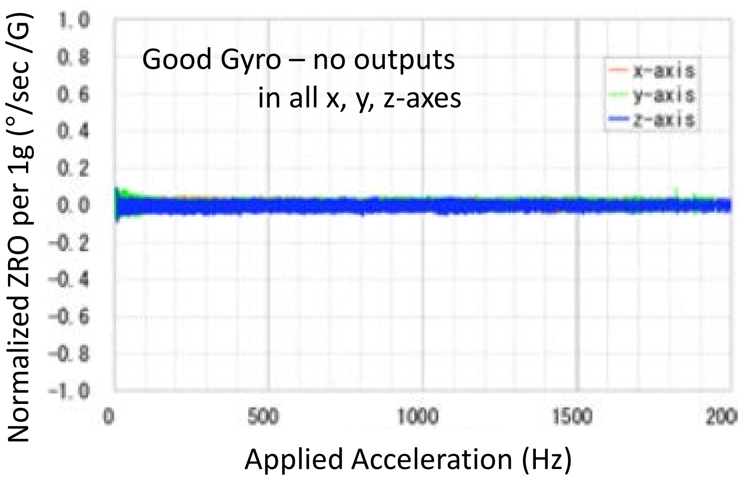
Cross-Axis Sensitivity vs. Sidewall Angle

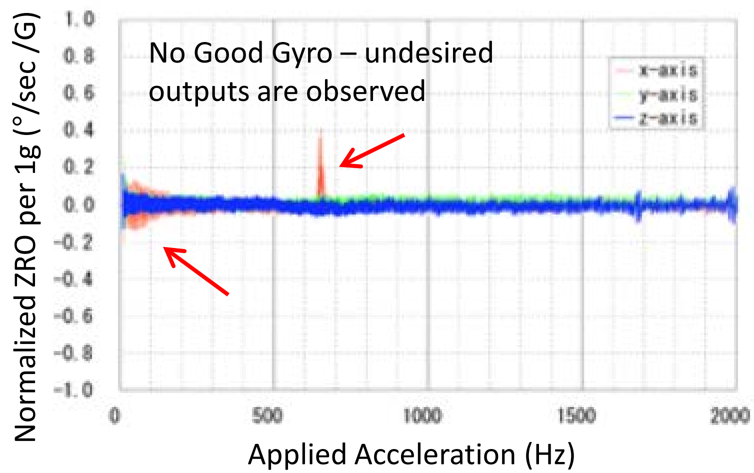
Other effects such as **misalignment** (In-Plane rotation Angle) or **anisotropic elasticity** can be included

Linear Acceleration Effect

Simulated in MATLAB
Transient Analysis

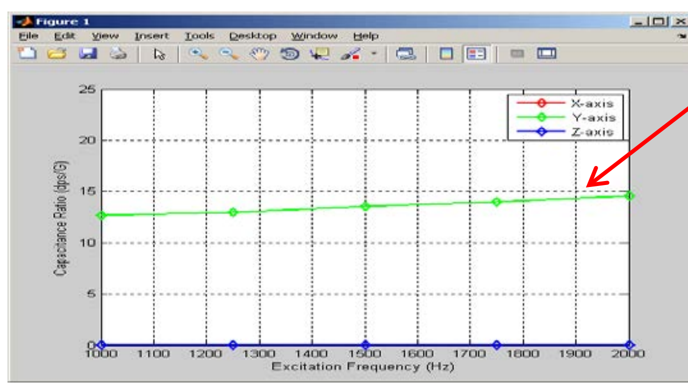
Measure linear acceleration stability, Reject external vibrations
Sample experimental data below from a source





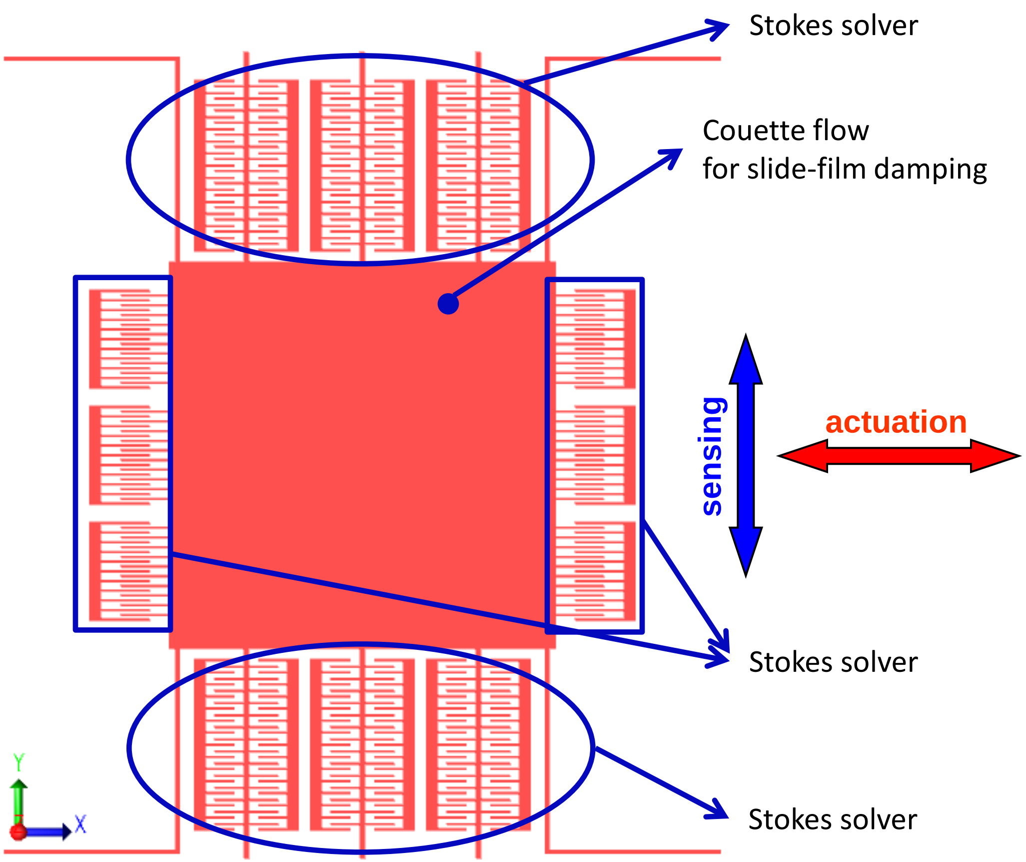
Source: www.epsontoyocom.co.jp

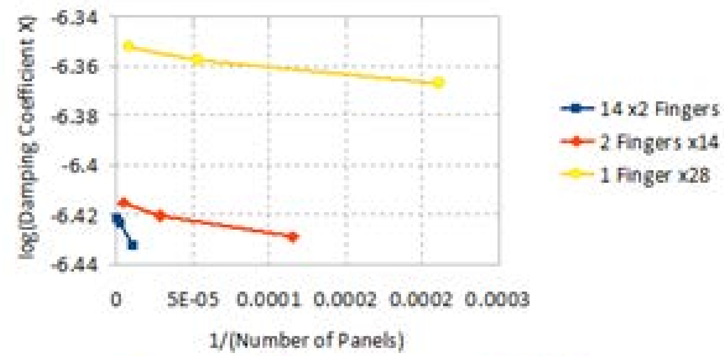
Apply sinusoidal acceleration (1g) to see acceleration stability over frequency

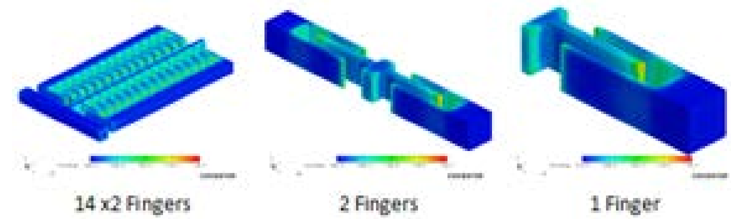


Capacitance change is observed in y-axis stimulus
Gyroscope register an incorrect reading when subjected to a linear acceleration in the same direction as Coriolis force to be sensed.

Gas Damping Analysis - System Decomposition







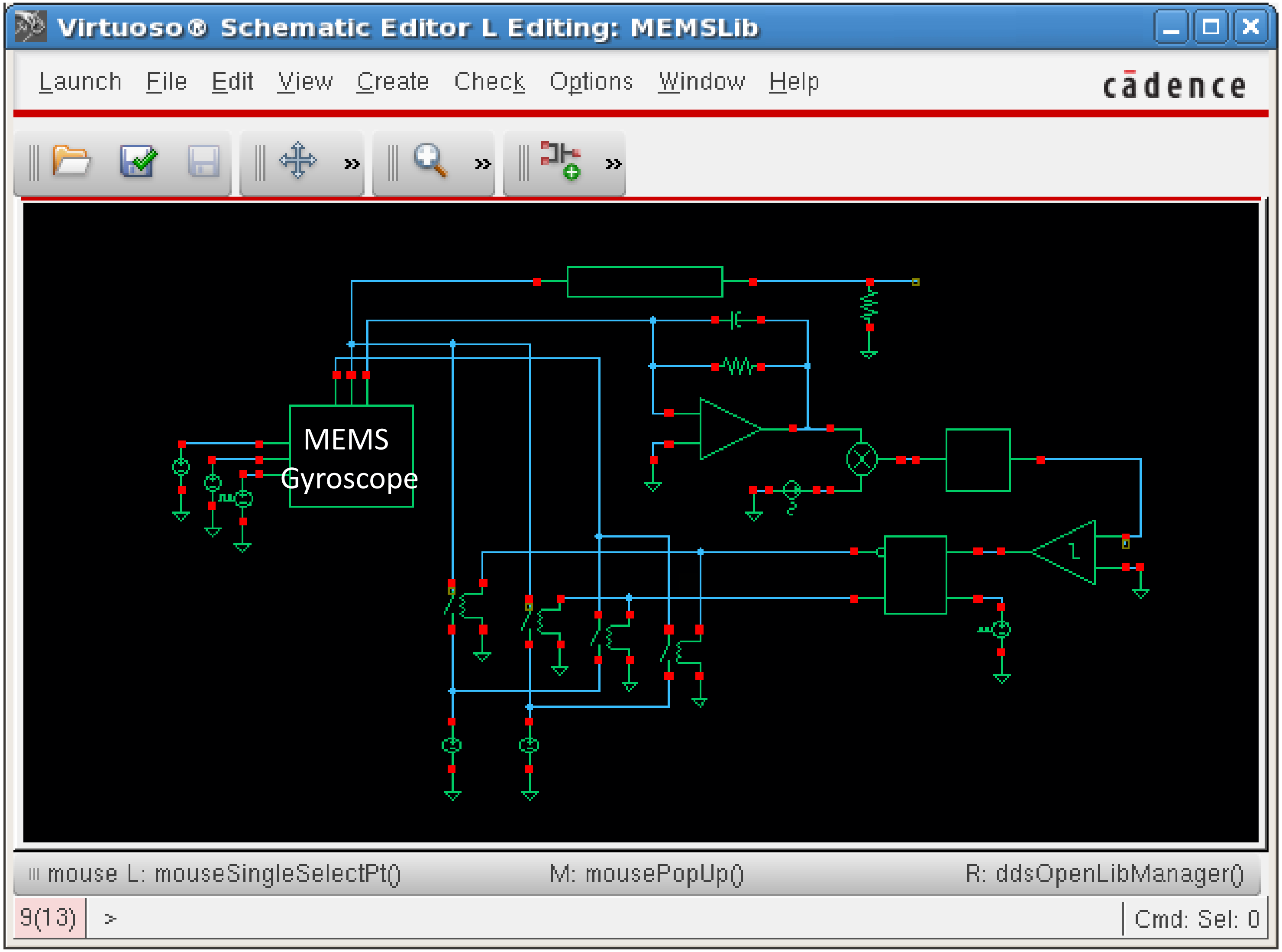
Simulated Results

	Proof Mass	Actuation Combs	Sensing Combs
Damping Coefficient (N/(m/s))	1.050e-5	2.485e-6	3.312e-5

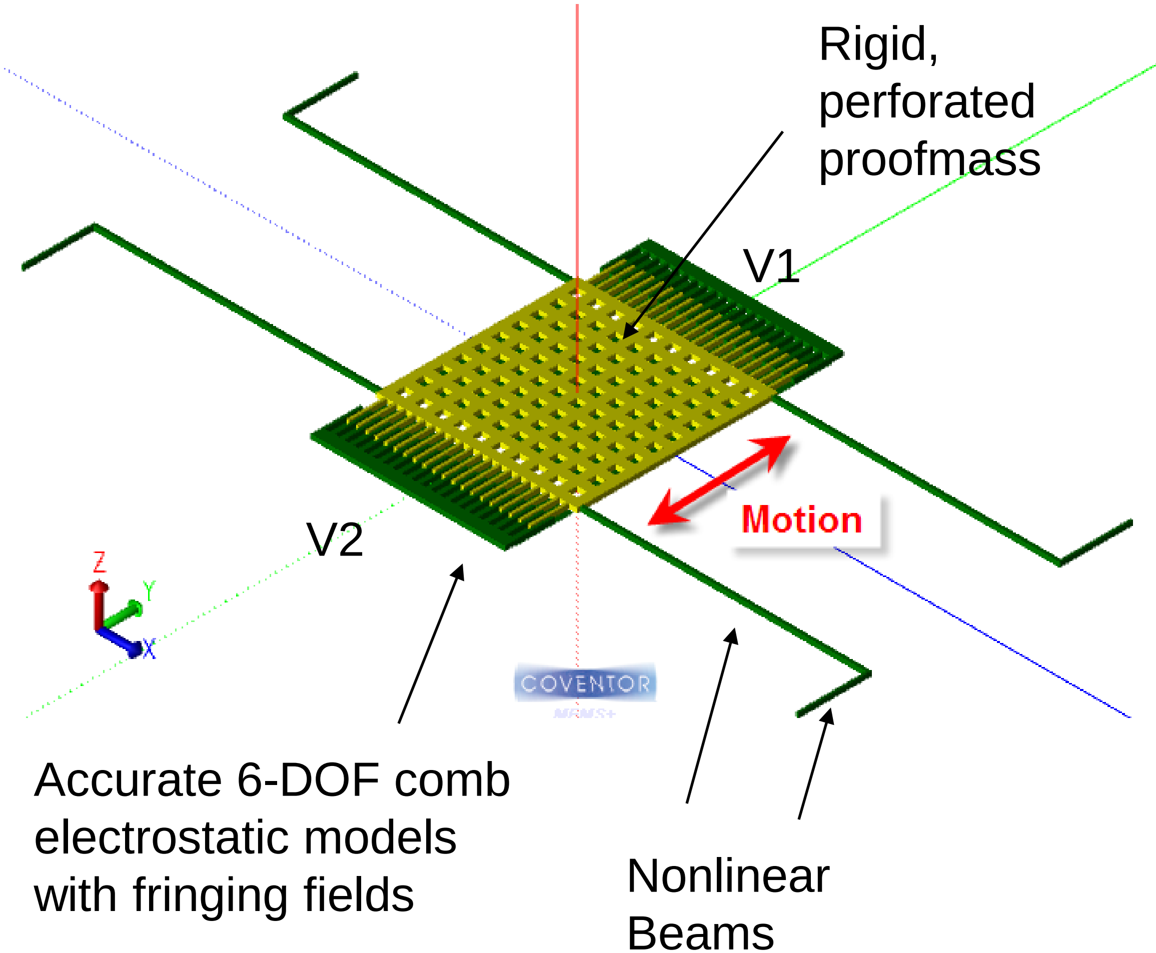
Total fluidic damping coefficients are
x-dir: 1.30e-5 (N/(m/s))
y-dir: 4.36e-5 (N/(m/s))

Contributions to x or *y*-direction gas damping of the gyroscope
(Note: other damping mechanisms are likely negligible at low frequencies)

Cadence Schematic Design



Non Linear Response



V1 = 13.1 + Vac sin(wt)

V2 = 13.1 – Vac sin(wt)

Out of phase voltages on stators resonates proof mass in Y direction

What amplitude of drive, Vac, leads to nonlinear frequency response?

30 DOF system, Q=1600, f0 = 7014 Hz

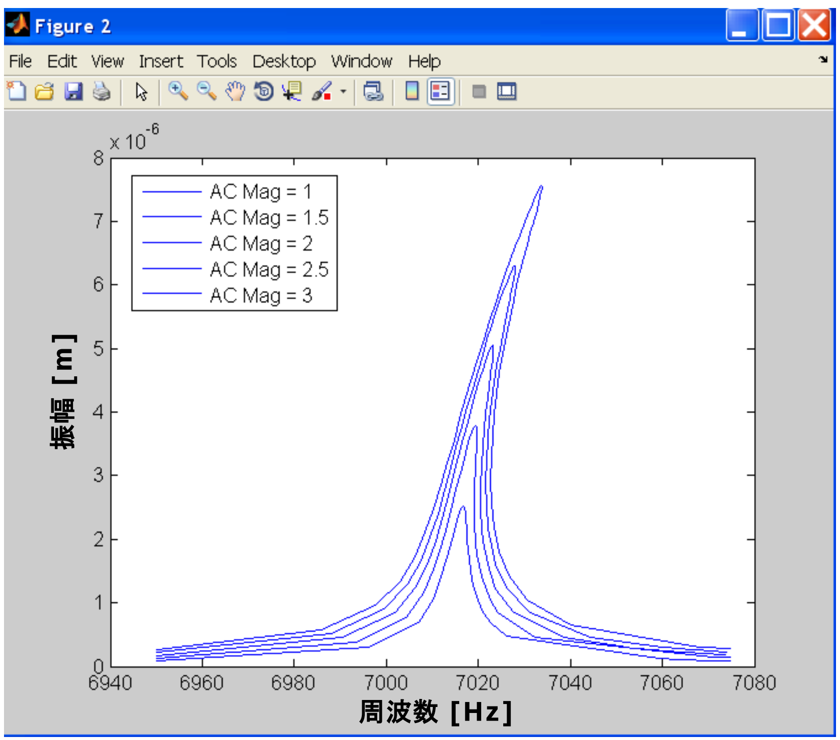
MEMS+ Matlab integration

Use FrequencyHysteresis module to compute nonlinear frequency response for

Vac = 1, 1.5, 2, 2.5, 3 Volts

Mechanical nonlinearity ‘bends’ curve to the right in typical Duffing effect.

Electrostatic nonlinearity would bend curve to left, but since motion is parallel to fingers, electrostatics remained comparatively linear.



Total CPU time to compute these 5 curves: 1100 seconds

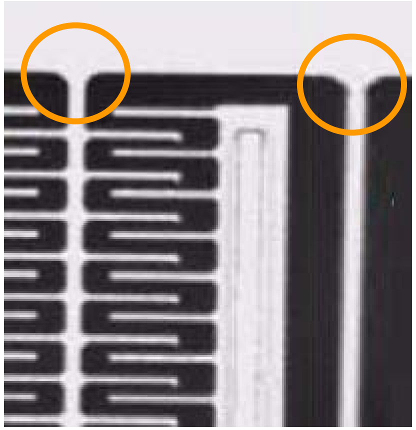
Conclusions

CoventorWare and *MEMS*+ together can simulate crucial gyroscope specs

- Sensitivity
- Cross-axis sensitivity
- Full-scale range and Nonlinearity
- Linear acceleration effect and shock response
- Noise

MEMS+ is ideal for design exploration and optimization

- Use CoventorWare to verify *MEMS*+ results
- Some physics require CoventorWare field solvers
  - Gas damping of comb drives
  - Mechanical details such as filets and anchors



Filets at connections

Solution for MEMS Accelerometer Design and Integration

Overview

Introduction

- Applications of MEMS accelerometers
- Typical accelerometer specifications

Simulation of key accelerometer specs using Coventor tools

- A single-axis accelerometer in IMEC's SiGe process
  - Frequency response and sensitivity of design
  - Damping Analysis
  - Harmonic Analysis
  - Verification with FEA
  - Transient response under a g pulse
  - Simulation of self-test functionality

Comparison between simulation and experimental results

Applications of MEMS accelerometers

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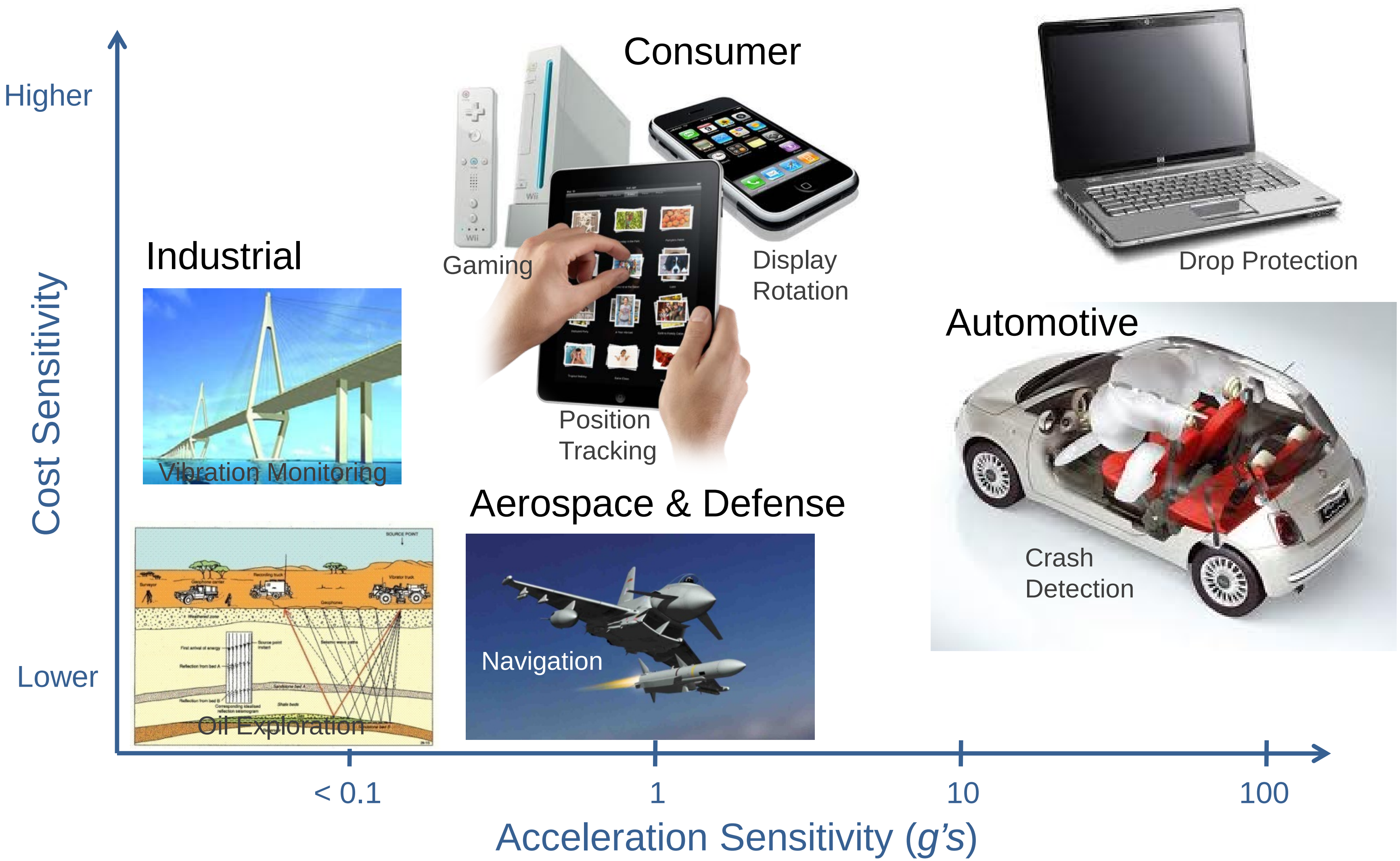


Spec sheet single-axis accelerometer (ADXL78)

Coventor tools can simulate these specs

Parameter	Conditions	Model No. AD22279 Min	Typ	Max	Model No. AD22280 Min	Typ	Max	Model No. AD22281 Min	Typ	Max	Unit
SENSOR											
Output Full-Scale Range	$I_{OUT} \leq \pm 100$ µA	37			55			70			*g*
Nonlinearity			0.2	2		0.2	2		0.2	2	%
Package Alignment Error			1			1			1		Degree
Cross-Axis Sensitivity		−5		+5	−5		+5	−5		+5	%
Resonant Frequency			24			24			24		kHz
Sensitivity, Ratiometric (Over Temperature)	V_{DD} = 5 V, 100 Hz	52.25	55	57.75	36.1	38	39.9	25.65	27	28.35	mV/*g*
OFFSET											
Zero-*g* Output Voltage (Over Temperature)[2]	$V_{OUT} - V_{DD}/2$, V_{DD} = 5 V	−200		+200	−150		+150	−150		+150	mV
NOISE											
Noise Density	10 Hz – 400 Hz, 5 V		1.1	3		1.4	3		1.8	3.5	m*g*/√Hz
Clock Noise			5			5			5		mV p-p
FREQUENCY RESPONSE	2-pole Bessel										
−3 dB Frequency		360	400	440	360	400	440	360	400	440	Hz
−3 dB Frequency Drift	25°C to T_{MIN} or T_{MAX}		2			2			2		Hz
SELF-TEST											
Output Change (Cube vs. V_{DD})[3]	V_{DD} = 5 V	440	550	660	304	380	456	216	270	324	mV
Logic Input High	V_{DD} = 5 V	3.5			3.5			3.5			V
Logic Input Low	V_{DD} = 5 V			1			1			1	V
Input Resistance	Pull-down resistor to GND	30	50		30	50		30	50		kΩ
OUTPUT AMPLIFIER											
Output Voltage Swing	$I_{OUT} = \pm 400$ µA	0.25		V_{DD} – 0.25	0.25		V_{DD} – 0.25	0.25		V_{DD} – 0.25	V
Capacitive Load Drive		1000			1000			1000			pF
PREFILTER HEADROOM			280			400			560		*g*
CFSR @ 400 kHz			5			4			3		V/V
POWER SUPPLY (V_{DD})		4.75		5.25	4.75		5.25	4.75		5.25	V
Functional Range		3.5		6	3.5		6	3.5		6	V
Quiescent Supply Current	V_{DD} = 5 V		1.3	2		1.3	2		1.3	2	mA
TEMPERATURE RANGE		−40		+105	−40		+105	−40		+105	°C

IMEC single-axis accelerometer

Process & design data provided for IMEC SiGe process

- University reference available, design files available from workshop

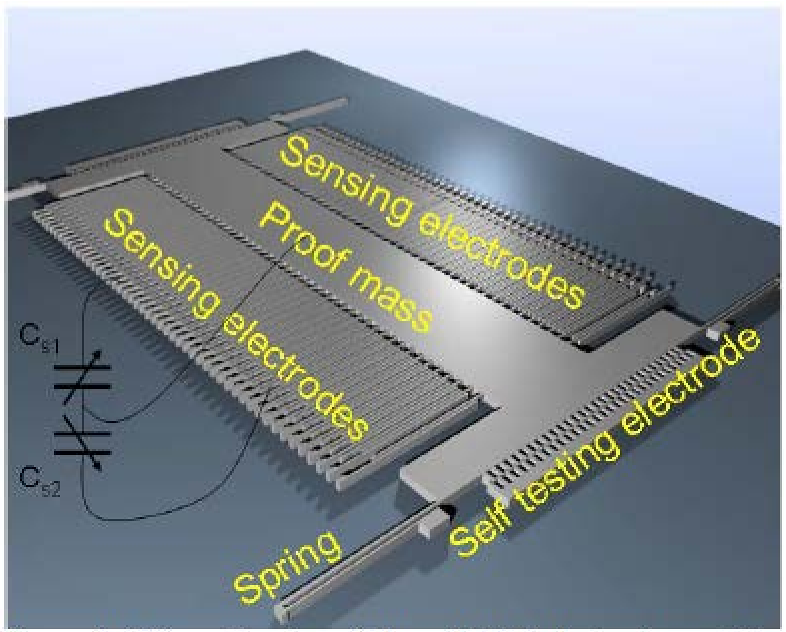


Figure 1: *Schematic view of the poly-SiGe lateral capacitive accelerometer with self-testing electrodes and shock protectors*

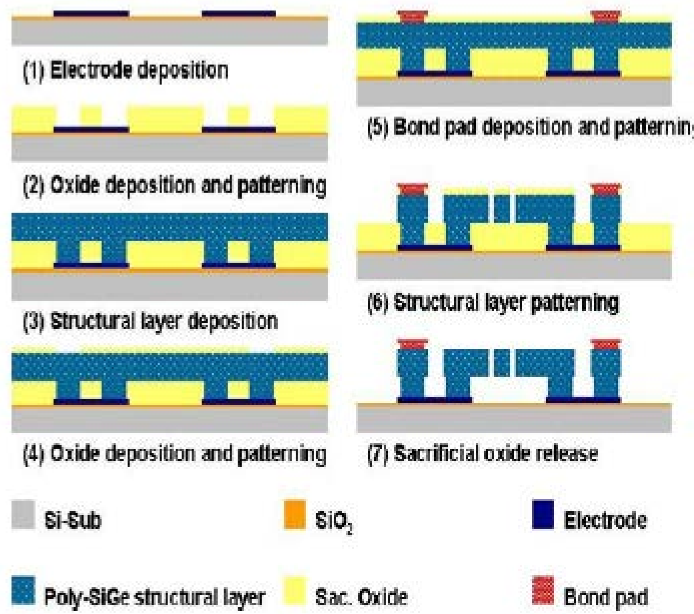
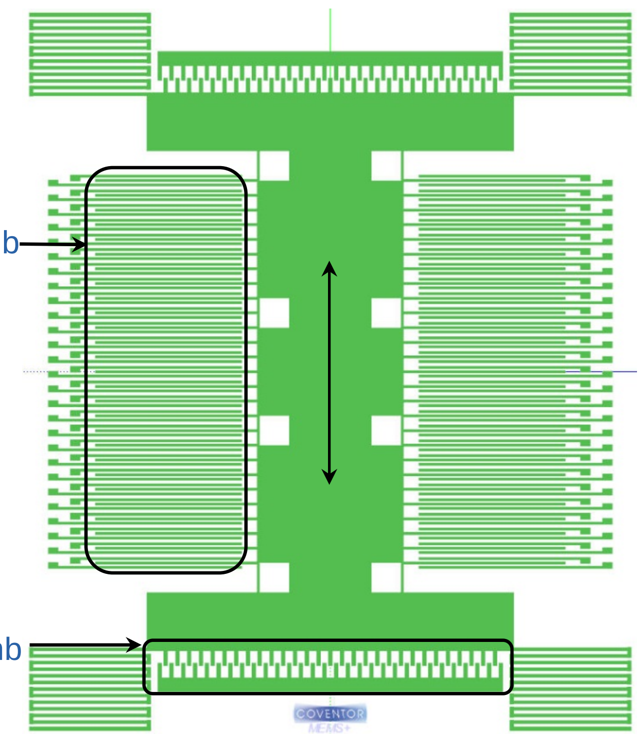


Figure 2: *Fabrication process flow of the poly-SiGe lateral capacitive accelerometer*

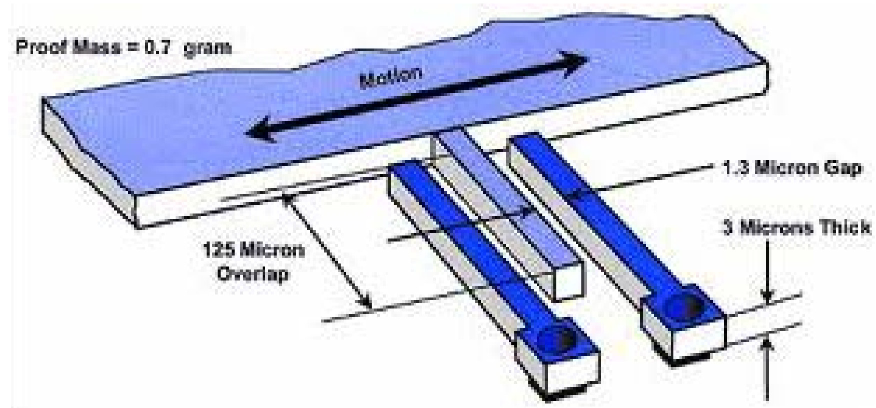
Reference: L. Wen, *et al*, “A Comb Based In-Plan Capacitive Accelerometer for Above-IC Integration, U. Leuven and IMEC, Belgium, 2010

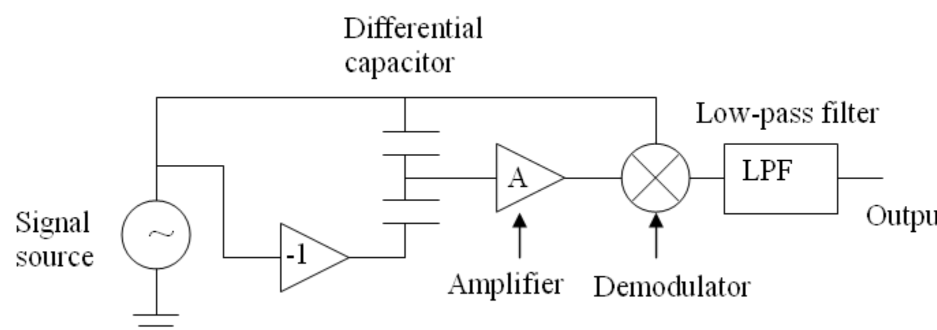
Layout of single-axis accelerometer

Sensing comb
MemElectro
or *MEMS+*



Self-test comb
MemElectro



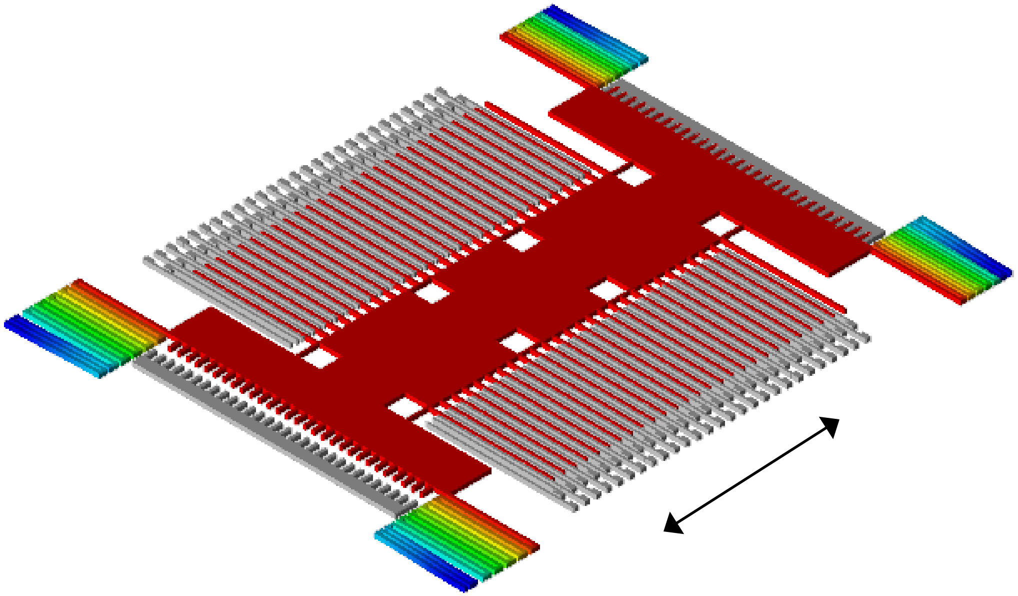


Sensor specs

COVENTOR

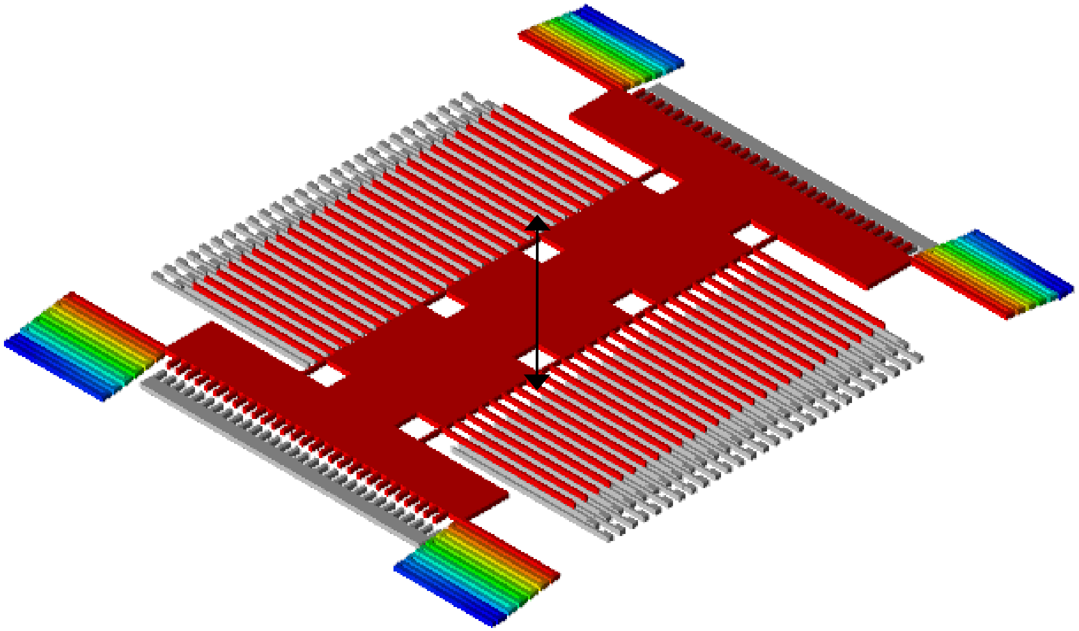
Parameter	Conditions	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Unit
SENSOR											
Output Full-Scale Range	$I_{OUT} \leq \pm 100$ µA	37			55			70			*g*
Nonlinearity			0.2	2		0.2	2		0.2	2	%
Package Alignment Error			1			1			1		Degree
Cross-Axis Sensitivity		−5		+5	−5		+5	−5		+5	%
Resonant Frequency			24			24			24		kHz
Sensitivity, Ratiometric (Over Temperature)	V_{DD} = 5 V, 100 Hz	52.25	55	57.75	36.1	38	39.9	25.65	27	28.35	mV/*g*

Resonant frequency modal frequencies and shapes

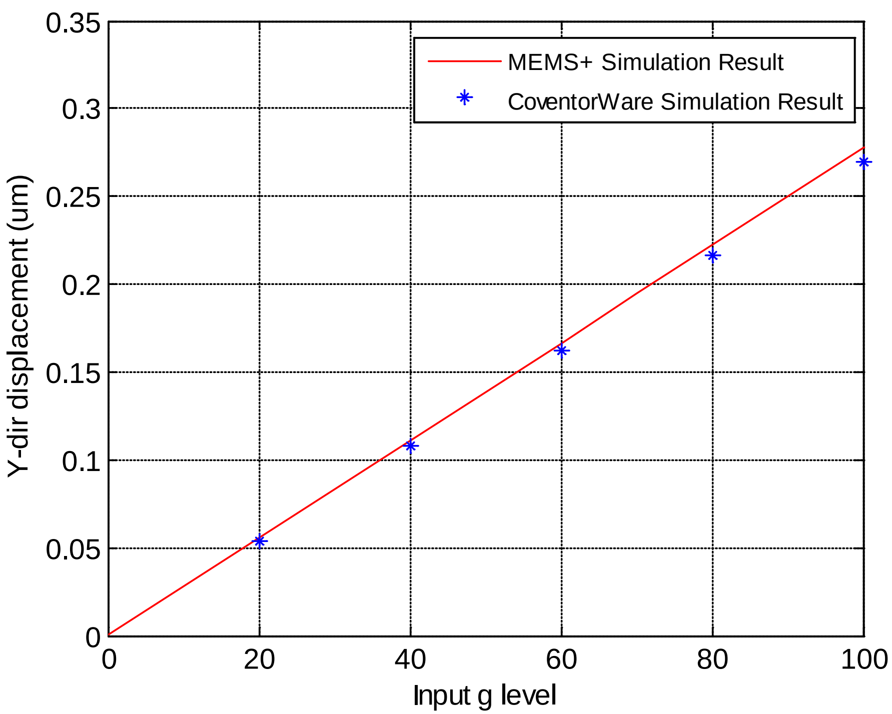


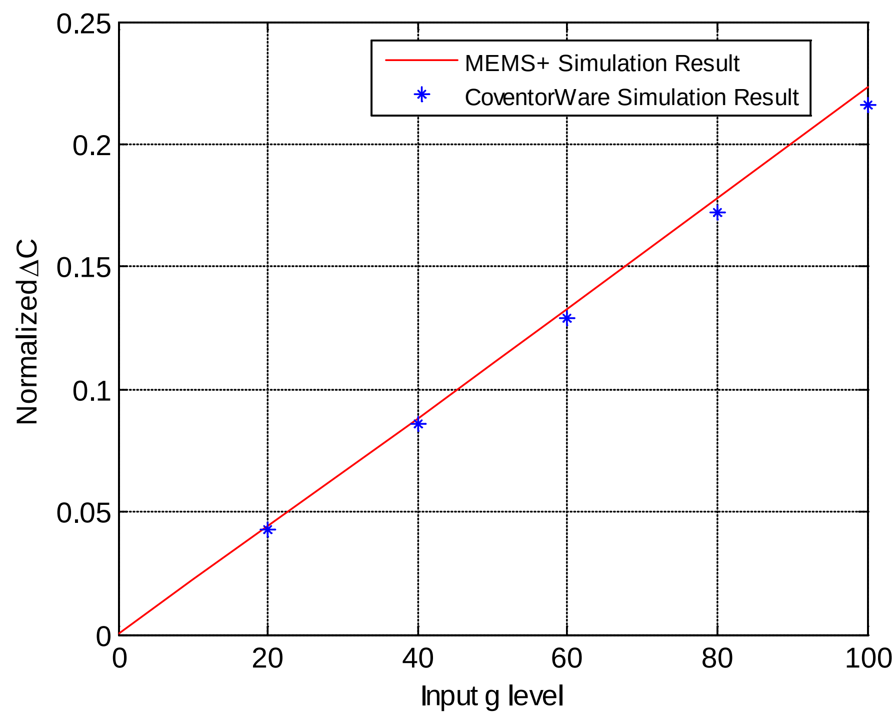
Mode 1 – Y direction
9.5 kHz

Mode 2 – Z direction
9.7 kHz



Output Range MEMS+ validated with FEA





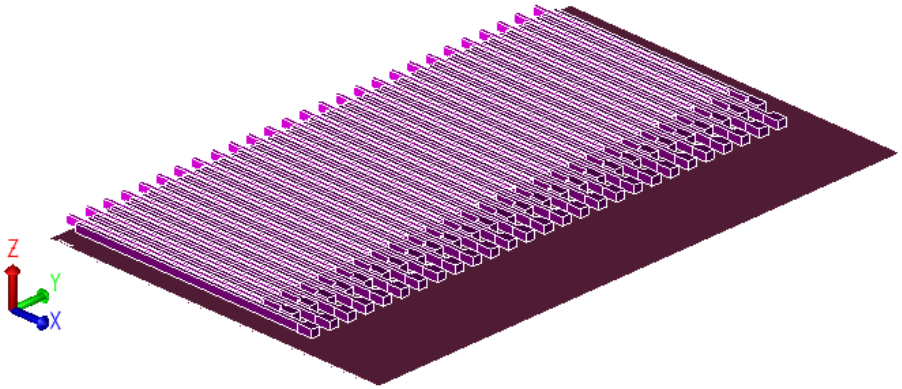
Input g Vs Y displacement of proof mass

Input g Vs normalized capacitance of sensing comb fingers

$$\text{Normalized Capacitance} = \frac{C_1 - C_2}{C_1 + C_2}$$

Fluidic damping analysis: system decomposition

Stokes solver for damping between sense comb fingers



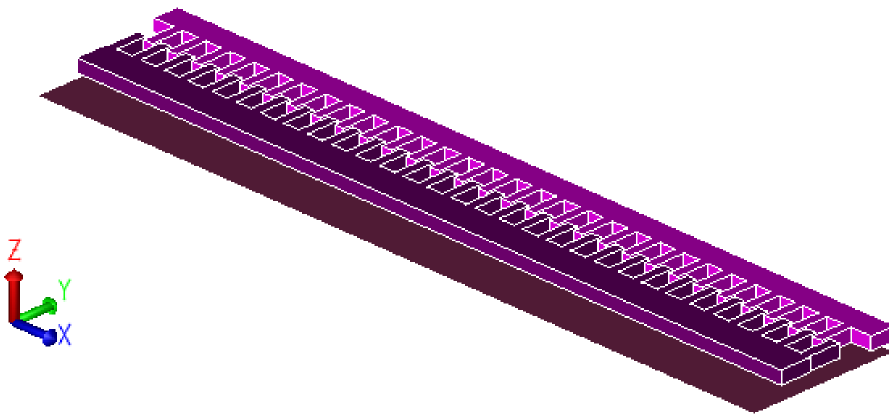
Key simulation parameters

Ambient gas: N_2

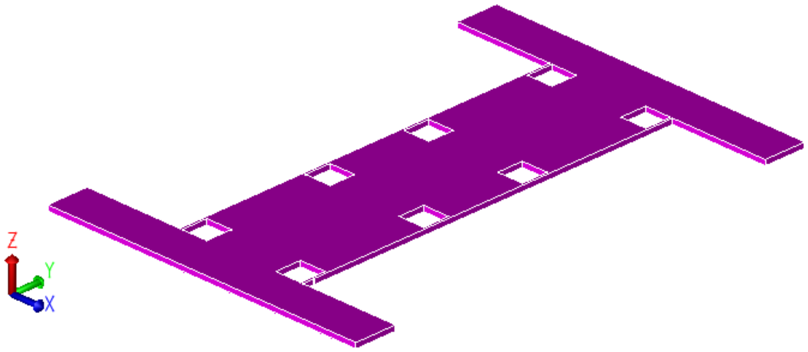
Pressure: 1 bar

Temperature: 300K

Stokes solver for damping between self test comb fingers

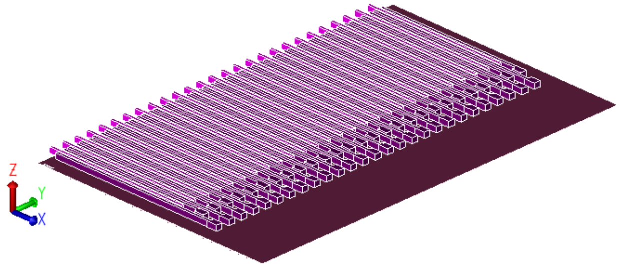


Reynolds solver for slide damping



(Note: other damping mechanisms are likely negligible at low frequencies)

Fluidic damping analysis: total damping coefficient



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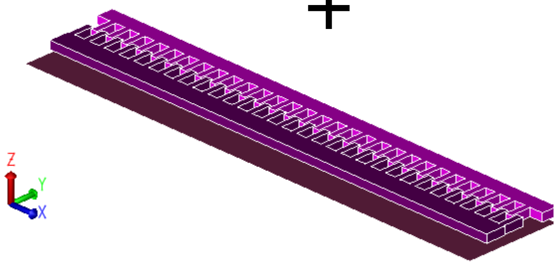

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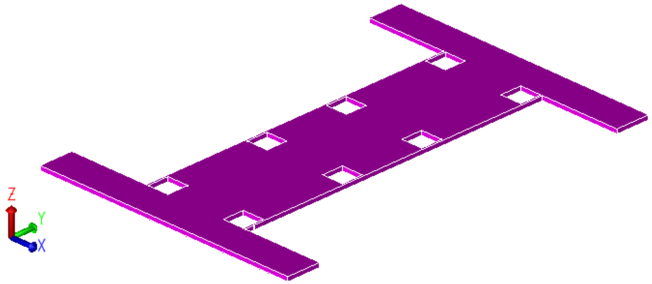
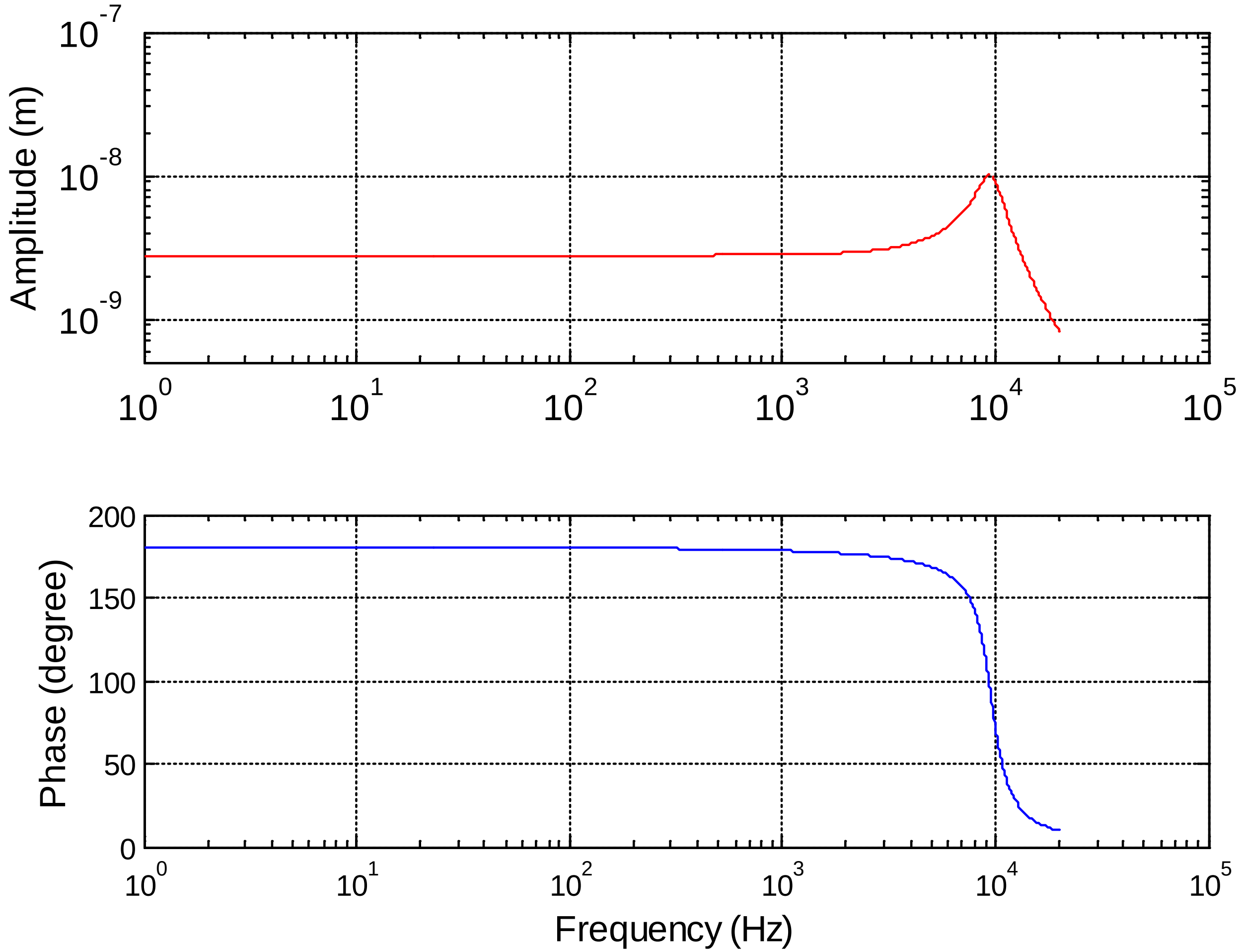


=

	Damping Coefficient (N/m/s)
Proof Mass	2.45E-07
ST Structures	1.83E-07
Comb Fingers	2.02E-05
Total	2.06E-05

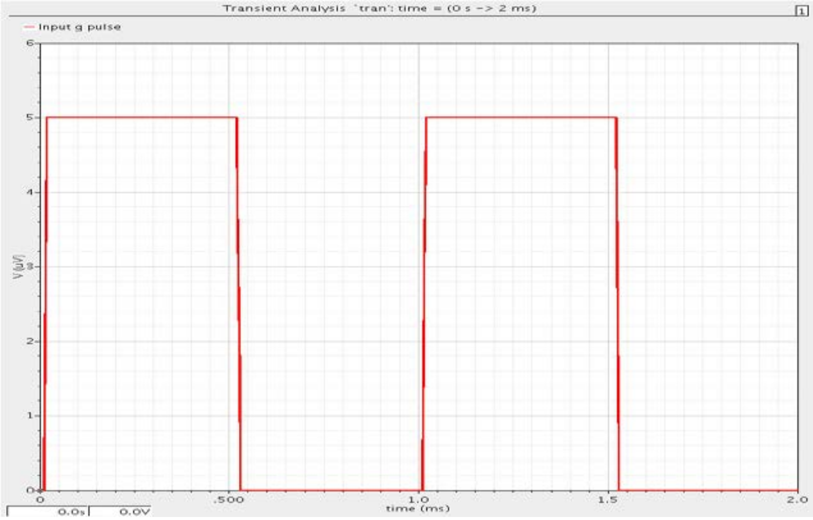
Harmonic analysis with damping



Natural frequency: 9.58 kHz

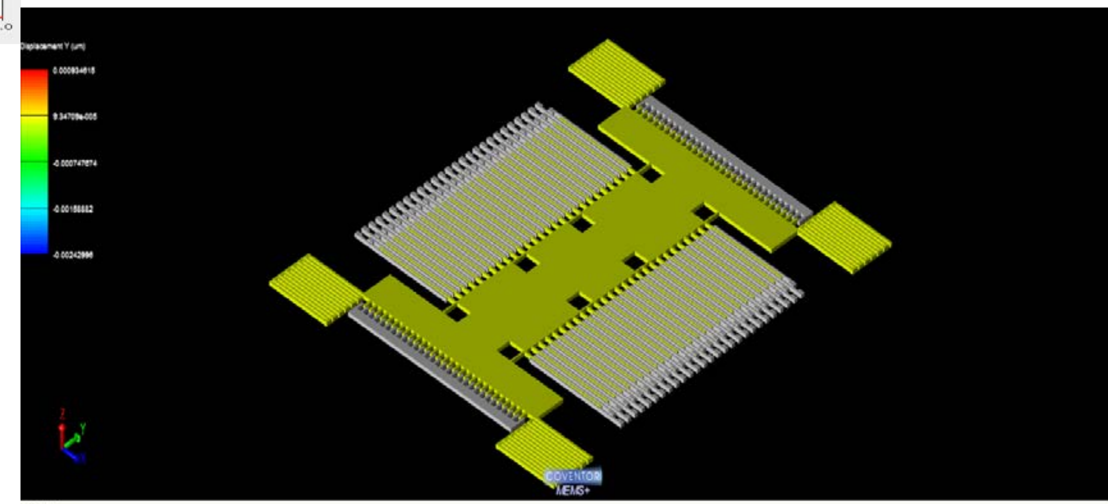
Damping ratio: 13.3%

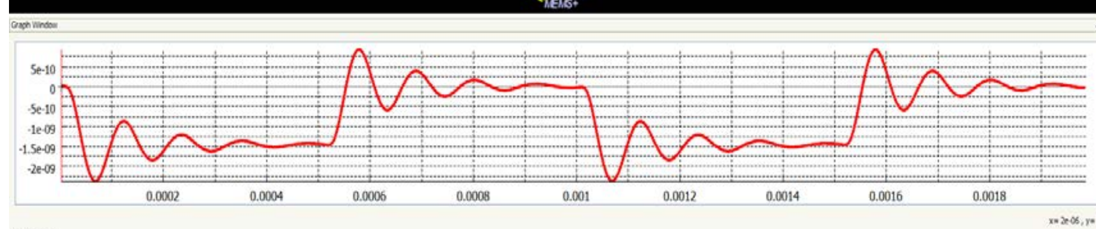
Transient response under g pulse



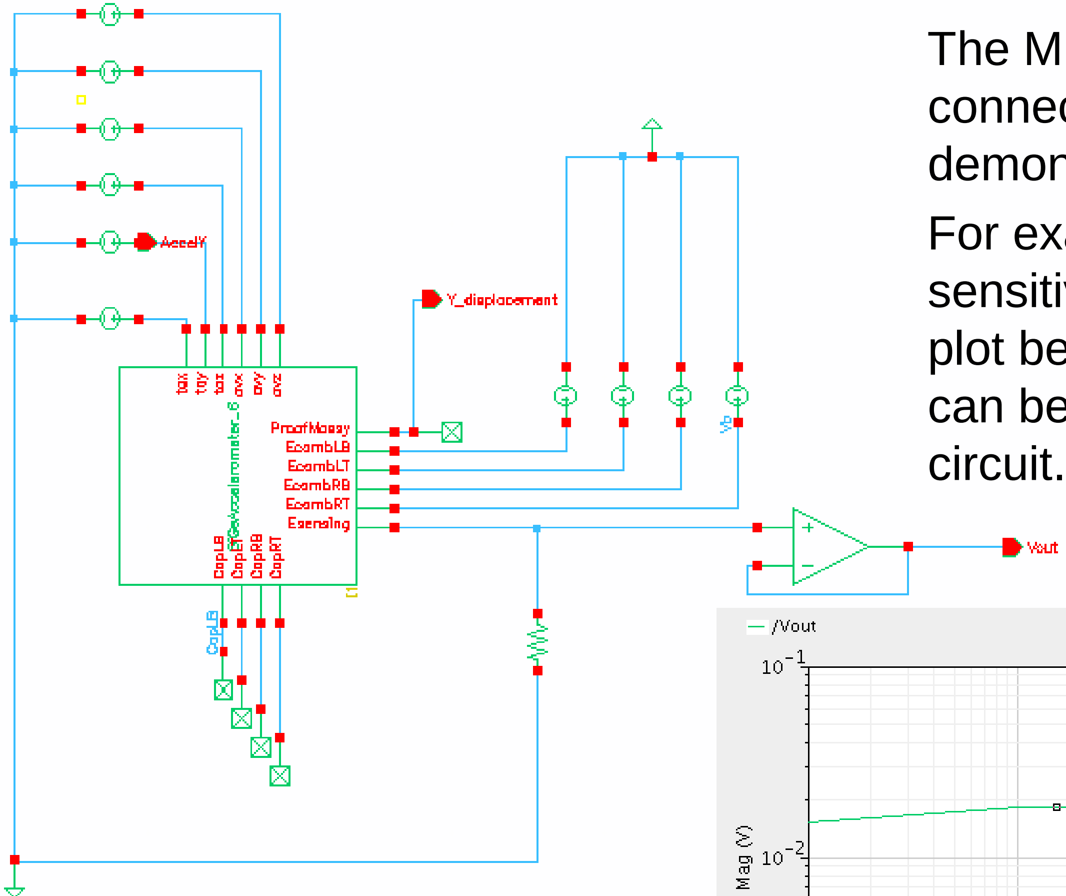
0.5 g pulsetrain

Transient response of accelerometer



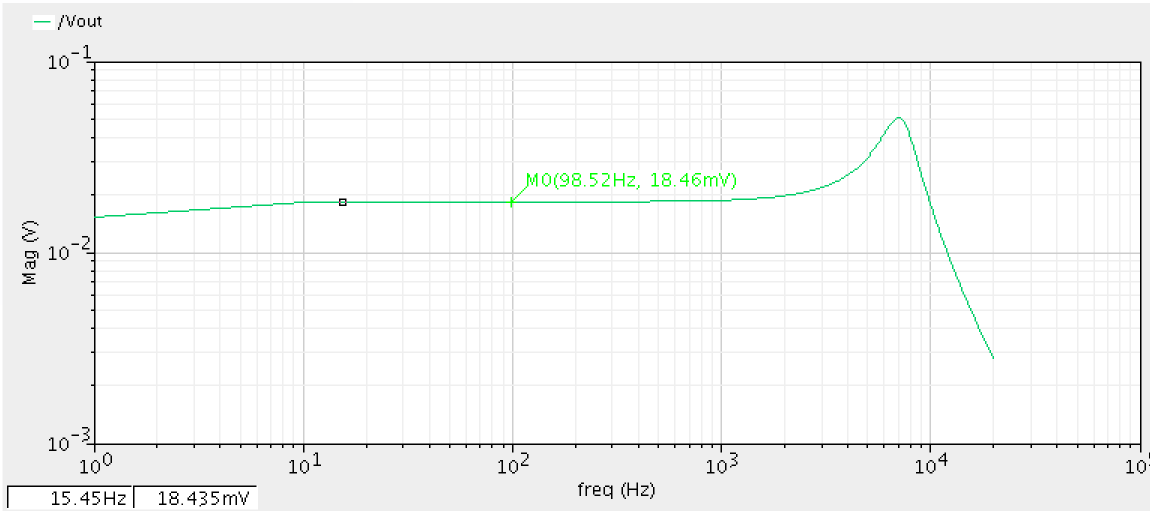


MEMS + IC



The MEMS+ model of the accelerometer is connected to a simple IC circuit here to demonstrate the MEMS + IC co-simulation.

For example, we can simulate the sensitivity of the device as shown in the plot below. Other performance parameters can be studied as well with this simple circuit.



Sensitivity: ~18.5 mV/g with Vdd = 5V

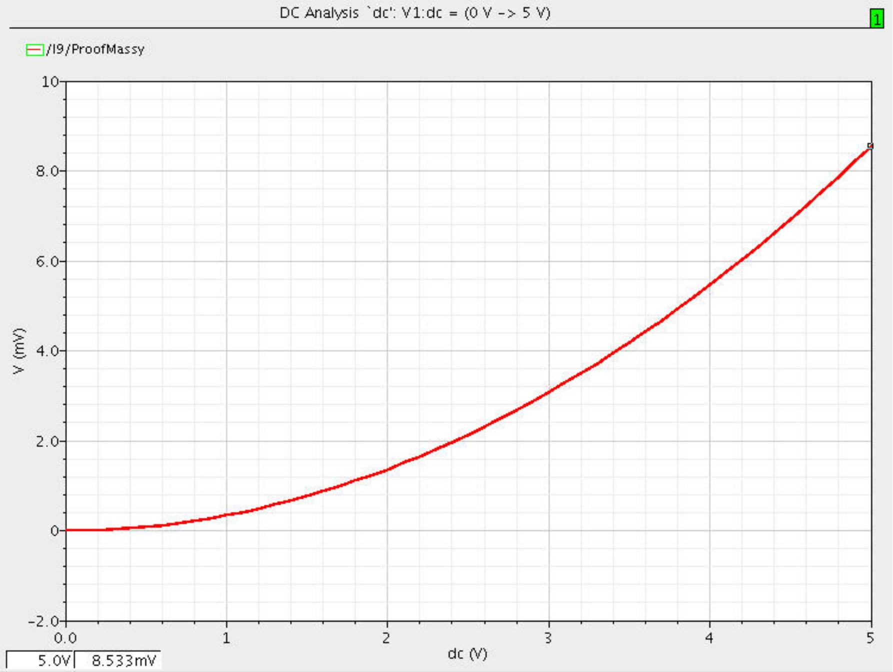
Self-test specification

NOISE											
Noise Density	10 Hz – 400 Hz, 5 V		1.1	3		1.4	3		1.8	3.5	mg/√Hz
Clock Noise			5			5			5		mV p-p
FREQUENCY RESPONSE	2-pole Bessel										
−3 dB Frequency		360	400	440	360	400	440	360	400	440	Hz
−3 dB Frequency Drift	25°C to T_{MIN} or T_{MAX}		2			2			2		Hz
SELF-TEST											
Output Change (Cube vs. V_{DD})[3]	V_{DD} = 5 V	440	550	660	304	380	456	216	270	324	mV
Logic Input High	V_{DD} = 5 V	3.5			3.5			3.5			V
Logic Input Low	V_{DD} = 5 V			1			1			1	V
Input Resistance	Pull-down resistor to GND	30	50		30	50		30	50		kΩ

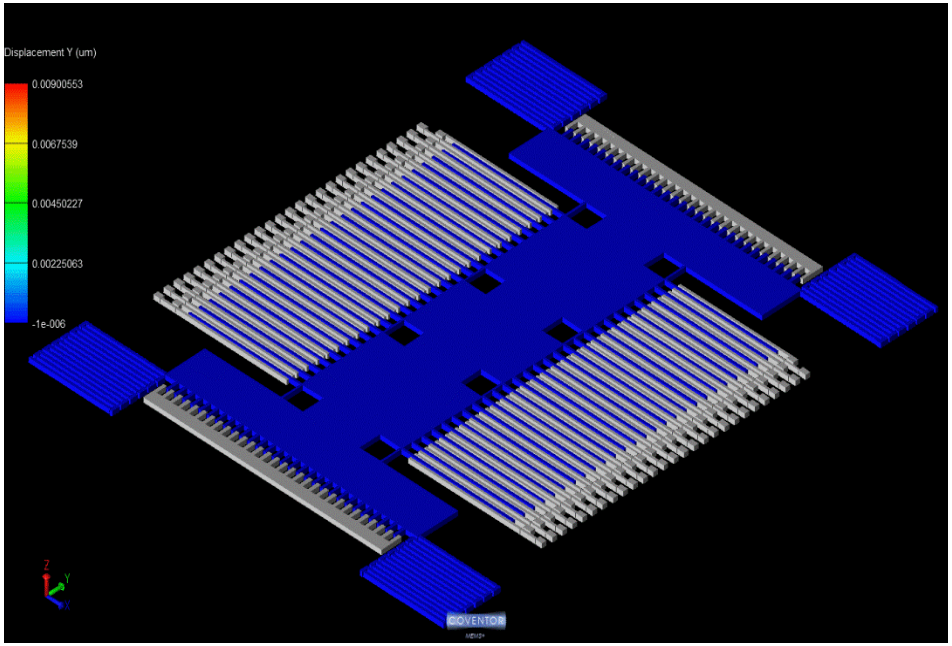
How much y-displacement due to 5V bias on self-test comb?

- Since we know sensitivity (mV/g) and *y*-displacement vs. acceleration, this will give us the output change in mV

Self test :
Cadence simulation results

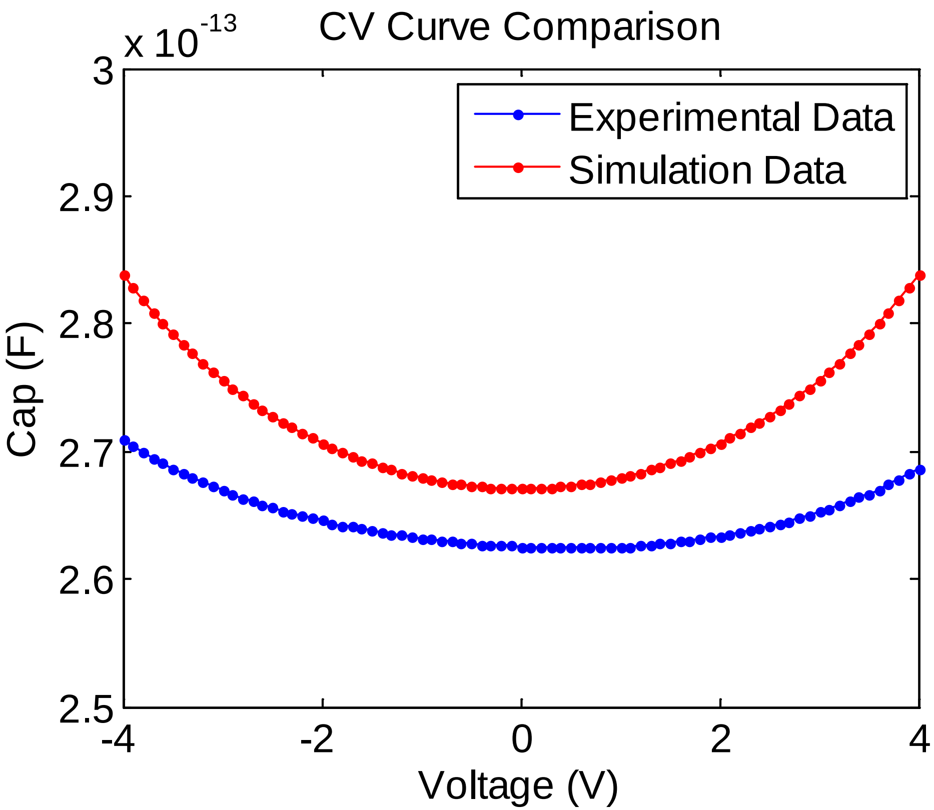


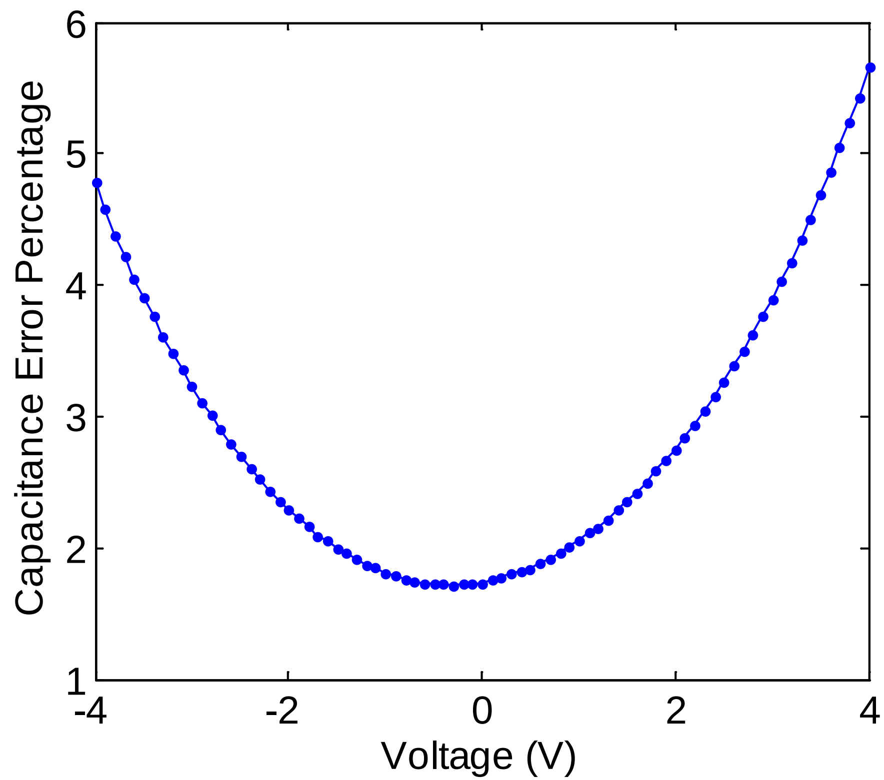
Y-dir displacement of Proof mass



Voltage on top self test comb is swept from 0 to 5V
Zero g is applied on the proof mass

Simulation and experimental results





The static CV results were plotted and compared. The left figure has both experimental and simulation data, and the right figure shows the difference in terms of percentage number for each voltage point.

Coventor Solutions for

Vibrational Piezoelectric Energy Harvester

Design and Integration

Overview

Introduction

- New applications for MEMS Energy Harvesters
- Energy Harvesting Principles
- Key characteristics
- Design and integration challenges

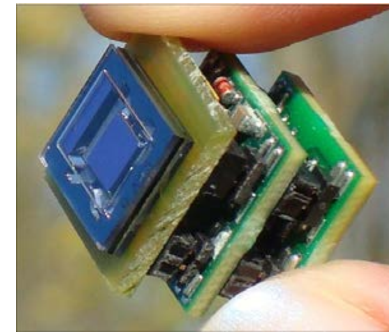
An example showing use of Coventor’s tools

- Energy Harvester and conditioning circuit design
- Validation with measures
- Packaging

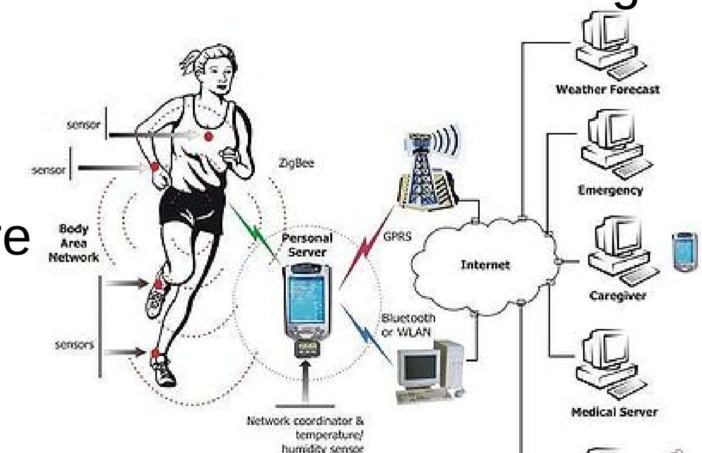
Conclusions

Applications of miniaturized Energy Harvesters

- Powering Distributed Wireless Sensor Nodes
- Powering Implanted Sensors for Health Monitoring
- Recharging batteries
- Monitoring Tire Pressure



Autonomous wireless temperature sensor
Source: Holst center



Wireless Body Area Network
Source: wikipedia

* IDTechEX (England)

"-*The Energy Harvesting Market will growto 4.4 billion dollars in 2020 from 650 million dollars in 2010* "

* Innovative Research and Products (USA)

- " *The market will expand 73.6% to 1.254billion dollars in 2014 from 79.5 million dollars in 2009*"

Source: Hi-Globe website

Energy Harvesting Principles

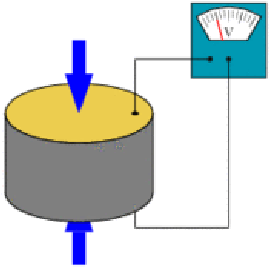
Power sources:

Vibrations
Thermal
RF waves
Light
Wind

Source: Hi-Globe website

Harvesting methods:

Piezoelectric
Electromagnetic
Electrostatic
Thermoelectric
Pyroelectric
Photovoltaic
...



Vibration Energy Harvesting Efficiency

Piezoelectric:

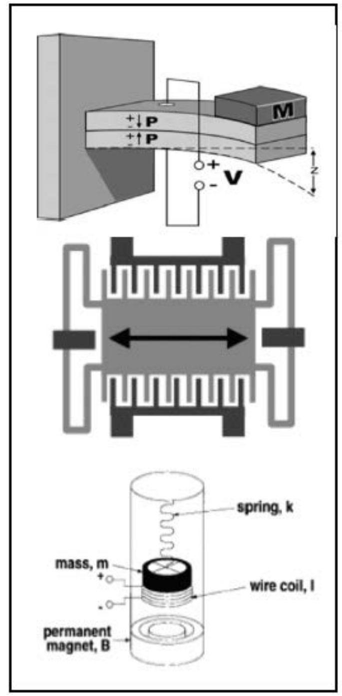
Piezoelectric material has its dynamical strain converted into voltage difference

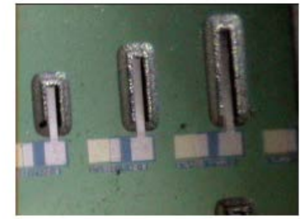
Electrostatic:

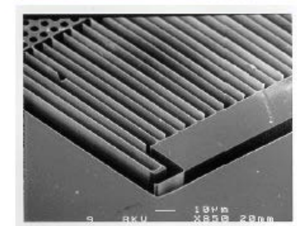
Capacitive harvesting with geometrical variations inducing voltage difference

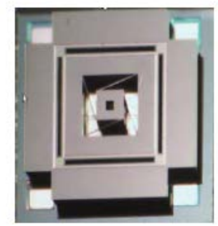
Electromagnetic:

Inductive behavior thanks to dynamical oscillations of magnets inducing electric current in coils









Type	Governing Equation	Practical Maximum	Theoretical Maximum
Piezoelectric	$u = \sigma_y^2 k^2 / 2Y$	17.7 mJ/cm^3	335 mJ/cm^3
Electrostatic	$u = \frac{1}{2}\varepsilon E^2$	4 mJ/cm^3	44 mJ/cm^3
Electromagnetic	$u = B^2 / 2\mu_0$	4 mJ/cm^3	400 mJ/cm^3

Source: H. Vocca, NiPS Laboratory, Dipartimento di Fisica, Università degli Studi di Perugia, Italy

Vibration Energy Harvester Specifications

COVENTOR

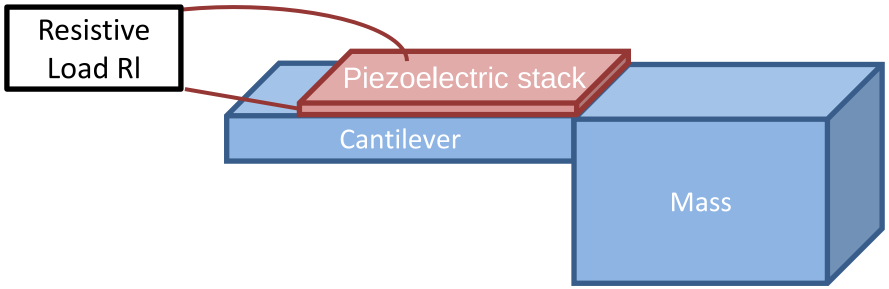
Key Characteristics

- Operational frequency range :
  - Depends on application : ambient vibration harvesting => low frequency and broadband or tunable harvester
- Generalized ElectroMechanical Coupling
  - Material and technology choice
- **Power density** (W/cc)
  - Power to size compromise
- Energy management and storage
  - Different conditioning circuits depending how the energy will be used

Vibration Energy Harvester Example Design

Cantilever with mass :

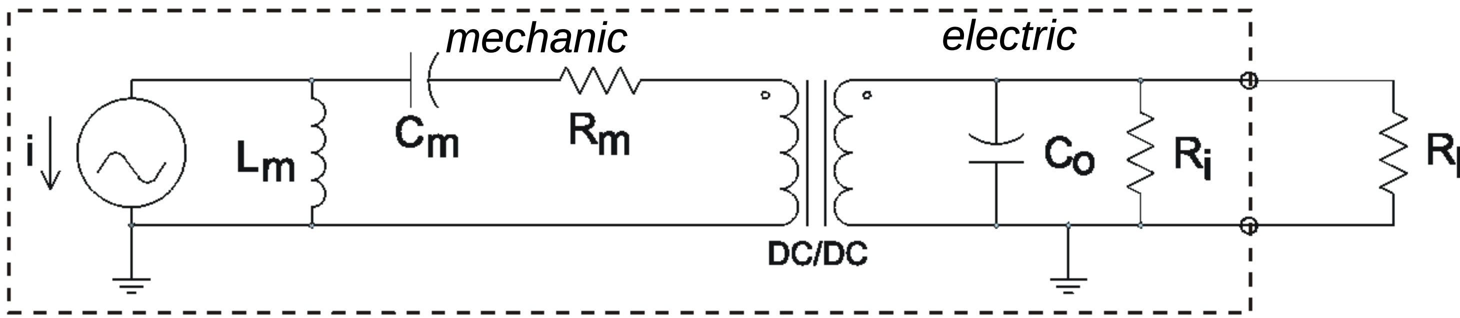
Use of the d31 piezoelectric coefficient



Spring **k**
Mass **m**
Damping **d**

Design Options
Electrodes: On sides of piezo layer for d31 or interdigited combs on top for use of d33
Piezoelectric stack: Unimorph, bimorph or multistack with series or parallel configuration

Equivalent Model :

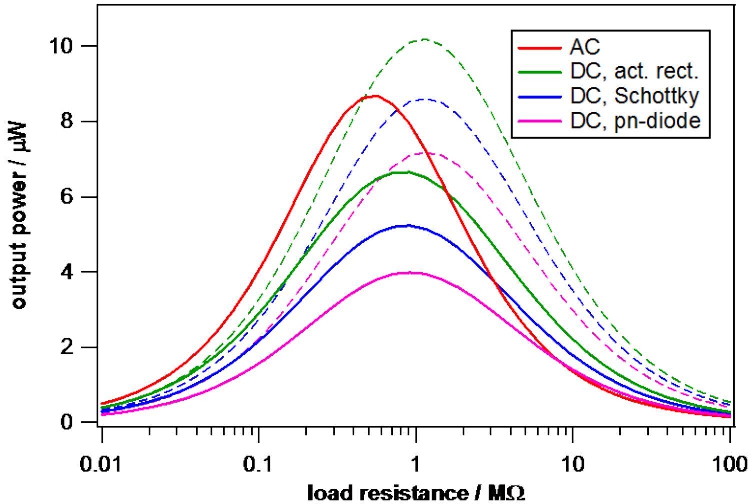


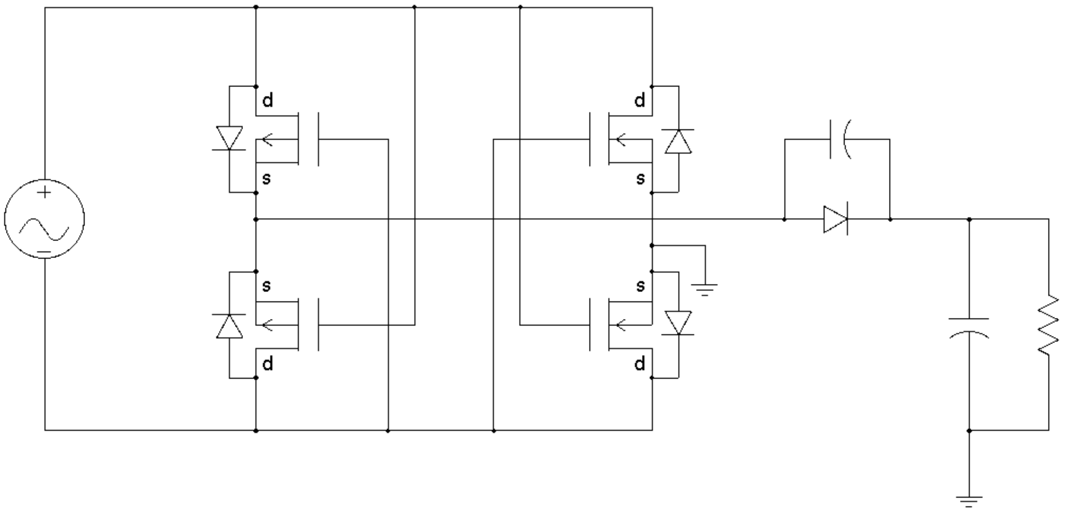
$$R_{load,opt.} = \frac{R_m}{\sqrt{1+\omega_m^2 R_m^2 C_0^2}}$$

$$P_{load,\max.} = \left(\frac{F}{\Gamma}\right)^2 \frac{1}{2R_m} \frac{1}{1+\sqrt{1+\omega_m^2 R_m^2 C_0^2}}$$

Vibration Energy Harvester Simulation Challenges

Power output of different conditioning circuits vs resistive load value





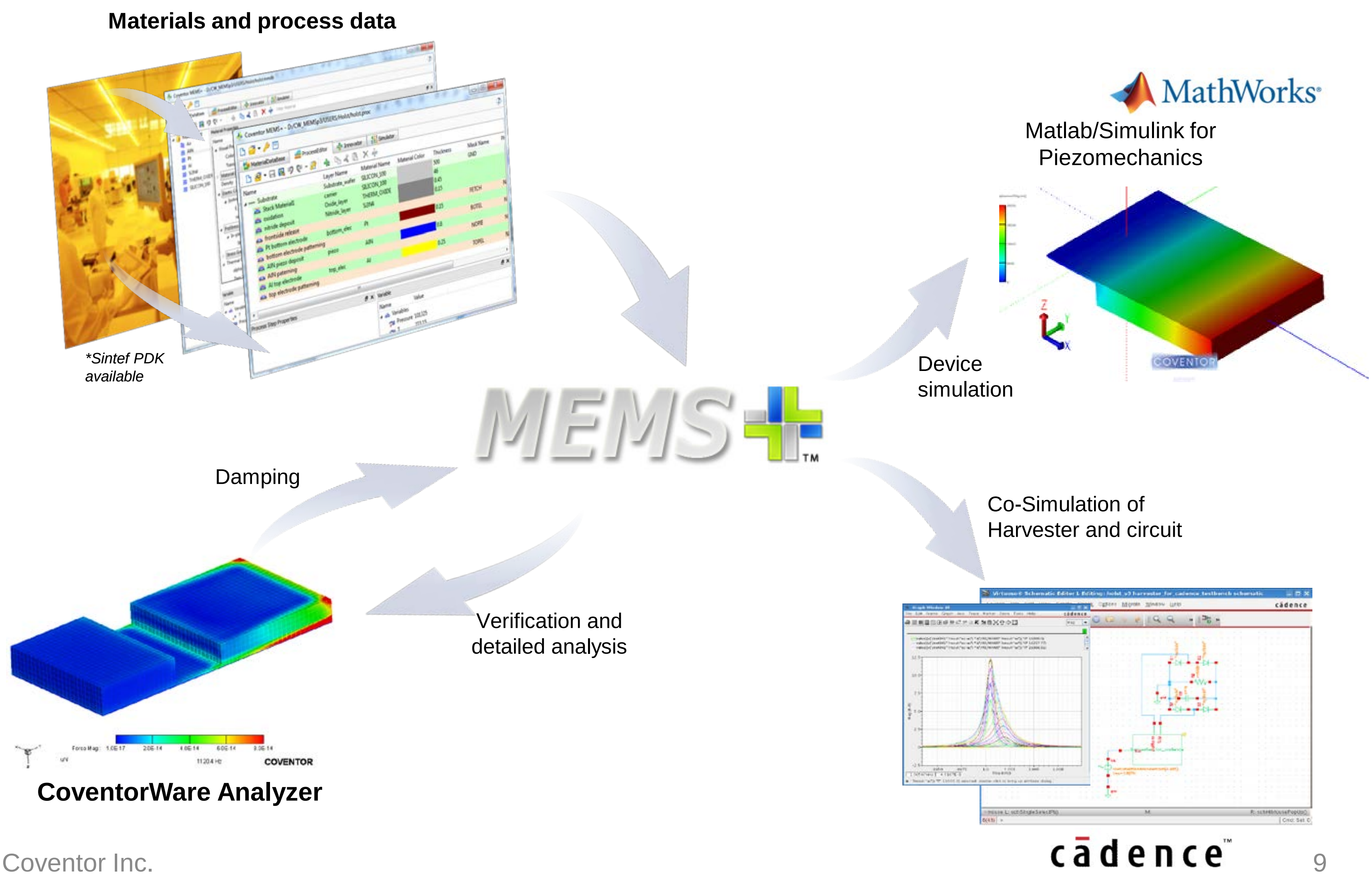
FEA result is limited to power through a basic passive load

- Basic RLC circuit can be plugged to piezoelectric electrodes

Including diodes or transistors is impossible

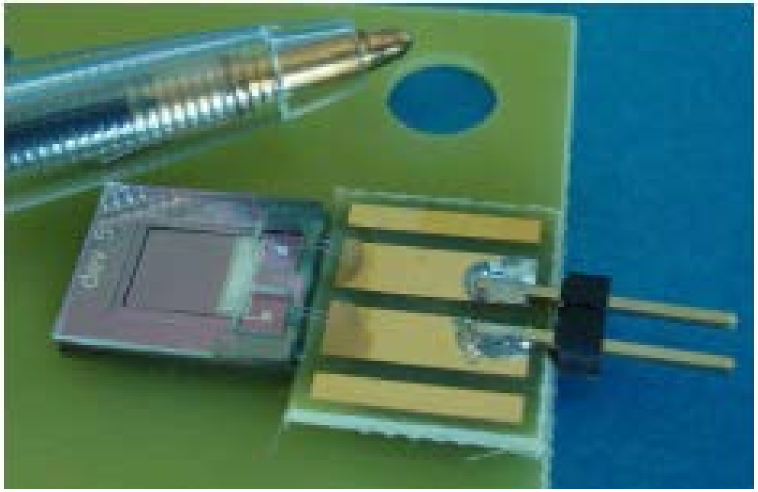
⇒ **Circuit simulator is needed** for getting the real output power from the energy harvester complete system

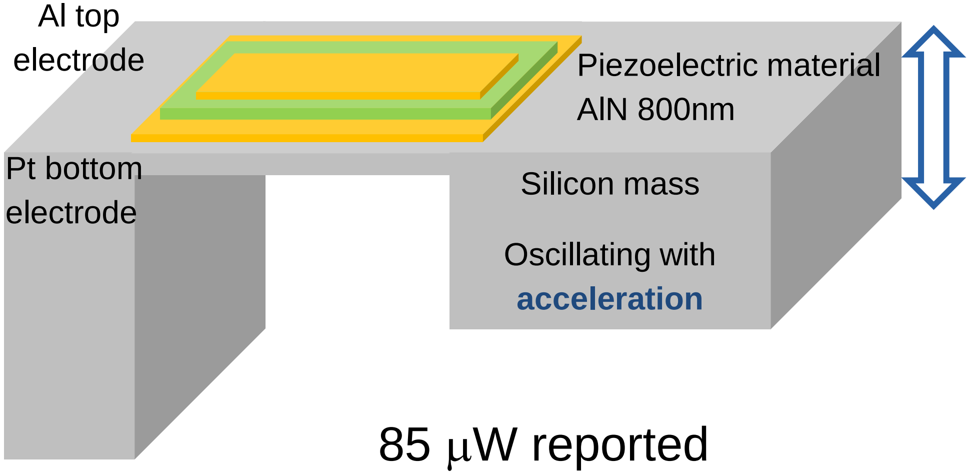
Coventor Design Flow



Case Study :
Holst Center cantilever VEH

Sputter deposition of Aluminum Nitride on a silicon wafer and glass packaging





85 μW reported

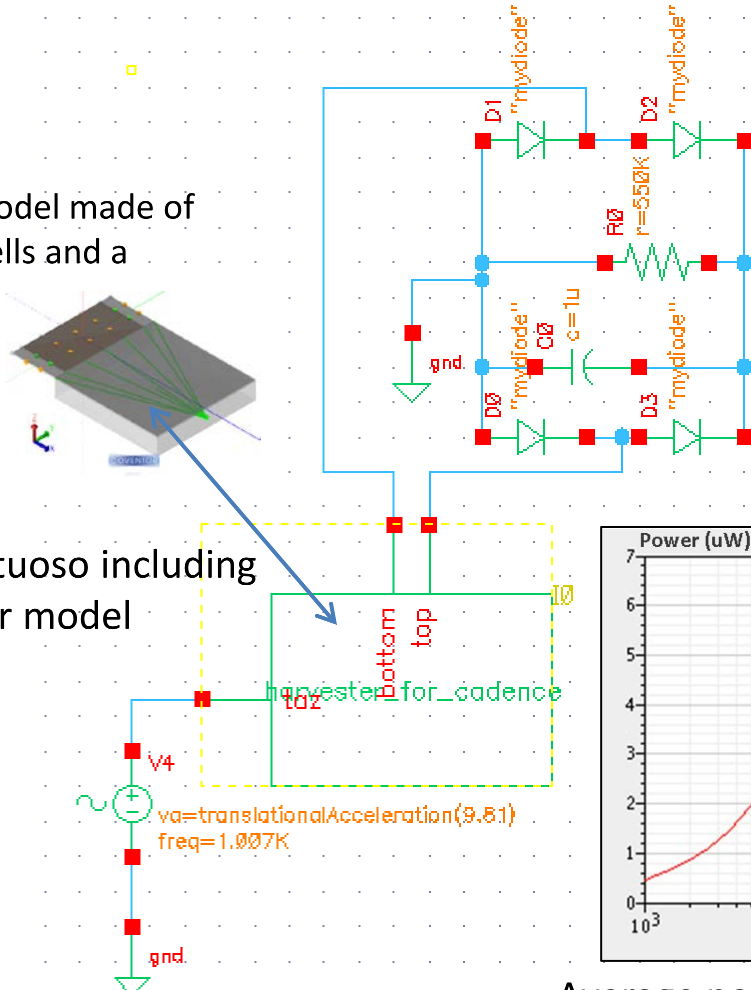
Vacuum-packaged piezoelectric vibration energy harvesters: damping contributions and autonomy for a wireless sensor system
R Elfrink, M Renaud, T M Kamel, C de Nooijer, M Jambunathan, M Goedbloed, D Hohlfeld, S Matova, V Pop, L Caballero and R van Schaijk
J. Micromech. Microeng. **20 june** 2010

Experimental Validation of Aluminum Nitride Energy Harvester Model with Power Transfer Circuit
S. Matova, D. Hohlfeld, R. van Schaijk, C. J. Welham, S. Rouvillois
Eurosensors XXIII conference 2009

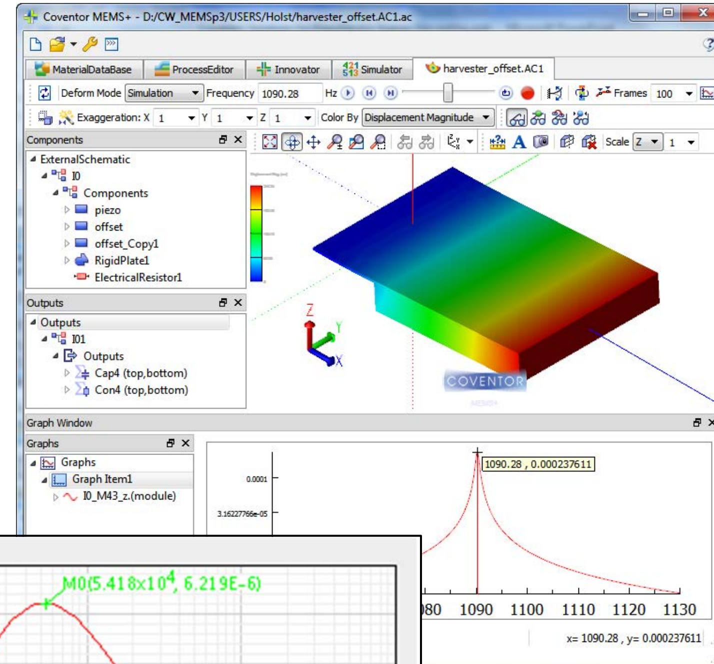
Energy Harvesting circuit design

- Piezoelectric Energy Harvester with conditioning circuit optimization

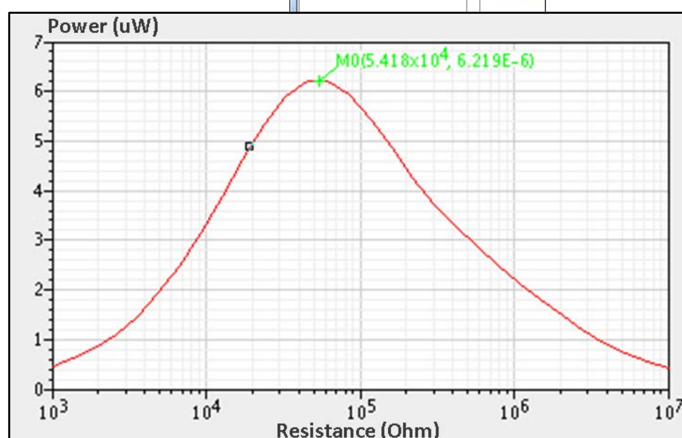
MEMS+ model made of a MITC shells and a rigid plate



Circuit in Virtuoso including the harvester model



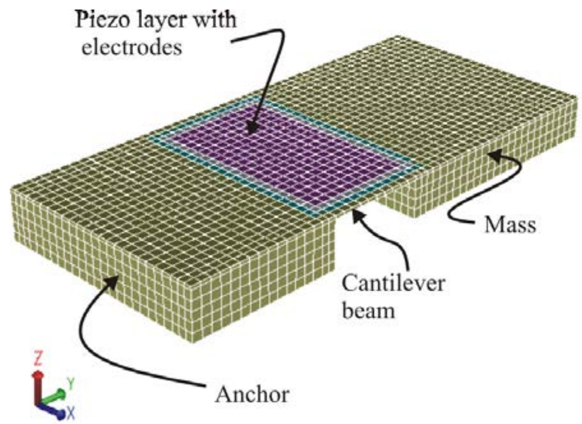
Harmonic response

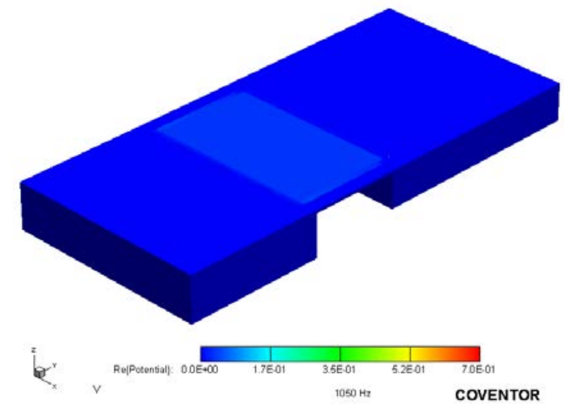


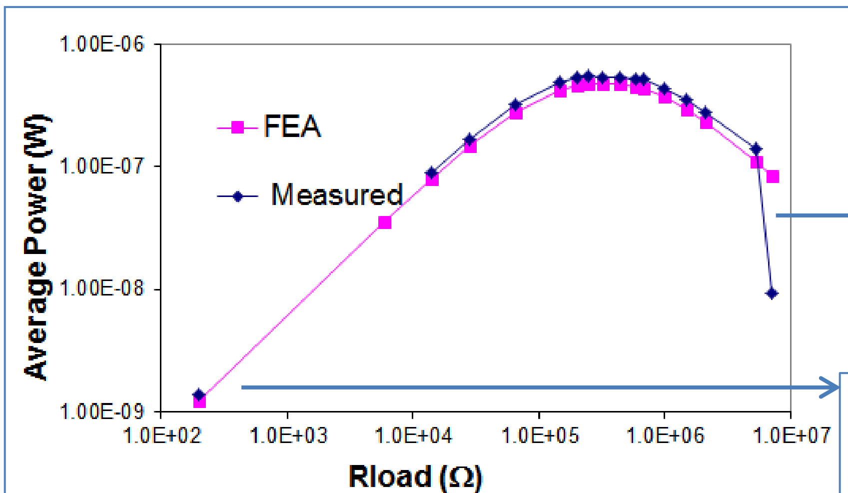
Average power variation with resistive load using full-bridge power transfer circuit

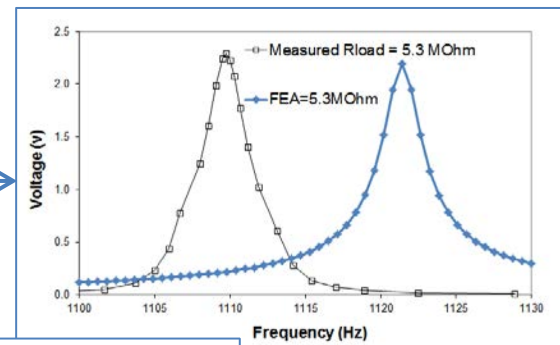
Verification and refinement

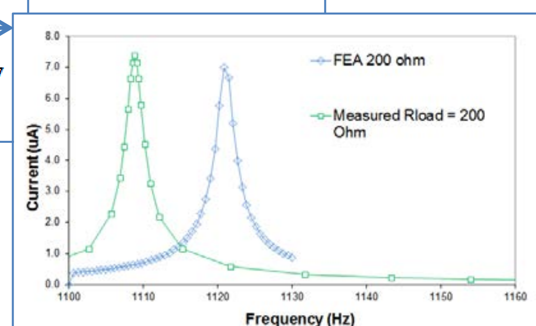
- Structure with non overlapping electrodes
- Anchor potential effects









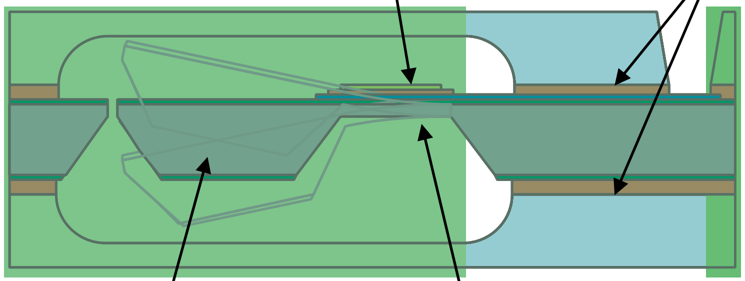


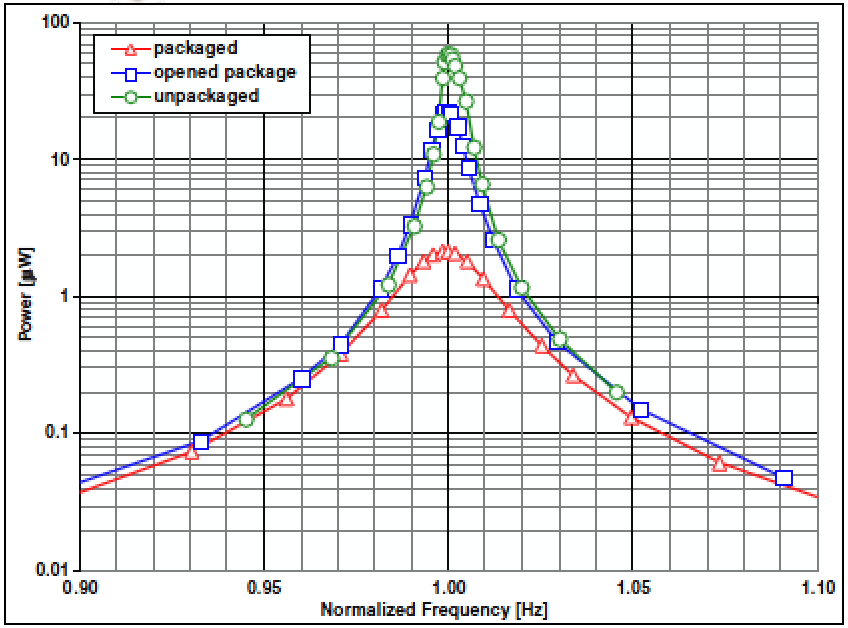
Comparison of FEA with measures of MEMS component performances

Direct harmonic FEA with resistive load and measured damping

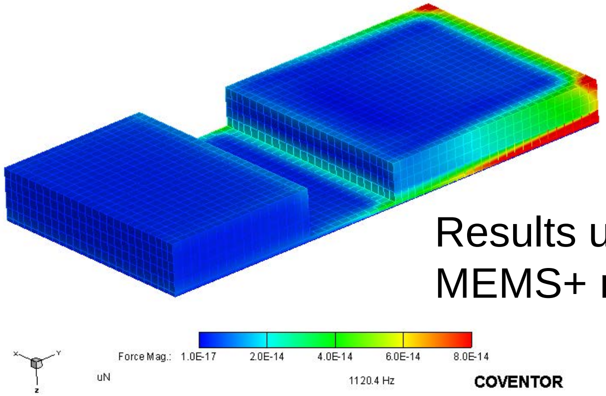
Packaging

- Three wafer process: two glass and one Silicon bonded by SU-8 roll coating
- Unique wafer-scale vacuum package between glass wafers





- Damping analysis in FEA



Results used in MEMS+ modelling

Advantages for Piezoelectric Energy Harvesters

MEMS+Cadence

- Optimum load analysis for different conditioning circuit
- Design of the Energy Storage System together with the harvester

CoventorWare

- Precise design of electrodes
- Stress map

Combination:

- Damping simulations
- Study of packaging effects

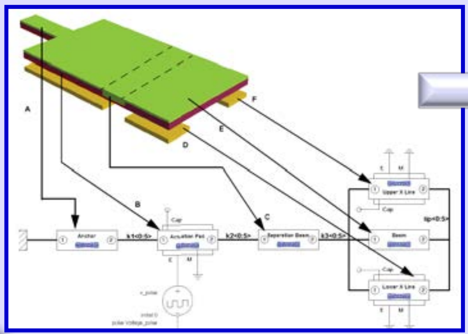
Coventor solutions for Pressure Sensor Design

CoventorWare™ 2012

Material Properties Database and Process Editor

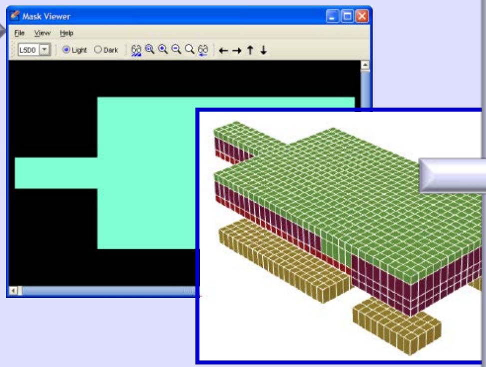
MEMS+

- MEMS behavioral modeling environment
- Based on Saber from Synopsys



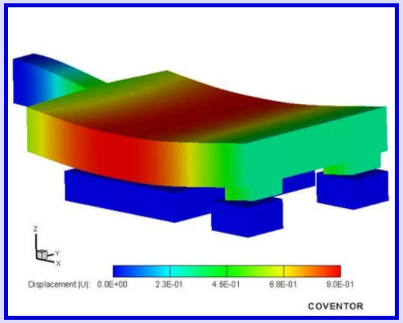
DESIGNER

- 2D Layout Editor
- Solid Modeler (2D to 3D)
- Preprocessor for FEA



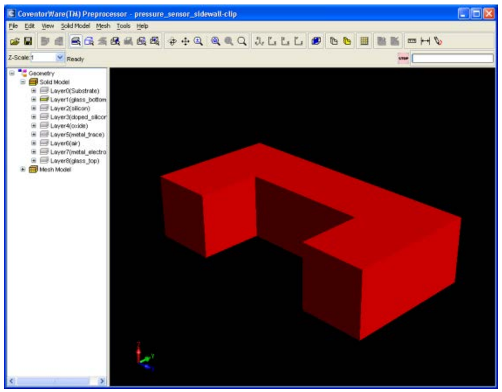
ANALYZER

- Suite of field solvers, hybrid FEM & BEM
- Comprehensive coverage for MEMS multi-physics

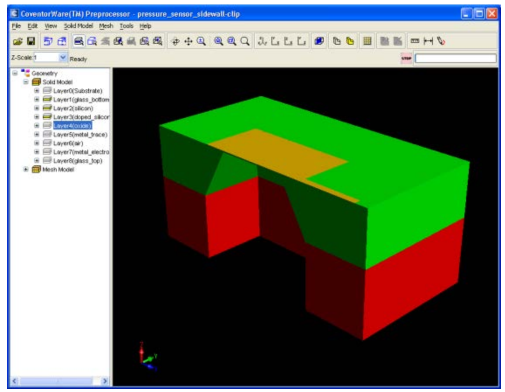


Capacitive Pressure Sensor

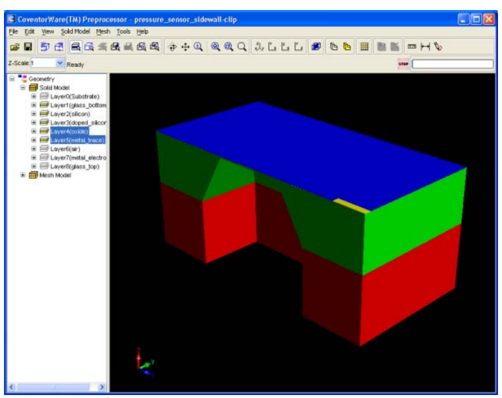
Bottom glass cap



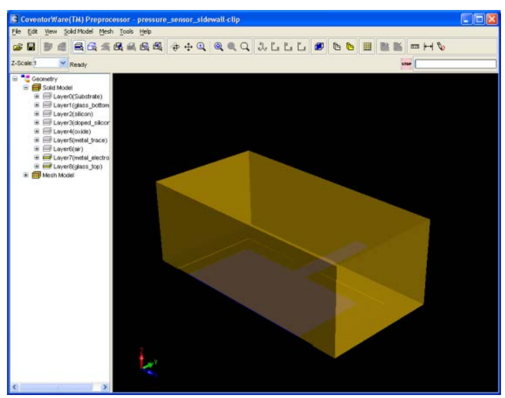
Back-side etch membrane doping



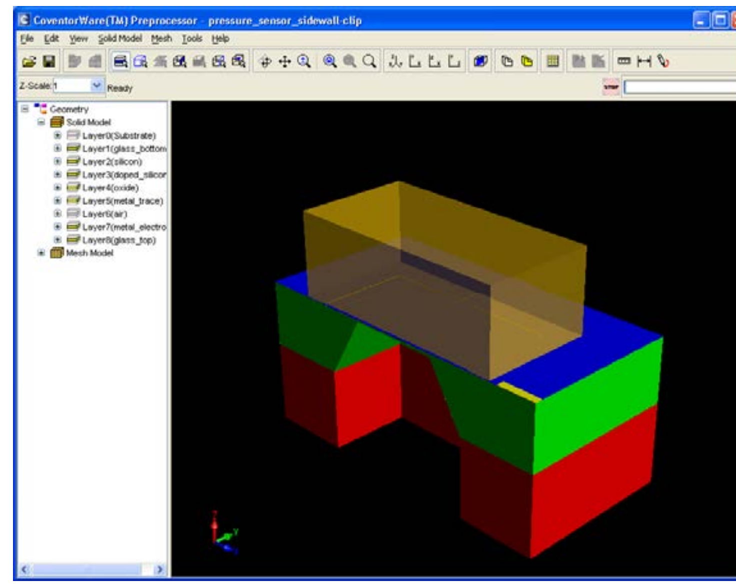
Passivation metal trace



Top glass cap sensing electrode

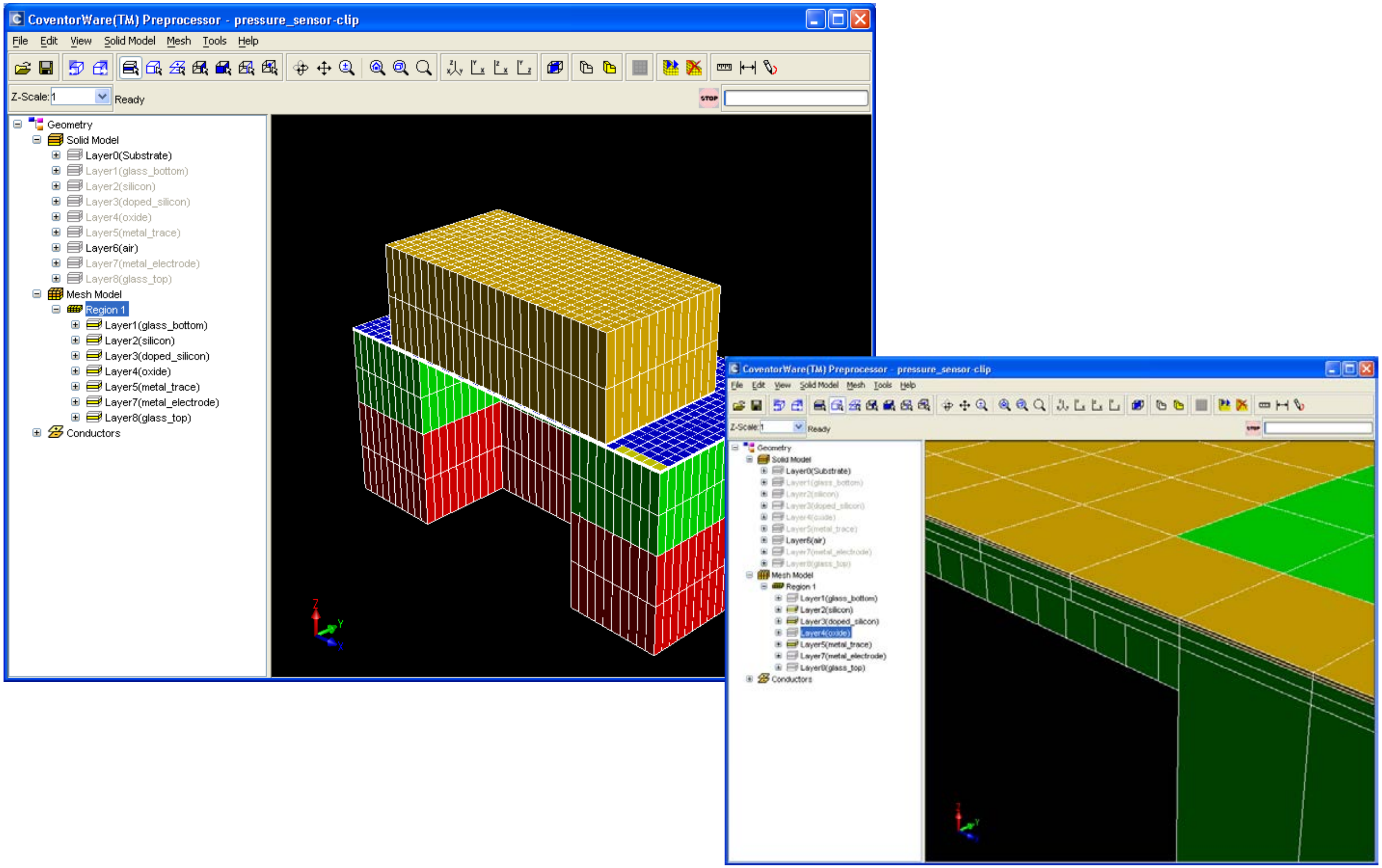


Device



COVENTOR

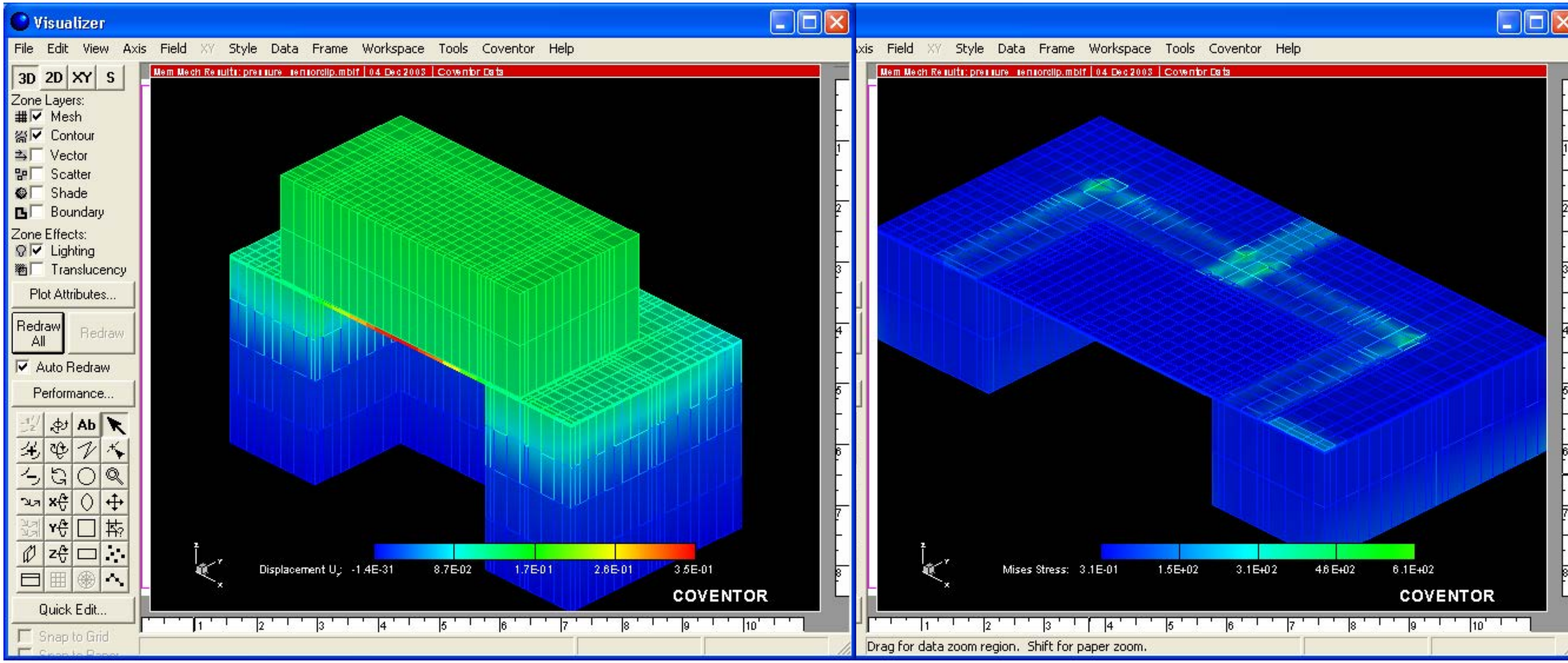
DESIGNER™: AutoMesher™



Effect of Silicon-Glass Stack

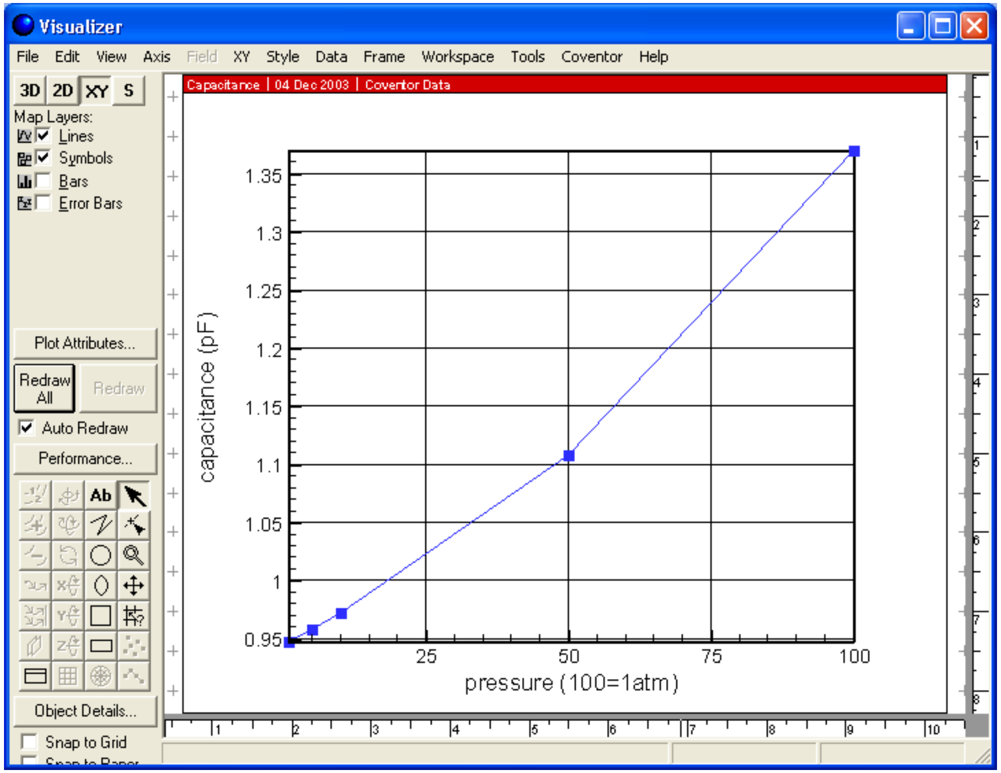
Z-displacement
T=100 ºC

Von-Mises stress
T=100 ºC



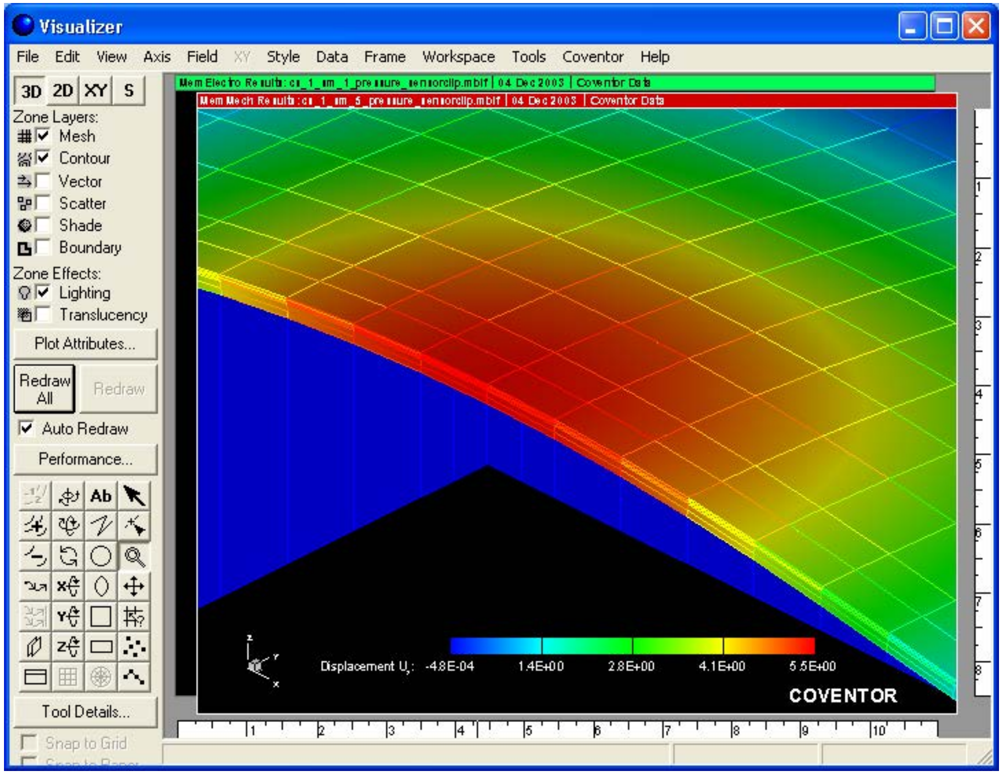
ANALYZER™: Capacitance

0-1 atm
25 °C
no residual stress
bias 5V



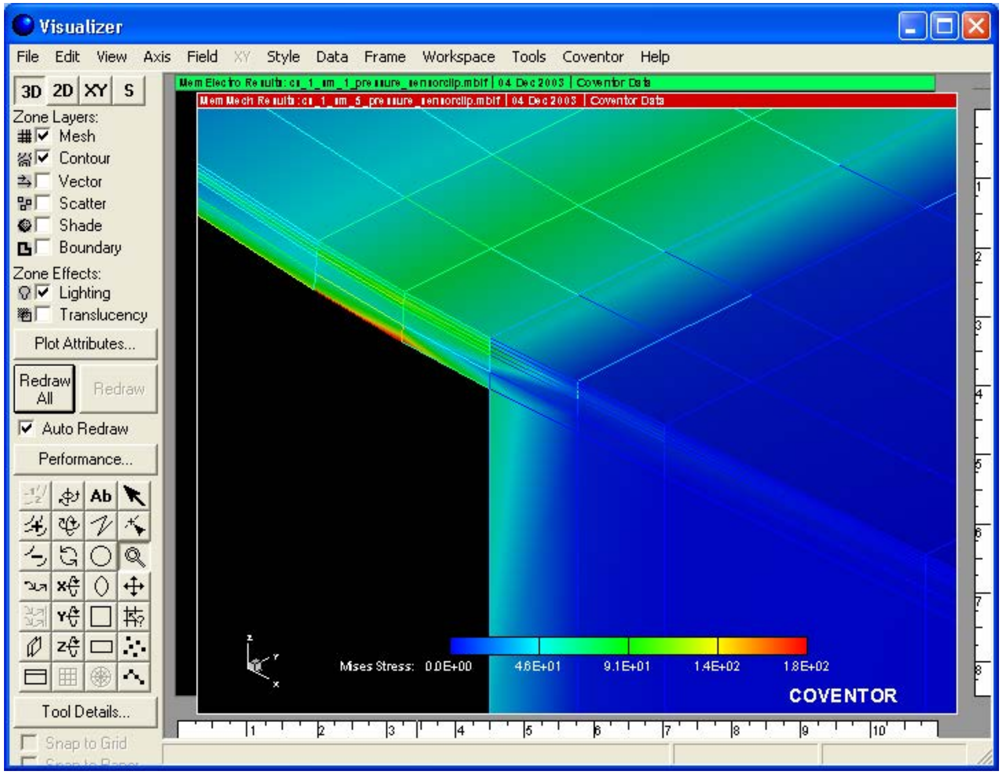
ANALYZER^{TM}: Z-displacement

1 atm
25 ^{o}C
no residual stress
bias 5V

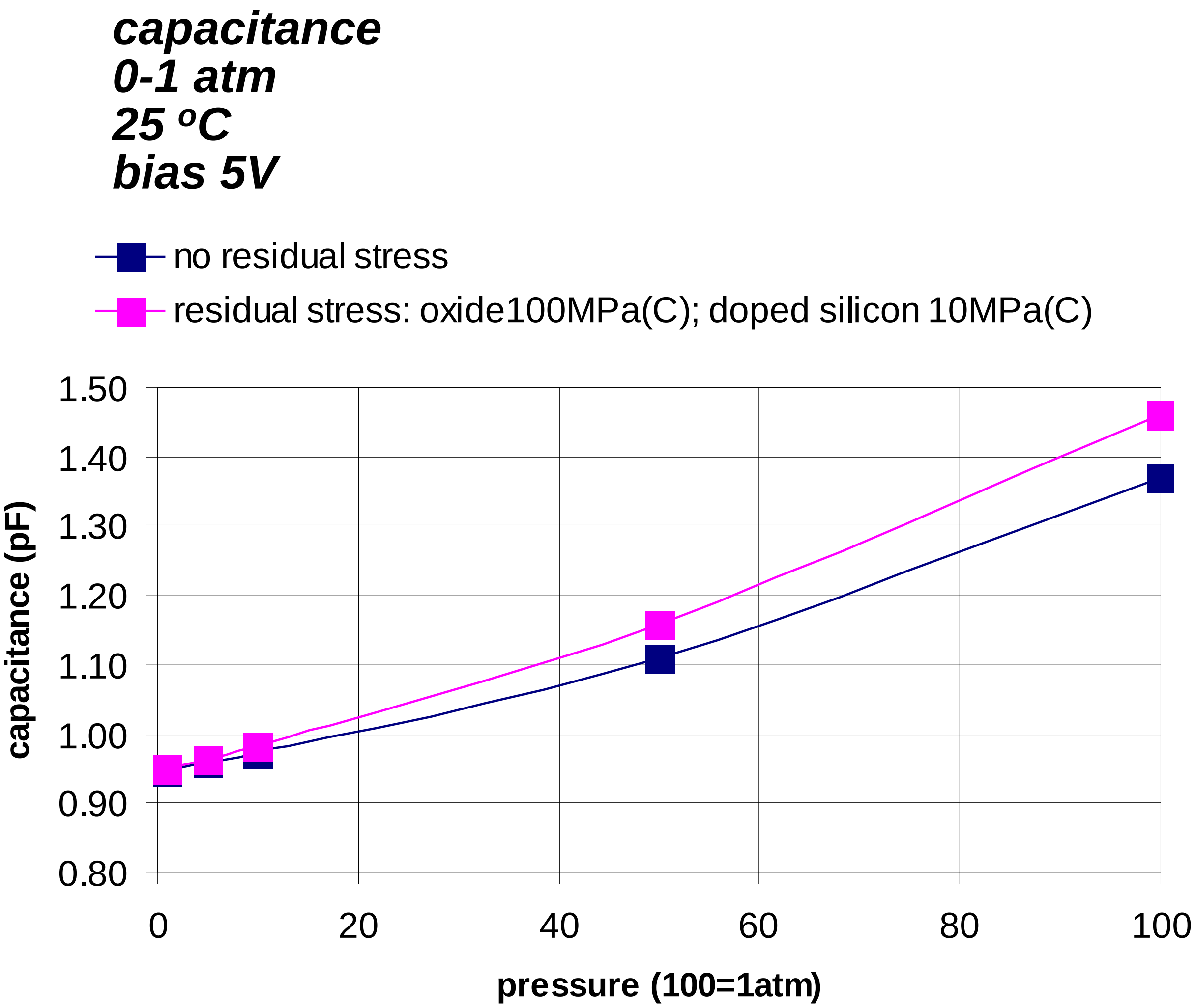


ANALYZER^{TM}: Von-Mises Stress

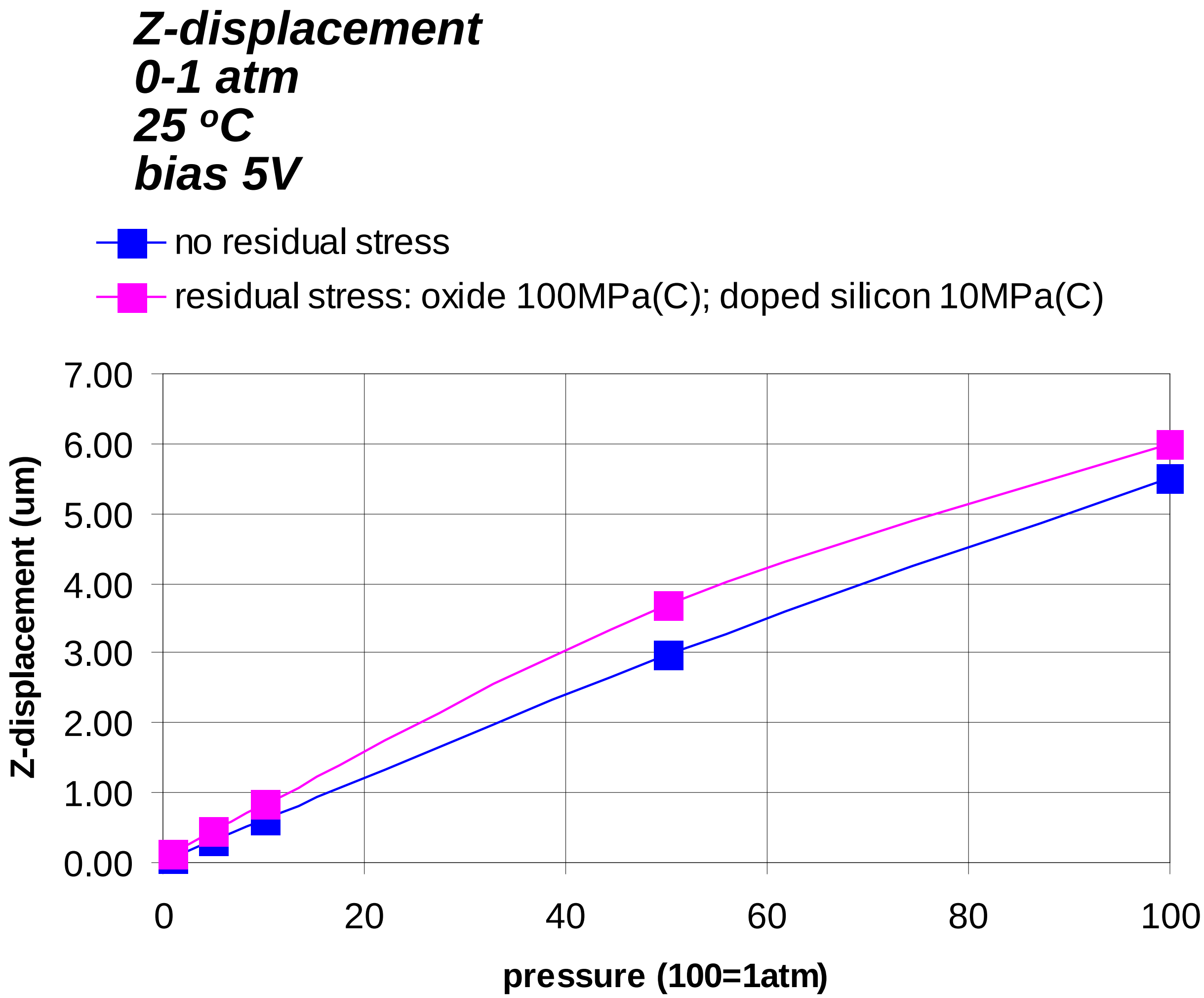
1 atm
25 ^{o}C
no residual stress
bias 5V



Effect of Residual Stress

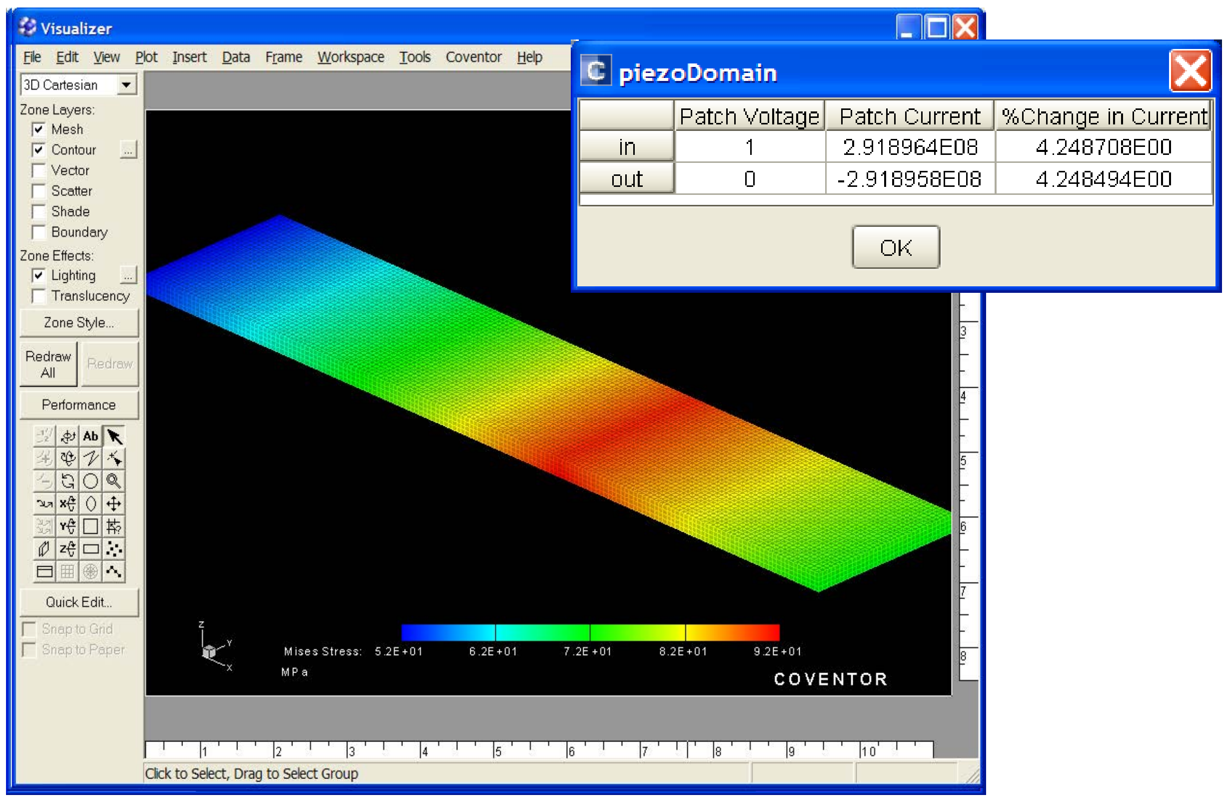


Effect of Residual Stress



MEMPZR

- MemPZR finite element solver
  - Stress mapped from mechanical mesh onto PZR mesh



ANALYSER™ Keypoints

- Developers of MEMS and Micro-fluidic devices use CoventorWare ANALYZER solvers to simulate the physics required
- ANALYZER incorporates all the physical field solvers necessary to successfully analyze, understand and verify these devices
  - Well-Established Finite Element solvers for mechanics, thermal, electrostatic, piezoresistive and piezoelectric problems
  - MEMS specific finite and boundary elements
  - MEMS specific physics
  - Simulations run in a Job queue
    - Status monitoring
  - Multi-core support
  - 64 bit support
  - Powerful results viewer
  - Many options on rendering, data calculation, macro recorder

Coventor Solutions for MEMS Capacitive Microphone
Design and Integration

Overview

Introduction

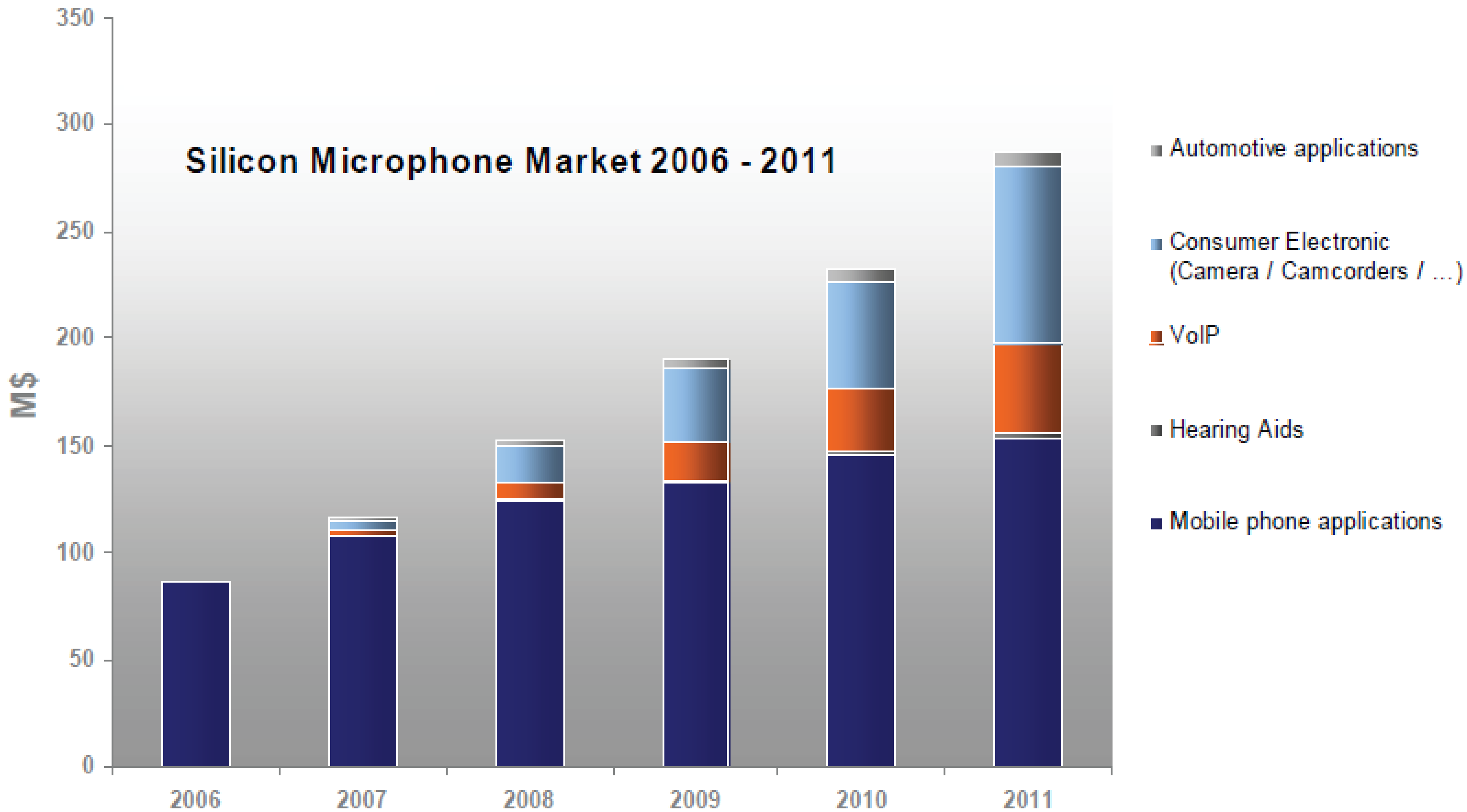
- Applications of Capactive MEMS Microphones
- A typical product spec and which specs be simulated
- Design and integration challenges

An example showing use of Coventor's tools

- Simulation sensitivity
- Simulation of electro-mechanics
- MEMS sensitivity noise analysis for SNR spec
- Design optimisation to minimize noise

Applications

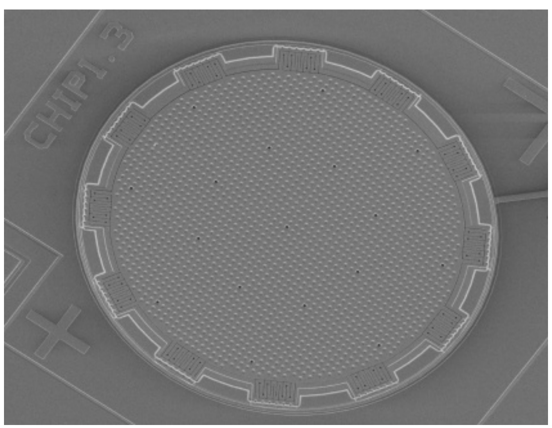
MEMS Capacitive Microphones



Source: Yole Development

Spec sheet for Microphone

Microphone specs that can be simulated with Coventor tools



ADMP404

SPECIFICATIONS

$T_A = 25°C$, $V_{DD} = 1.8$ V, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

Table 1.

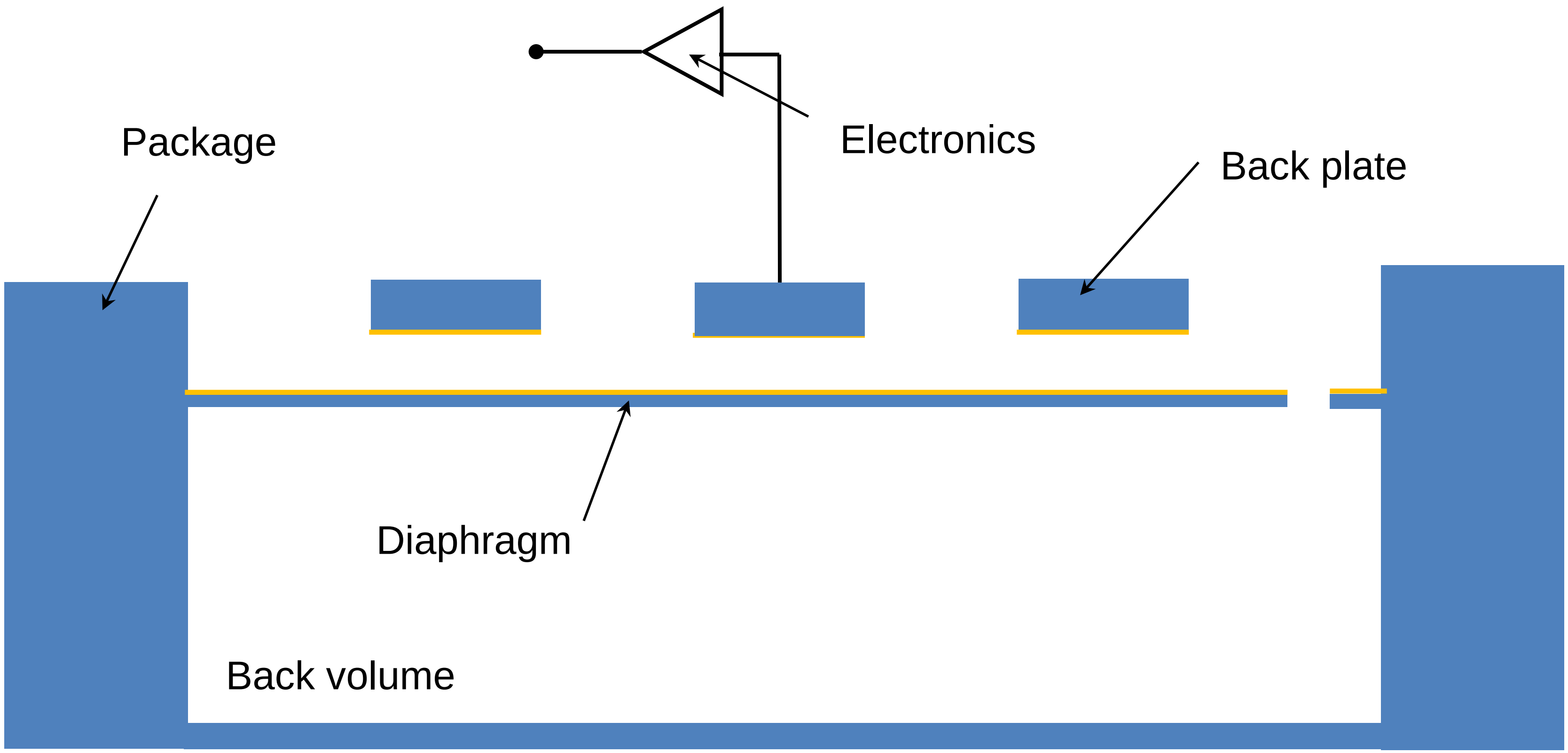
Parameter	Symbol	Test Conditions/Comments	Min	Typ	Max	Unit
PERFORMANCE						
Directionality				Omni		
Sensitivity		1 kHz, 94 dB SPL	−41	−38	−35	dBV
Signal-to-Noise Ratio	SNR			62		dBA
Equivalent Input Noise	EIN			32		dBA SPL
Dynamic Range		Derived from EIN and maximum acoustic input		88		dB
Frequency Response[1]		Low frequency −3 dB point		100		Hz
		High frequency −3 dB point		15		kHz
		Deviation limits from flat response within pass band		−3/+2		dB
Total Harmonic Distortion	THD	105 dB SPL			3	%
Power Supply Rejection Ratio	PSRR	217 Hz, 100 mV p-p square wave superimposed on $V_{DD} = 1.8$ V		70		dB
Maximum Acoustic Input		Peak		120		dB SPL
POWER SUPPLY						
Supply Voltage	V_{DD}		1.5		3.6	V
Supply Current	I_S				250	µA
OUTPUT CHARACTERISTICS						
Output Impedance	Z_{OUT}			200		Ω
Output DC Offset				0.8		V
Output Current Limit				90		µA

Capacitive Load Drive		1000			1000			1000			pF
PREFILTER HEADROOM			280			400			560		g
CFSR @ 400 kHz			5			4			3		V/V
POWER SUPPLY (V_{DD})		4.75		5.25	4.75		5.25	4.75		5.25	V
Functional Range		3.5		6	3.5		6	3.5		6	V
Quiescent Supply Current	$V_{DD} = 5$ V		1.3	2		1.3	2		1.3	2	mA
TEMPERATURE RANGE		−40		+105	−40		+105	−40		+105	°C

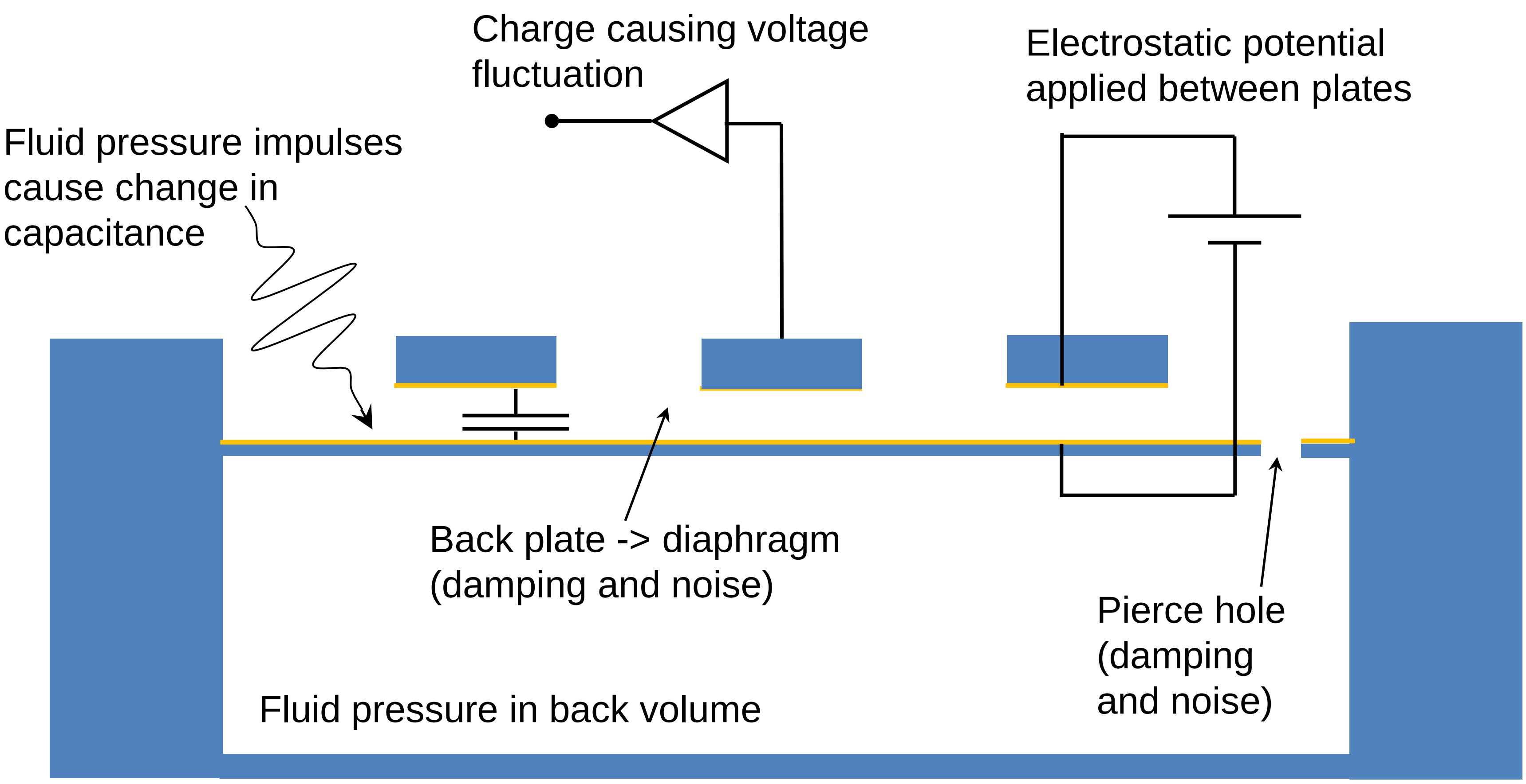
Design and Integration Challenges

Architecture: Multi domain physics

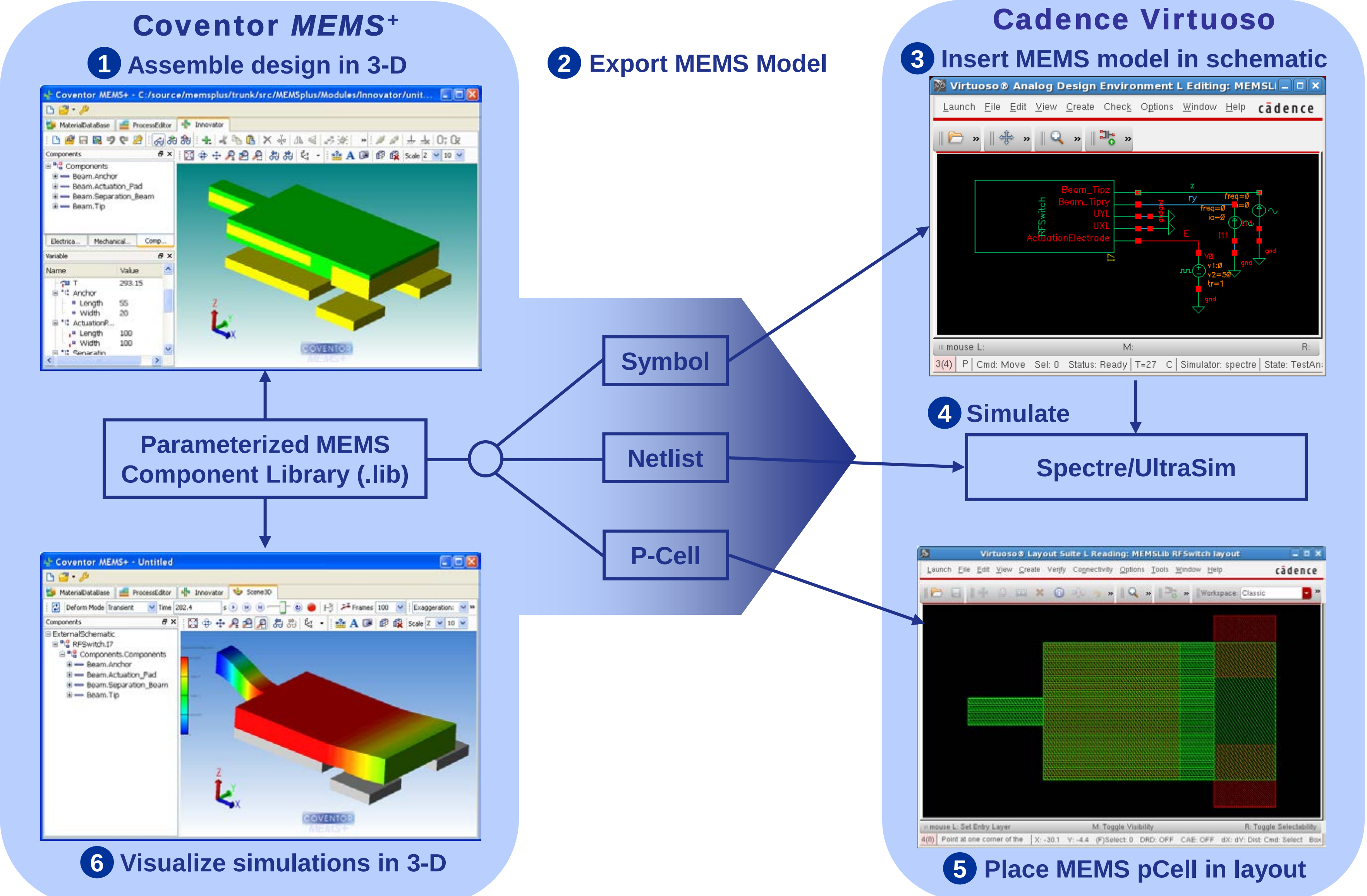
- Mechanics, electrostatics, fluidics & electronics



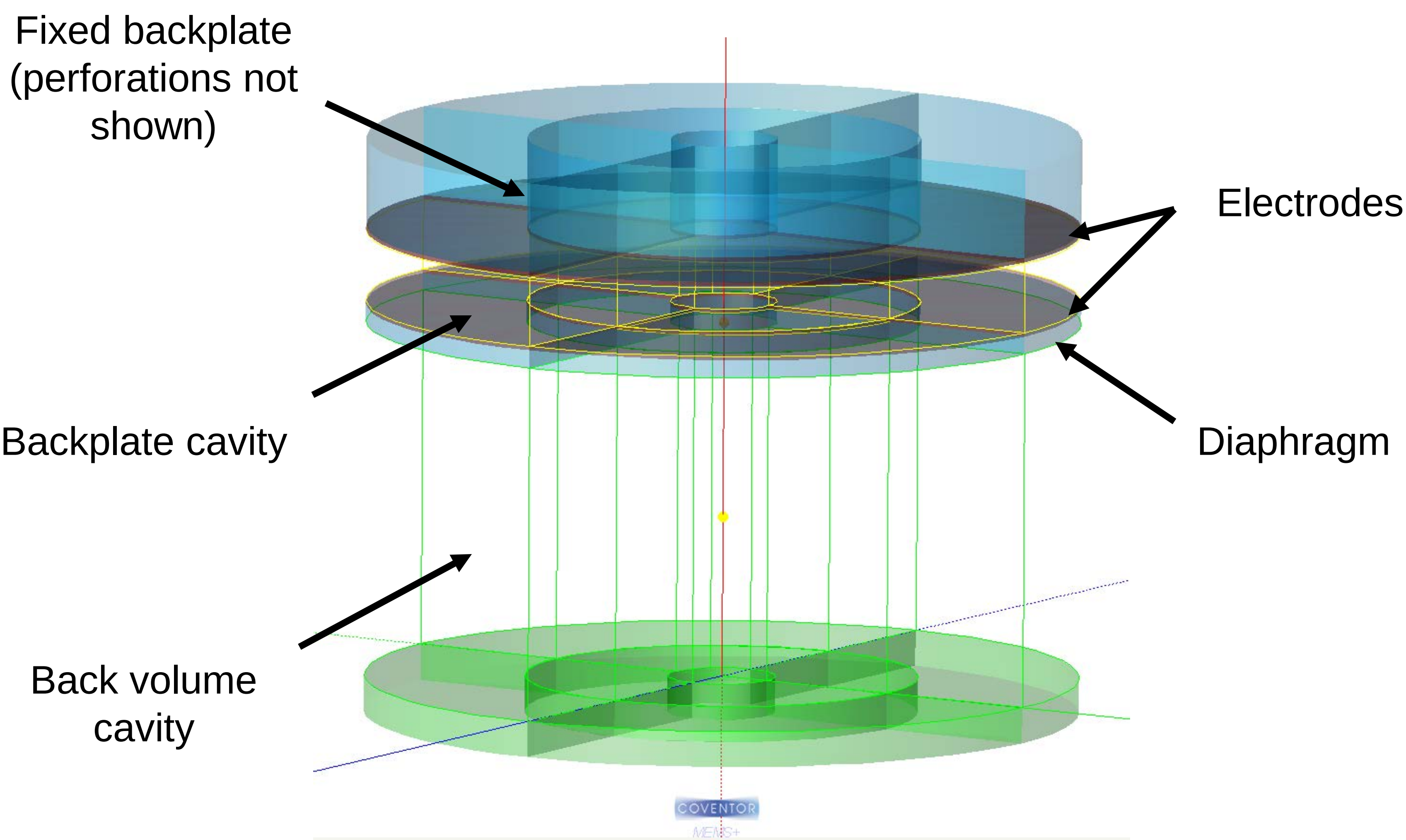
Co-simulation of:



Coventor MEMS+ for Cadence Virtuoso



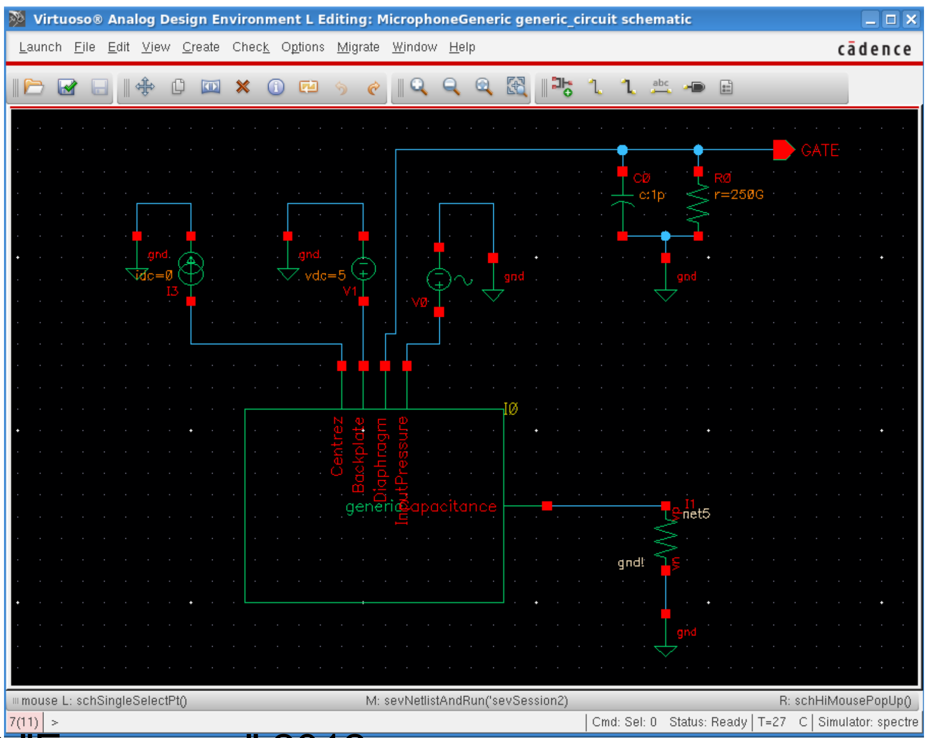
MEMS+ Model

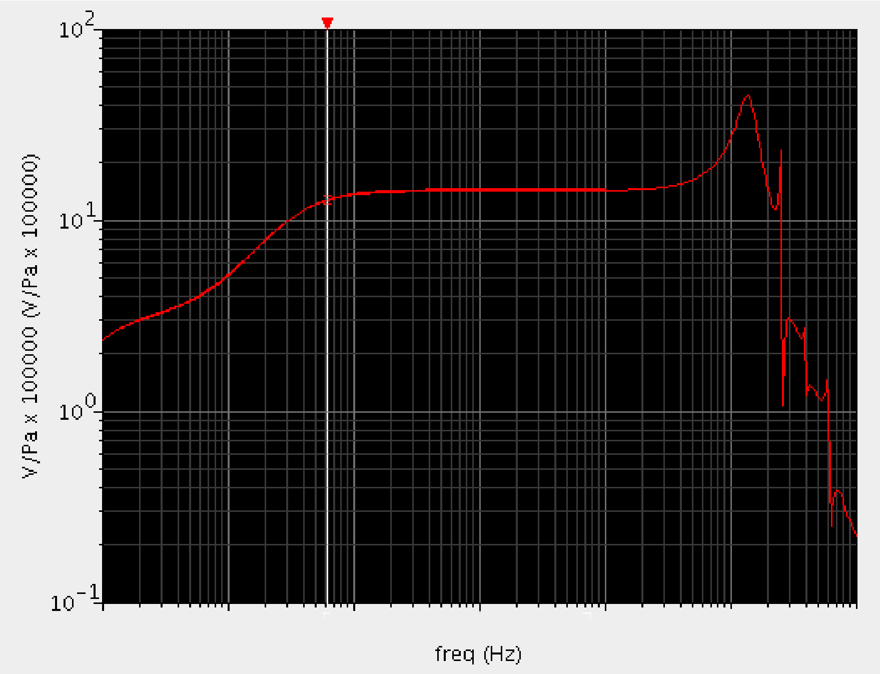


Fixed backplate (perforations not shown)
Electrodes
Backplate cavity
Diaphragm
Back volume cavity
COVENTOR
MEMS+

Sensitivity Simulation

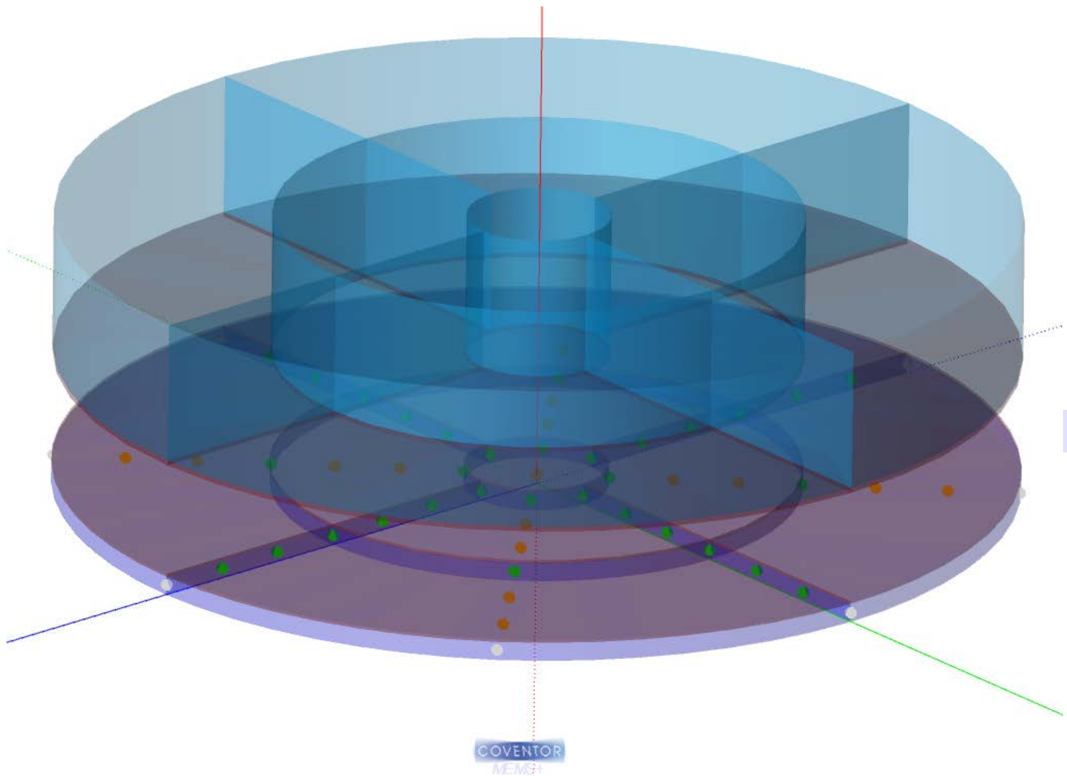
- Fully coupled simulation between microphone and IC
  - **Sensitivity**,
  - d.c., a.c., transient, noise.
  - Monte-Carlo, optimization
    - Enabled by parametric model



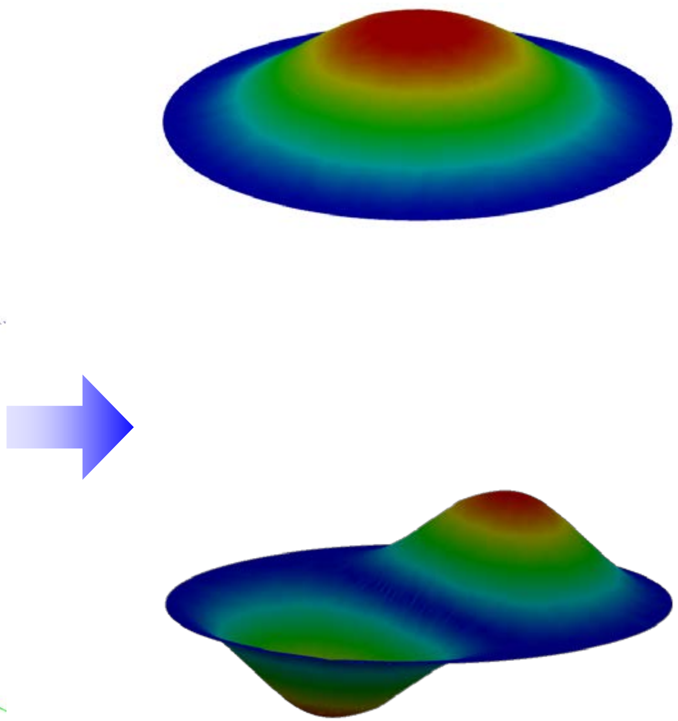


ElectroMechanical Device Simulation

- Microphone with perforated back plate using circular and arc shaped flexible plates with pressure loads and electrodes



(Perforation are not shown in the image)



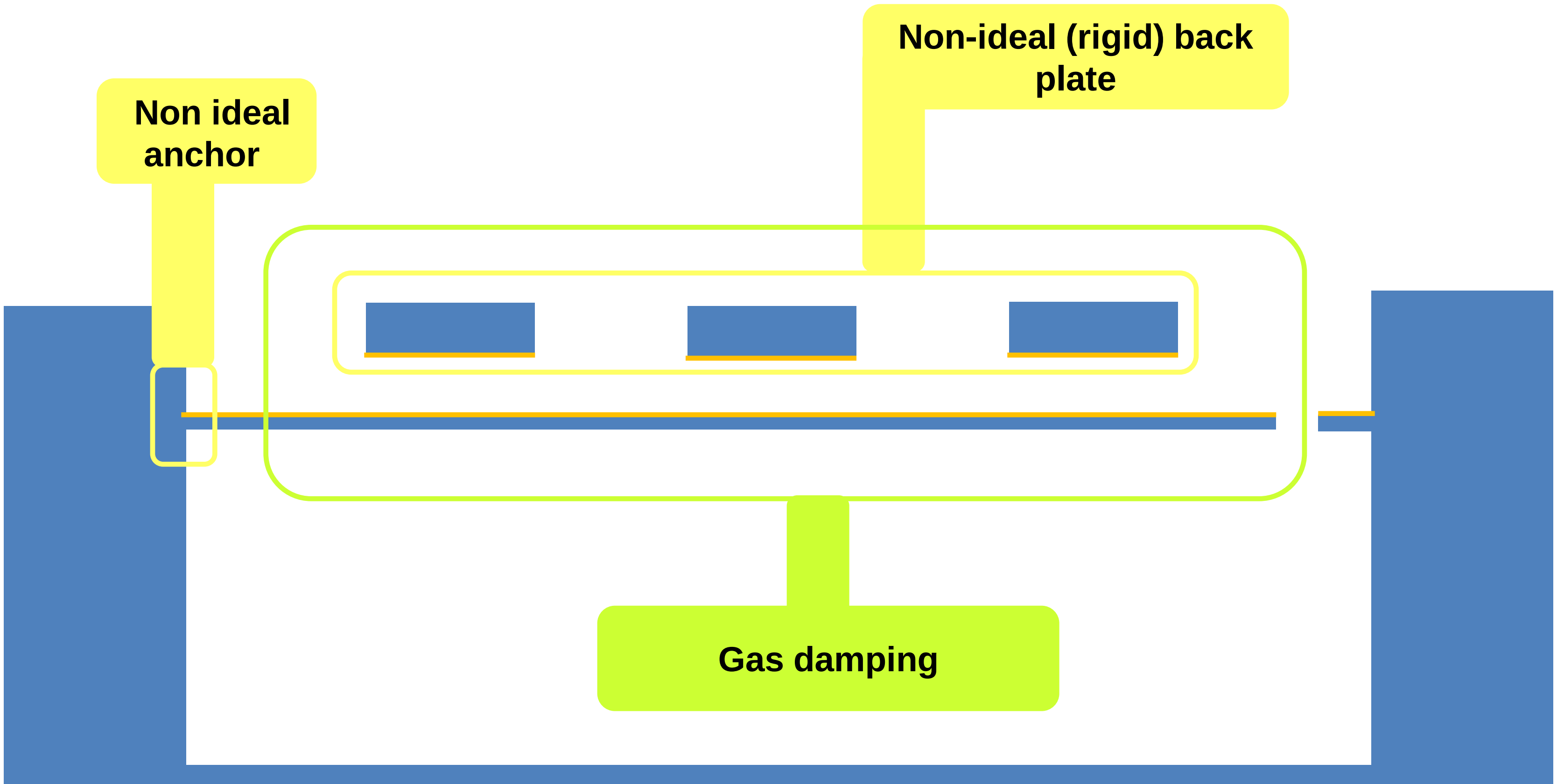
Results of a Modal
Analysis with Cadence or Matlab/Simulink

ElectroMechanical Detailed Design

COVENTOR

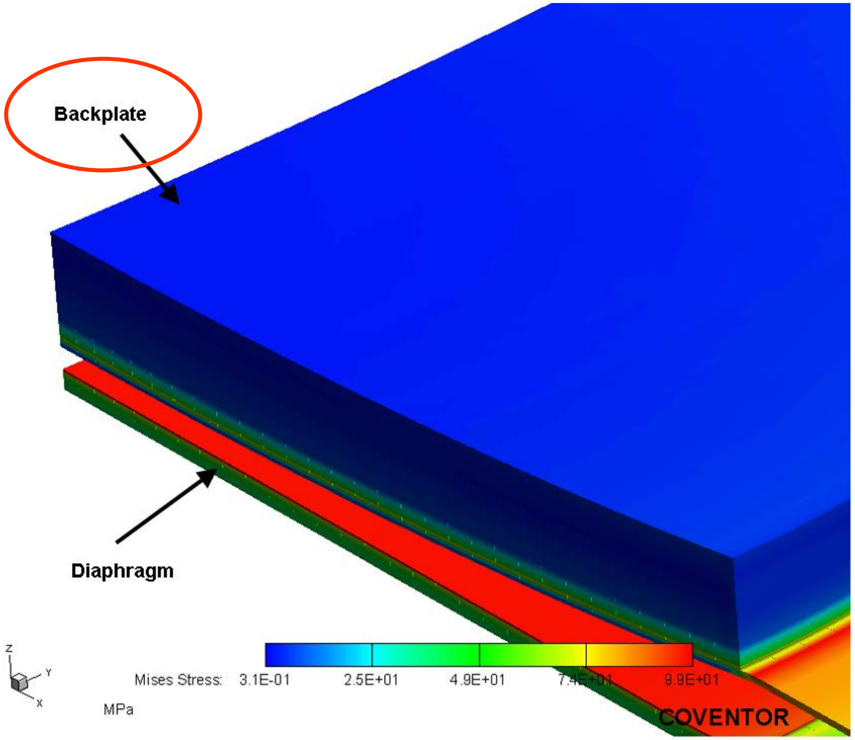
Analyzer, MemMech

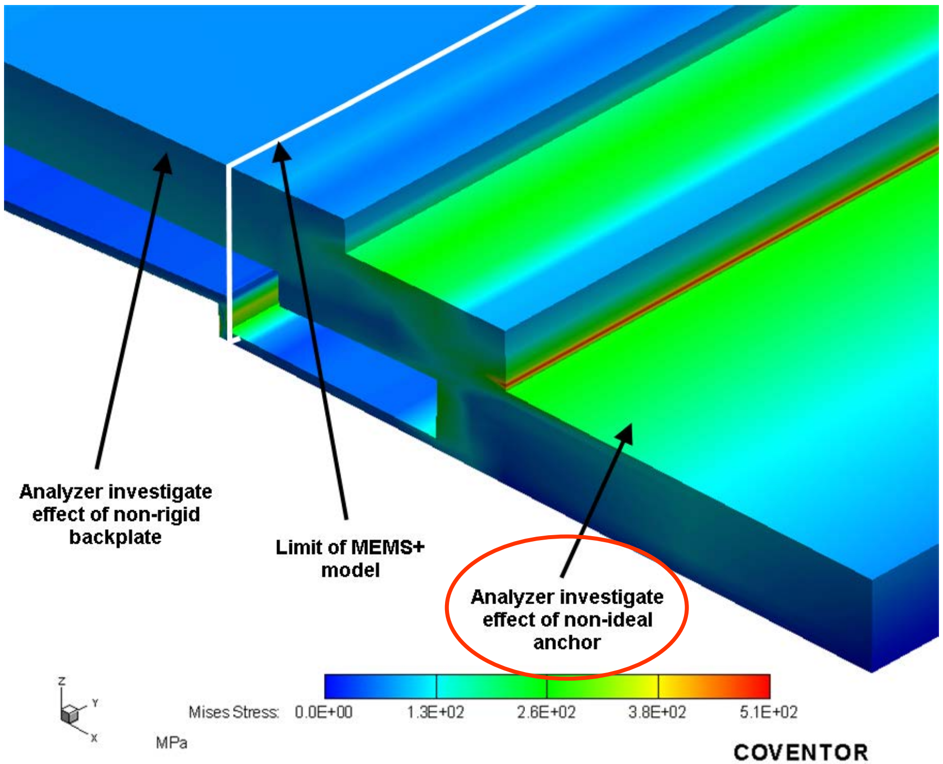
Analyzer, DampingMM



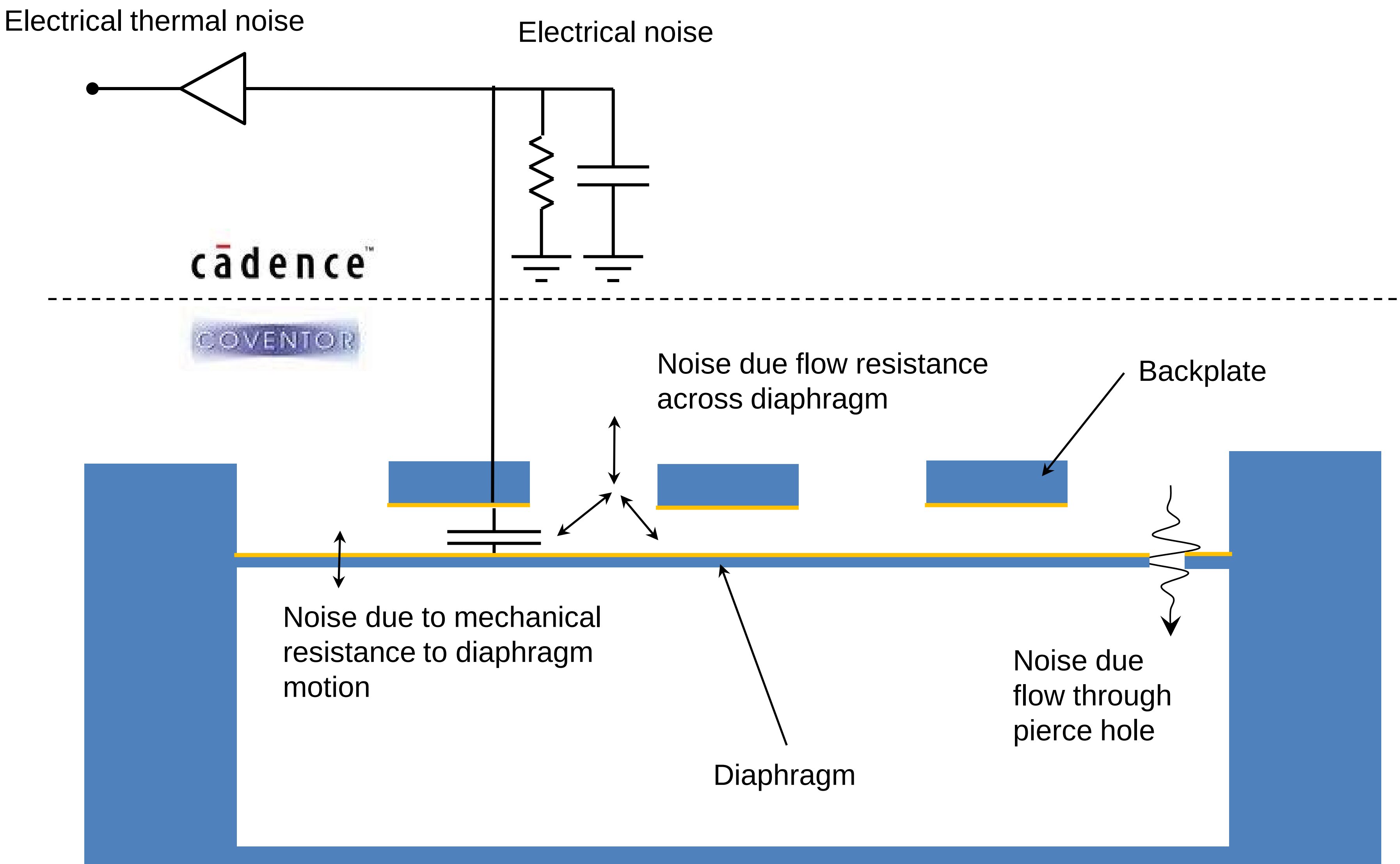
ElectroMechanical Detailed Design

- Determine effect backplate stiffness
- Determine effect of non ideal anchor on diaphragm stiffness



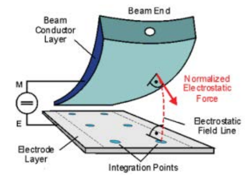


MEMS Microphone noise sources

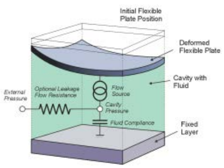


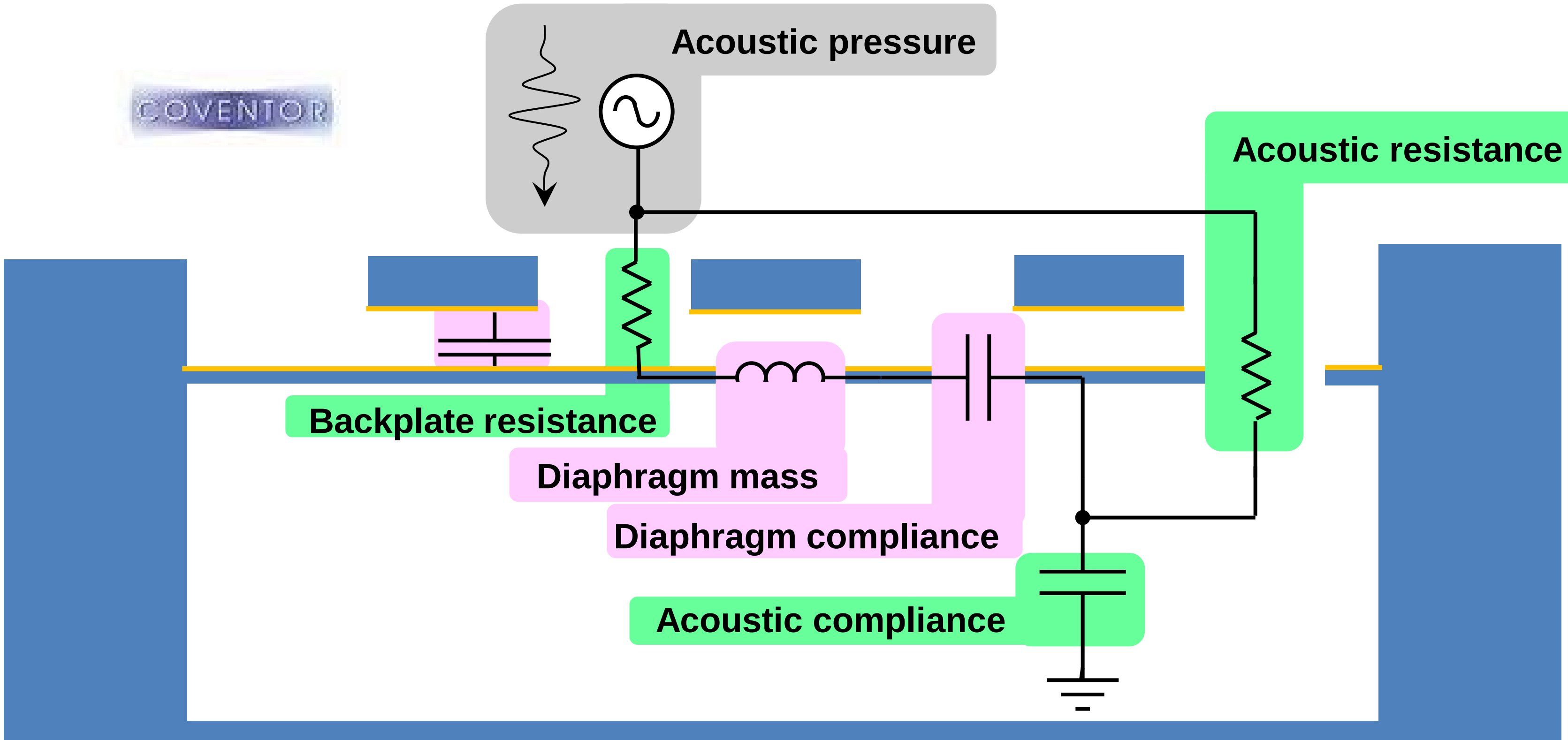
MEMS Microphone noise sources

MEMS+ Flexible plate electrode model



MEMS+ Cavity model supports noise

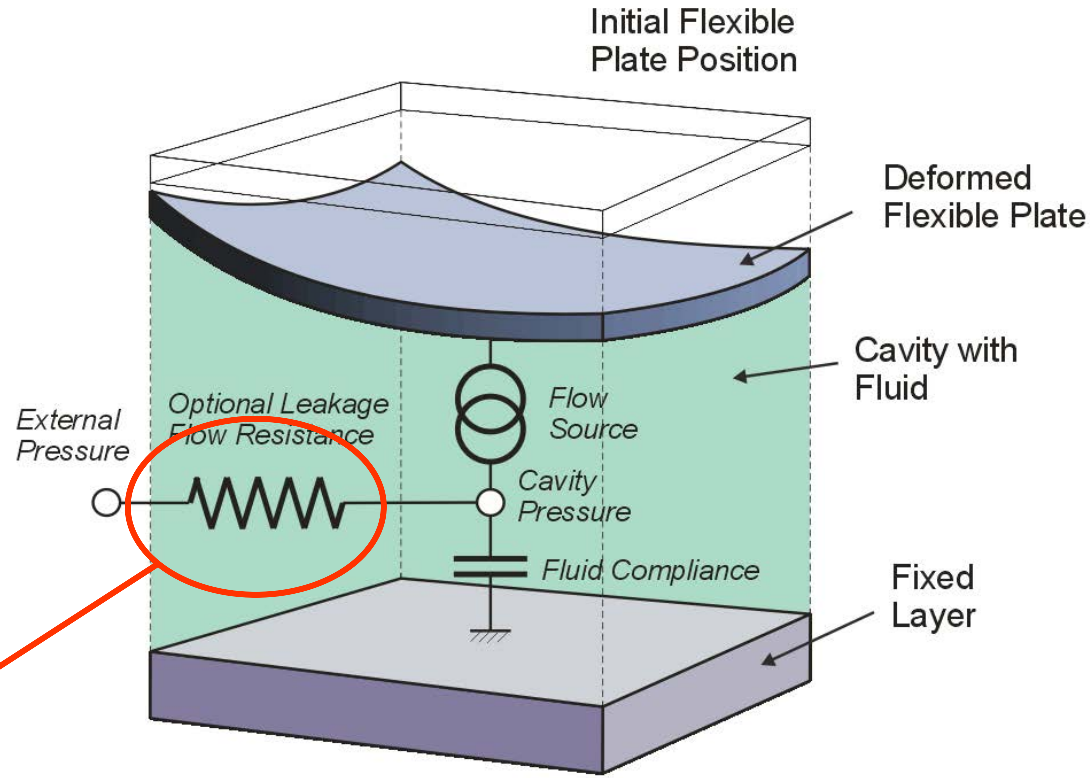


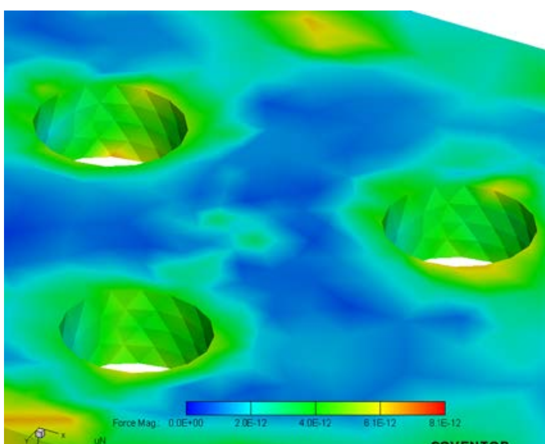


MEMS+
Cavity Model

- The Cavity component is an add-on to all MEMS+ flexible plate models for Microphones

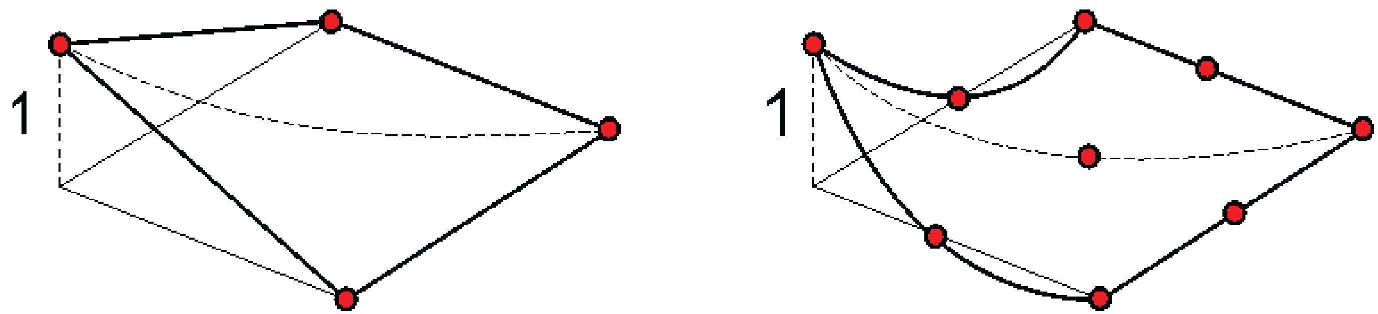
- Models the effect of a fluid trapped in a cavity underneath of above a flexible plate.
- Fluidic connector for the cavity pressure and an optional pressure connector for the external pressure
- The model supports the Cadence noise analysis



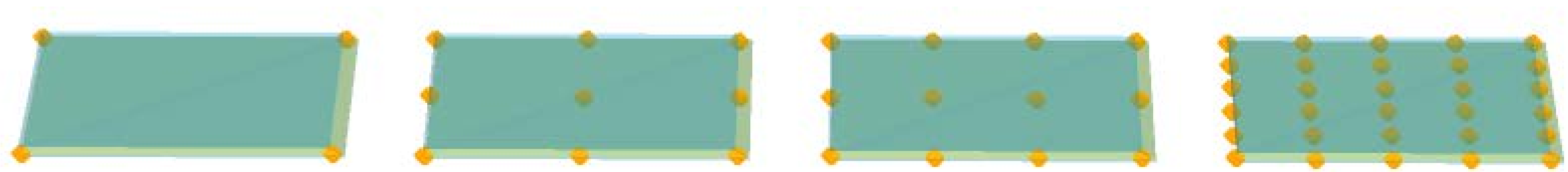


Flexible Plate Model

- The individual layers of each plate component are modeled by a **finite shell element** known as MITC (mixed interpolation of tensorial components)
- The approximation of the shell edges is defined by the number of mechanical connectors being used

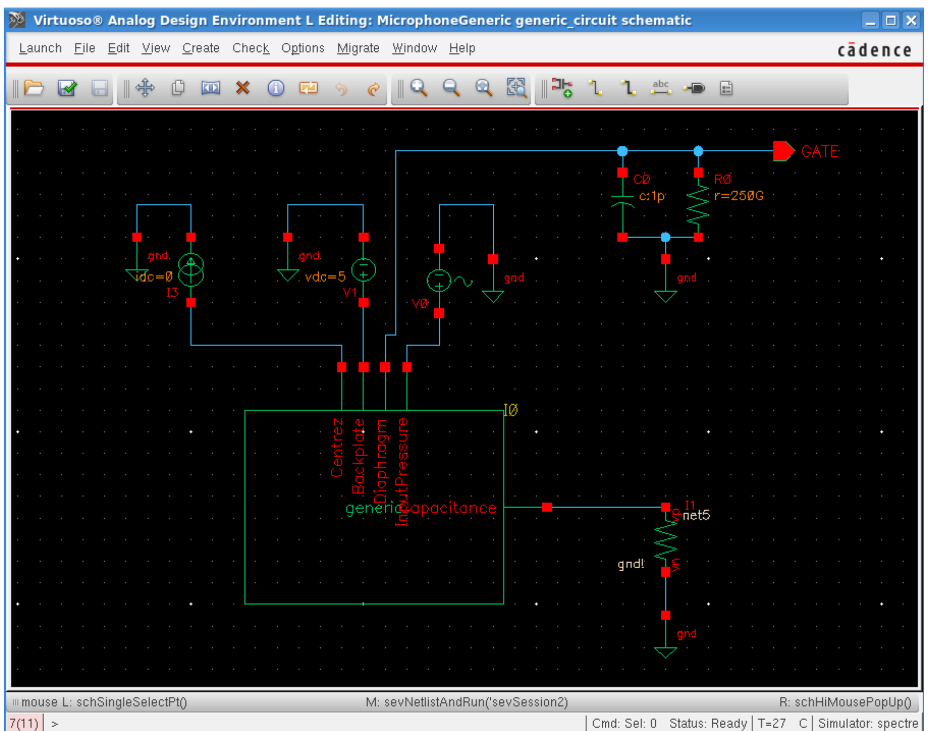


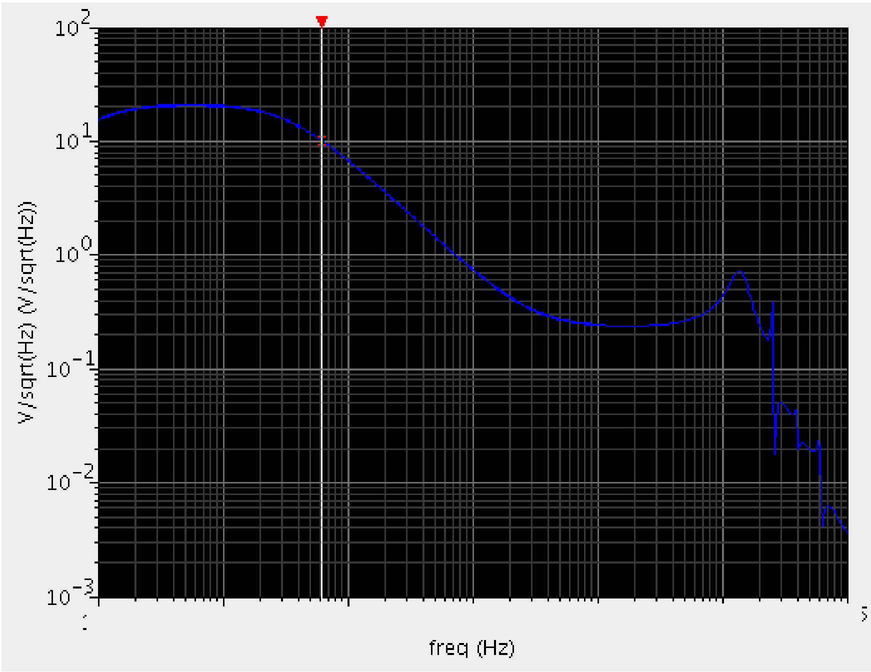
- The number of mechanical connectors can be set in the parameters of the corresponding plate component



Noise

- Fully coupled simulation between microphone and IC
  - **Noise**,
  - d.c., a.c., transient
  - Monte-Carlo, optimization
    - Enabled by parametric model





Advantages for Microphone simulation

Microphone model from MEMS+

- State of the art flexible plate and cavity model suitable for microphones
  - Mechanical and electrical non-linearity
    - Stress, stress gradient, inertial force, contact
  - Electrode perforations for fringing fields
  - Motion in 6 degrees of freedom
  - Flow compliance, resistance, intertance
  - Parametric
- Leverage 20 man years of model development
  - Physics *and* simulation performance

Microphone + IC model simulations in Cadence

- Fully coupled simulation between microphone and IC
  - d.c., a.c., transient, **noise**, sensitivity, Monte-Carlo, optimization

Validate, verify design details with FEA/BEM tools

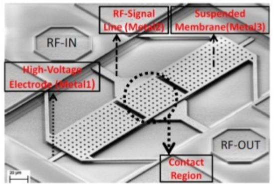
Coventor Solutions for RF Switch Design and Integration

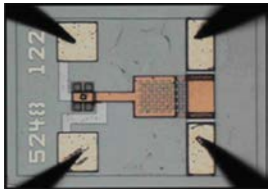
RF MEMS - A Variety of Applications

COVENTOR

MEMS Switches

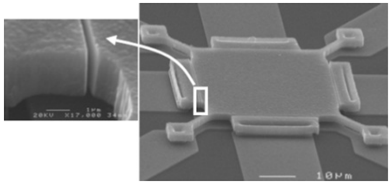
- Transmit/Receive Duplexers (TDD)
- Band/Mode Selection
- Time-Delay for Phased-Arrays
- Antenna Diversity
- Reconfigurable Antennas

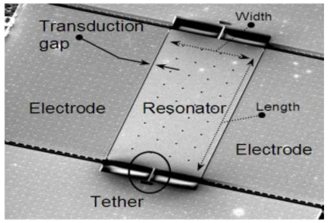




MEMS Filters (Resonators)

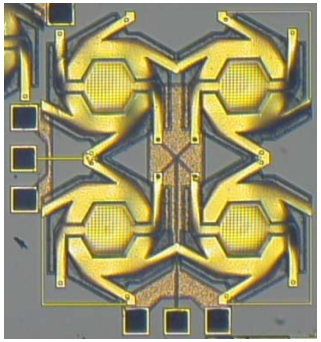
- Transmit/Receive Duplexers (FDD)
- Band-Select Filters
- IF Channel Filters
- Image Rejection
- RF Filter Bank
- VCO Stabilization
- Self-Filtering Mixers





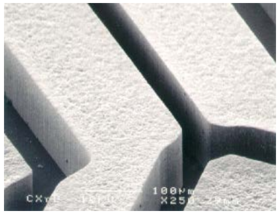
MEMS Varactors

- VCO Tuning
- Variable Matching
- Variable Delay Lines
- Variable Filters



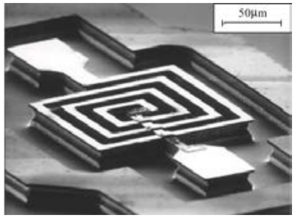
Micromachined Transmission Lines

- Filters / Diplexers
- Antennas
- Antenna Array Manifolds



MEMS Inductors

- Oscillator Tank Circuits
- LC Filters
- Bias & Matching Circuits



Challenges of RF MEMS

COVENTOR

Specialized Physics

- 3D electrostatics
- Electro-mechanical coupling
- Energy loss mechanisms
- Piezoelectric, magnetic,…
- Residual stresses
- Contact forces
- Sticking

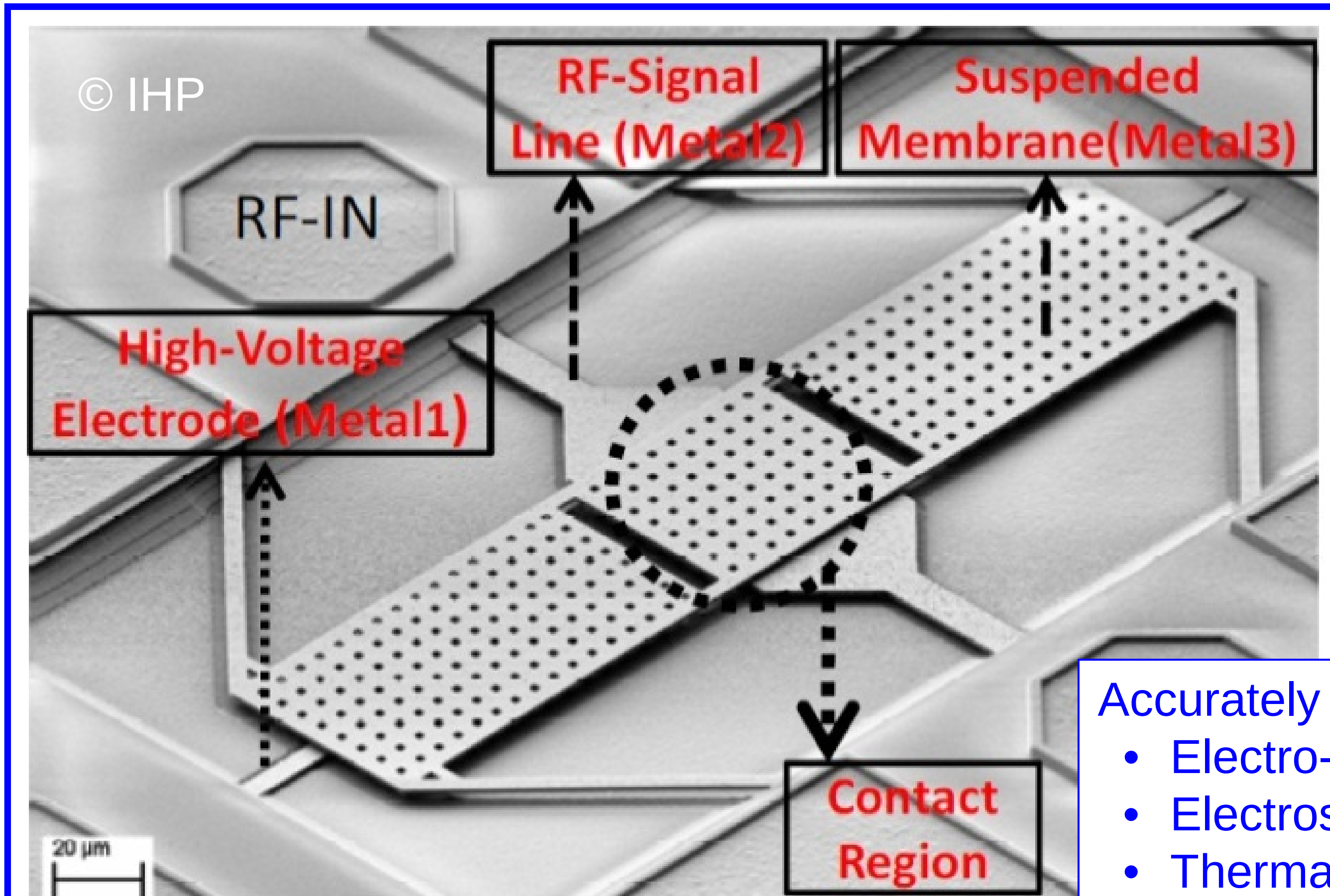
Integration Challenges

- Different processes
- Different packaging
- MEMS co-design with IC and RF
- Different design tools

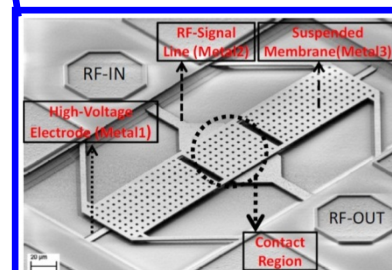
~~“Build & Test”~~
~~Product Development~~

Coventor’s Mission:
Replace *build & test*
with simulation

Example: RF MEMS Switch



ical Transduction



Relays, switches and varactors

Angular rate (gyroscopes)

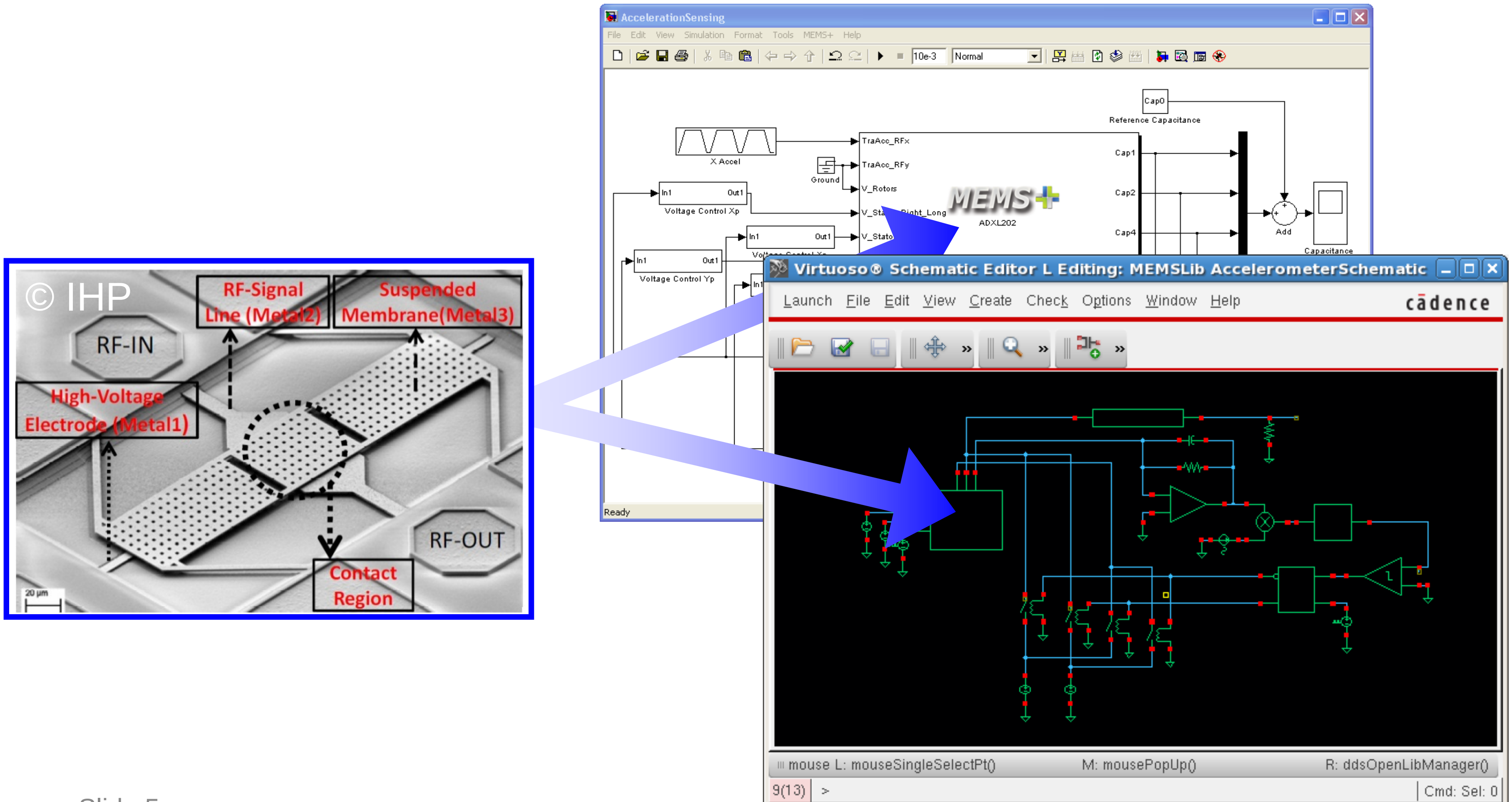
(Qua

Accurately simulate

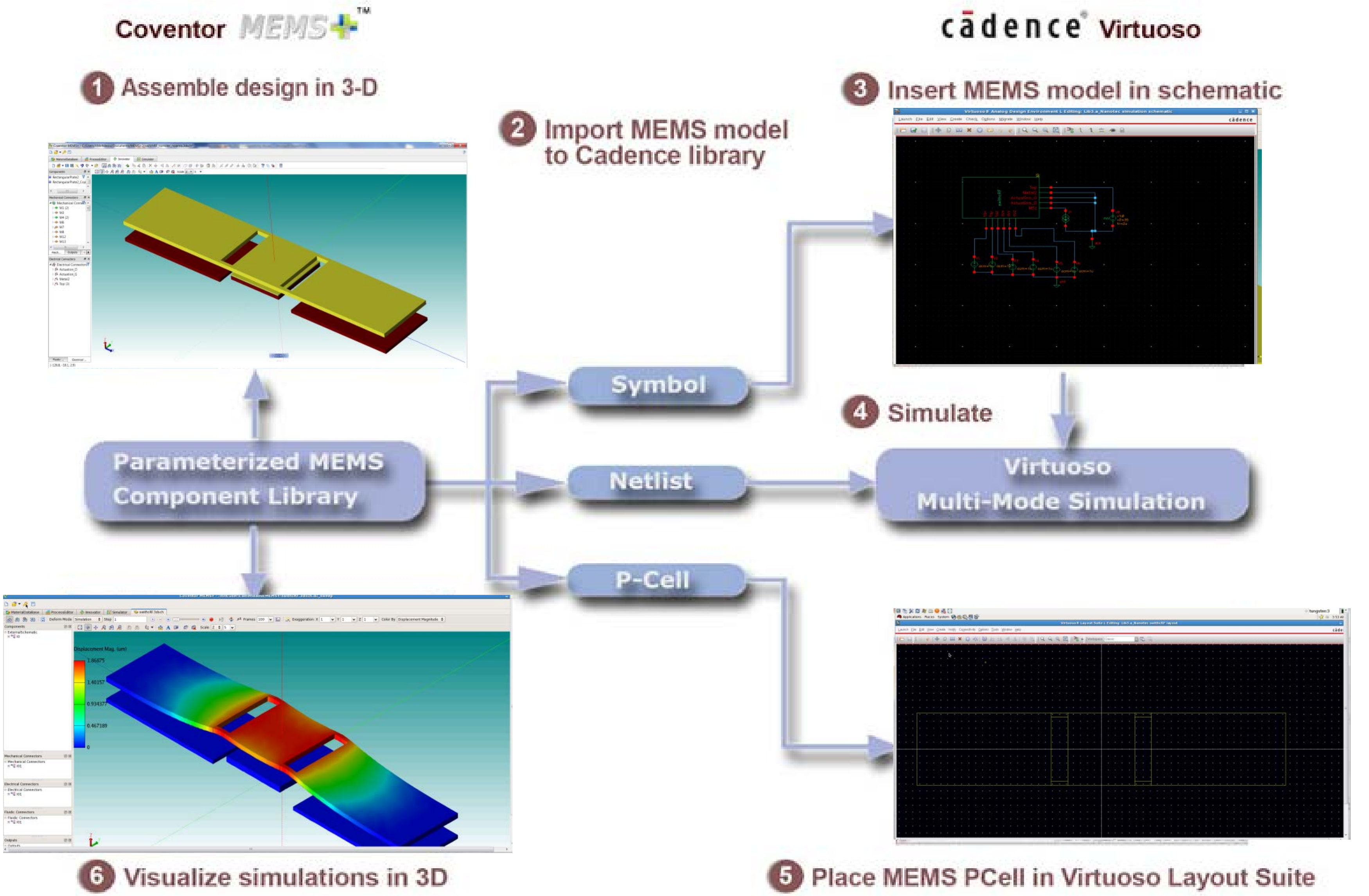
- Electro-mech. coupled actuation
- Electrostatic fringing fields
- Thermal sensitivity
- Gas damping effects
- Actuation voltage (pull-in)
- Switching time
- Contact force …

MEMS+IC Integration Challenge

IC designers and system architects require a MEMS device block for their schematic-based simulation environment of choice

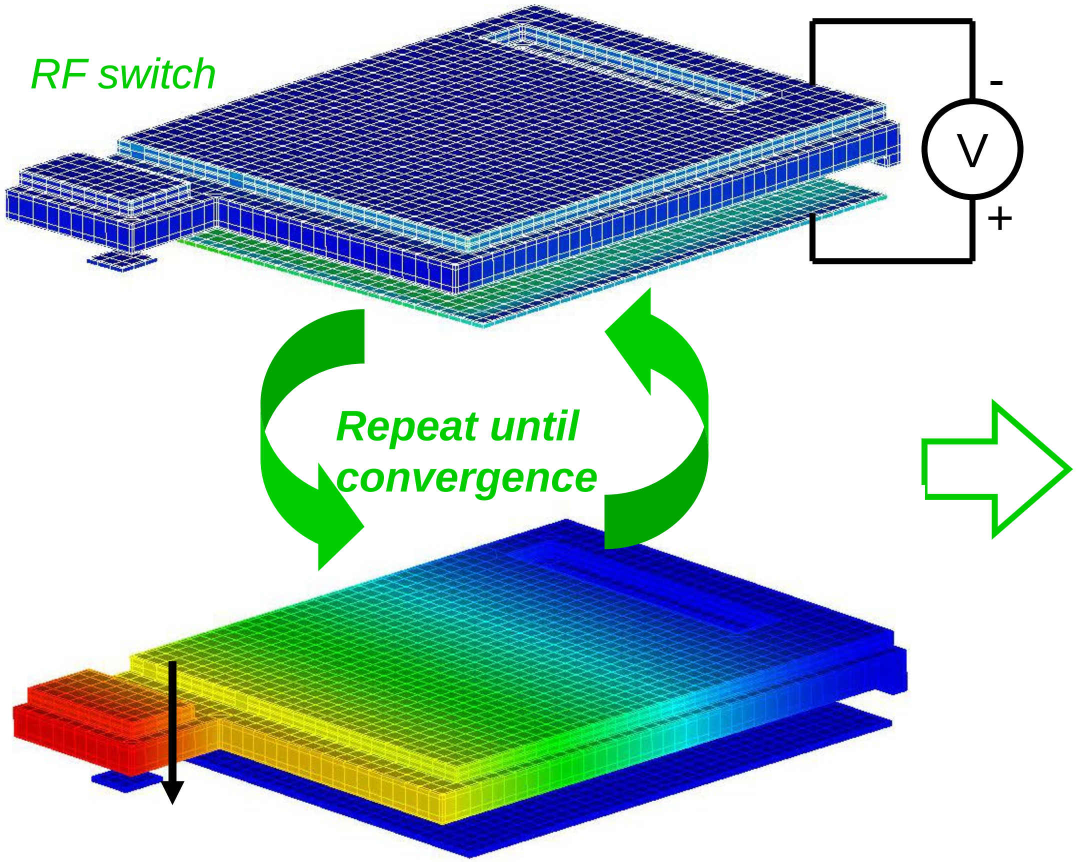


MEMS+ with Cadence

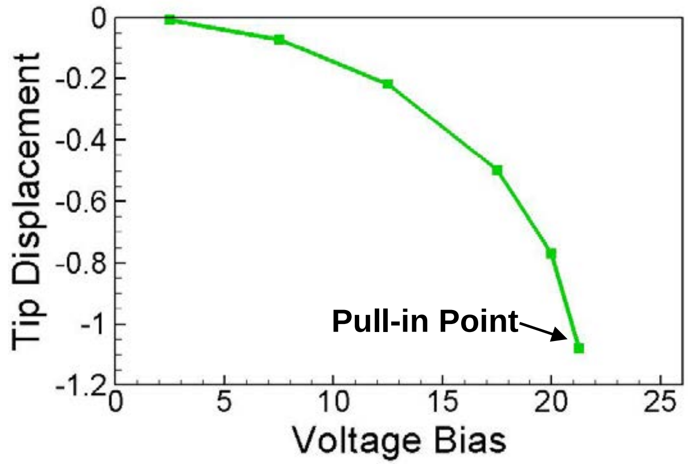


CoventorWare:
Coupled Electro-Mech. Field Solver

BEM solver for electrostatic force due to bias voltage
-- uses surface mesh

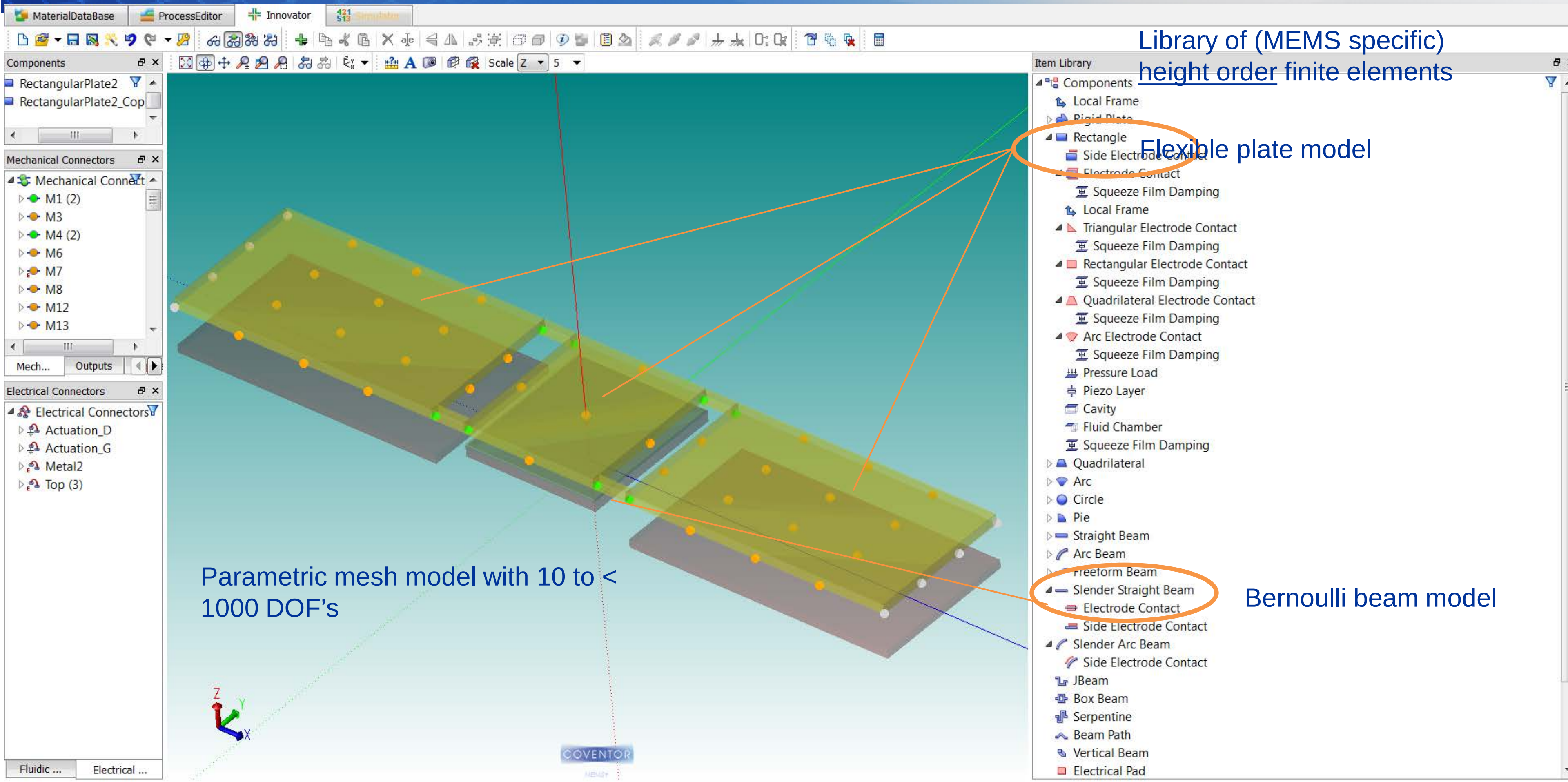


"Pull-in" Result
-- find last stable voltage



FEM solver for solid mechanics displacement
-- uses volume mesh

MEMS+ Innovator
(3D Design Entry)



MEMS+ Innovator

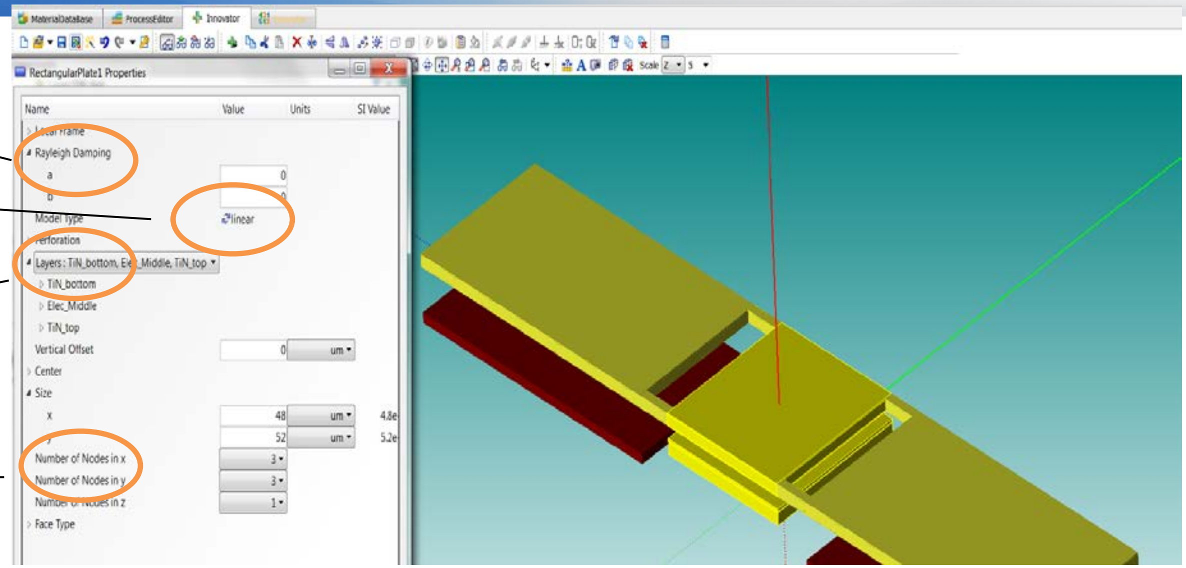
COVENTOR

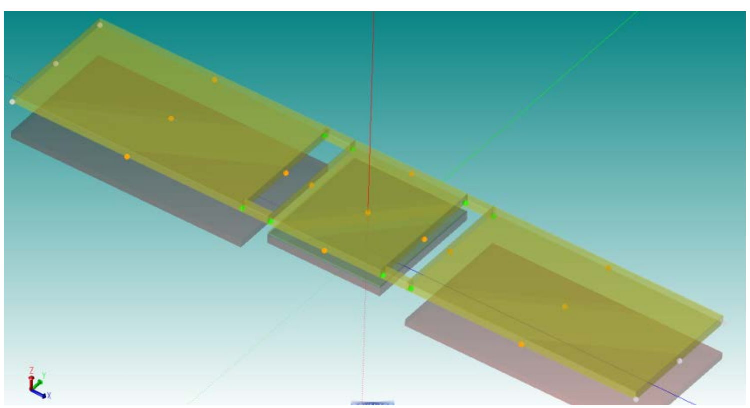
Rayleigh damping

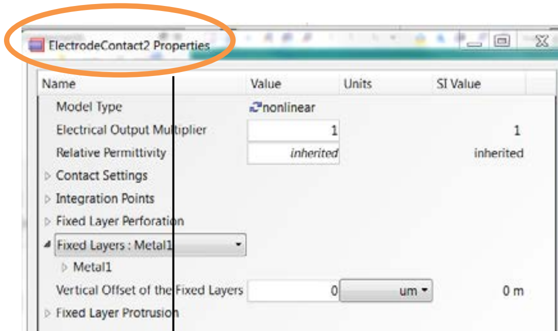
Model type : Linear or no linear

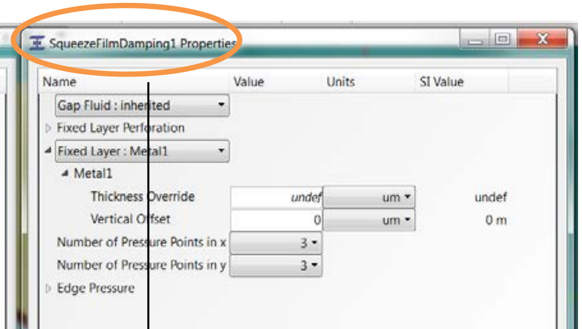
Layers definition

Number of nodes





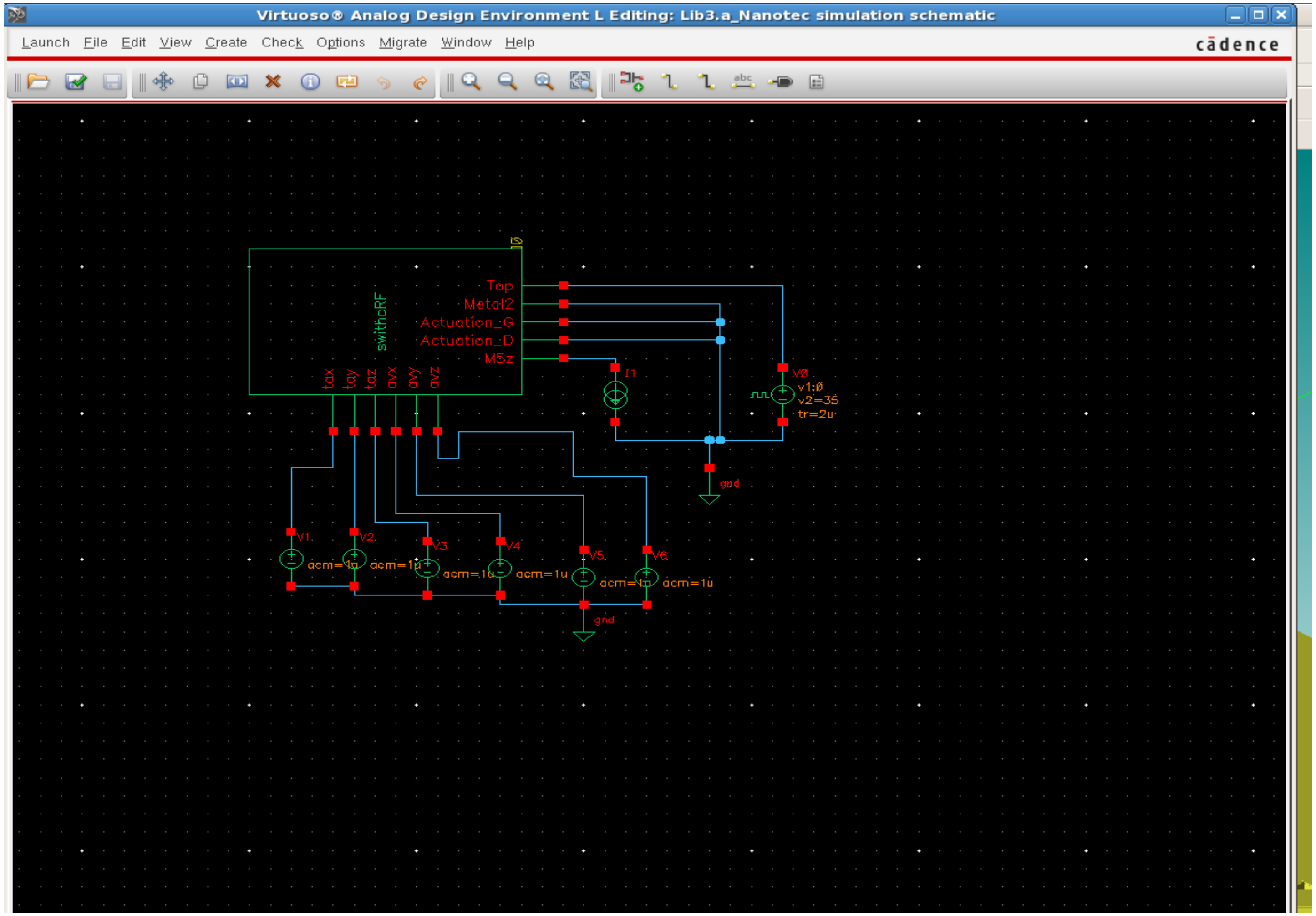




Electrical contact

Damping

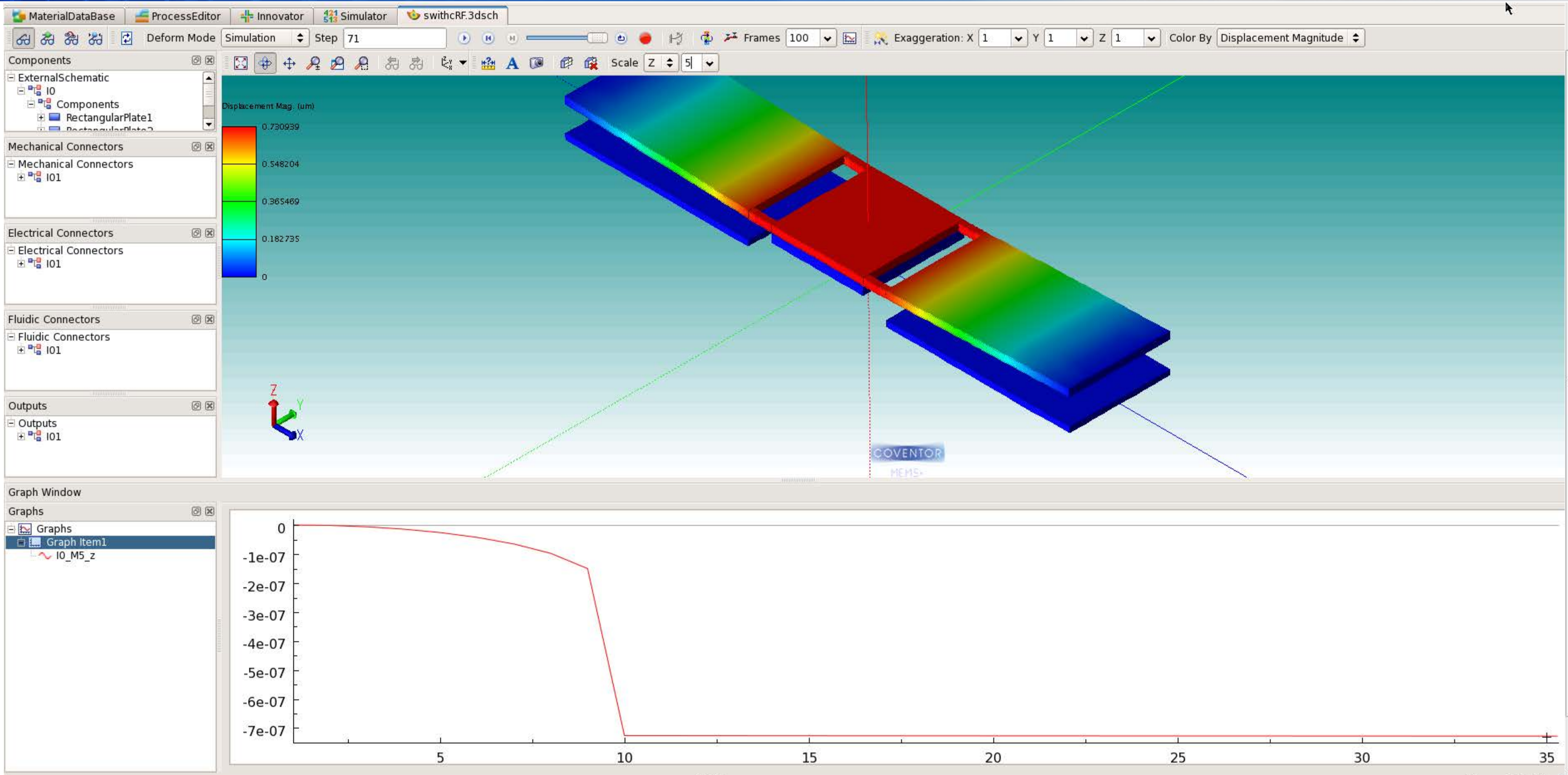
MEMS+ model in Cadence



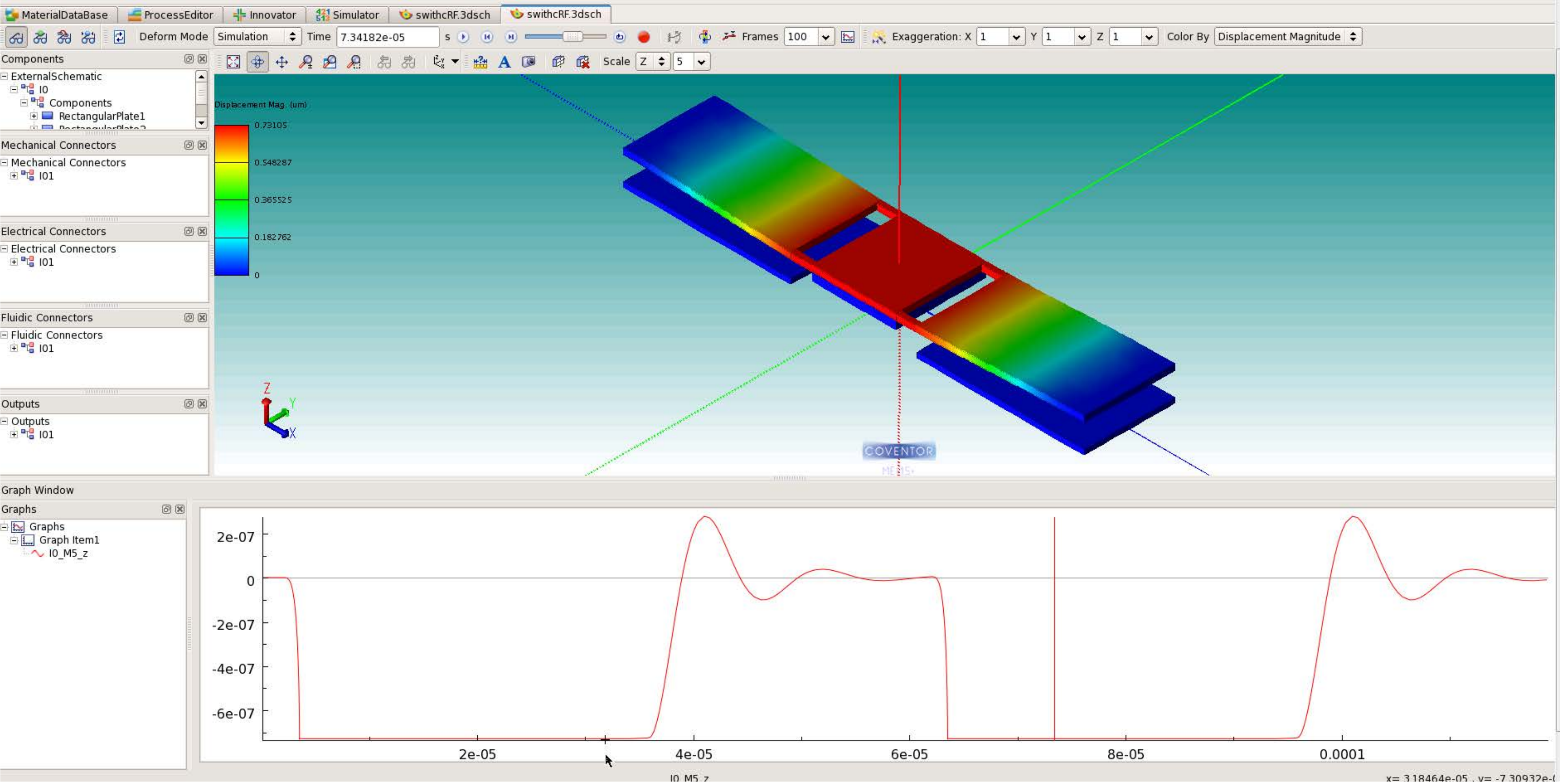
Visualize simulations in MEMS+ 3D

System
MEMS / IC co-simulation

Results in MEMS+ Pull-in Voltage



Results in MEMS+: Switching time



OOO "Евроинтех" 2012

MEMS and System Design: MEMS+ for Matlab/ Simulink

Chris Welham

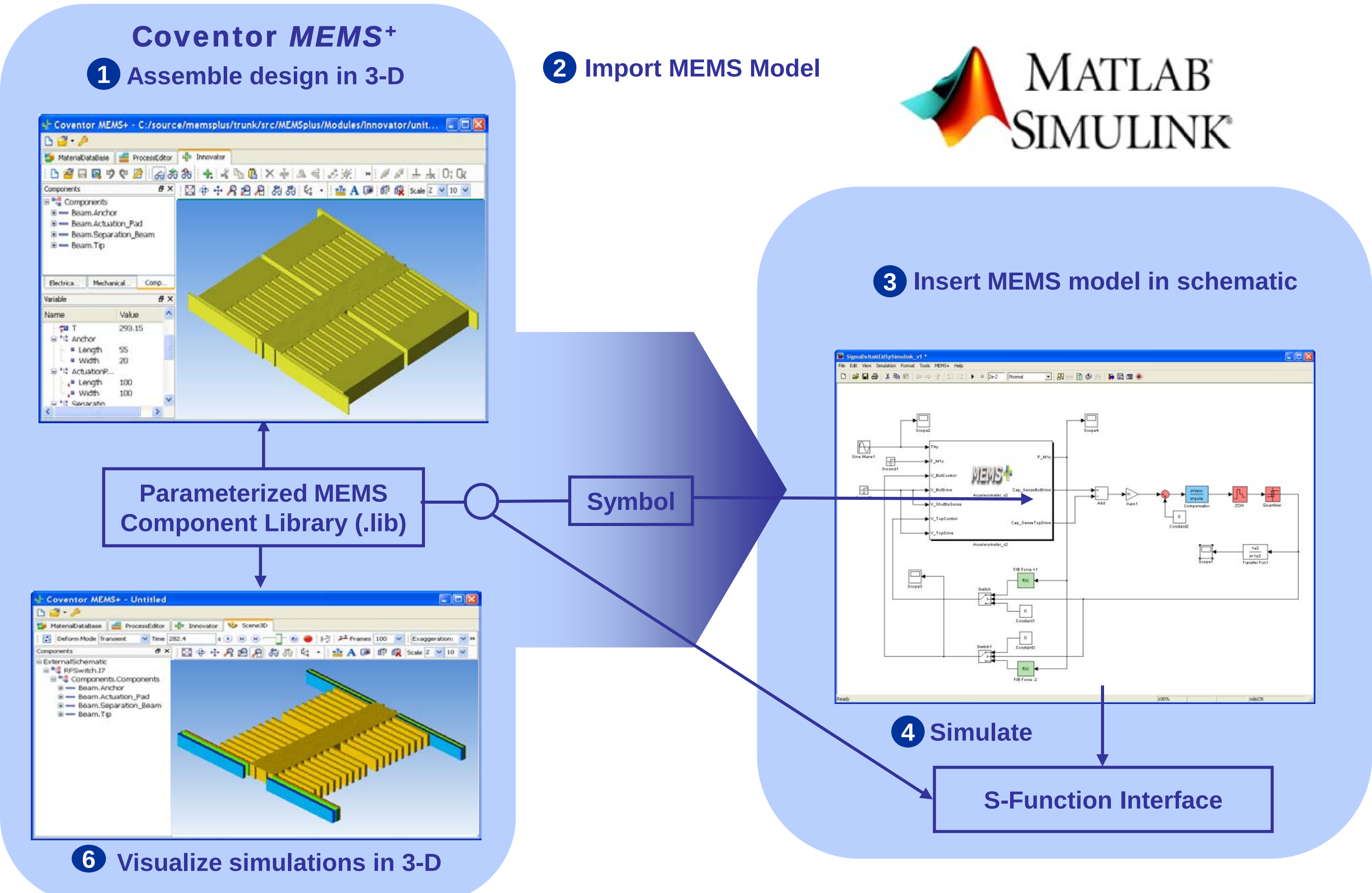
Application Engineering Manager

Coventor Paris

Outline

- MEMS+System and IC Challenge
- The MEMS+ approach
- Accelerometer example in Simulink
- Using Matlab scripting
- Conclusions

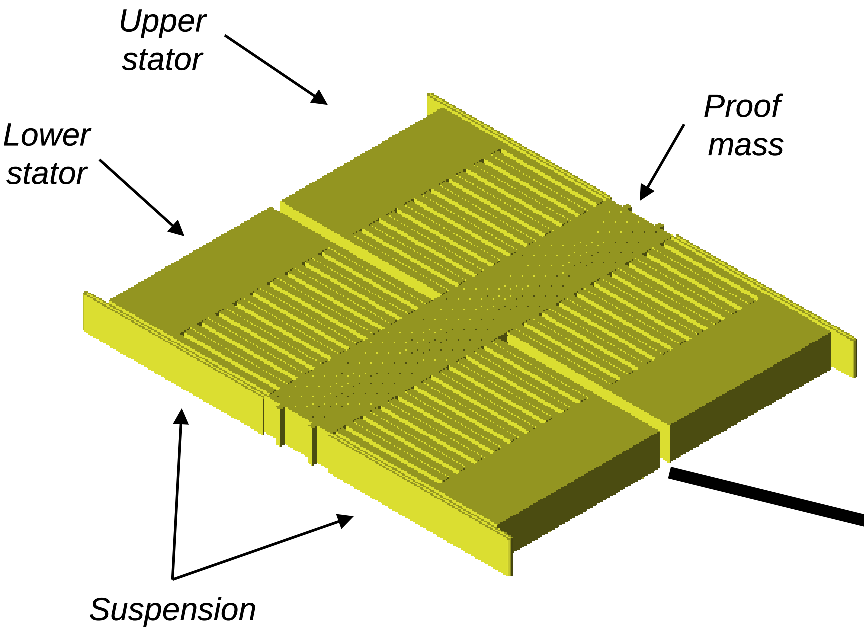
Coventor MEMS+ for Matlab Simulink

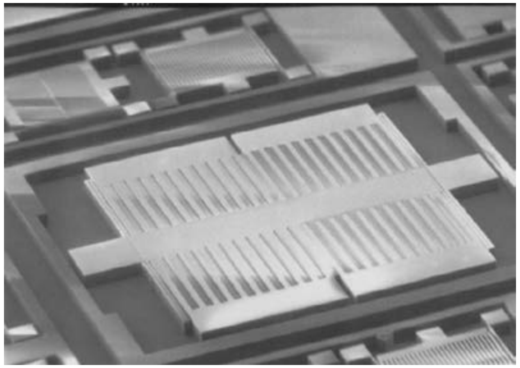


Accelerometer Design Example

Single-axis accelerometer

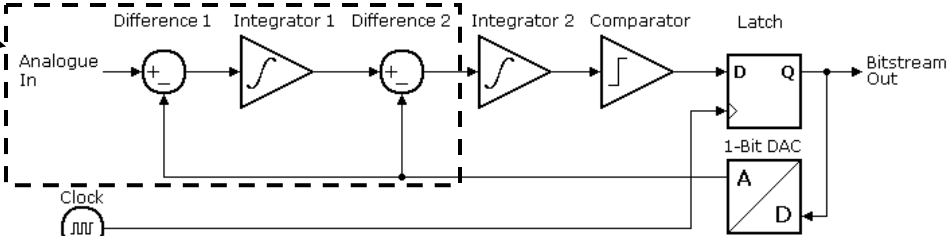
- Differential capacitance
- Made with DRIE on SOI





Sigma-delta modulator

- 2nd order--> good stability
- Provides control & ADC
- Increases dynamic range and sensitivity



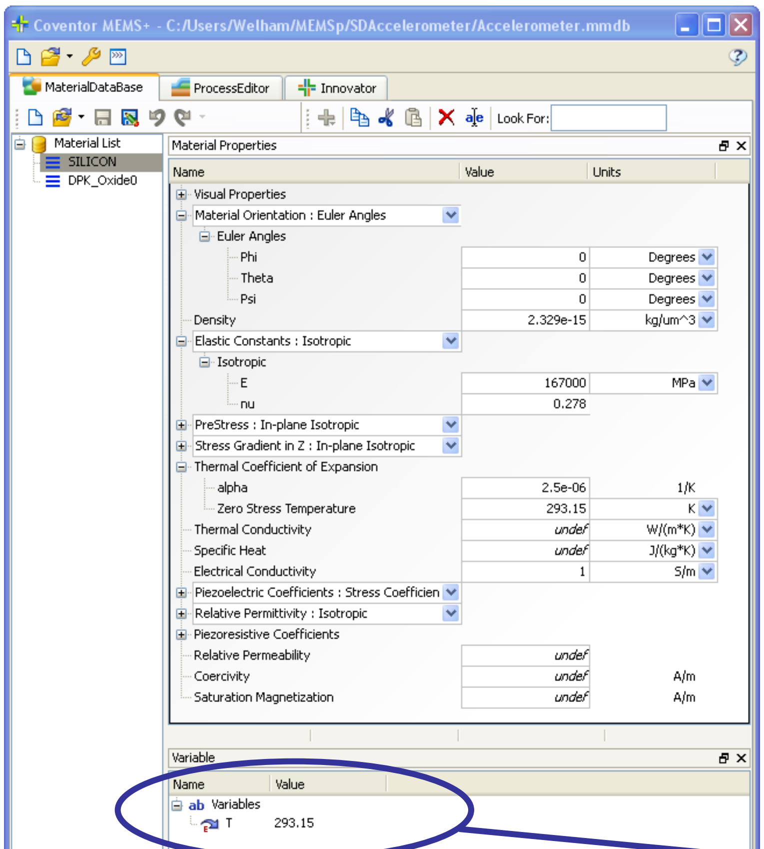
http://www.beis.de/Elektronik/DeltaSigma/DeltaSigma.html

COVENTOR

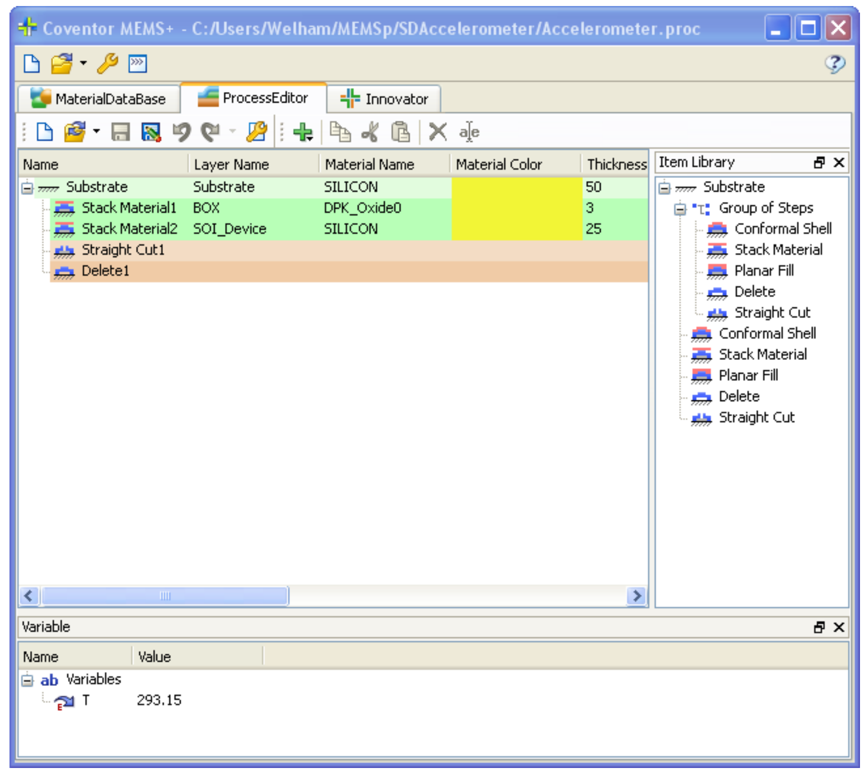
Define Materials and Process

- Material and process properties can be specified as constants, variables, or algebraic expressions

MEMS+ Material Database

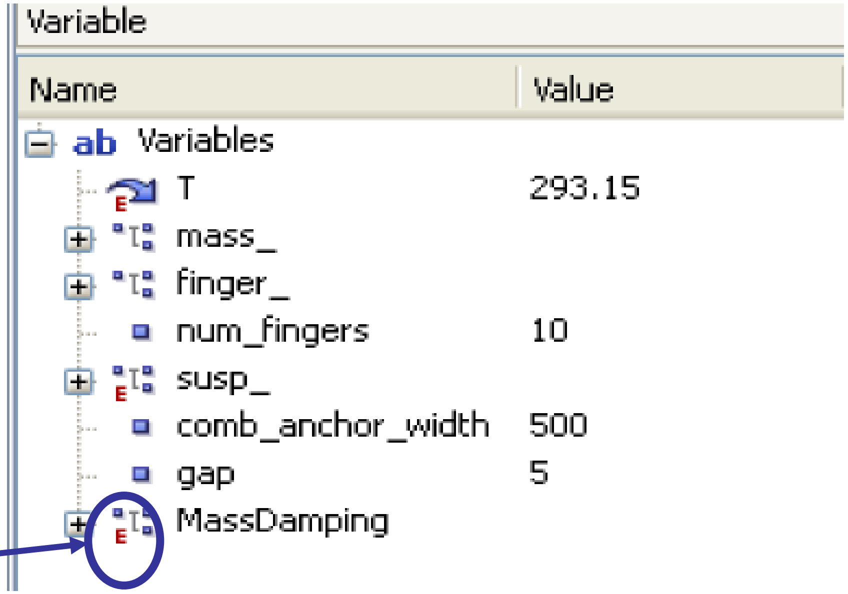


MEMS+ Process Database



Temperature “T” is defined as a variable then linked to material properties

- The MEMS device models are created with a library of parametric component generators for suspensions, plates, combs and electrical pads

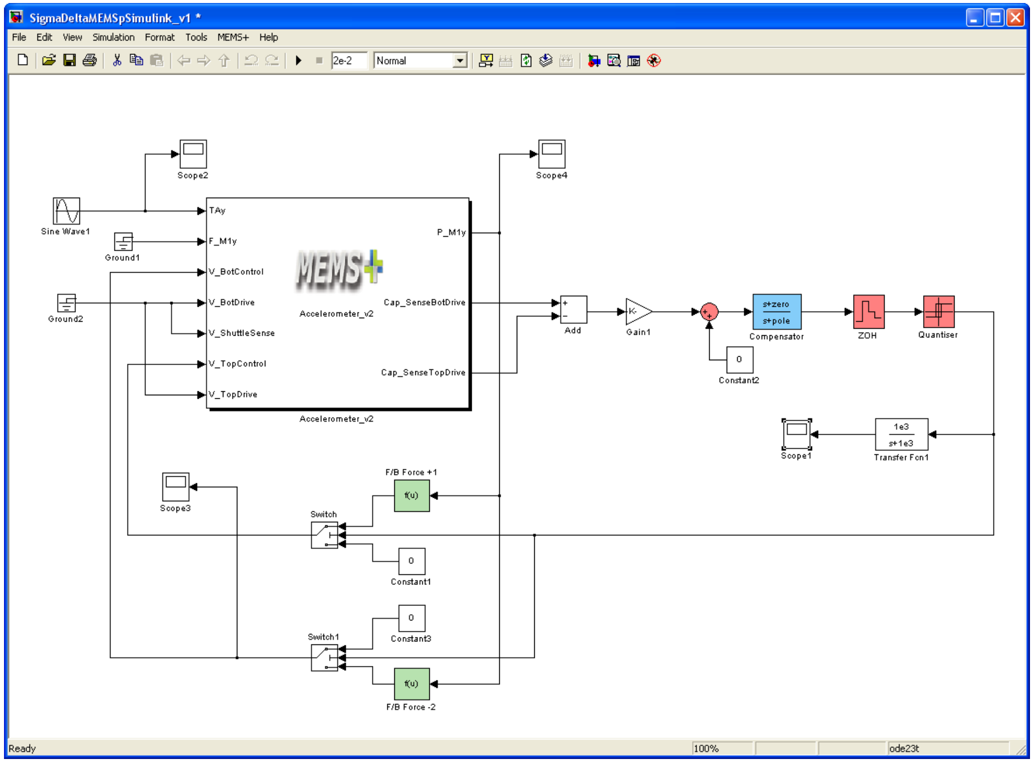


2) Expose variables to the Simulink or Cadence symbol
1

Demonstration

System Simulation

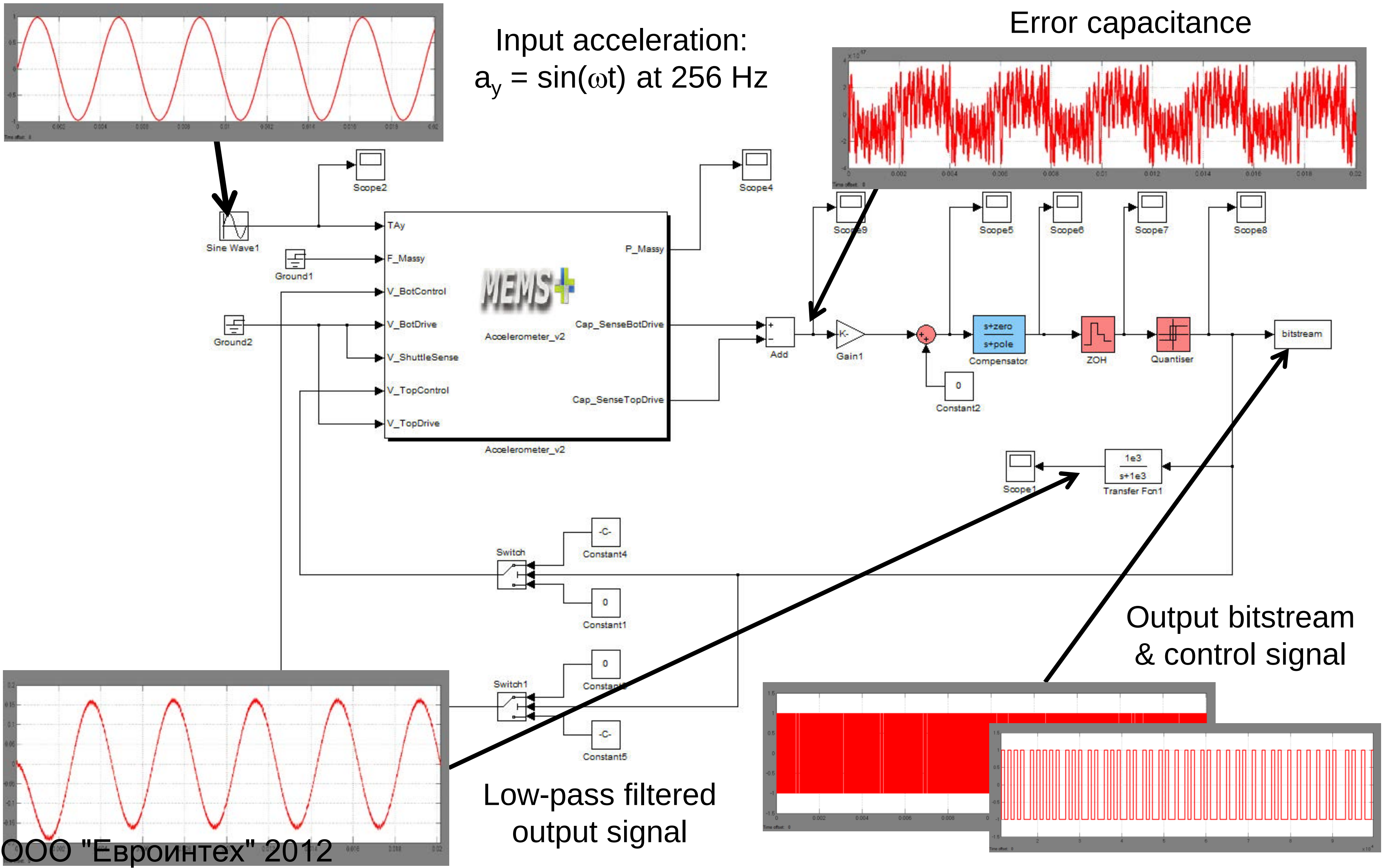
- MEMS system design completed with addition of sigma-delta control loop using models from the Simulink library



Concept:

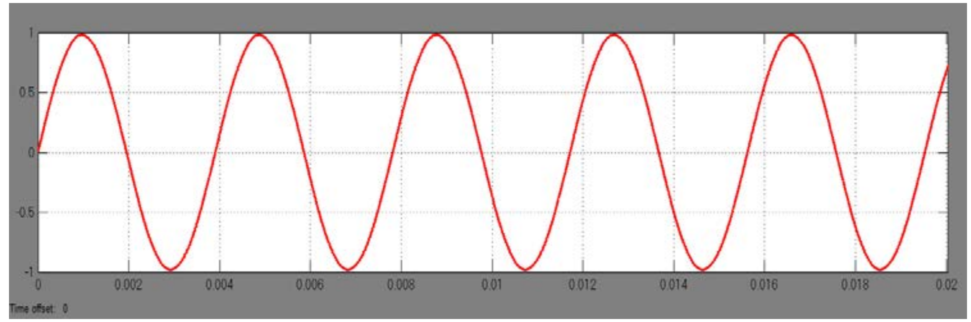
Use controller to hold proof mass steady for any acceleration, and use feedback control signal as output.

Force-feedback control of accelerometer



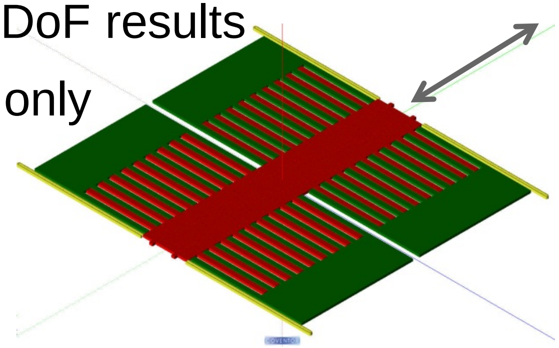
Stability Simulations in Simulink

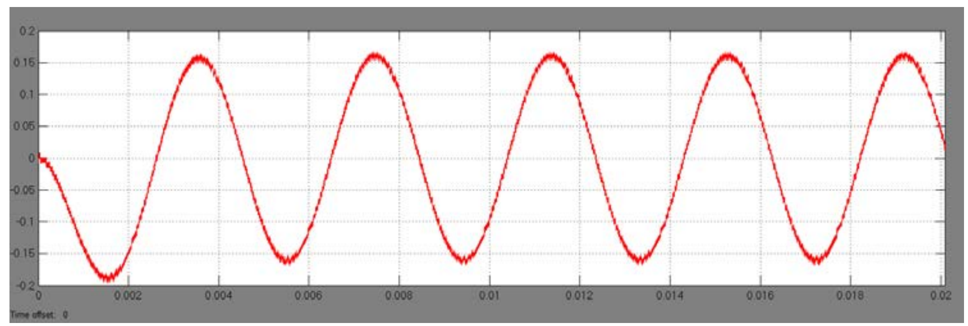
256 Hz input acceleration



Single-DoF results

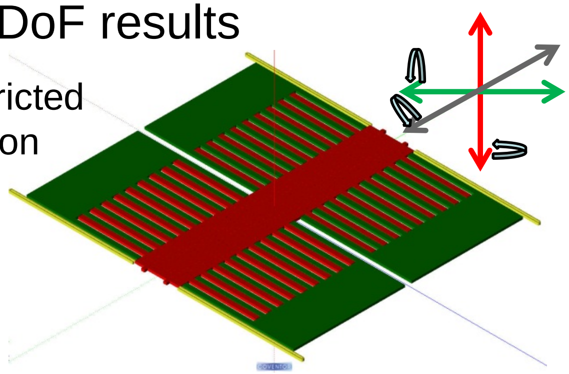
y DoF only

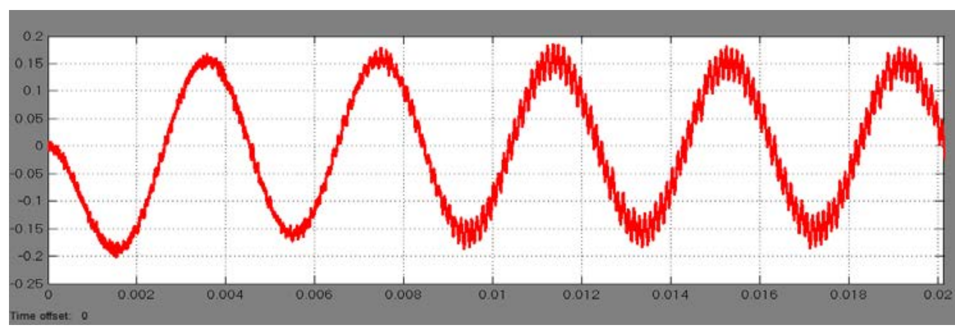




Multi-DoF results

Unrestricted motion

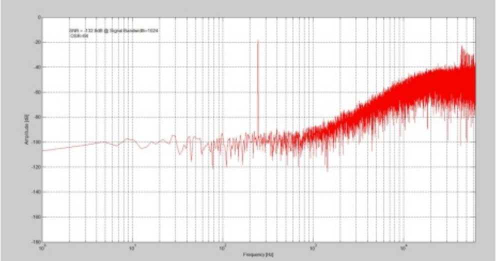




Unstable: “Noise” grows until the combs pull-in!

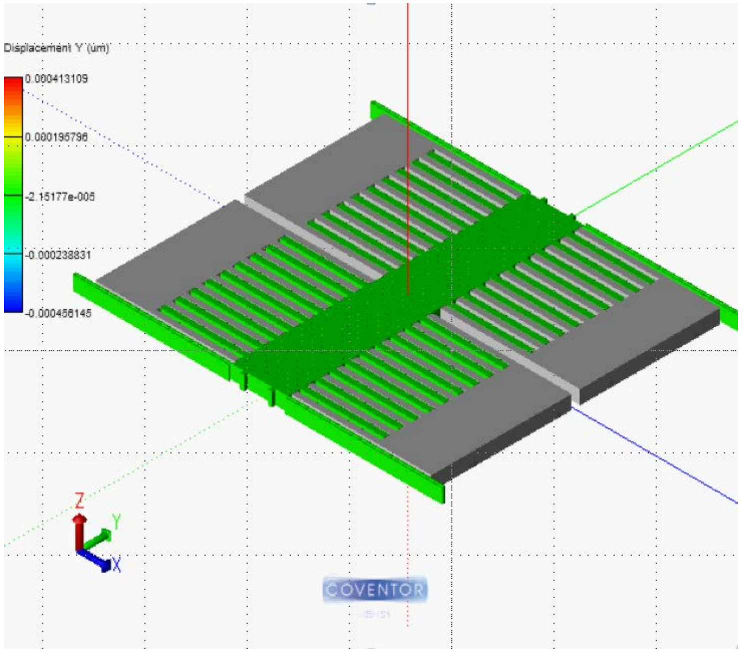
Stability Simulations in Simulink

Could do FFT of bitstream and attempt to interpret….

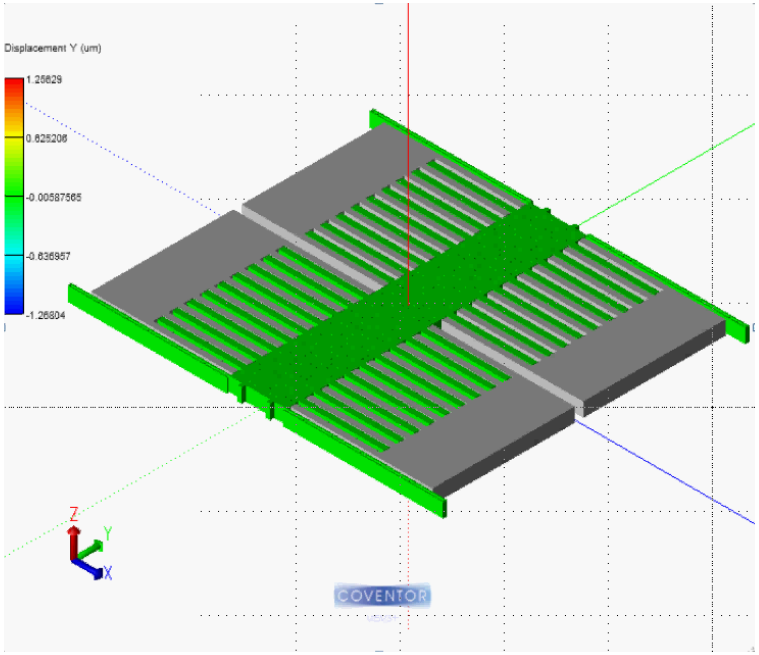


Instead, load into *MEMS+* to visually observe device behavior:

1-DOF model in *MEMS+*



Multi-DoF model MEMS+



1-DOF model erroneously considers the system stable

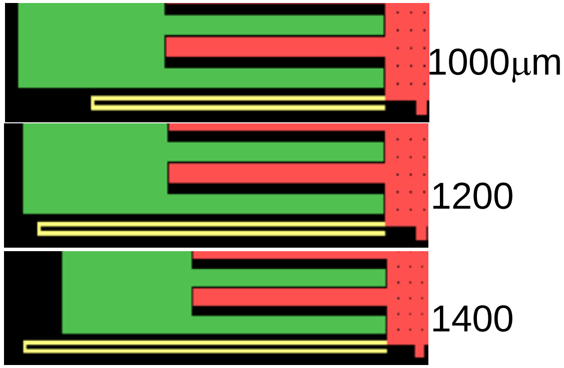
Controller excites suspensions into flapping uncontrollably

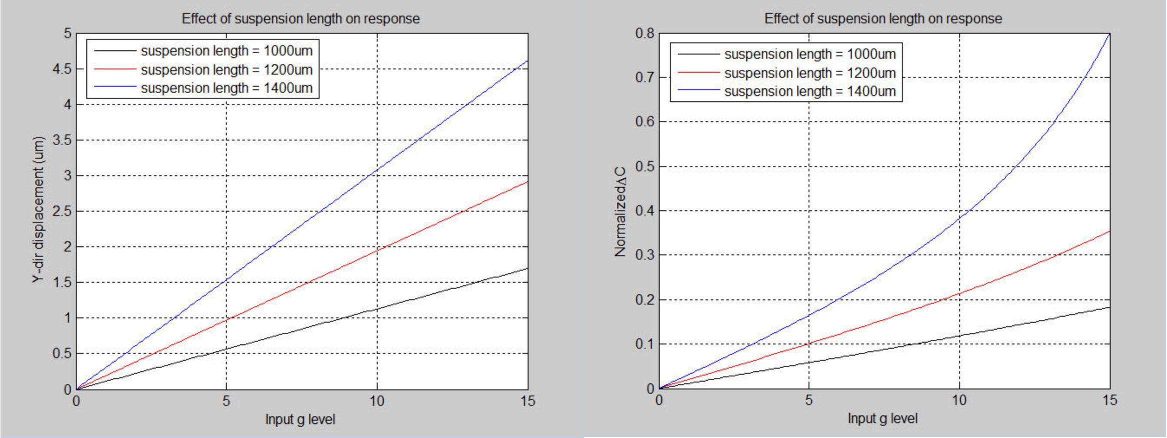
MEMS Concept

Geometric design

Design Tradeoff: Sensitivity vs. Linearity

Vary suspension length





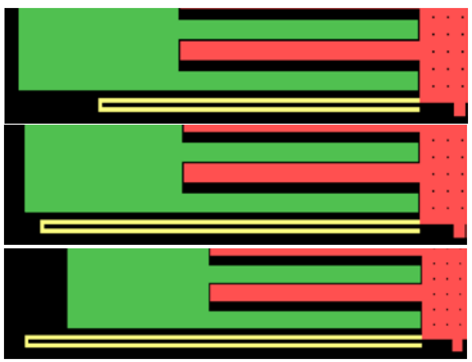
- Nonlinearities from mechanics and comb electrostatics
- Parameter sweeps computed in seconds

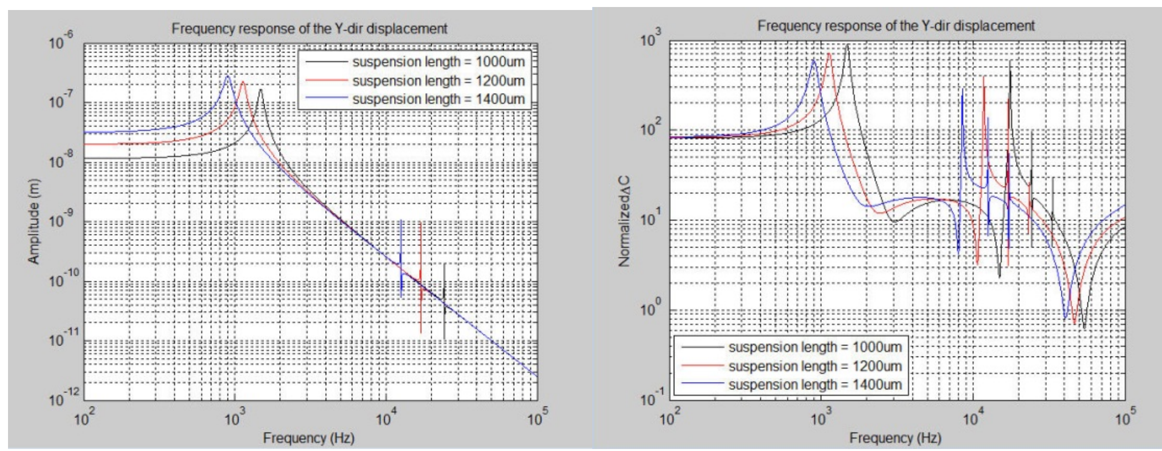
Component Design

MEMS Concept ⇄ Geometric design

Design Tradeoff: Sensitivity for Bandwidth:

Vary suspension length





- Not just mechanics or electrostatics: Whole system characteristic

System performance tradeoffs

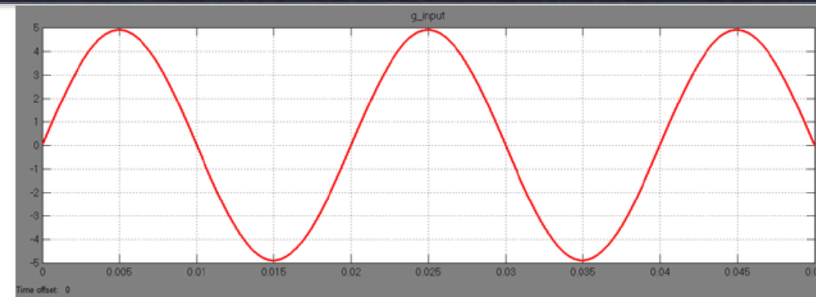
MEMS Concept ⇄ Geometric design ⇄ Circuit/Control Design

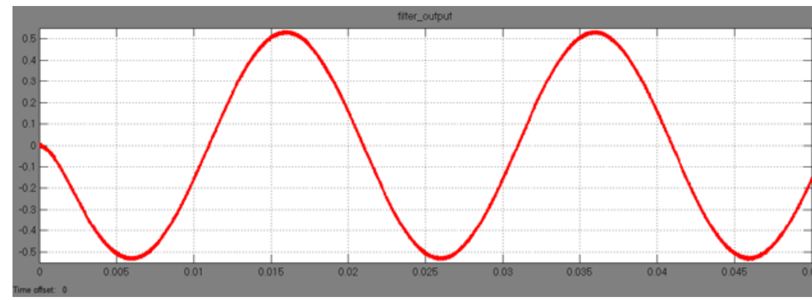
Increase comb finger gap to improve robustness

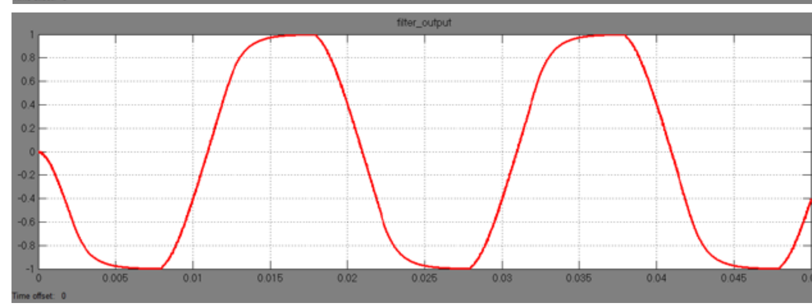
5 um

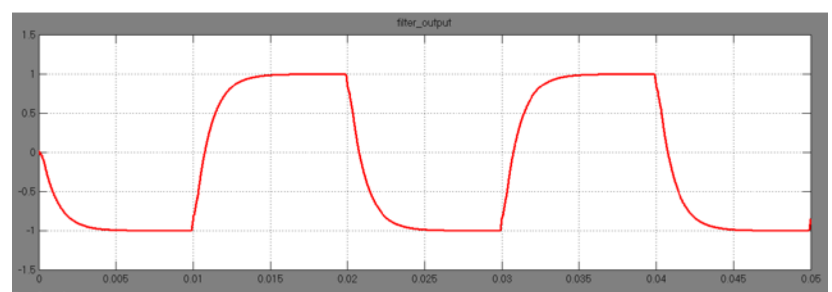
7

11





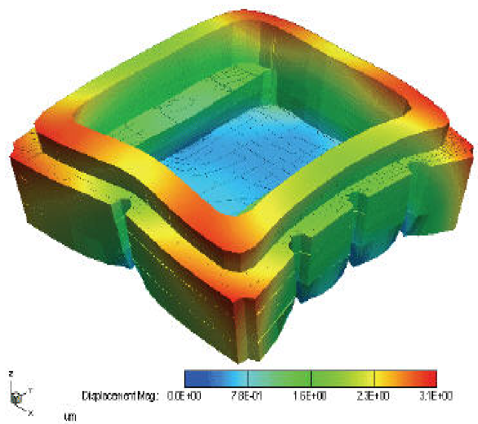




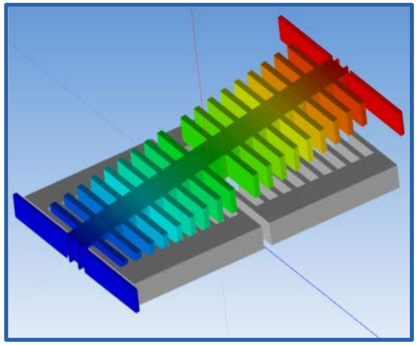
Package Deformation

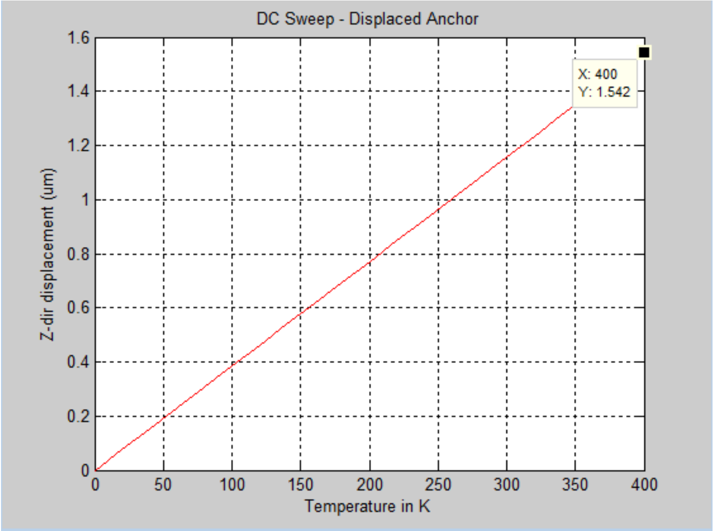
Package deforms due varying ambient temperature

- Deformation causes zero-*g* offset
- Can only predict zero-*g* offset with multi-DOF model
- Can the effect be minimized?



FEA of package

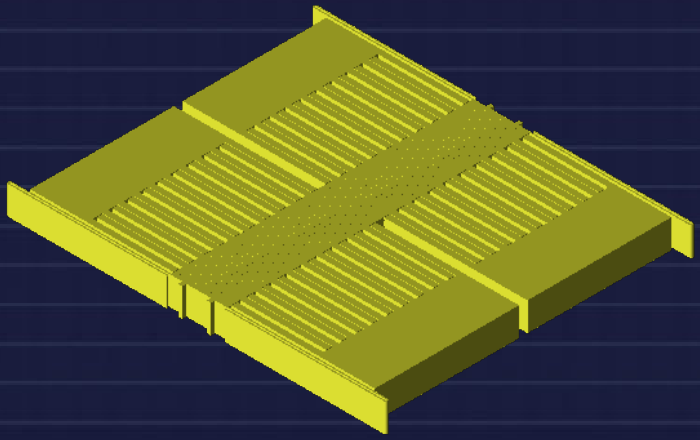


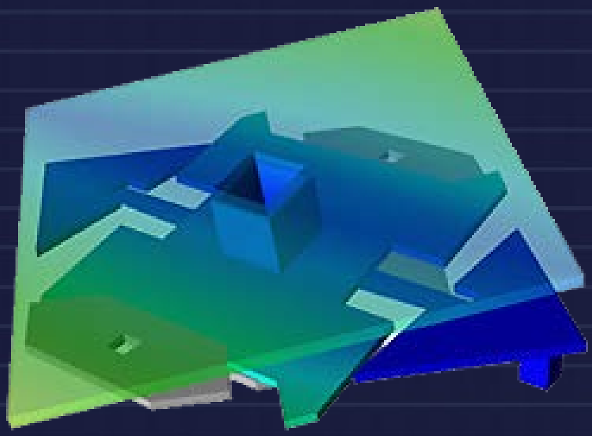


MEMS+ simulation with package deformation

Exaggerated thickness and displacements

Design optimization using MATLAB and MEMS+

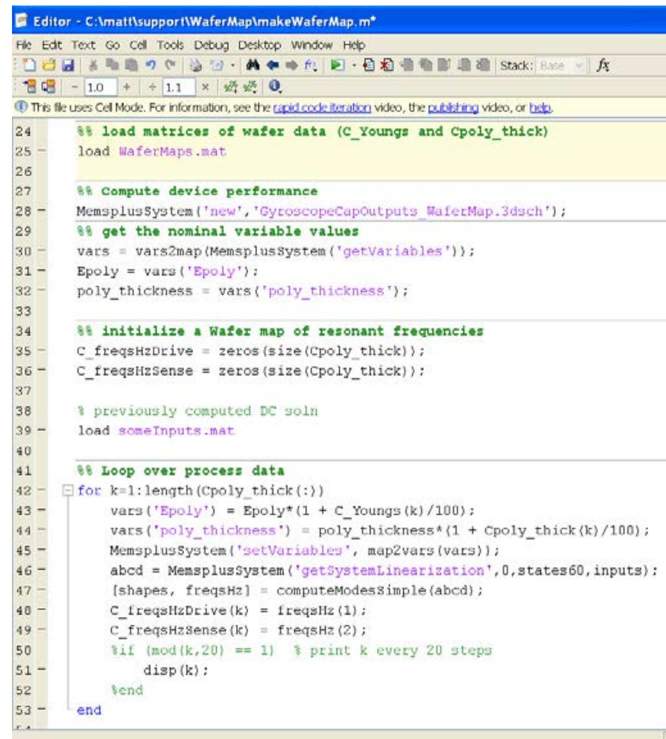




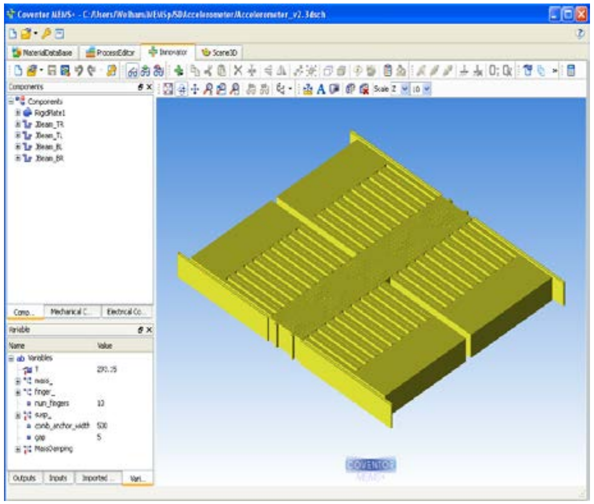
MEMS+-Matlab Interface (no Simulink)

- Drive MEMS+ from MATLAB

1. Open MEMS+ 3D schematic
2. Creating an instance of the analysis object: DC, AC, Modal
3. Setting the desired inputs
4. Calling compute() on object
5. Extract result data from object

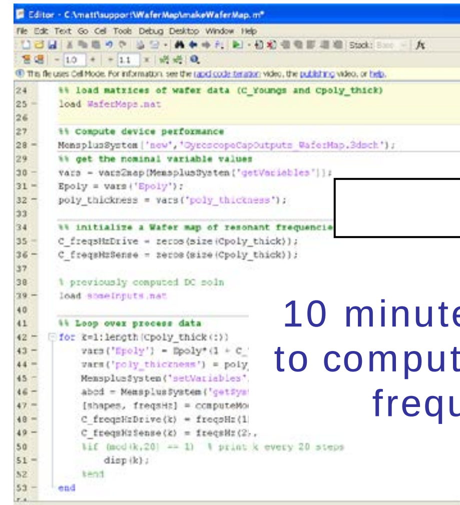


MEMS+-Matlab Interface (no Simulink)

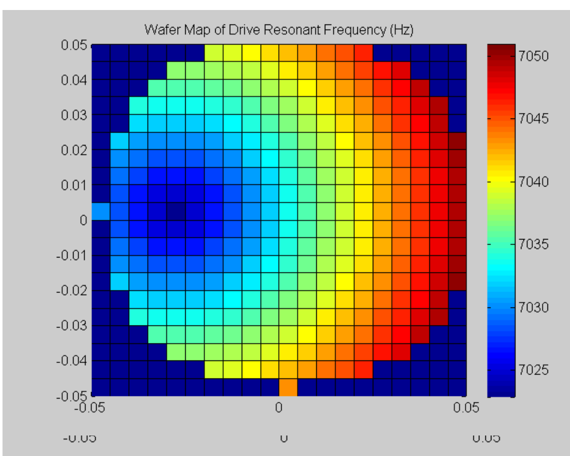


Matlab script

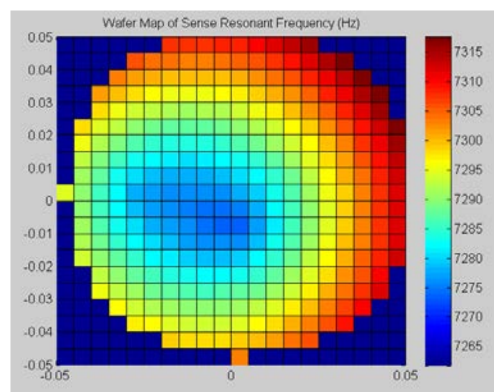
+



10 minutes CPU time to compute 400 mode frequencies

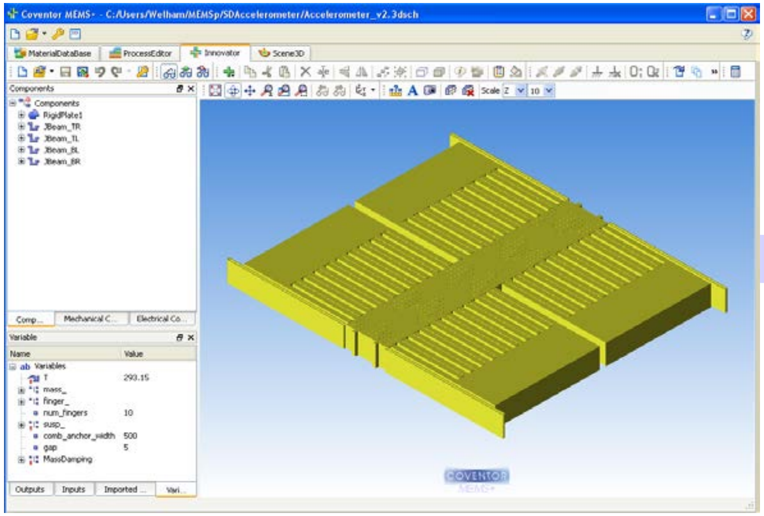


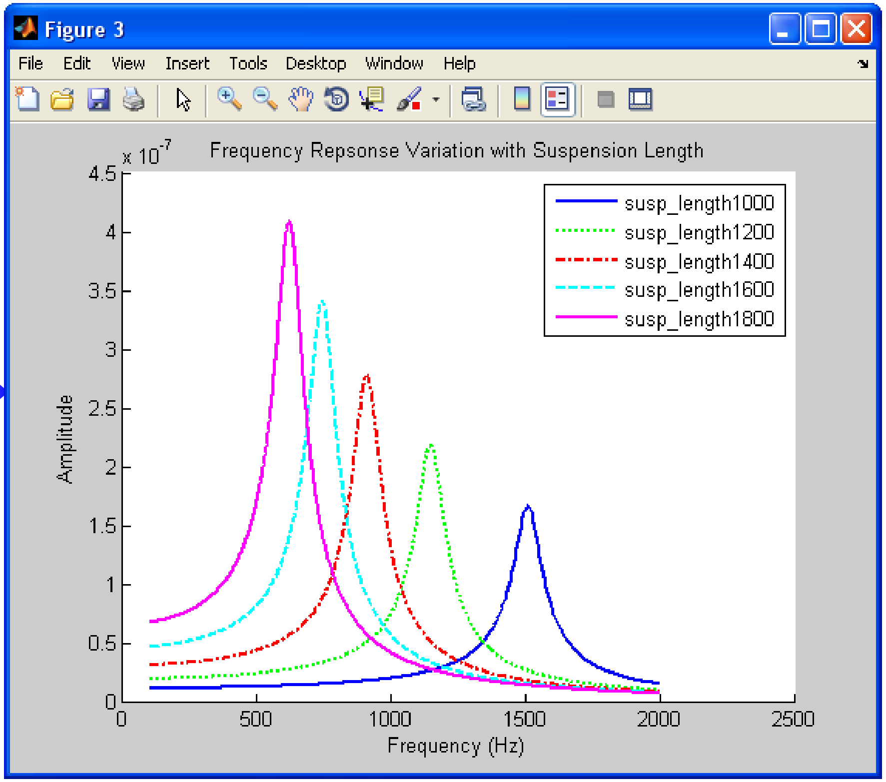
Sense Frequency



Drive Frequency

MEMS+-Matlab Interface (no Simulink)

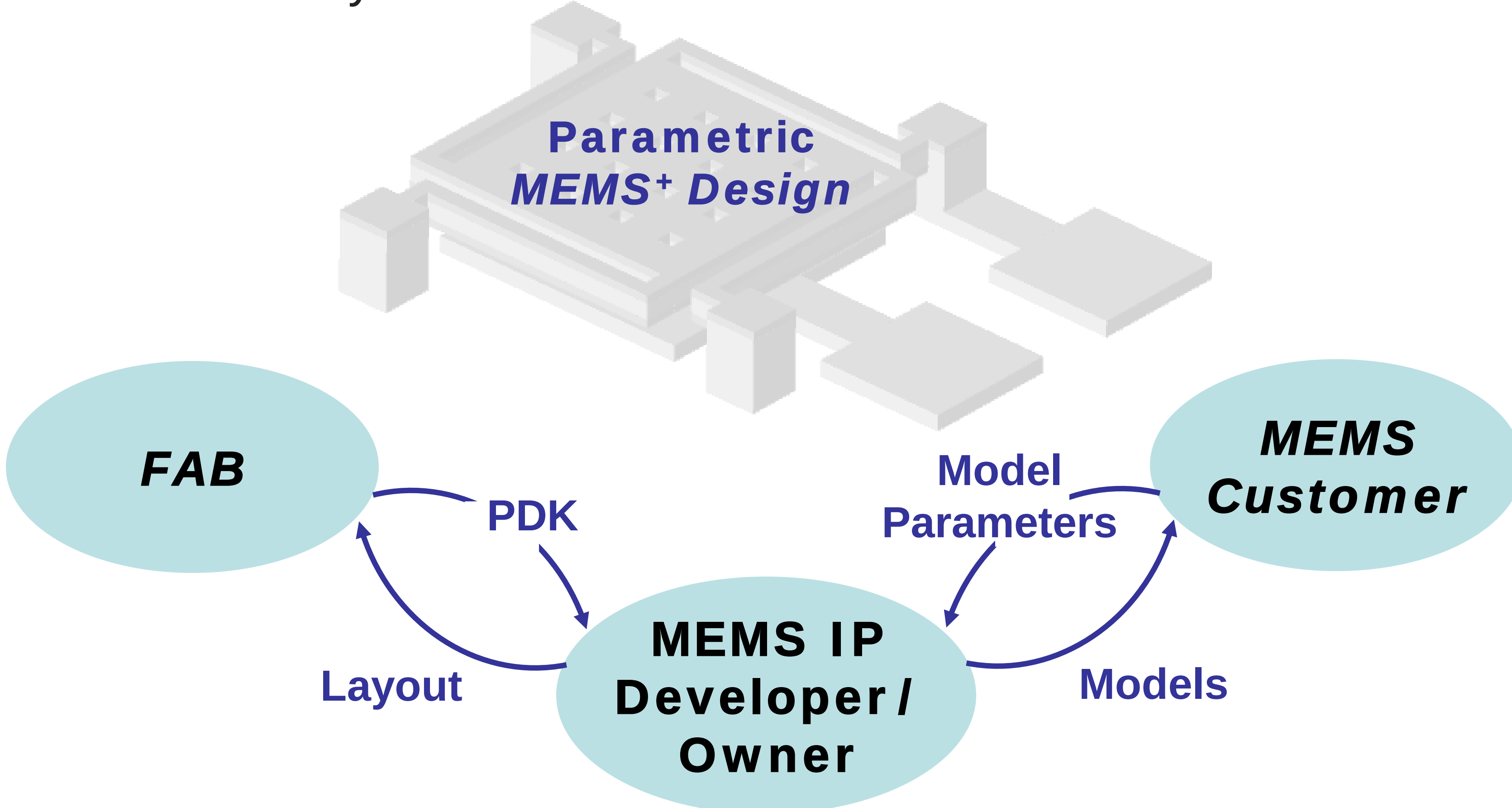




Vary suspension width and plot response

Enable MEMS Eco-System

- ***MEMS+*** parametric design format provides a new standard to facilitate the communication between the partners of the MEMS eco-system

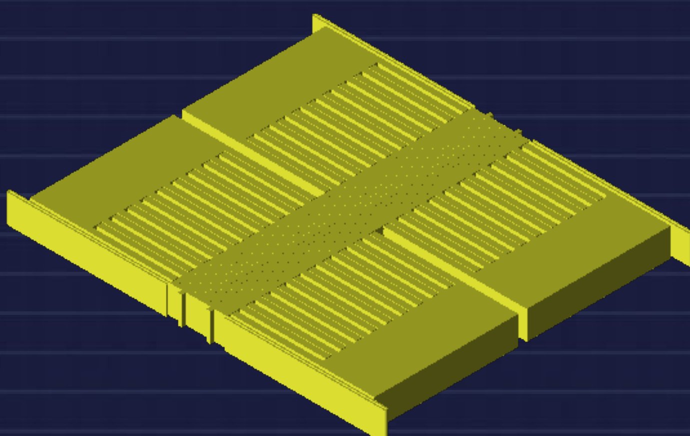


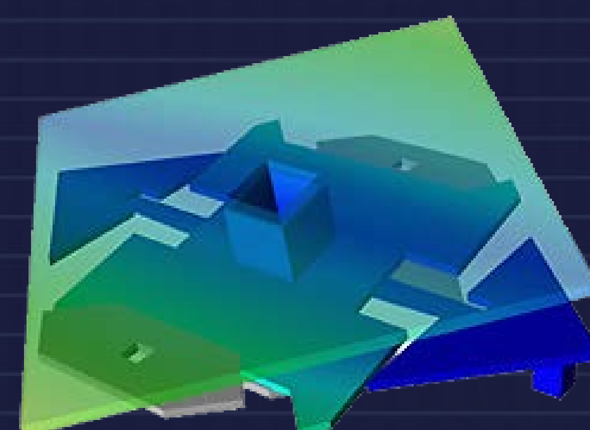
MEMS device and ASIC Integration: MEMS+ for Cadence

Chris Welham

Application Engineering Manager

Coventor Paris





COVENTOR

3D MEMS & Semiconductor SOFTWARE

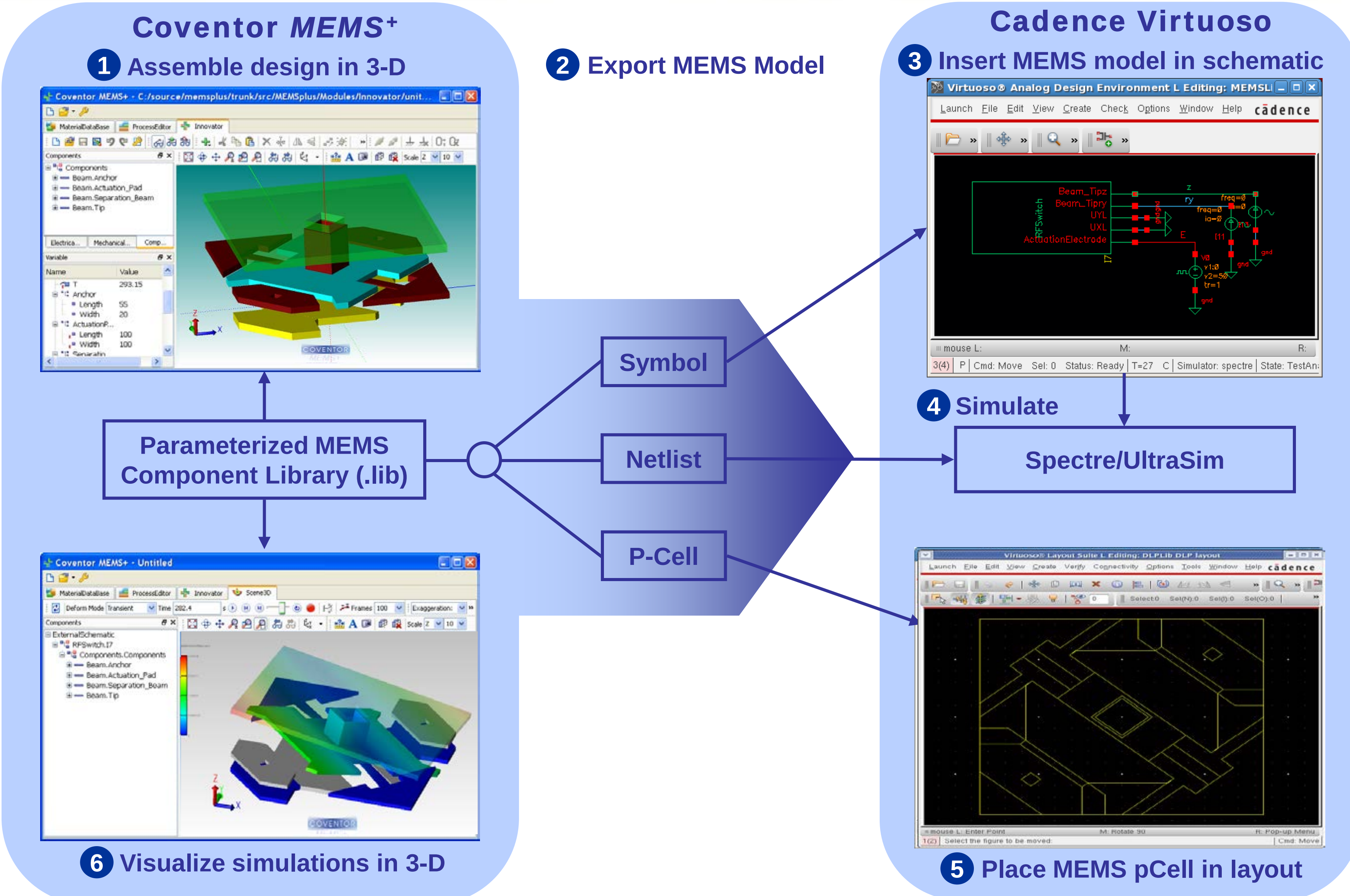
MEMS and ASIC Integration, Optimization issues: MEMS+ for Cadence Virtuoso

Chris Welham

Application Engineering Manager

Coventor Paris

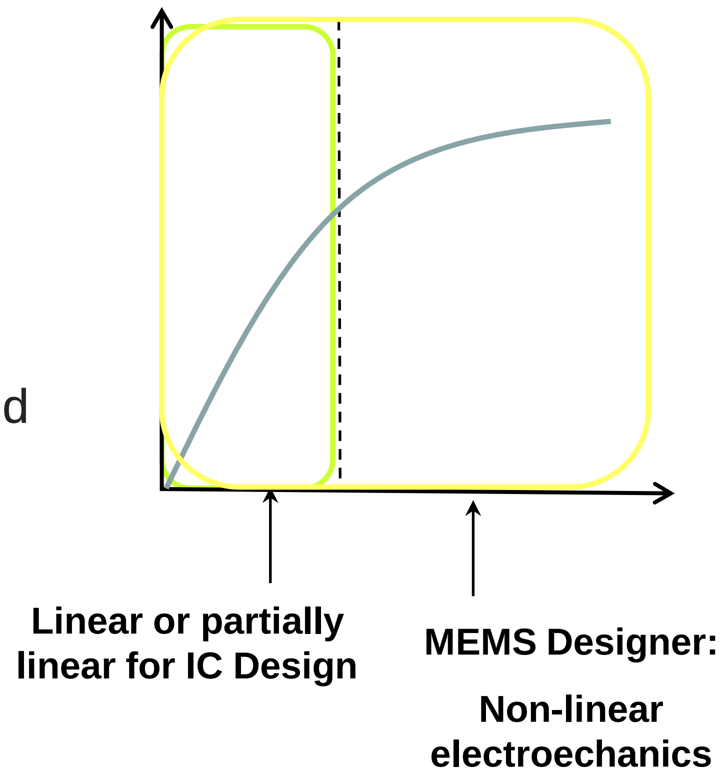
Coventor MEMS+ for Cadence Virtuoso



Coventor's Value

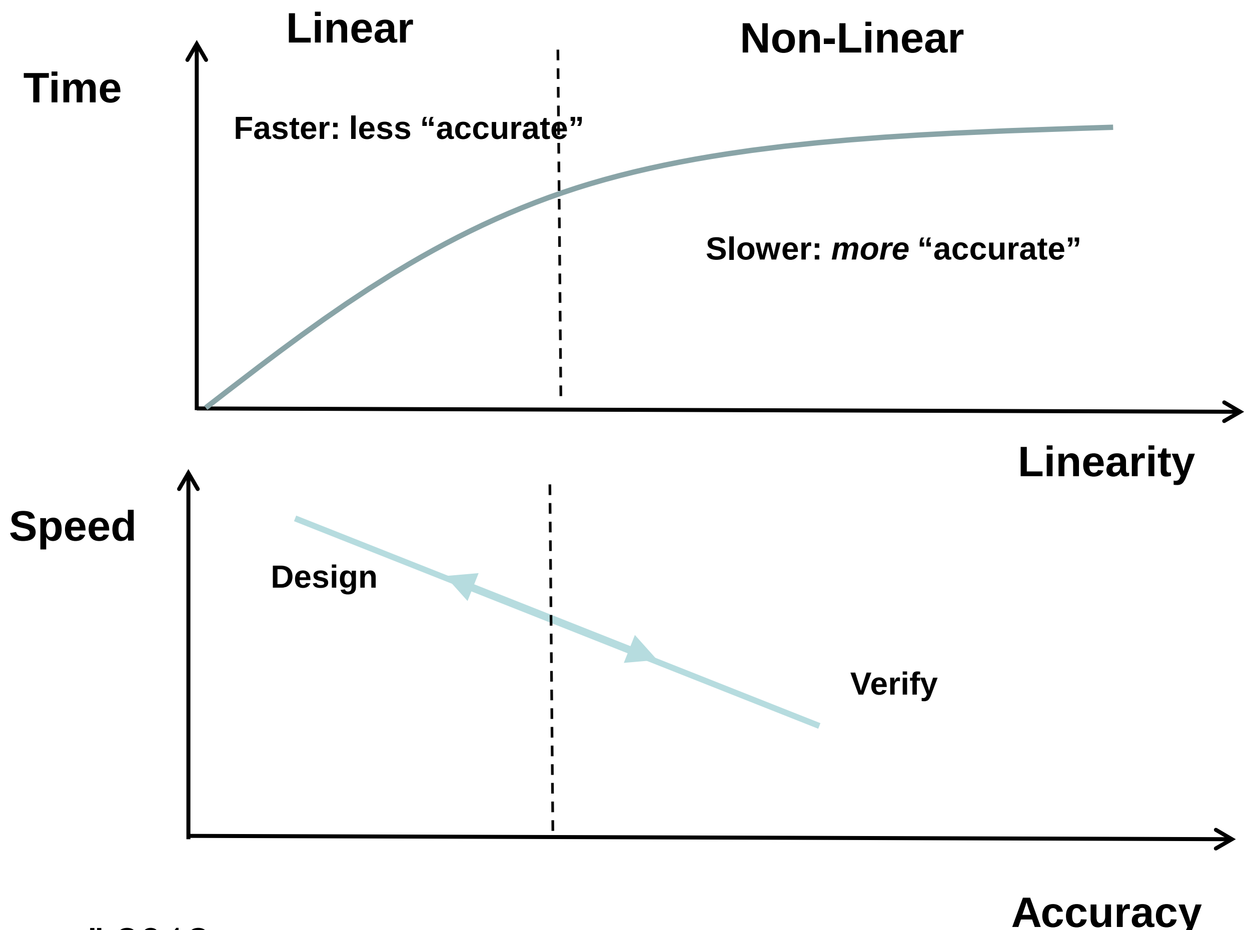
MEMS Multi-Physics: mechanical + electrostatic + IC

- With complex geometry
- With Linear and non-linearity coupled physics



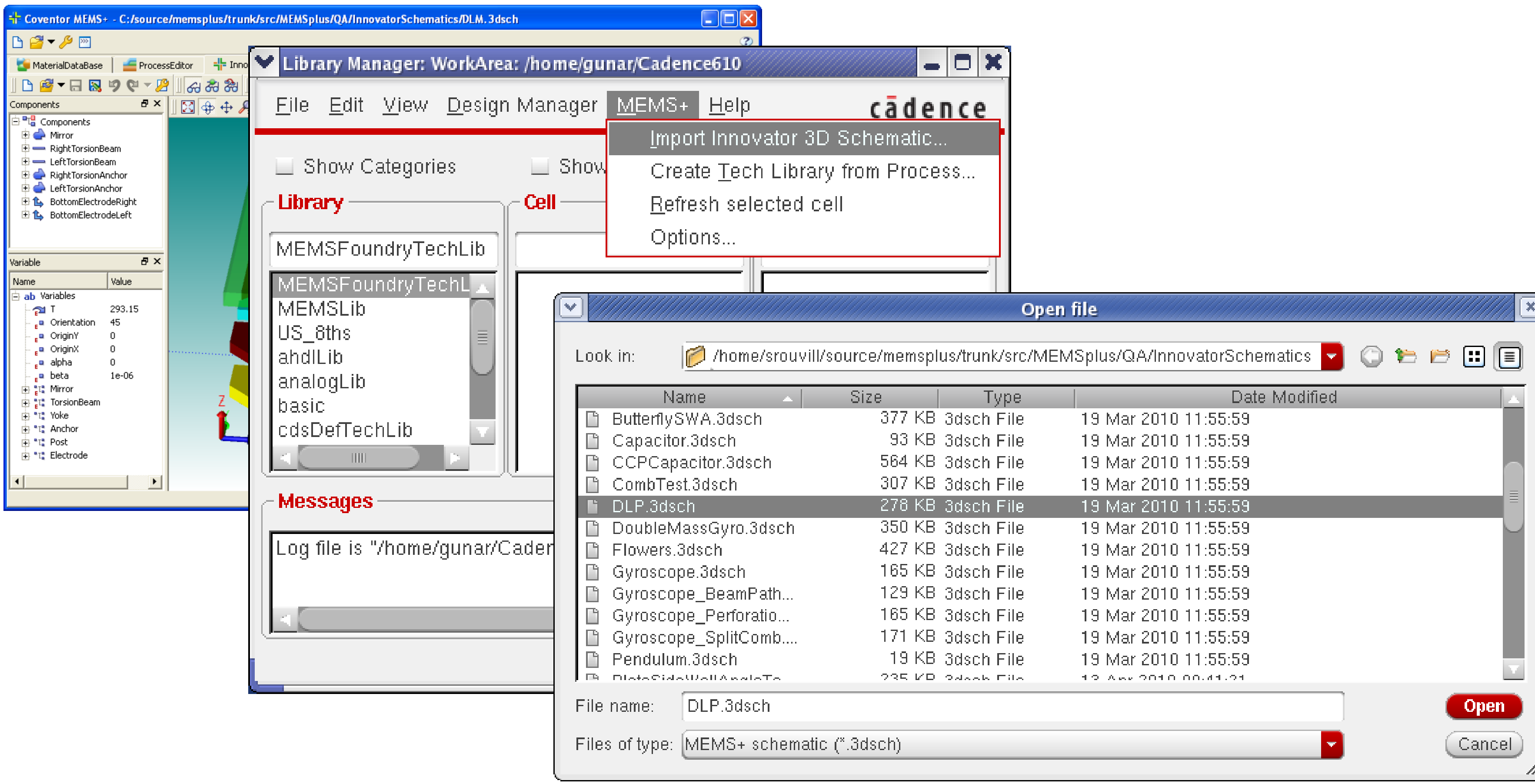
Coventor's Value

- Speed vs accuracy



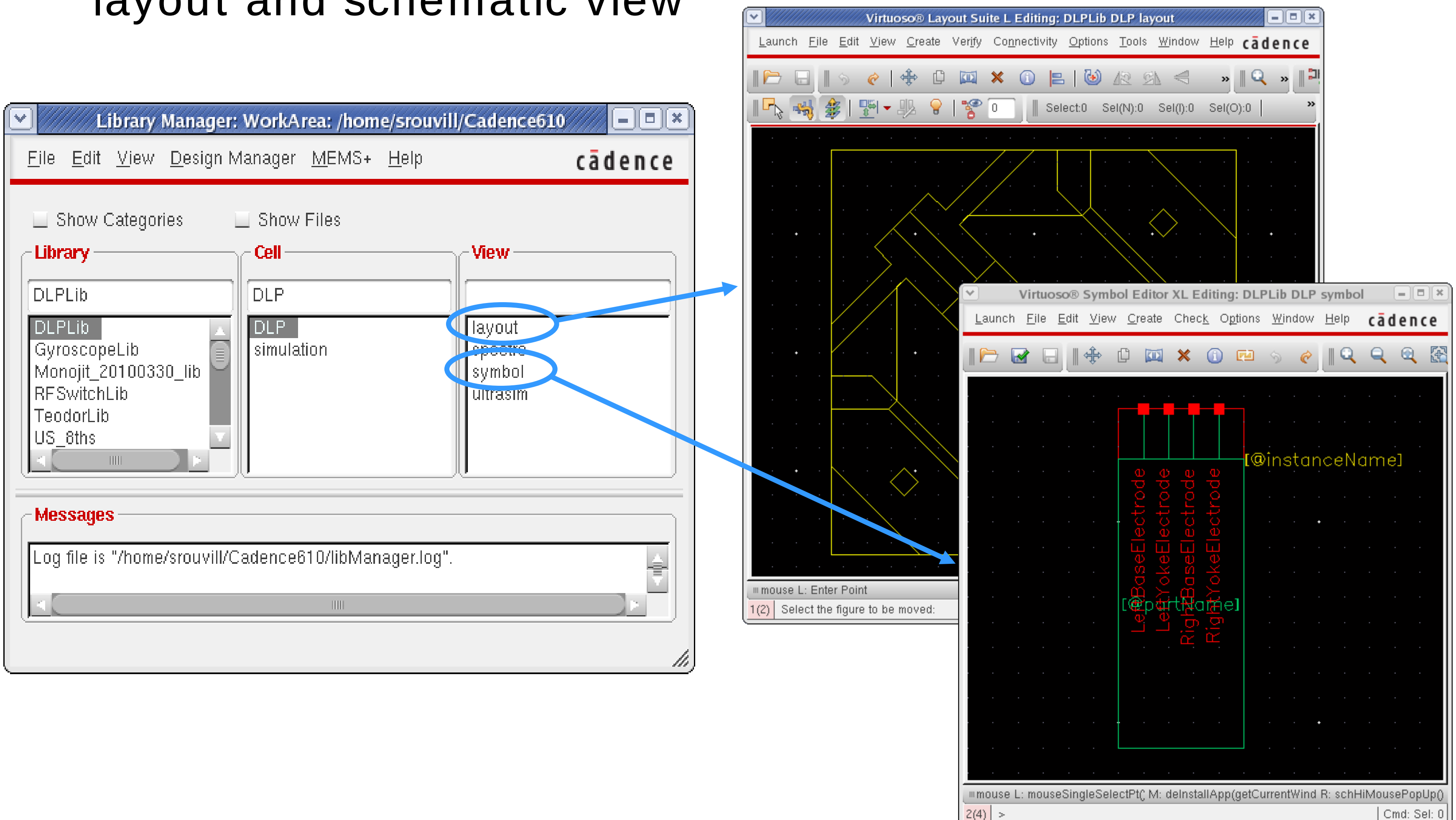
Cadence Virtuoso Cell Generation

- The 3D ***Innovator*** design is imported into the Cadence Library Manager using the ***MEMS+*** import tool



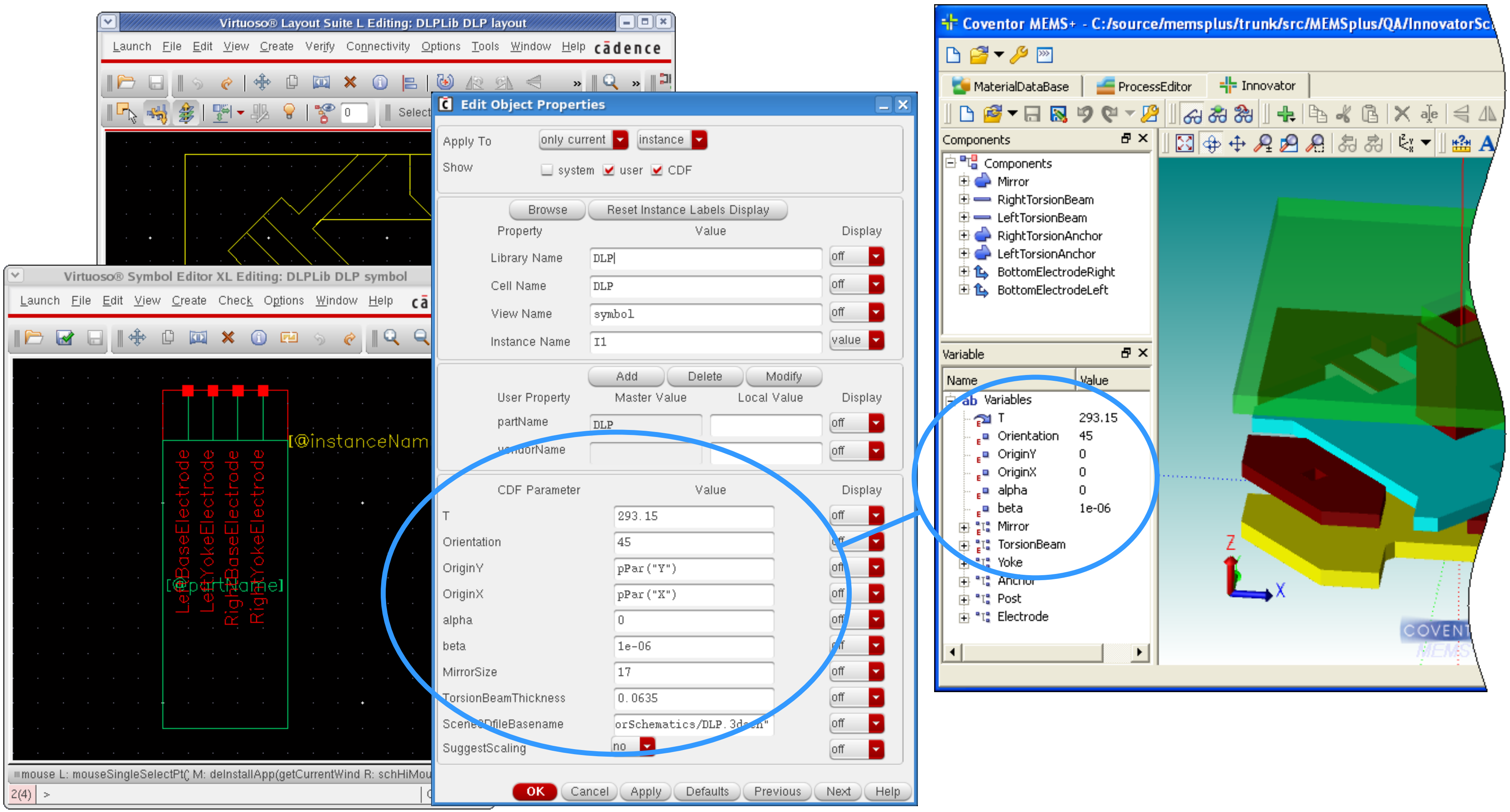
Parametric Cell Views

- The ***MEMS+*** import tool automatically creates a parametric layout and schematic view

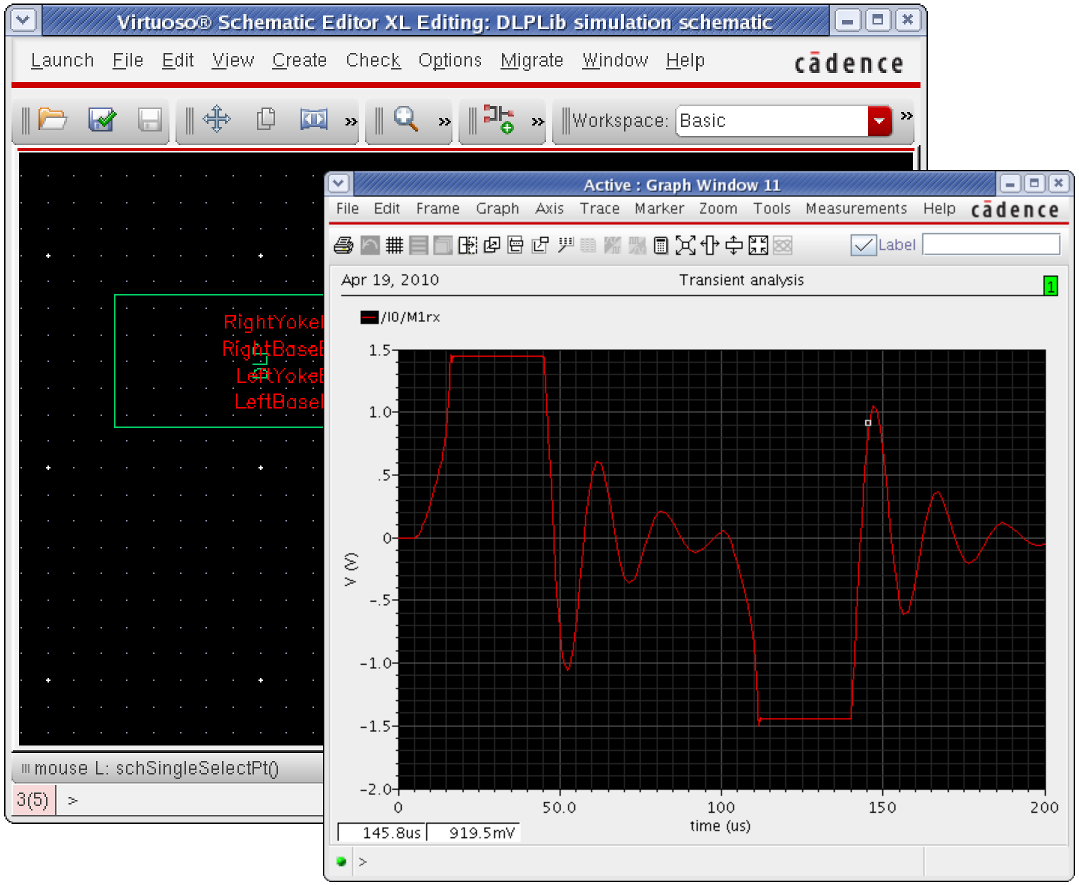


Virtuoso Cell Parameters

- The created cell views features all parameters that were exposed in ***MEMS+***

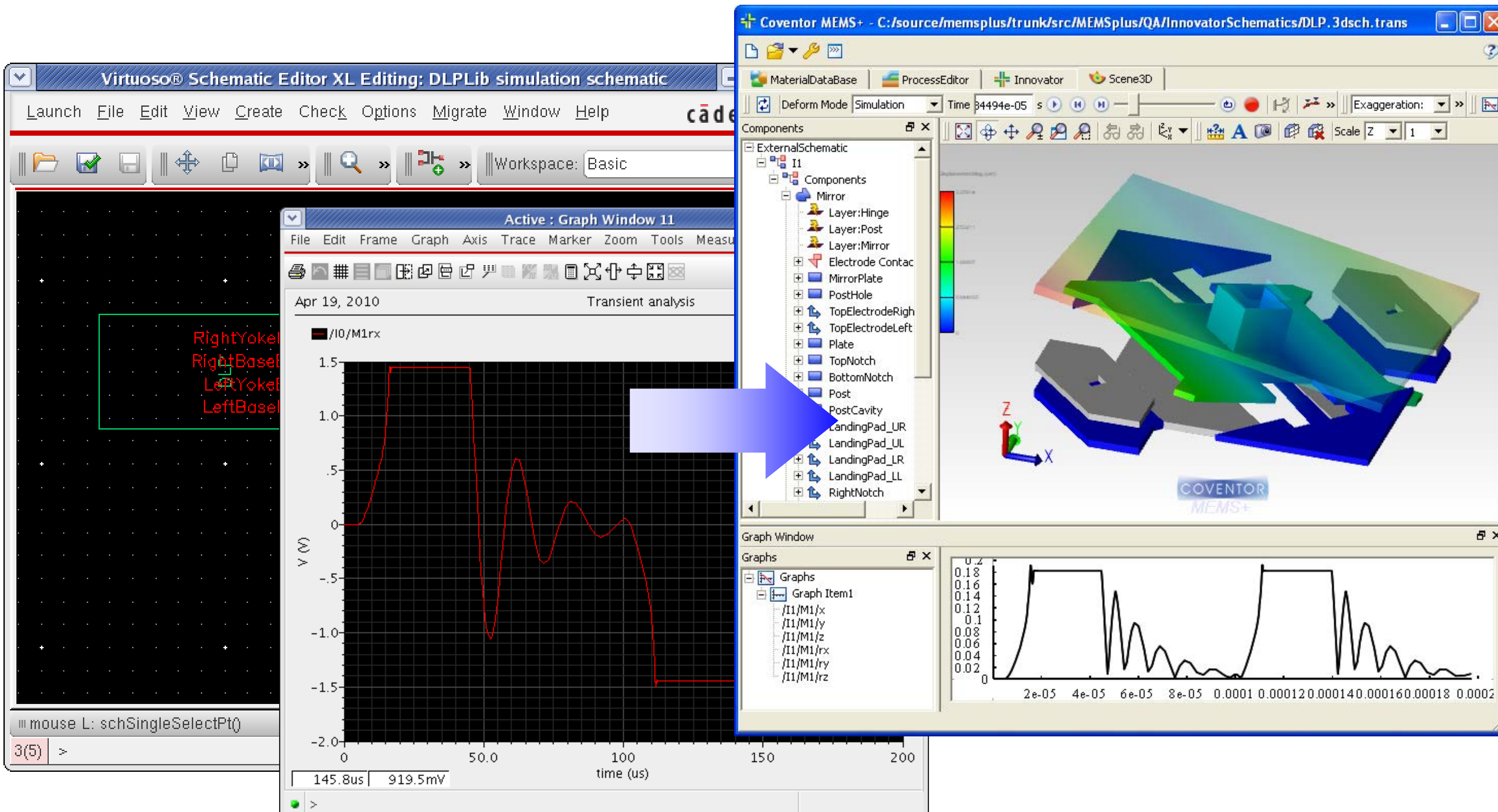


- The MEMS designer adds sources to the exposed electrical pins and confirms the device performance running DC, AC and transient simulations



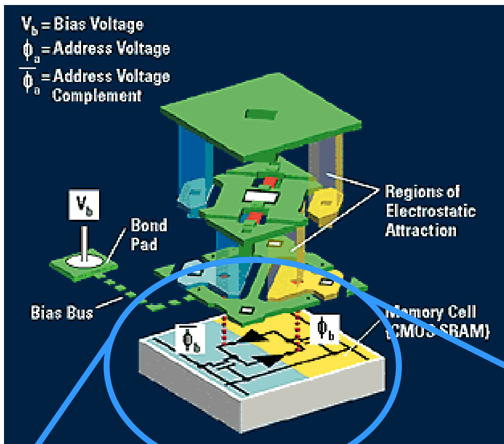
MEMS Device Simulation

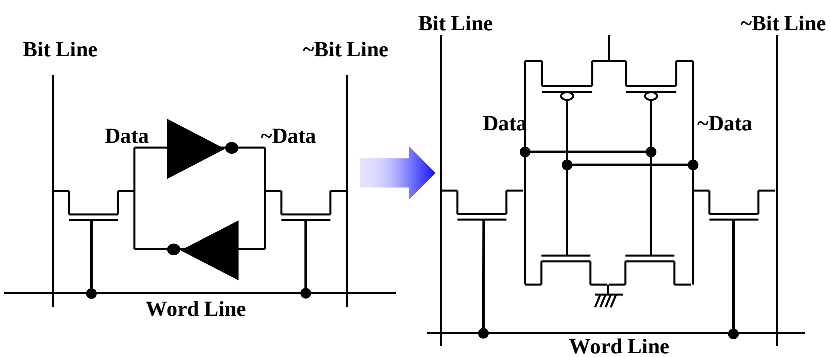
- Simulation results can be loaded back into ***MEMS+*** and animated in the 3-D canvas

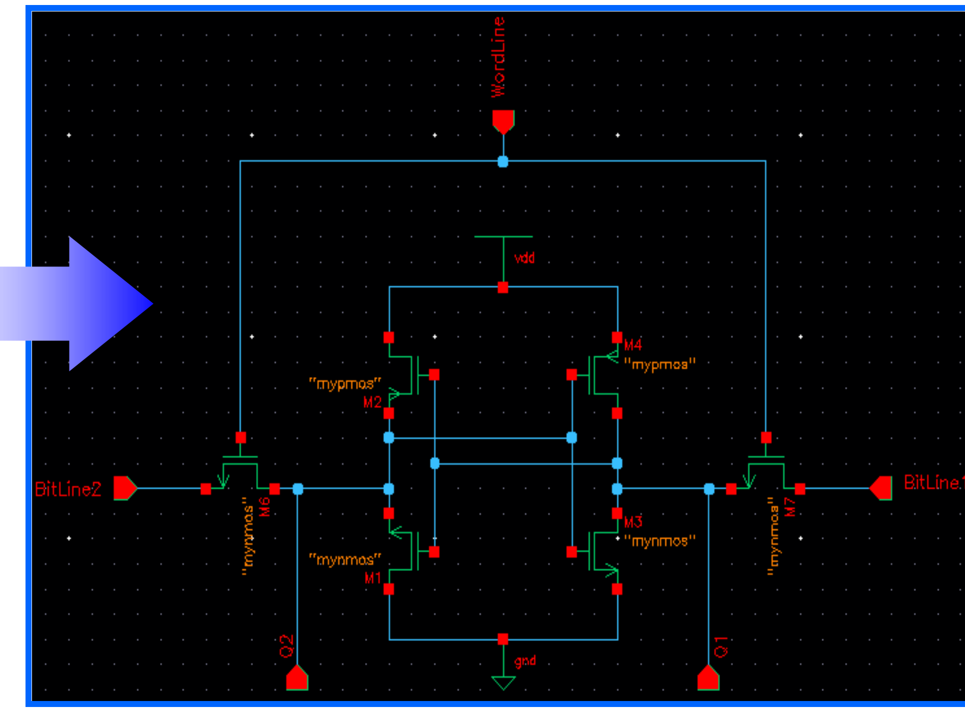


SRAM Memory Cell Design

- The IC designer, meanwhile, creates a schematic of the SRAM memory cell underneath each mirror…





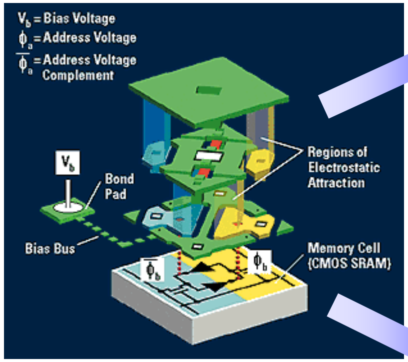


Cadence Virtuoso schematic of the memory cell

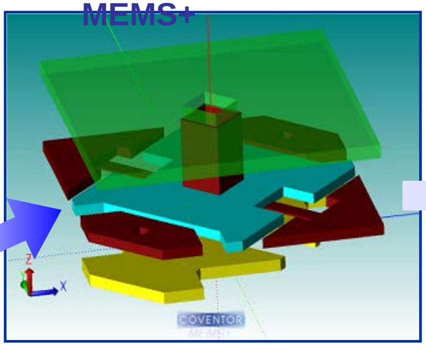
Complete Pixel Cell

- The CMOS SRAM cell can in turn be connected to the mirror to assemble the complete pixel cell

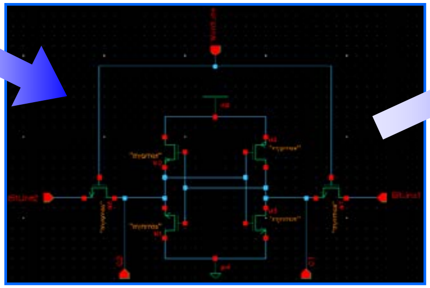
1 DMD mirror with memory cell



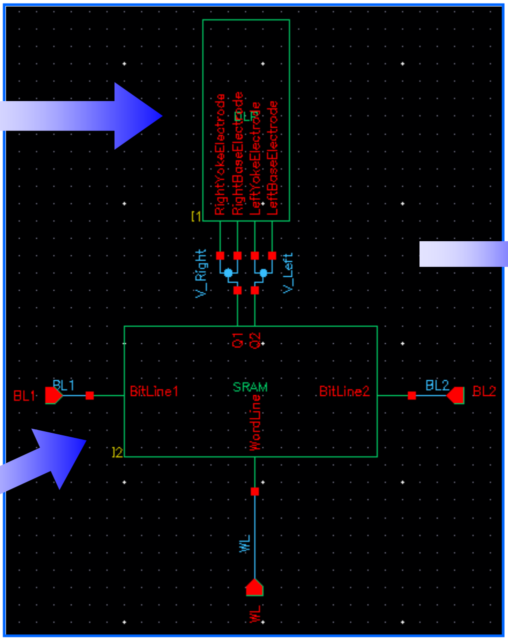
2 DMD mirror in MEMS+



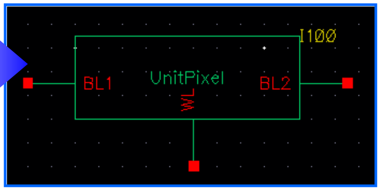
3 Memory cell schematic



4 Schematic of the combined device and memory cell model

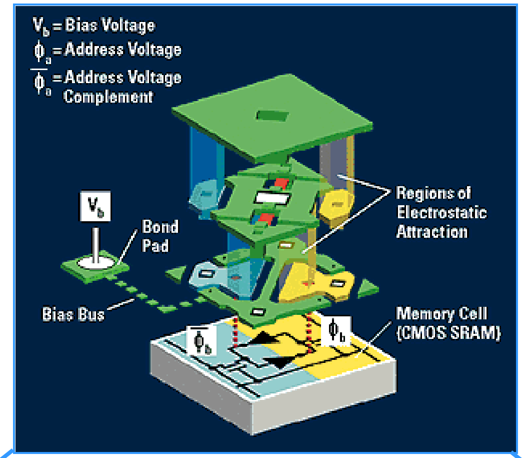


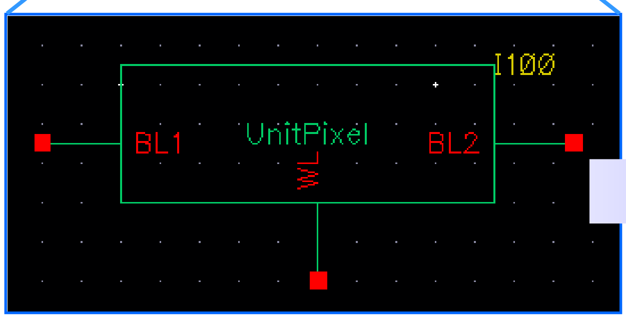
5 Hierarchical symbol of a DMD mirror with memory cell



Mirror Array Schematic

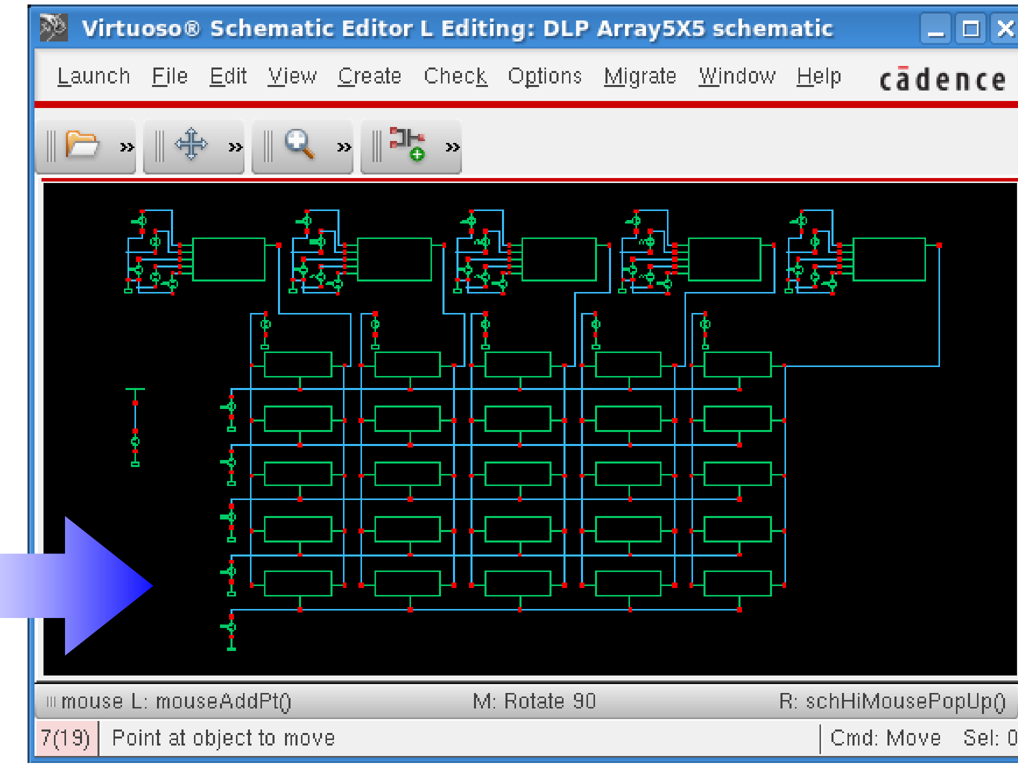
- The pixel cell is replicated to form an array and connected to the driving electronics





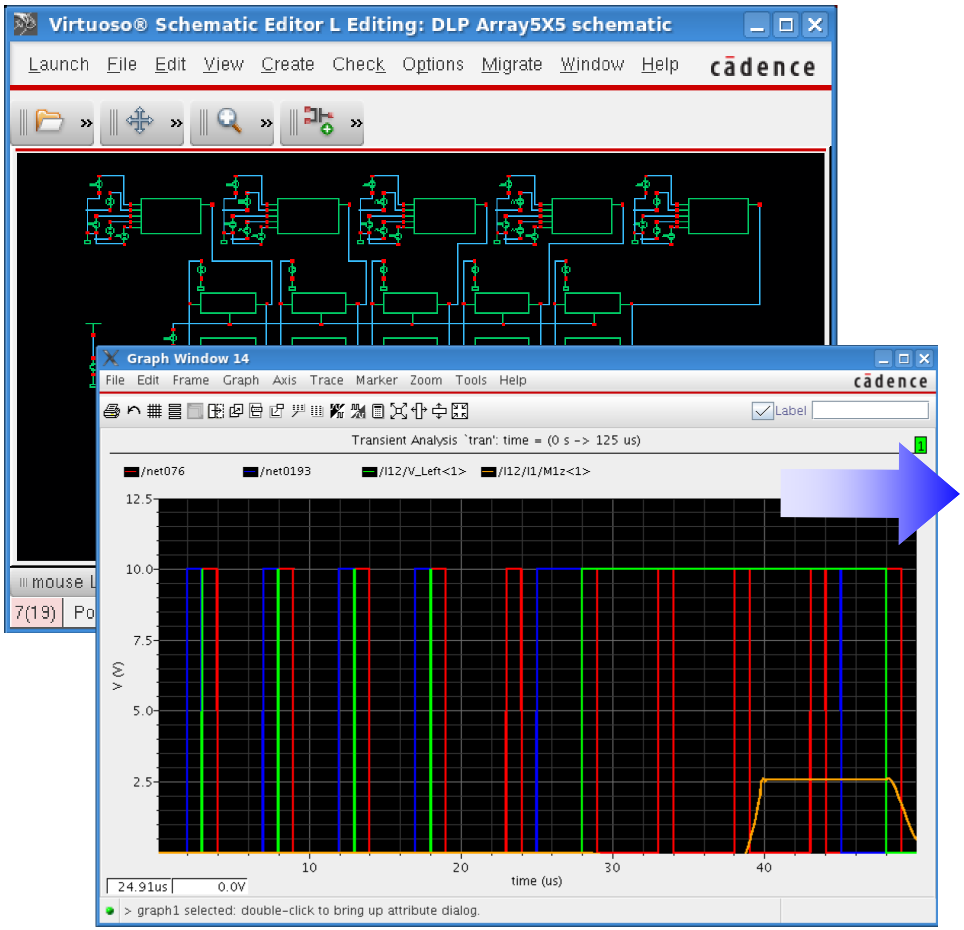
Hierarchical symbol of a DMD mirror with memory cell

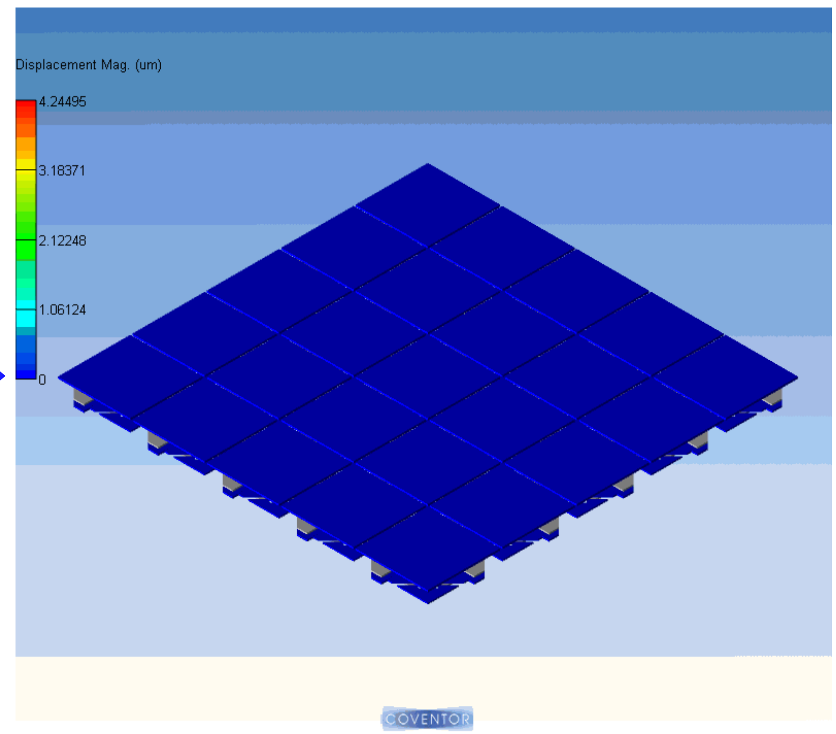
Cadence Virtuoso schematic of memory cell



Mirror Array Simulation

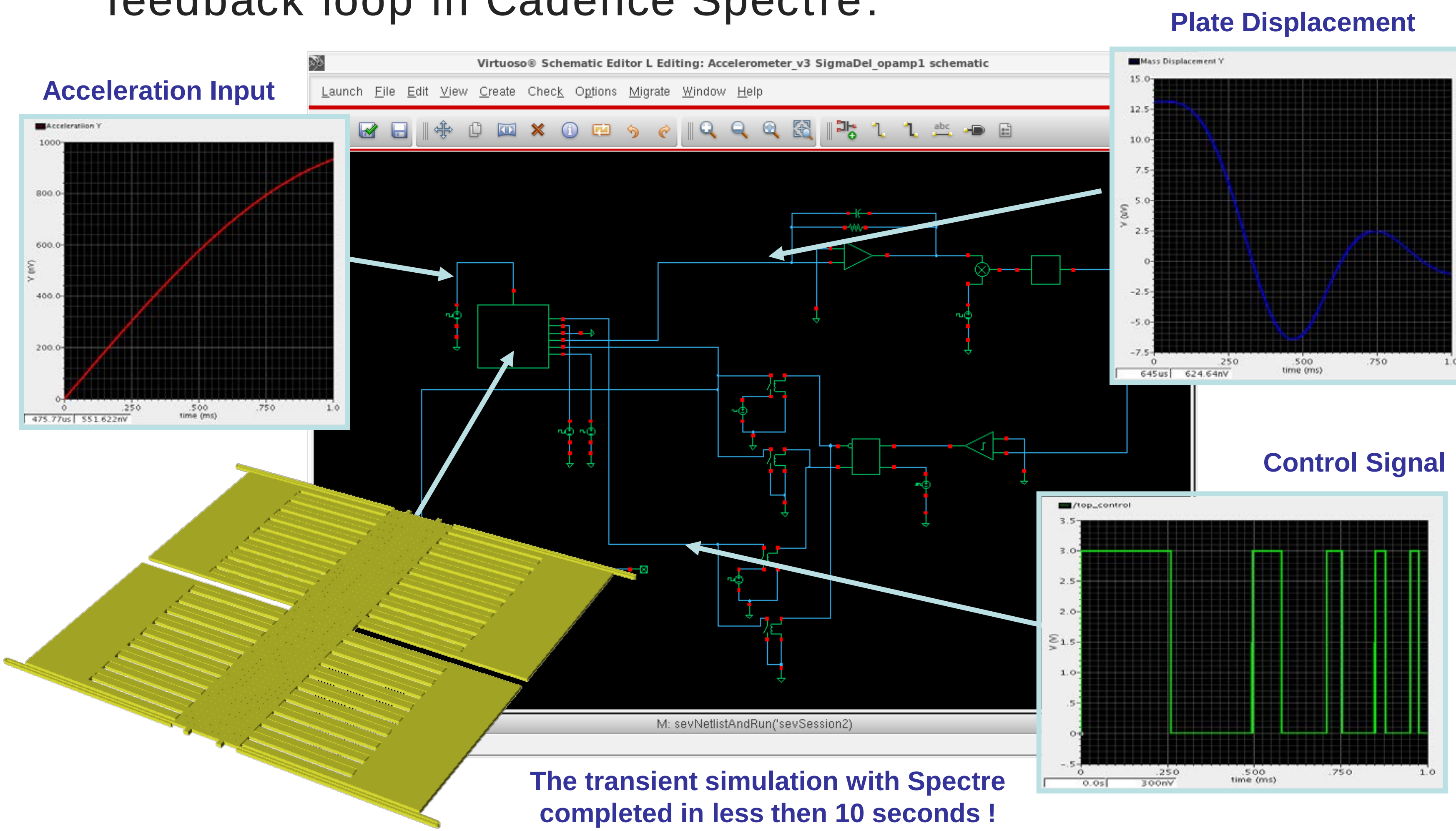
- The complete mirror array can now be simulated with the Virtuoso simulators: Spectre, UltraSim or APS





Accelerometer with ΣΔ Feedback Loop

- ***MEMS+*** generated accelerometer model with ΣΔ force feedback loop in Cadence Spectre:



The transient simulation with Spectre completed in less then 10 seconds !

Conclusions

MEMS+

- Device design via state-of-the-art non-linear FEA models
  - Electrostatics
  - Mechanical and electrical non-linearity
    - Stress, stress gradient, inertial force, contact
  - Motion in 6 degrees of freedom
  - Parametric
- Access 30 man years of model development
  - Physics *and* simulation performance
- Cadence available for gate level simulations
- Leverage all the benefits of Matlab & Simulink for system level design
  - Toolboxes
  - Scripting