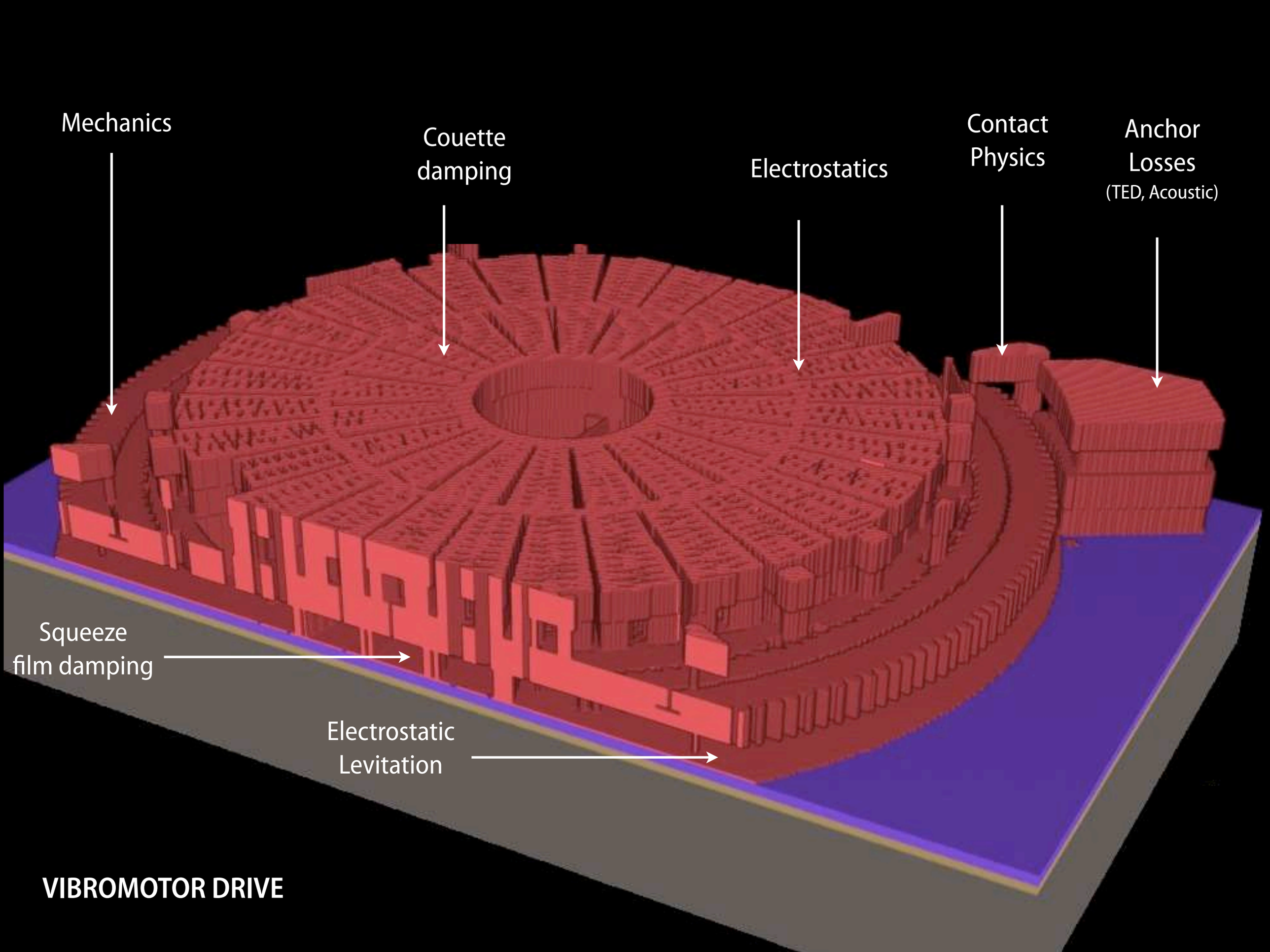
Design Flow in IntelliSuite v8.6

Design flow

MEMS design is highly interdisciplinary


Mechanics
Couette damping
Electrostatics
Contact Physics
Anchor Losses
(TED, Acoustic)
Squeeze film damping
Electrostatic Levitation
VIBROMOTOR DRIVE

Colliding domains

Mechanics

Electrostatics

Magnetostatics

Fluidics

Optics

Electromagnetics

Acoustics

Biochemistry

Electrokinetics

Physics

Piezoelectrics

Ferromagnetics

Piezoresistive

Magnetorestrictive

Proteomics

Genomics

Materials

Electronics

Biology

Control theory

Systems

Process design

Process simulation

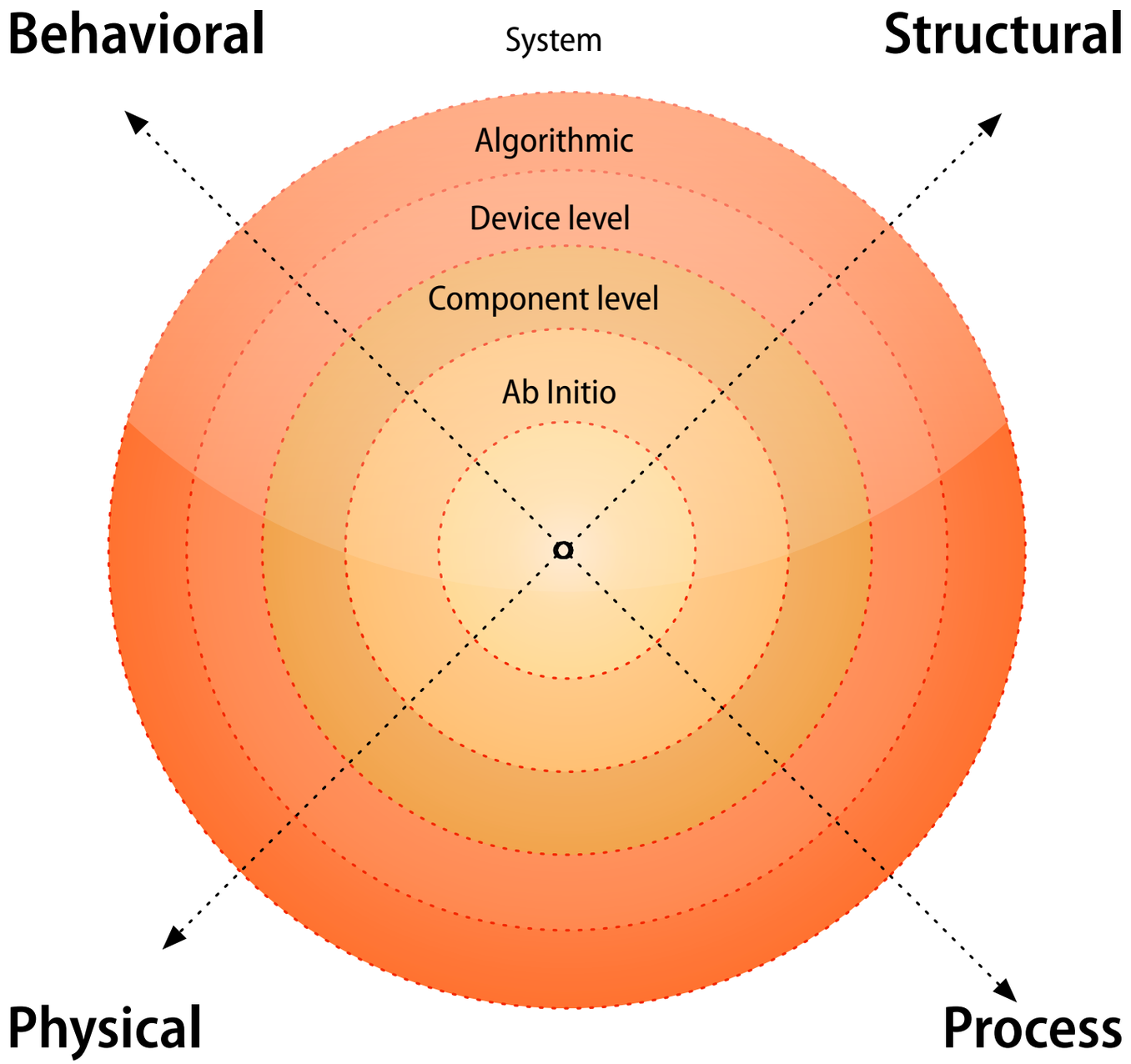
Packaging

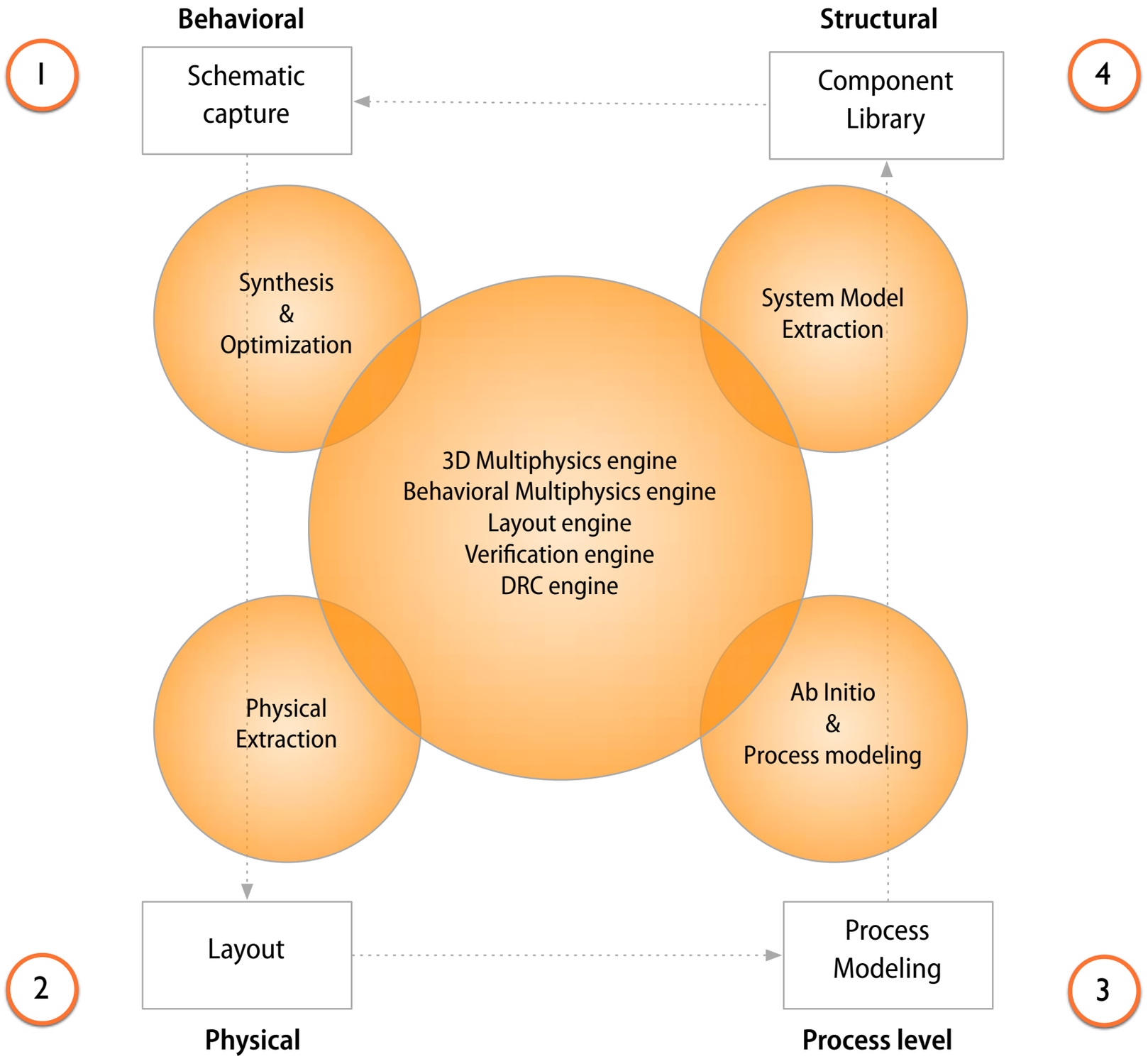
Yield optimization

DfM

Manufacturing

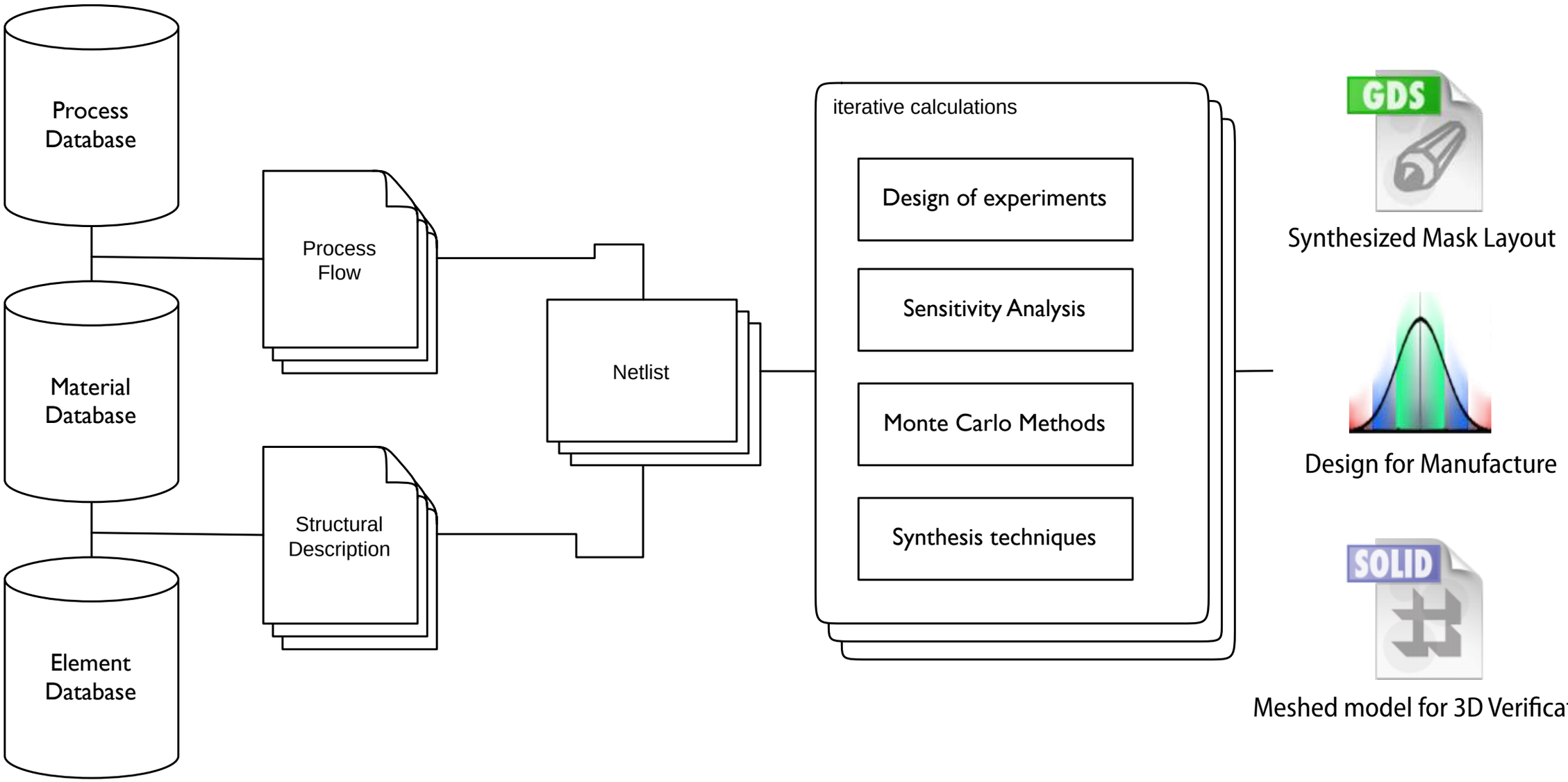
Hierarchy of MEMS modeling





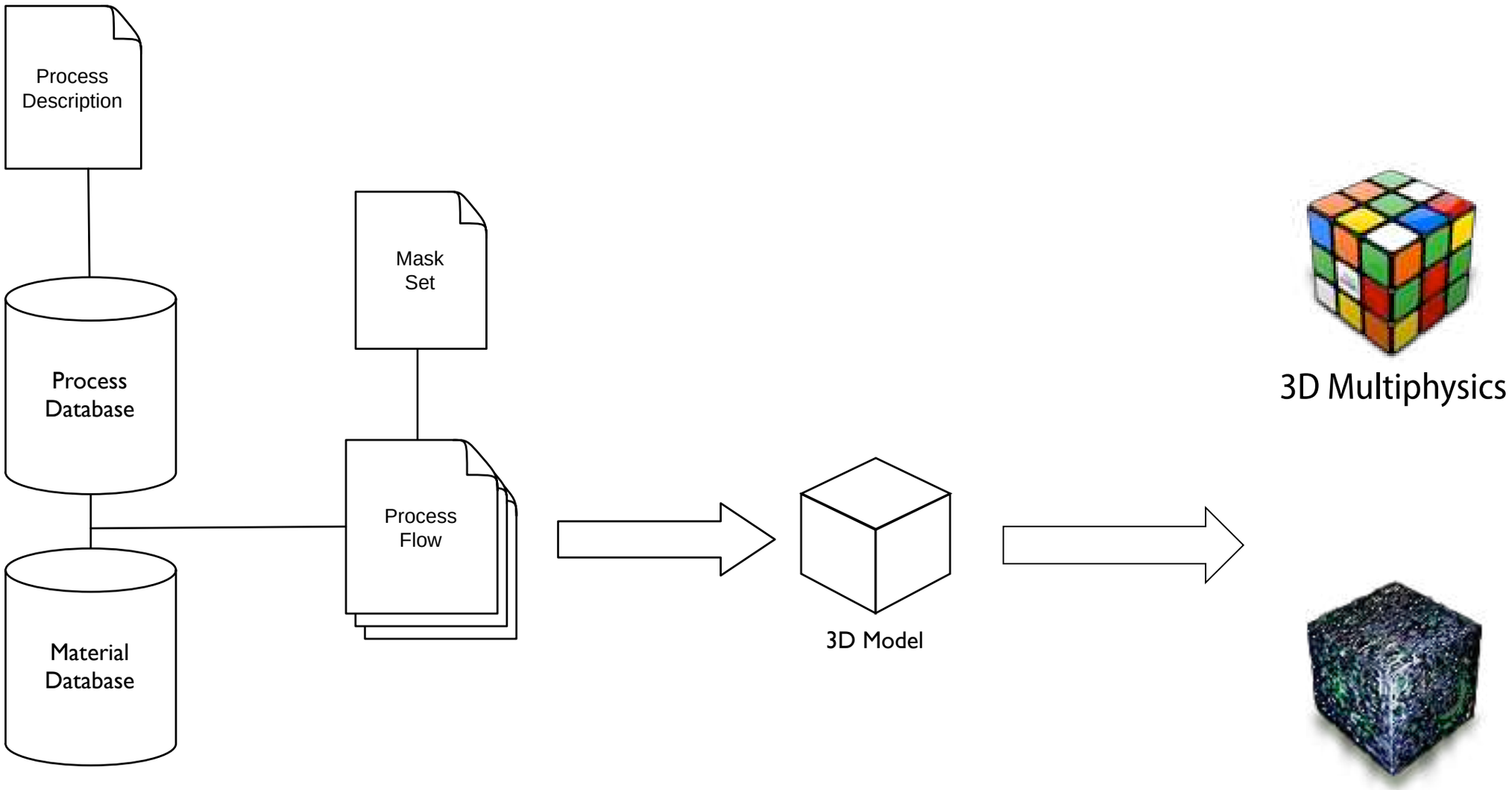
Seamless integration of design flow…

Top down flow: schematic based…



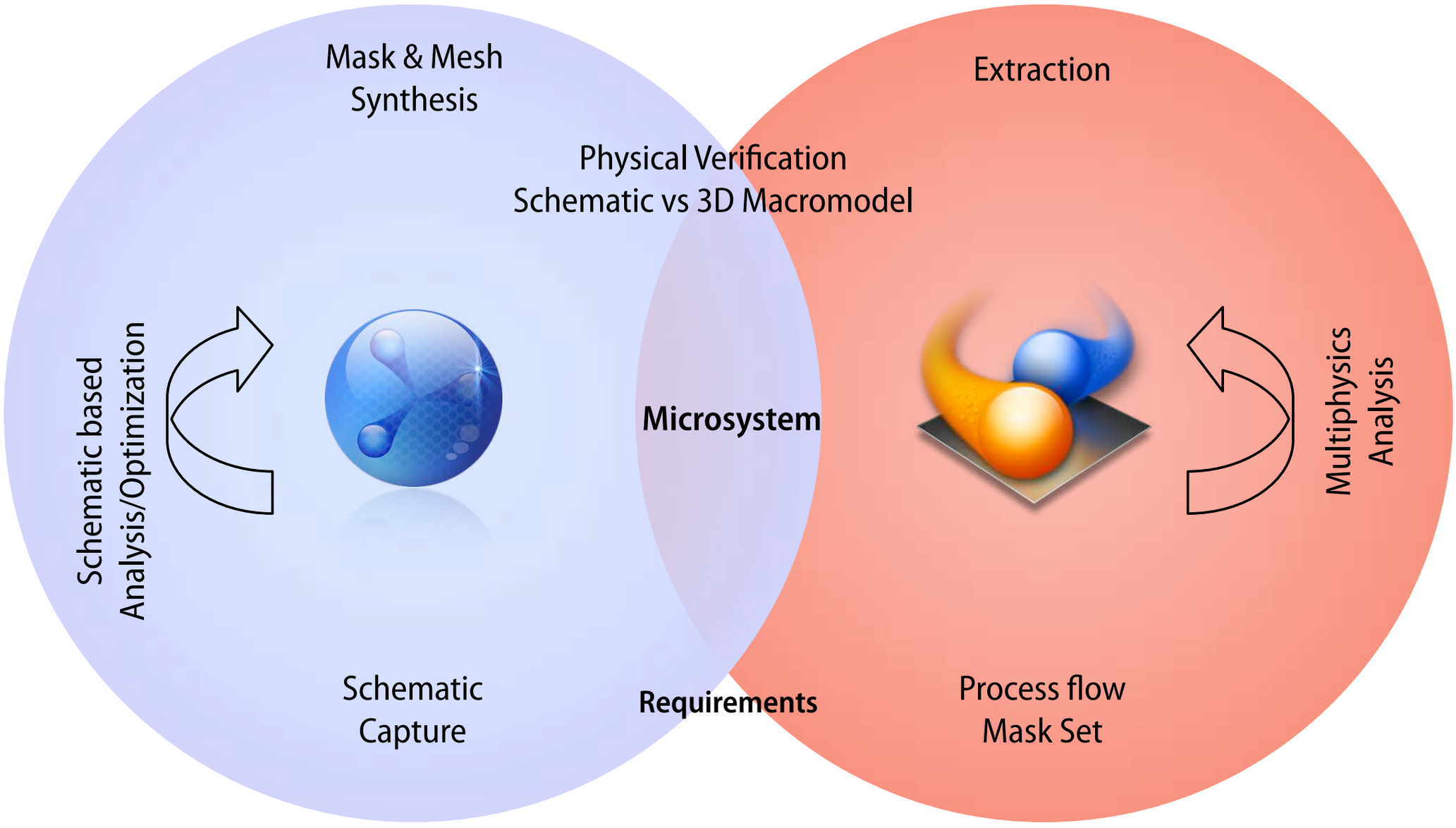
Fast but less accurate…

Bottom up design flow: 3D based



Accurate but slower…

IntelliSuite: Best of both worlds



Accurate + Fast

IntelliSuite Tool Chain

Synple
Schematic capture
Component based
Design exploration
Mask and 3D synthesis

Blueprint
Physical design
Layout/DRC
Tape Out

Clean Room
Process flow design
Process debug
Process visualization

Fast Field
Multiphysics solvers
Coupled field analysis
System model extraction

EDA Linker
Link to EDA tools
Cadence, Mentor,
Synopsys, Ansoft,
Mathworks etc…

Behavioral modeling

Synple capabilities (Behavioral)

Schematic capture
Design Exploration
Optimization
Design for manufacture

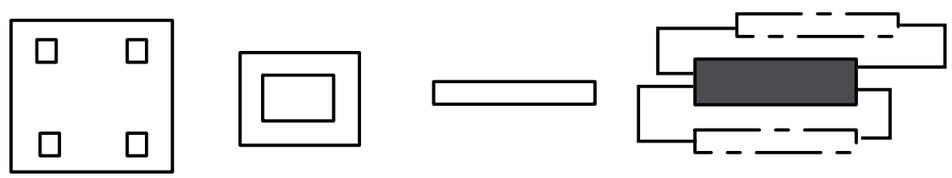
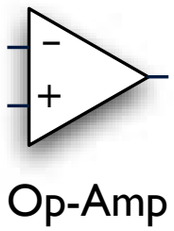
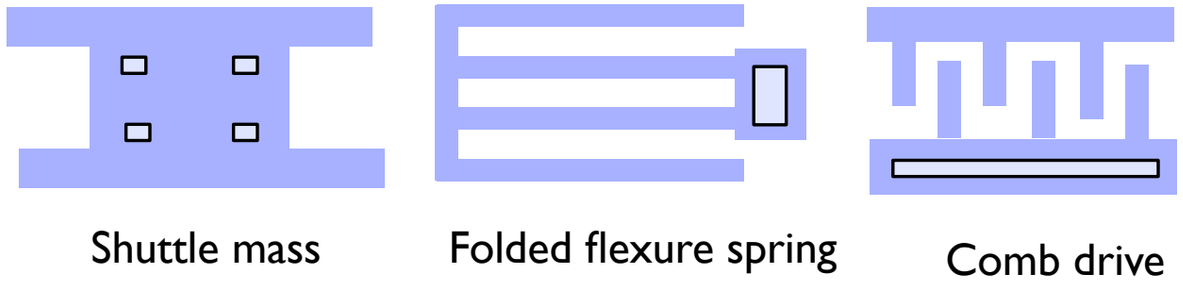
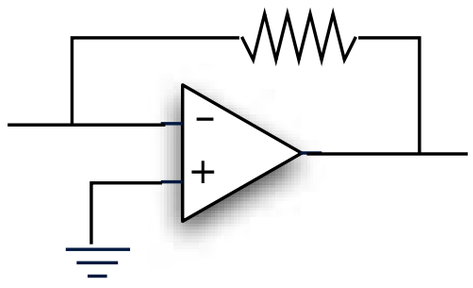
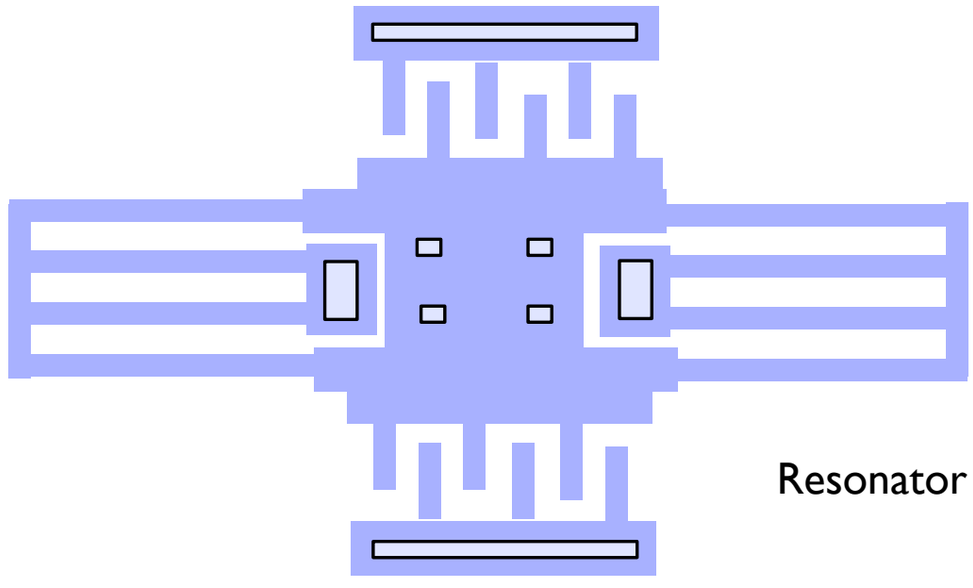
Multiphysics computation
Mechanics
Electrostatics
Damping/Dissipation
Piezo
Mixed Signal
Control Systems
1000X faster than FEA

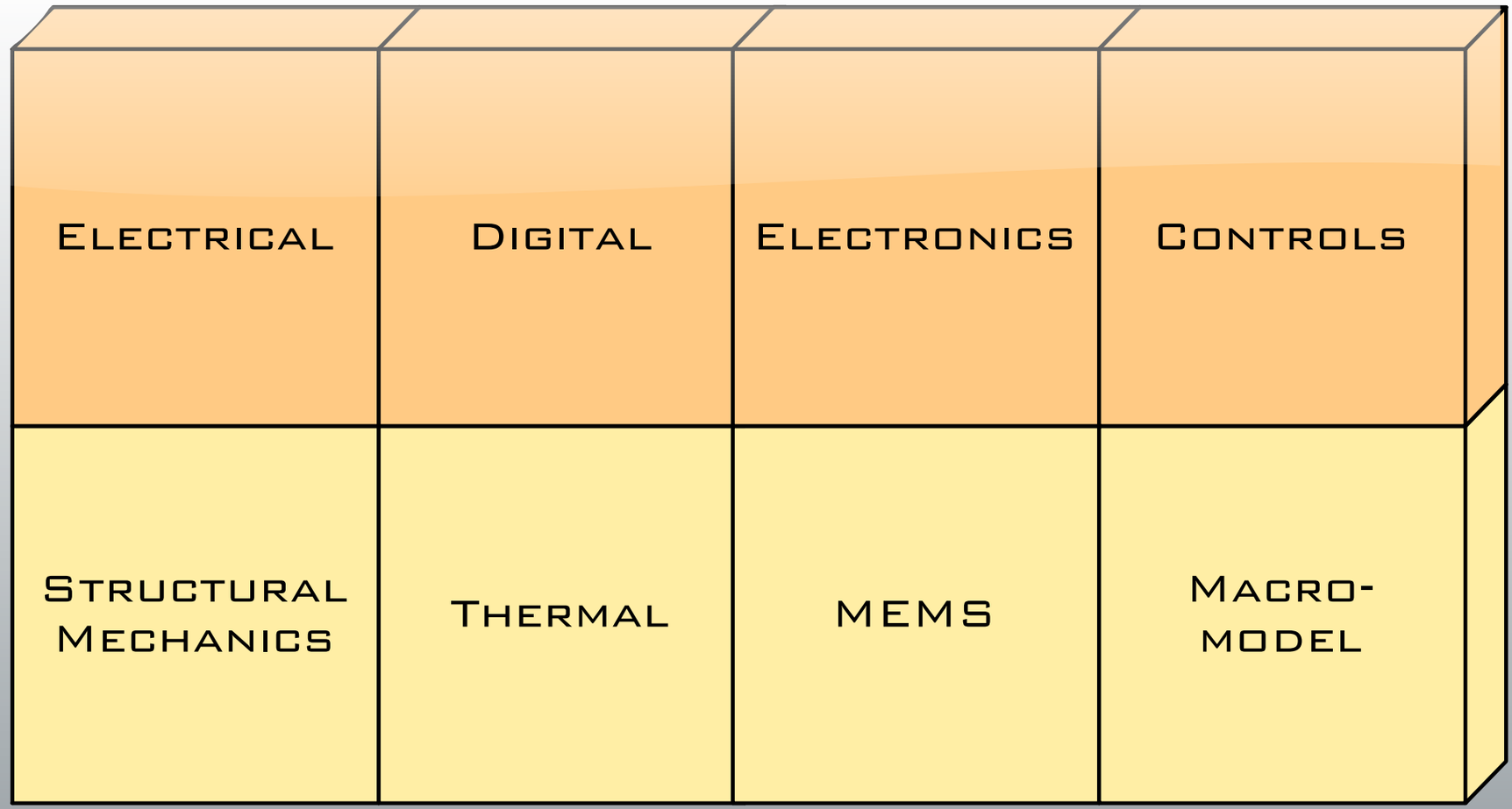
Synthesis
Schematic to mask
Schematic to 3D
Schematic to mesh

Yield Engineering
DfM
Process Corner studies
Yield prediction

Link to other tools
Automatic meshing
Derive process flow

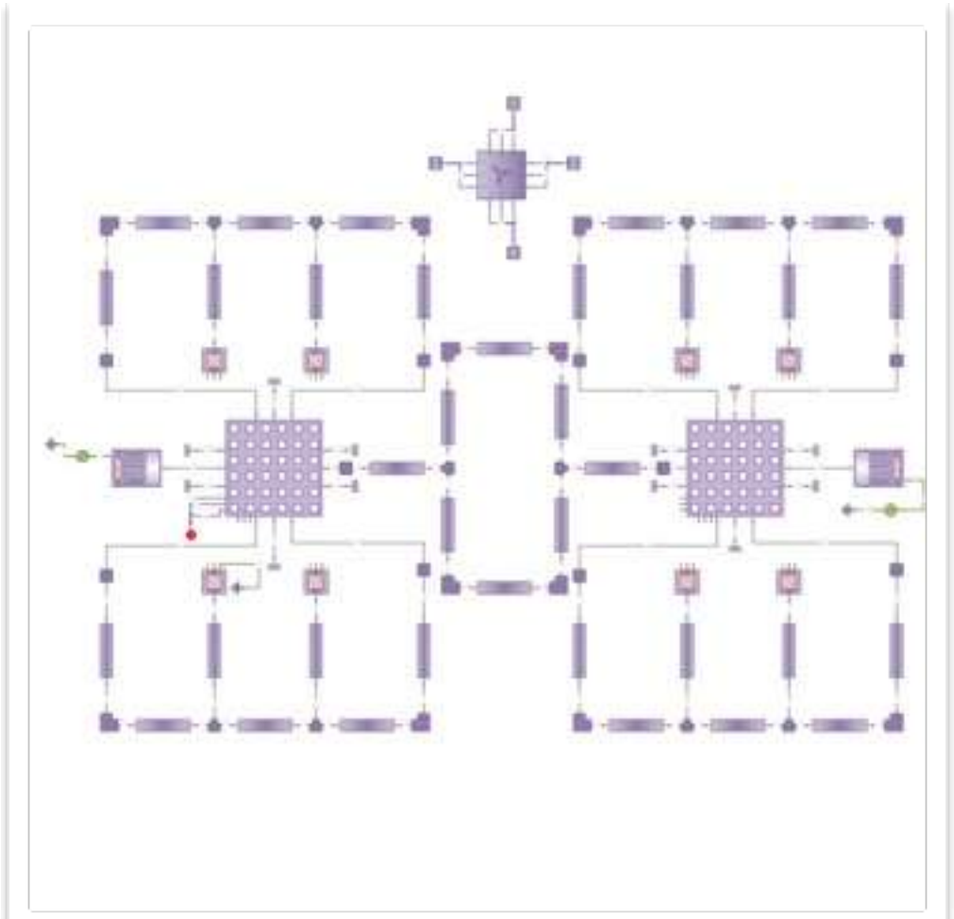
Hierarchical multi-domain design

Atomic elements	 Transistor RLC	
Compound elements	 Op-Amp	 Shuttle mass Folded flexure spring Comb drive
Device elements	 Interface circuit	 Resonator

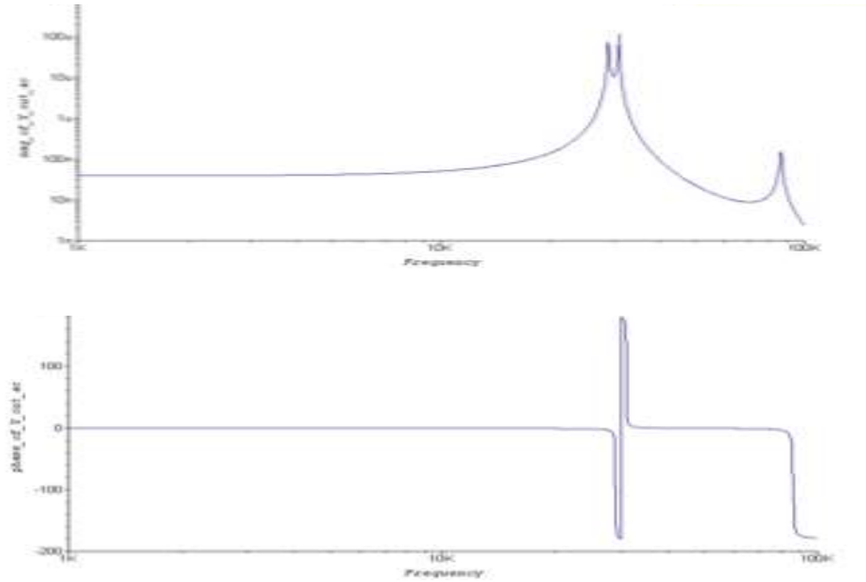


Wide Range of Building Blocks

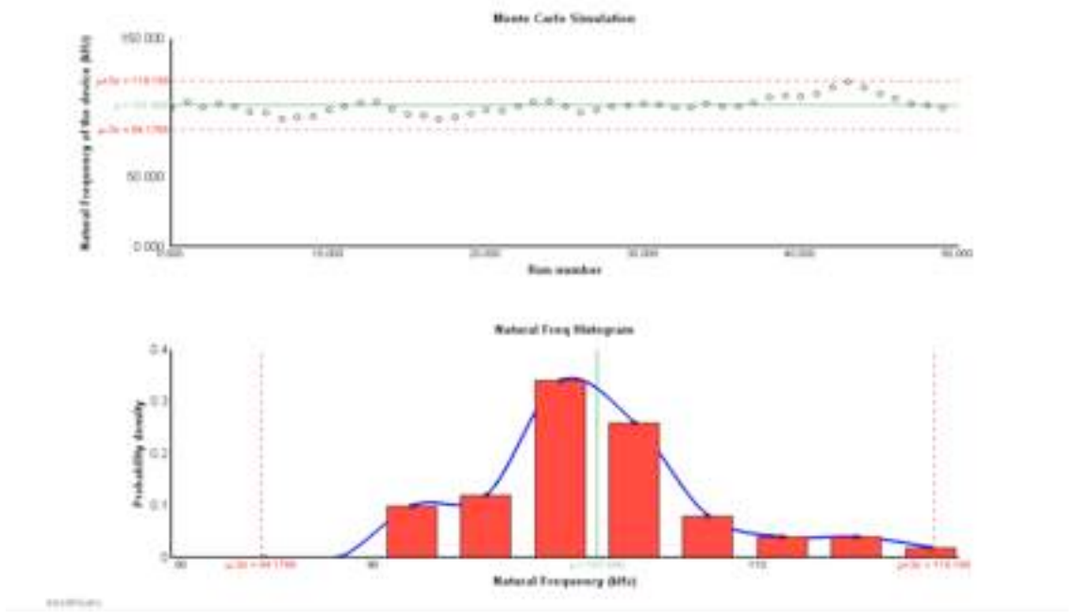
Schematic based design exploration



Band pass filter

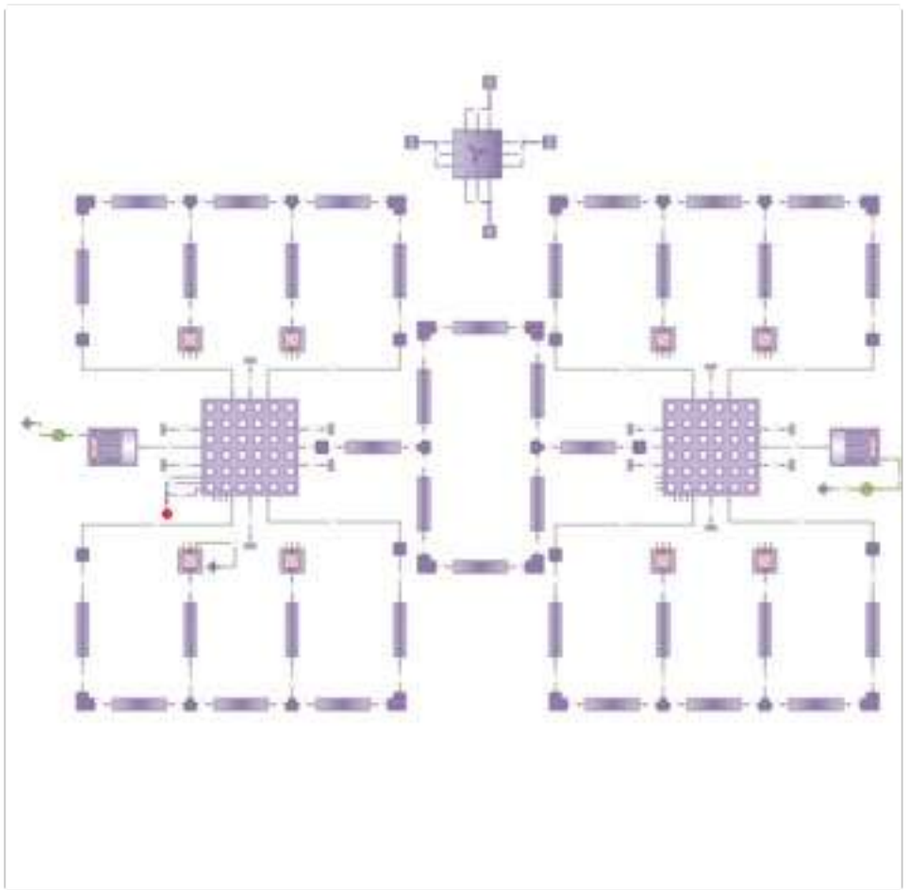


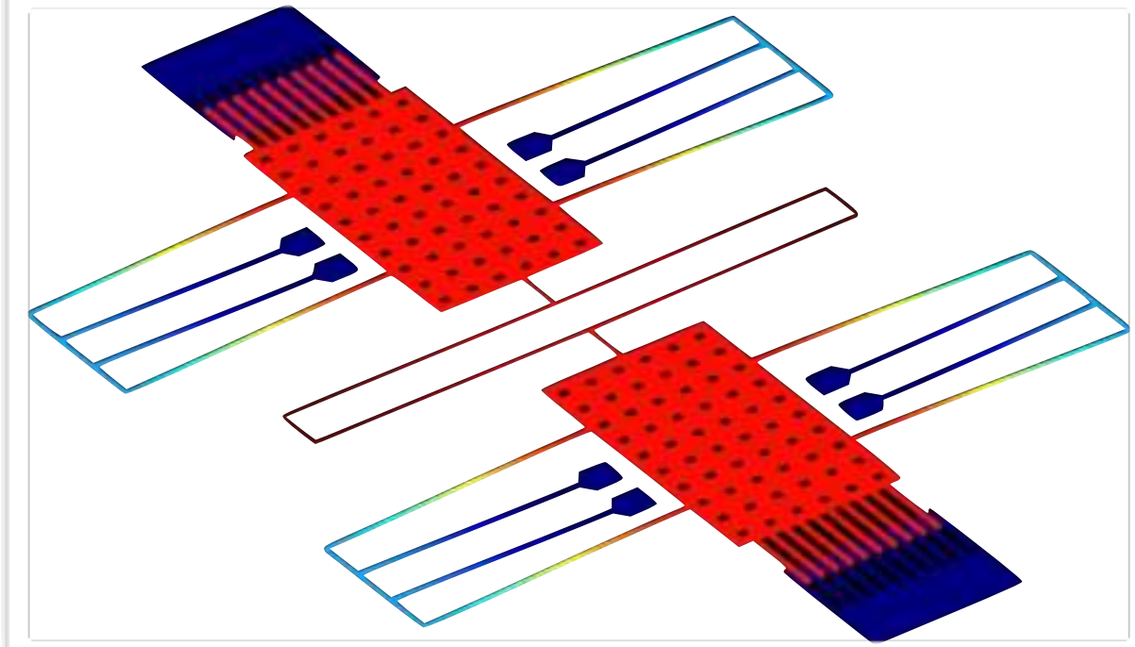
Compute time: 4 hr (Full 3D) vs 30s (compact)



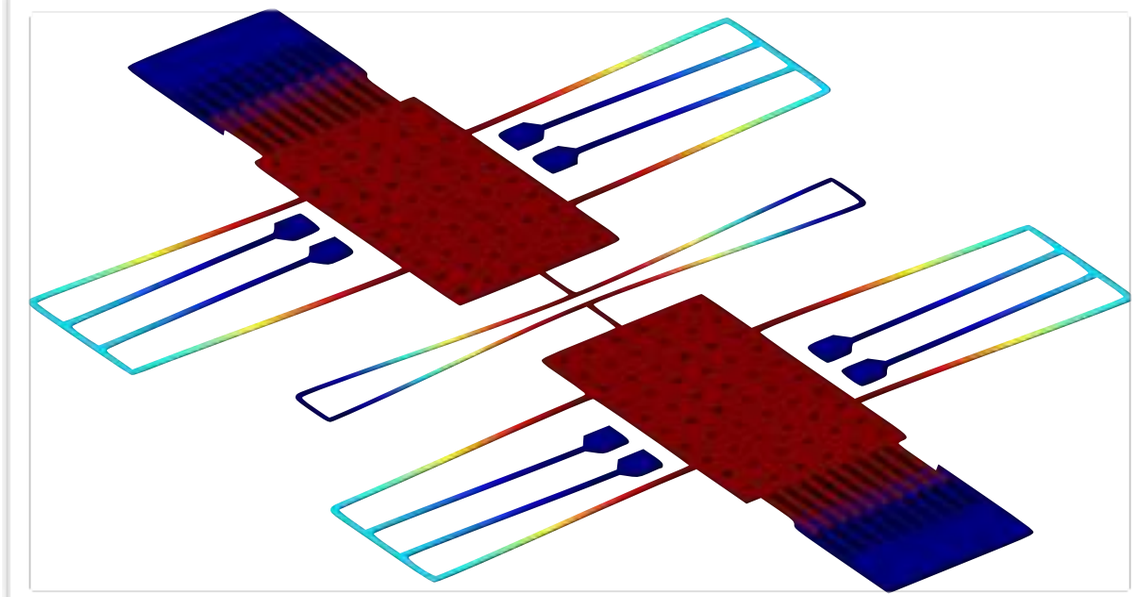
Monte Carlo based
process variation analysis

Visualize schematic results in 3D



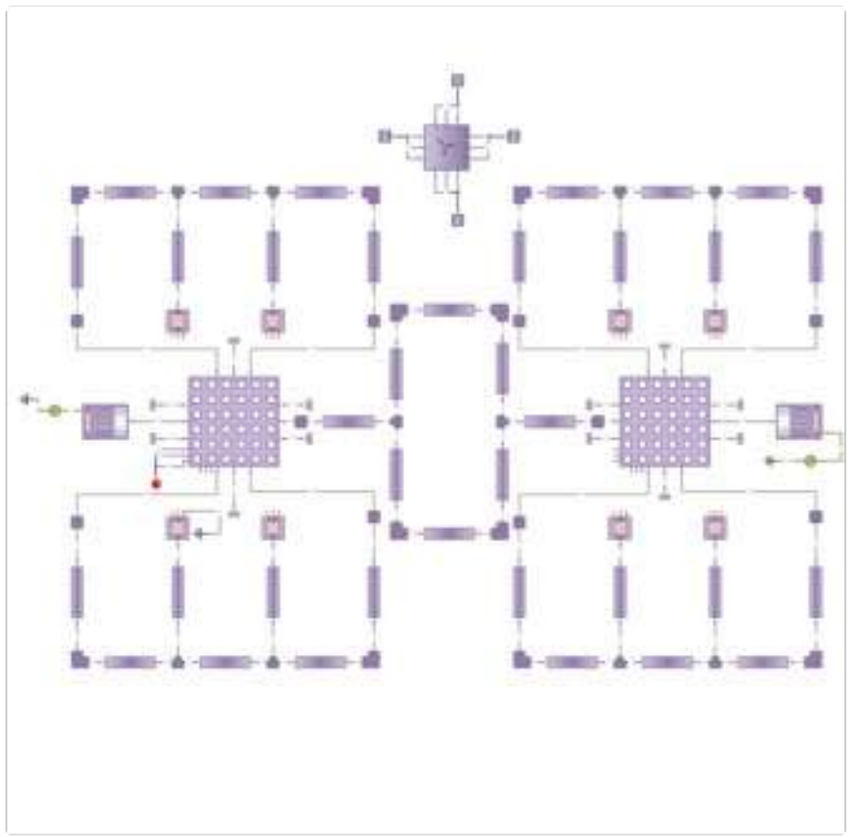


Mode 1: In Phase

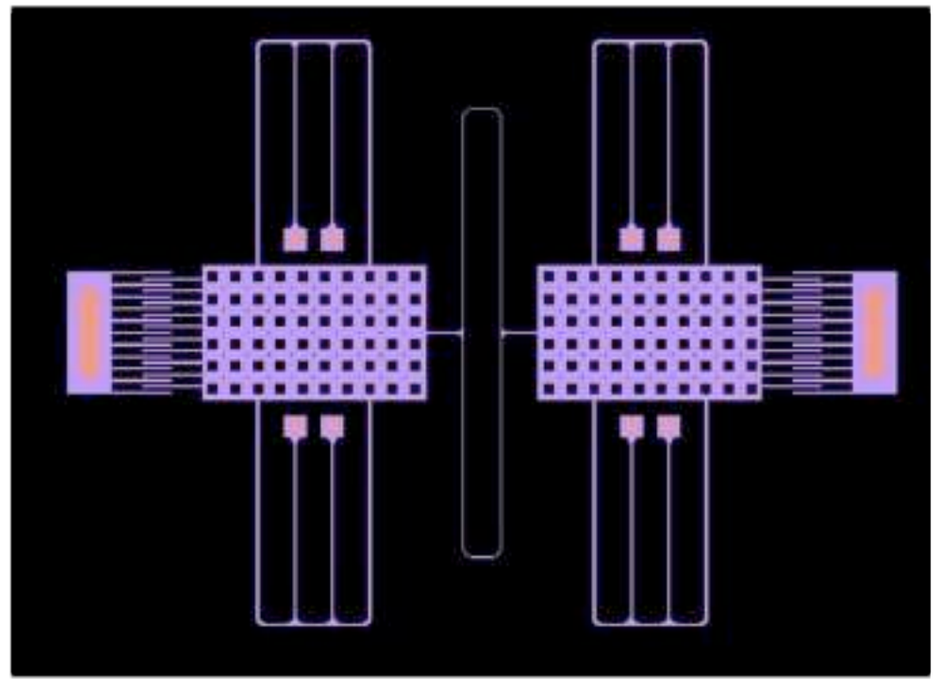


Mode 2: Anti Phase

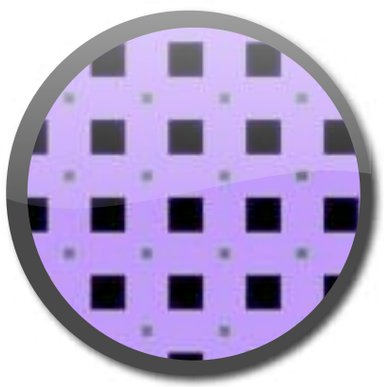
Schematic to mask



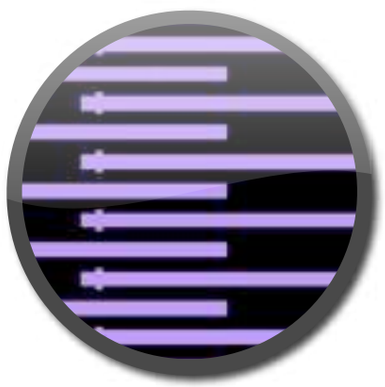
Automated layout synthesis



Stress relief curves



Dimples

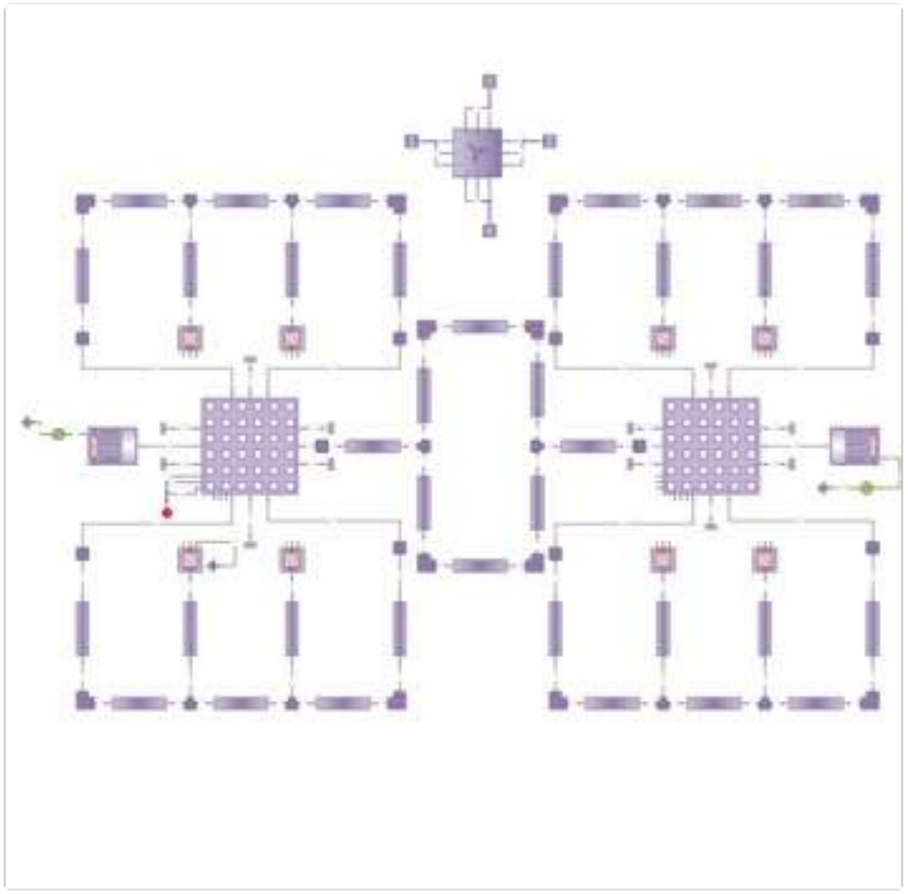


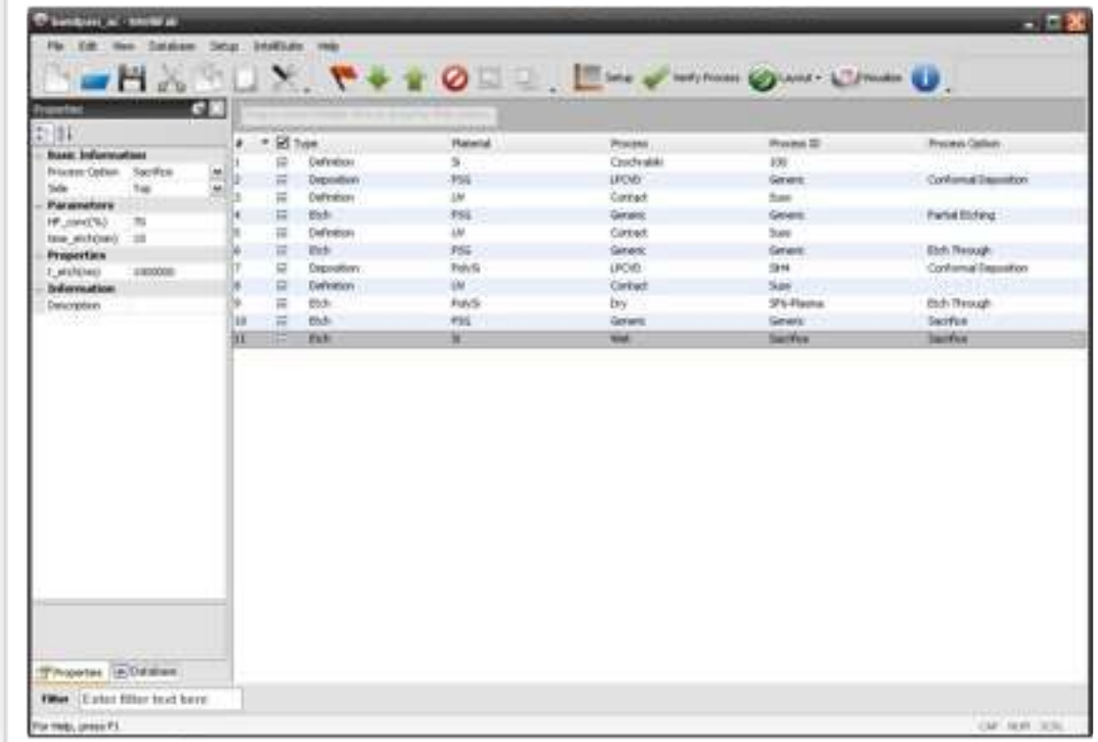
Comb bumpers

Etch compensation features

Attention to detail

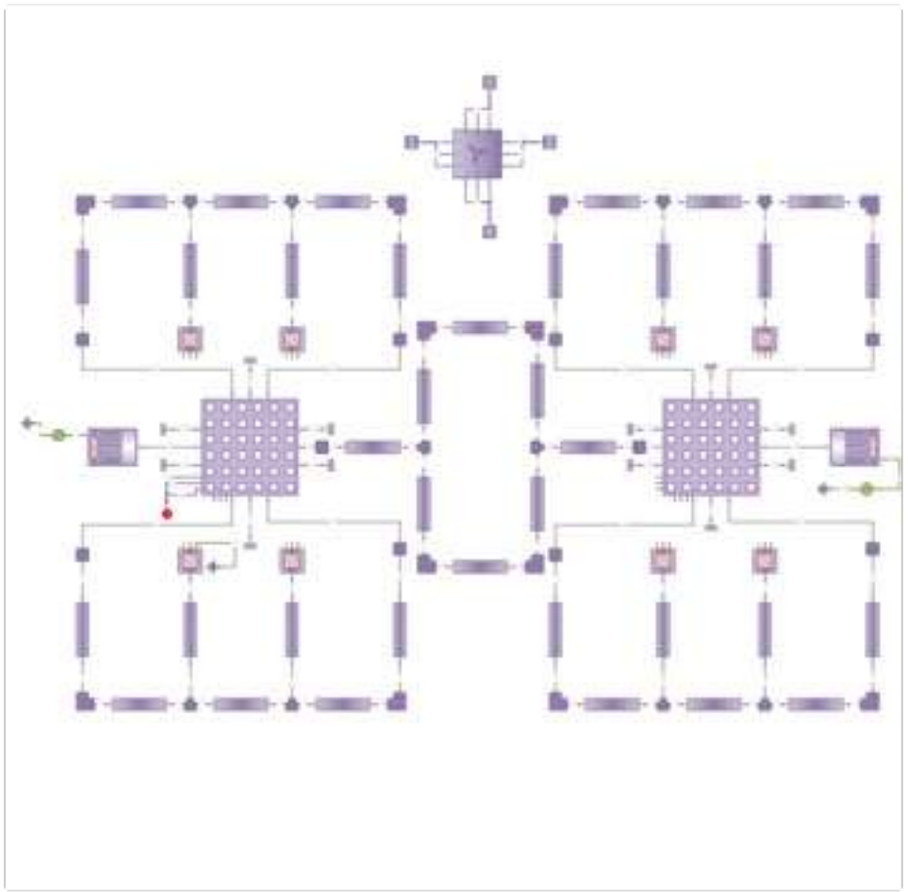
Schematic to process flow

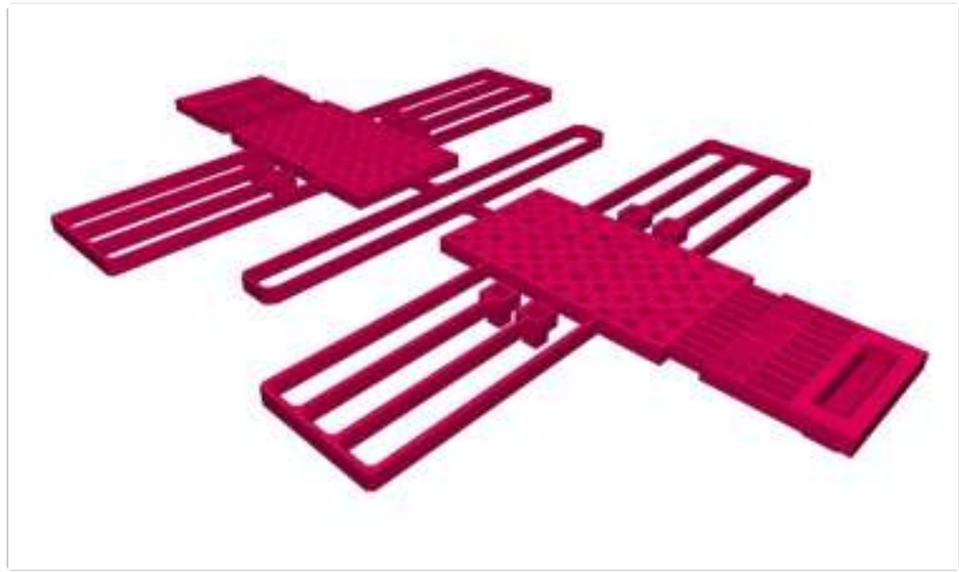


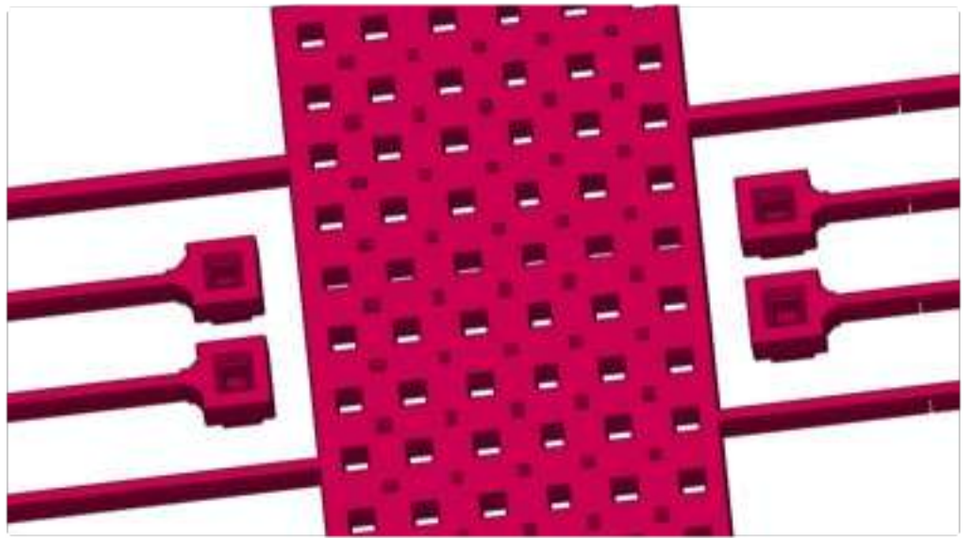


Process flow for fabricating the device is automatically derived from the schematic and technology file information

Schematic to 3D model

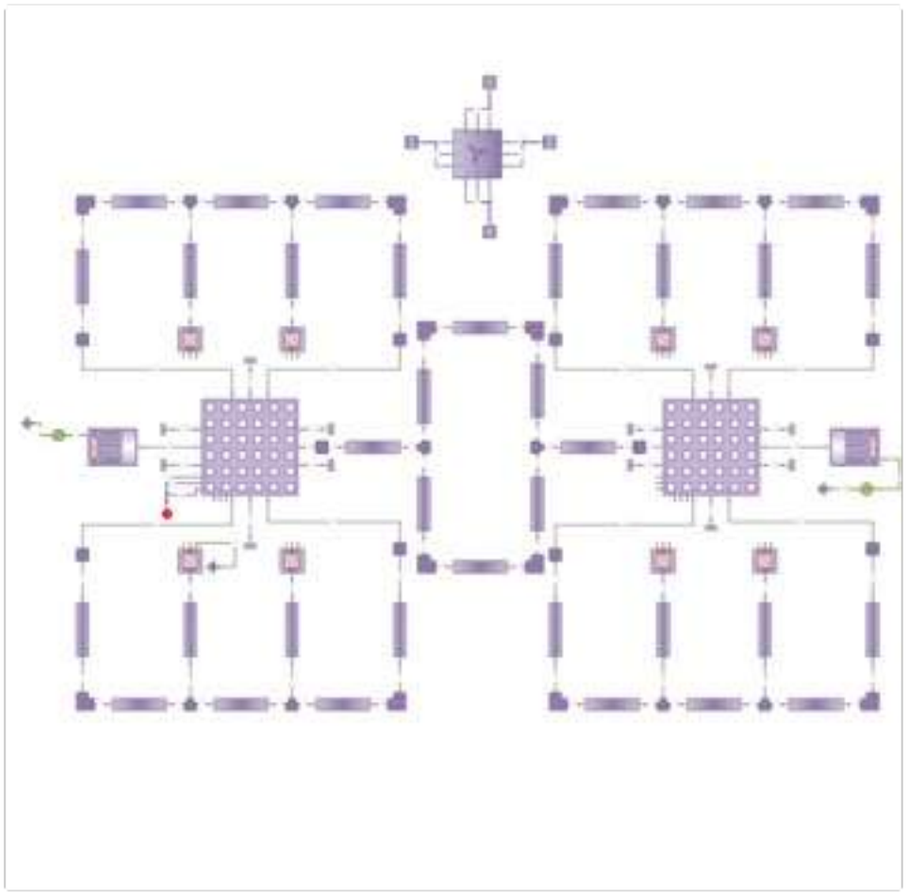


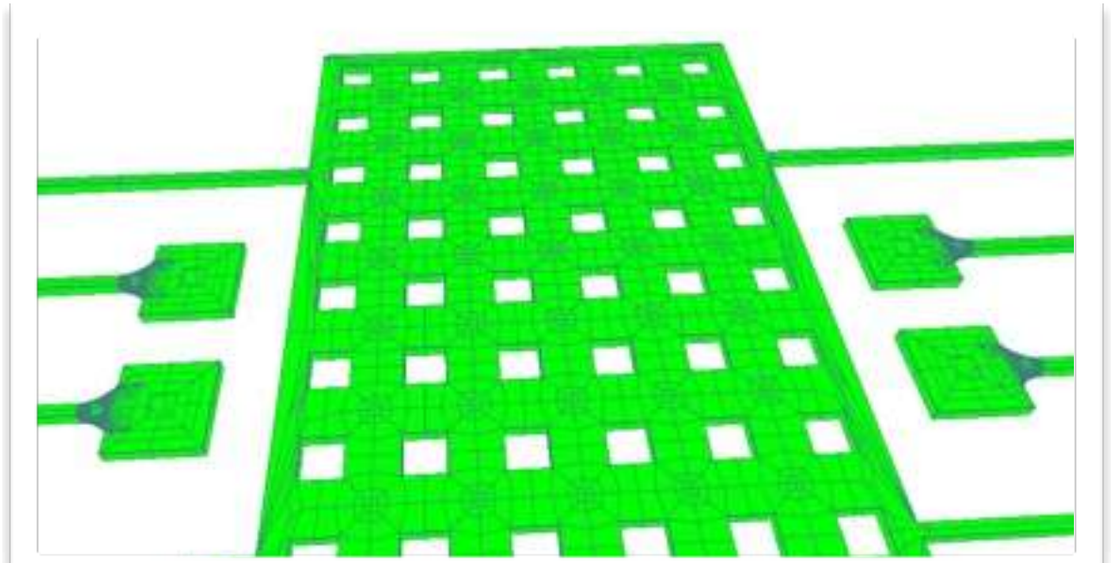


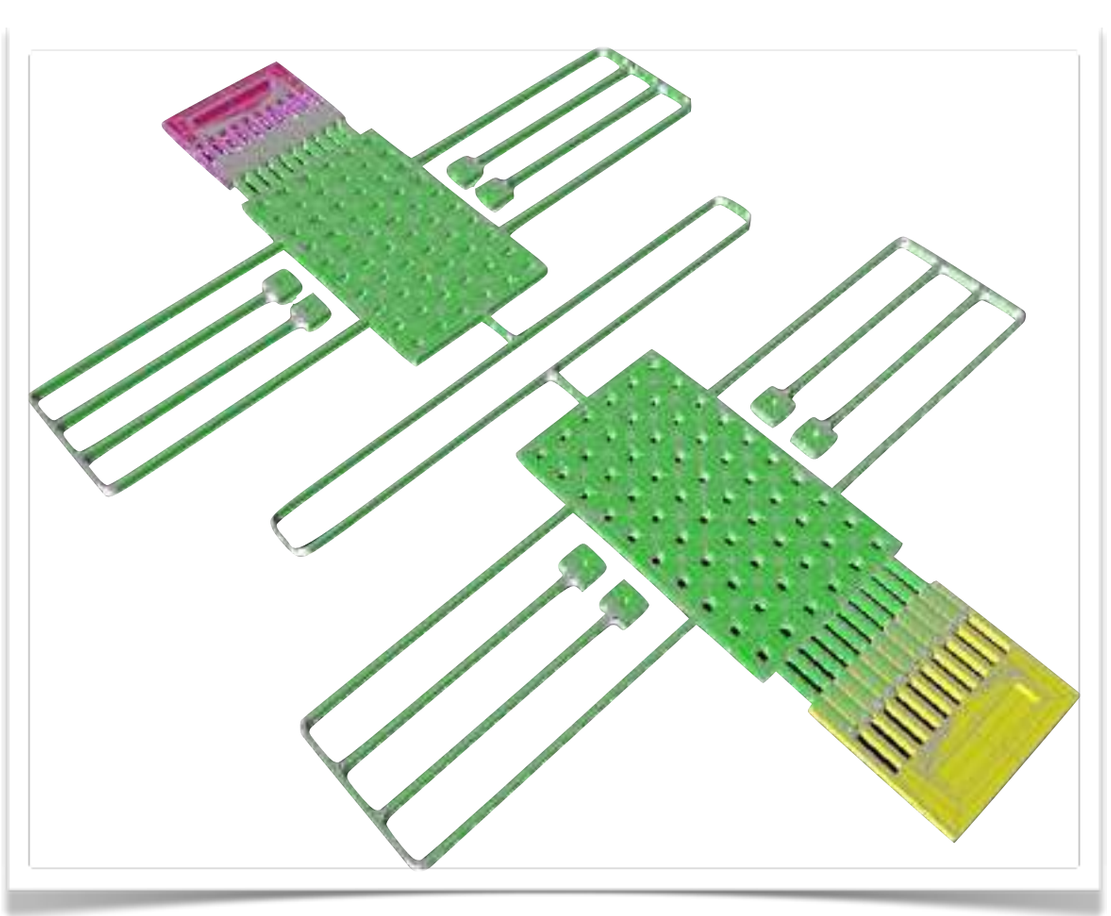


Attention to detail
Automatic placement of dimples, anchors and other secondary features

Schematic to mesh







Automated Hexahedral Meshing of the Structure

Benefits

- **Schematic driven design**

  Entry point for parametric design and design exploration

- **Hierarchical modeling**

  Model your device at system or circuit level

- **Save time**

  100-1000X faster than FEA models.

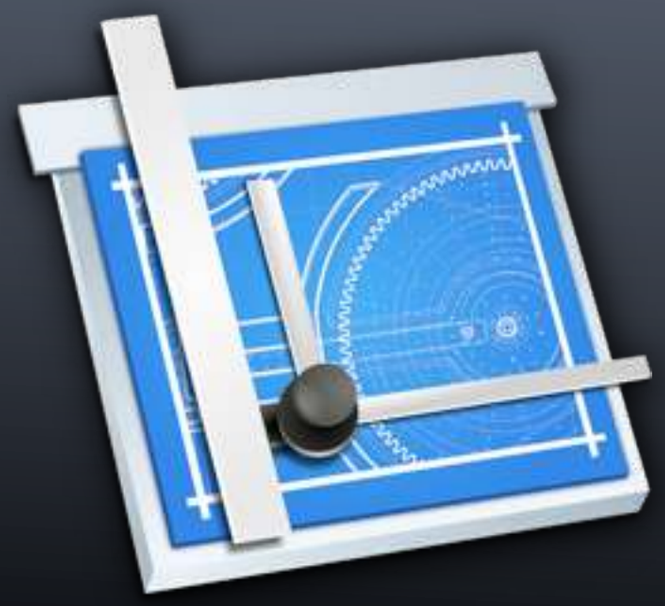
- **Design exploration and optimization**

  Quickly prototype and explore multiple designs

- **3D System modeling**

  View your results in 3D

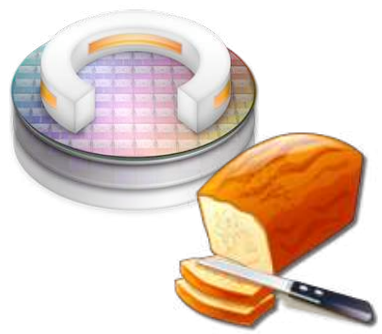
Physical design & verification



Blueprint capabilities (Physical)

Design capture
Layout optimized for MEMS
AutoCAD™ like interface
Large design library
Hierarchy support
Smart Layers
Pathfinders
Scripting

Design Rule Check
Tape Out DRC Editor
Powerful hierarchical DRC
All angle support
Easy Error Navigator

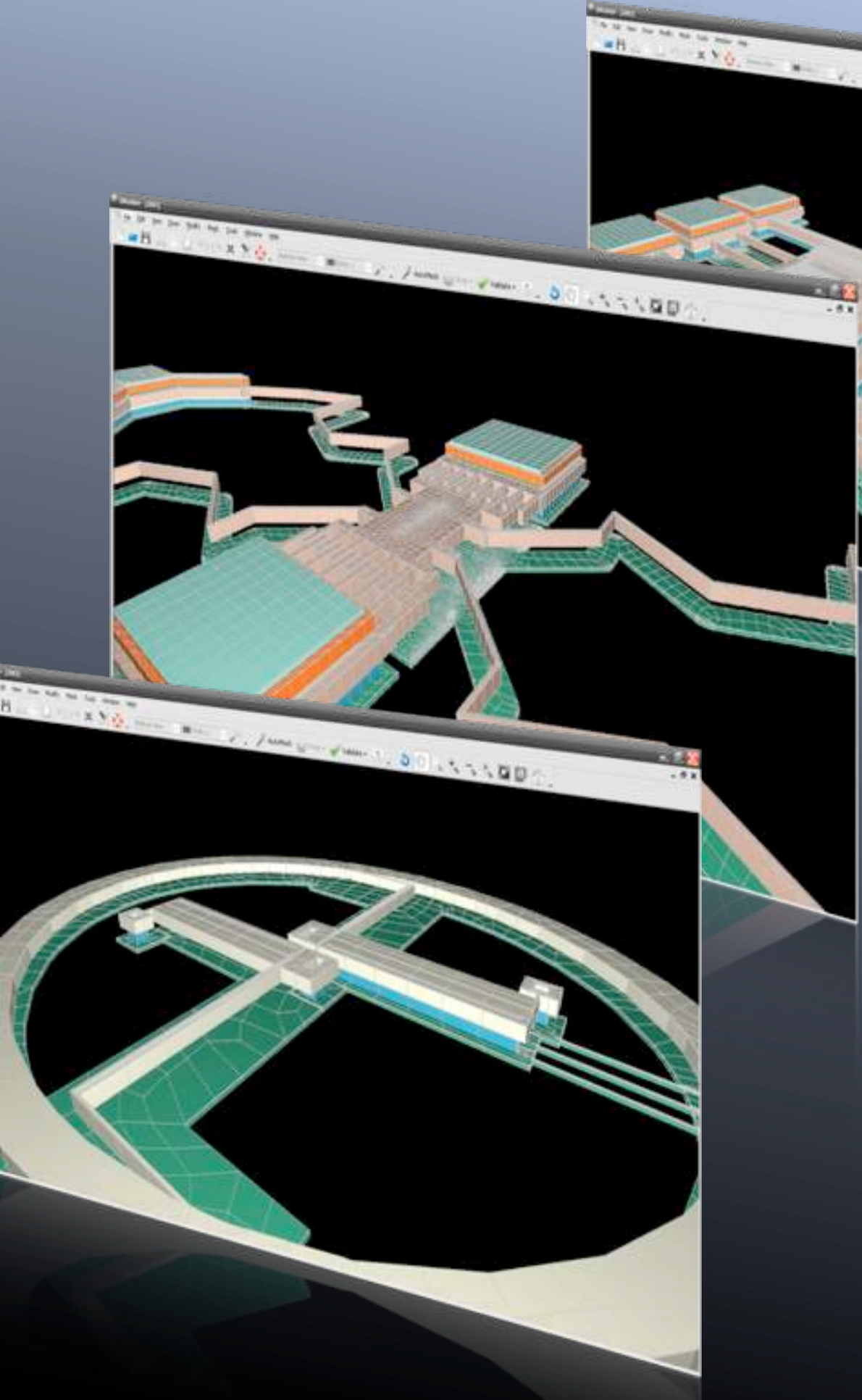


Layout visualization
Cross section drawing
3D Visualization of layout

Hexpresso
Automated HEX mesher
1 click Mask to Mesh

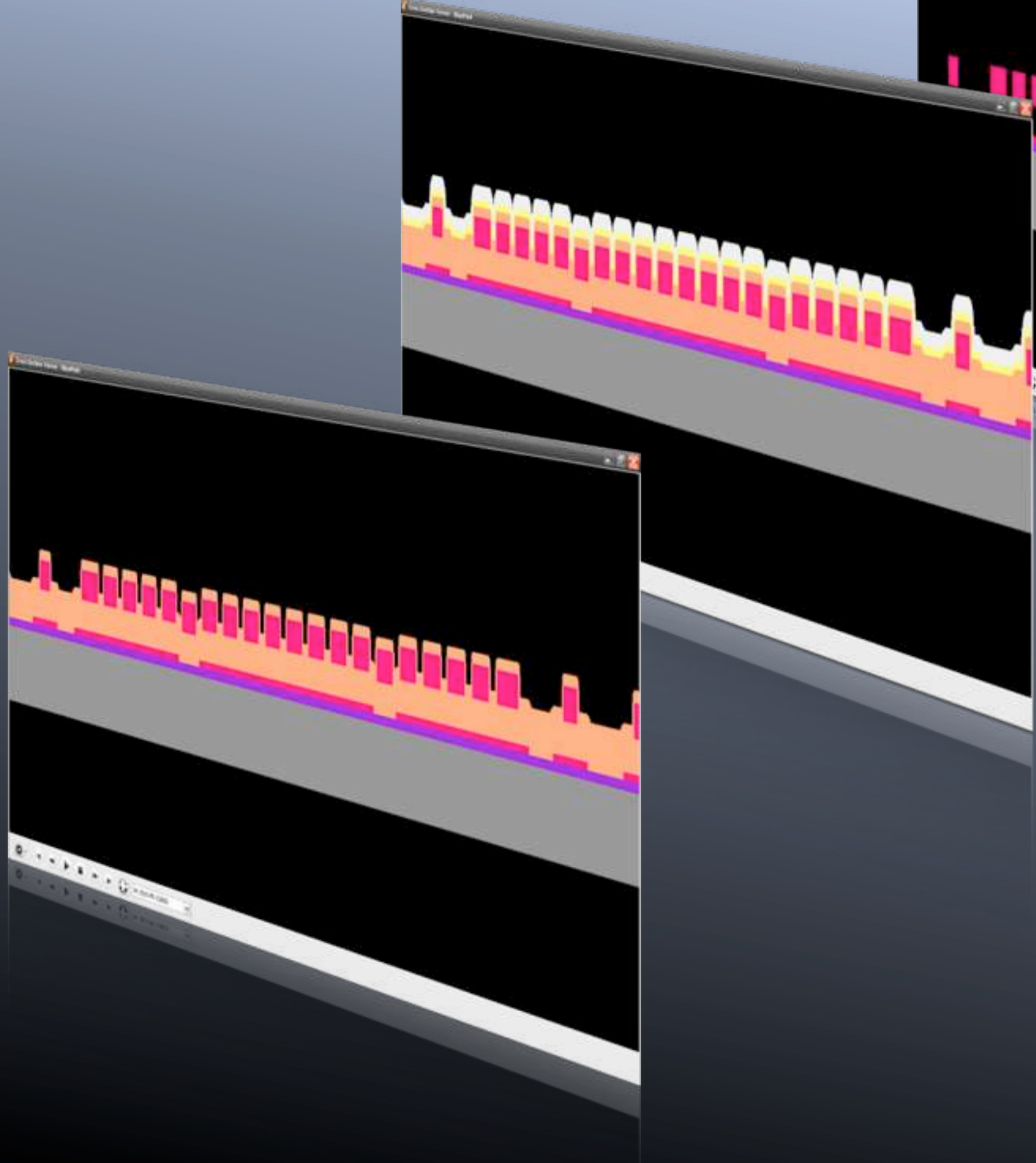
Blueprint

mems design editor



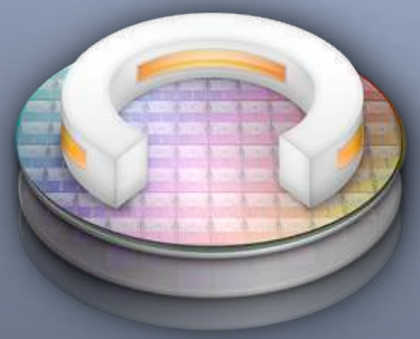
Hexpresso

hex meshing in a jiffy

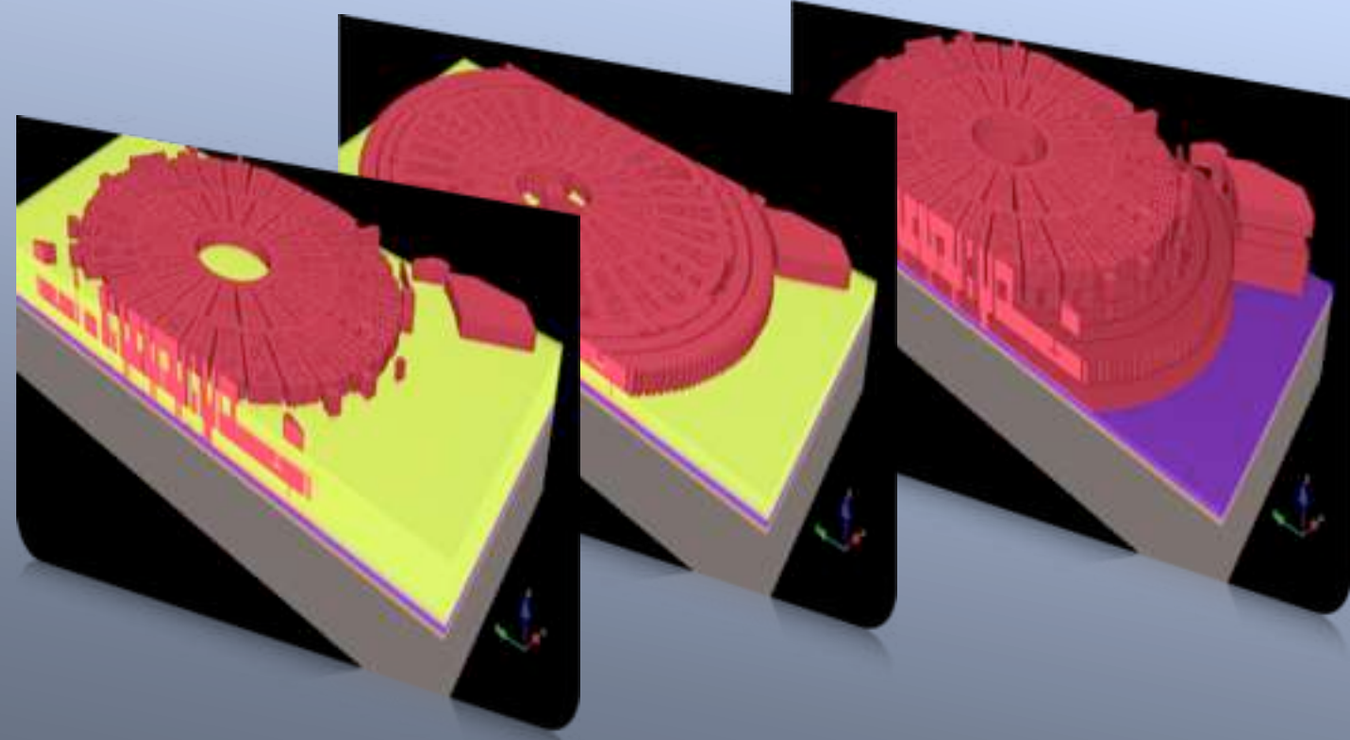


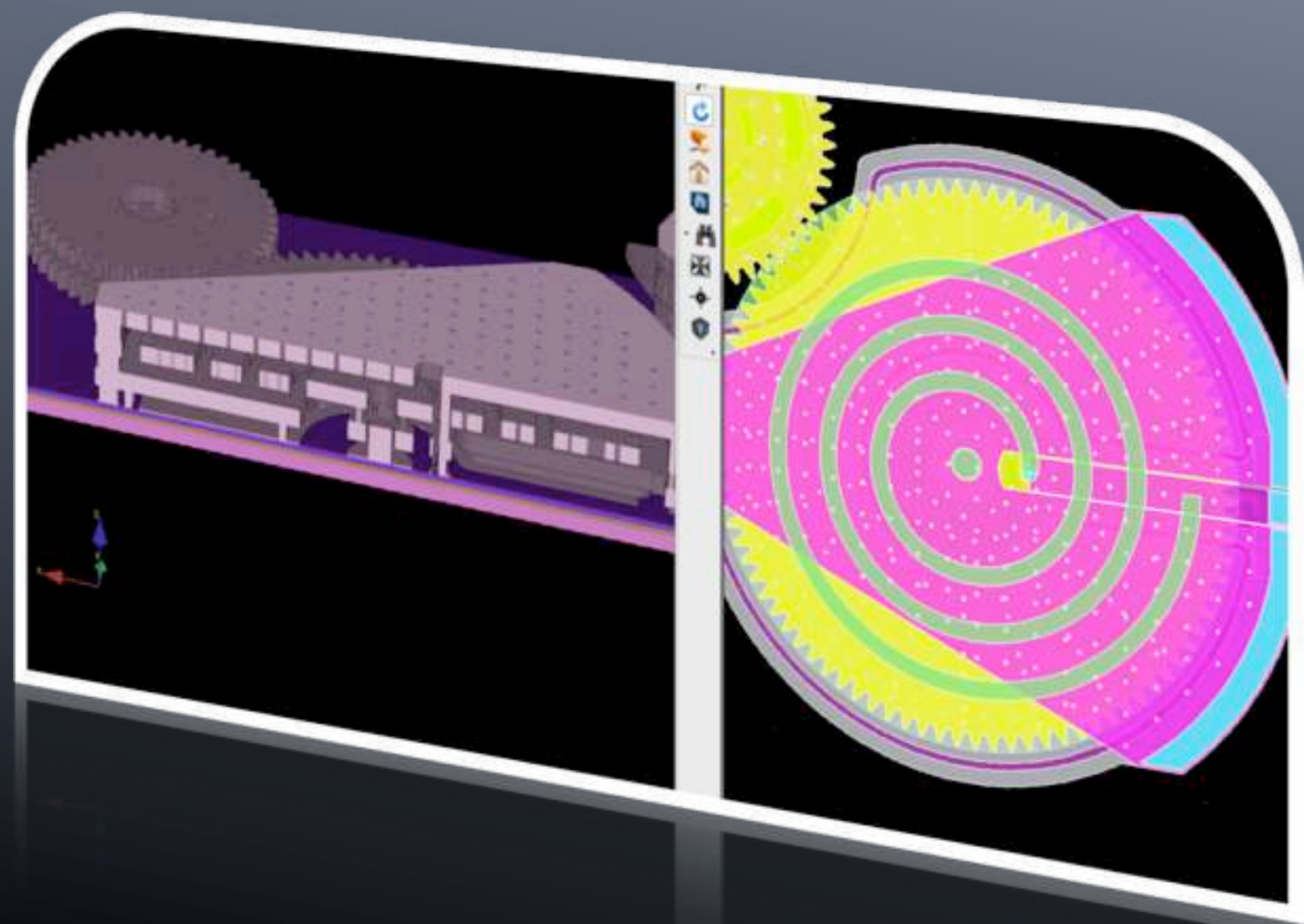
CS Viewer

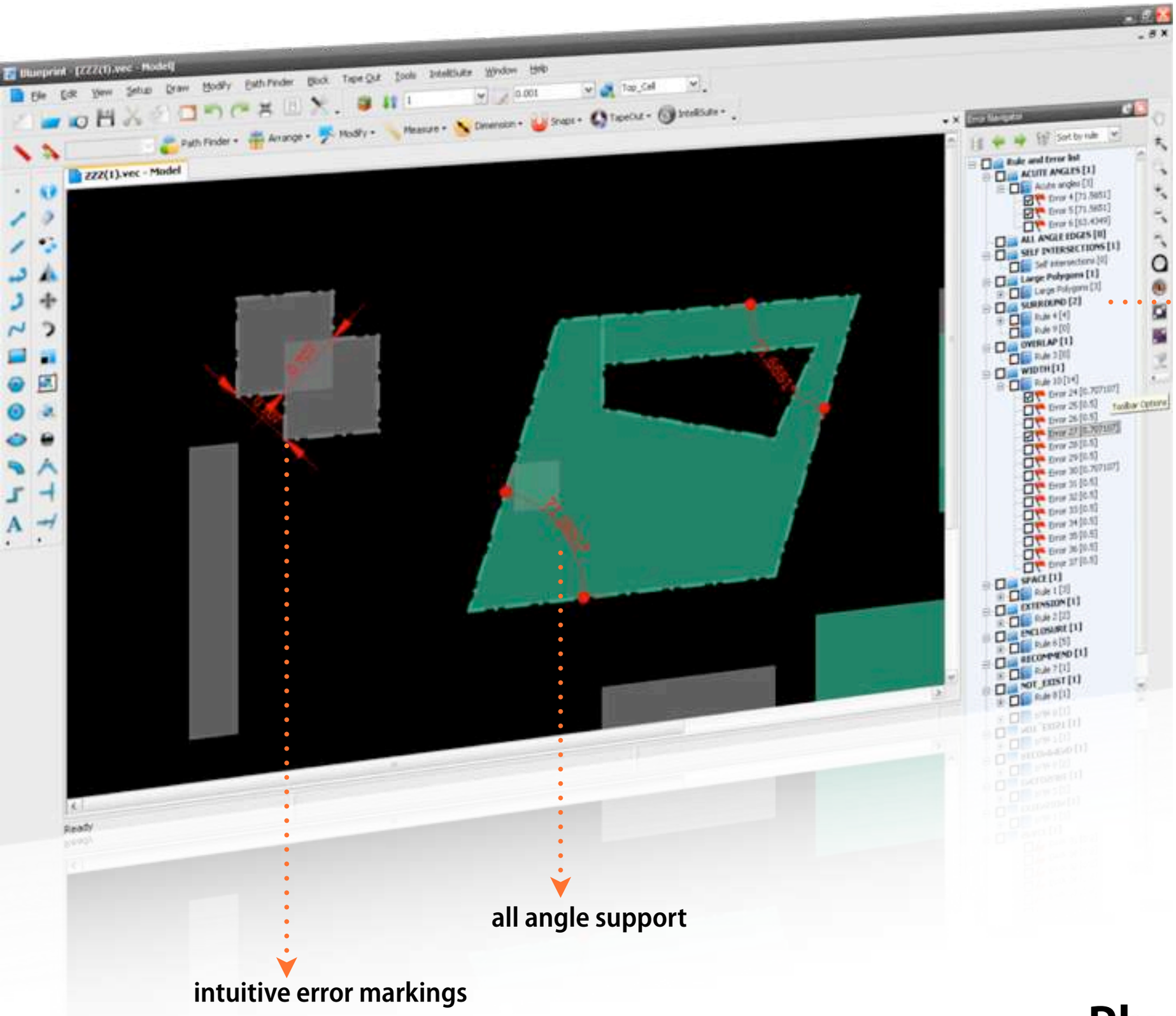
Step by step process visualization



Cleanroom integration







Tape Out

Physical verification

CS Viewer

- Tightly integrated with layout
- Step by step process visualization
- Process debug
- Output cross sections to Powerpoint

Hexpresso

hex meshing in a jiffy

- One click meshing
- Mask to mesh
- Process based meshing
- Adaptive meshing
- Quick and robust mesher

Process validation

What is Clean Room?

Process simulation and visualization

State of the art 3D process modeling

MEMaterial

Material databases & process optimization

RECIPE

RIE/ICP/Bosch etch simulation
STS etch database

IntelliFAB

Process traveller creation and visualization.

IntelliEtch

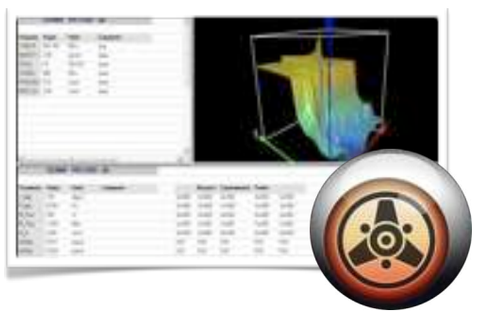
Ab initio based etch modeling
wet and dry etch modeling

Hexpresso

Automated hexahedral meshing engine for FEA/BEA model creation

Clean Room capabilities (Process)

Process capture
Develop process traveller
Debug traveller
Create process databases



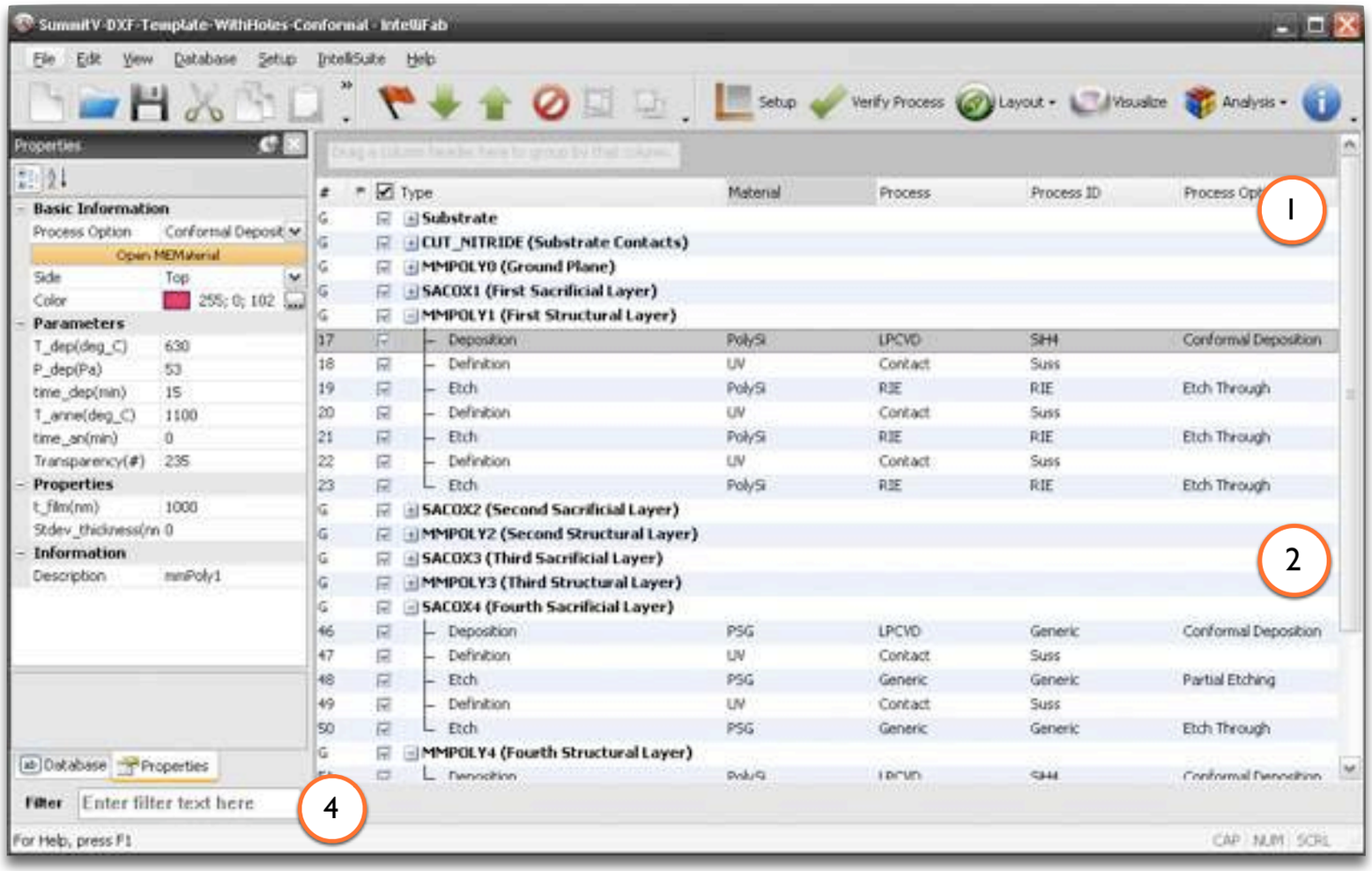
Material databases
Process correlated databases
Material properties

Process simulation
FABViewer: Flow visualization
AnisE - Anisotropic etching
IntelliEtch - ***ab initio*** etching
RECIPE - RIE/ICP etch simulator

Hexpresso
Automated HEX mesher
1 click Mask to Mesh

Setup complex process flows…

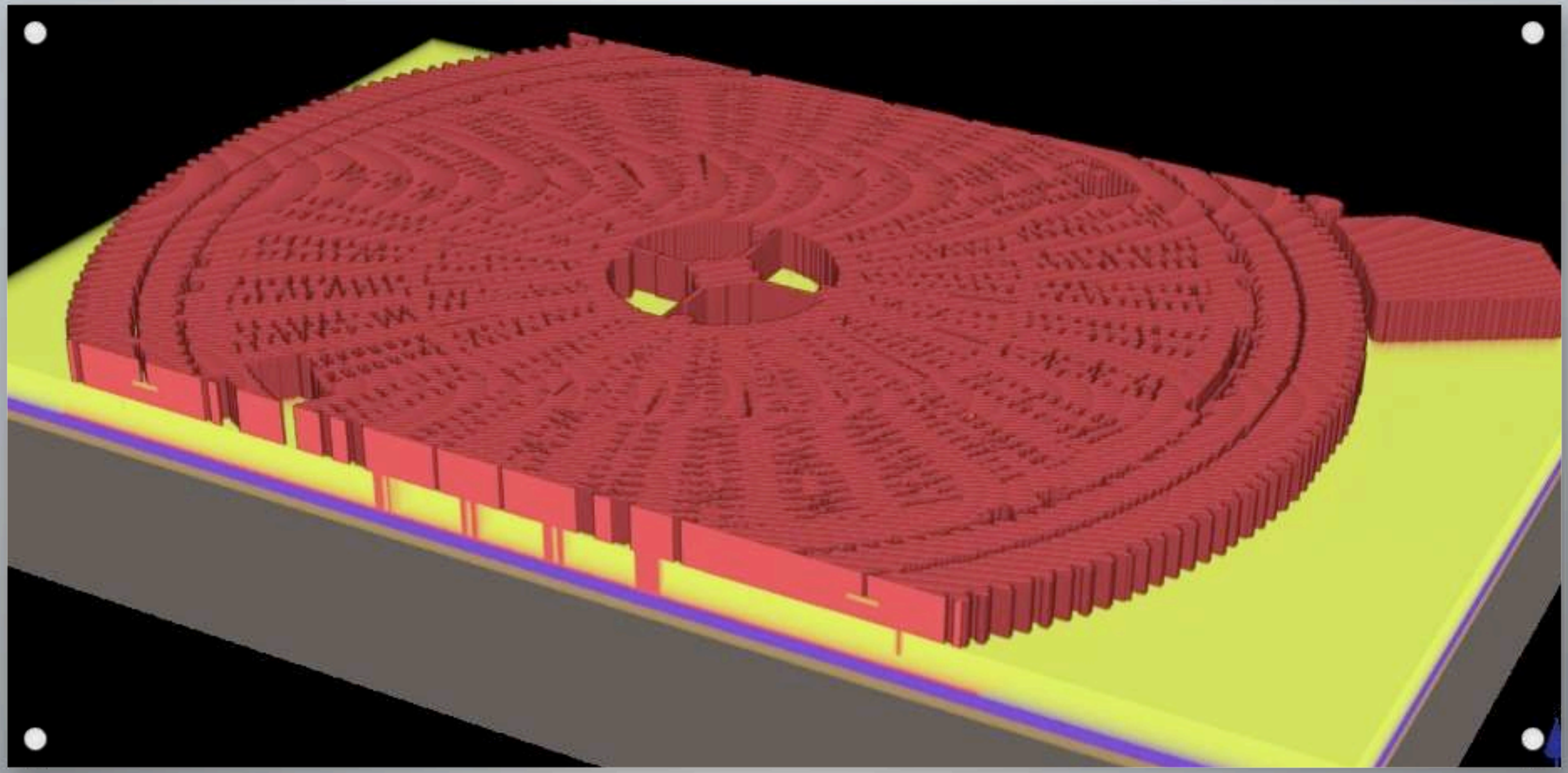
Process Pane
Enter process parameters, tolerances and visualization settings in a single consolidated pane



Filter with ease
Filtering tools allow you to quickly focus on the processes that you want to explore

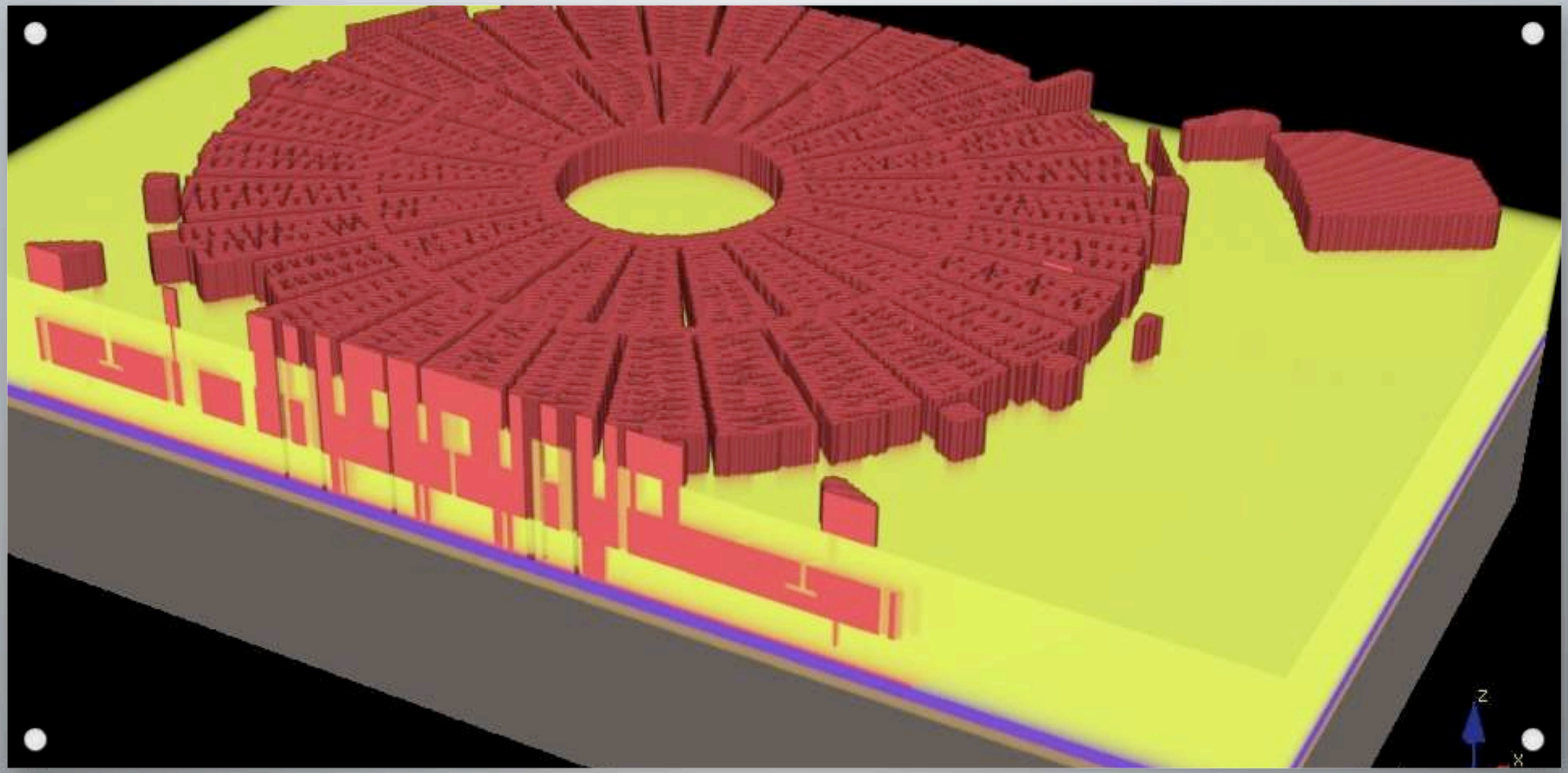
Process Editor for MEMS
IntelliFAB makes editing and organizing a process table quick and easy. Setup your virtual process traveller exactly as you would for a real foundry.

Group, section, organize
Grouping common sets of processes into process subsets makes the organizing a complex traveler easy. You can group your process flow in any which way you please: by material, by process type or by process option.



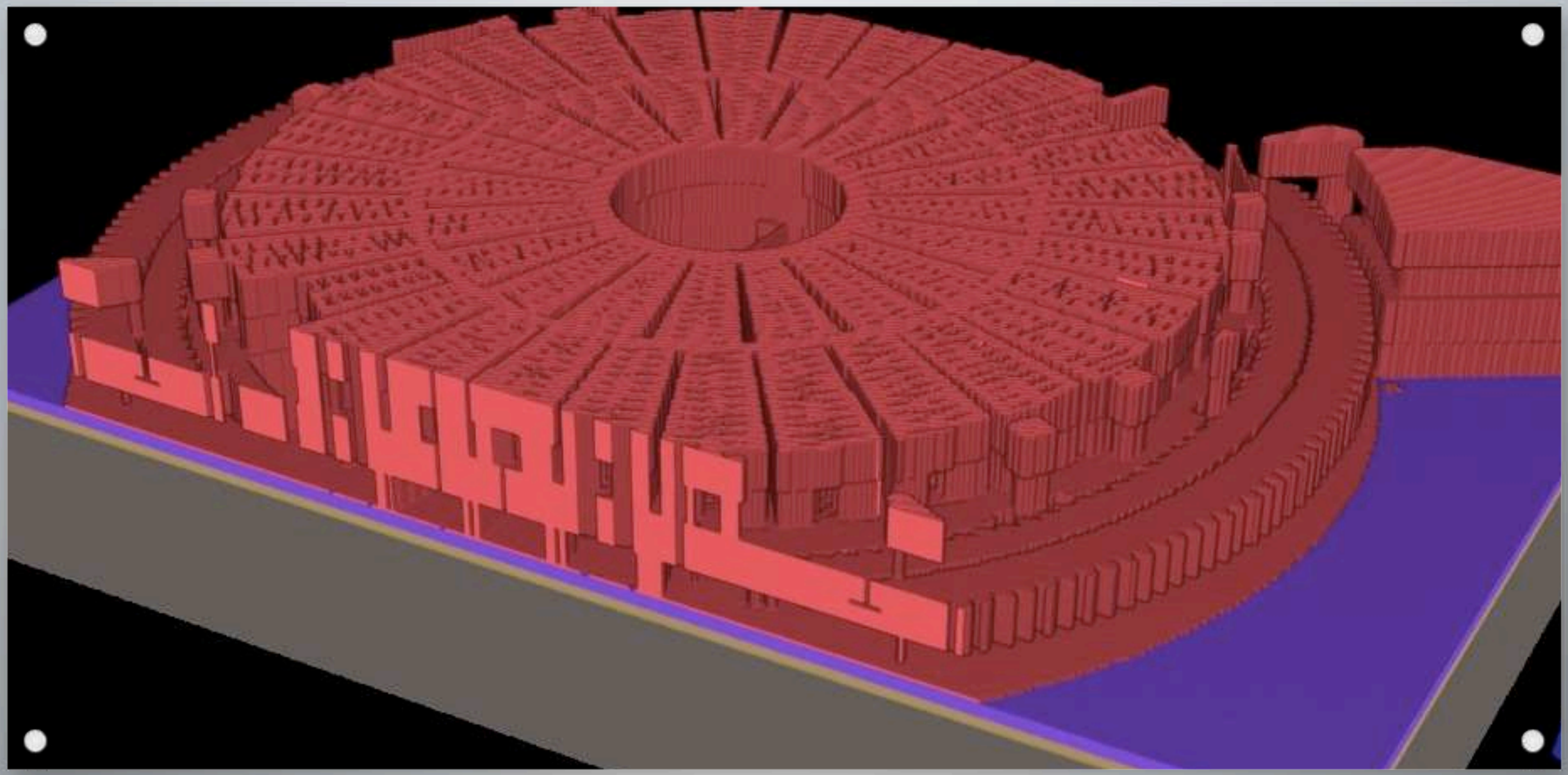
Visualize Complex process flows

Courtesy, Prof Tim Dallas, Texas Tech



Visualize Complex process flows

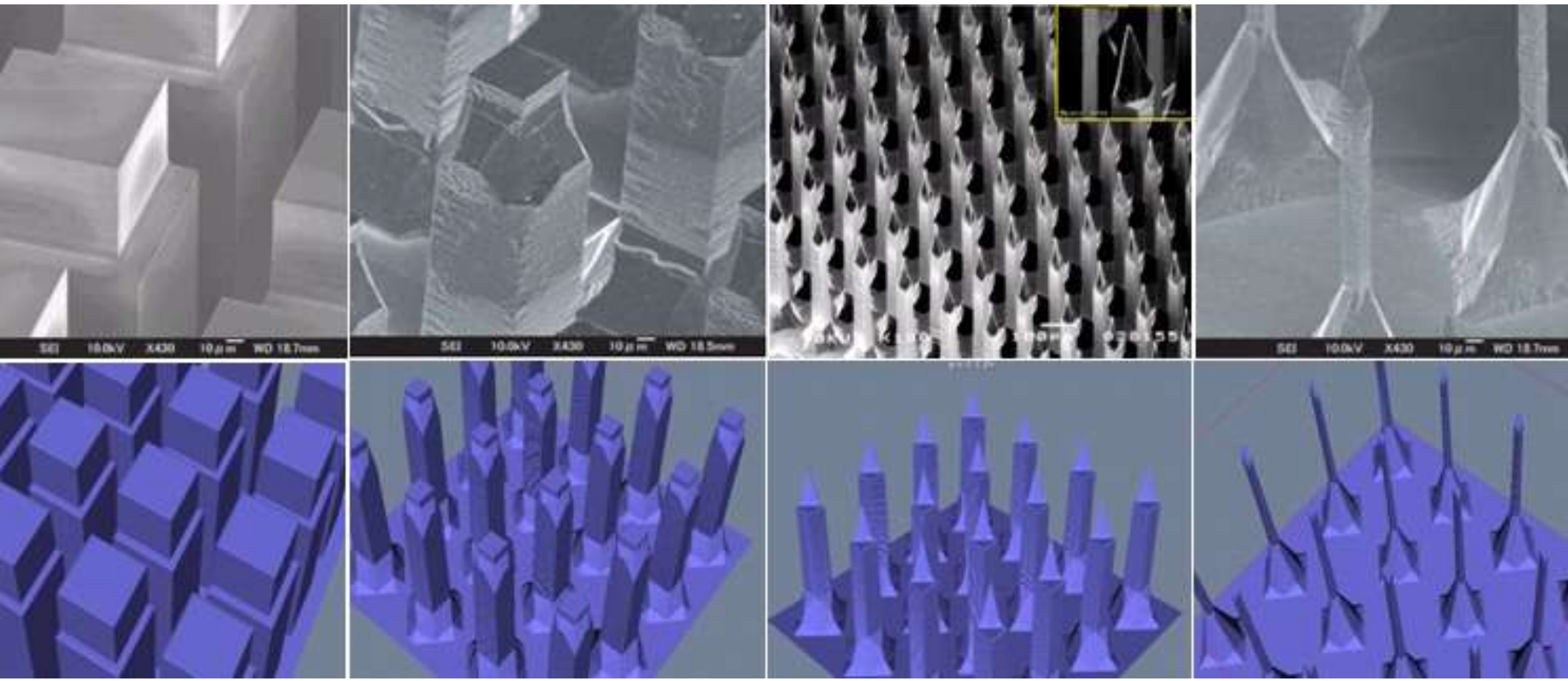
Courtesy, Prof Tim Dallas, Texas Tech



Visualize Complex process flows

Courtesy, Prof Tim Dallas, Texas Tech

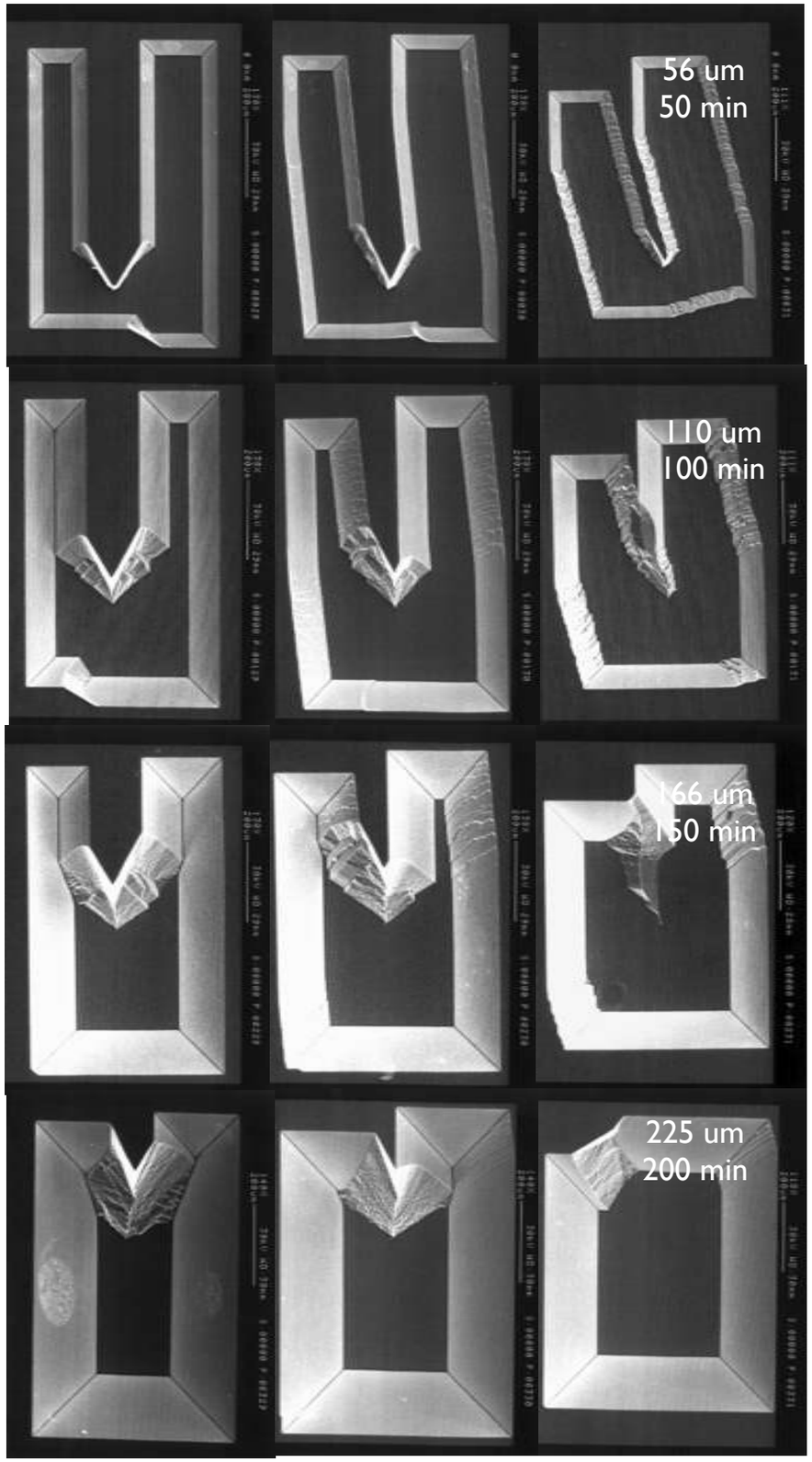
Simulate composite MEMS processes



Combination of multi-step mask transfers, oxide and nitride layers, sacrificial layer deposition and wet etching and DRIE processes.

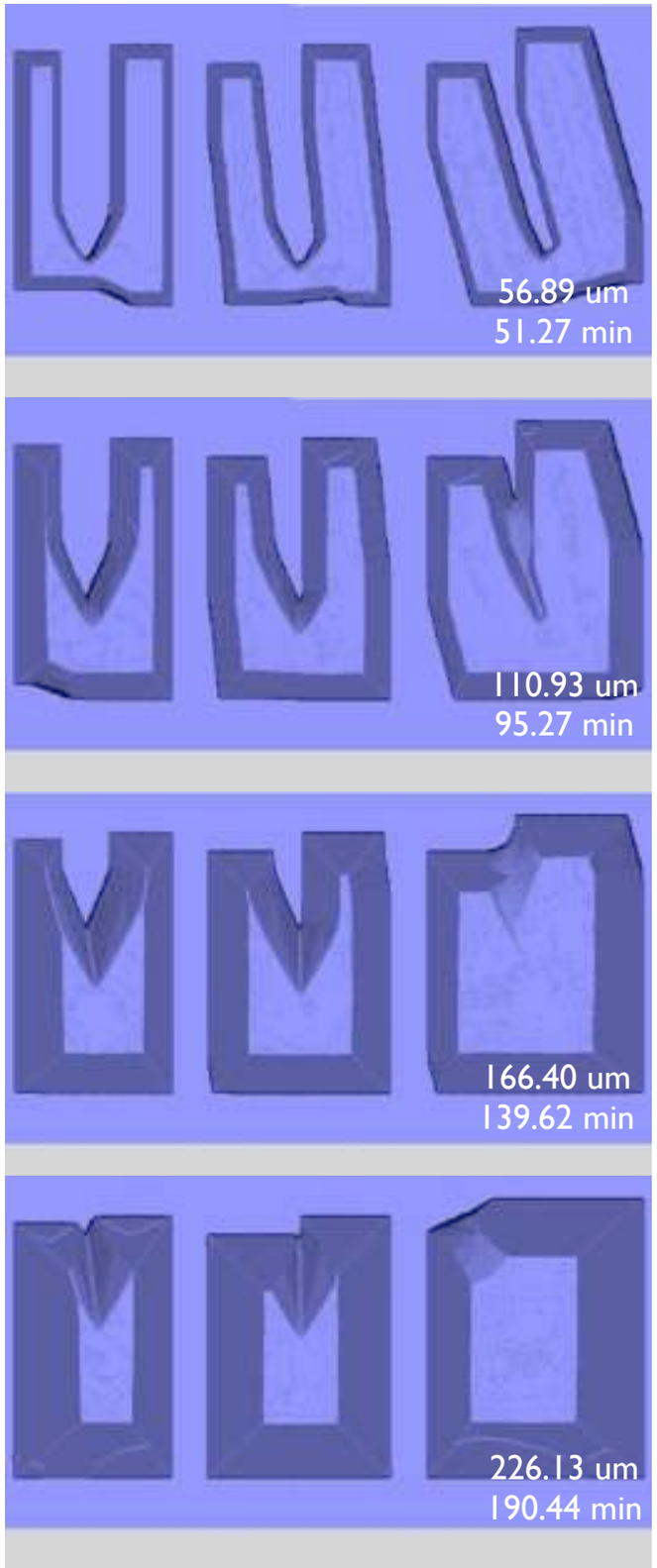
Composite processes, Shikida Mitsuhiro, J. Micromech. Microeng. 14

Validate processes in design



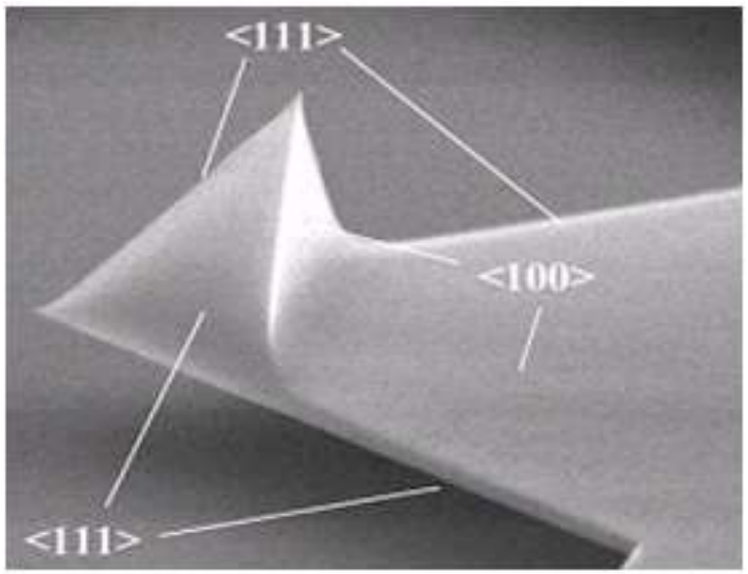
Measured

vs

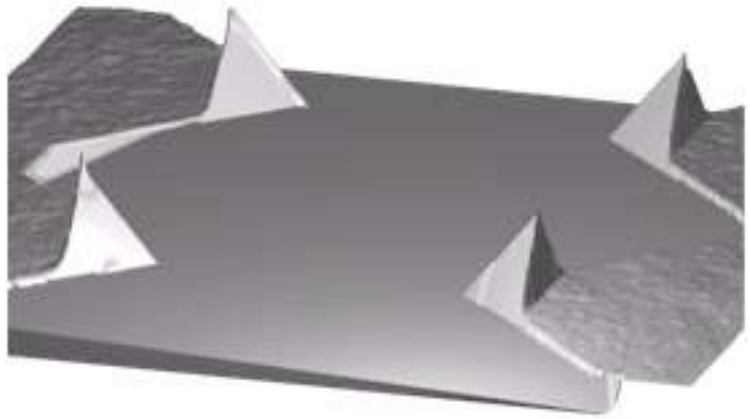


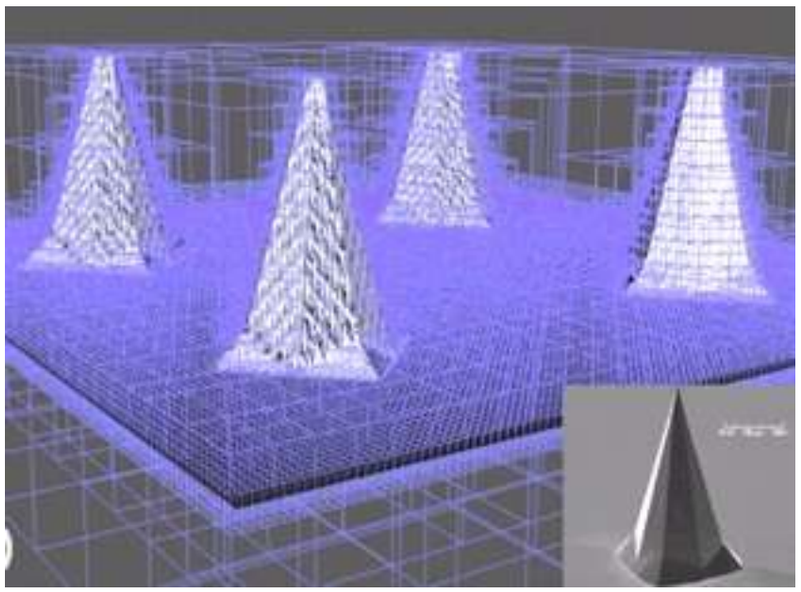
Modeled

Higher order plane etching



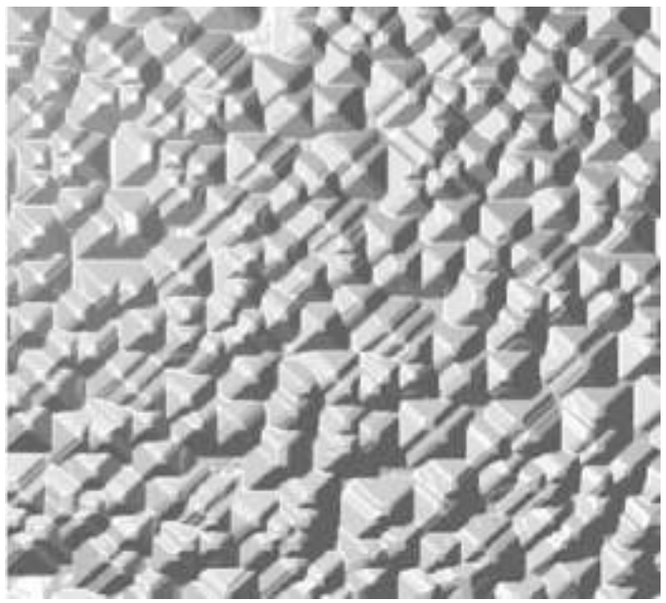
D. Saya, Sensors & Actuators A95 (2002)



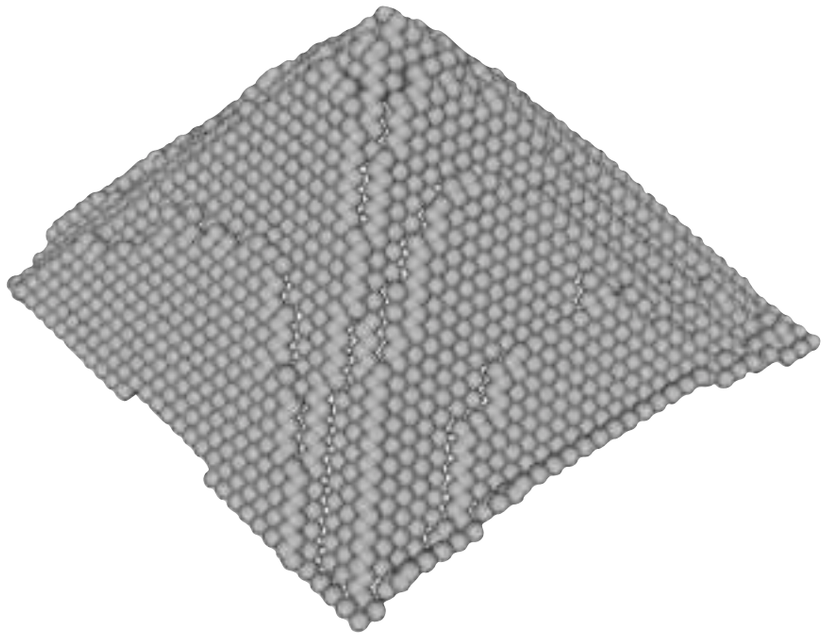


Simulation results

Surface morphology prediction

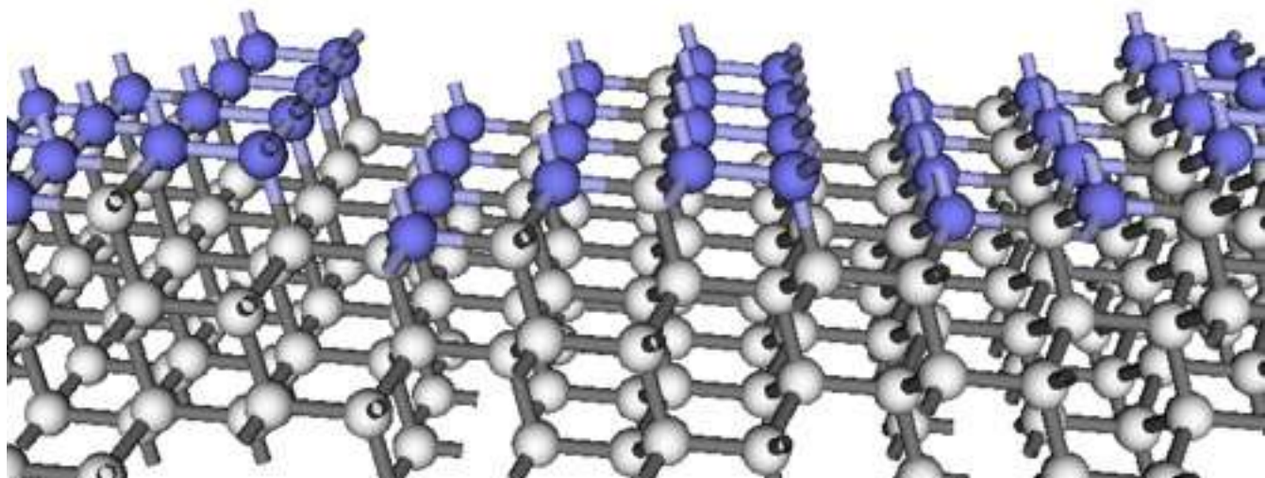


Pyramid like morphology on 100 Si
subject to wet anisotropic etching

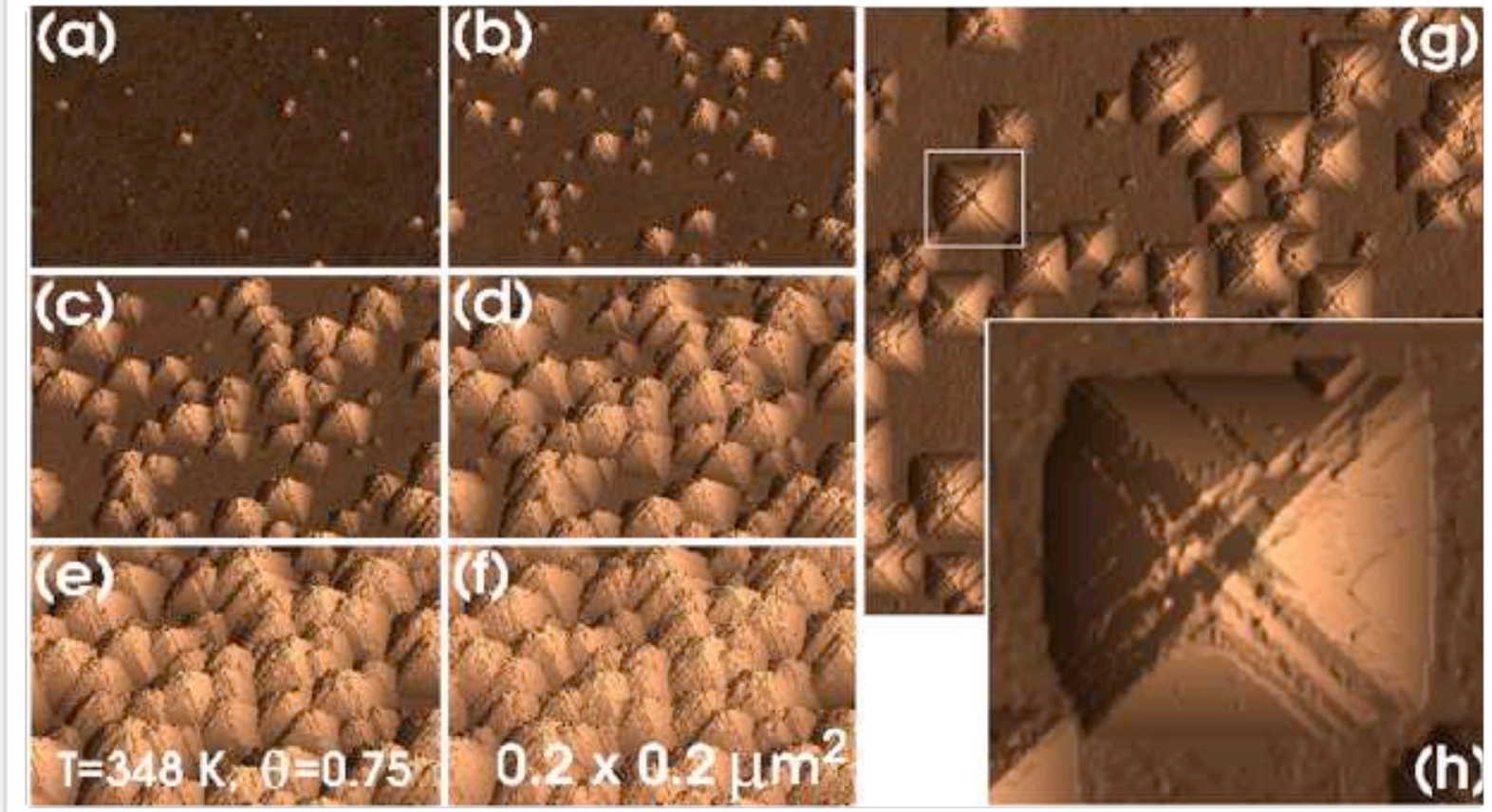


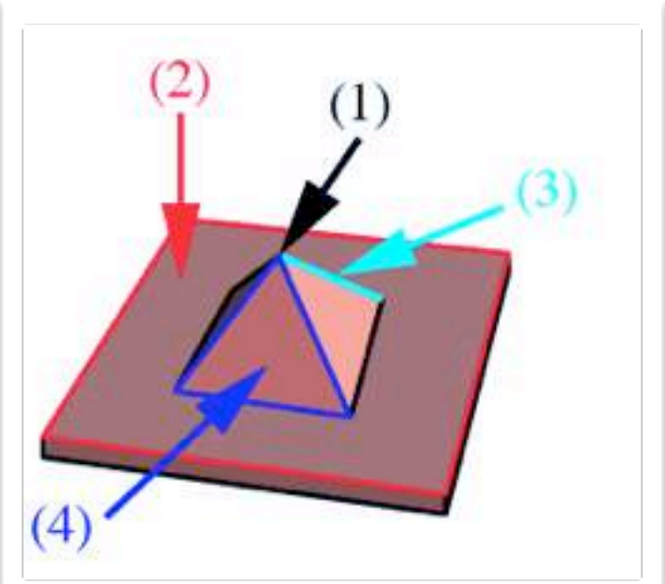
Simulation results predict pyramid formation

Arbitrary Cut Planes <533>
to understand the physics



Surface morphology prediction

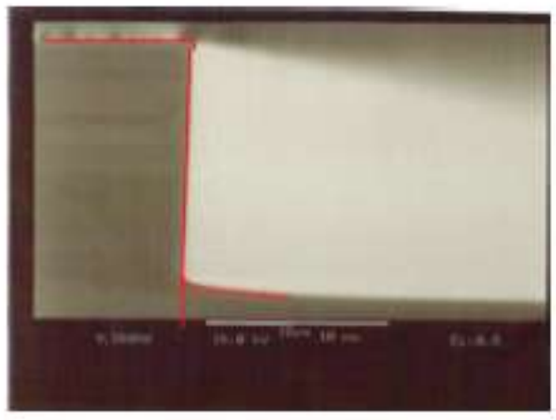


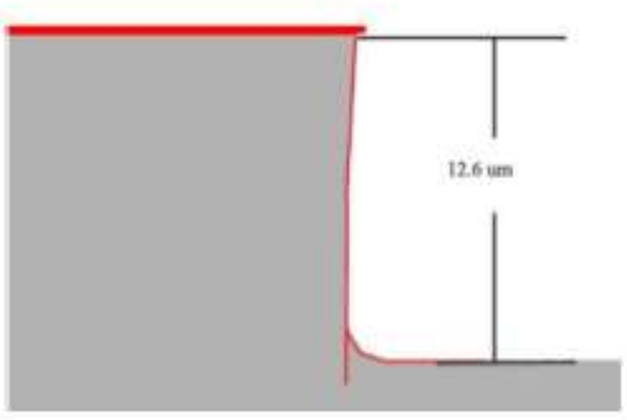


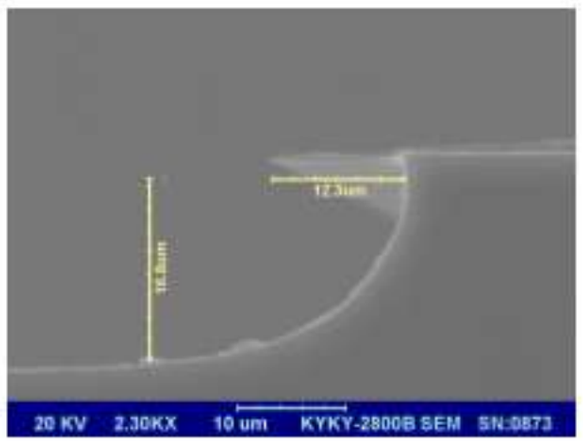
1 Micromasking of apex
2 Floor moves down fast
3 Edges are stable
4 Facets are very stable

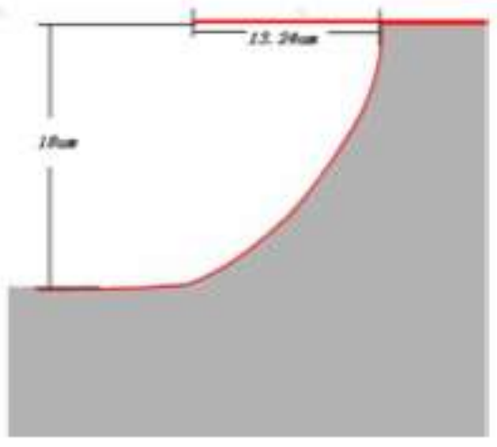
Hillock formation prediction

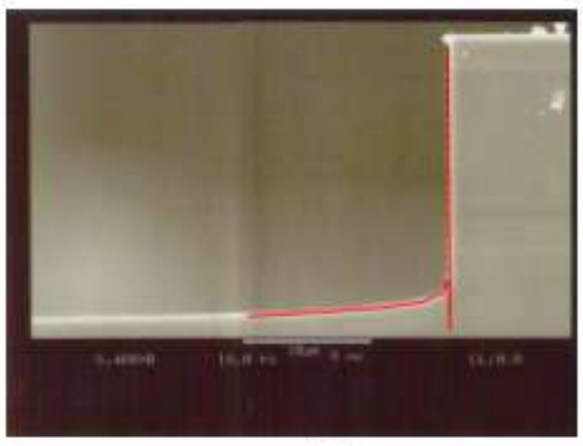
DRIE Etch characterization experiments (1)

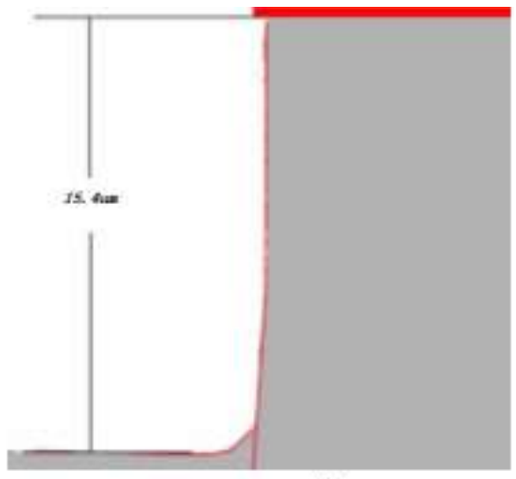


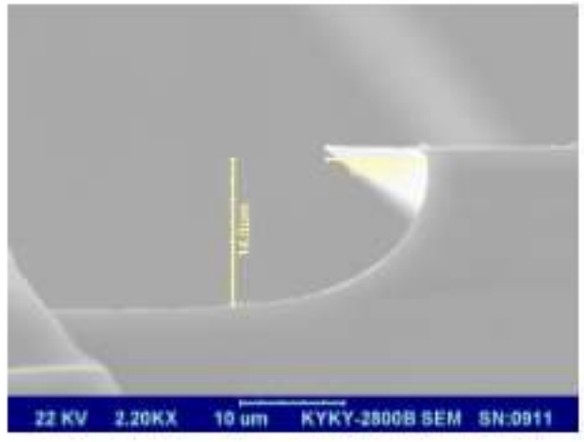


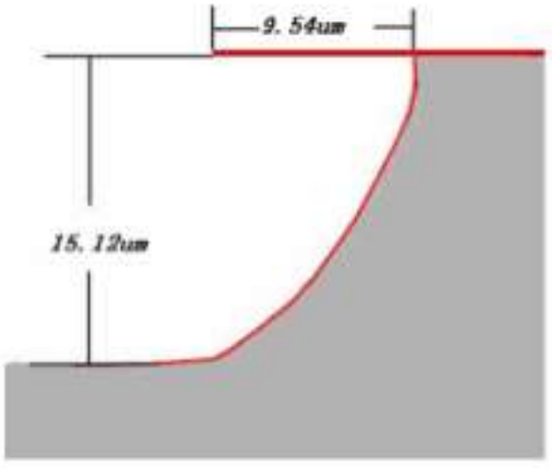




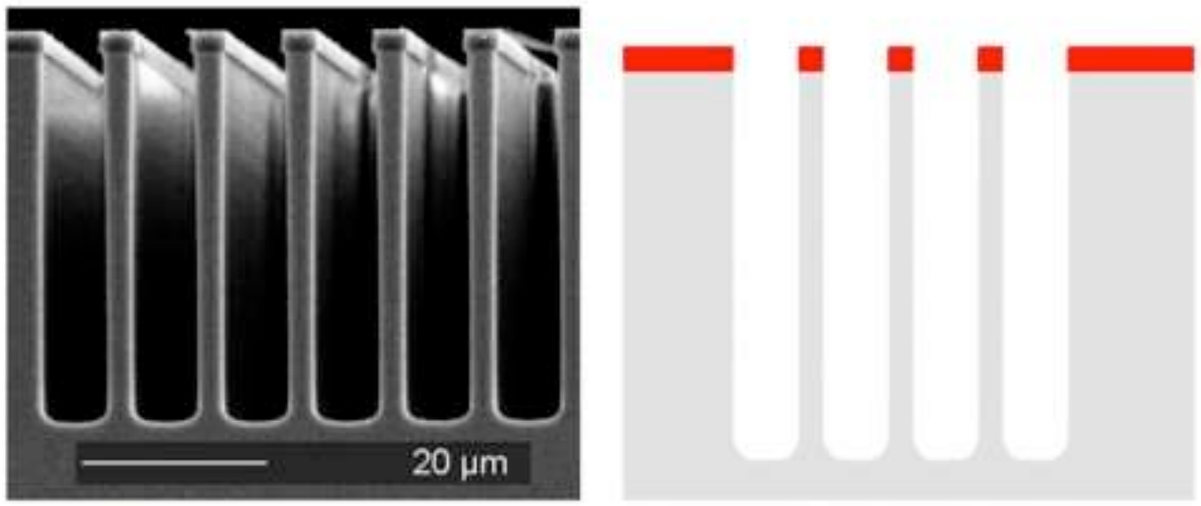




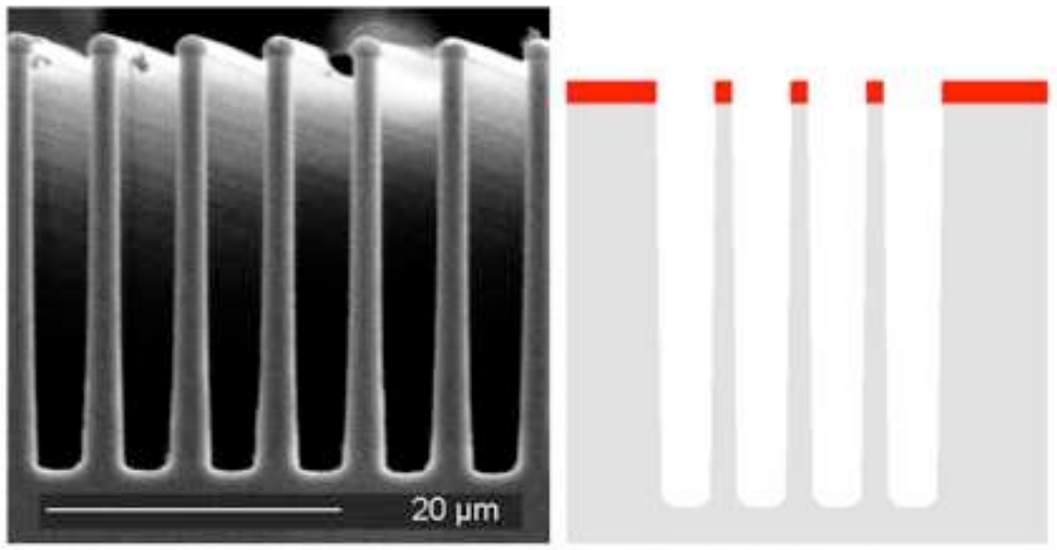




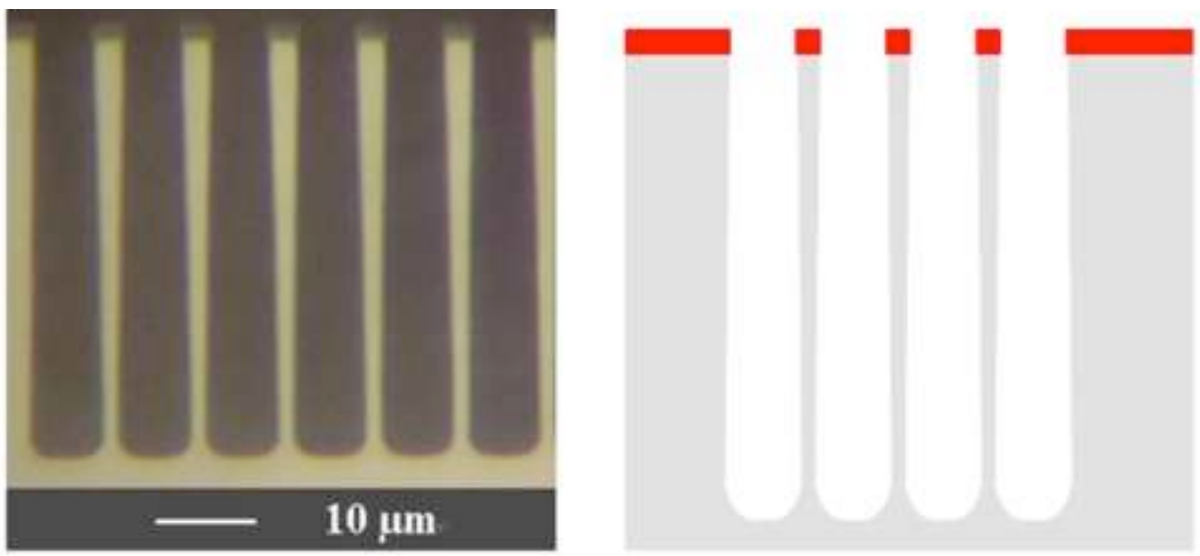
DRIE Etch characterization experiments (2)



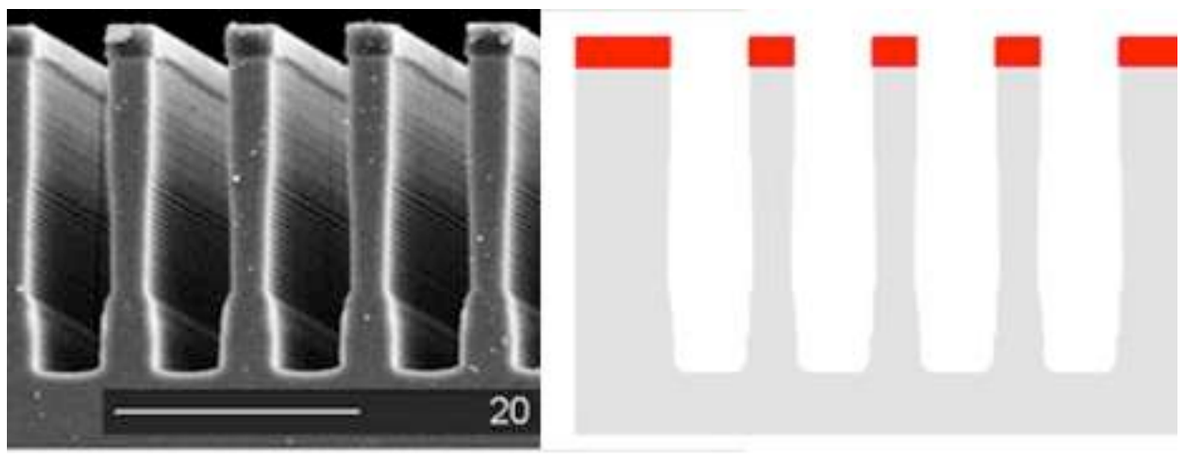
The experimental results of the etching. Comparison of etching 5 µm openings with an etch/dep cycle of 7s/7s.



Comparison of etching a 5 µm trench with a 5s/7s cycle

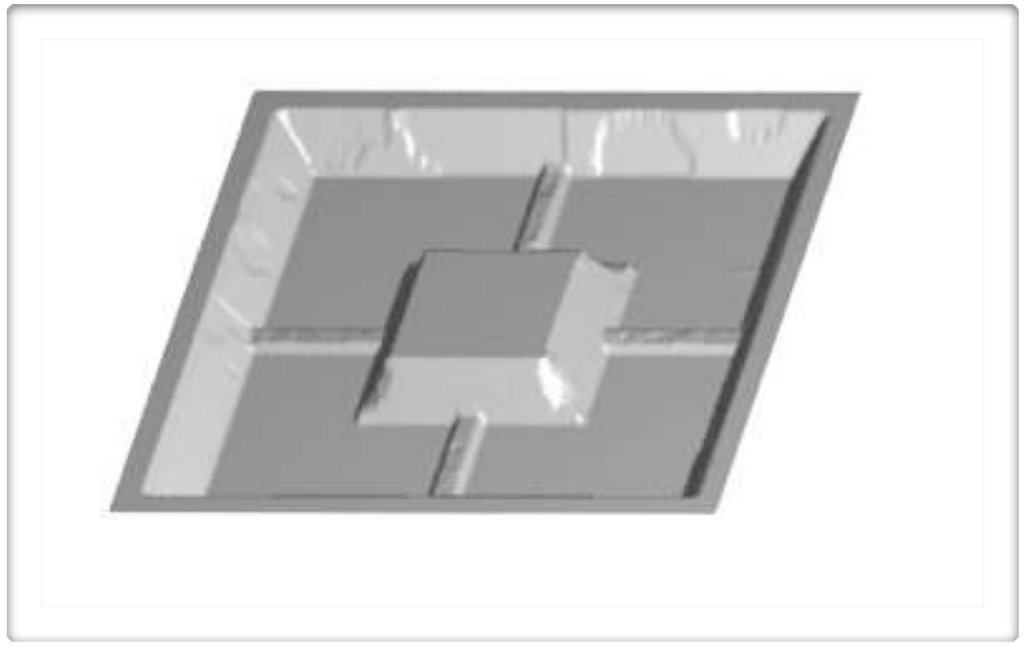


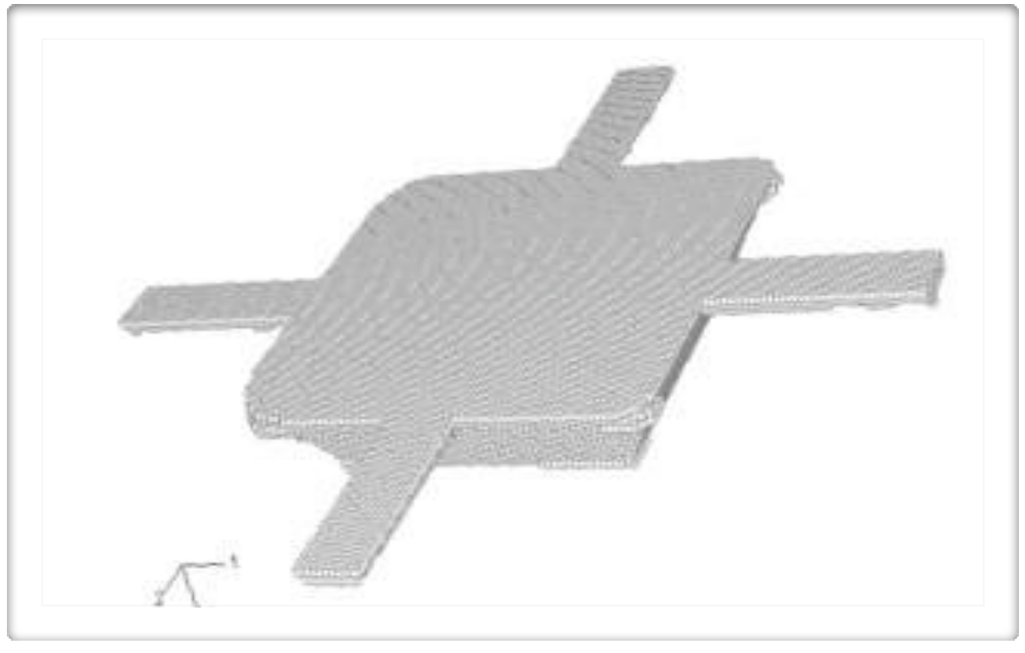
Comparison of etching a 5 µm trench with a 7s/8s cycle

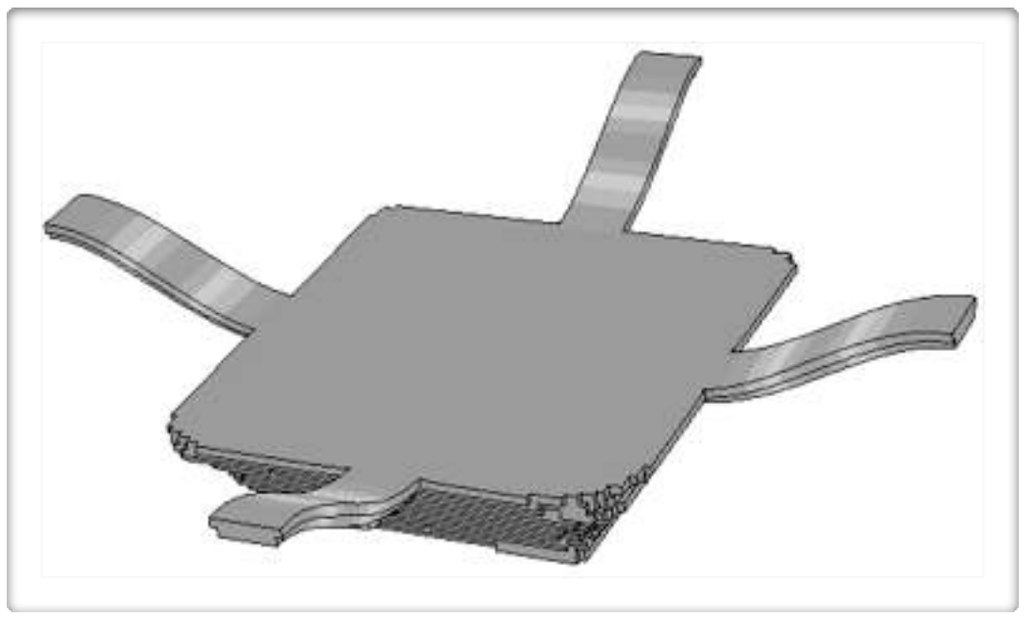


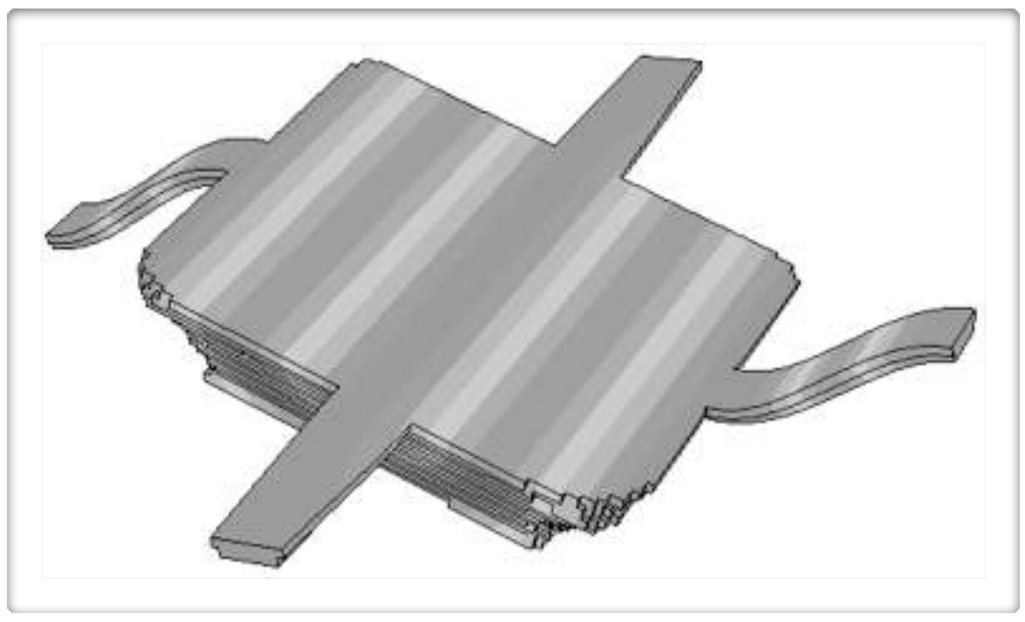
The experimental result of the etching of trenches using three etching steps with different etching/polymerization time configurations. 7s/7s, 9s/7s and 5s/7s are used sequentially, each for 5 minutes.

Output to FEA

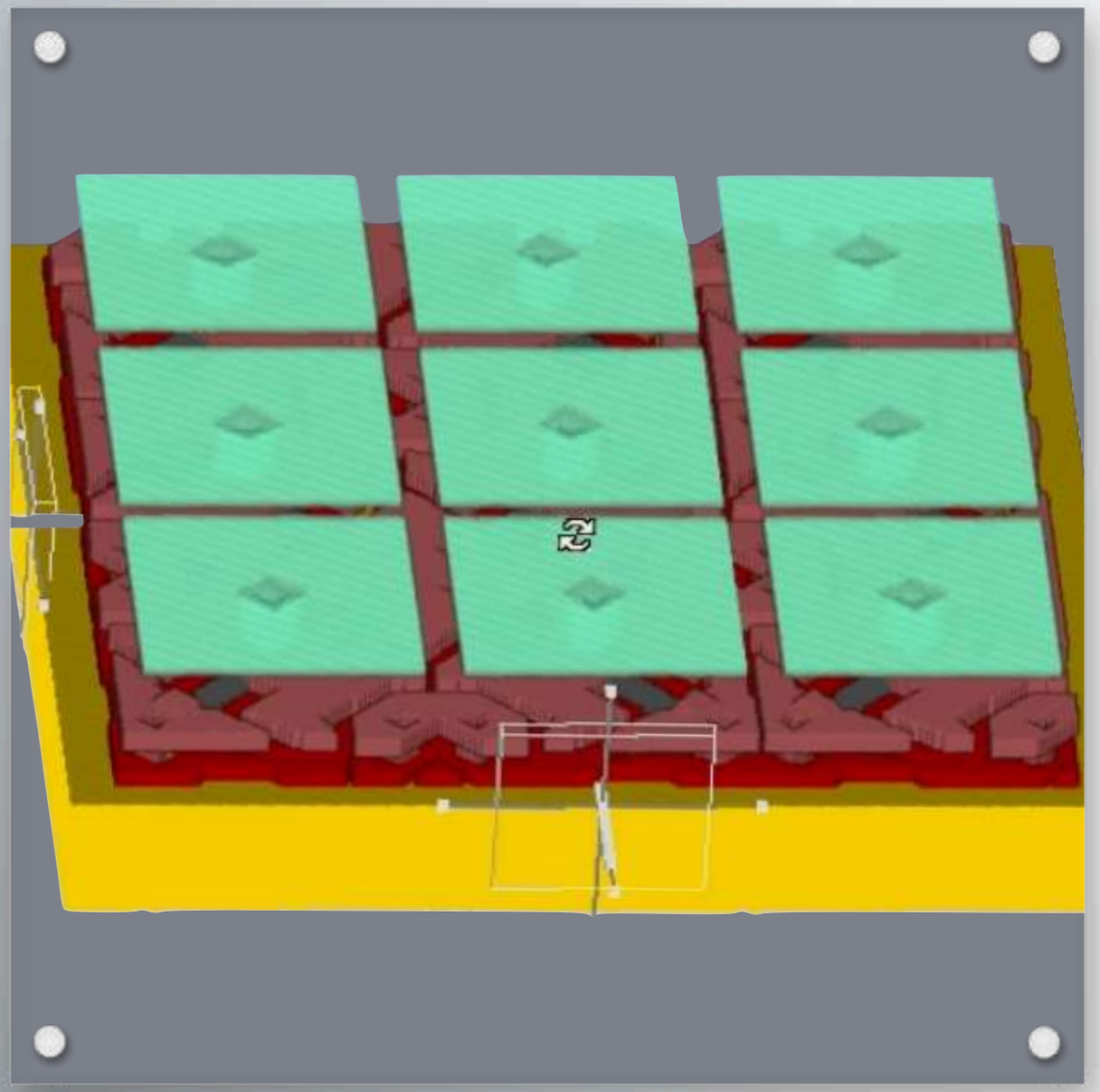


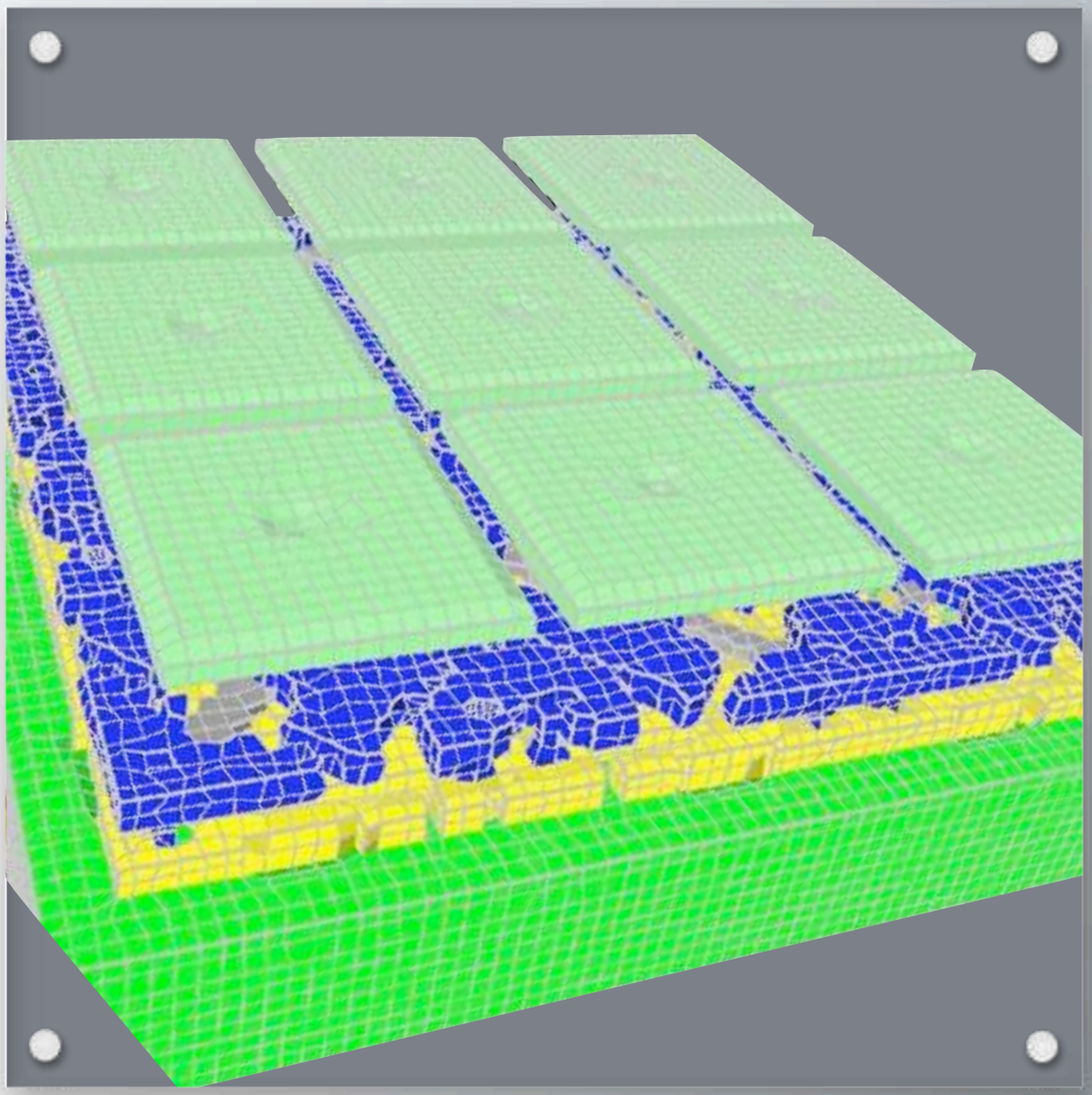






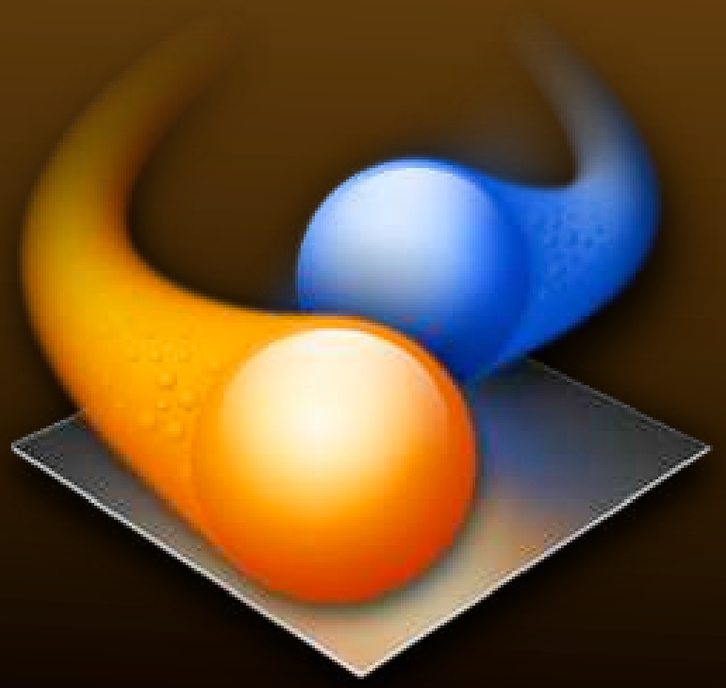
Interface with analysis tools: Direct export to IntelliSuite and other industry formats



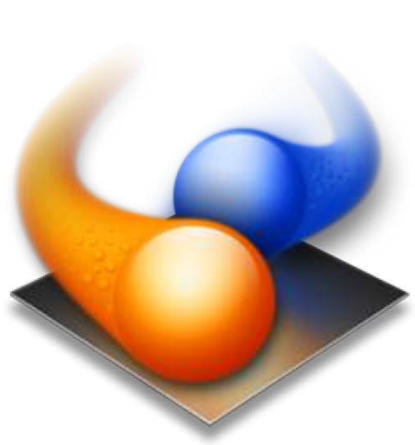


PROCESS TO MODEL

Fastfield solvers



Fastfield capabilities (Structural)



Fastfield Multiphysics
Unique FEM-BEM formulation
64 bit multi-processor enabled
5-10X than pure FEM based

Fully coupled
Thermal
Electrostatics
Mechanical
Fluidics
Contact physics
Piezo
Magnetostatics

Specialized engines
BioMEMS
High frequency EMag

Extraction
Multiphysics capture
Efficient for verification
Lagrangian models
1000X more efficient that FEA

What is Fastfield Multiphysics?

- **Coupled solver formulation**

  ANSYS, Algor, Comsol, etc are all pure Finite Element tools

- **Best solver for each physics domain**

  Boundary Element Method (BEM): Electrostatics, Electromagnetics

  Finite Element Method (FEM): Thermal, Mechanical and Electromagnetics

  Volume of Flow (VoF) and Finite Volume (FV): Fluidics, Electrokinetics, Chemical Reactions

- **Advanced pre-correction and solver techniques**

  Pre-corrected FFT (pFFT++), GMRES, Arnoldi, OpenMP based multi-processor solvers

Why Fastfield Multiphysics?

- **Speed and efficiency**

  2-10X Faster than pure FEA formulation (Algor, Ansys, Comsol, etc)

  Handle large real world problems

- **Surface meshing vs volume meshes**

  Internal volumes, air gaps, etc do not need to be meshed

  Ease of meshing, no costly re-meshing during deformation

- **Ease of convergence**

  Quickly run your analysis without convergence issues

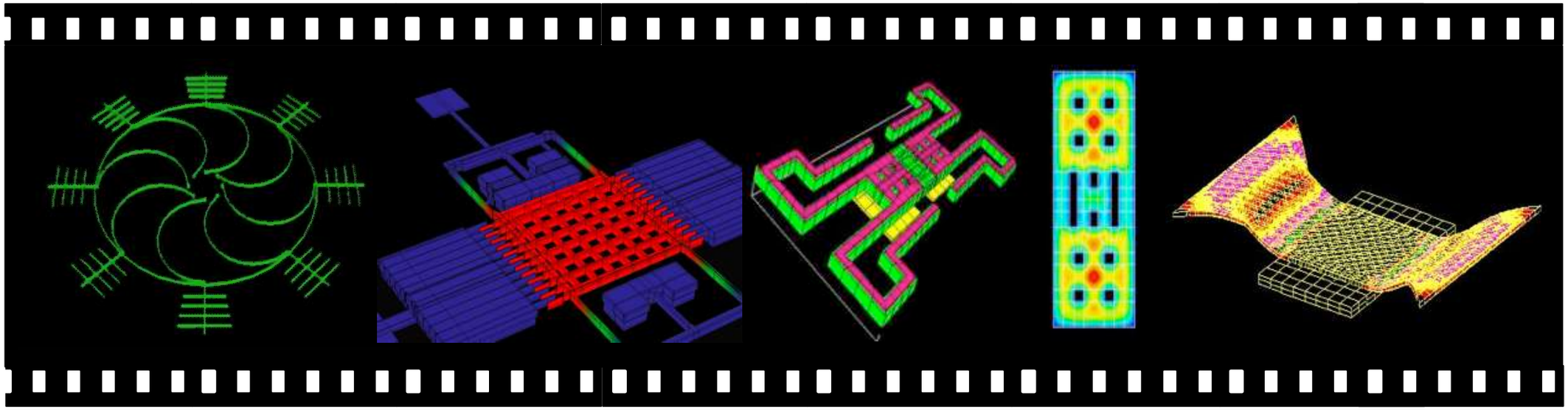
  Deal with large deformations, contact and post-contact without convergence issues

Rotary ring gyro
Rate/Coriolis analysis

Draper vibratory gyro
Electrostatic drive

Lockheed inertial device
Squeeze film analysis

Raytheon/TI RF switch
Non-linear contact analysis

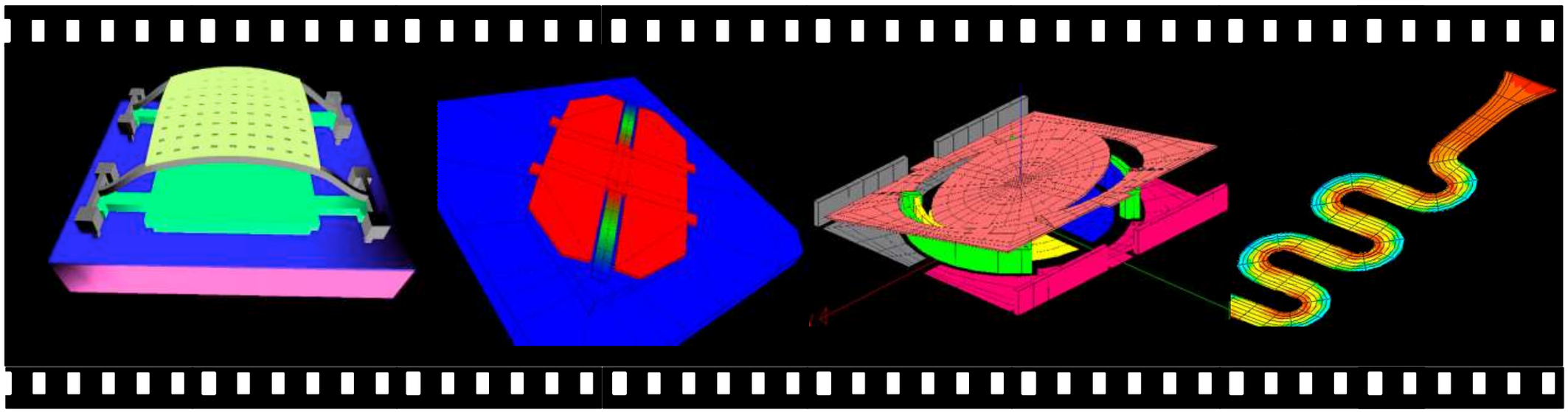


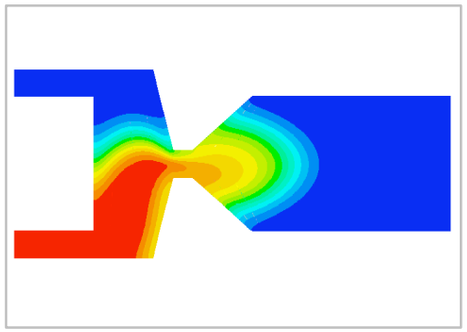
Hitachi
RF Tunable Filter

NASA
Adaptive optics

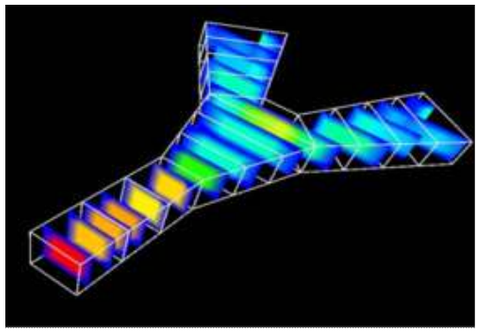
Corning
3D Optical cross connect

NASA
Radiation detectors

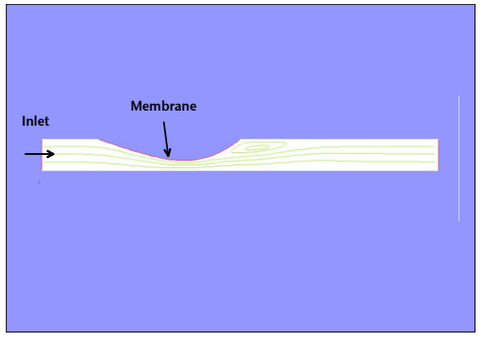




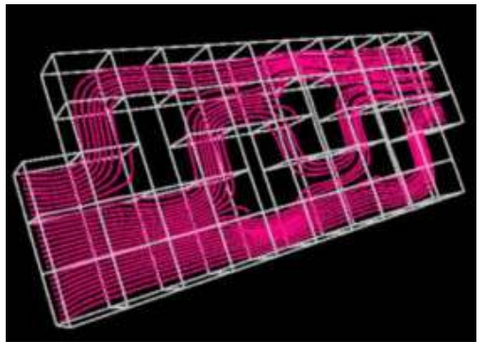
Micro-mixing in a valve
Concentration gradient evolution



Flow mixing
Y combiner

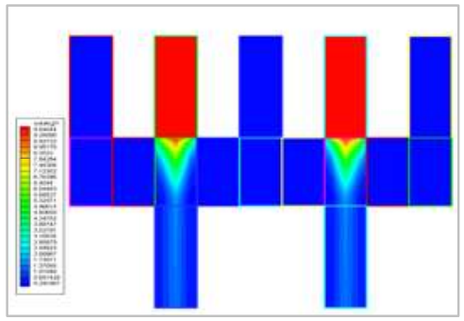


Fluid Structure Interaction
Inlet flow - membrane interaction

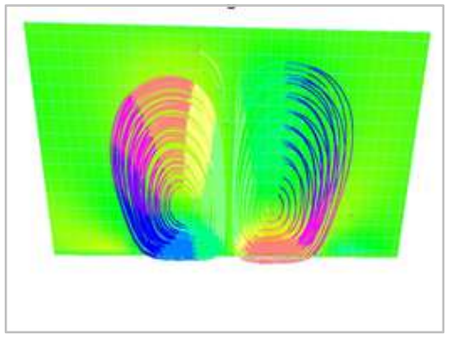


Flow separation device

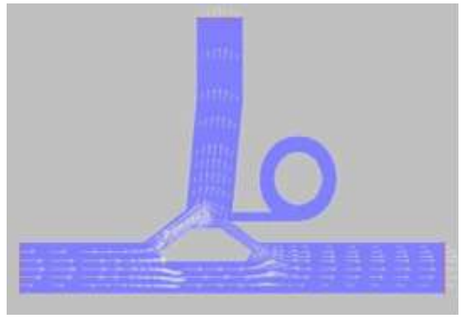
Microfluidics• Electrokinetics • Transport stochiometry • Heat transfer • Electro-Wetting on Dielectric (EWOD) • Digital droplet microfluidics • Free Surface Flow • Fluid Structure Interaction • Electrochemistry • Micro-mixing • Electrophoresis • Dielectrophoresis • Capillary flow and electro-separation • Electro-osmosis • Electro-hydrodynamics • Micro-pumps



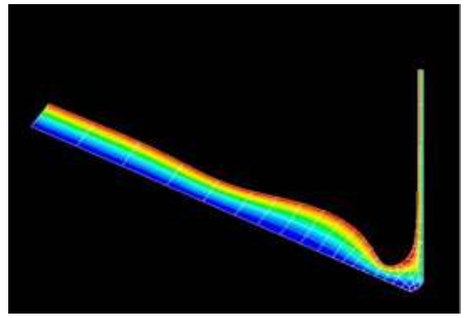
Electrokinetics
Multiplex focusing



Electro-osmotic driven flow
Electrohydrodynamics for cooling

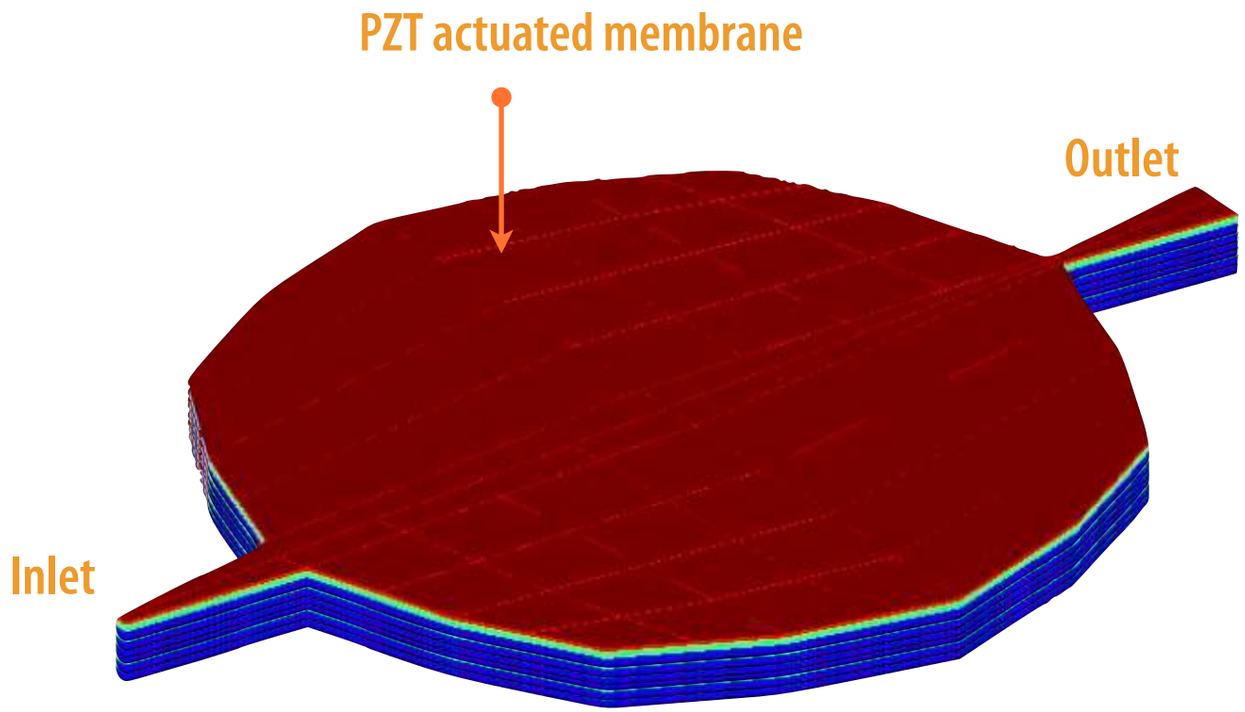


Electrophoresis/Dielectrophoresis
High Frequency Waste separation

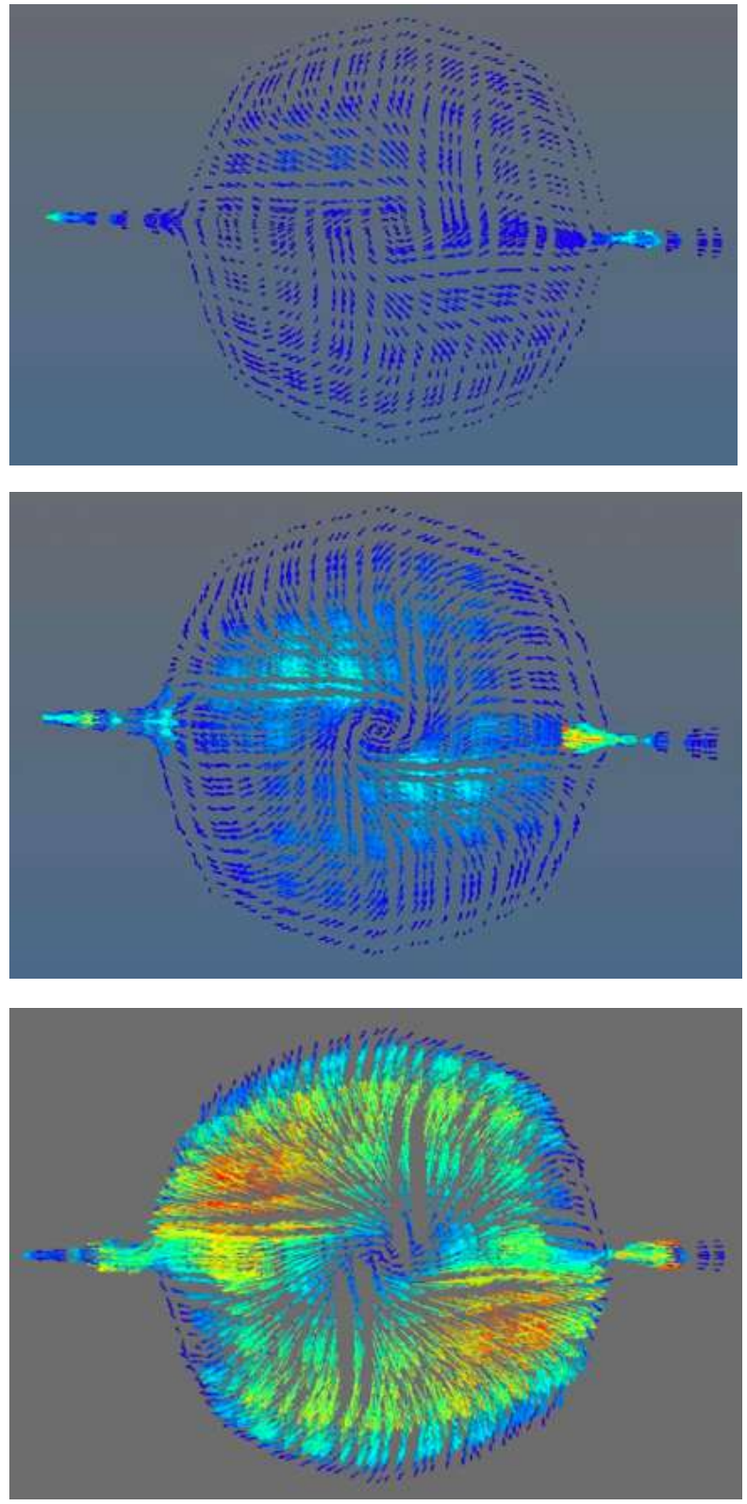


Free surface flow
Slide coater

Advanced FSI

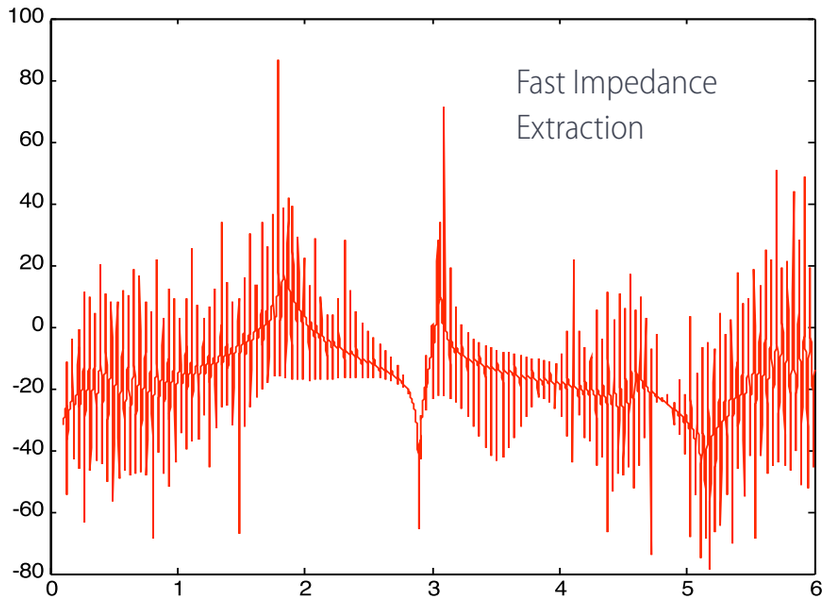


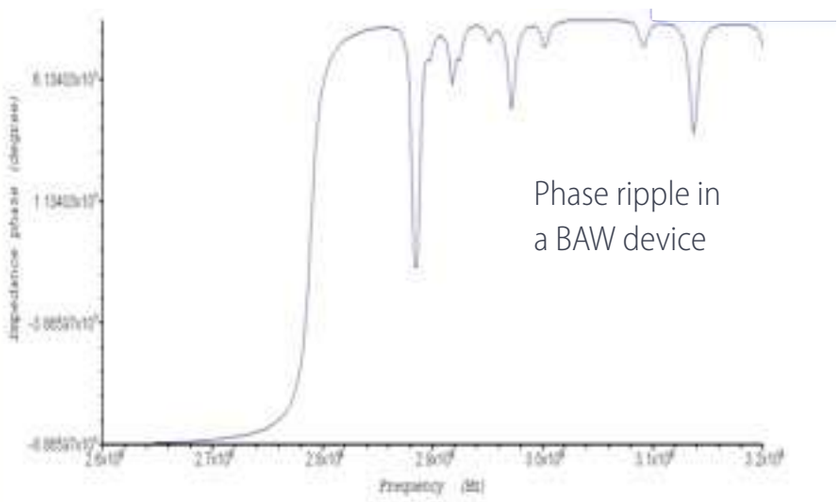
Example: Valveless piezoelectrically actuated micropump



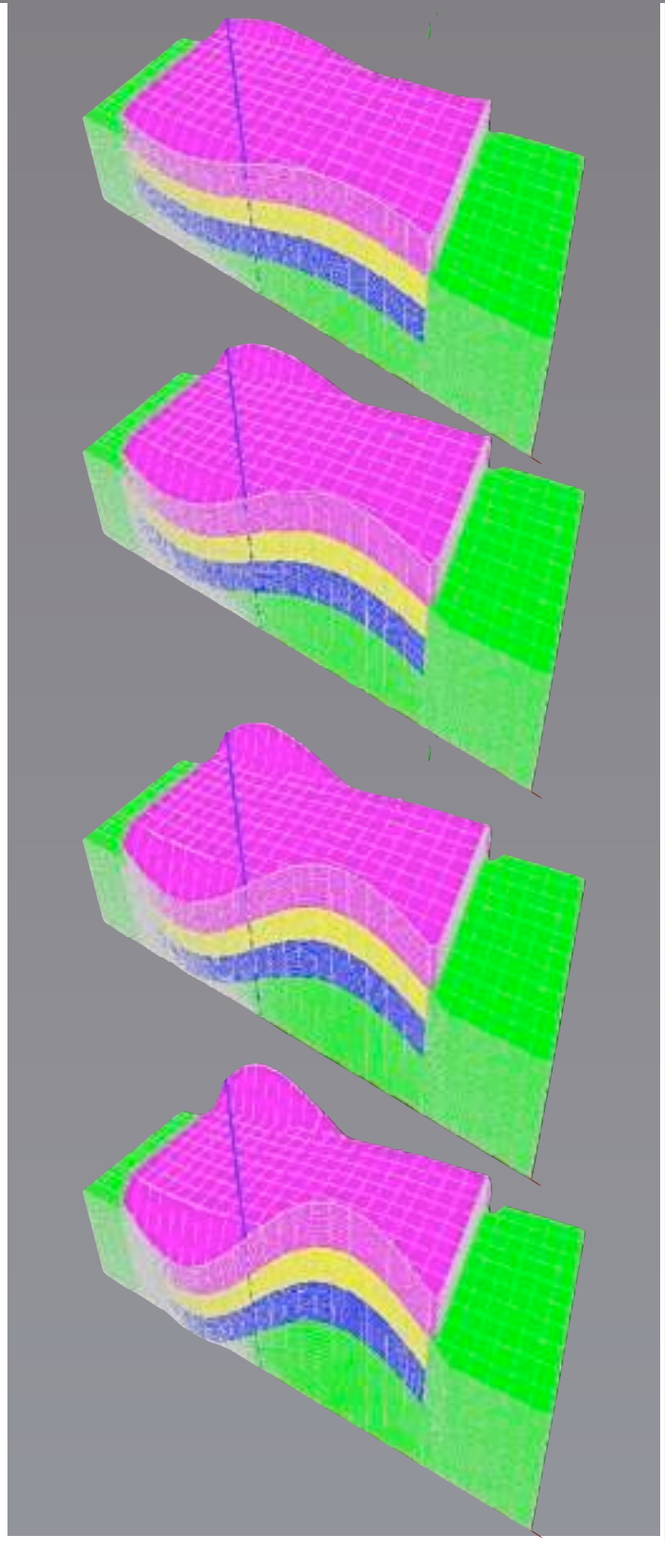
Flow evolution in a piezoelectric membrane micro pump

Piezo-Acoustics



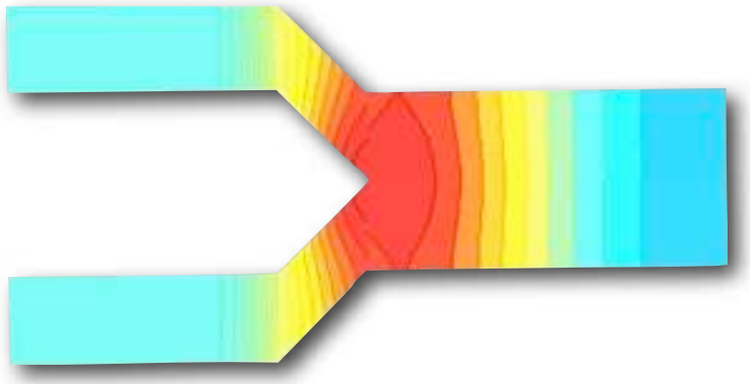


1 **Multi-processor enabled BAW/SAW simulation**
Fast impedance and phase ripple calculations

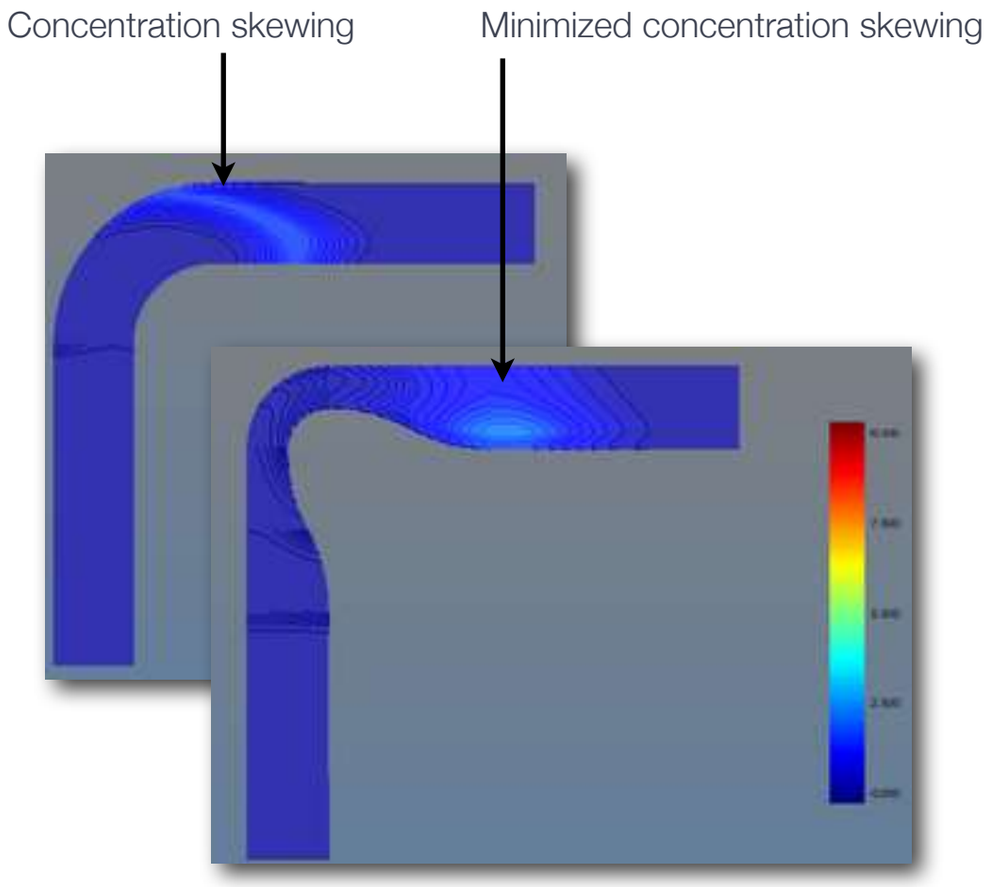


2 Piezo-acoustic
wave generation

Microfluidics



Two reactants meeting at the junction and reacting to form a new analyte. Support for multivalent reactions is new in v 8.5

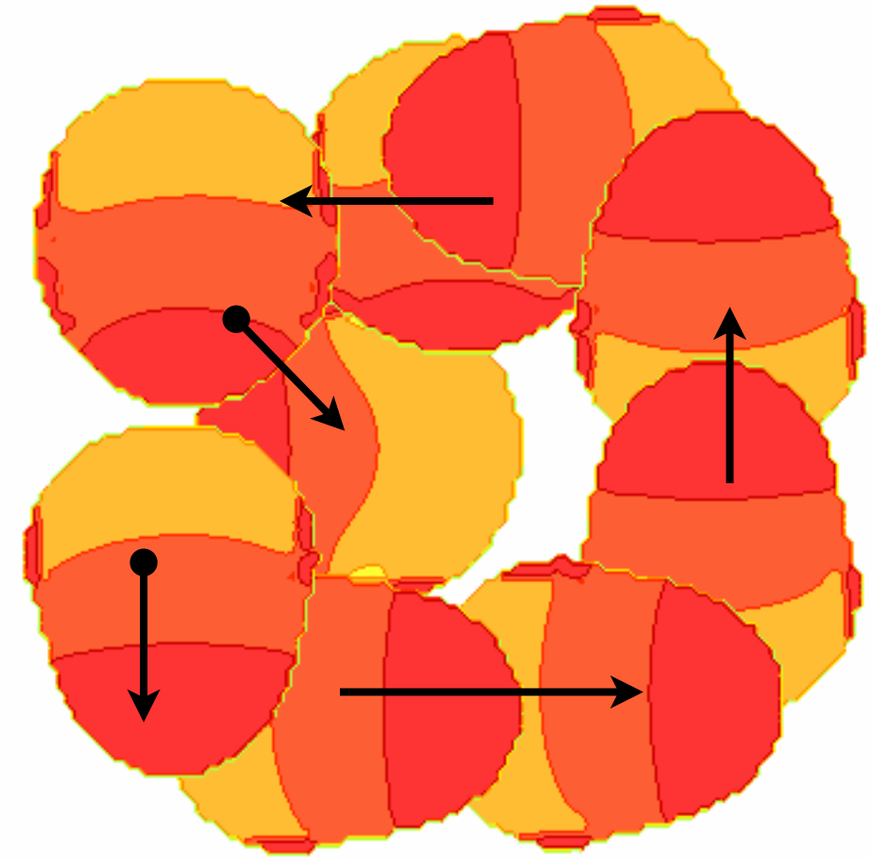


Enhanced ion drag calculations allows you to optimize elbow turns to minimize concentration skews

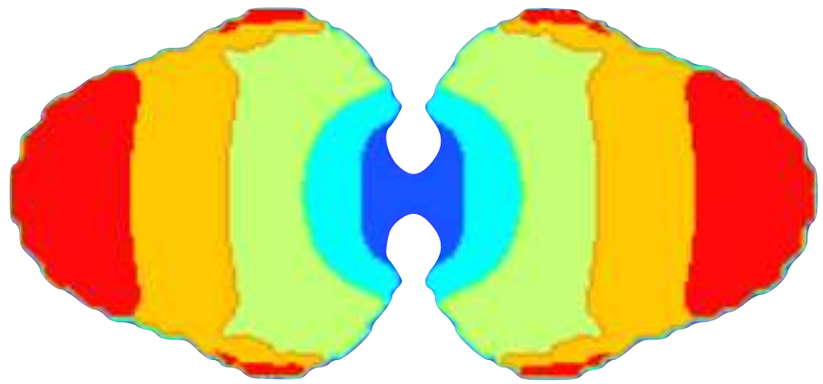
1 **Enhanced Chemical Reaction**
Microfluidics with enhanced transport kinetics

2 **Enhanced transport behavior**
Multivalent Ion drag calculations in electrokinetic transport

Microfluidics



Droplet moving around a pre-set track (top view)

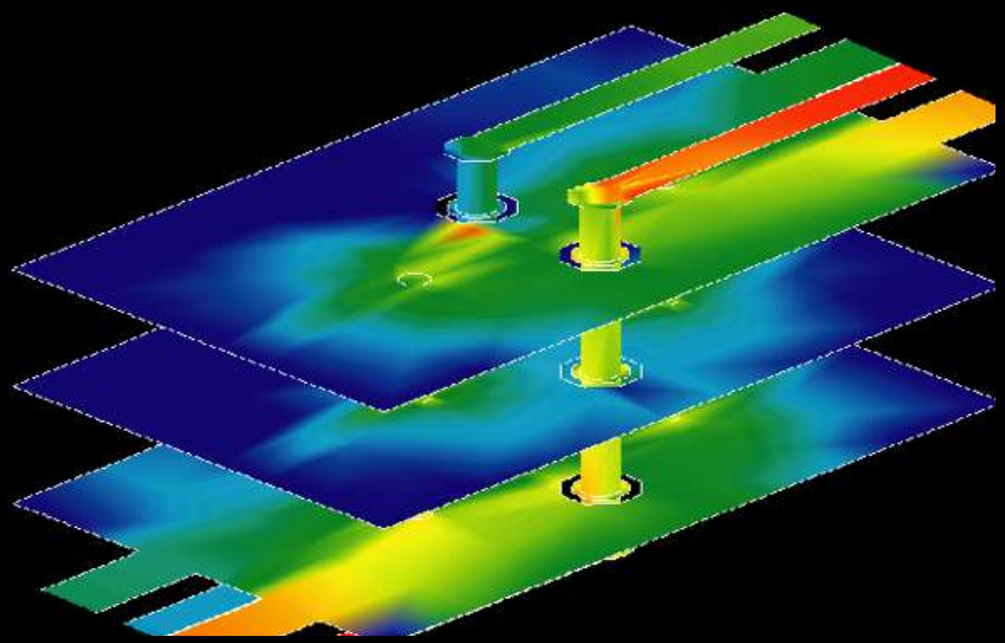


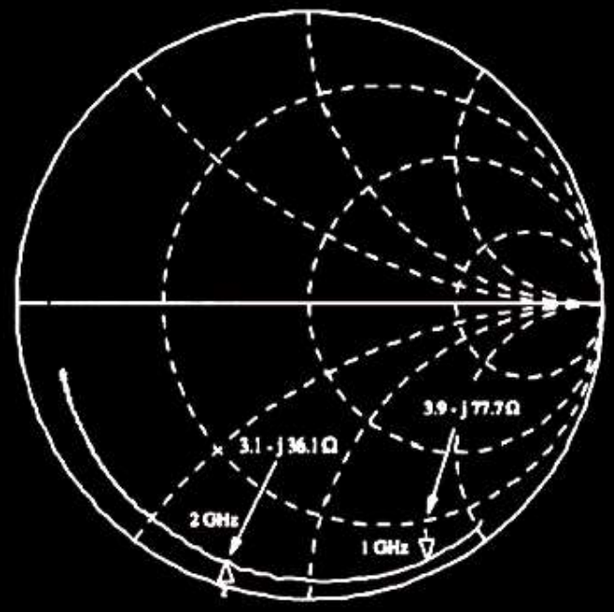
Droplet fission (top view)

3

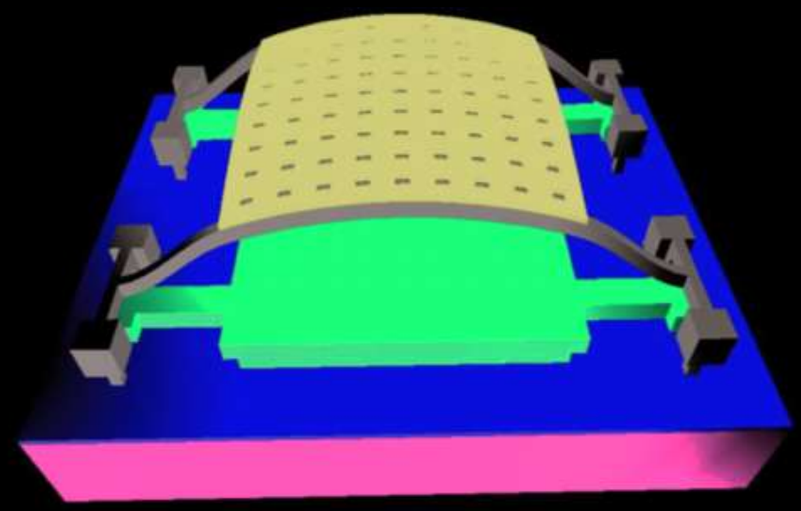
Electrowetting on dielectric (EWOD)
3D Electrowetting calculations

ElectroMagnetics





IntelliSuite is the only tool on the market that allows you to perform coupled Thermo-Electro-Mechanical & Full Wave ElectroMagnetic analyses— this is particularly useful in designing deformable RF-MEMS such as switches, tunable capacitors and varactors.



Extraction & verification

What is extraction?

Simplifying a full 3D model into behavioral model

Convert FEA/BEA model (large DOFs) into computationally efficient model

Develop pre-computed energy based model that captures multiphysics

What is extracted ?

Mechanical Strain Energy of Modes of Interest (Including stress and stress gradient effects)

Capacitive energy

Thermal effects (deformation due to temperature change)

Fluidic Structure Interaction (due to compressive or non-compressive media)

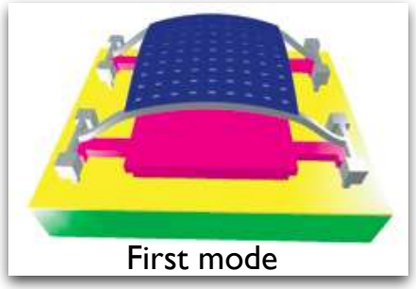
Other dissipation sources (thermoelastic damping (v8.6.1) and anchor acoustic losses (v8.6.2))

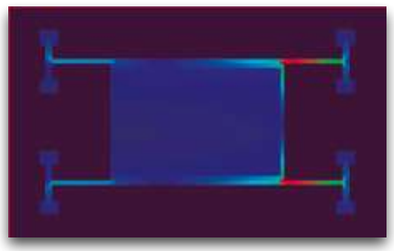
System Model Extraction (SME)

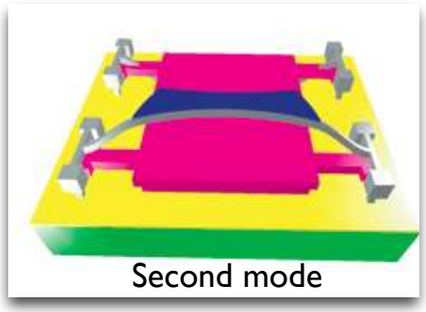
Capture strain energy associated with each mode

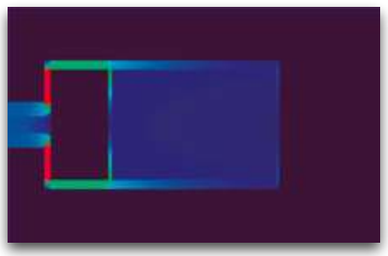
Capture electrostatic energy associated with each mode

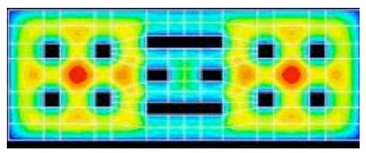
Capture fluid damping characteristics

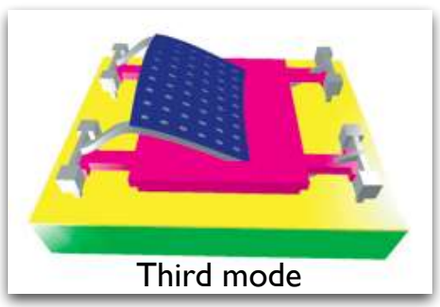

First mode

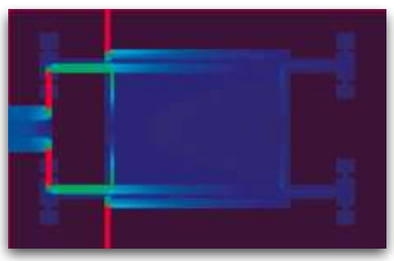



Second mode






Third mode



Arnoldi/Krylov sub-space reduction

N-DOF behavioral model based on Lagrangian formulation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial q_j}\right) - \frac{\partial L}{\partial q_j} = 0$$

Compact Representation

HDL

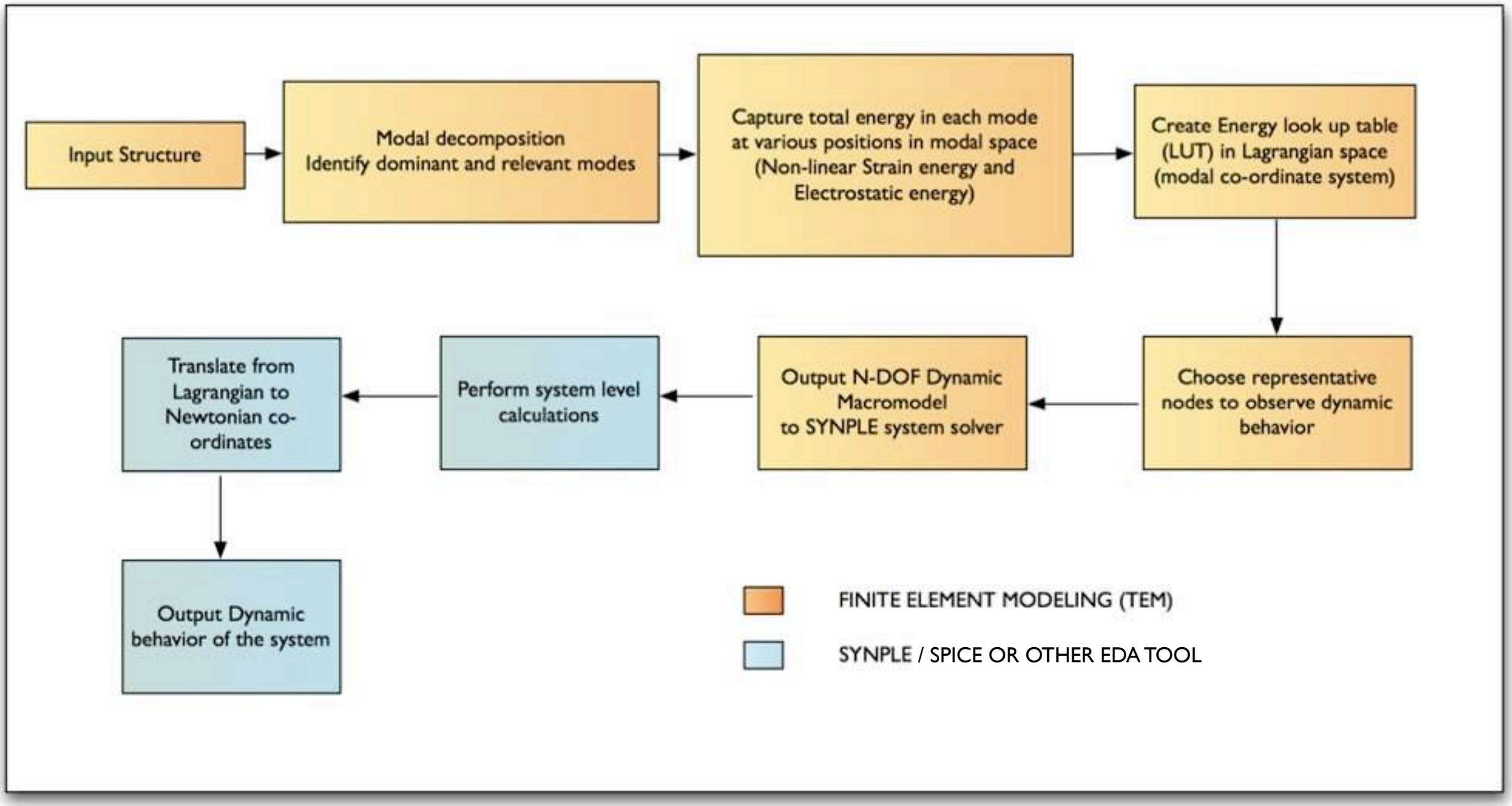
Hardware Description

❶ Capture total energy of relevant mode (Mechanical, Electrostatic, Dissipation)

❷ Krylov/Arnoldi methods to generate Lagrangian formulation

❸ Create Compact model for system modeling

System model extraction (SME) flow chart

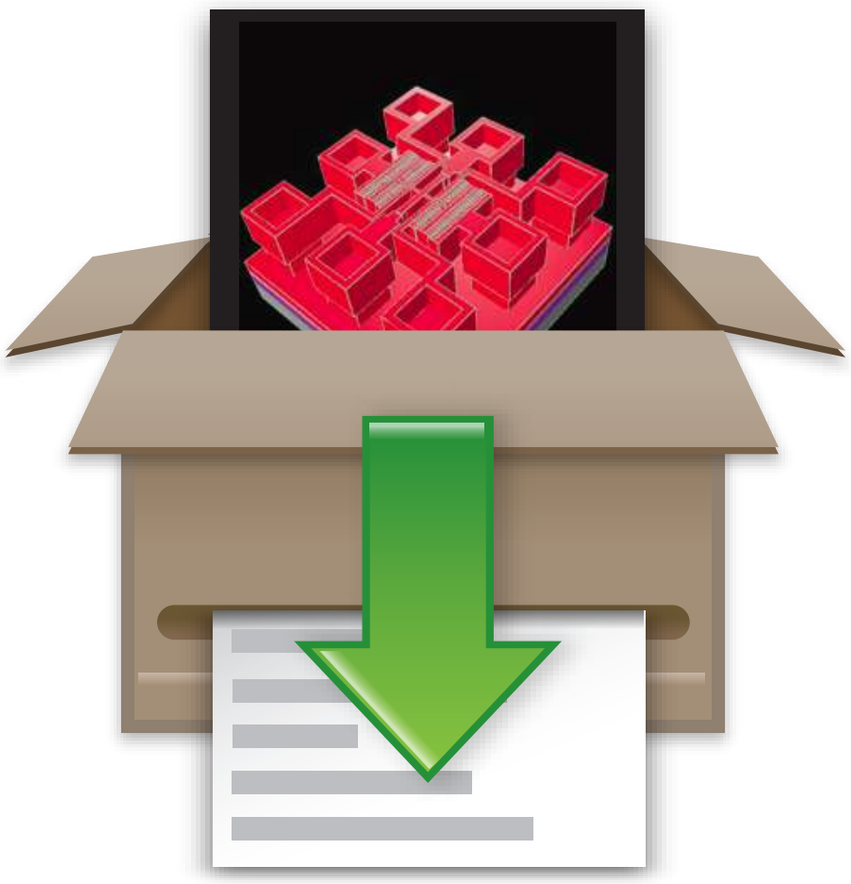


Summary: Convert problem from Newtonian (inertia based) to more efficient Lagrangian domain (energy based)

SME advantages

- Automated full multi-physics capture
- 1000 X faster than pure FEA
- Matches FEA to within 1% accuracy
- Fully capture harmonic responses
- 3D MEMS system simulation
- Device and package level extraction
- Automated VHDL/ Verilog/ SPICE generation

EDA Linker capabilities (compatibility)



- Create accurate N-DOF dynamic system model from MEMS FEA/BEA model

- Output system model into SPICE, HDL, and Simulink formats

- Compatible with EDA tools from Cadence, Mathworks, Mentor, Synopsys and Tanner

- Integrated CMOS-MEMS (SoC/SiP) compatibility

Integrated design flow for MEMS + IC

1. Device/System Design Exploration
   Design of Experiments
   (SYNPLE/IntelliSuite)
2. Final MEMS Device design
   (Multiphysics)
3. N-DOF Lagrangian
   System Model Extraction
   (IntelliSuite)
4. Transistor level design
   (SPICE/SYNPLE or other EDA tools)
5. Gate level
   Place and route, DRC, LVS
   (Cadence/Synopsys/Mentor/ViewLogic/Tanner etc)
6. Final Layout
   (IntelliMask Pro/ L-Edit/ Virtuoso/other)

MEMS-CMOS integration design flow can be based on :

- ✓ VHDL-AMS
- ✓ Verilog-A
- ✓ SPICE netlist
- ✓ Matlab/Simulink .MEX

What is verification?

Model verification (Schematic vs 3D)

Verify schematic model and 3D model match

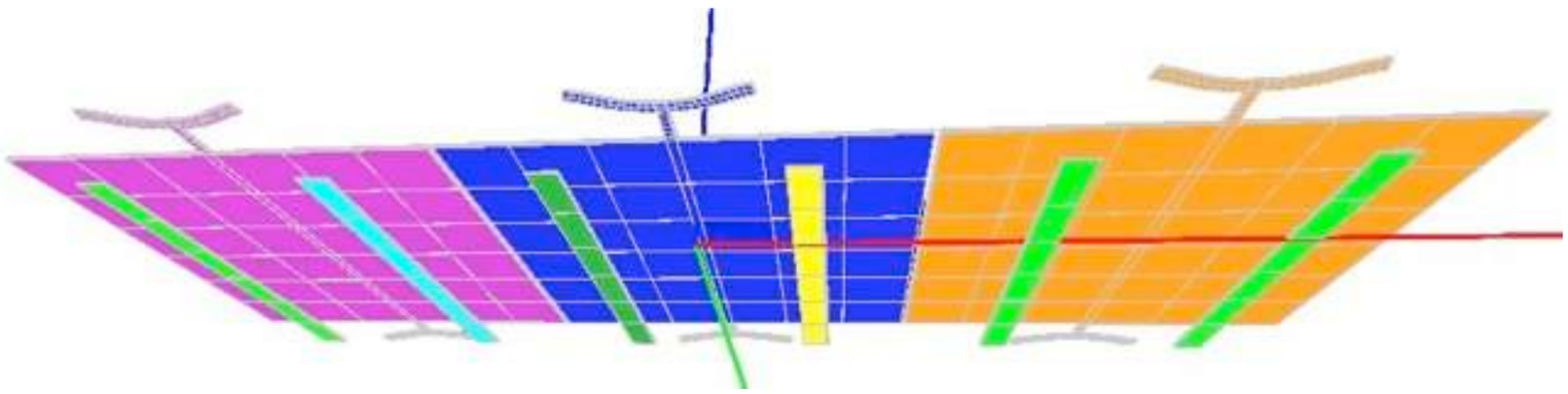
Ensure MEMS model used in circuit development is accurate

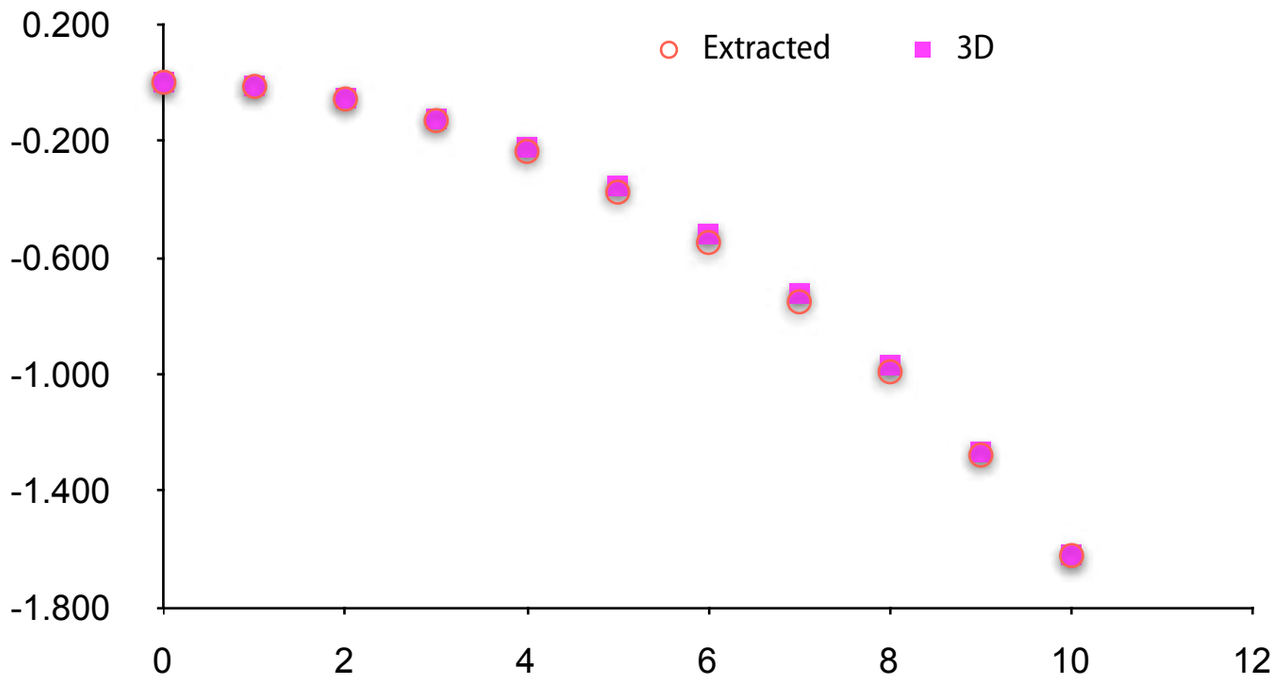
Physical verification (‘Tape Out’)

Verify physical layout is consistent with Design Rules

Ensure design meets manufacturability criteria

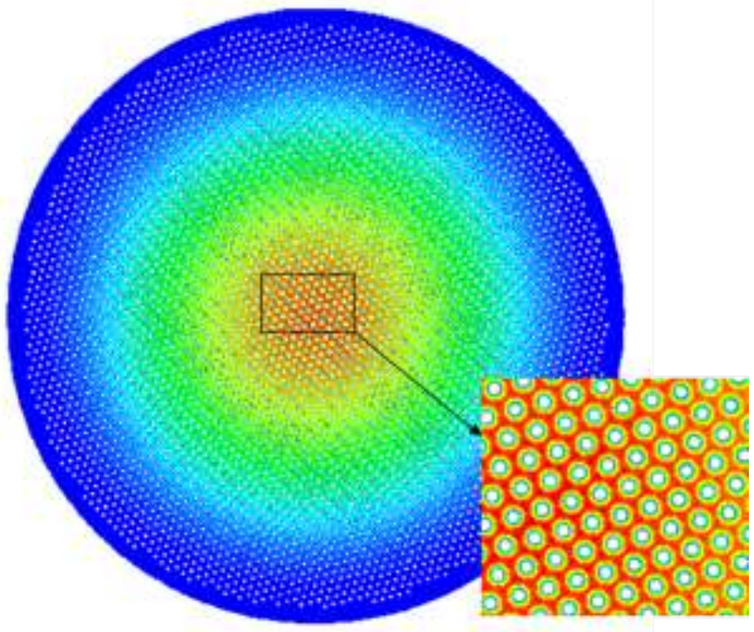
Static model verification



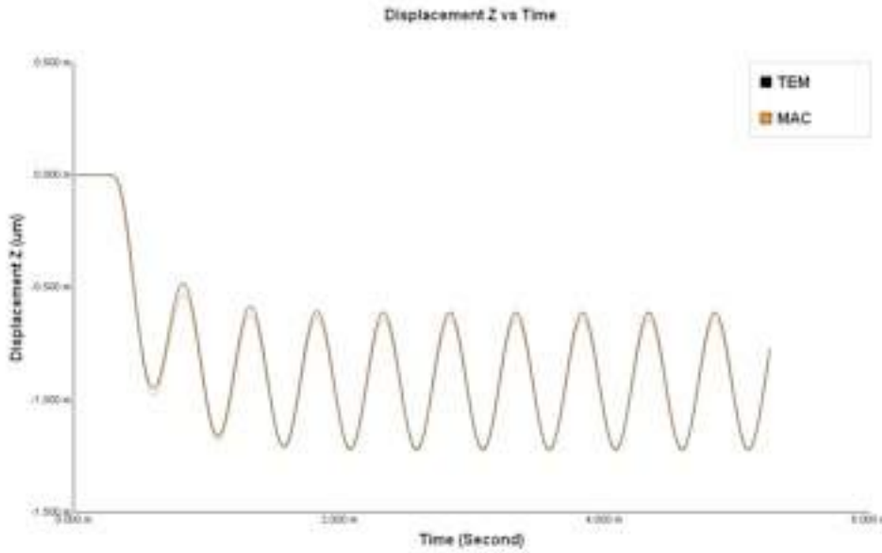


Pull-in: Schematic results vs Full 3D results

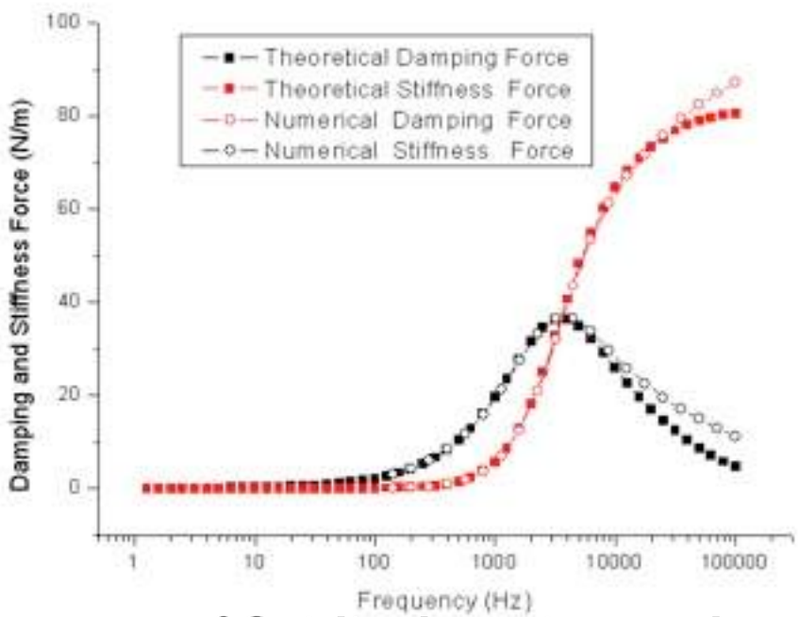
Damping model verification



Perforated condenser membrane

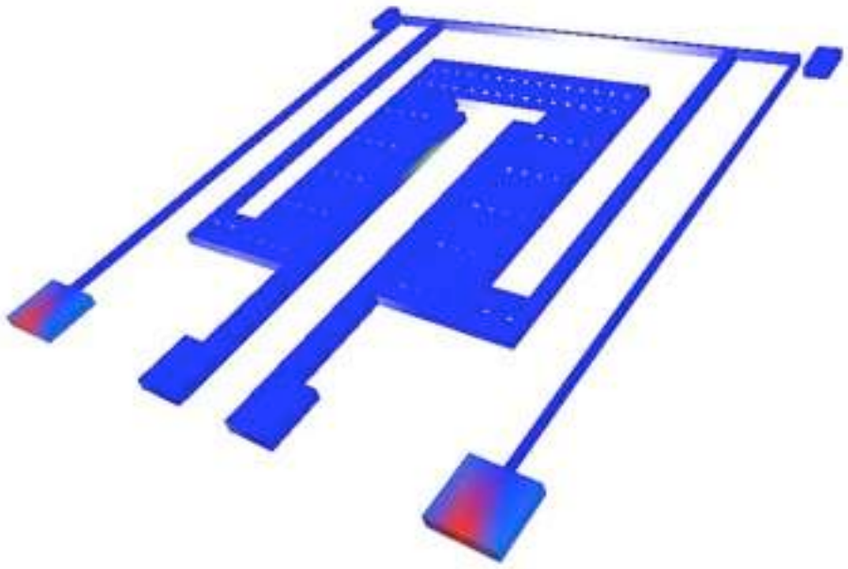


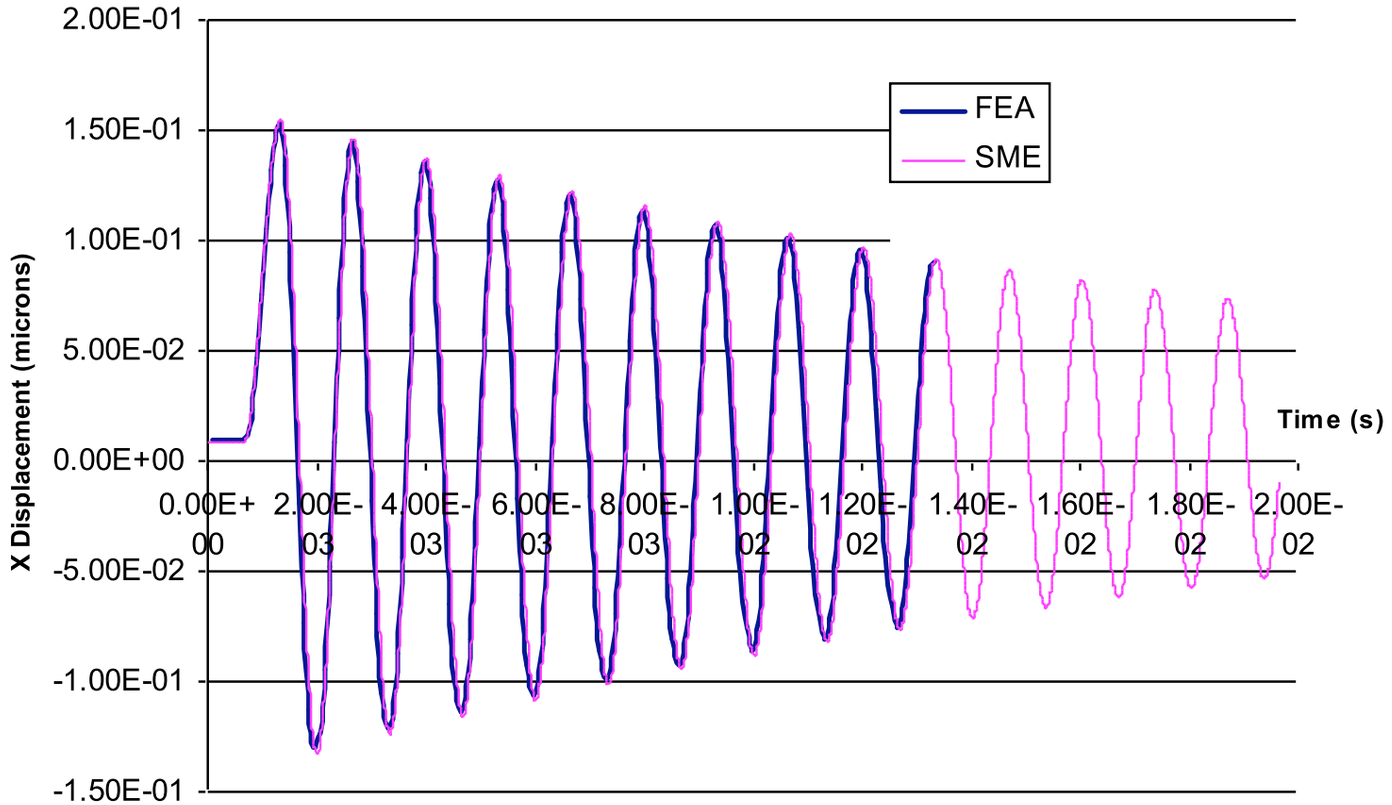
Full 3D (TEM) vs Macromodel comparison



Full capture of fluidic damping and spring force

Dynamic model verification





Transient response of device: Schematic vs FEA (3D)

Summary

- End to end design tools for MEMS
- Simulate MEMS at any level:

  Ab-initio, Component, Device, Algorithm and System
- Flexible design flow to achieve accurate and fast results
- Used by major customers in 30+ countries

Thank you

ありがとう·謝謝 • धन्यवाद • شكرا لكم

Grazie •Merci • Gracias • Danke •Obrigado • Dank U •Terima Kasih

Dziękuję • Спасибо • Ευχαριστώ • Asante Sana • Dankie

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