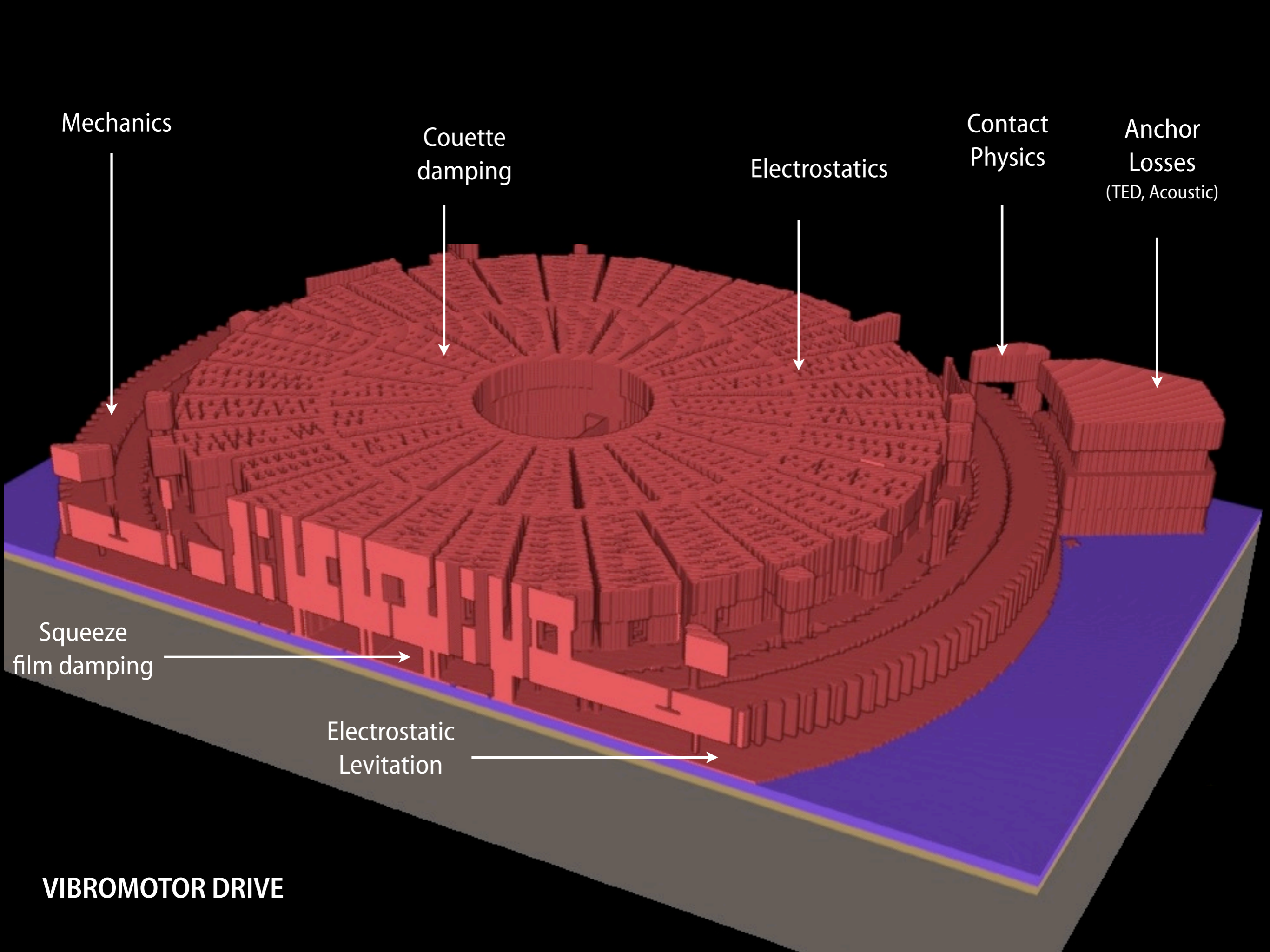




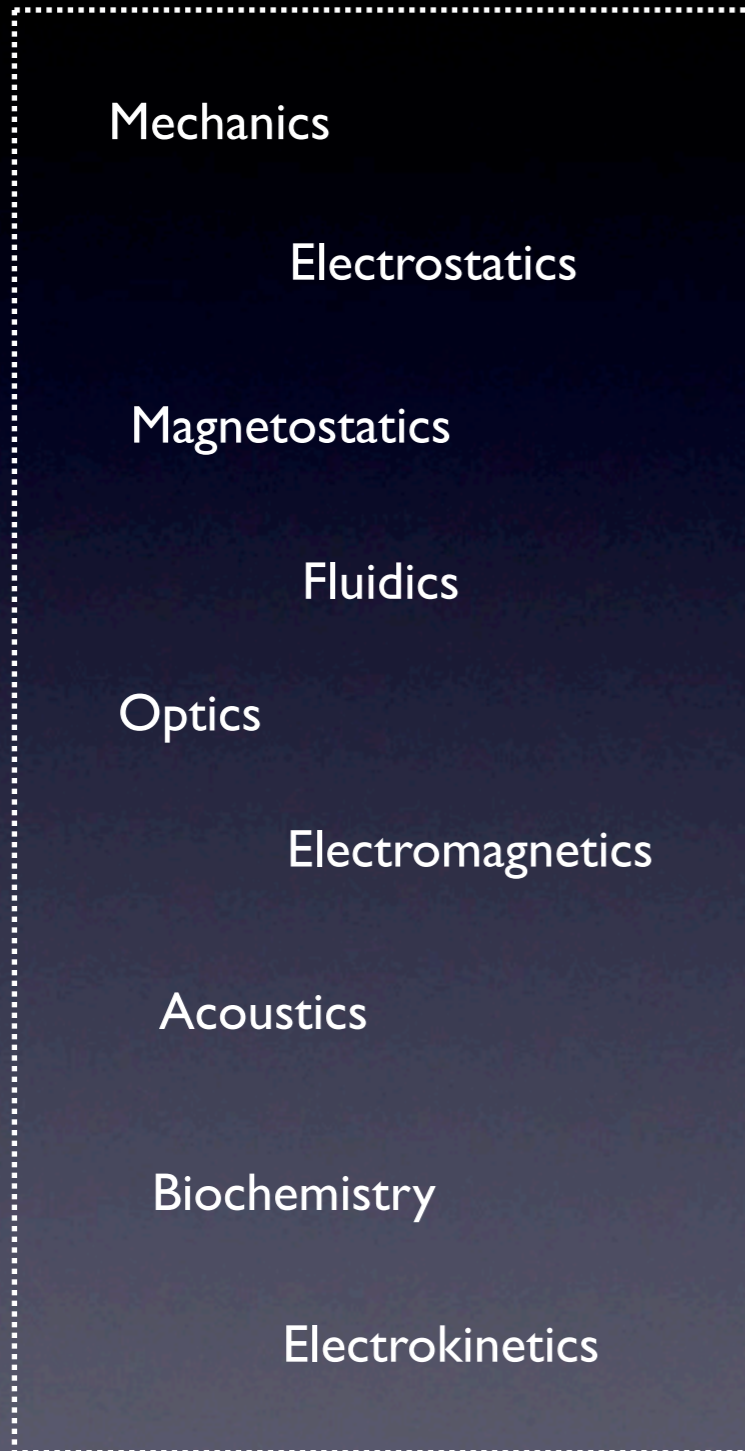
Design Flow in IntelliSuite v8.6

Design flow

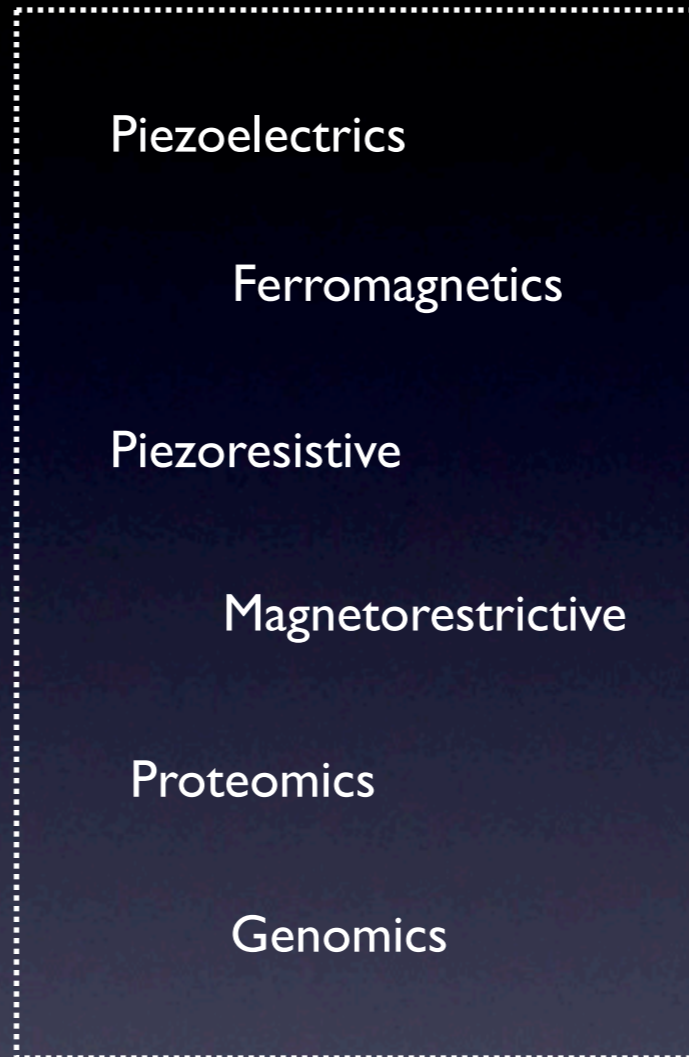
MEMS design is highly interdisciplinary



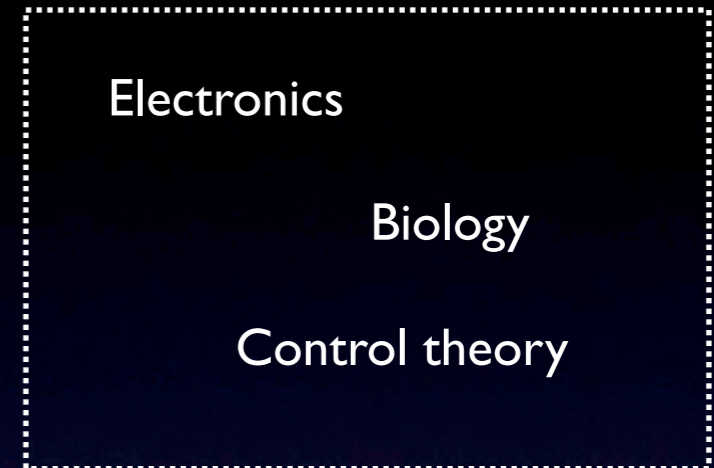
Colliding domains



PHYSICS



MATERIALS

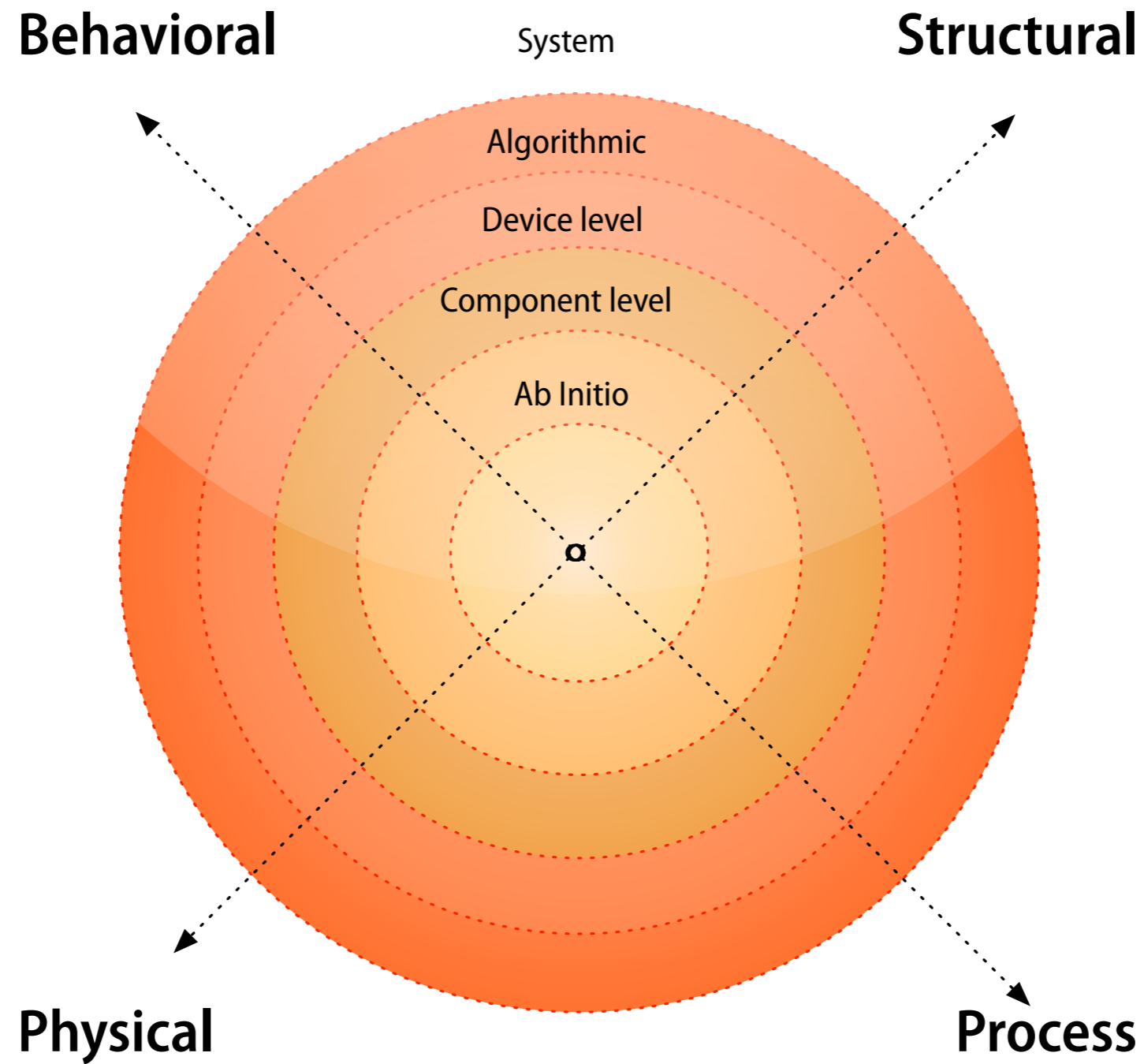


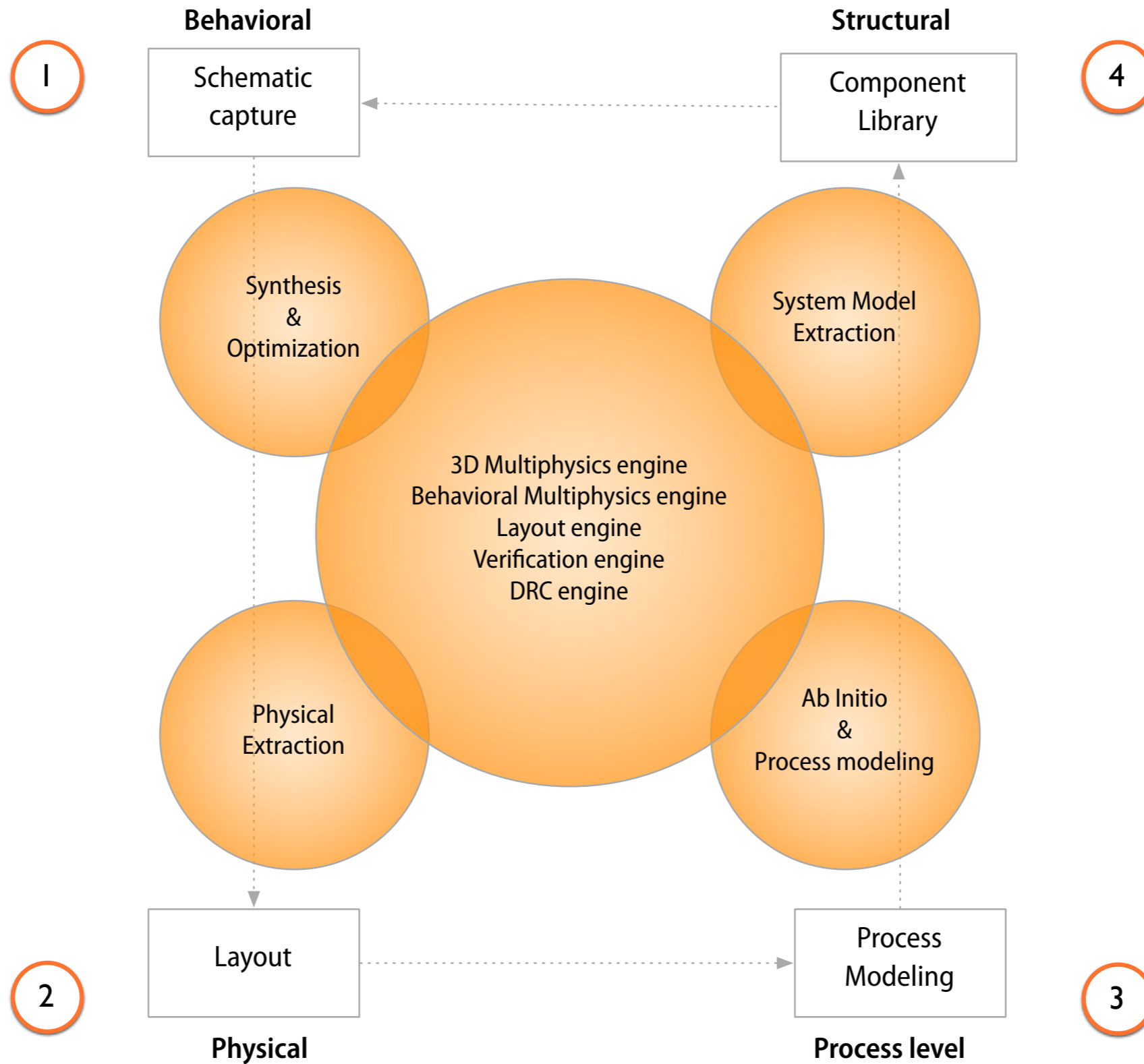
SYSTEMS



MANUFACTURING

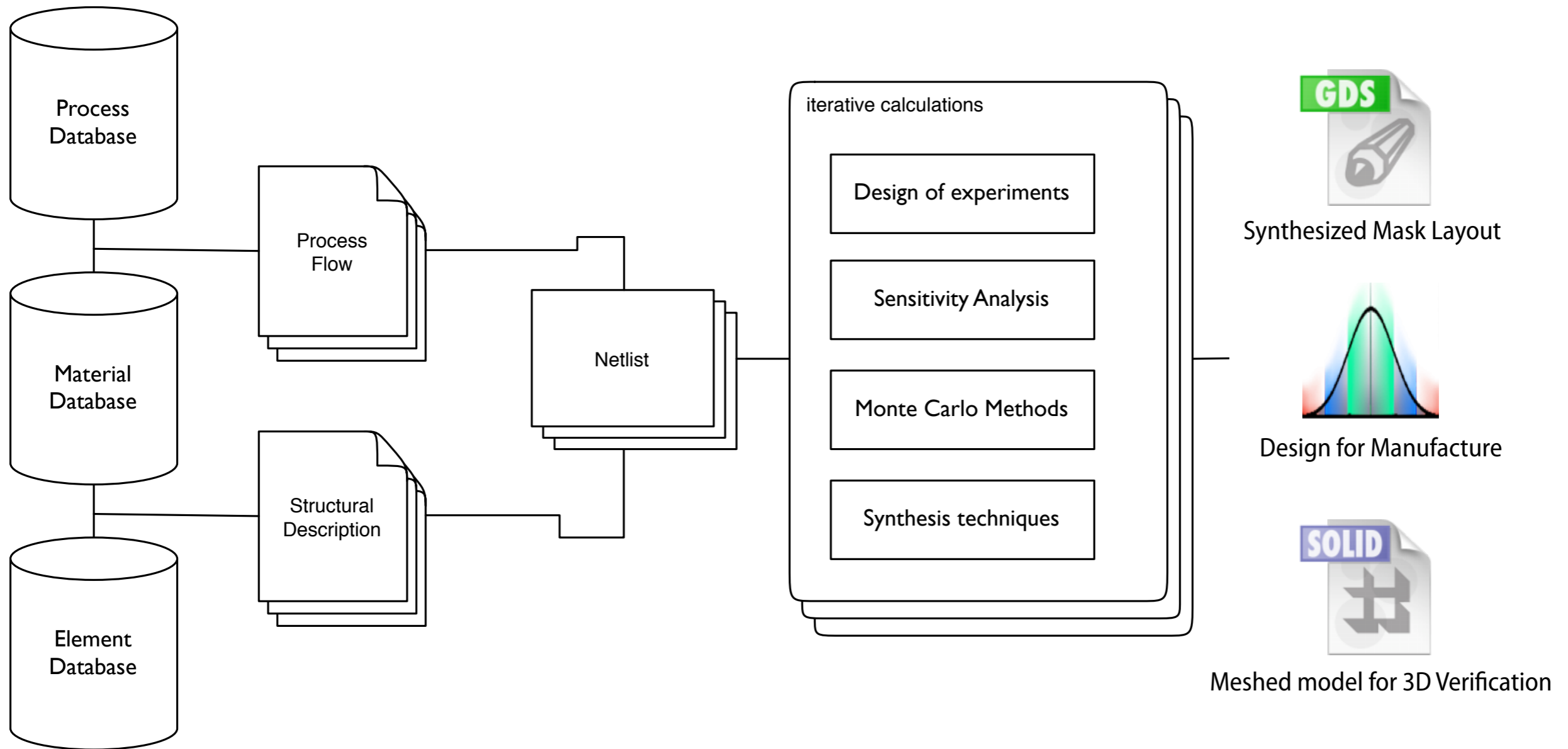
Hierarchy of MEMS modeling





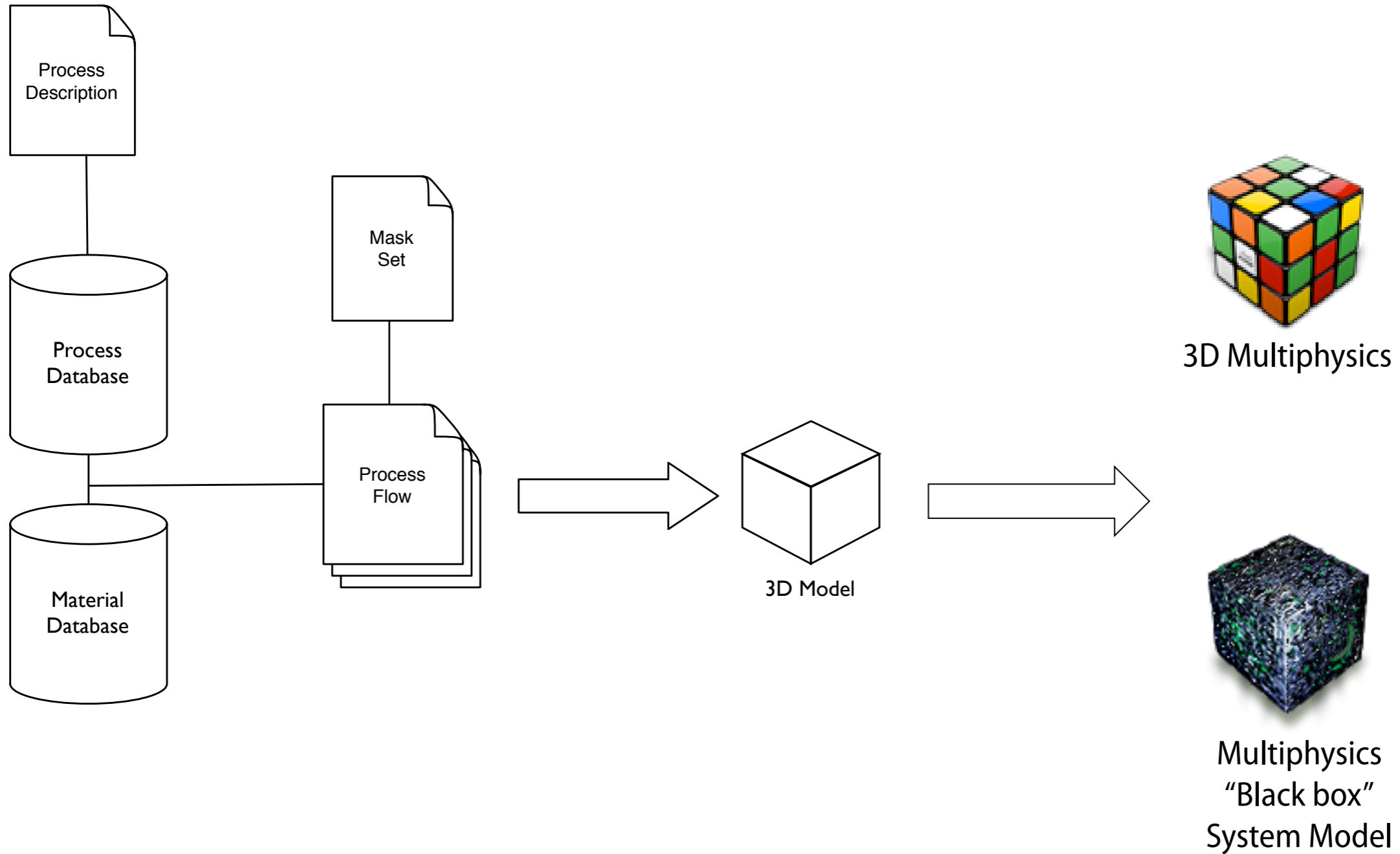
Seamless integration of design flow...

Top down flow: schematic based...



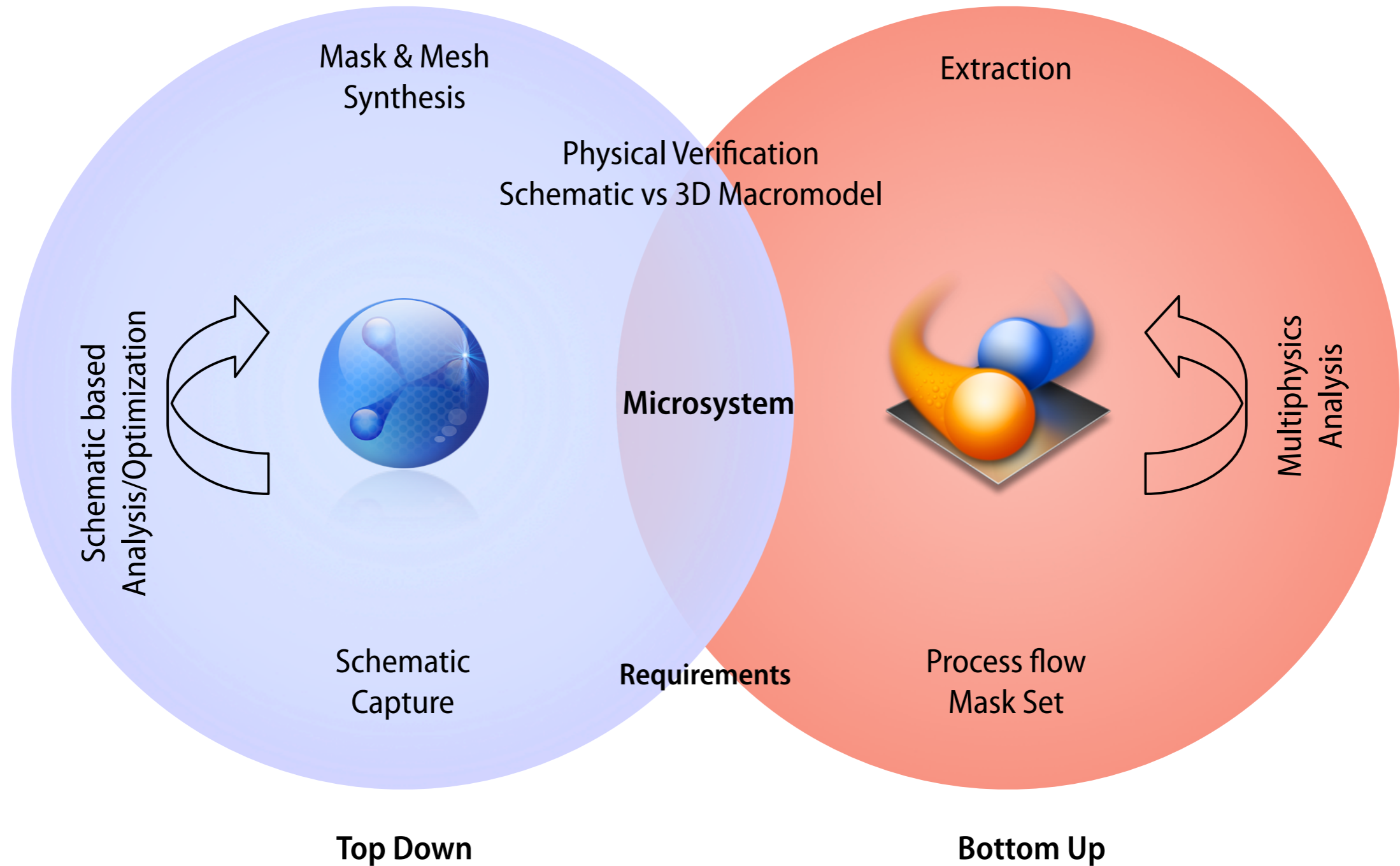
Fast but less accurate...

Bottom up design flow: 3D based



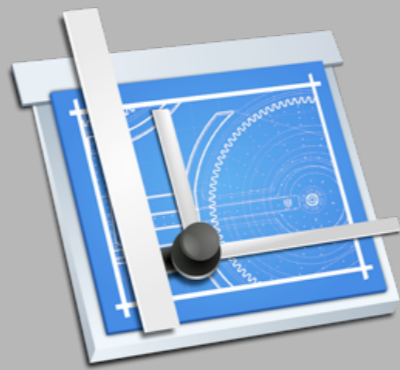
Accurate but slower...

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

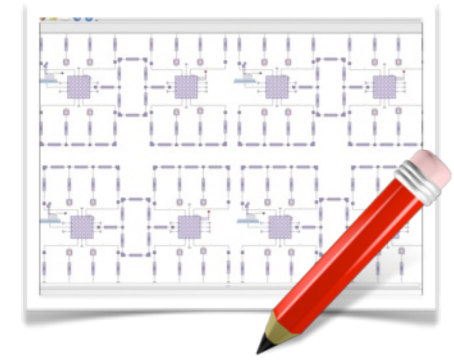
EDA Linker

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

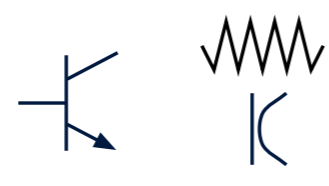
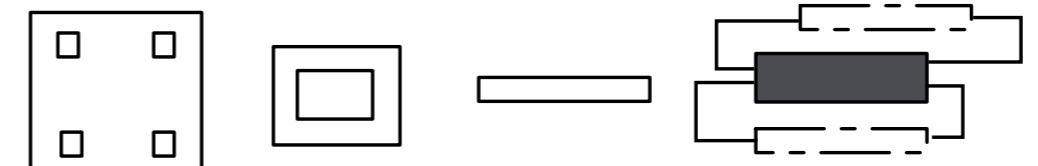
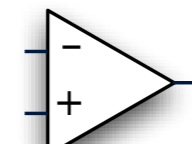

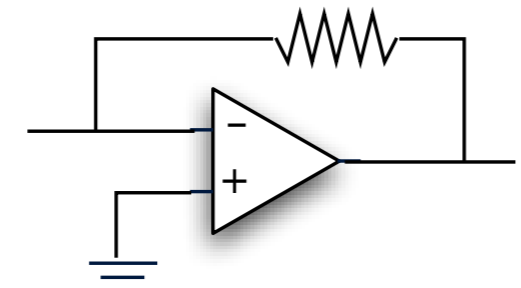
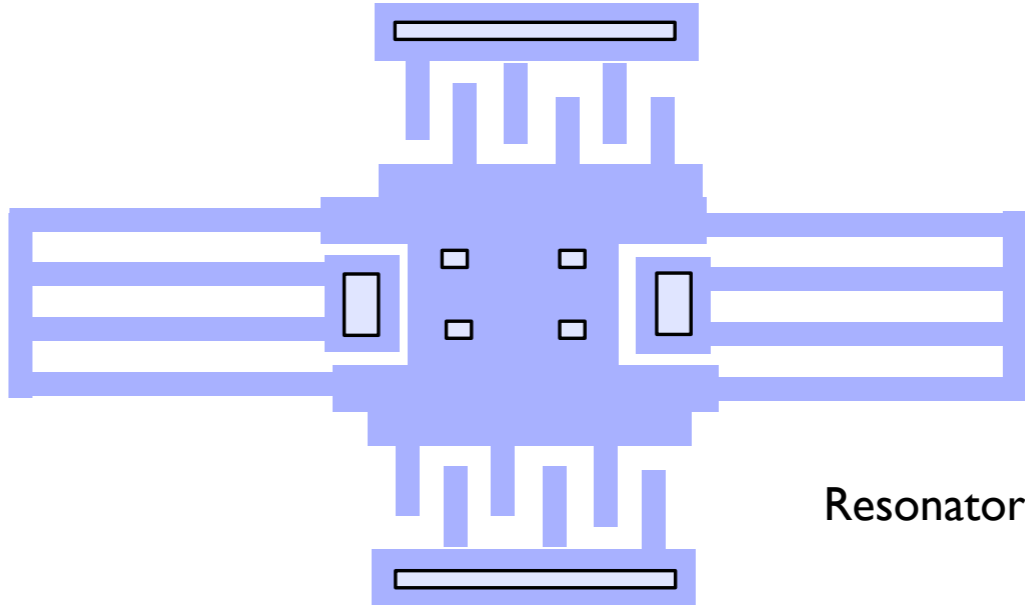
Yield Engineering

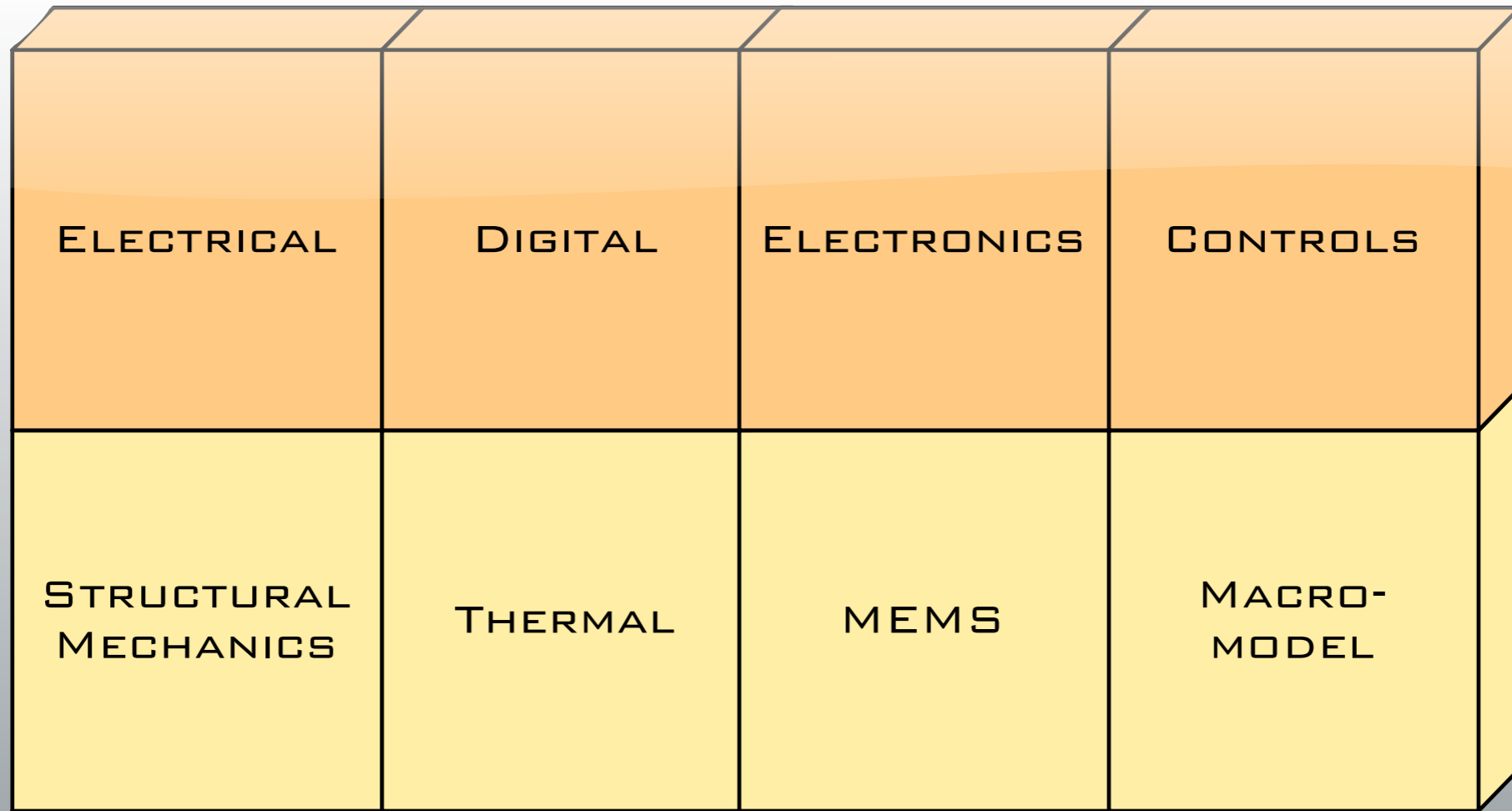
DfM
Process Corner studies
Yield prediction

Link to other tools

Automatic meshing
Derive process flow

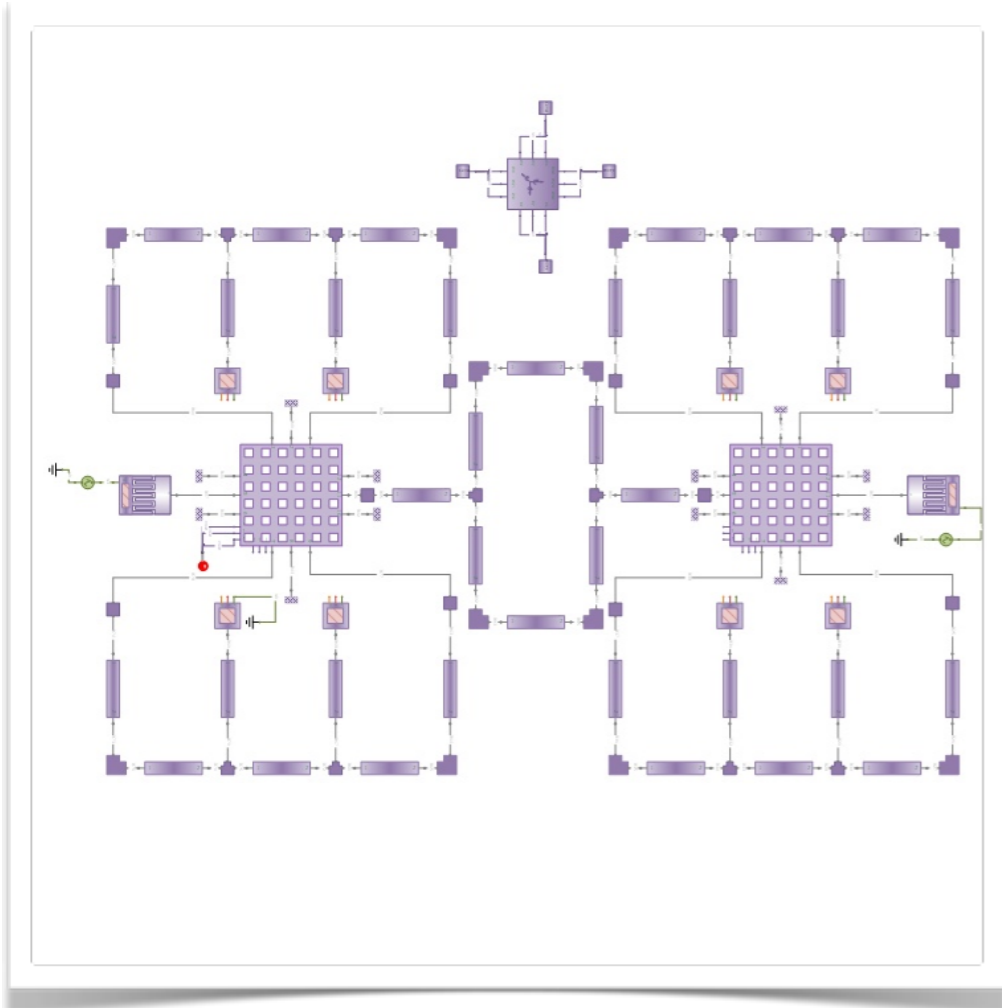
Hierarchical multi-domain design

<p>Atomic elements</p>	 <p>Transistor RLC</p>	 <p>Plate Anchor Beam Gap</p>
<p>Compound elements</p>	 <p>Op-Amp</p>	 <p>Shuttle mass Folded flexure spring Comb drive</p>
<p>Device elements</p>	 <p>Interface circuit</p>	 <p>Resonator</p>

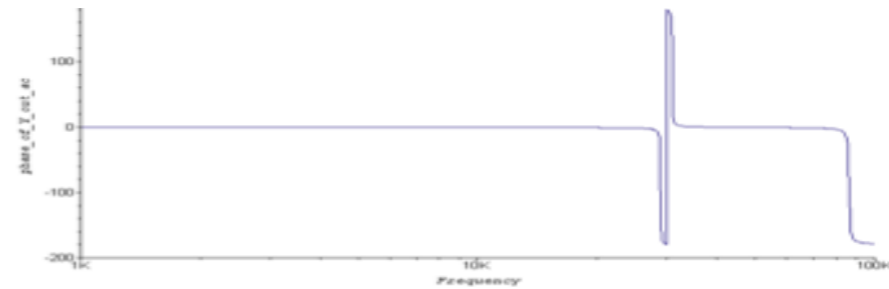
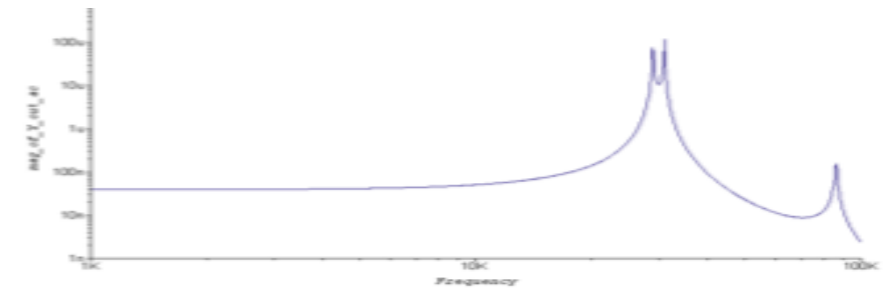


WIDE RANGE OF BUILDING BLOCKS

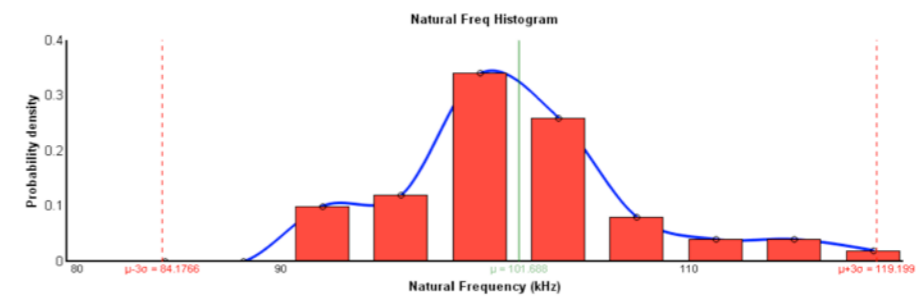
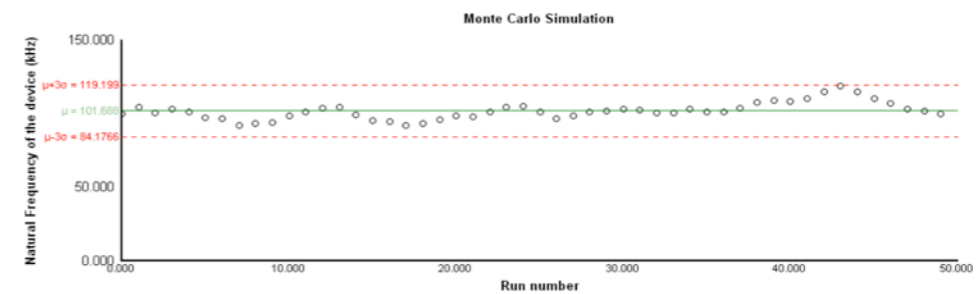
Schematic based design exploration



Band pass filter

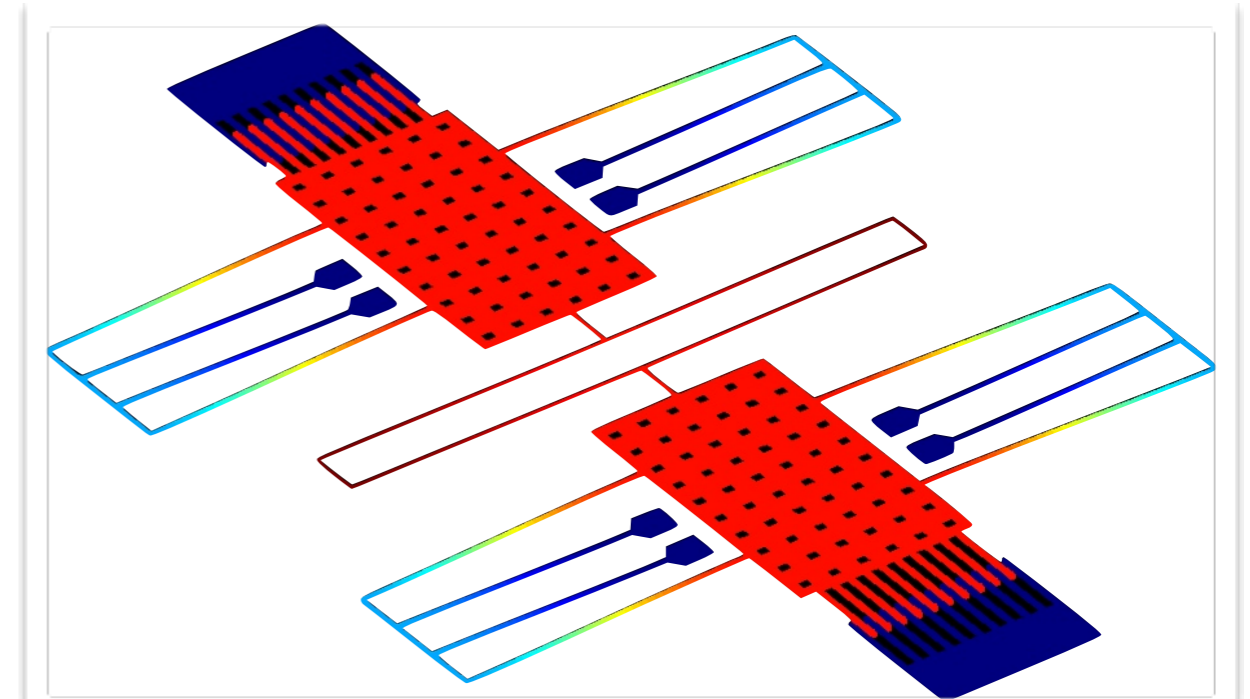
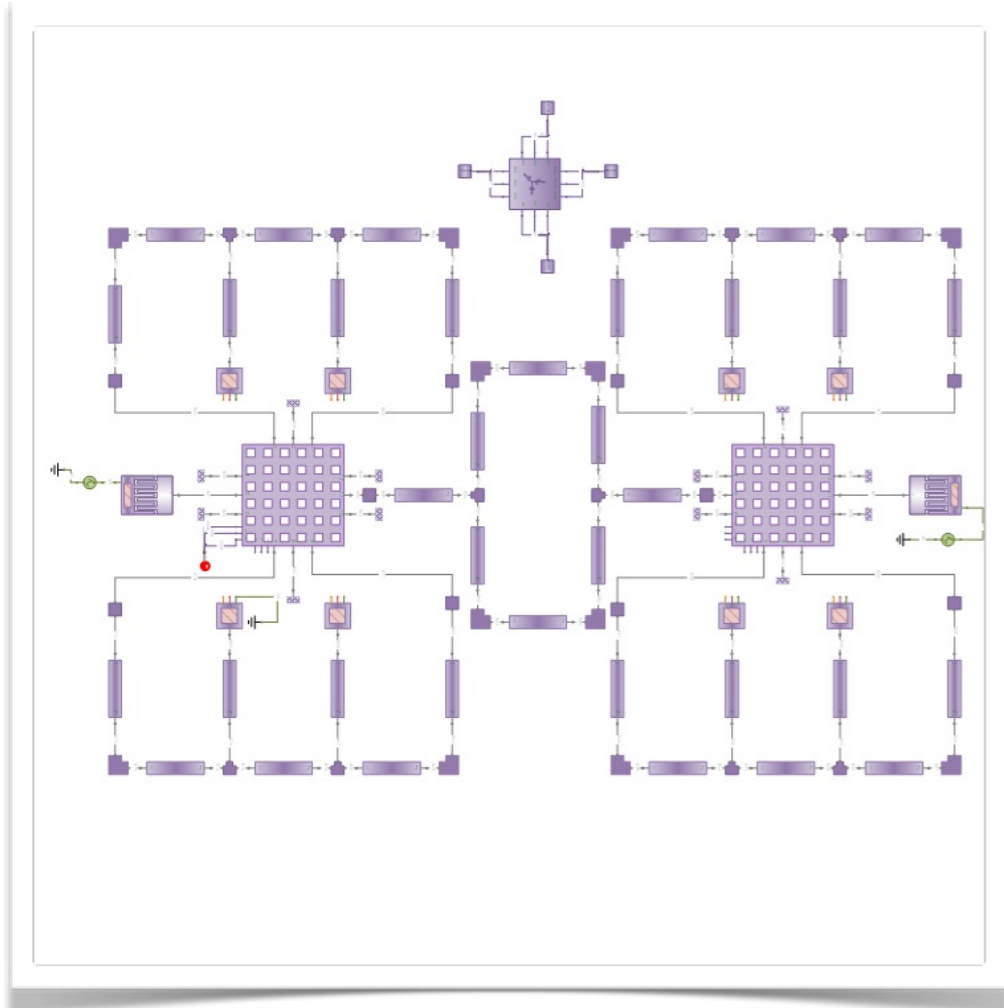


Compute time: 4 hr (Full 3D) vs 30s (compact)

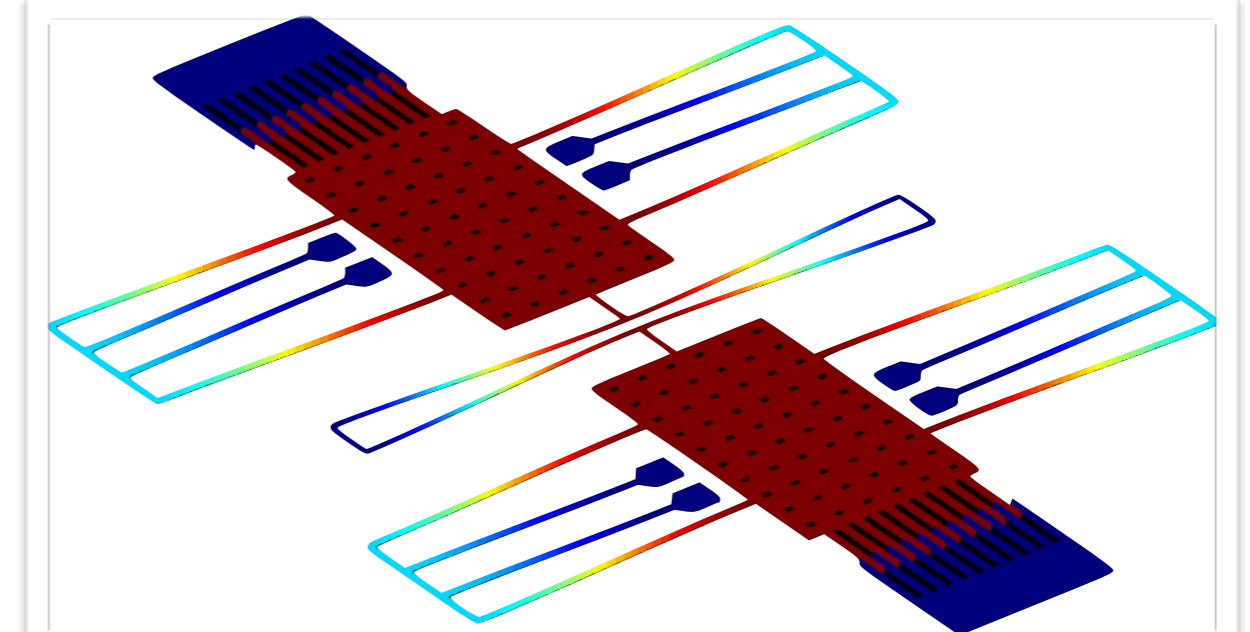


Monte Carlo based
process variation analysis

Visualize schematic results in 3D

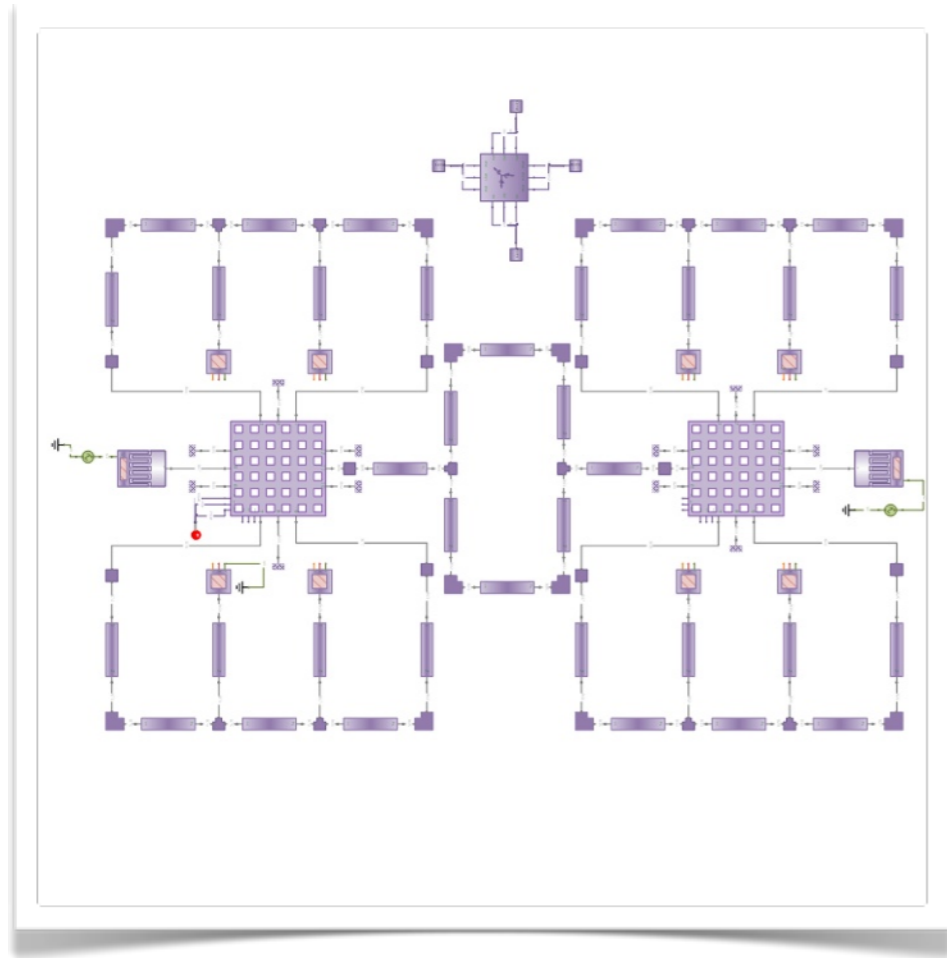


Mode 1: In Phase

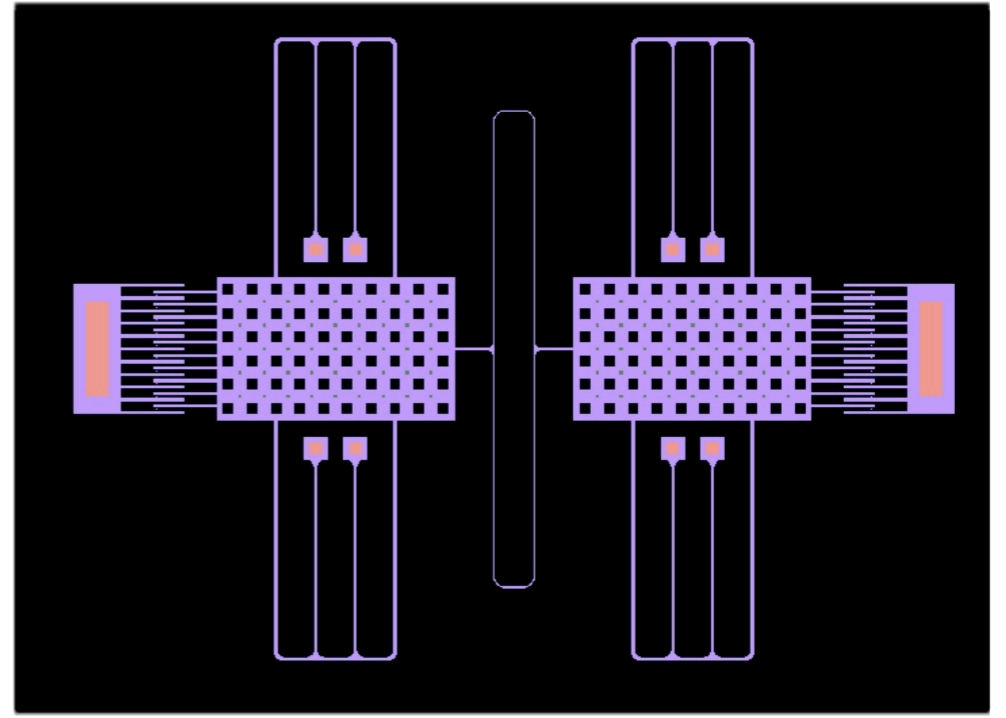


Mode 2: Anti Phase

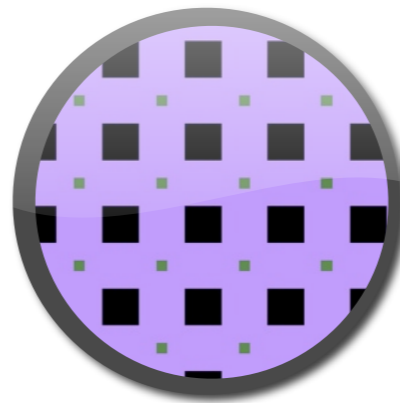
Schematic to mask



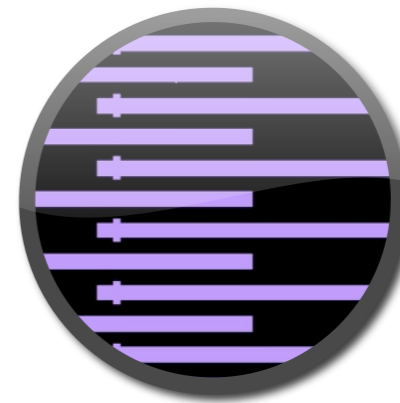
Automated layout synthesis



Stress relief curves



Dimples



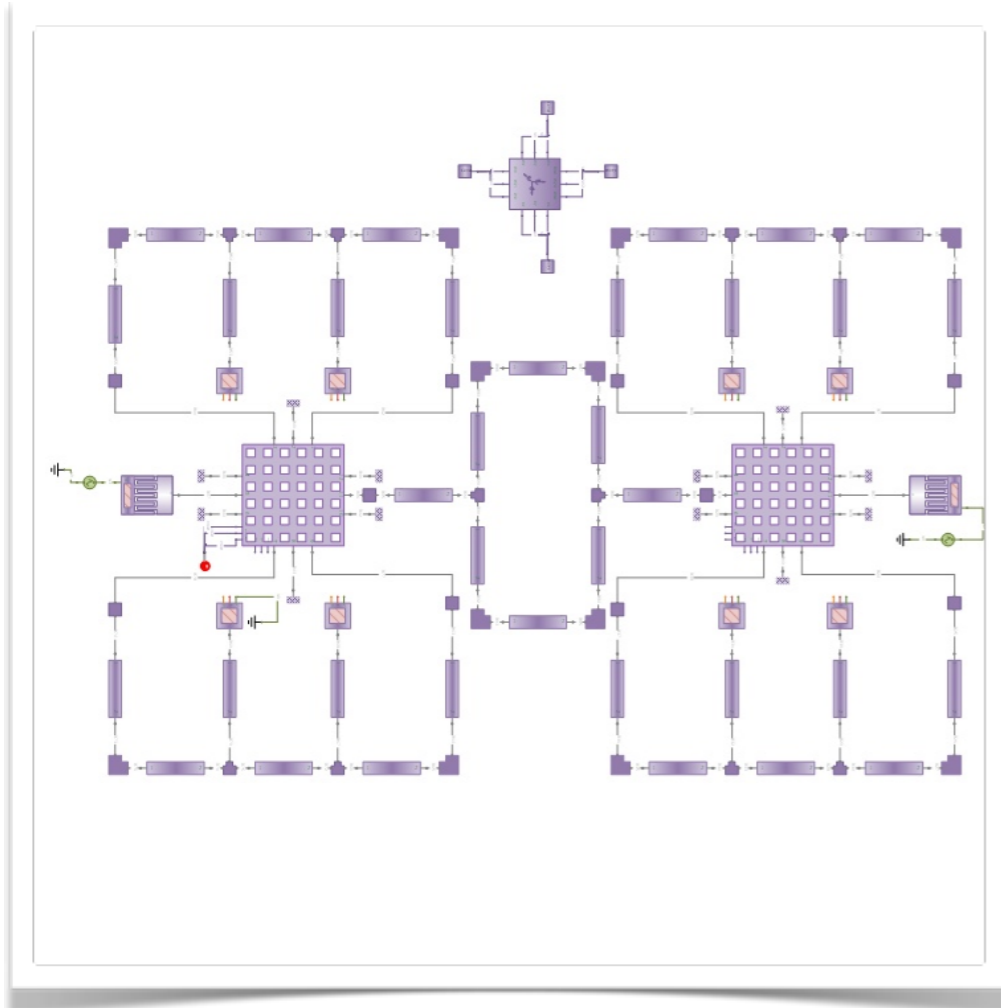
Comb bumpers



Etch compensation features

Attention to detail

Schematic to process flow



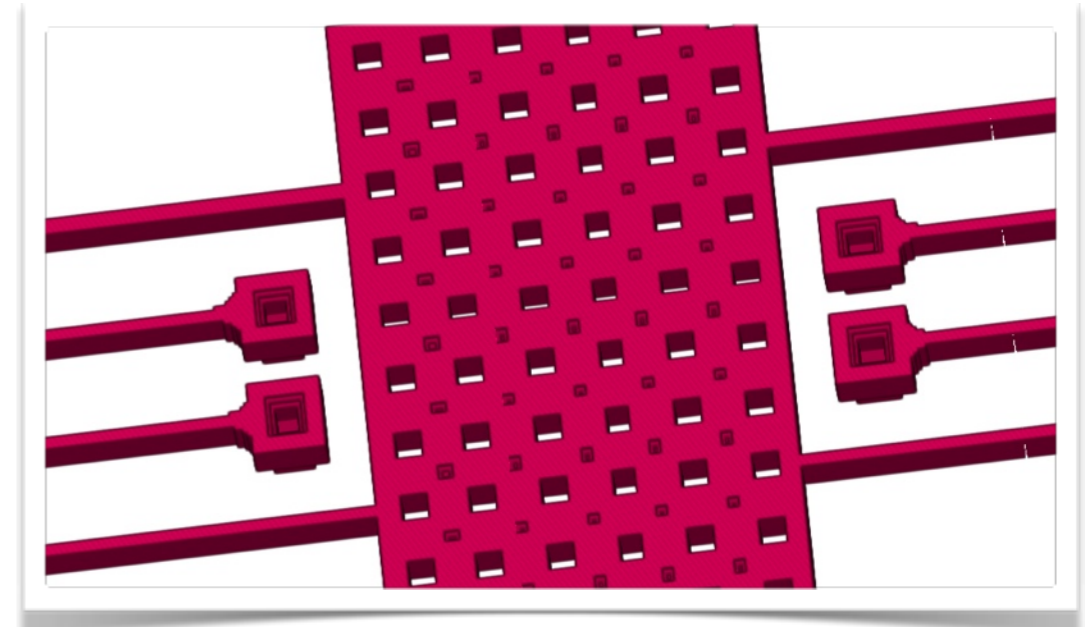
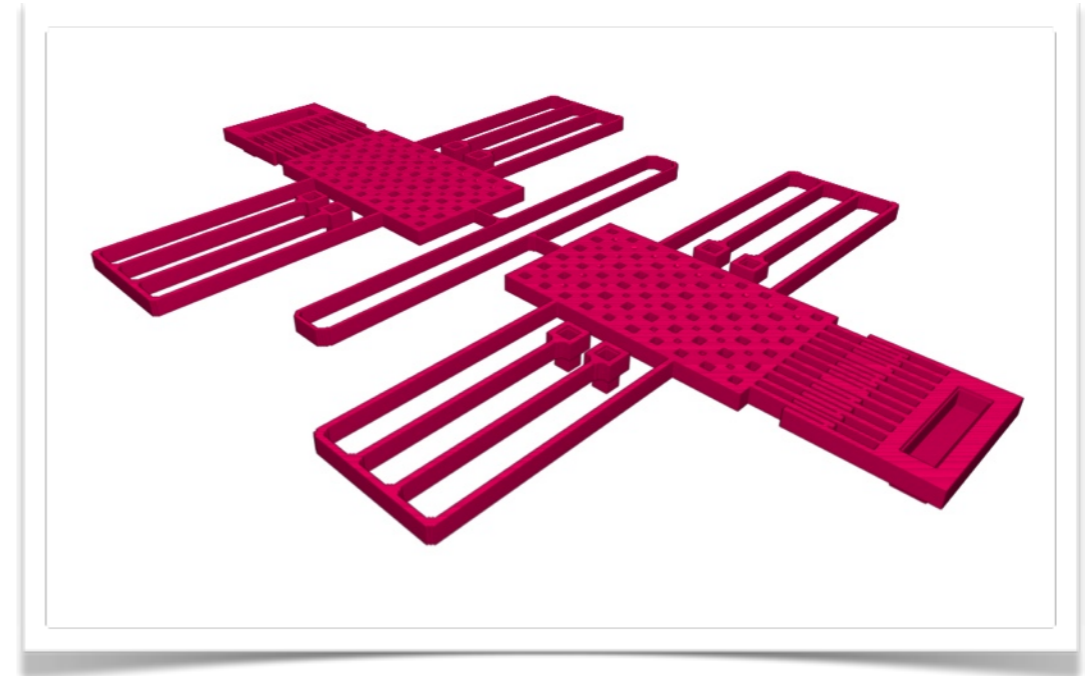
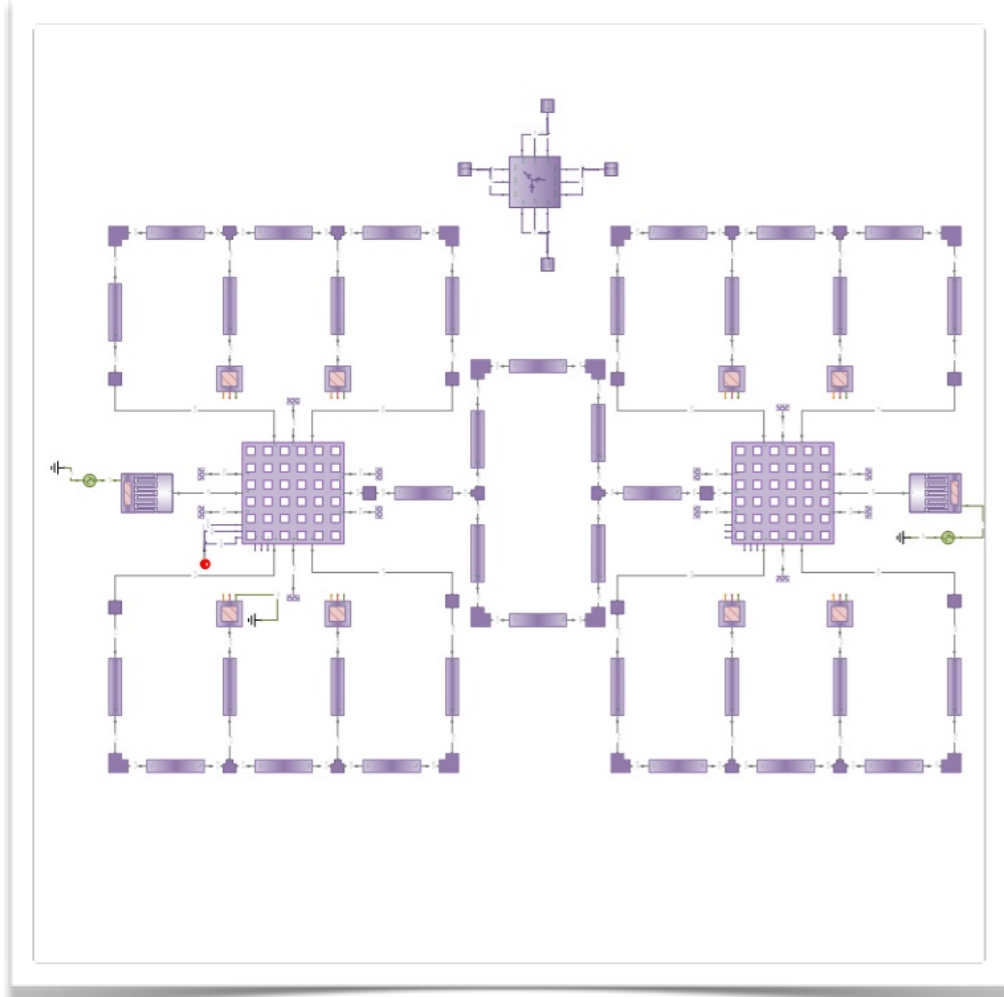
The screenshot shows the IntelliFab software interface. The main window displays a table of process steps. The table has columns for step number, type, material, process name, process ID, and process option. The steps are as follows:

#	Type	Material	Process	Process ID	Process Option
1	Definition	Si	Czochralski	100	
2	Deposition	PSG	LPCVD	Generic	Conformal Deposition
3	Definition	UV	Contact	Suss	
4	Etch	PSG	Generic	Generic	Partial Etching
5	Definition	UV	Contact	Suss	
6	Etch	PSG	Generic	Generic	Etch Through
7	Deposition	PolySi	LPCVD	SiH4	Conformal Deposition
8	Definition	UV	Contact	Suss	
9	Etch	PolySi	Dry	SF6-Plasma	Etch Through
10	Etch	PSG	Generic	Generic	Sacrifice
11	Etch	Si	Wet	Sacrifice	Sacrifice

The interface also includes a 'Properties' panel on the left with fields for 'Process Option' (Sacrifice), 'Side' (Top), 'HF_conc(%)' (70), 'time_etch(min)' (10), and 't_etch(nm)' (1000000). A 'Filter' input field is located at the bottom of the table.

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

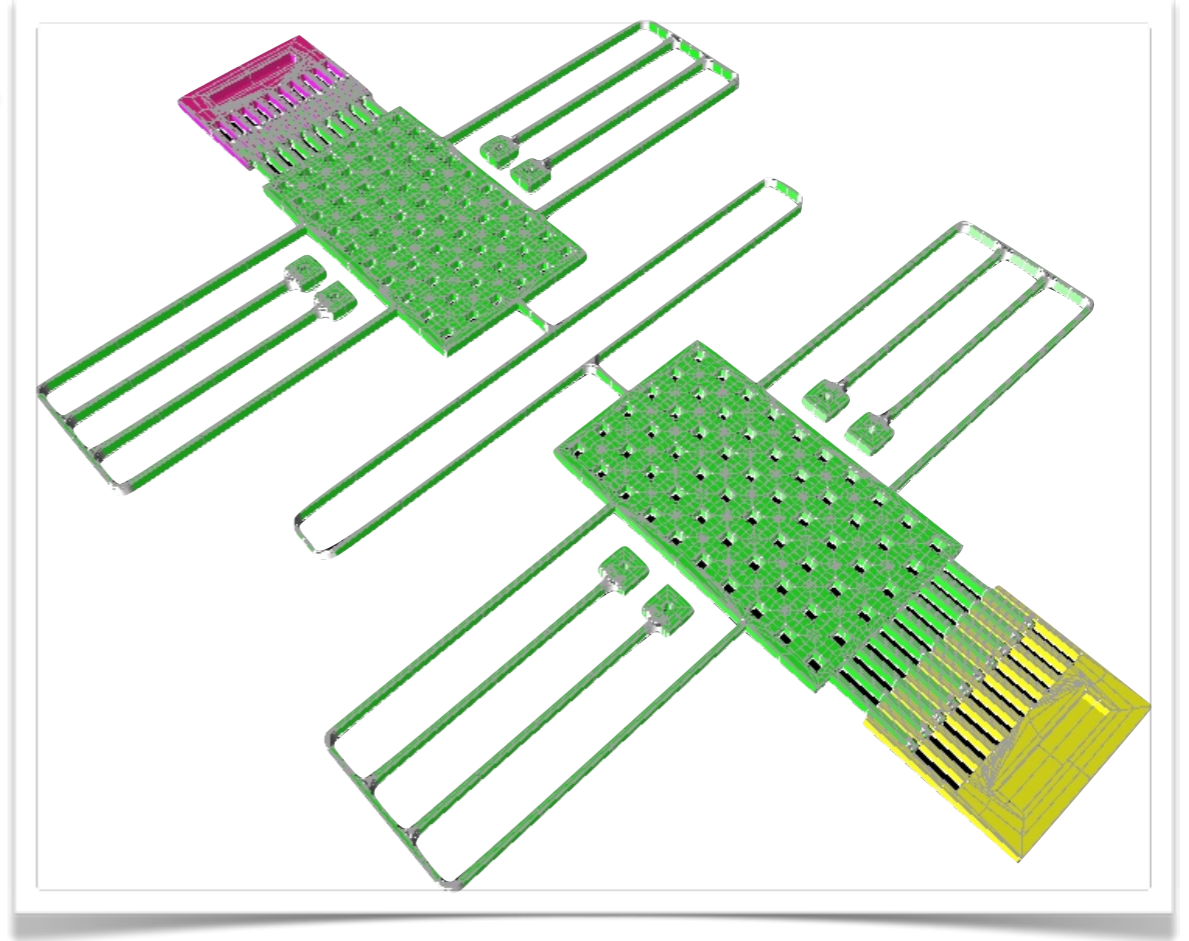
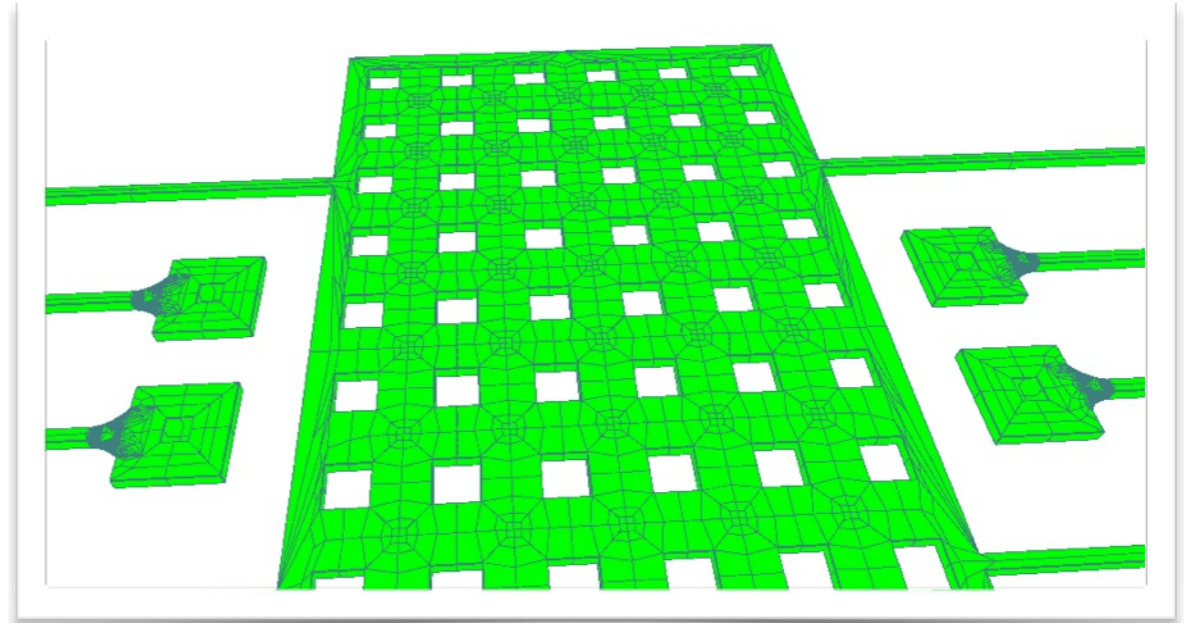
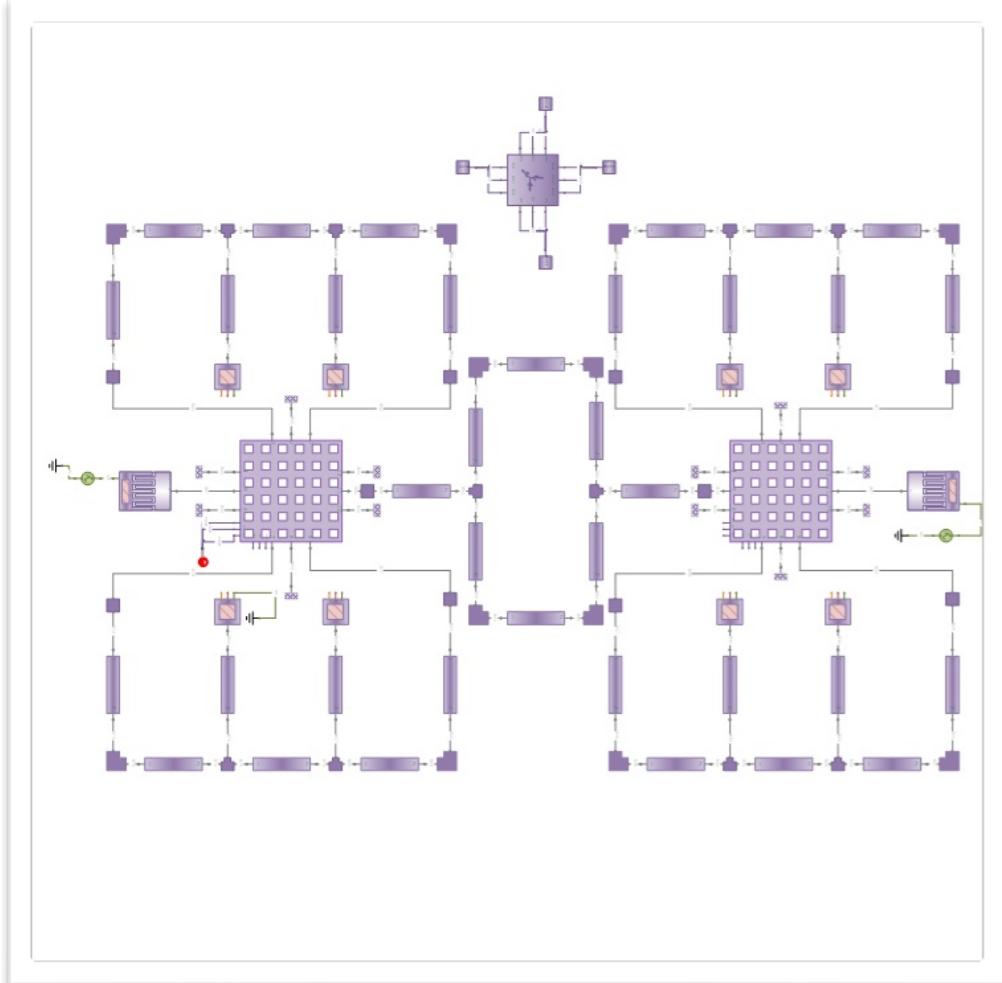
Schematic to 3D model



Attention to detail

Automatic placement of dimples, anchors and other secondary features

Schematic to mesh



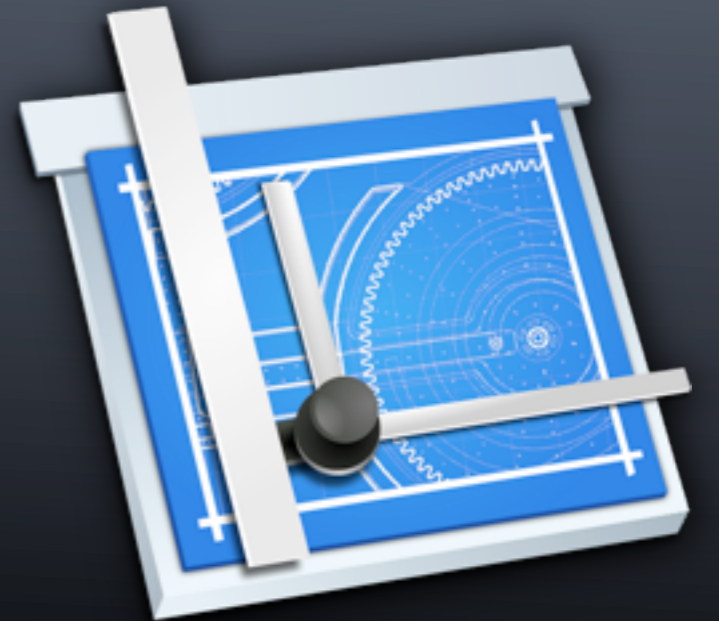
Automated Hexahedral Meshing of the Structure

Benefits

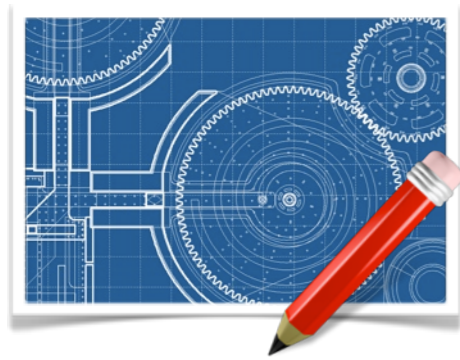


- &• **Schematic driven design**
Entry point for parametric design and design exploration
- &• **Hierarchical modeling**
Model your device at system or circuit level
- &• **Save time**
100-1000X faster than FEA models.
- &• **Design exploration and optimization**
Quickly prototype and explore multiple 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



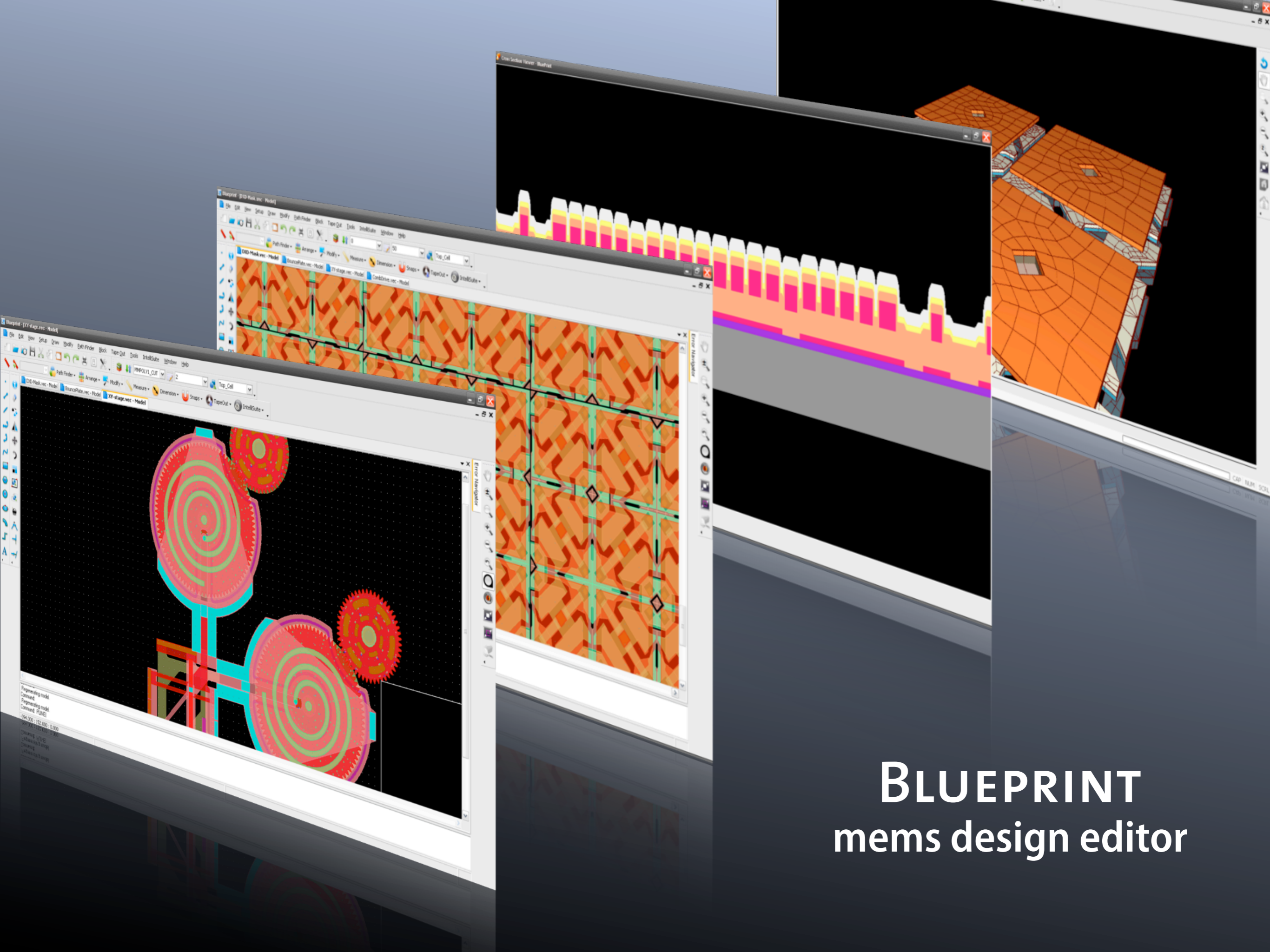
Layout visualization

- Cross section drawing
- 3D Visualization of layout

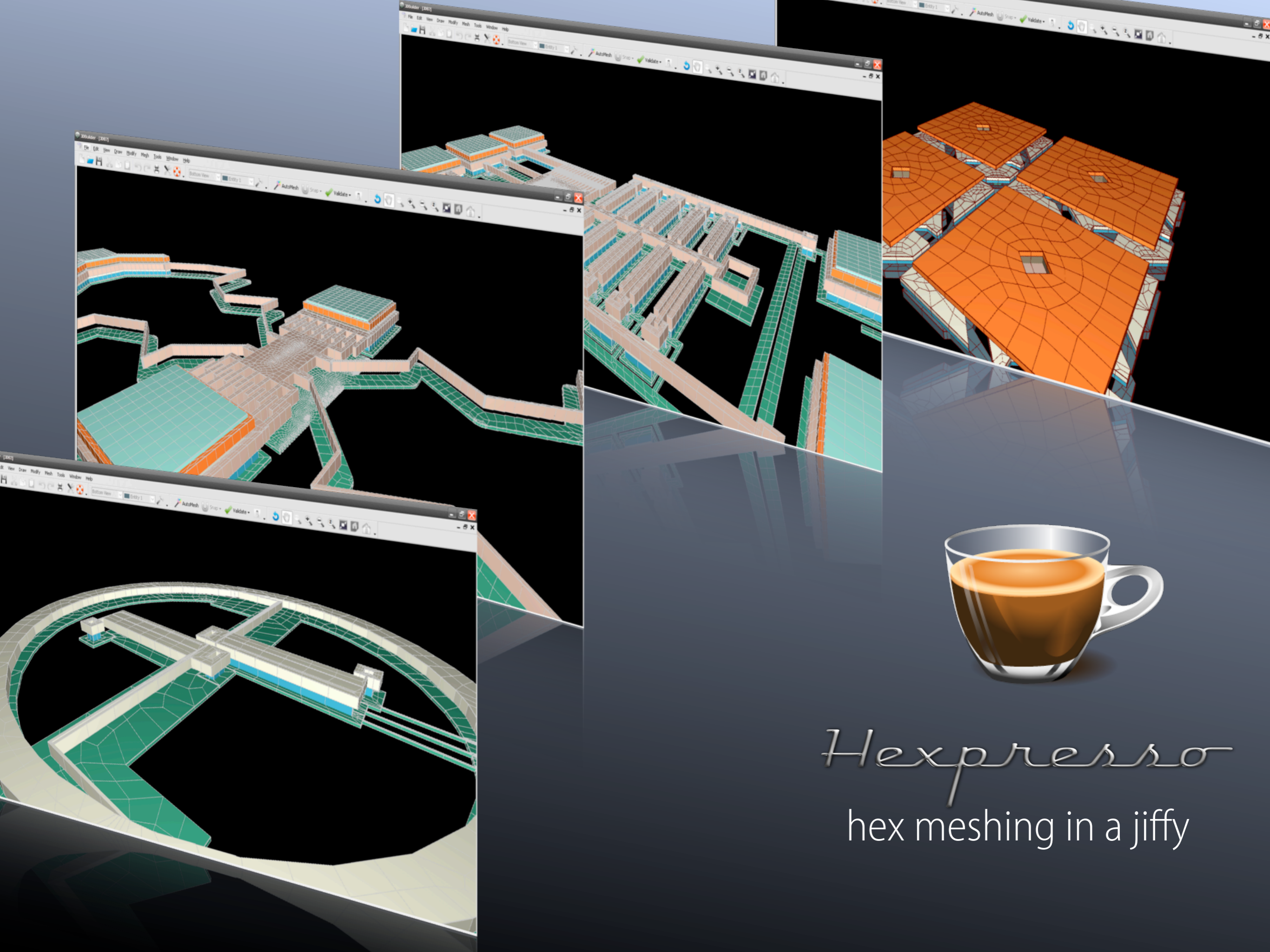


Hexpresso

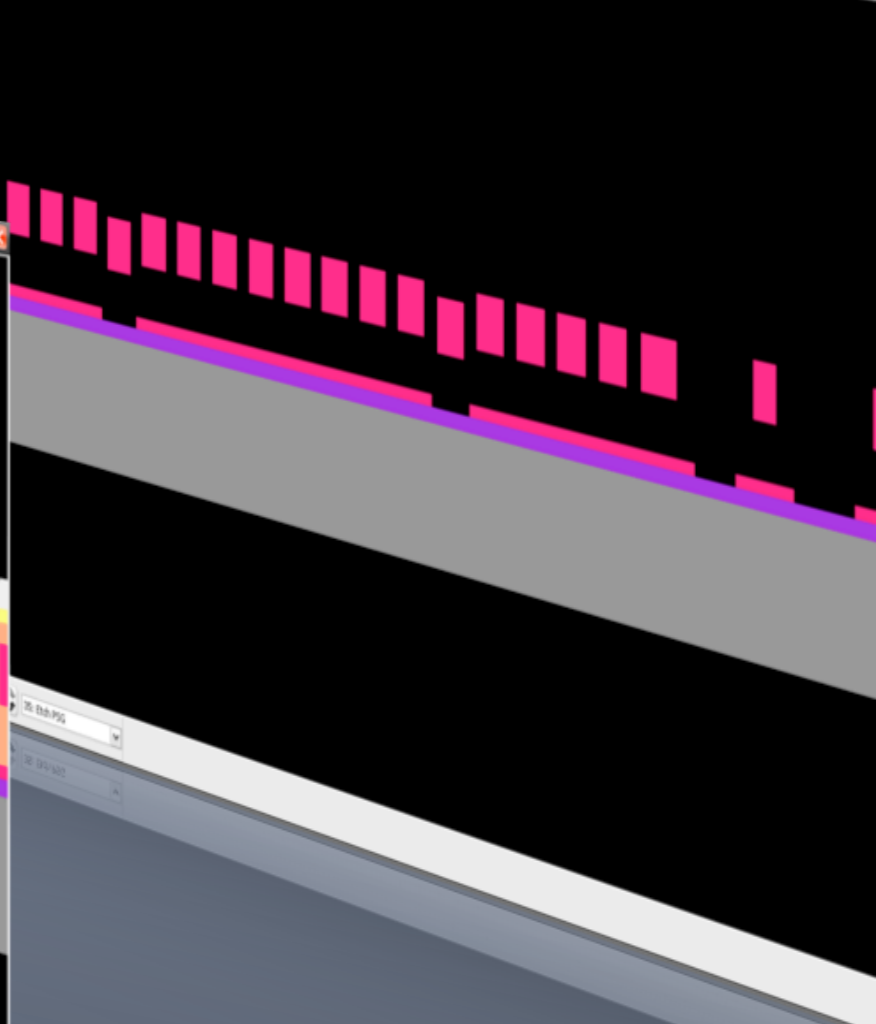
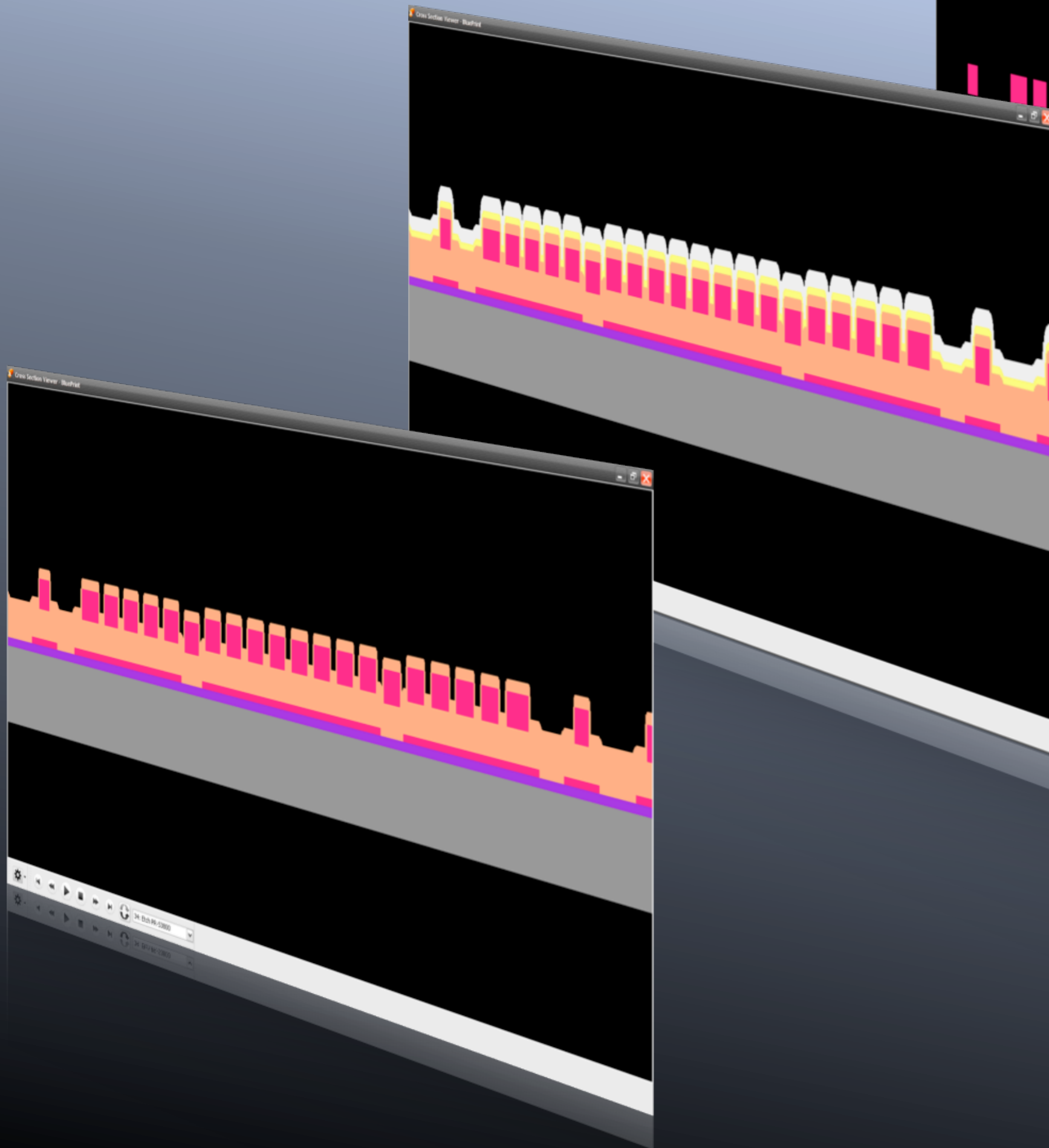
- Automated HEX mesher
- 1 click Mask to Mesh



BLUEPRINT
mems design editor

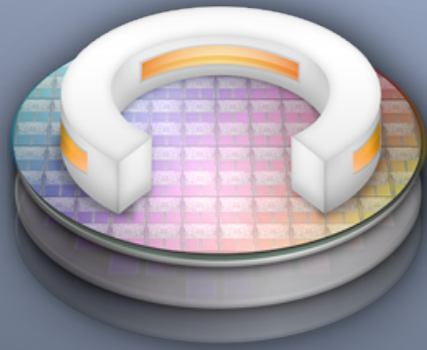


Hexpresso
hex meshing in a jiffy

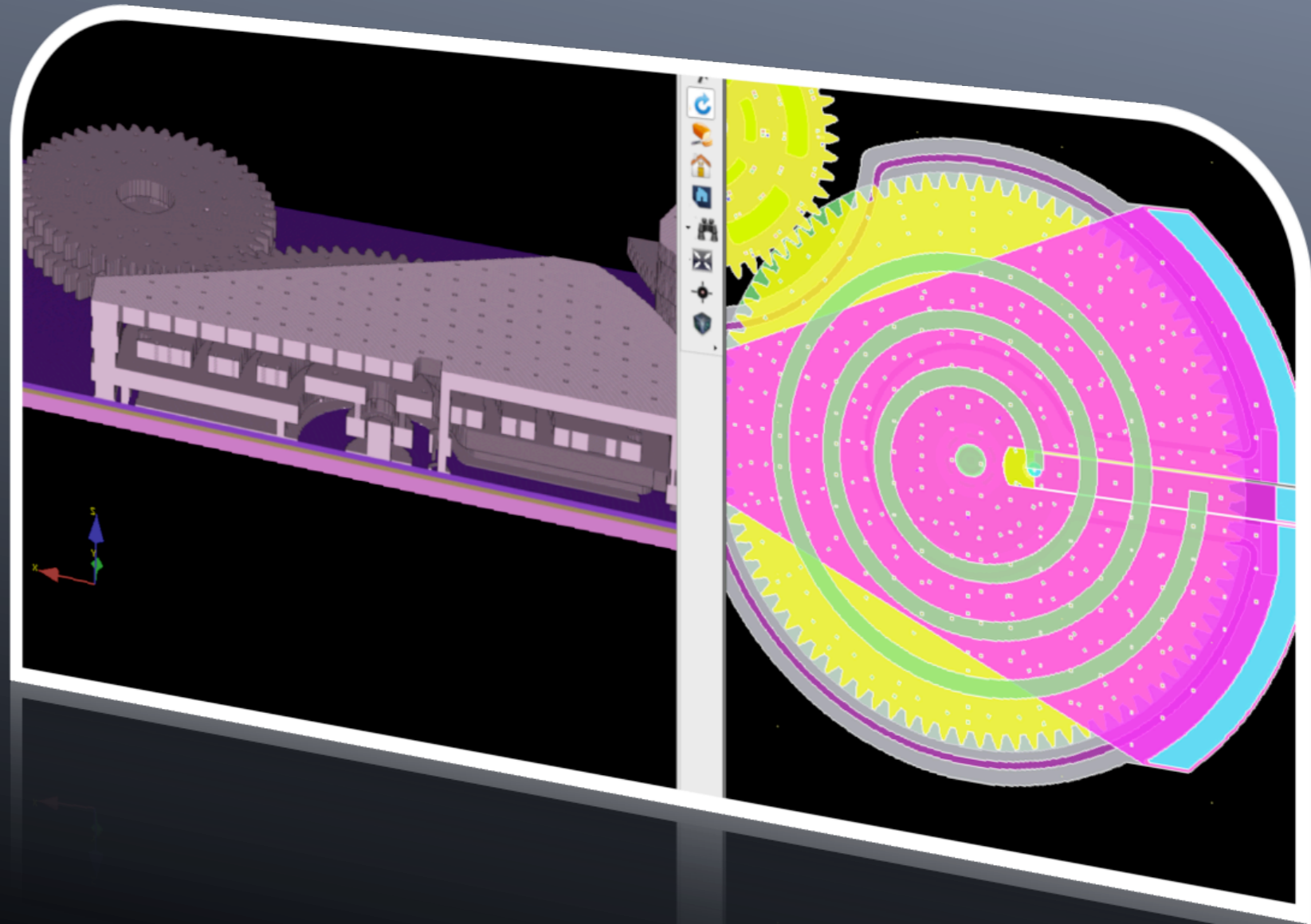
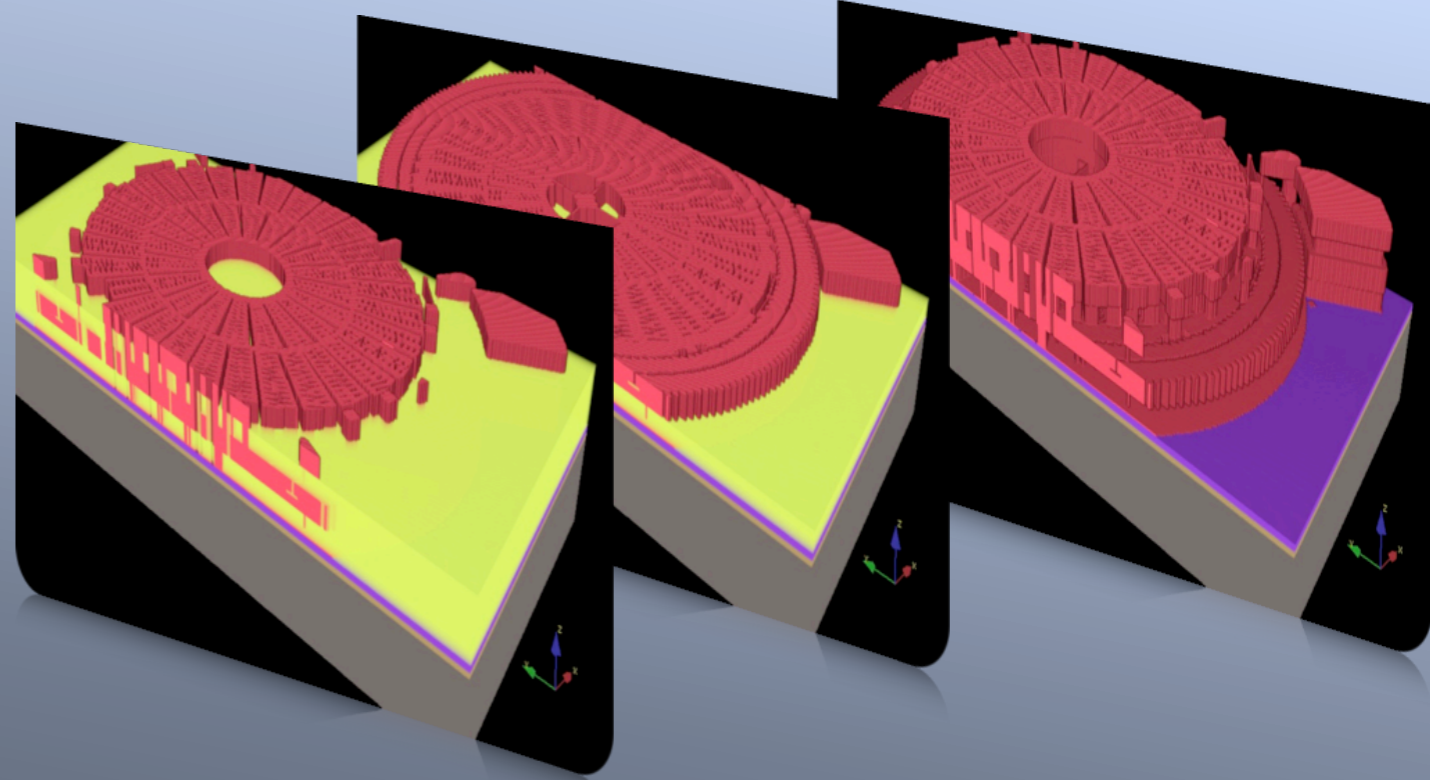


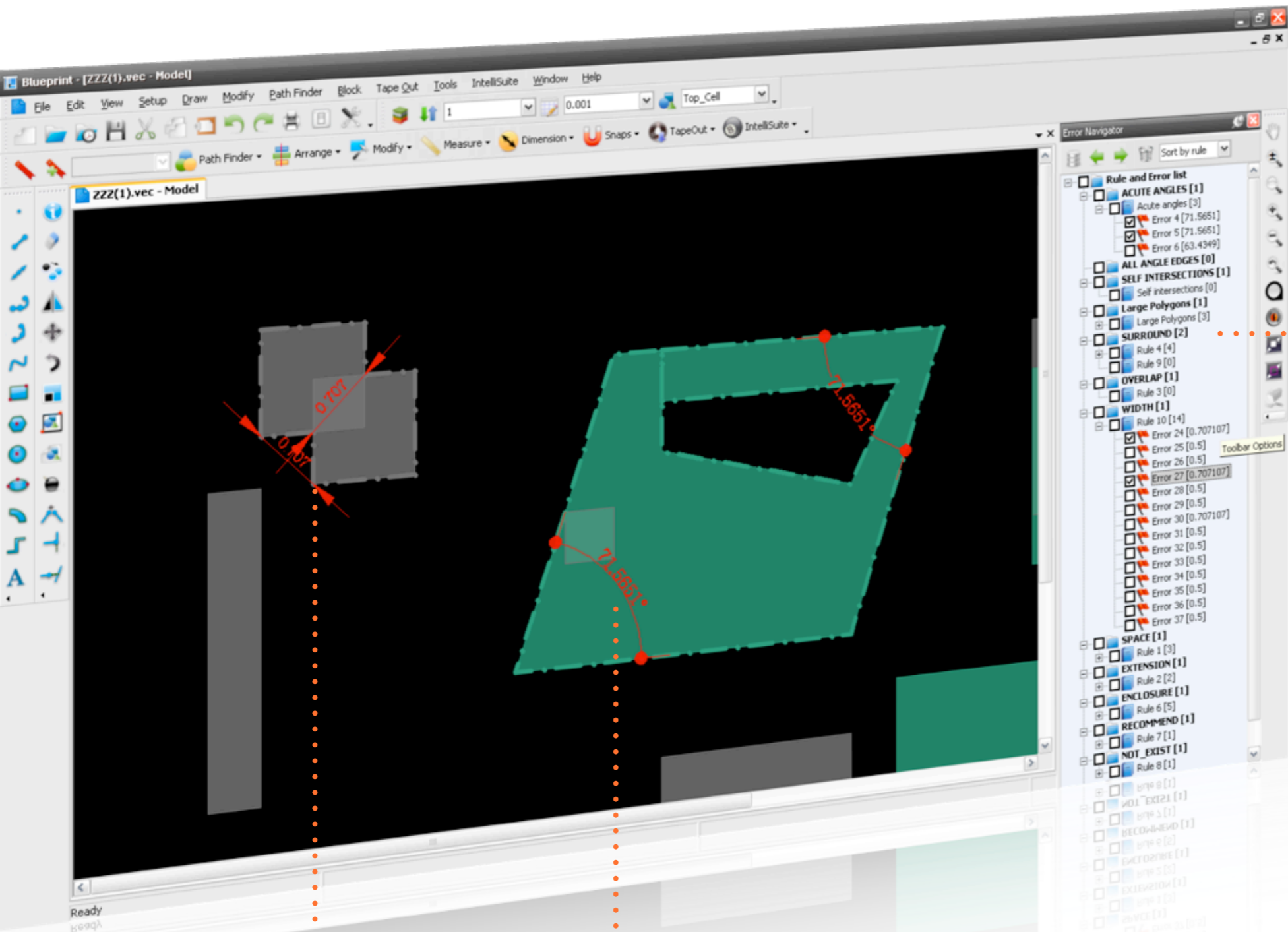
CS Viewer

Step by step process visualization



Cleanroom integration





- Rule and Error list
- ACUTE ANGLES [1]
 - Acute angles [3]
 - Error 4 [71.5651]
 - Error 5 [71.5651]
 - Error 6 [63.4349]
- ALL ANGLE EDGES [0]
- SELF INTERSECTIONS [1]
 - Self intersections [0]
- Large Polygons [1]
 - Large Polygons [3]
- SURROUND [2]
 - Rule 4 [4]
 - Rule 9 [0]
- OVERLAP [1]
 - Rule 3 [0]
- WIDTH [1]
 - Rule 10 [14]
 - Error 24 [0.707107]
 - Error 25 [0.5]
 - Error 26 [0.5]
 - Error 27 [0.707107]
 - Error 28 [0.5]
 - Error 29 [0.5]
 - Error 30 [0.707107]
 - Error 31 [0.5]
 - Error 32 [0.5]
 - Error 33 [0.5]
 - Error 34 [0.5]
 - Error 35 [0.5]
 - Error 36 [0.5]
 - Error 37 [0.5]
- SPACE [1]
 - Rule 1 [3]
- EXTENSION [1]
 - Rule 2 [2]
- ENCLOSURE [1]
 - Rule 6 [5]
- RECOMMEND [1]
 - Rule 7 [1]
- NOT_EXIST [1]
 - Rule 8 [1]

Easy error navigation



Tape Out
Physical verification

intuitive error markings

all angle support



CS Viewer

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

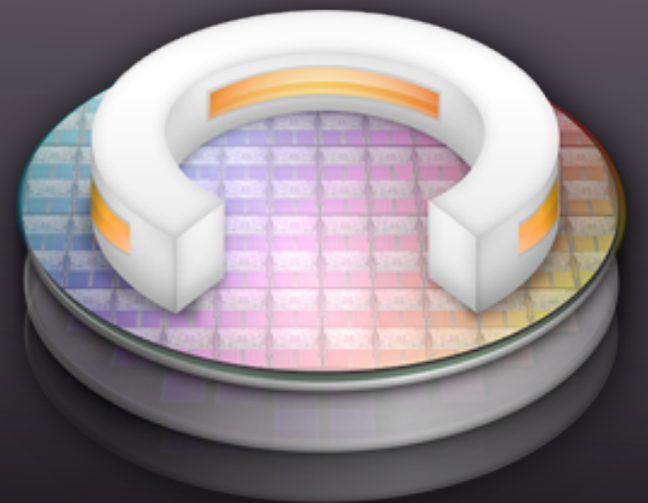


Hexpresso

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

RECIPE

RIE/ICP/Bosch etch simulation
STS etch database

IntelliEtch

Ab initio based etch modeling
wet and dry etch modeling

MEMaterial

Material databases & process optimization

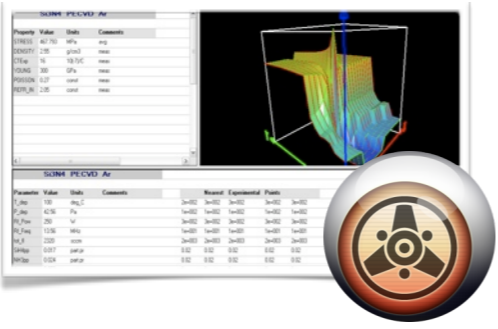
IntelliFAB

Process traveller creation and visualization.

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

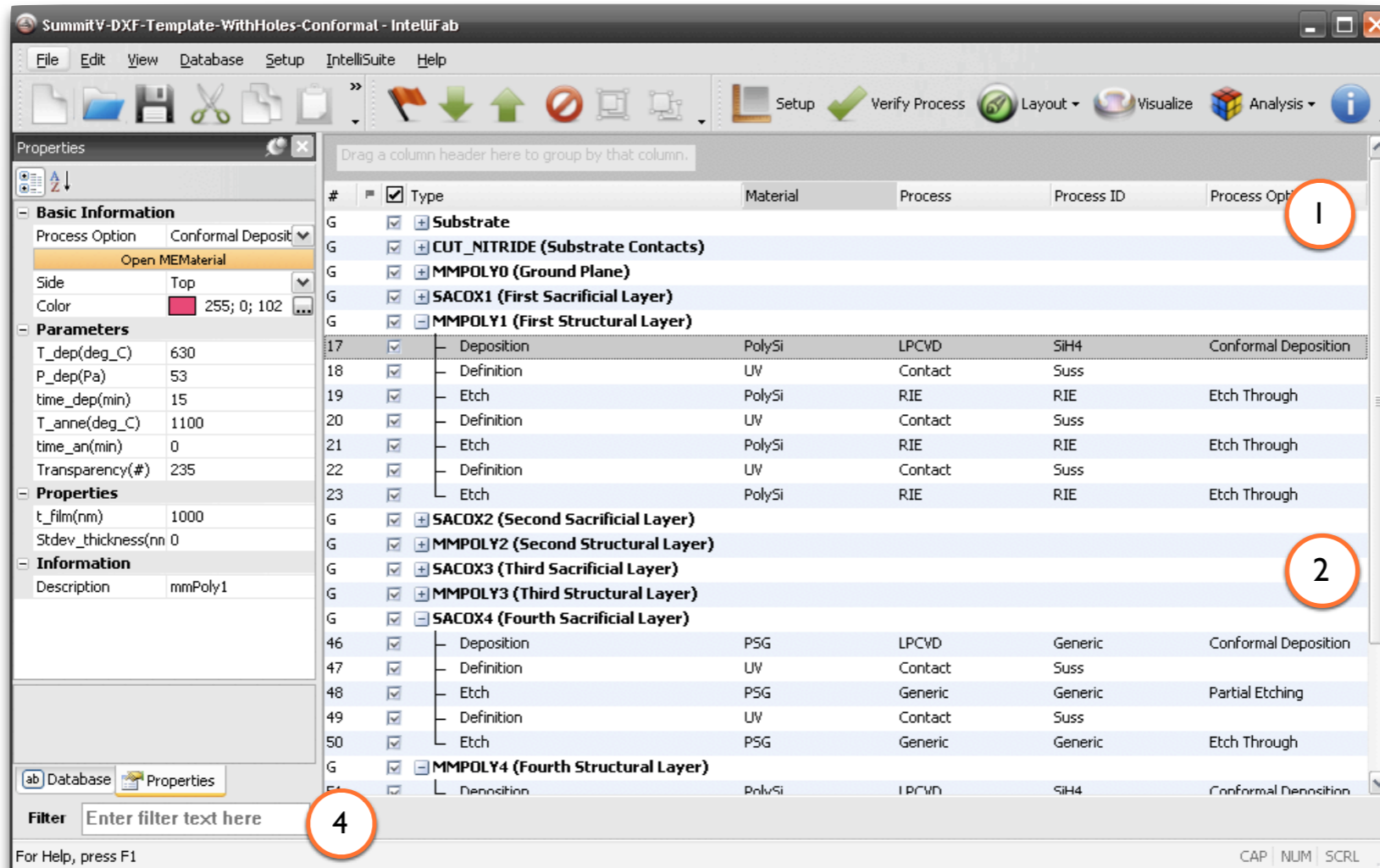
Process simulation

- 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...



3

Process Pane

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

1

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.

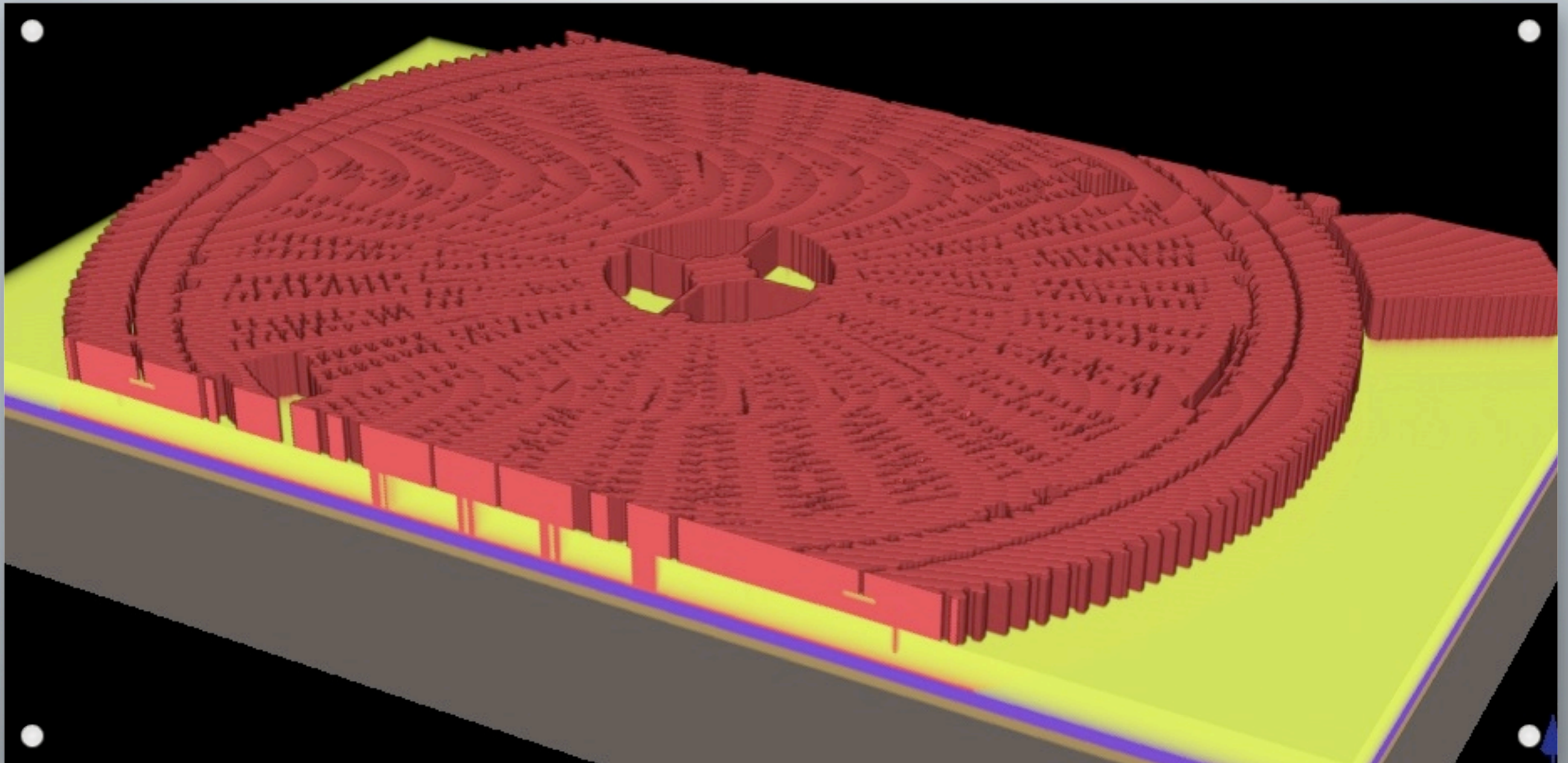
2

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.

4

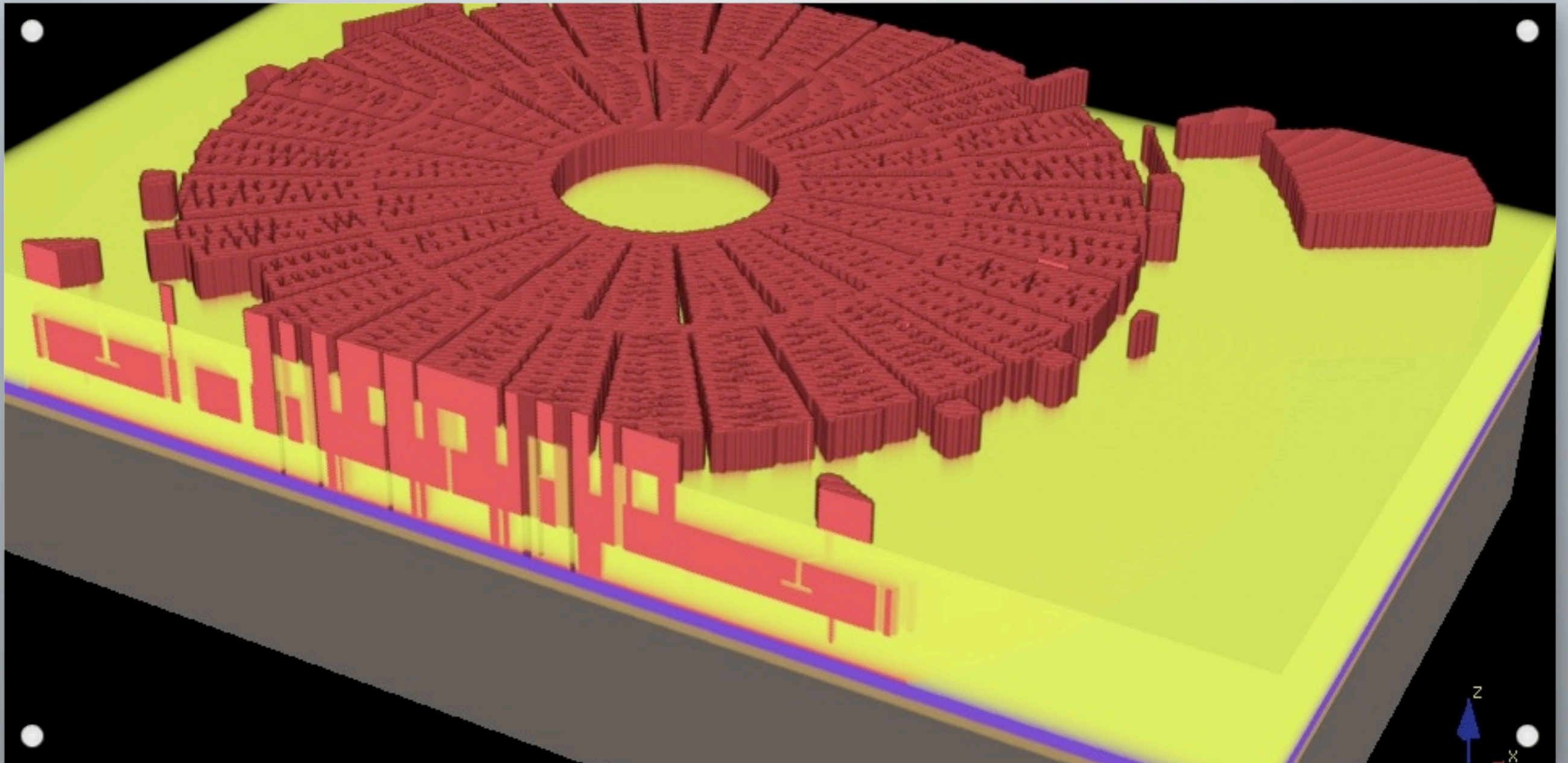
Filter with ease

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

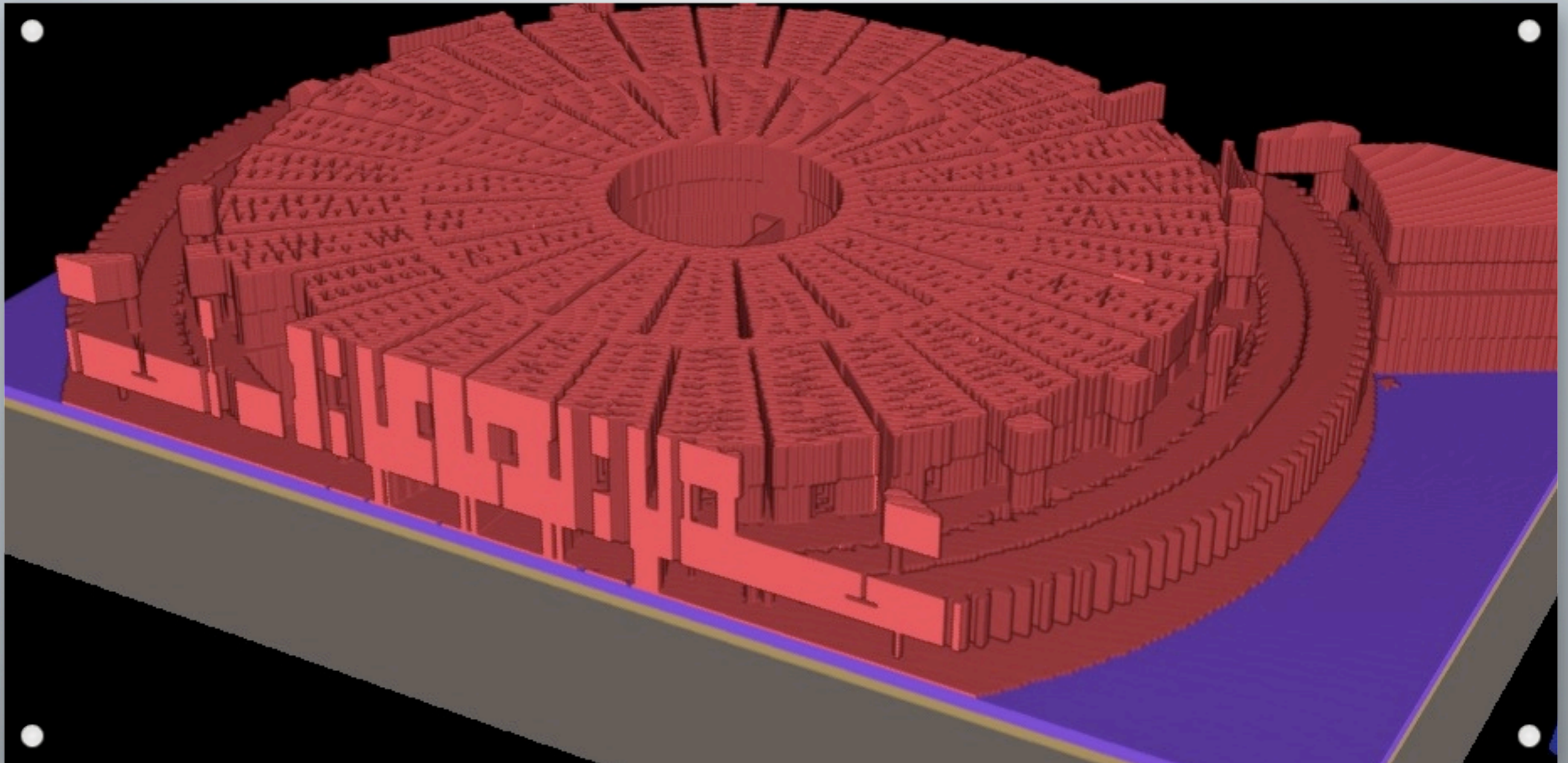


VISUALIZE COMPLEX PROCESS FLOWS

Courtesy, Prof Tim Dallas, Texas Tech



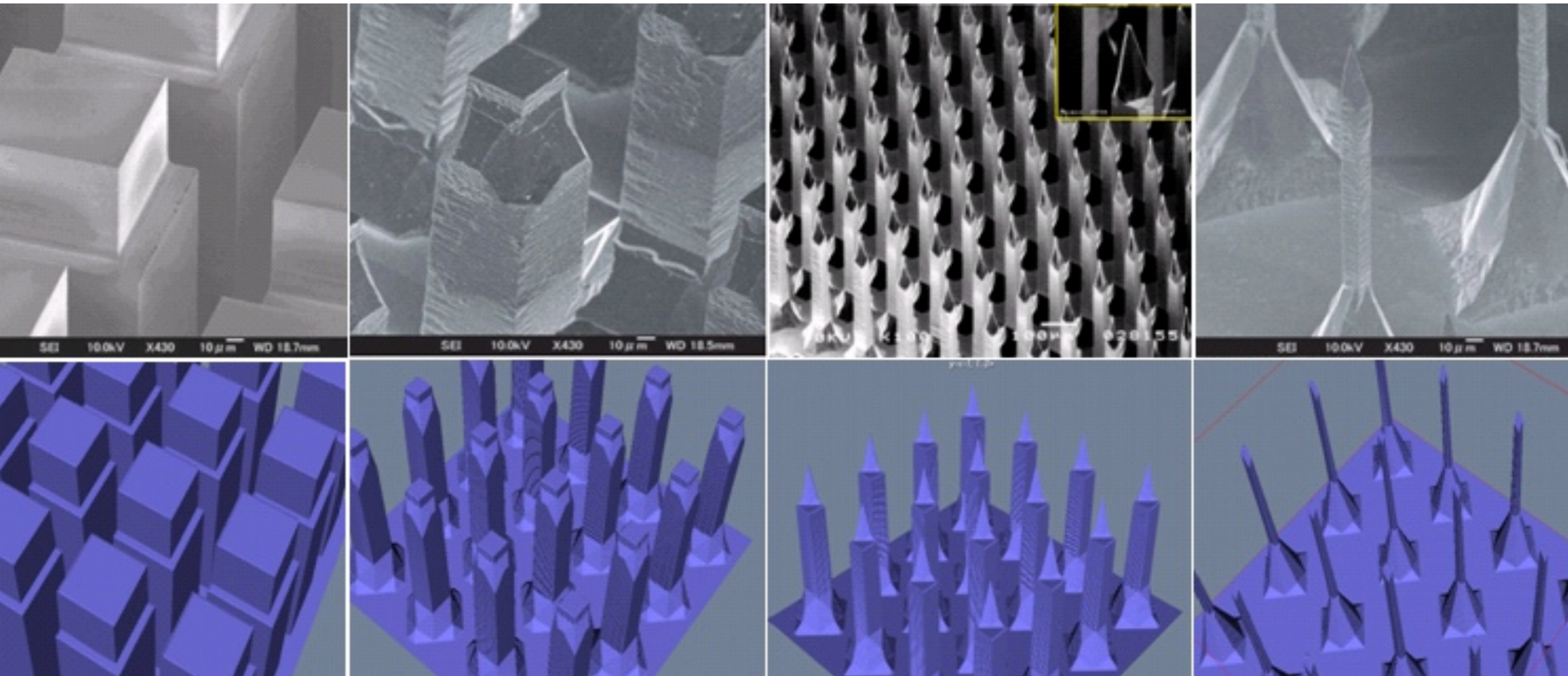
VISUALIZE COMPLEX PROCESS FLOWS



VISUALIZE COMPLEX PROCESS FLOWS

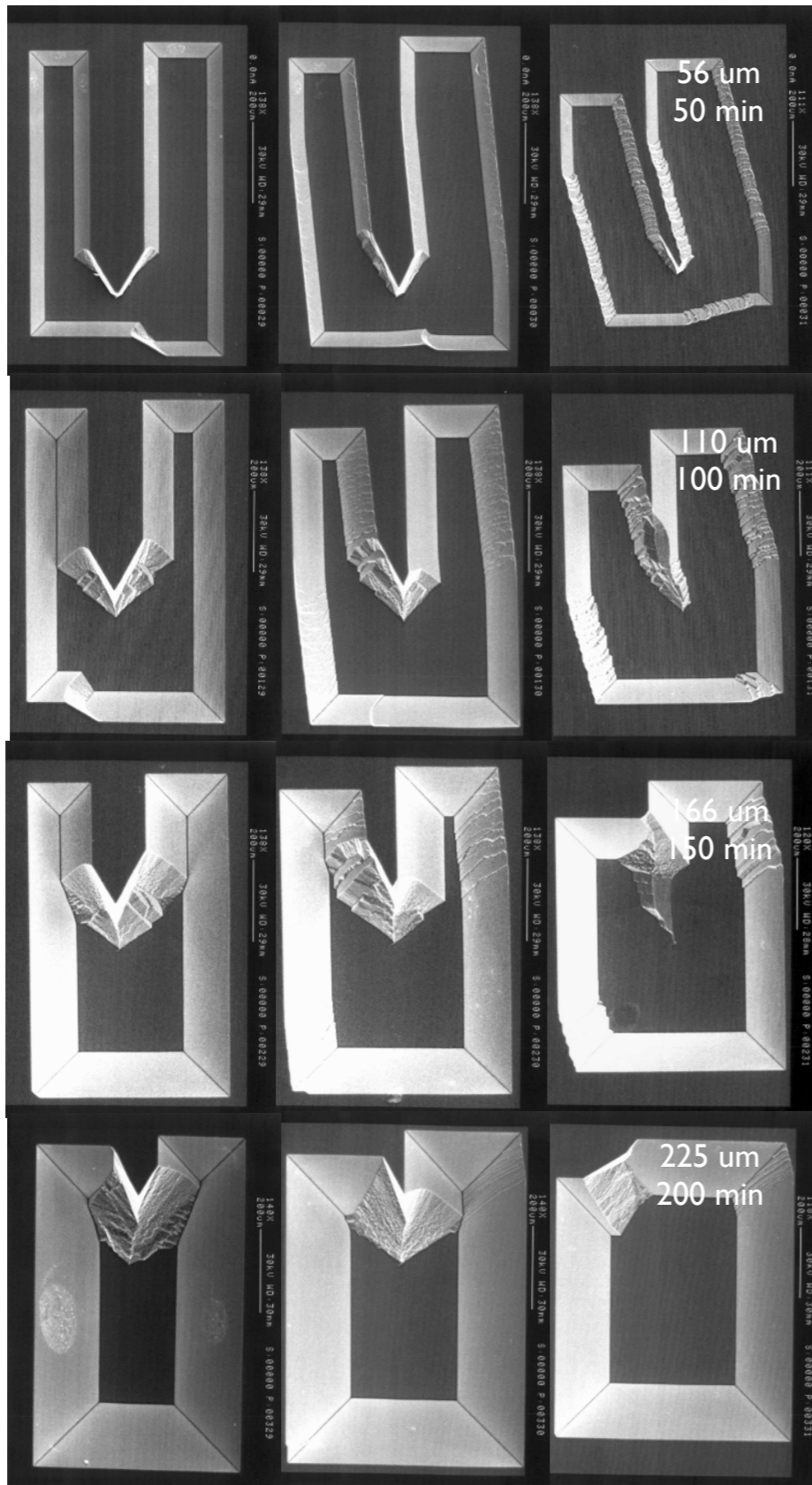
Courtesy, Prof Tim Dallas, Texas Tech

Simulate composite MEMS processes



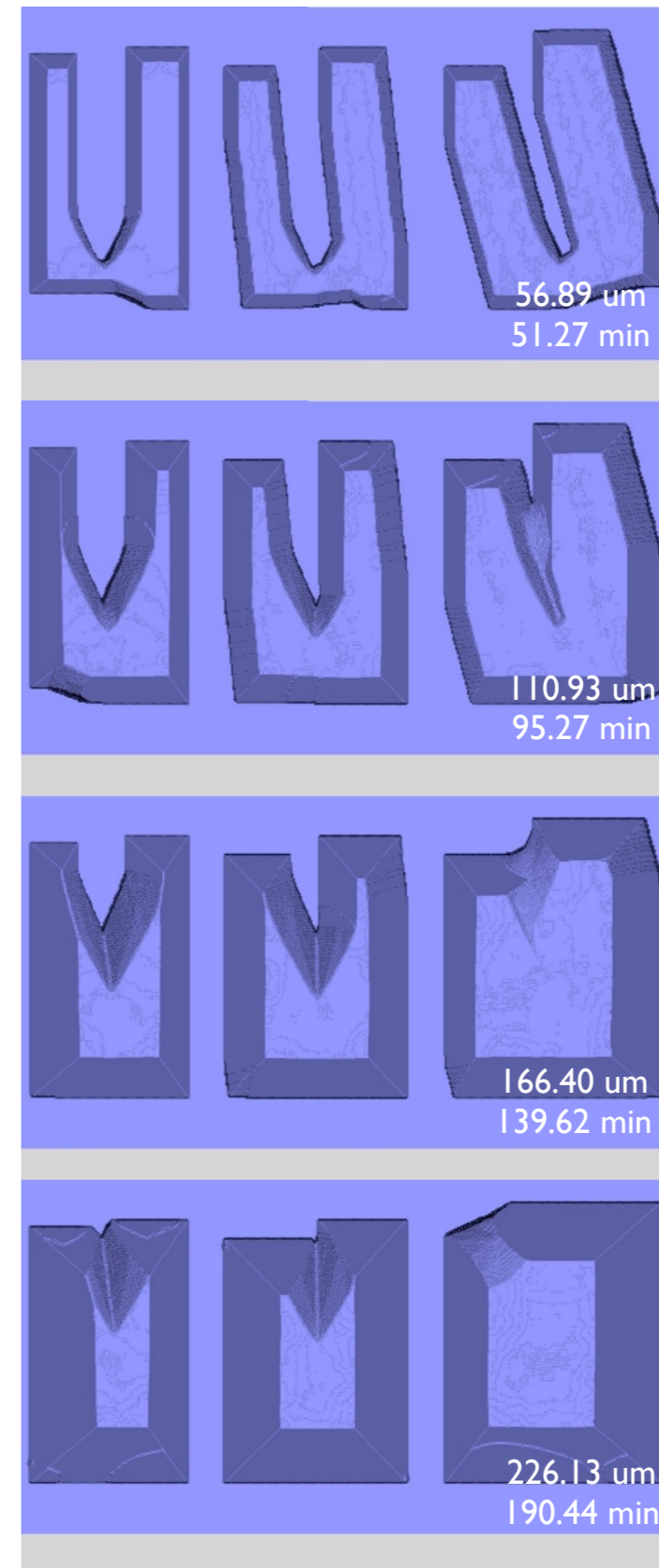
Combination of multi-step mask transfers, oxide and nitride layers, sacrificial layer deposition and wet etching and DRIE processes.

Validate processes in design



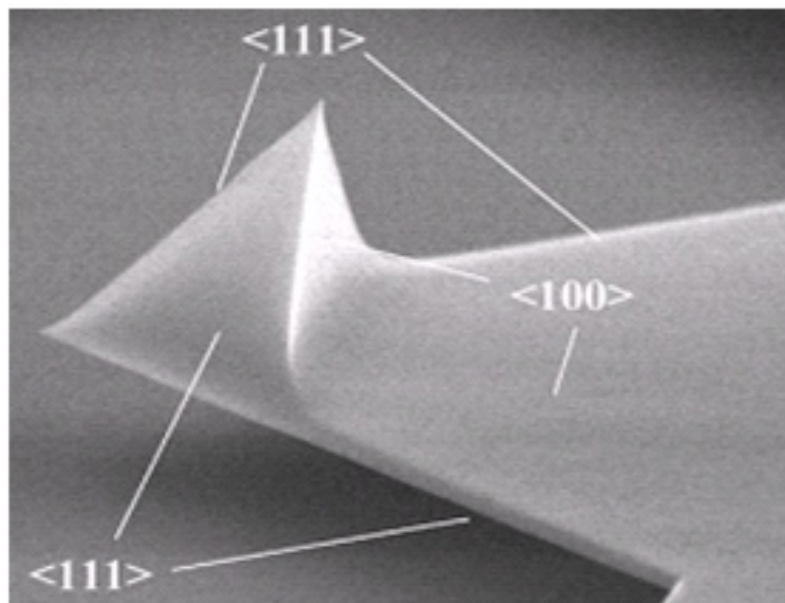
Measured

vs

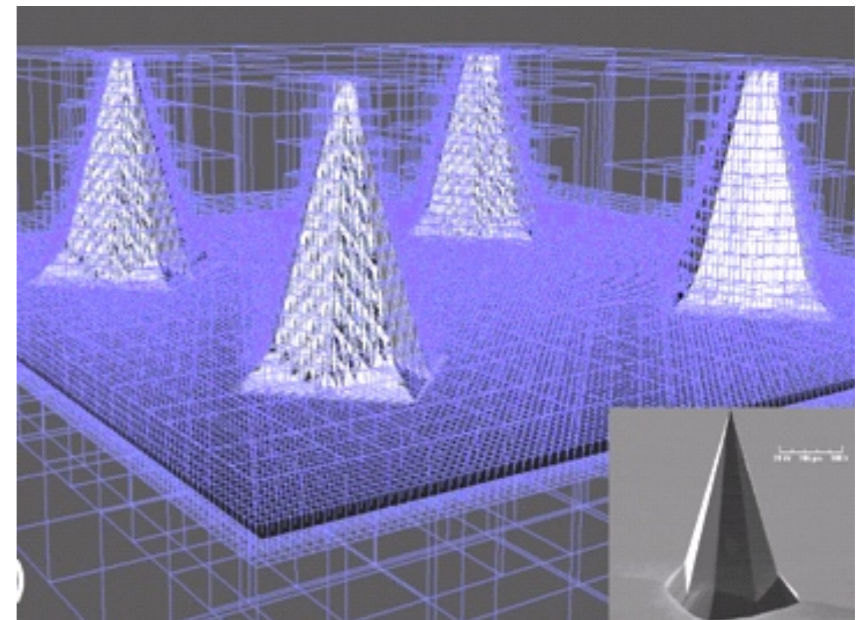
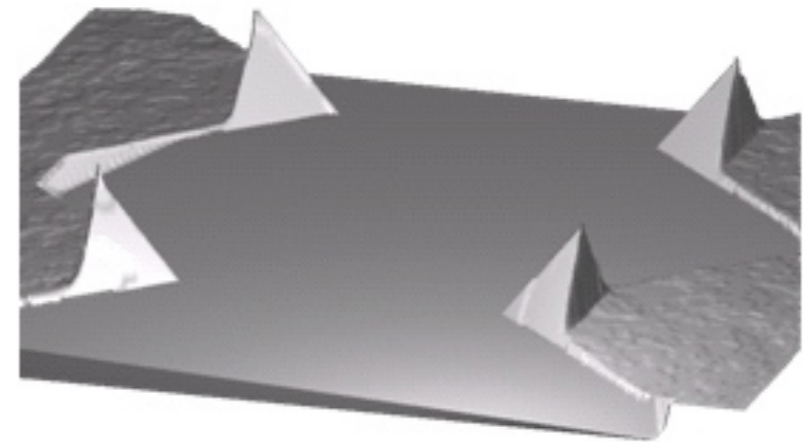


Modeled

Higher order plane etching

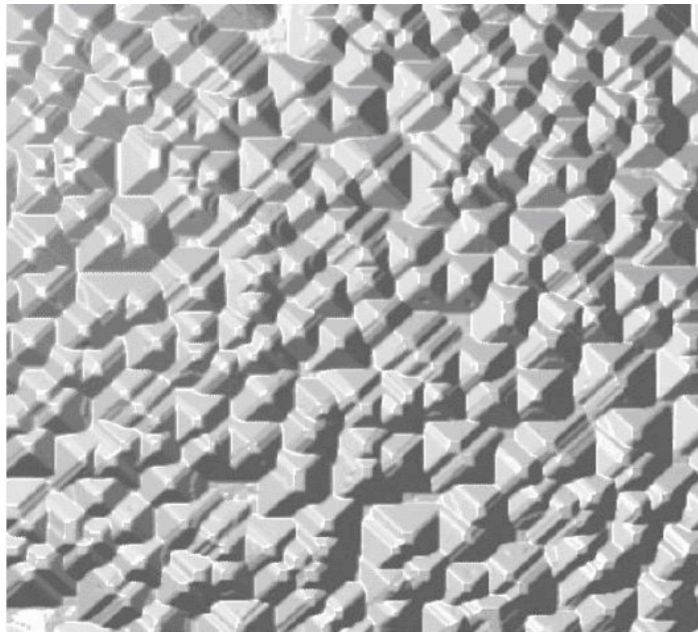


D. Saya, Sensors & Actuators A95 (2002)

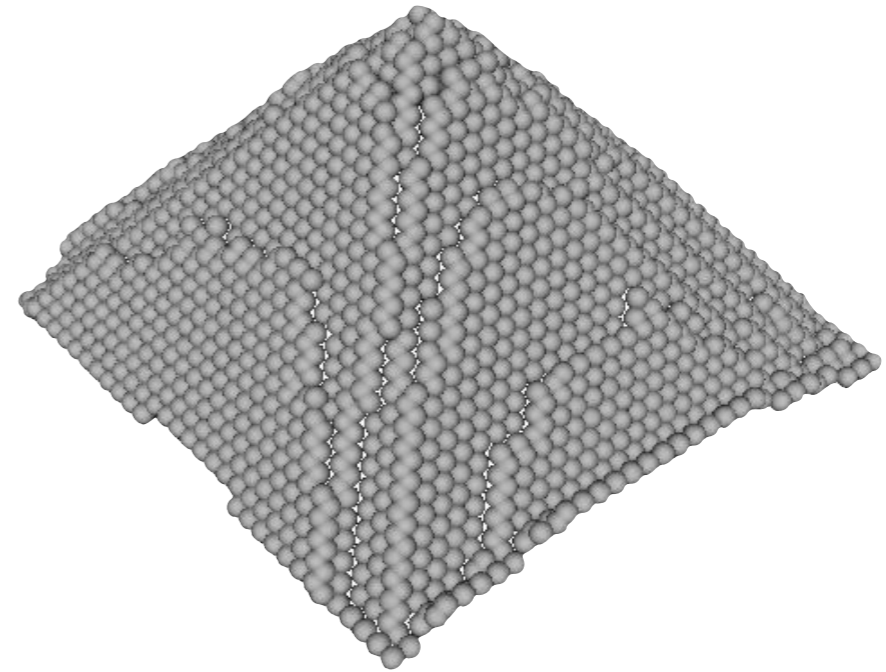


Simulation results

Surface morphology prediction

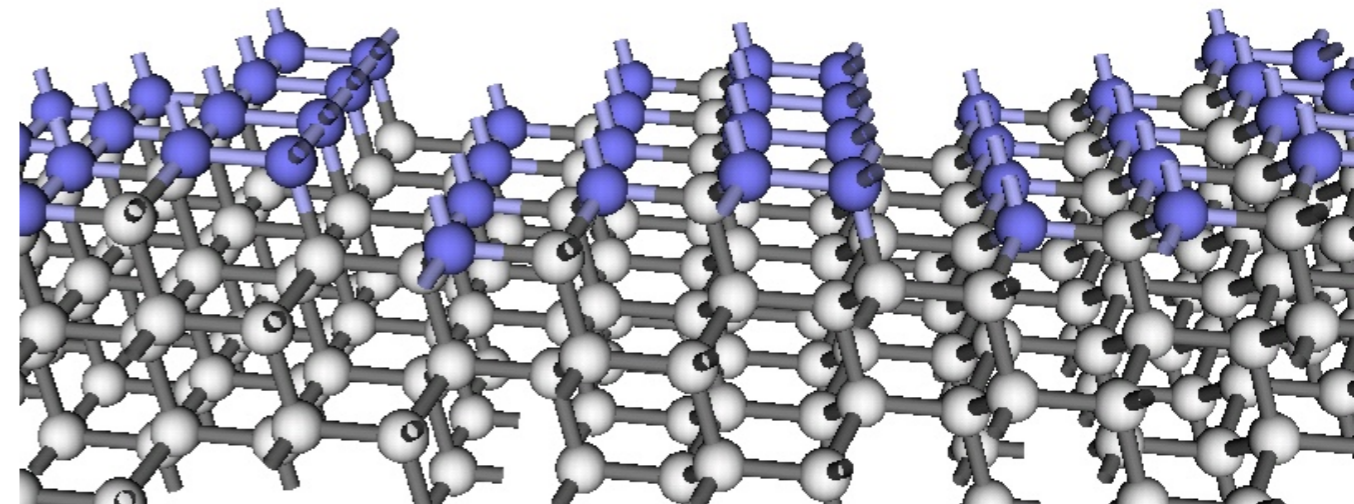


Pyramid like morphology on 100 Si
subject to wet anisotropic etching

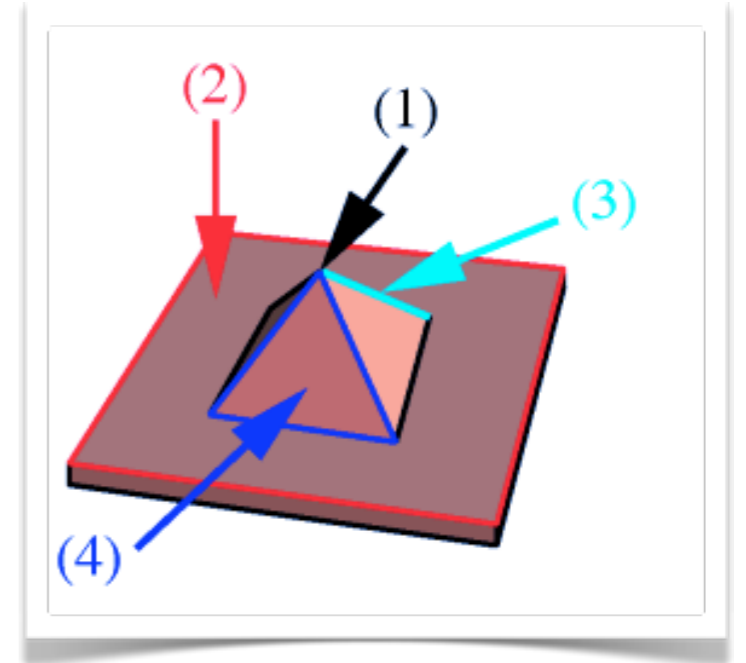
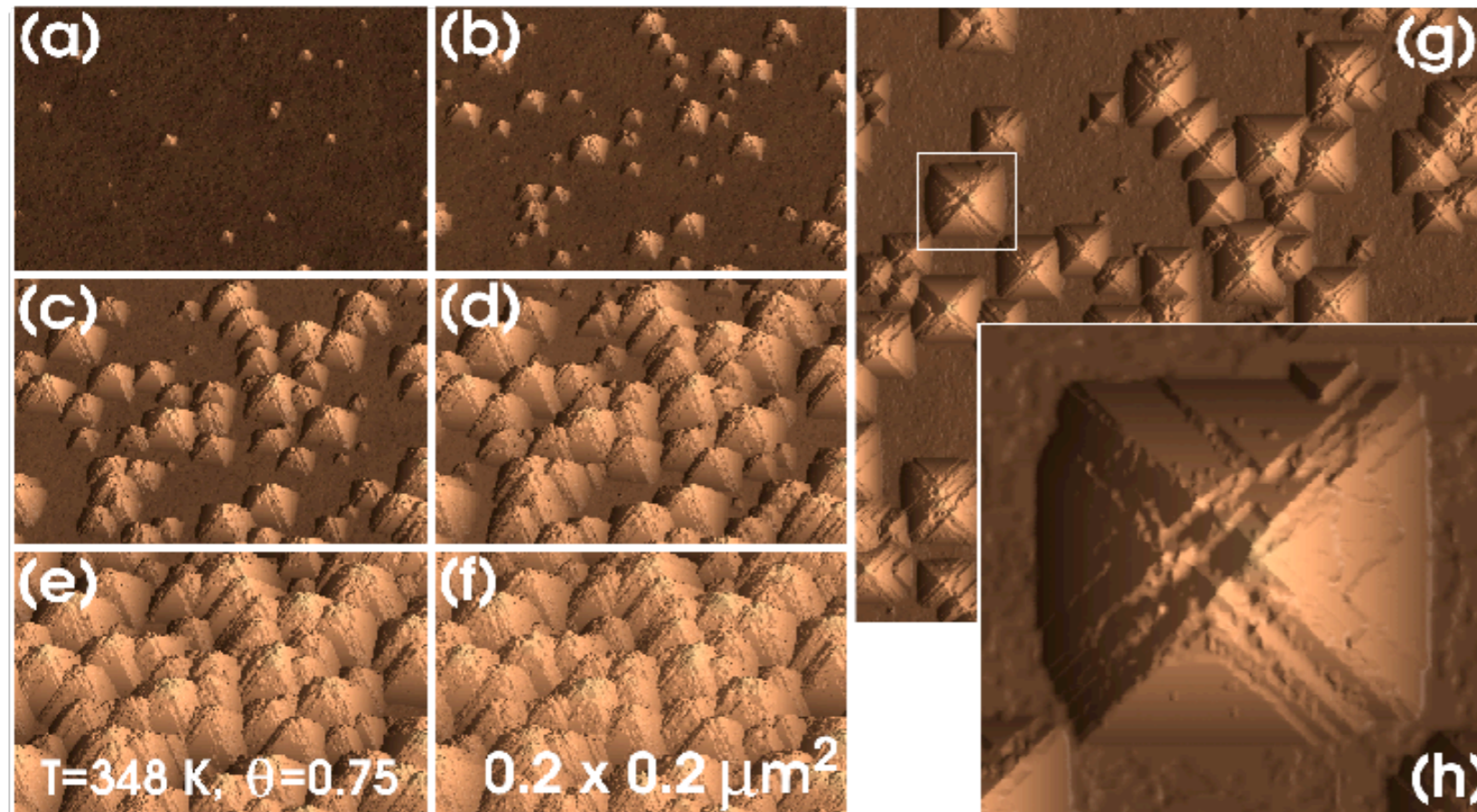


Simulation results predict pyramid formation

Arbitrary Cut Planes $\langle 533 \rangle$
to understand the physics



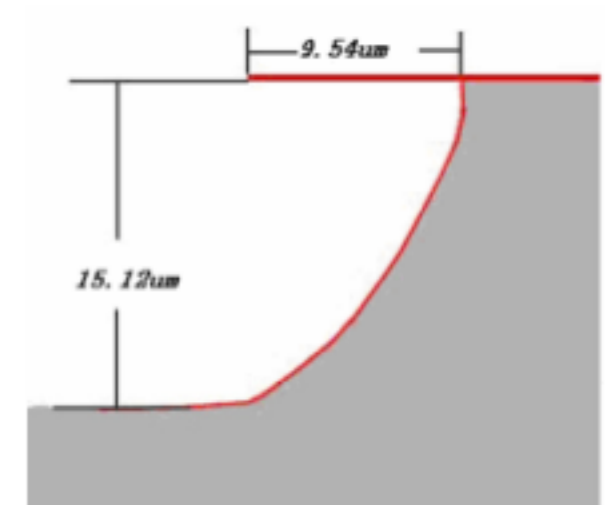
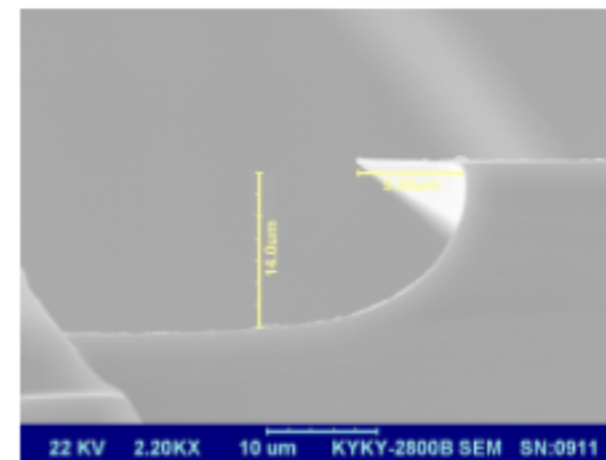
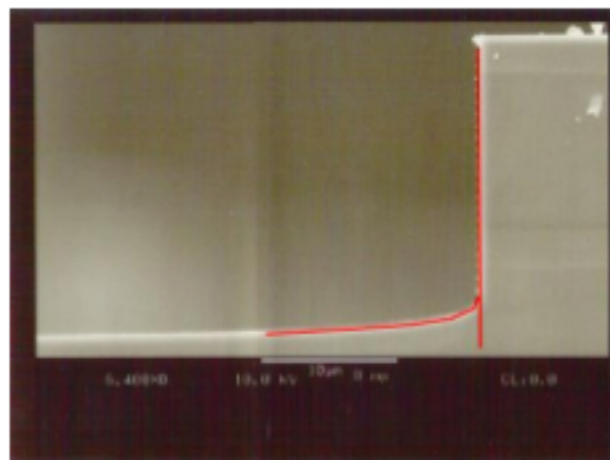
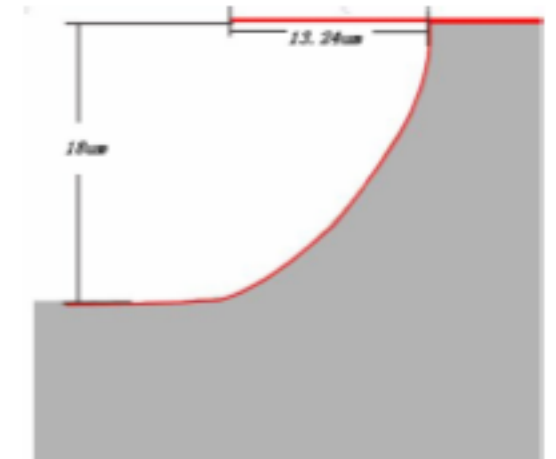
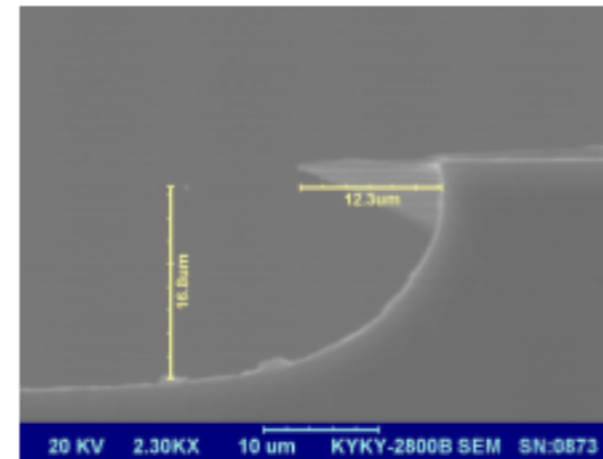
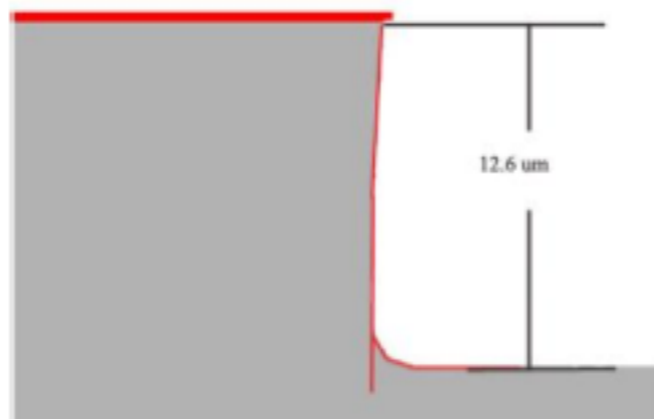
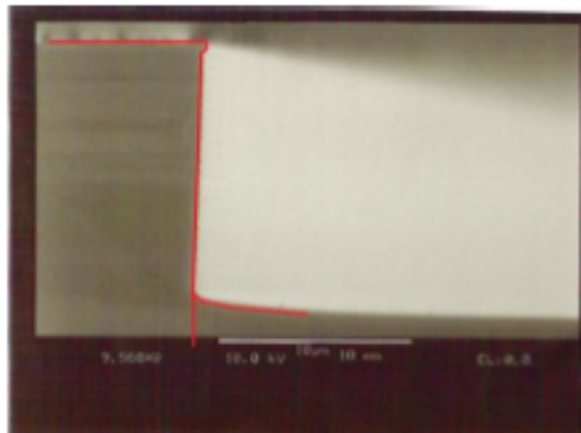
Surface morphology prediction



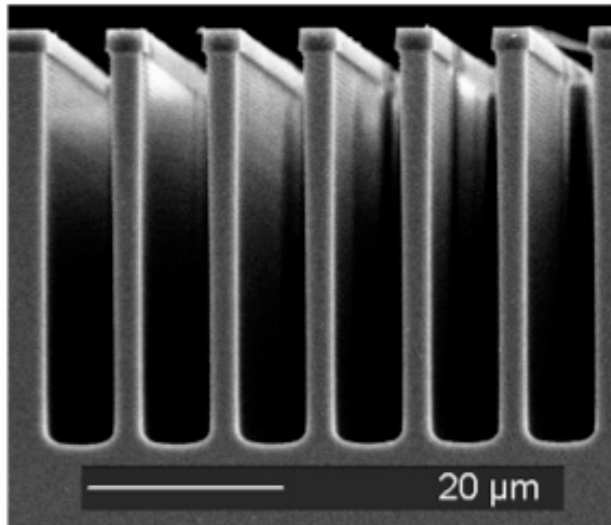
- 1 Micromasking of apex
- 2 Floor moves down fast
- 3 Edges are stable
- 4 Facets are very stable

Hillock formation prediction

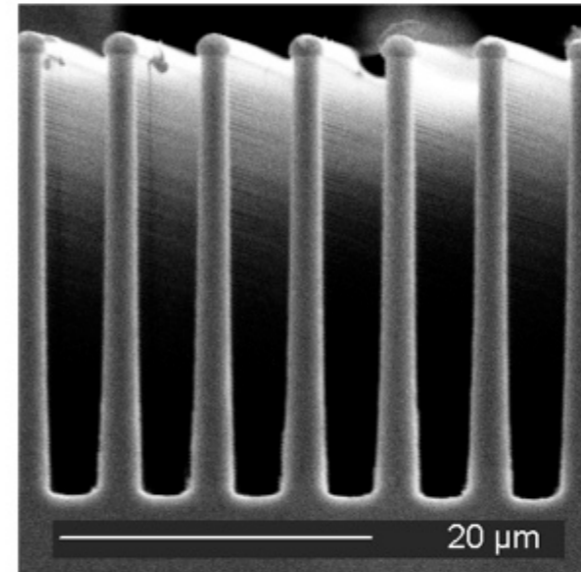
DRIE Etch characterization experiments (1)



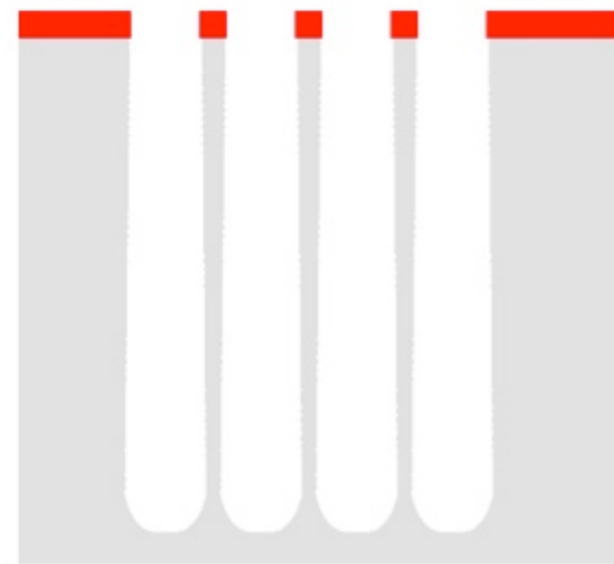
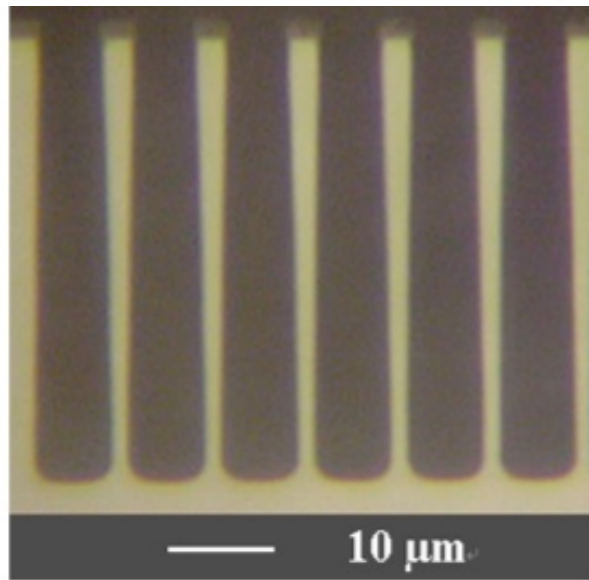
DRIE Etch characterization experiments (2)



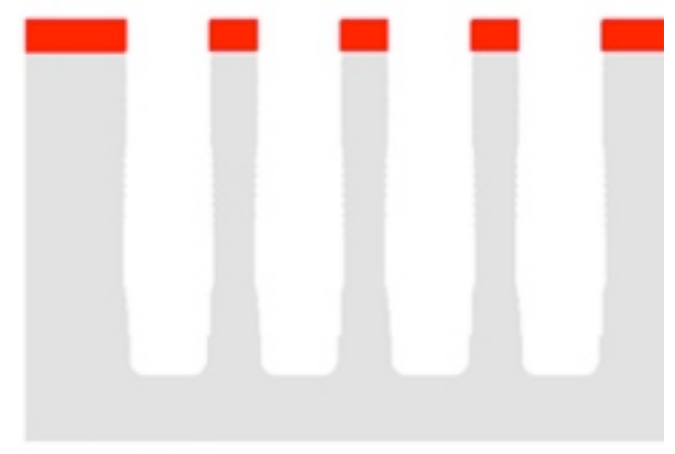
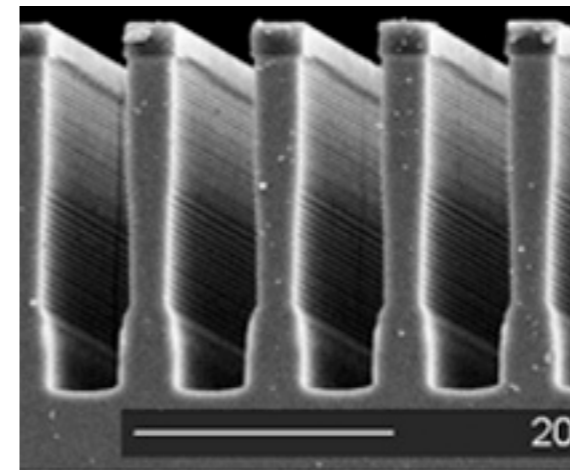
The experimental results of the etching. Comparison of etching 5 μm openings with an etch/dep cycle of 7s/7s.



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

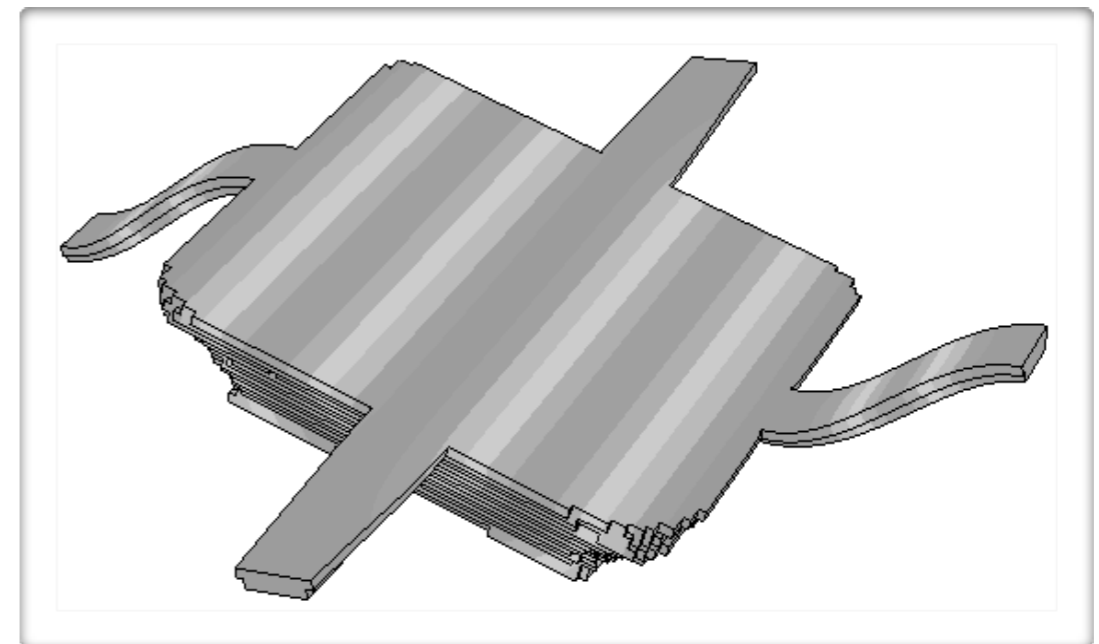
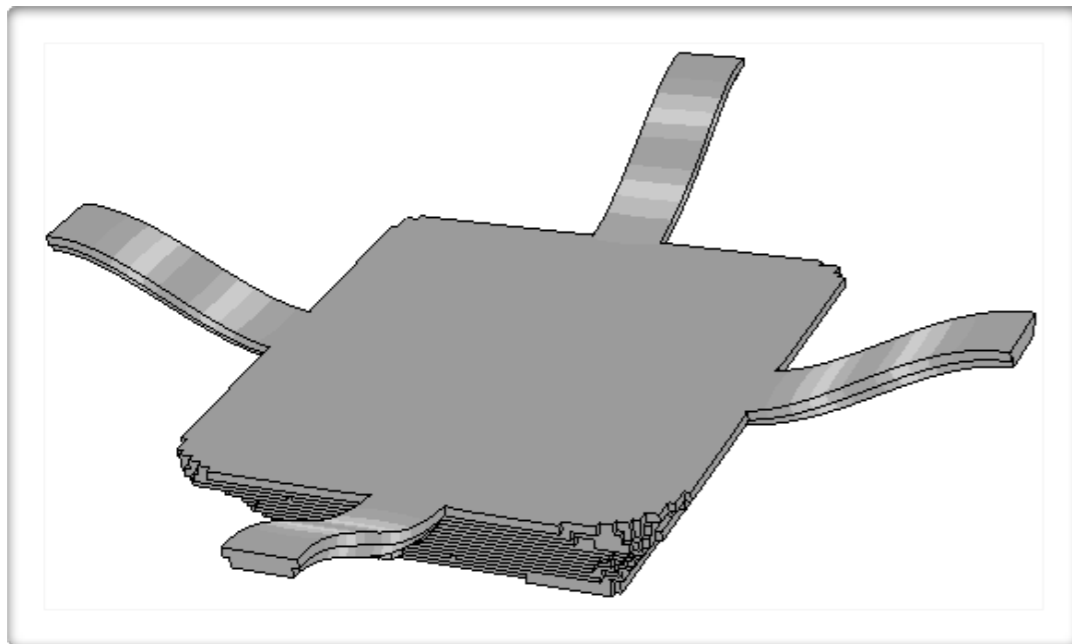
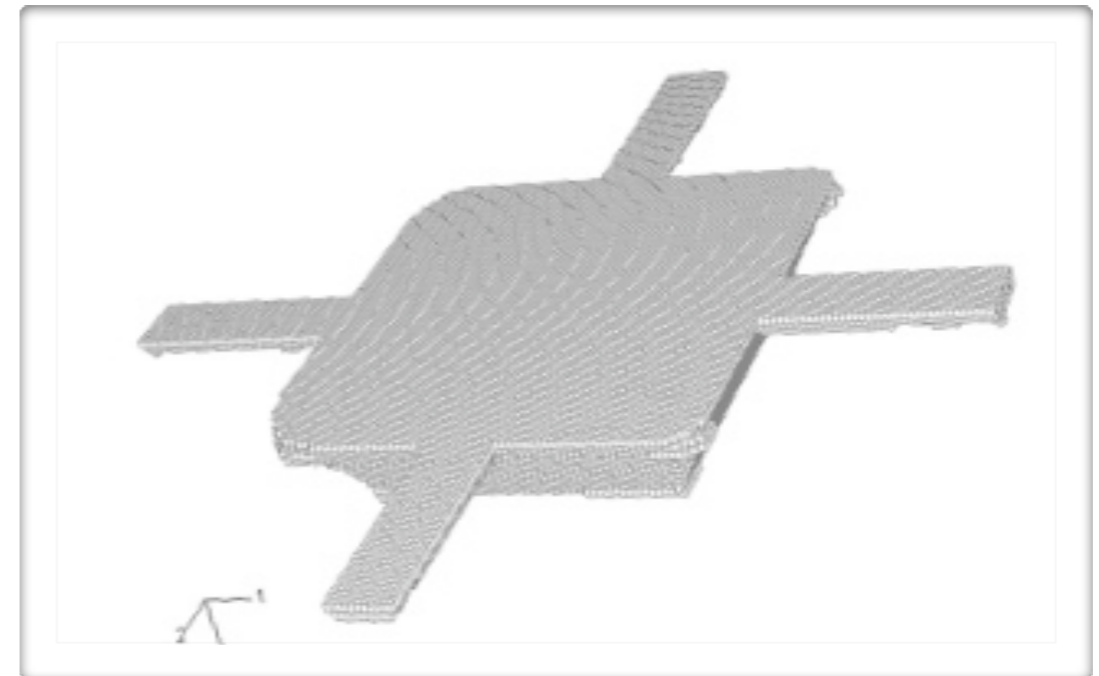
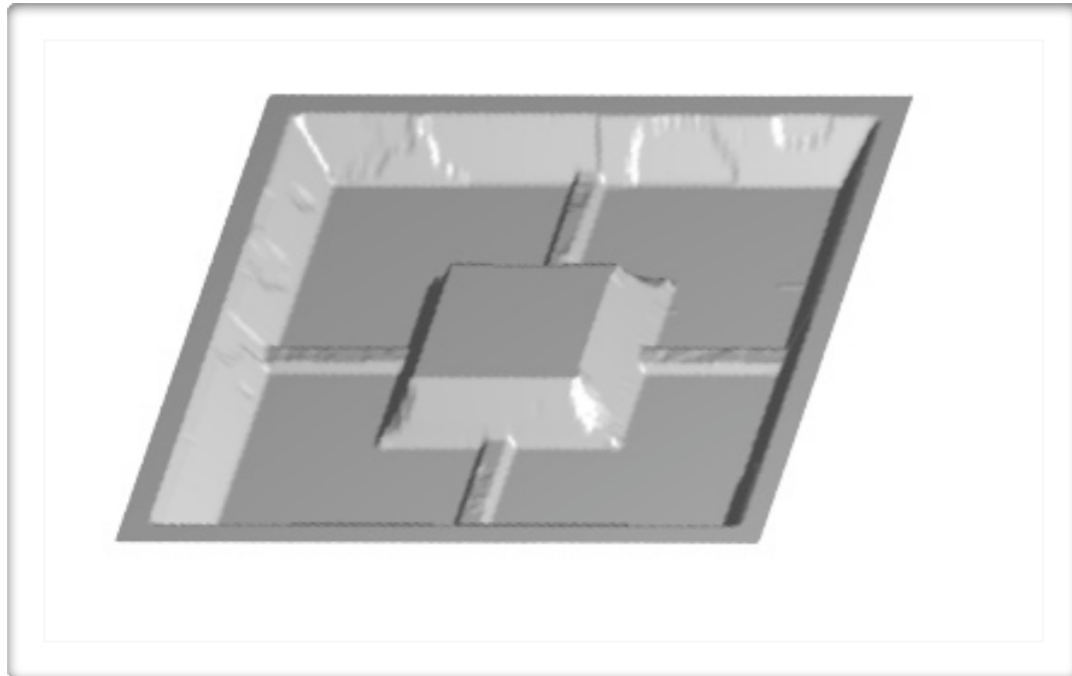


Comparison of etching a 5 μm trench with a 7s/8s cycle

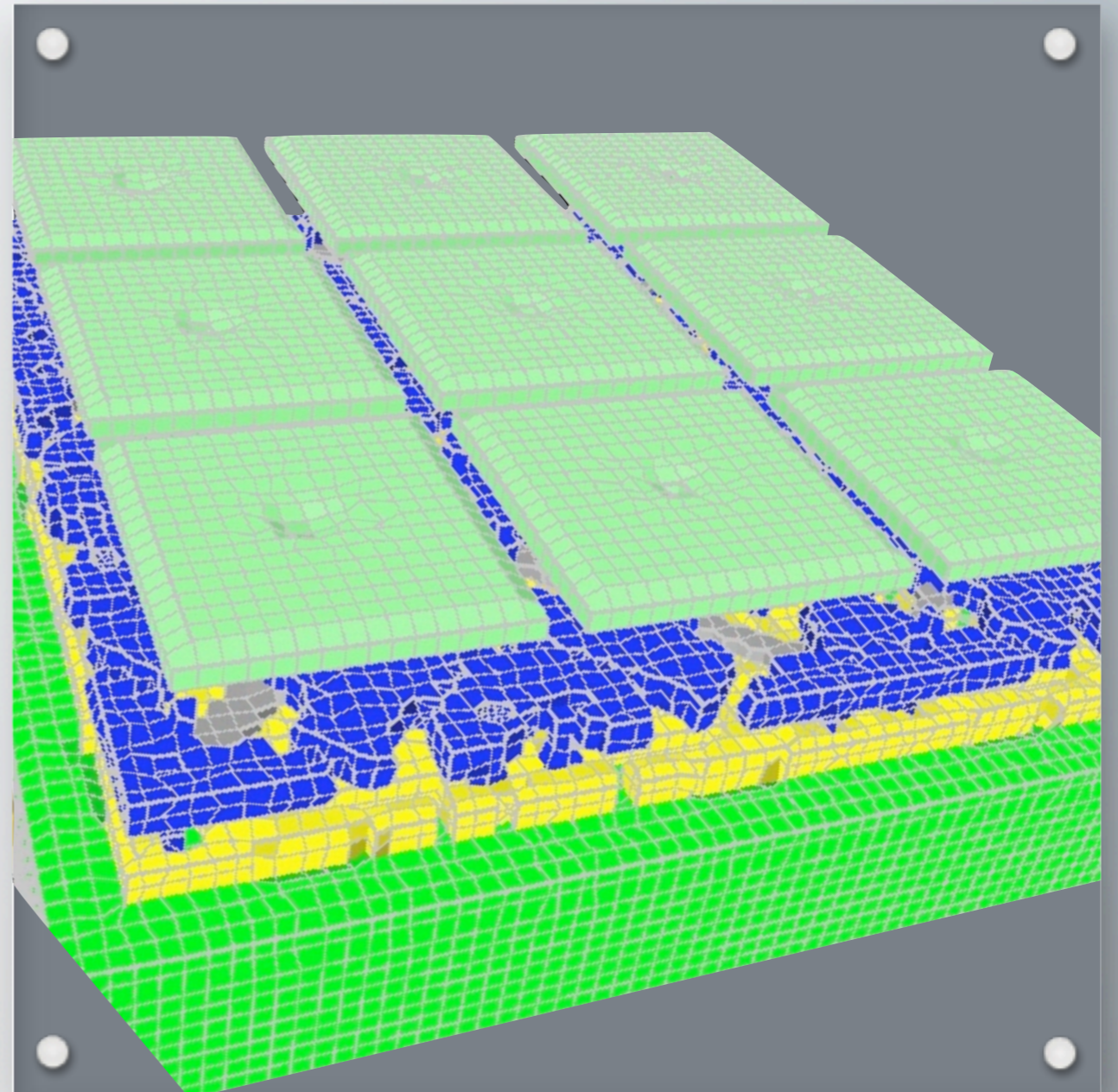
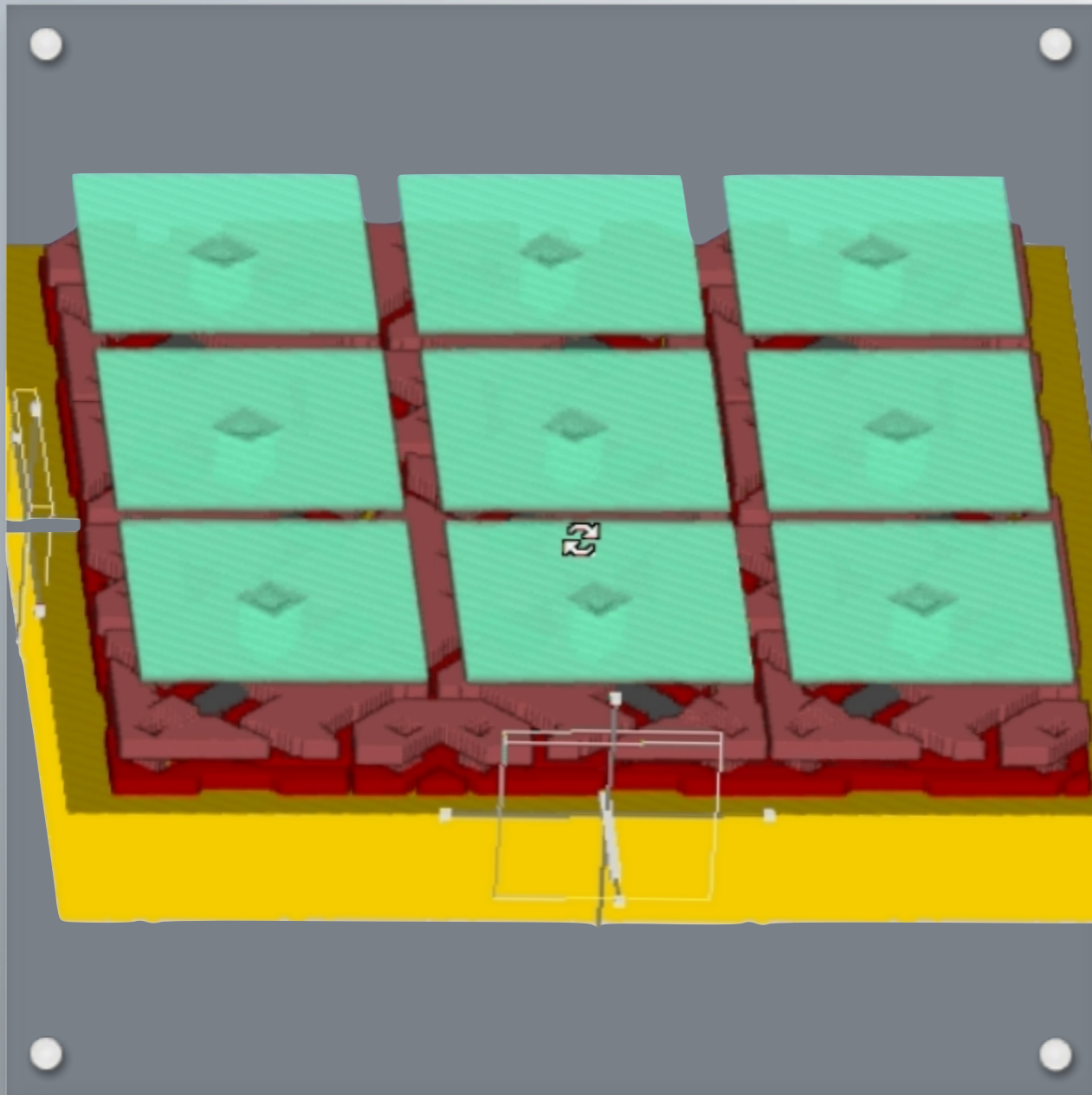


The experimental result of the etching of trenches using three etching steps with different etching/polymerization time configurations. 7s/7s, 9s/7s and 5s/7s are used sequentially, each for 5 minutes.

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 than 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**

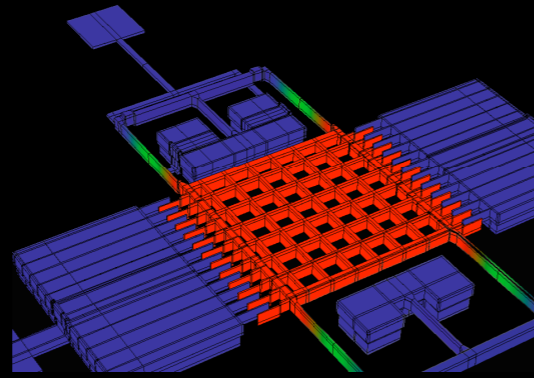
Quickly run your analysis without convergence issues

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

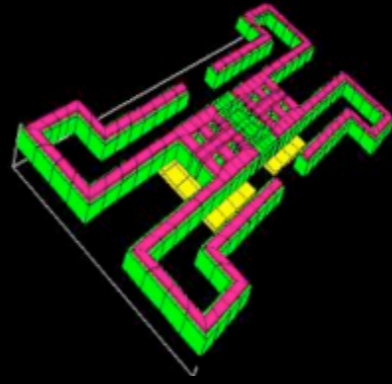
*Rotary ring gyro
Rate/Coriolis analysis*



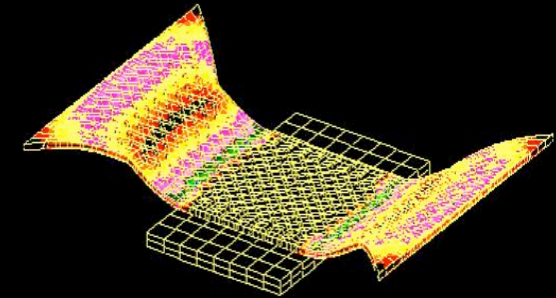
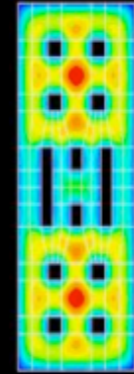
*Draper vibratory gyro
Electrostatic drive*



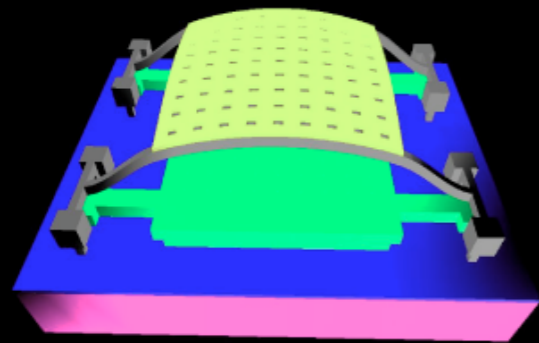
*Lockheed inertial device
Squeeze film analysis*



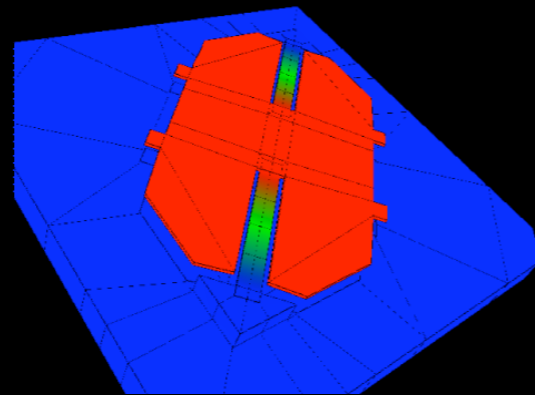
*Raytheon/TI RF switch
Non-linear contact analysis*



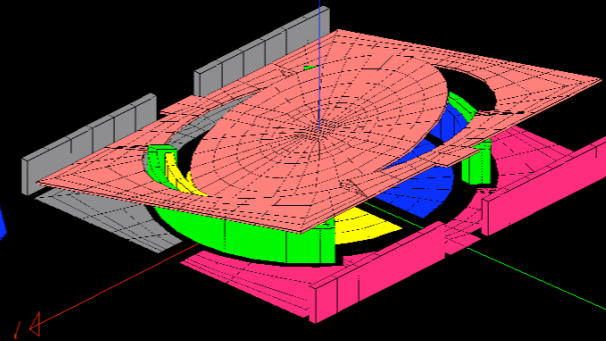
*Hitachi
RF Tunable Filter*



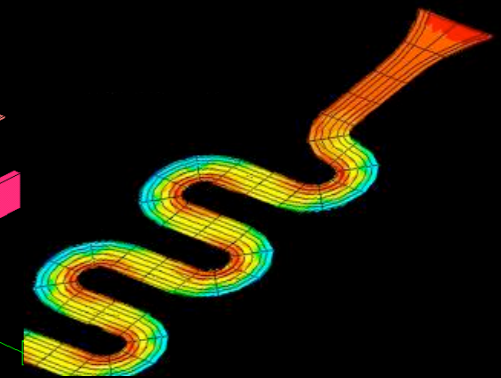
*NASA
Adaptive optics*

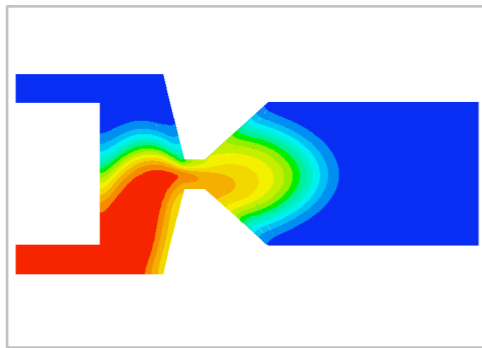


*Corning
3D Optical cross connect*

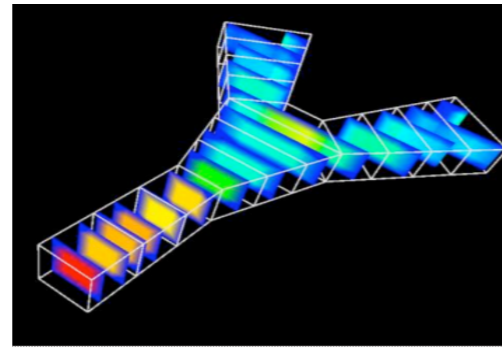


*NASA
Radiation detectors*

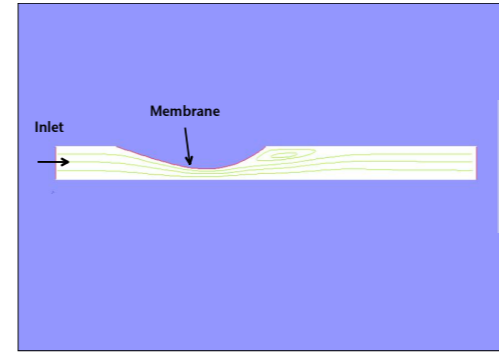




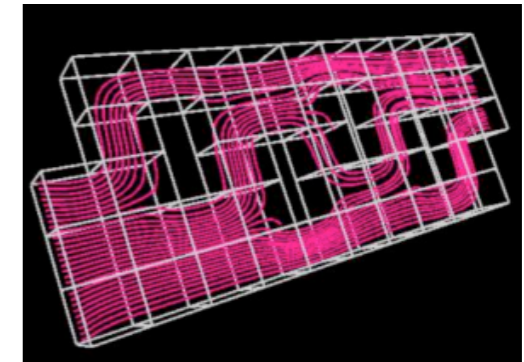
*Micro-mixing in a valve
Concentration gradient evolution*



*Flow mixing
Y combiner*

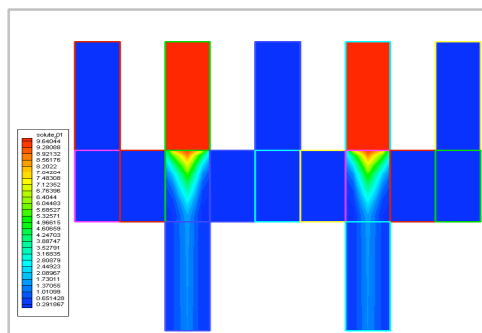


*Fluid Structure Interaction
Inlet flow - membrane interaction*

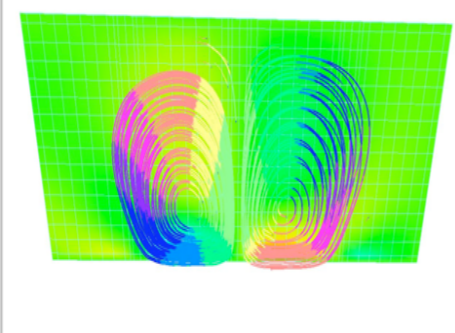


Flow separation device

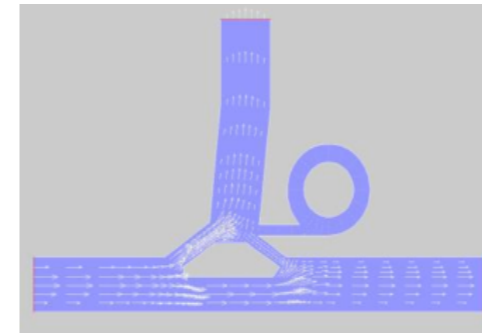
Microfluidics • Electrokinetics • Transport stoichiometry • Heat transfer • Electro-Wetting on Dielectric (EWOD) • Digital droplet microfluidics • Free Surface Flow • Fluid Structure Interaction • Electrochemistry • Micro-mixing • Electrophoresis • Dielectrophoresis • Capillary flow and electro-separation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



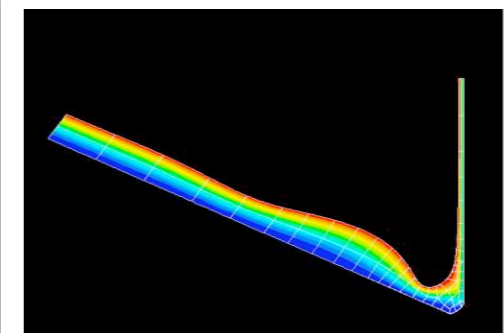
*Electrokinetics
Multiplex focusing*



*Electro-osmotic driven flow
Electrohydrodynamics for cooling*

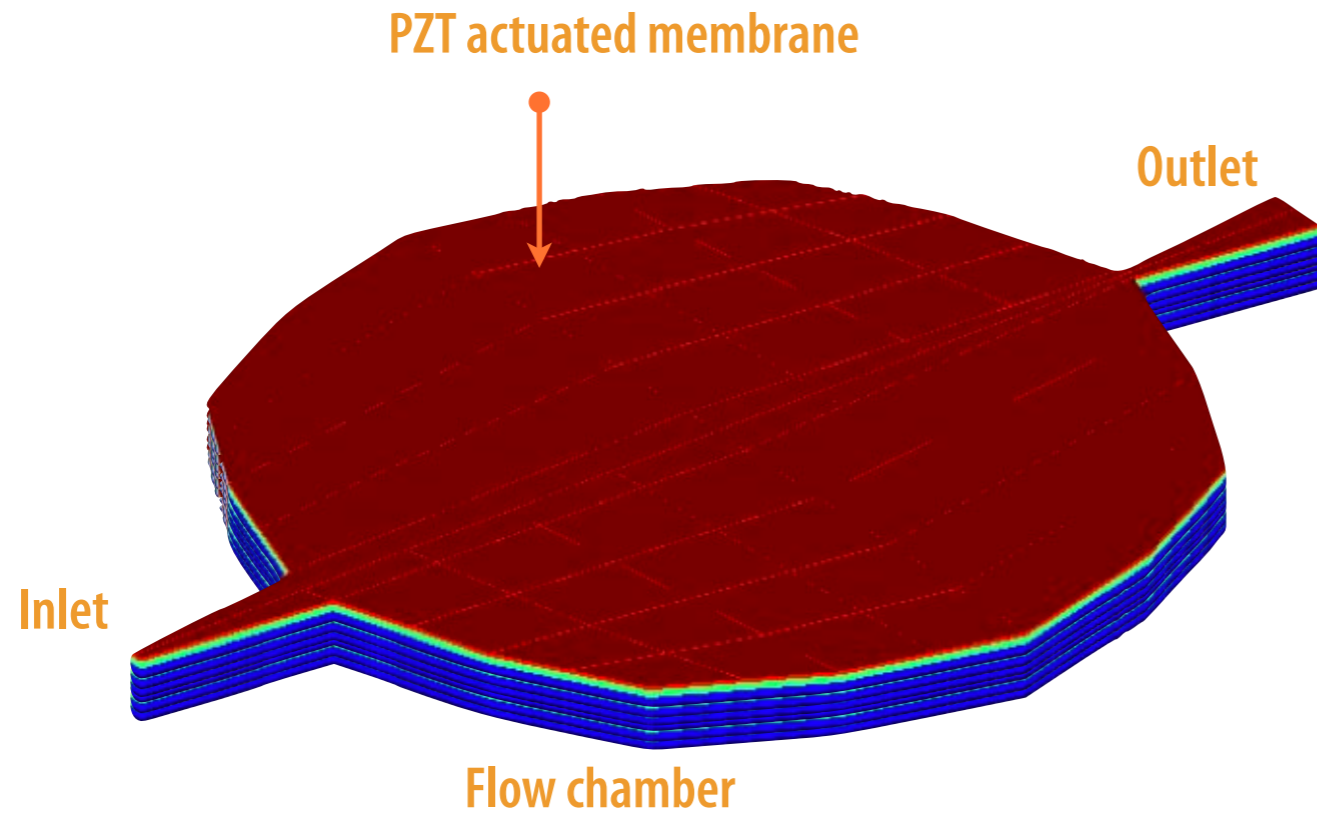


*Electrophoresis/Dielectrophoresis
High Frequency Waste separation*

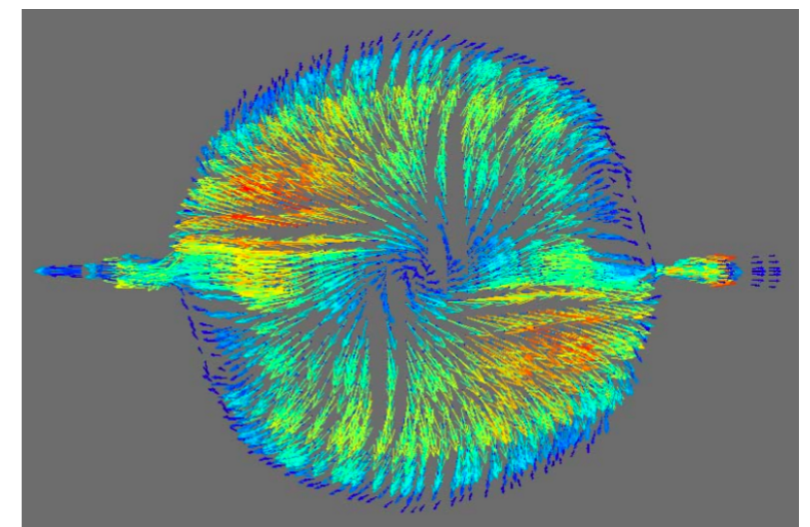
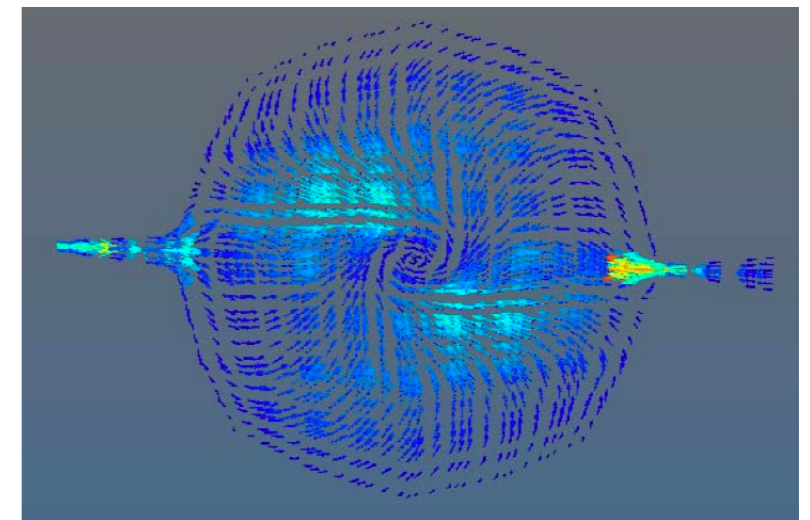
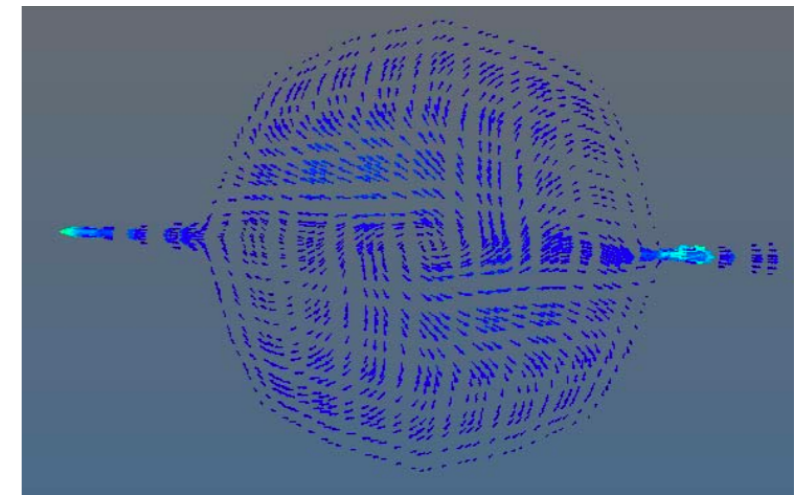


*Free surface flow
Slide coater*

Advanced FSI

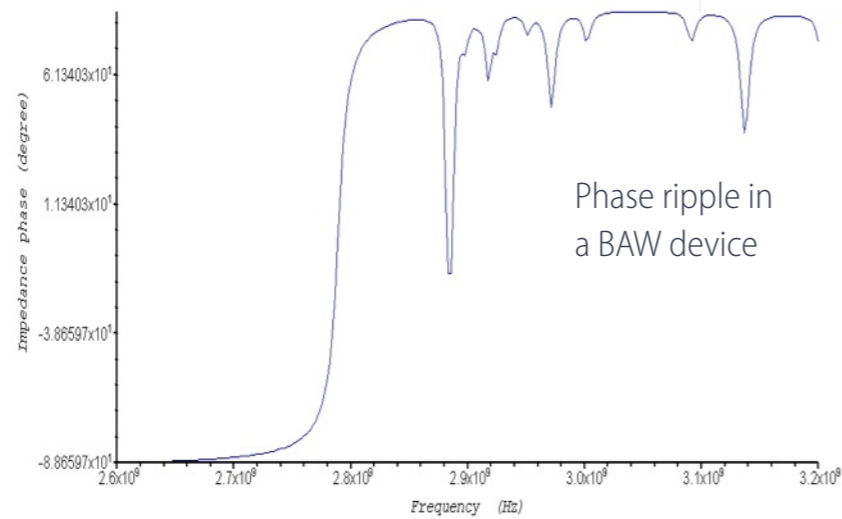
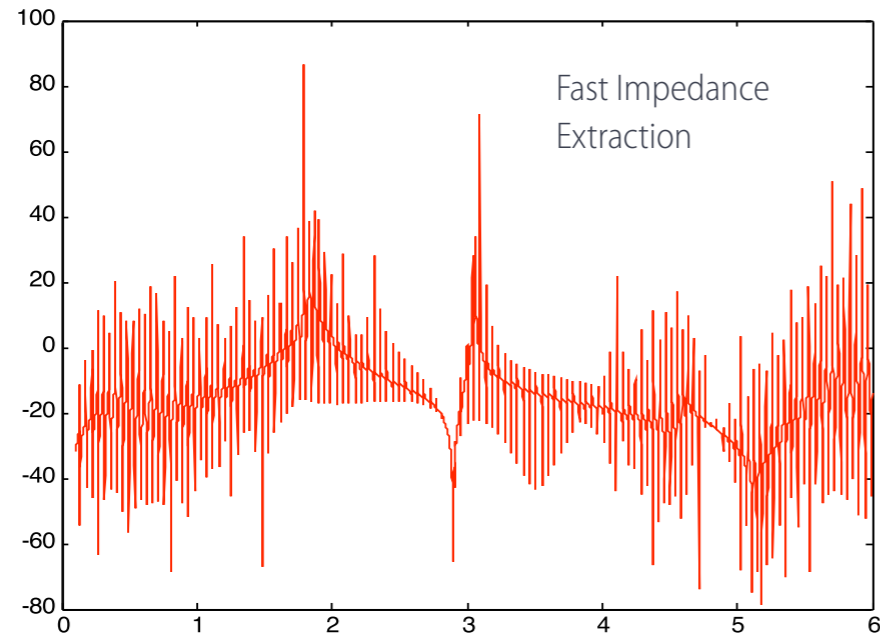


Example: Valveless piezoelectrically actuated micropump

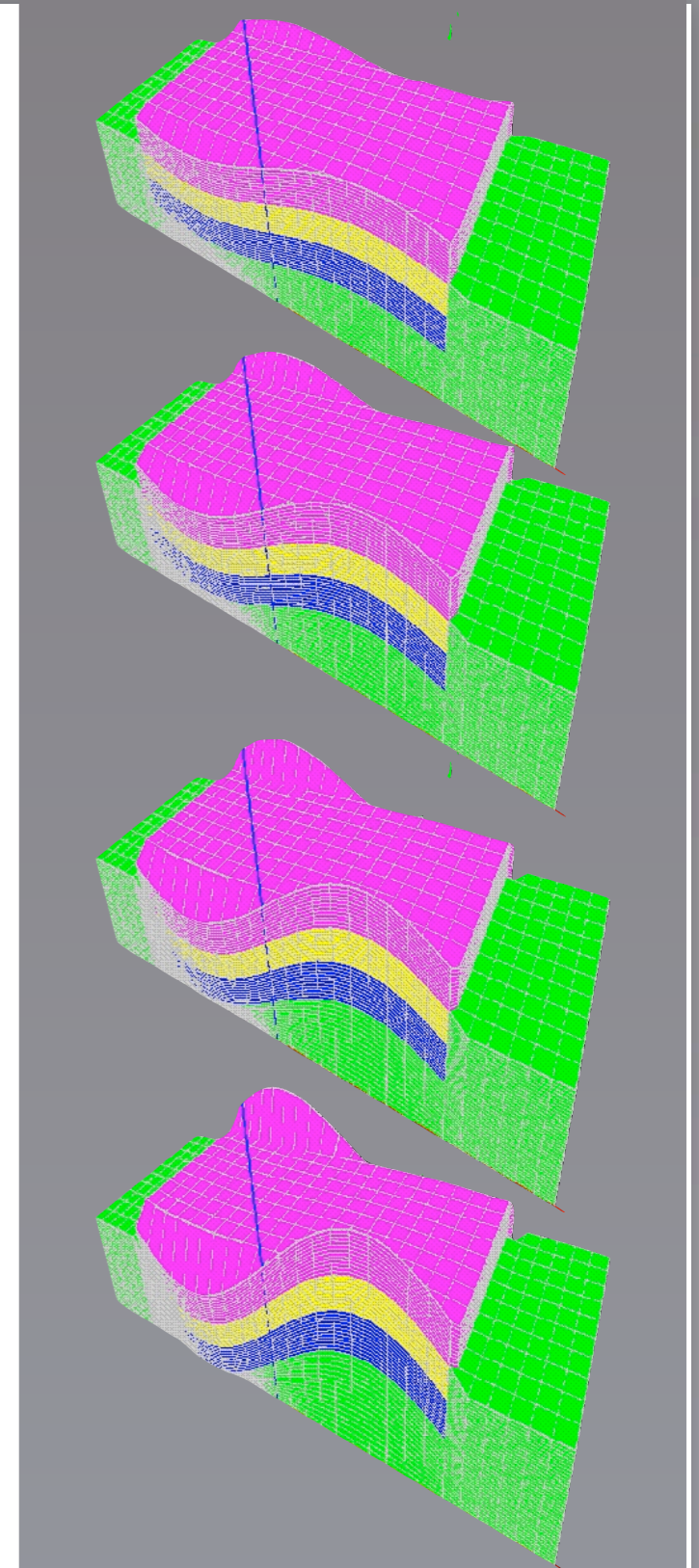


Flow evolution in a piezoelectric membrane micro pump

Piezo-Acoustics

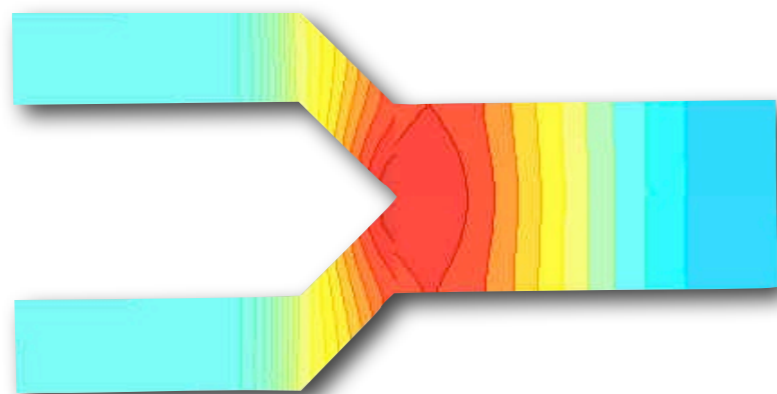


1 Multi-processor enabled BAW/SAW simulation
Fast impedance and phase ripple calculations



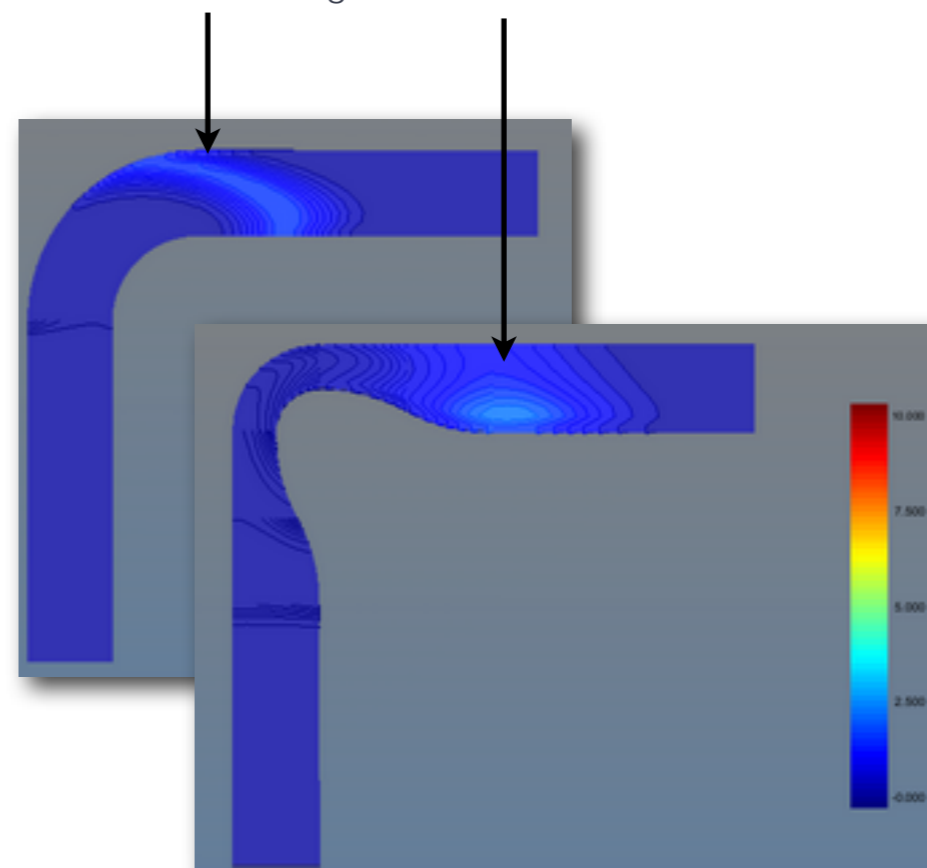
2 Piezo-acoustic wave generation

Microfluidics



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

Concentration skewing Minimized concentration skewing



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

1

Enhanced Chemical Reaction

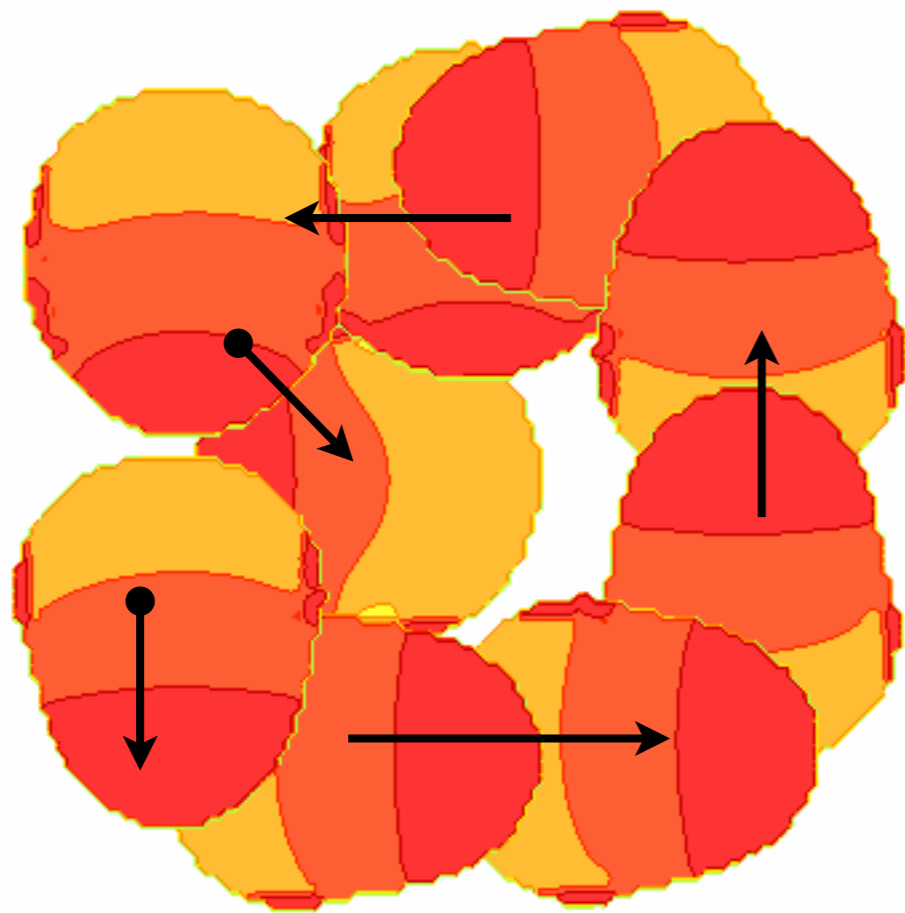
Microfluidics with enhanced transport kinetics

2

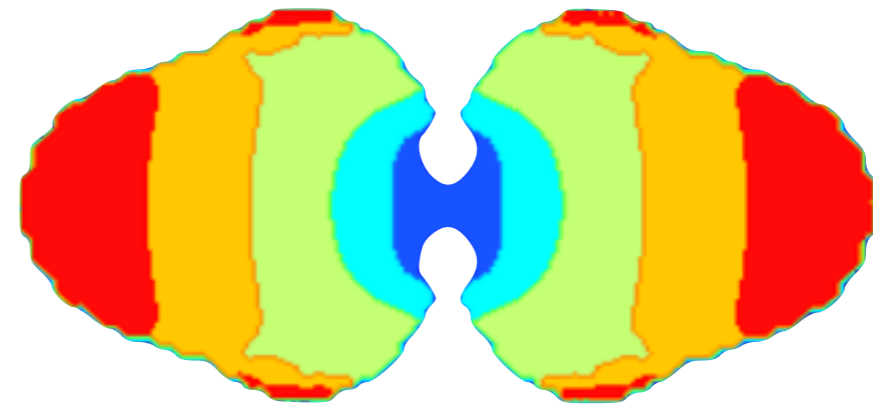
Enhanced transport behavior

Multivalent Ion drag calculations in electrokinetic transport

Microfluidics



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



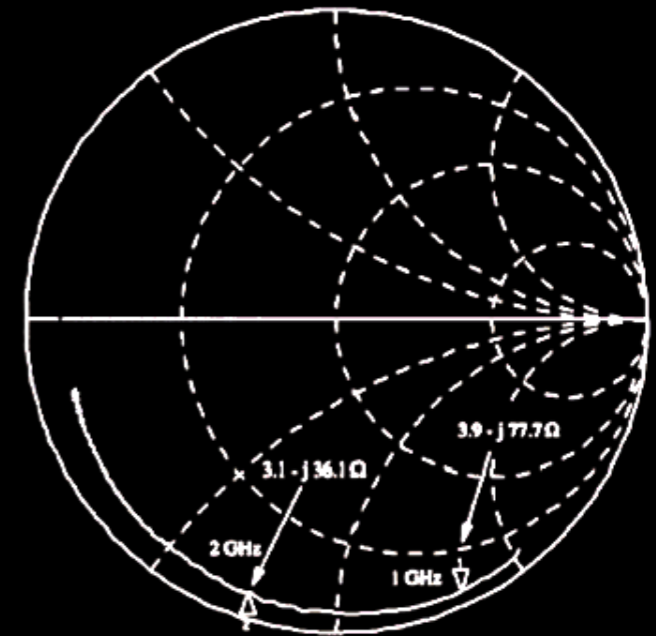
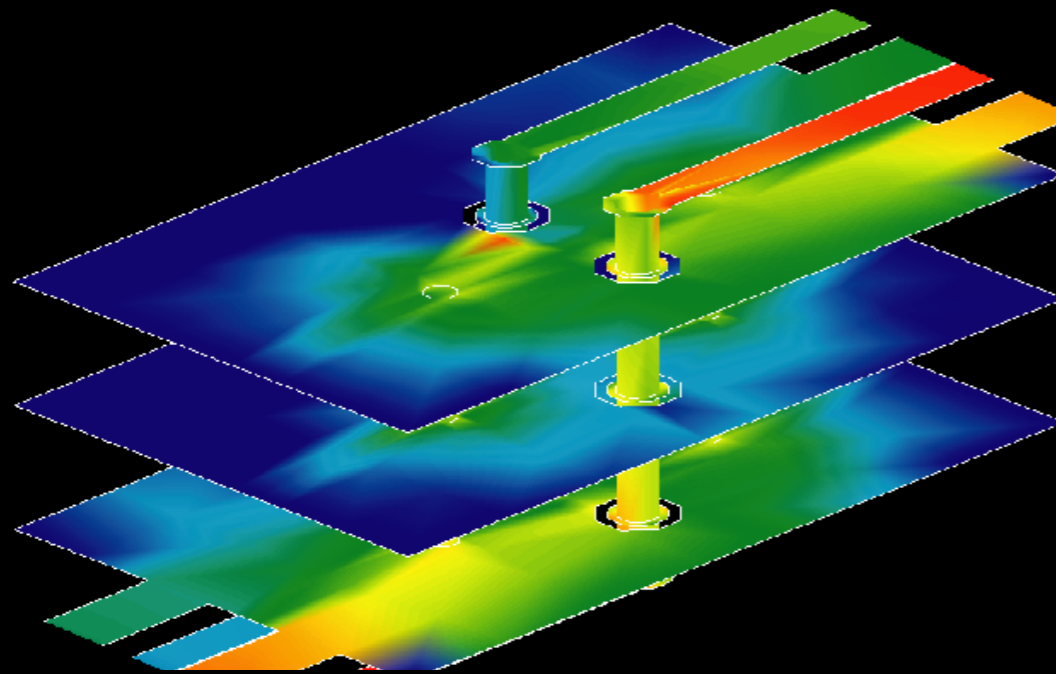
Droplet fission (top view)

3

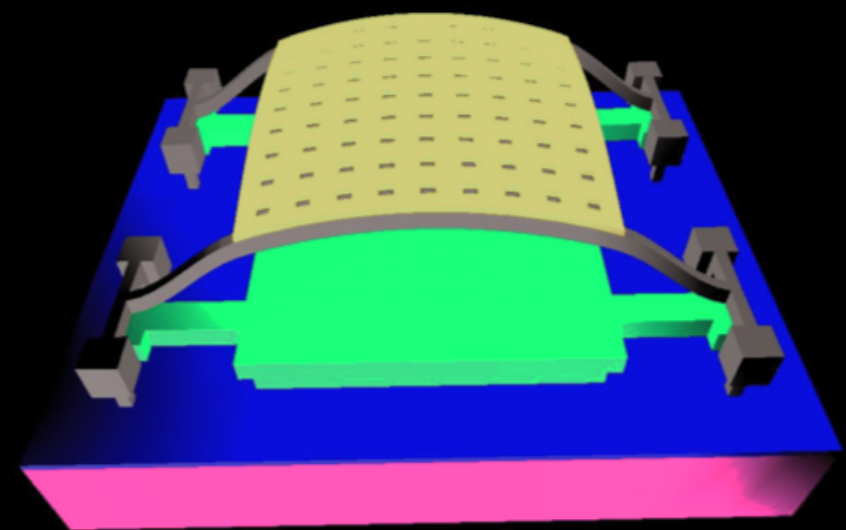
Electrowetting on dielectric (EWOD)

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)

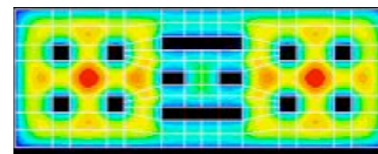
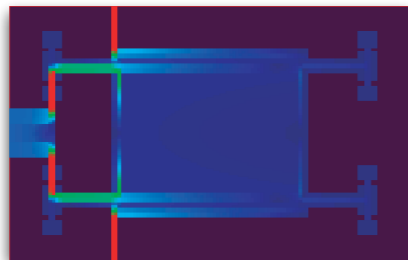
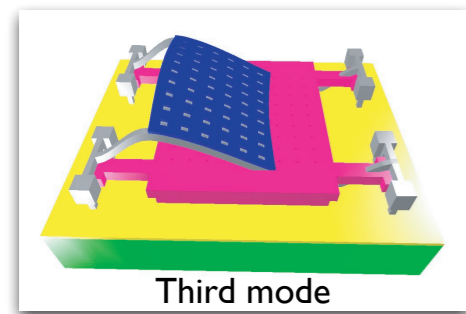
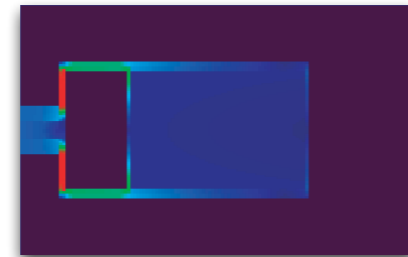
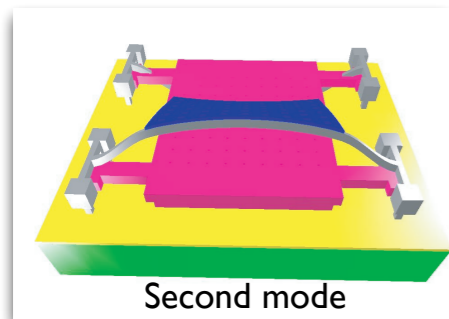
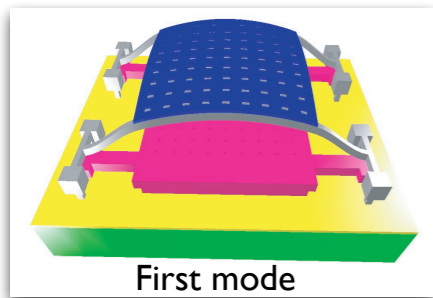
Other dissipation sources (thermoelastic damping (v8.6.1) and anchor acoustic losses (v8.6.2))

System Model Extraction (SME)

Capture strain energy associated with each mode

Capture electrostatic energy associated with each mode

Capture fluid damping characteristics



Arnoldi/Krylov sub-space reduction



N-DOF behavioral model based on Lagrangian formulation

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



Compact Representation



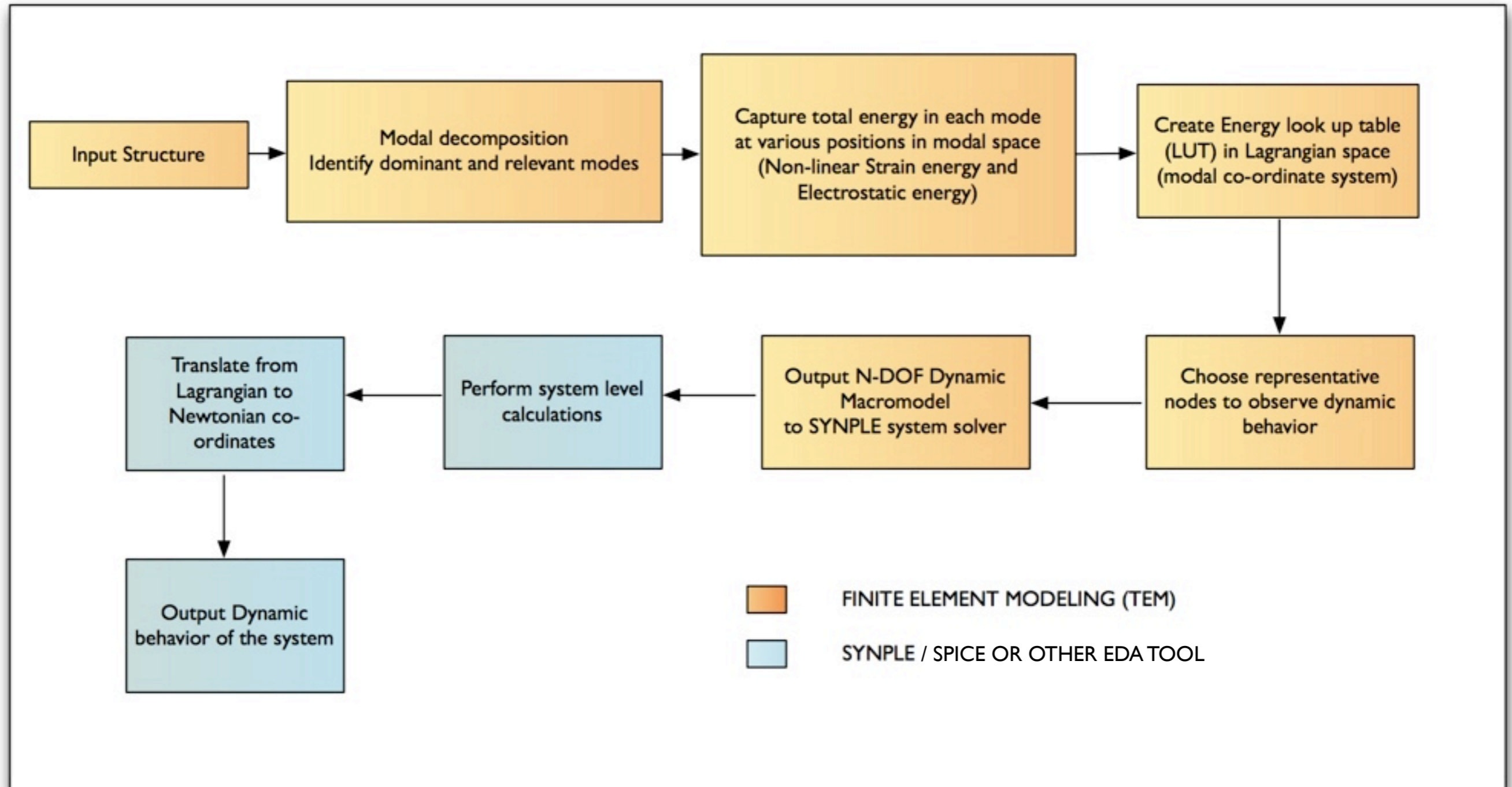
Hardware Description

① Capture total energy of relevant mode (Mechanical, Electrostatic, Dissipation)

② Krylov/Arnoldi methods to generate Lagrangian formulation

③ 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

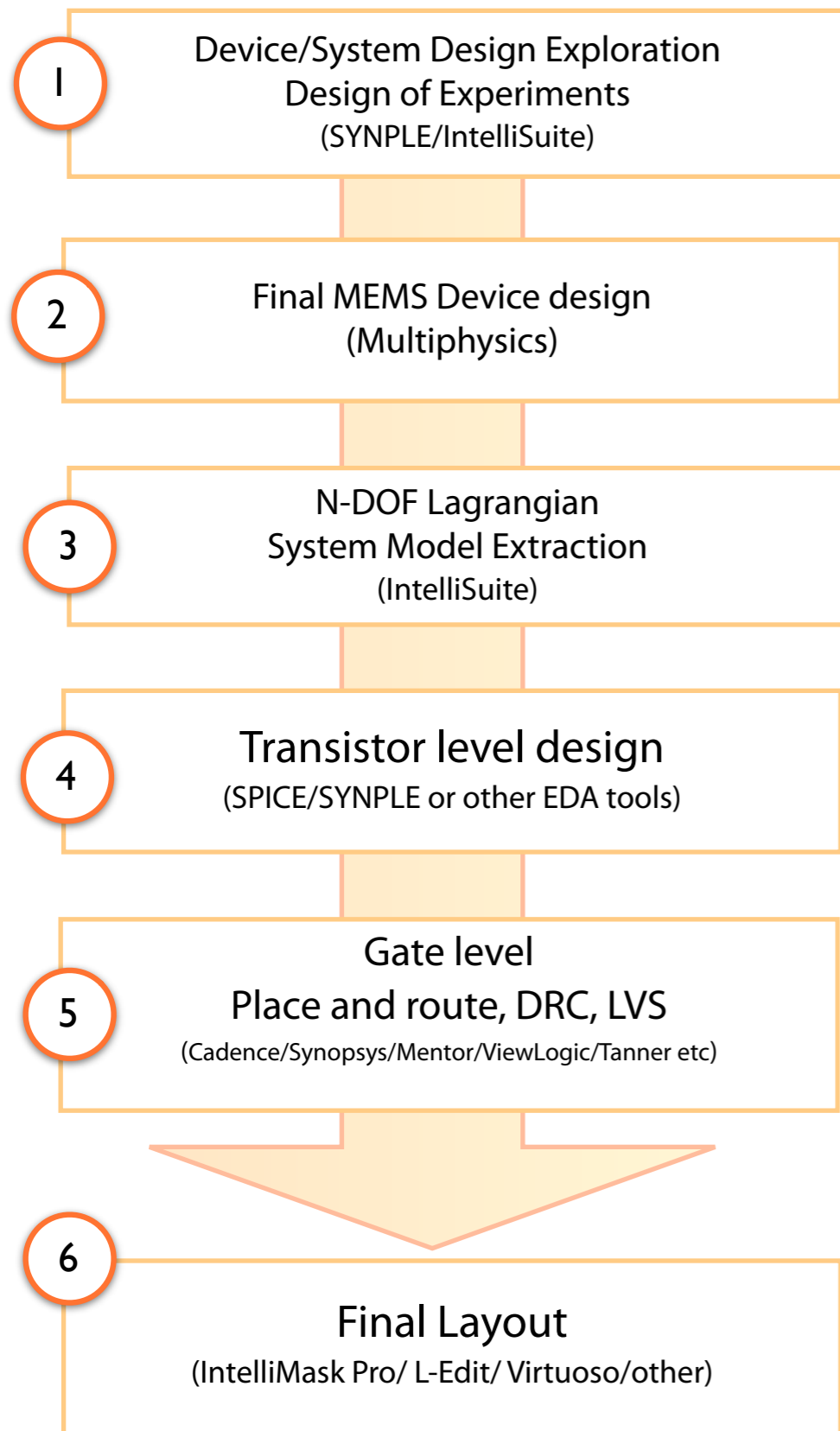


EDA Linker capabilities (compatibility)



- 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



**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

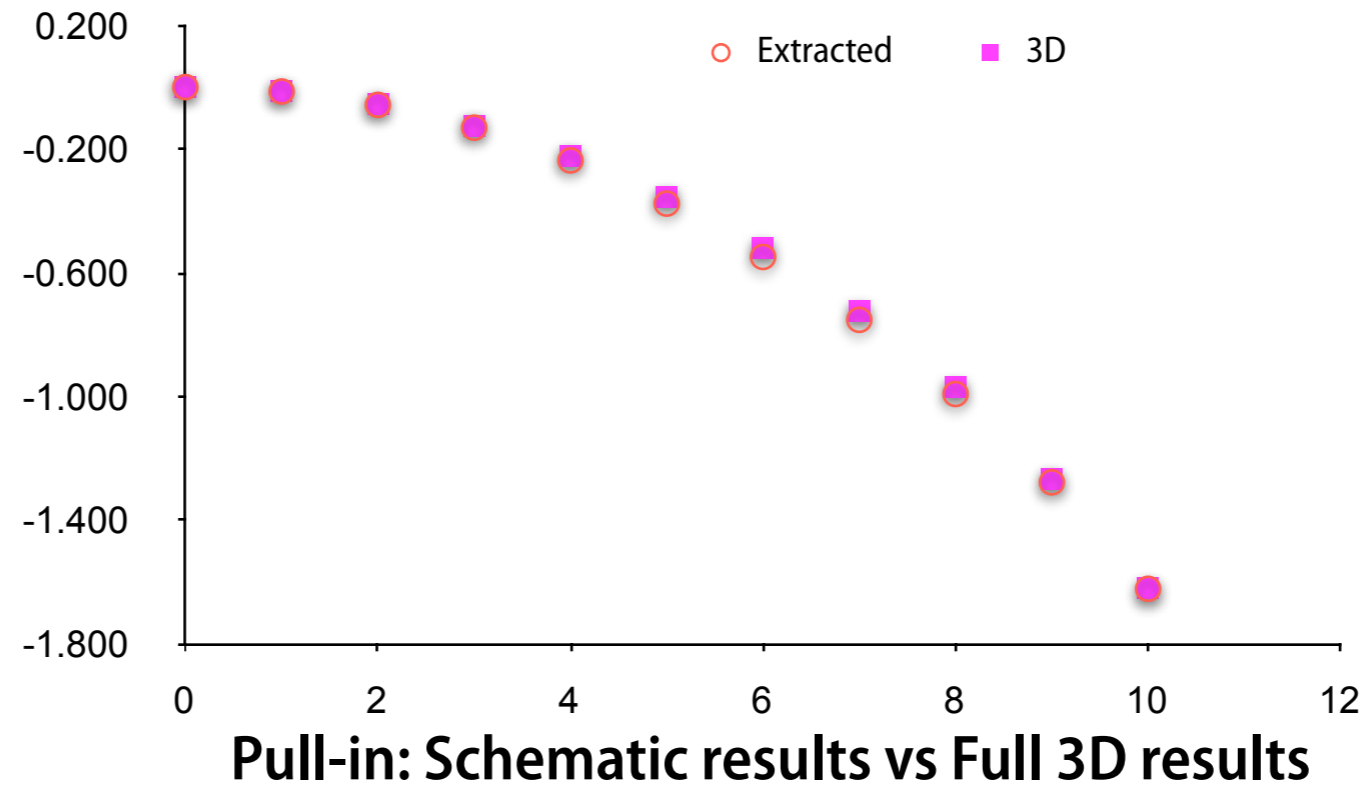
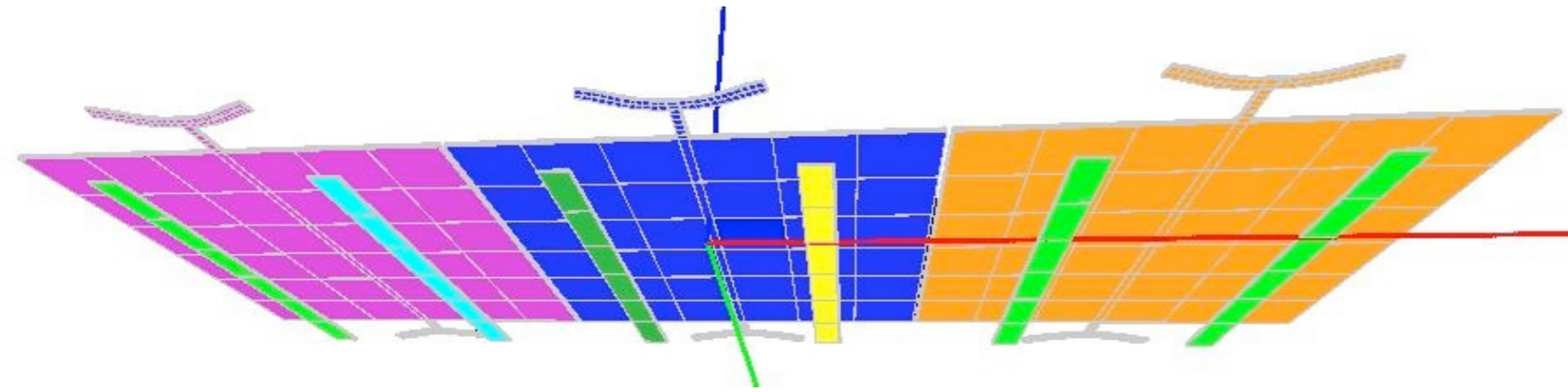
Ensure MEMS model used in circuit development is accurate

Physical verification ('Tape Out')

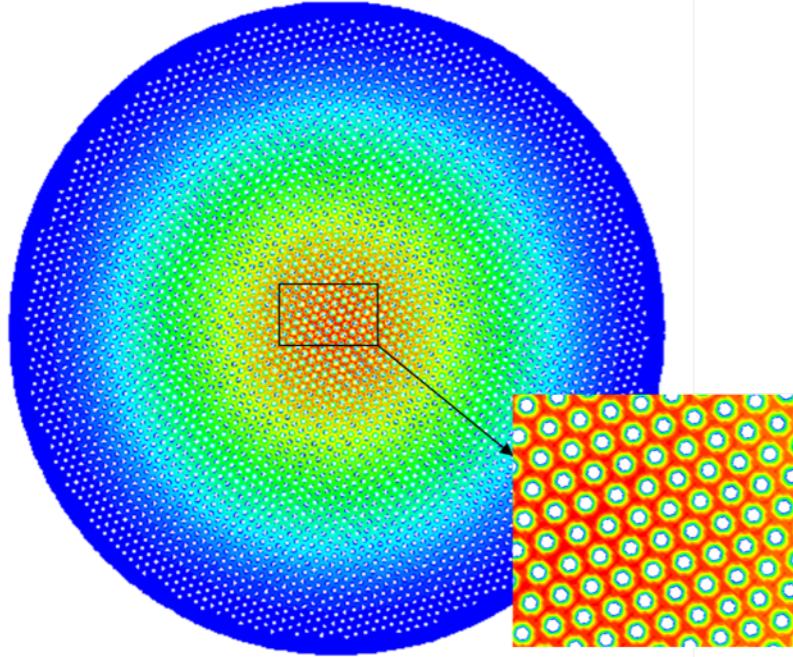
Verify physical layout is consistent with Design Rules

Ensure design meets manufacturability criteria

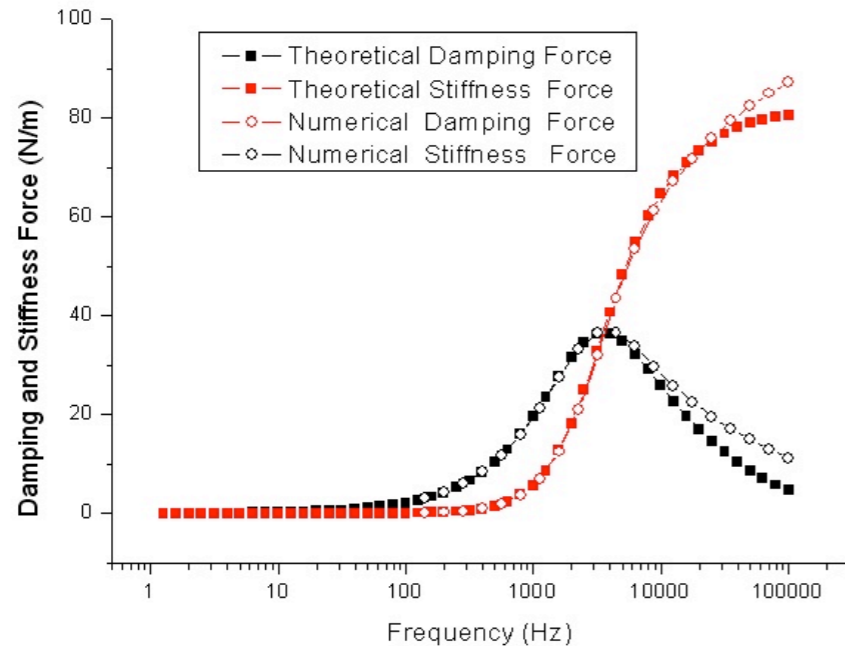
Static model verification



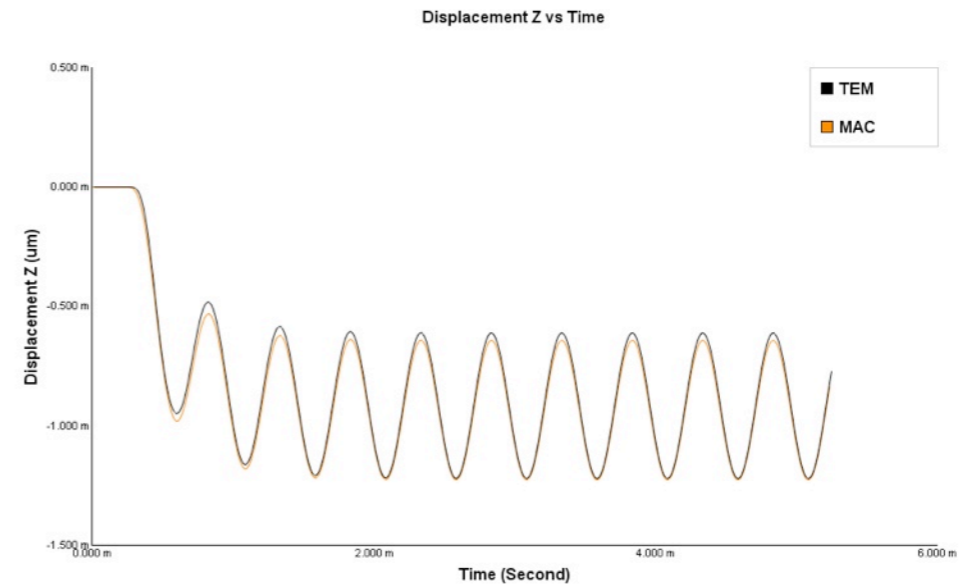
Damping model verification



Perforated condenser membrane



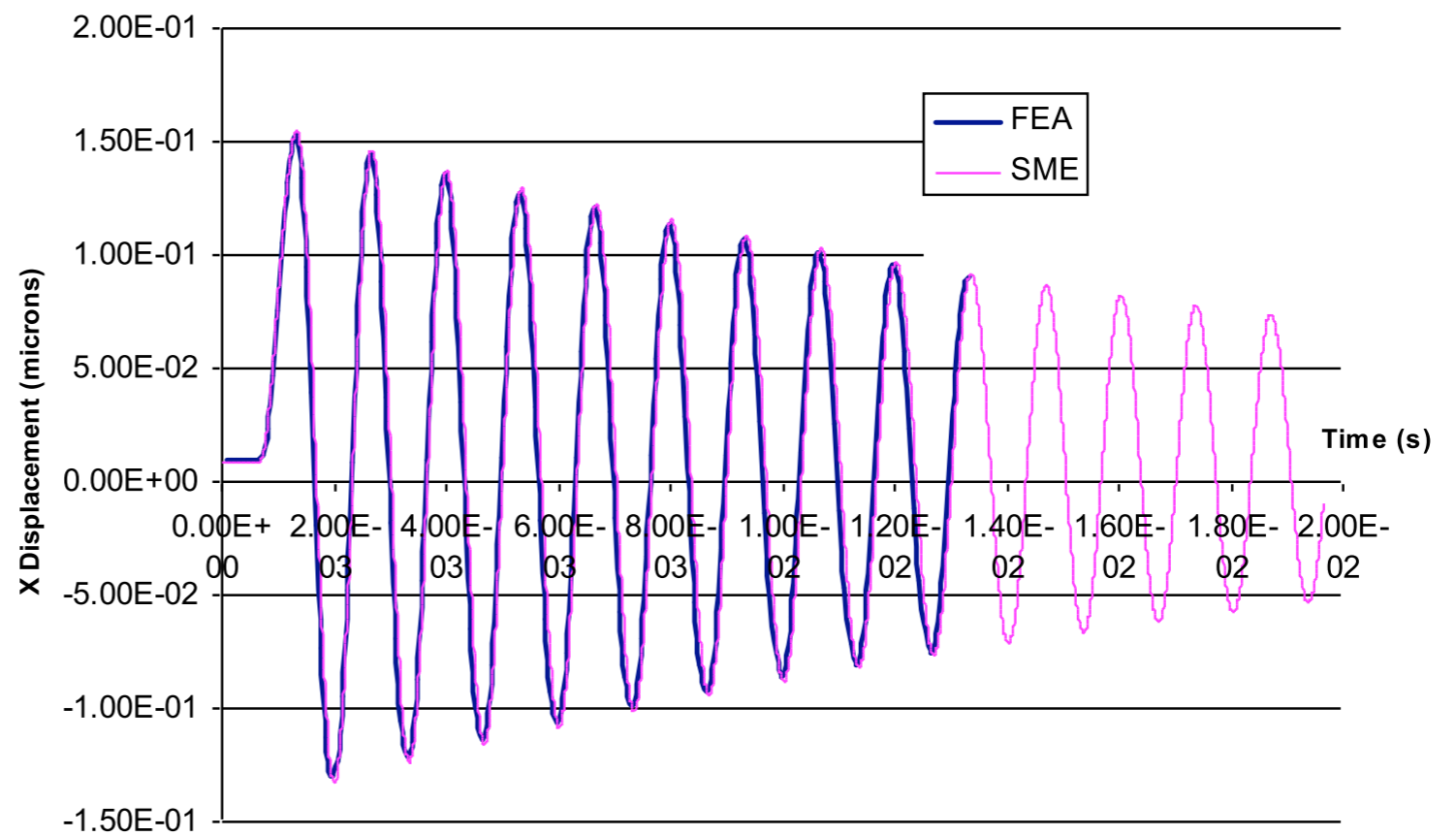
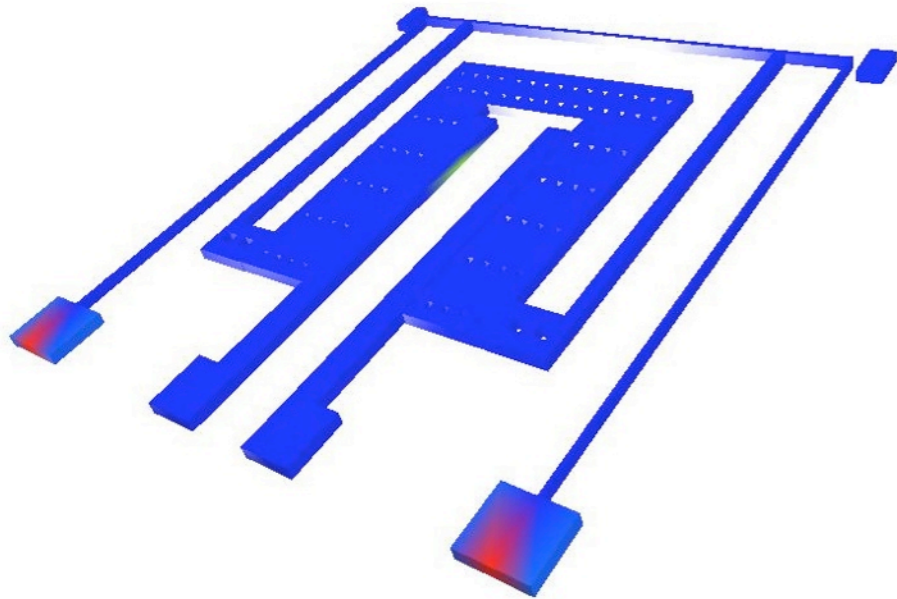
Full capture of fluidic damping and spring force



IntelliSuite

Full 3D (TEM) vs Macromodel comparison

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・شكرالكم

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

Dziękuję • Спасибо • Ευχαριστώ • Asante Sana • Dankie



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