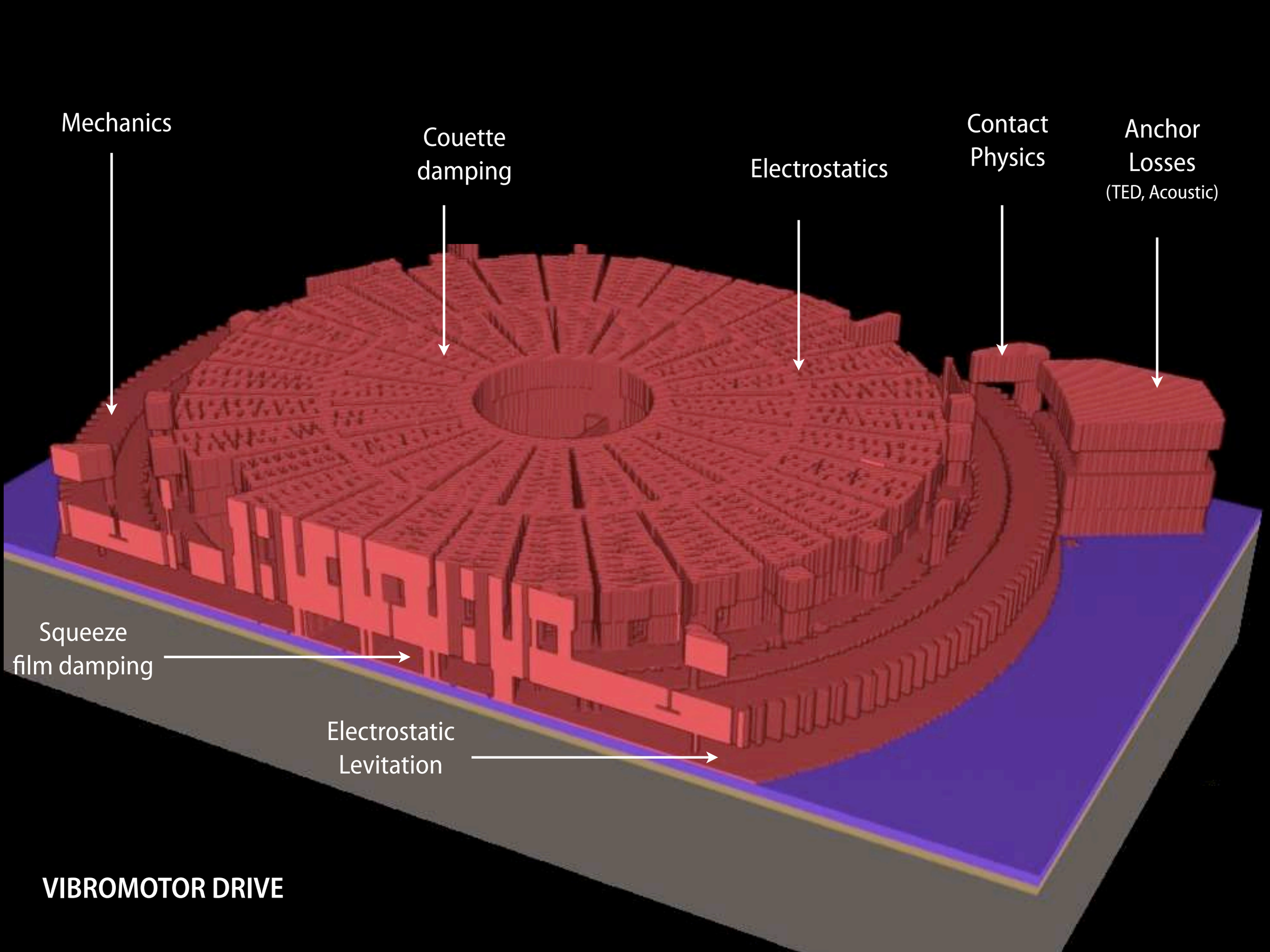
# Design Flow in IntelliSuite v8.6

# 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

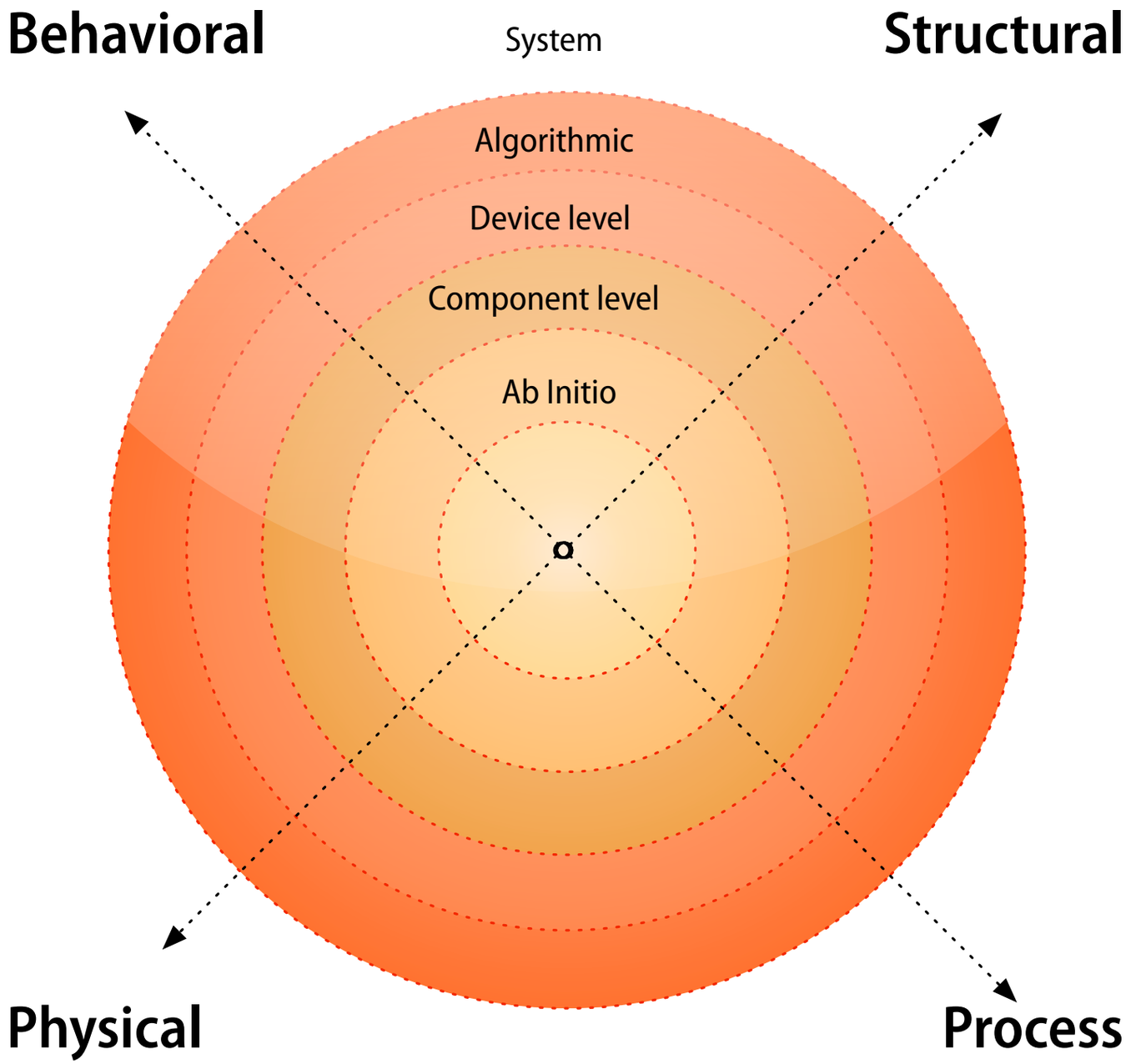
Packaging

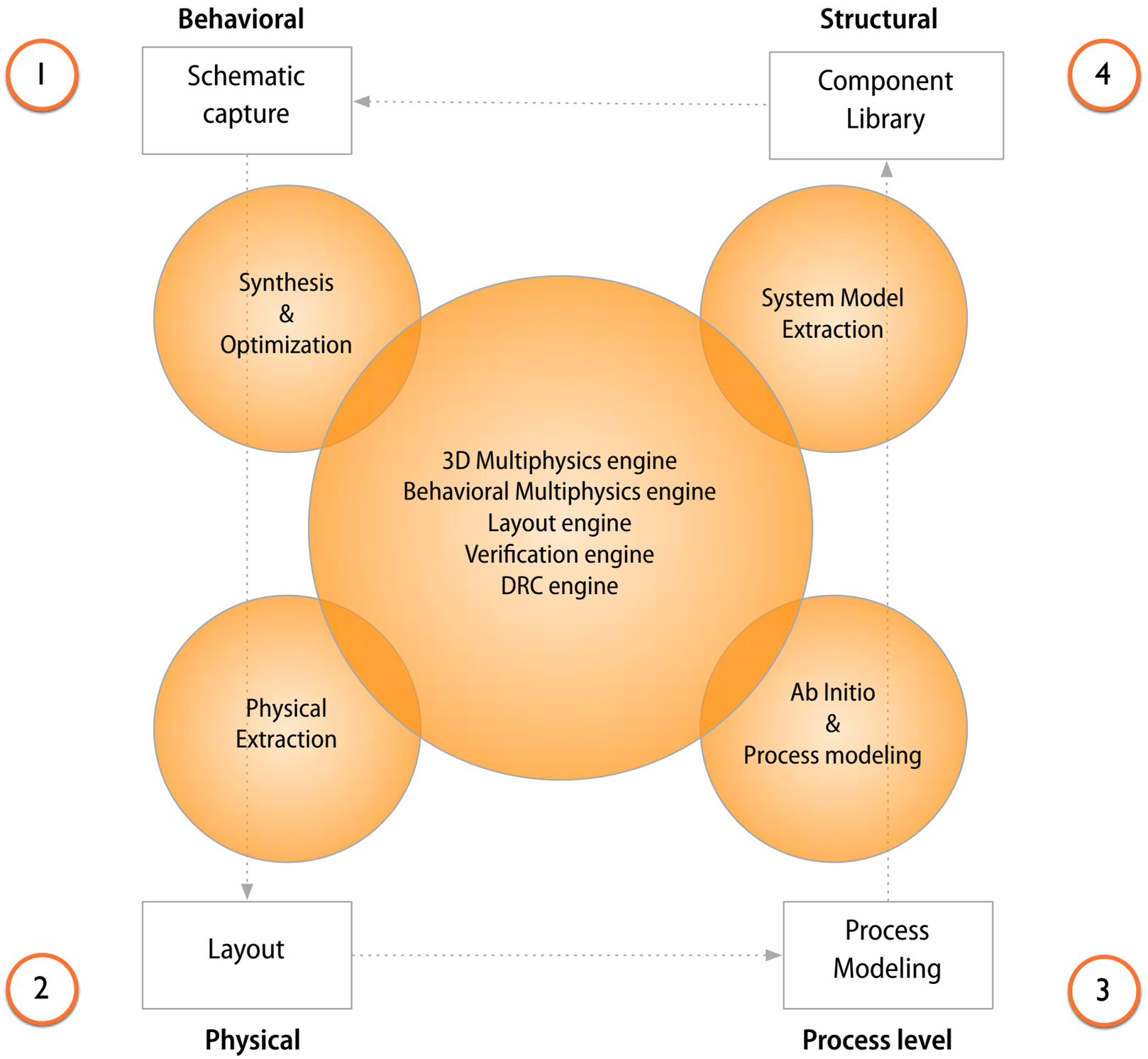
Yield optimization

DfM

**Manufacturing**

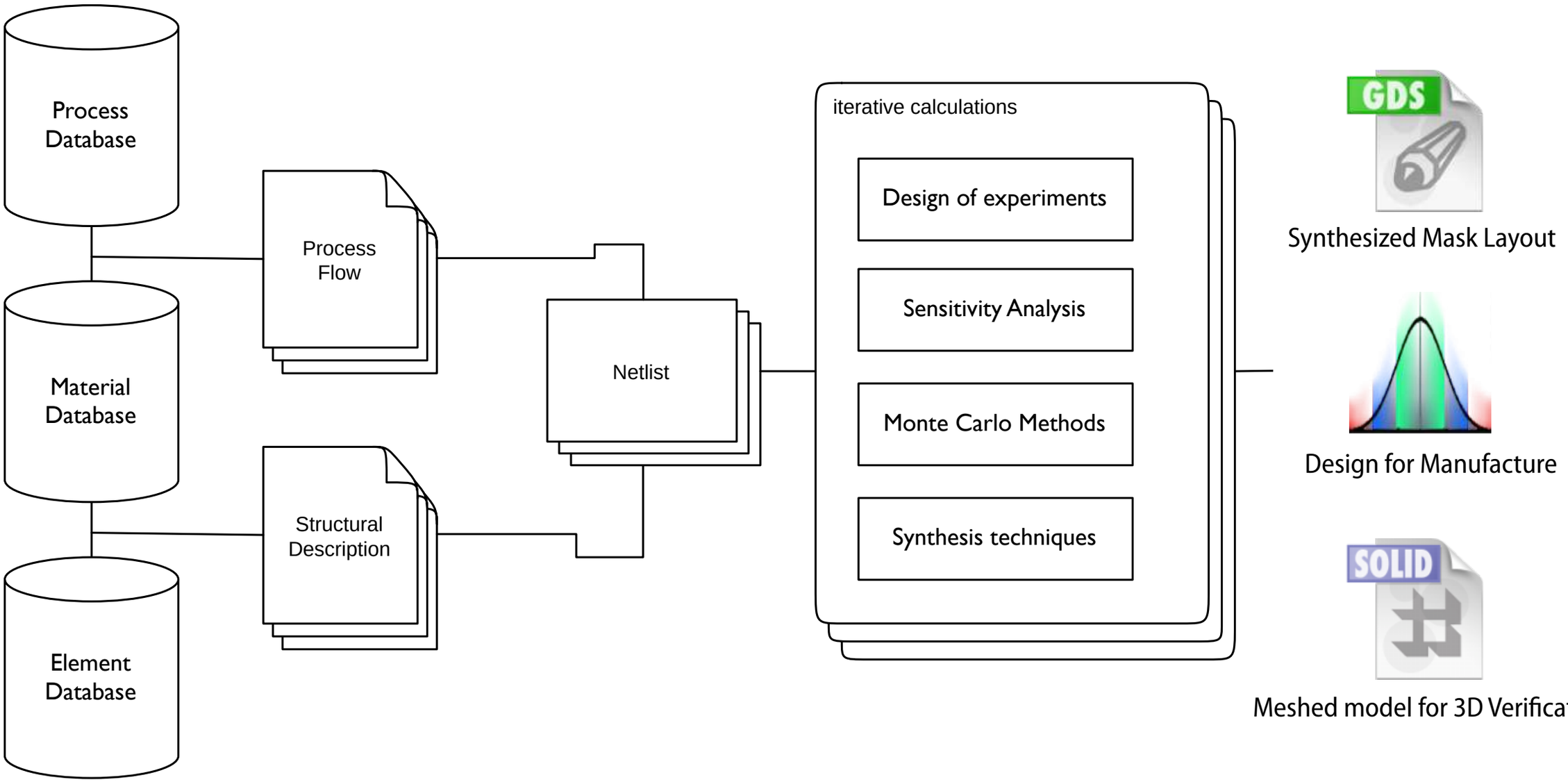
# Hierarchy of MEMS modeling





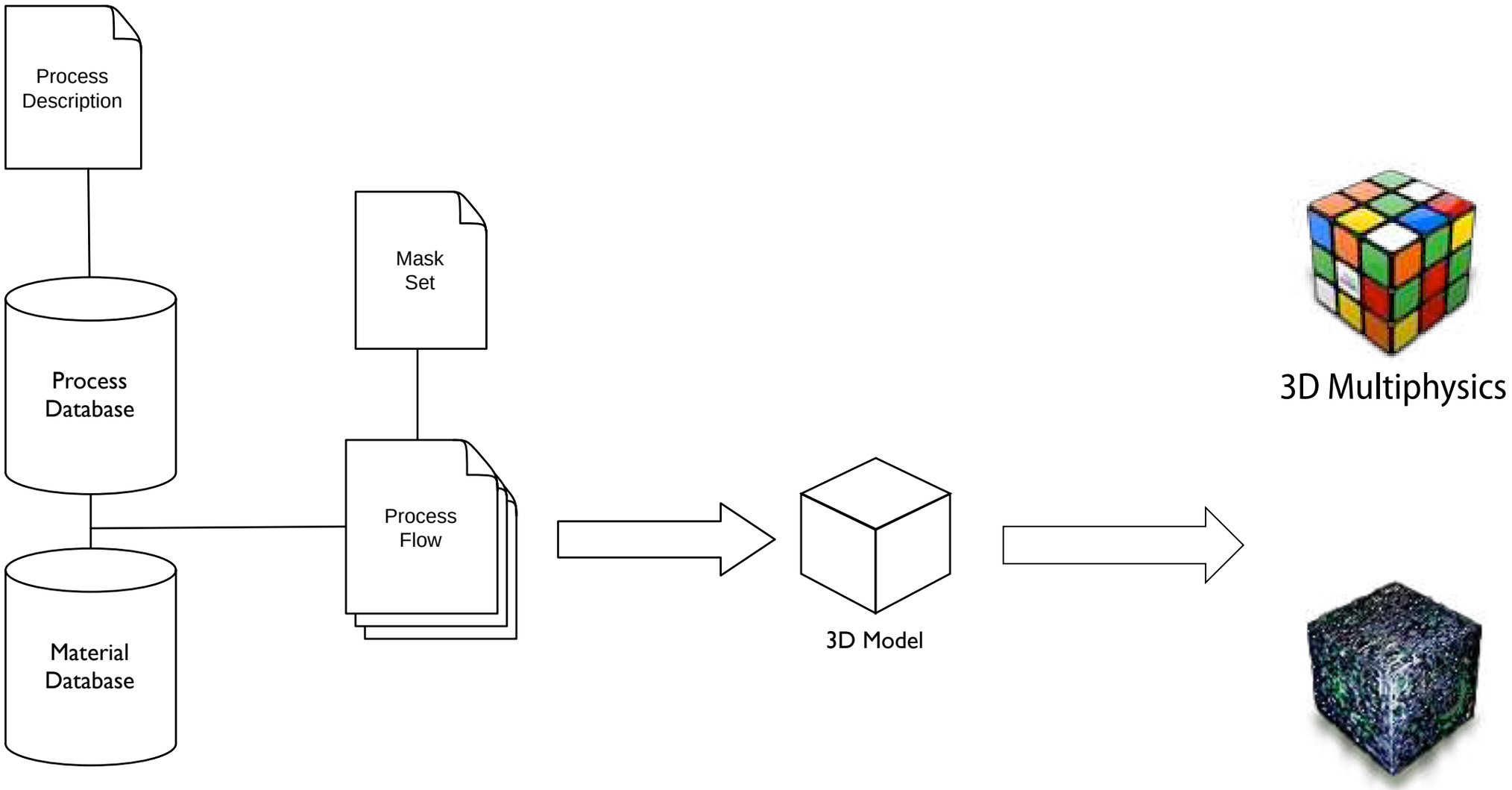

# Seamless integration of design flow…

# Top down flow: schematic based…



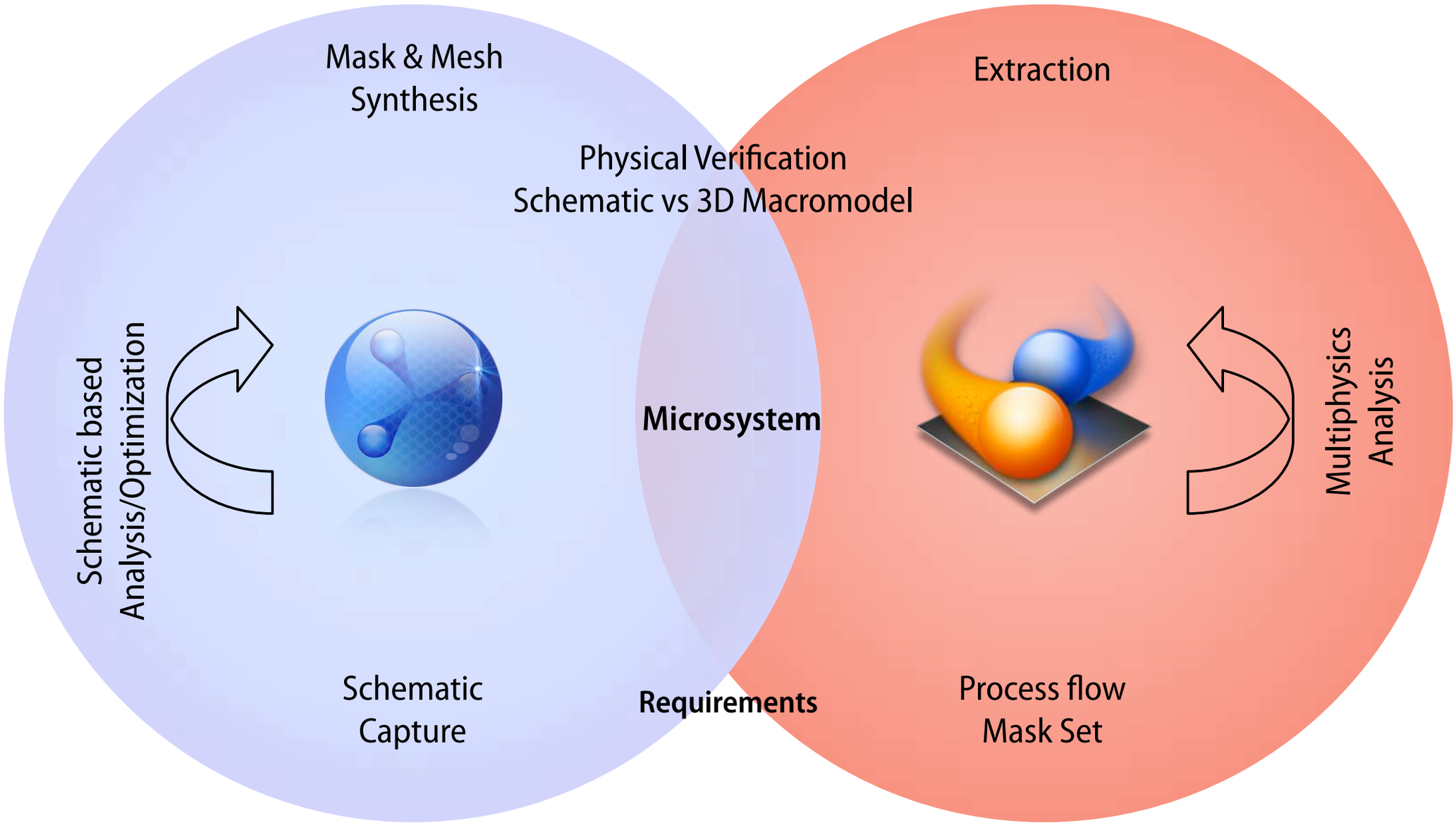

## Fast but less accurate…

# 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

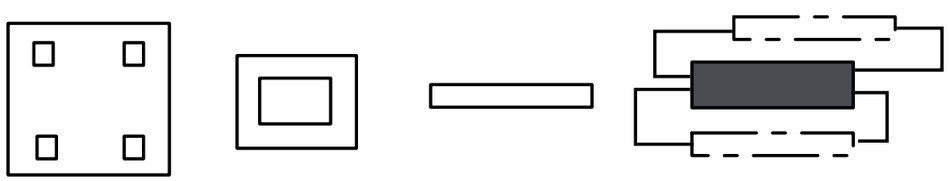
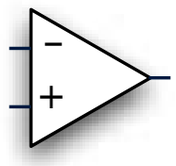
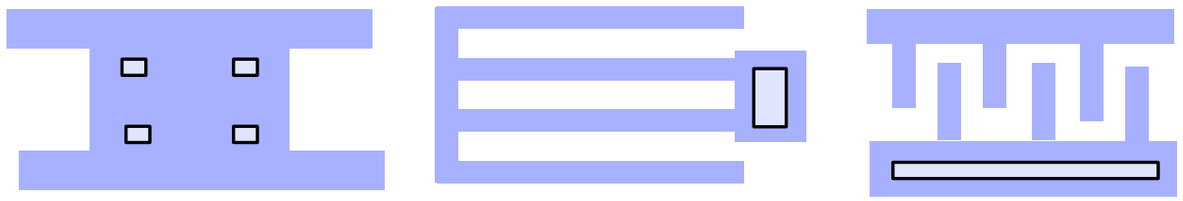
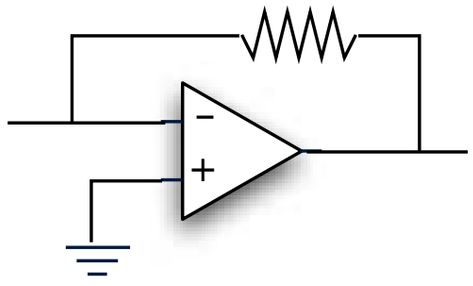
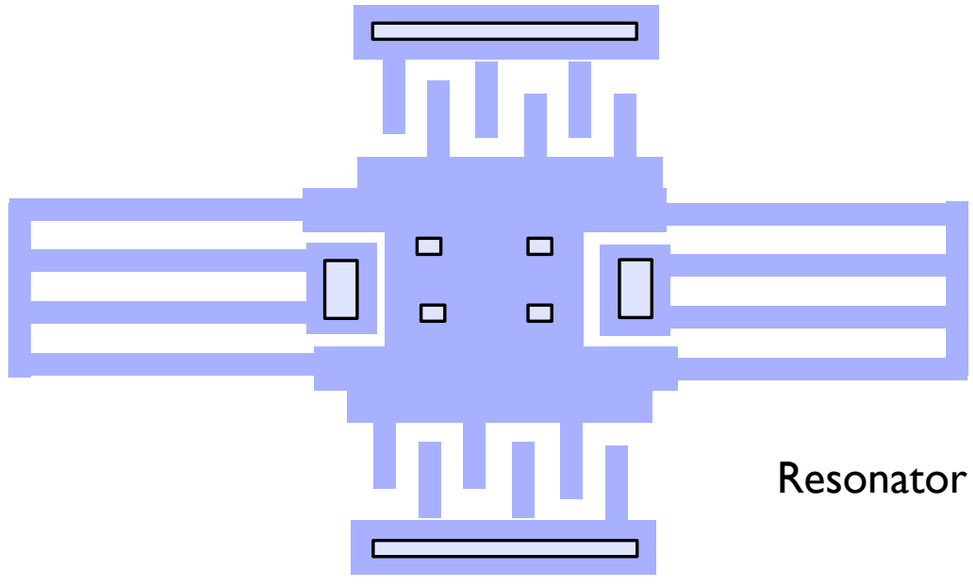
**Multiphysics computation**
Mechanics
Electrostatics
Damping/Dissipation
Piezo
Mixed Signal
Control Systems
1000X faster than FEA

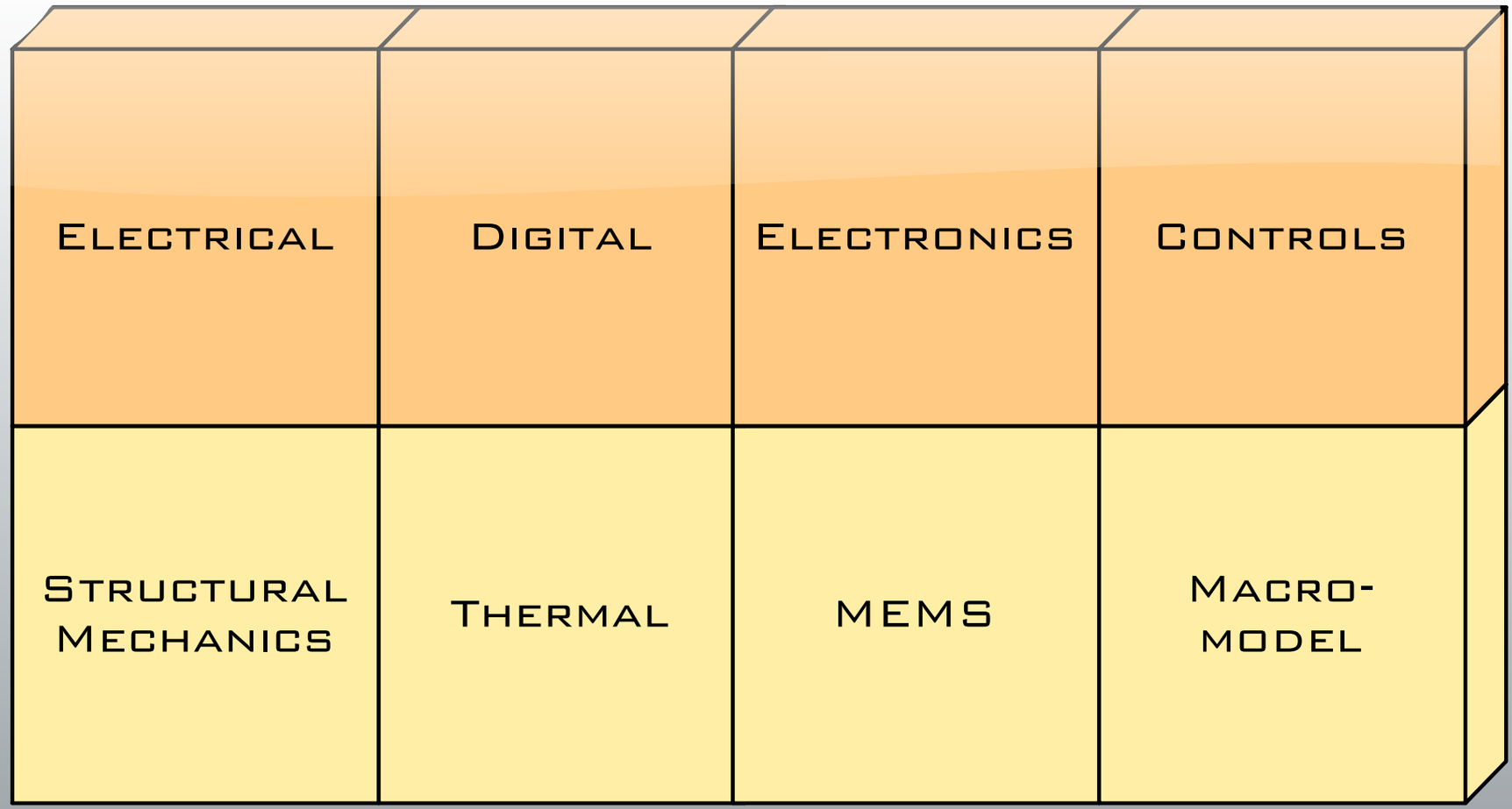

**Synthesis**
Schematic to mask
Schematic to 3D
Schematic to mesh

**Yield Engineering**
DfM
Process Corner studies
Yield prediction

**Link to other tools**
Automatic meshing
Derive process flow

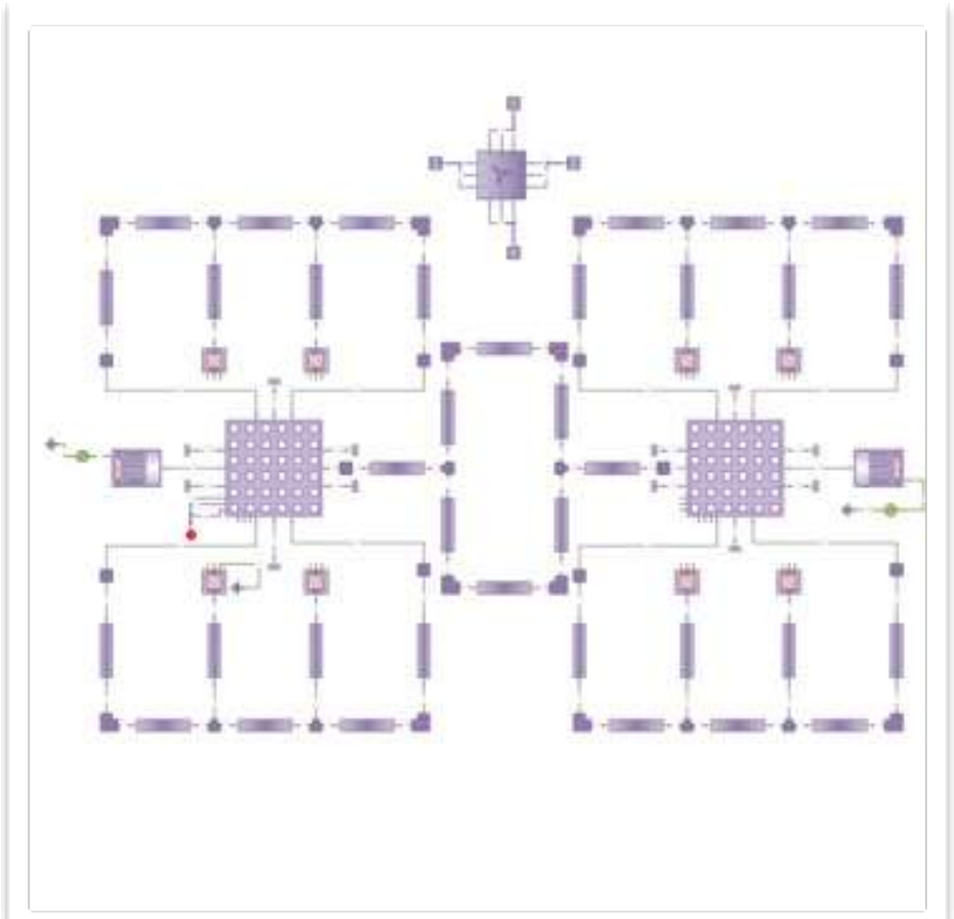
# Hierarchical multi-domain design

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

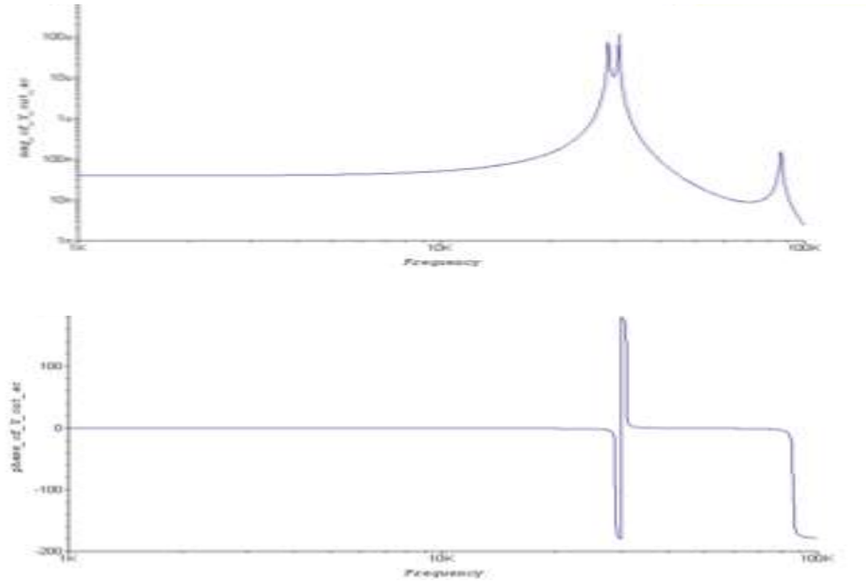



# Wide Range of Building Blocks

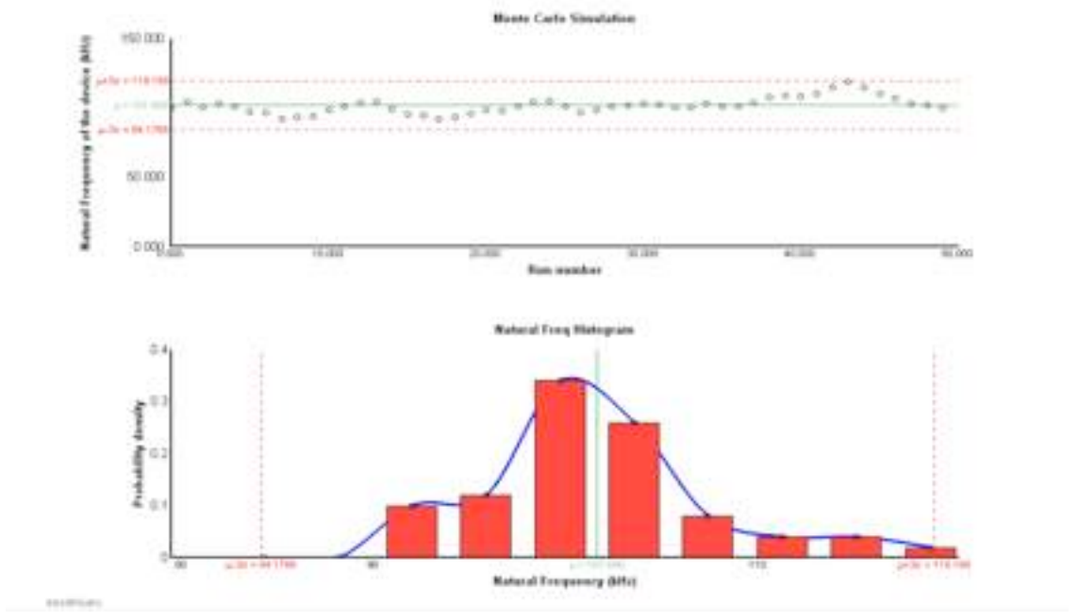
# Schematic based design exploration



Band pass filter

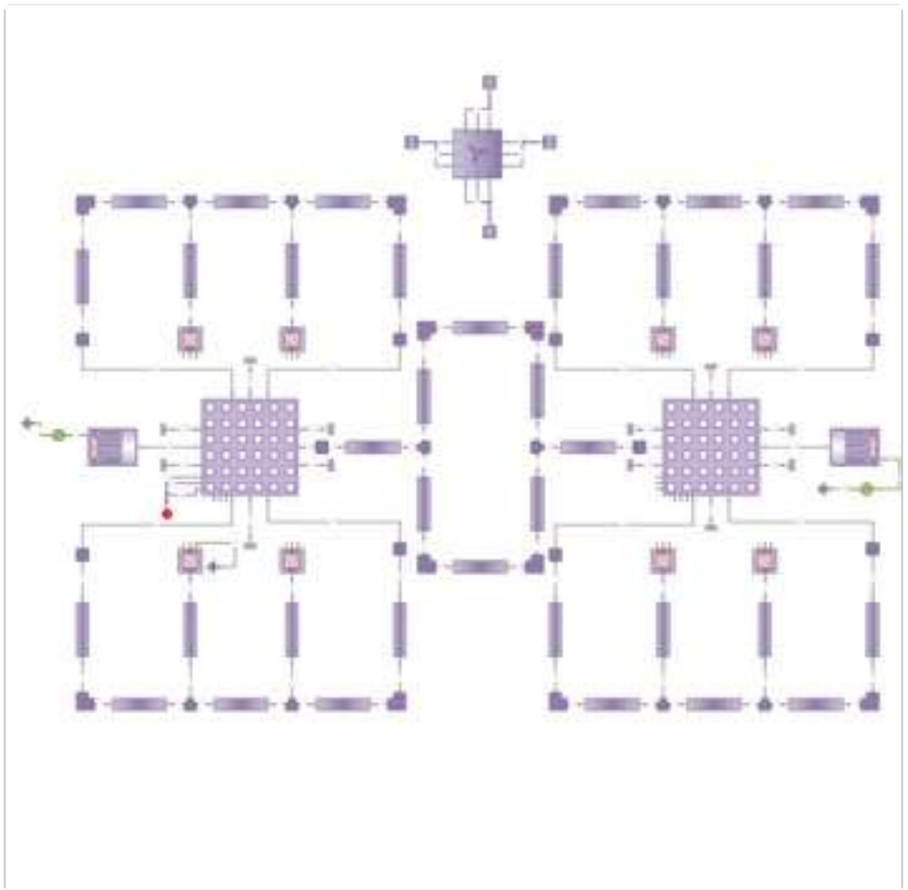


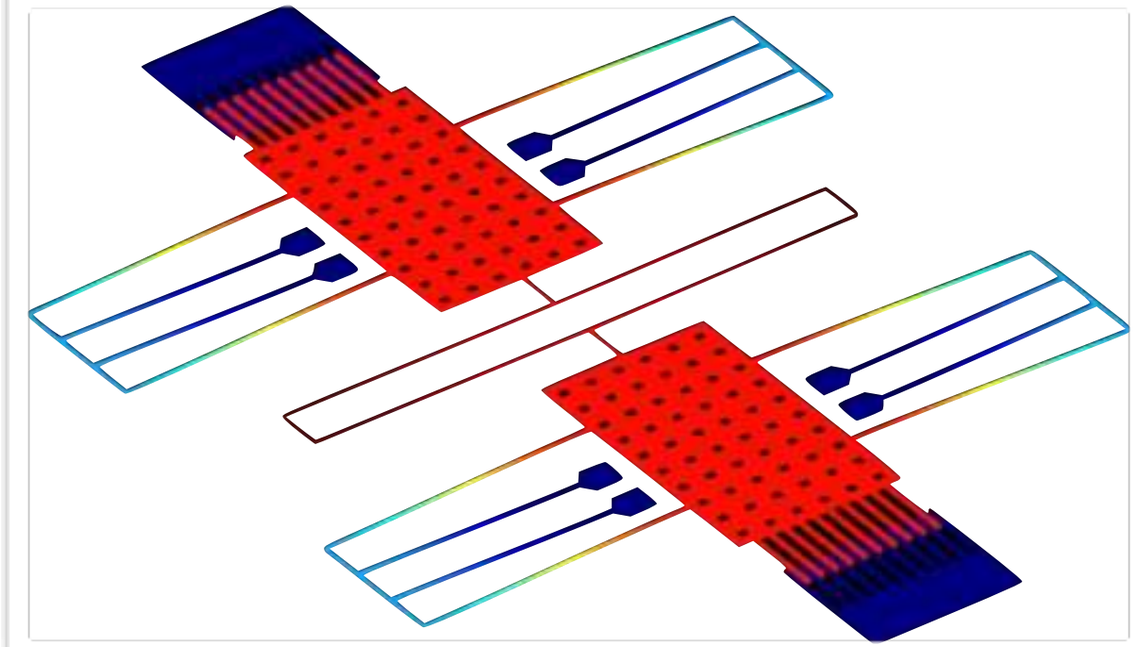
Compute time: 4 hr (Full 3D) vs 30s (compact)



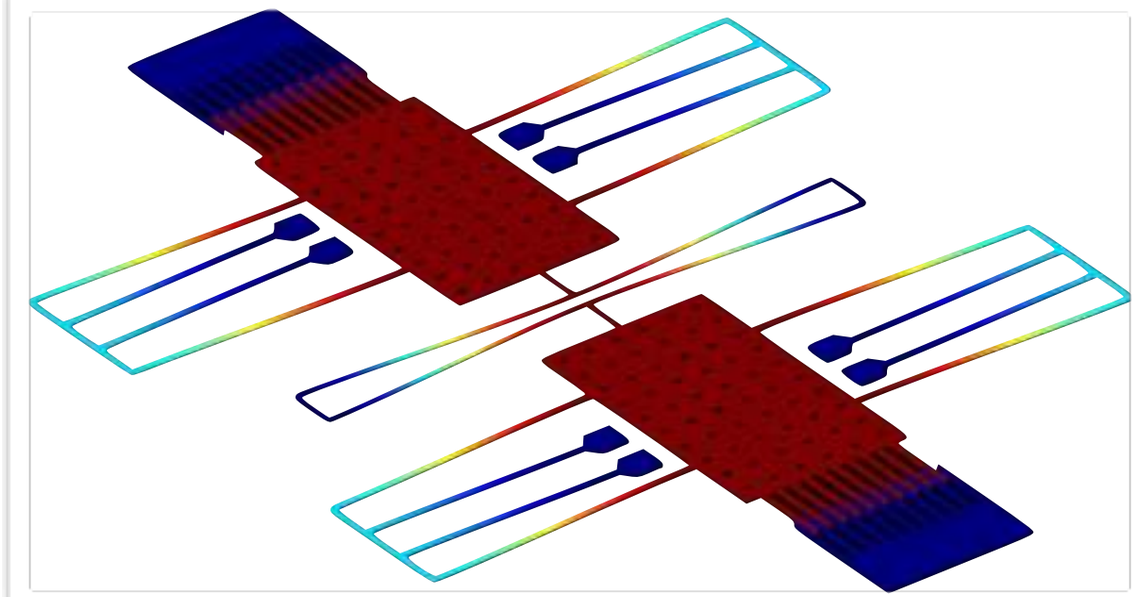

Monte Carlo based
process variation analysis

# Visualize schematic results in 3D



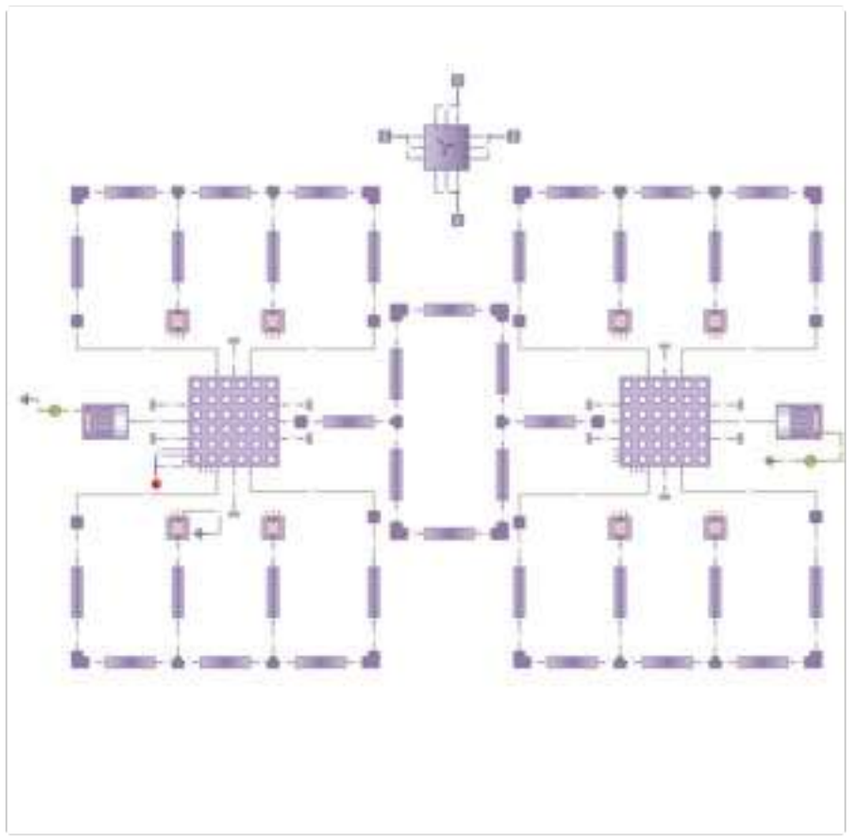


**Mode 1**: In Phase

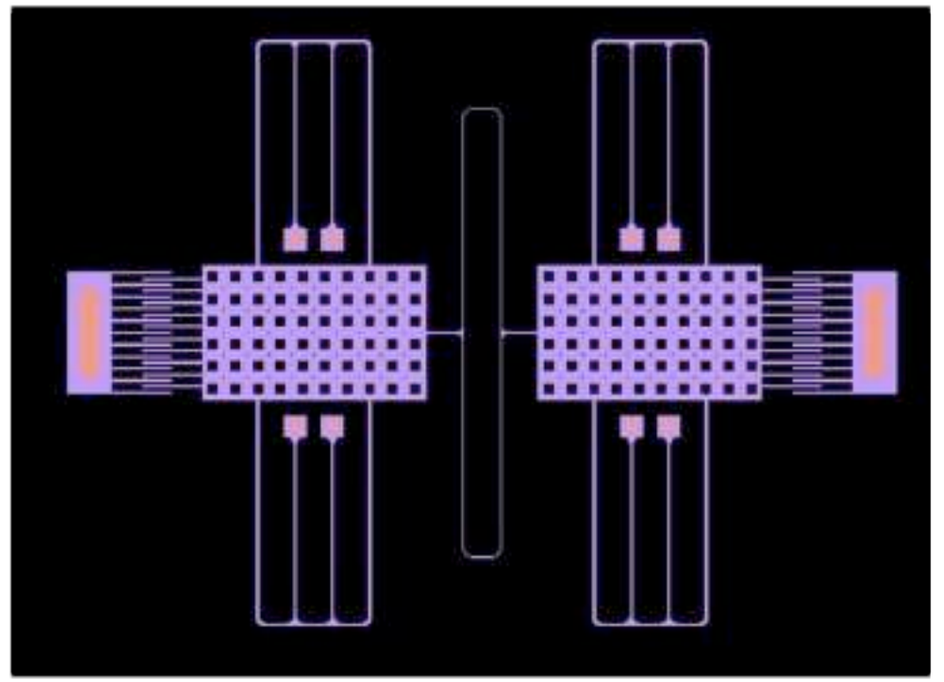


**Mode 2**: Anti Phase

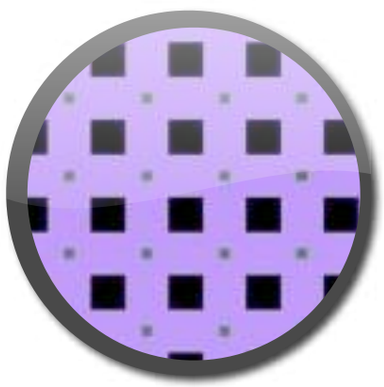
# Schematic to mask



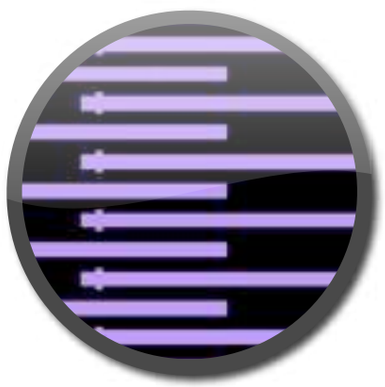
Automated layout synthesis



Stress relief curves



Dimples

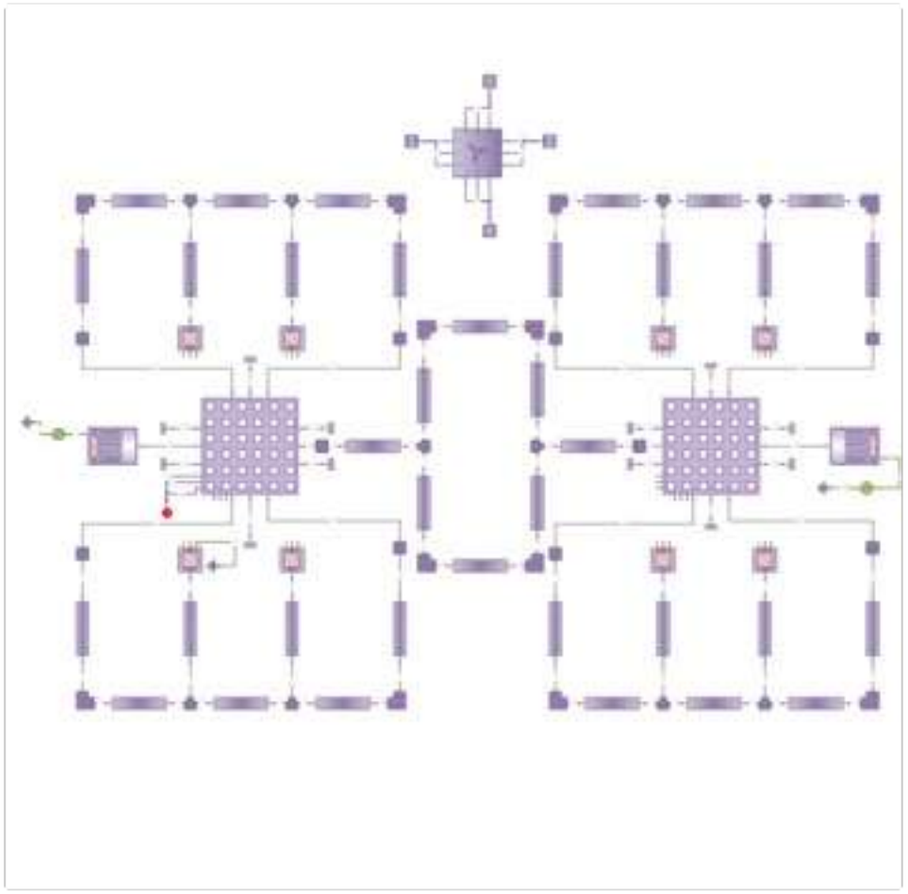


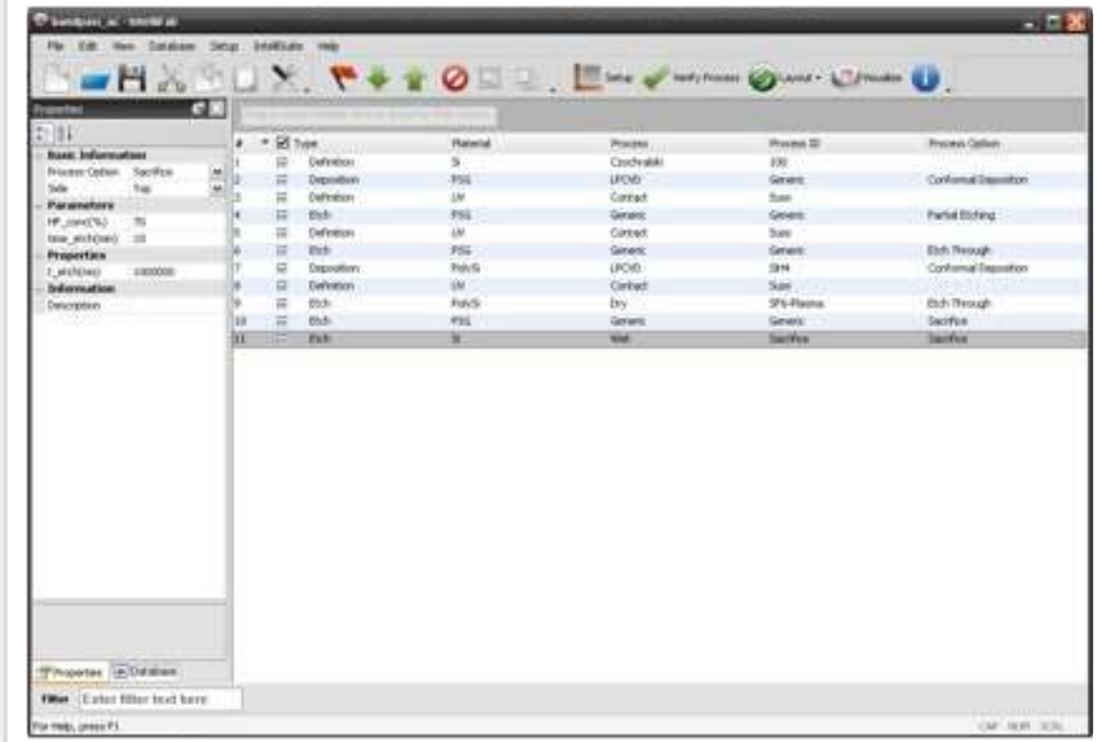
Comb bumpers

Etch compensation features

**Attention to detail**

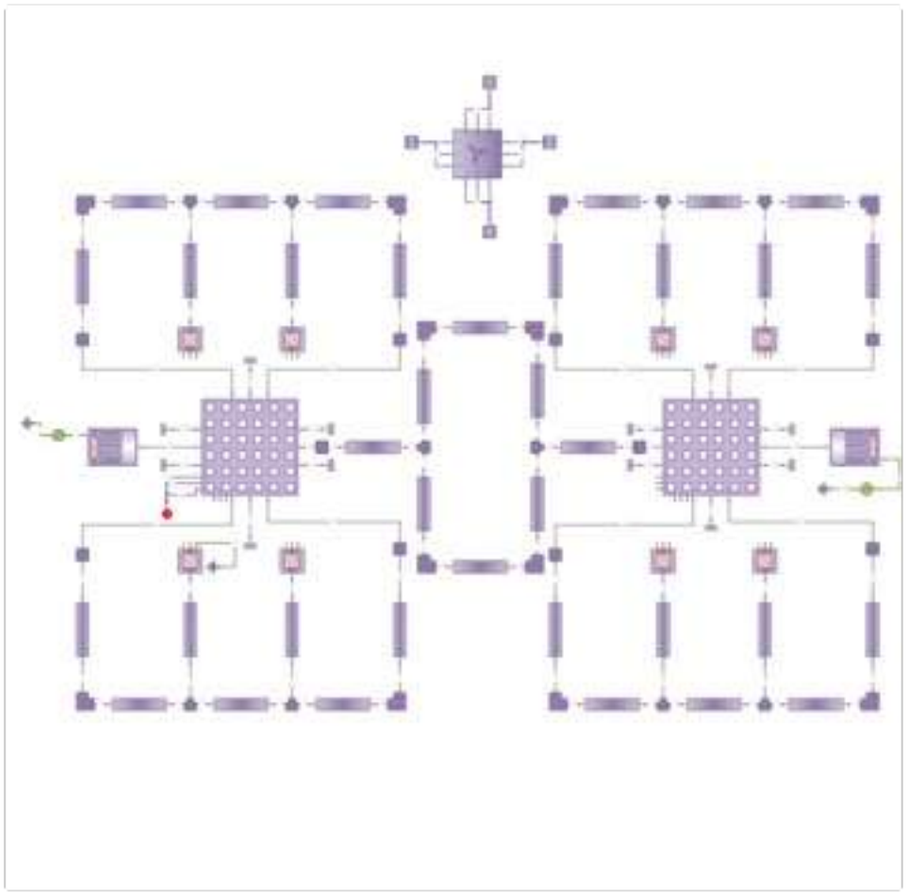
# Schematic to process flow

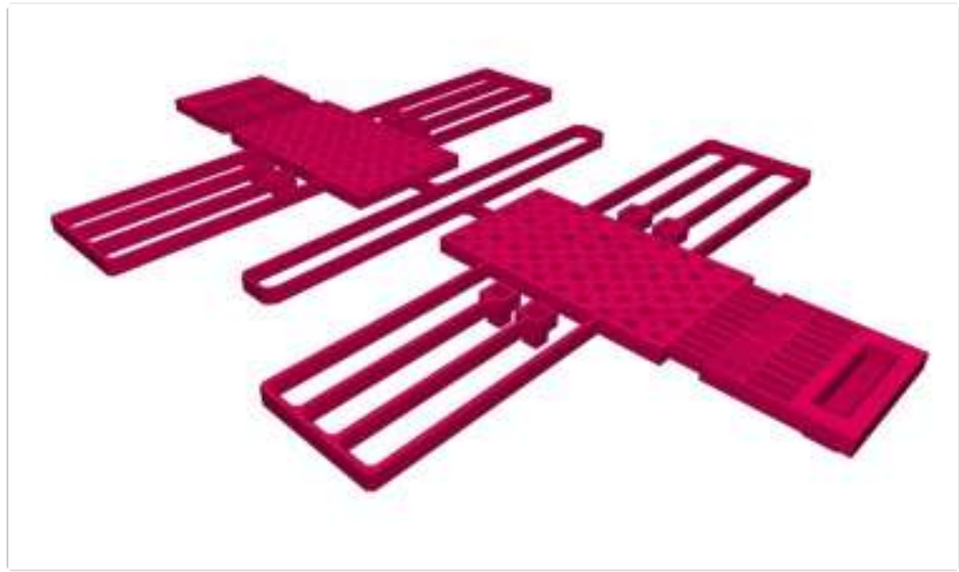


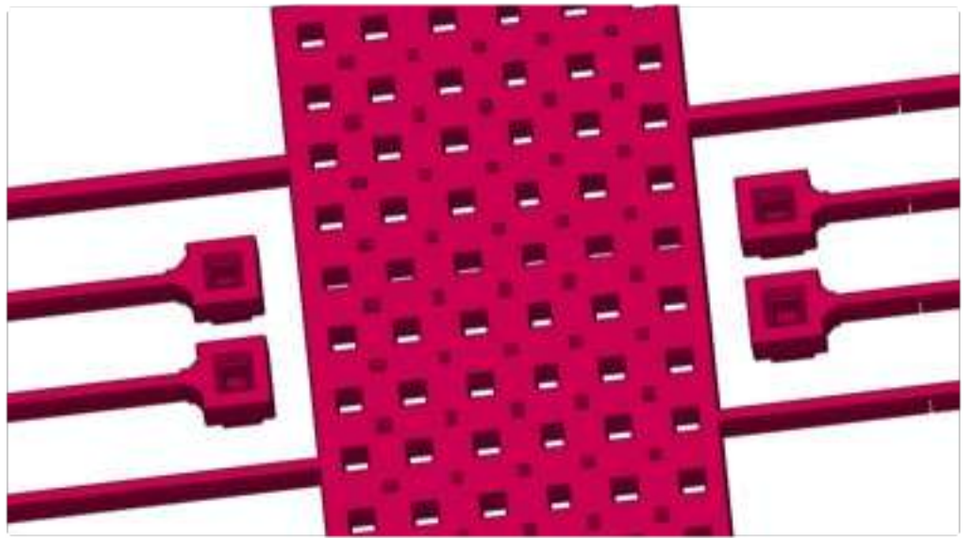


Process flow for fabricating the device is automatically derived from the schematic and technology file information

# Schematic to 3D model

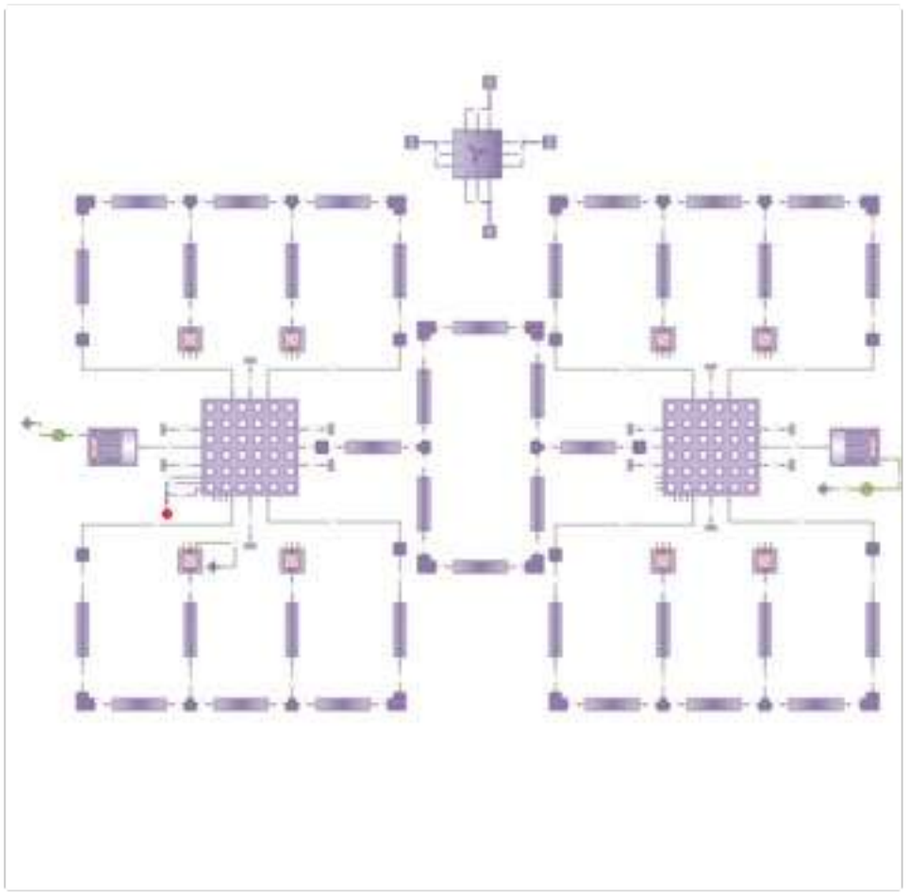


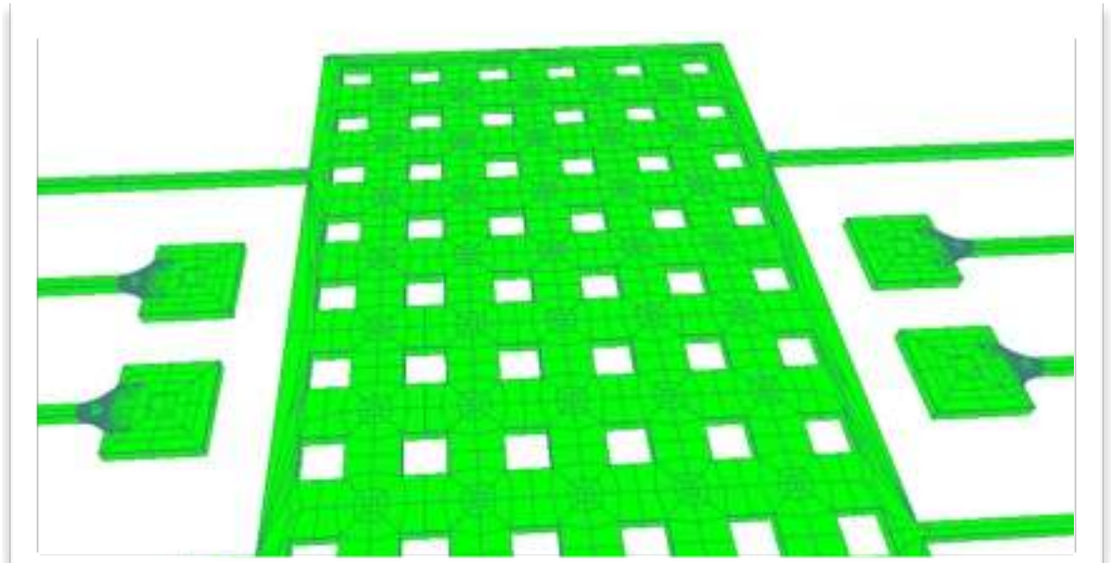


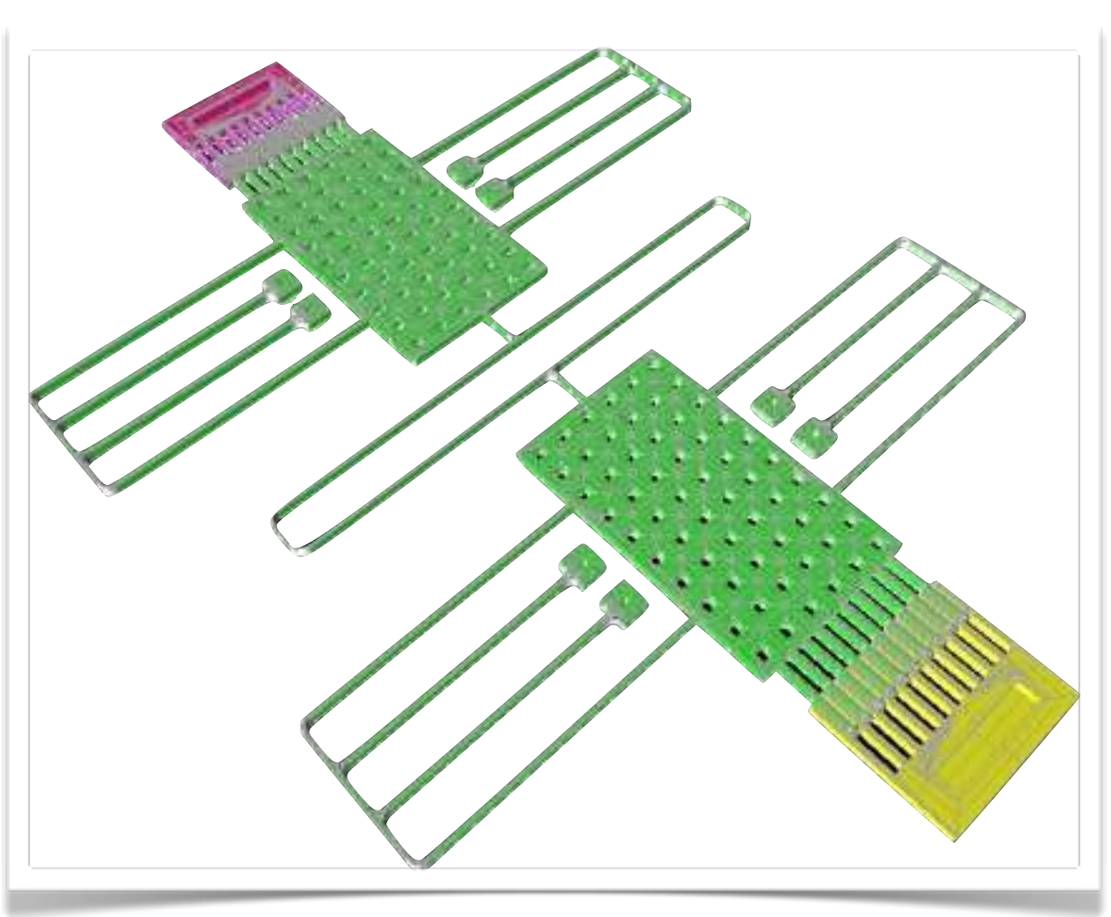


**Attention to detail**
Automatic placement of dimples, anchors and other secondary features

# 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.

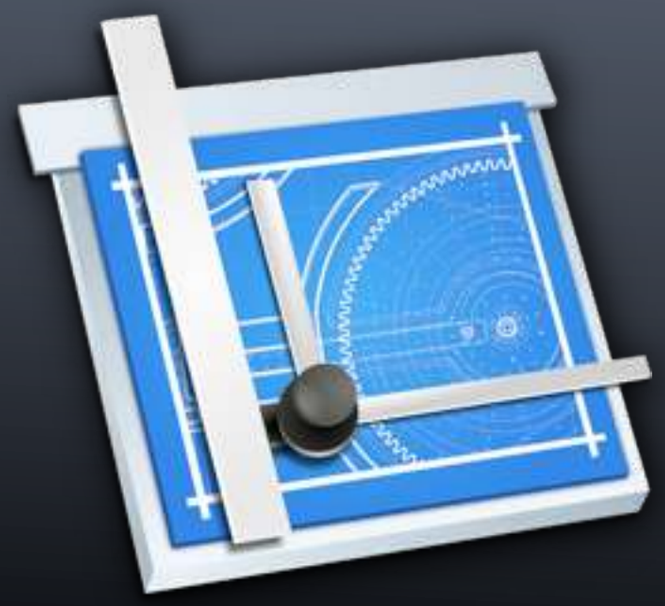
- **Design exploration and optimization**

  Quickly prototype and explore multiple designs

- **3D System modeling**

  View your results in 3D

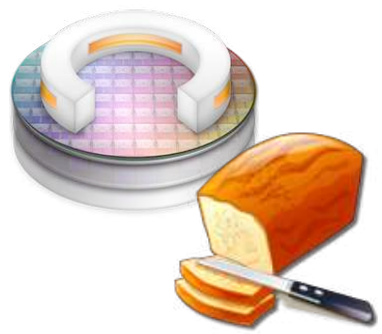
# Physical design & verification



# 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

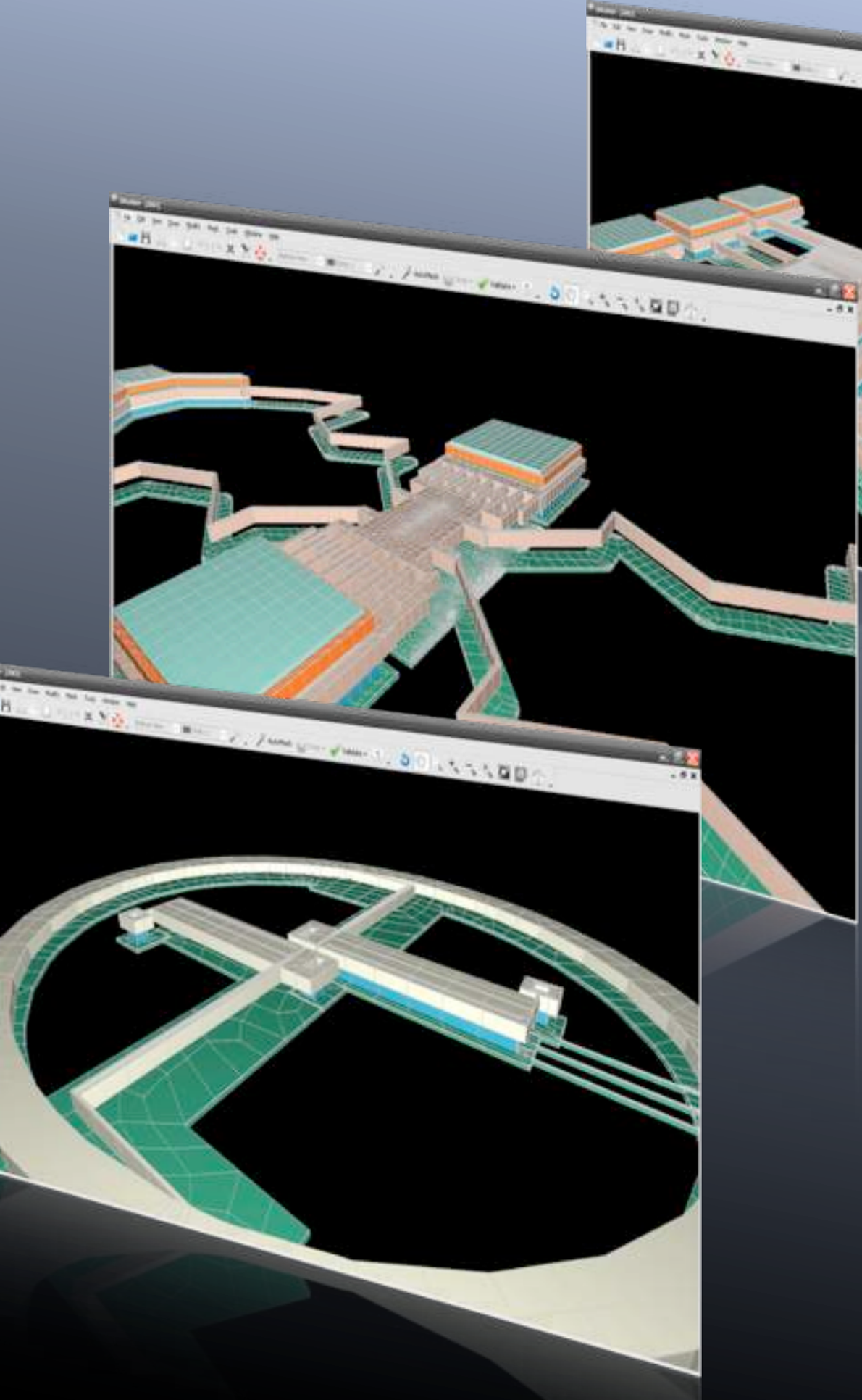


**Layout visualization**
Cross section drawing
3D Visualization of layout

**Hexpresso**
Automated HEX mesher
1 click Mask to Mesh

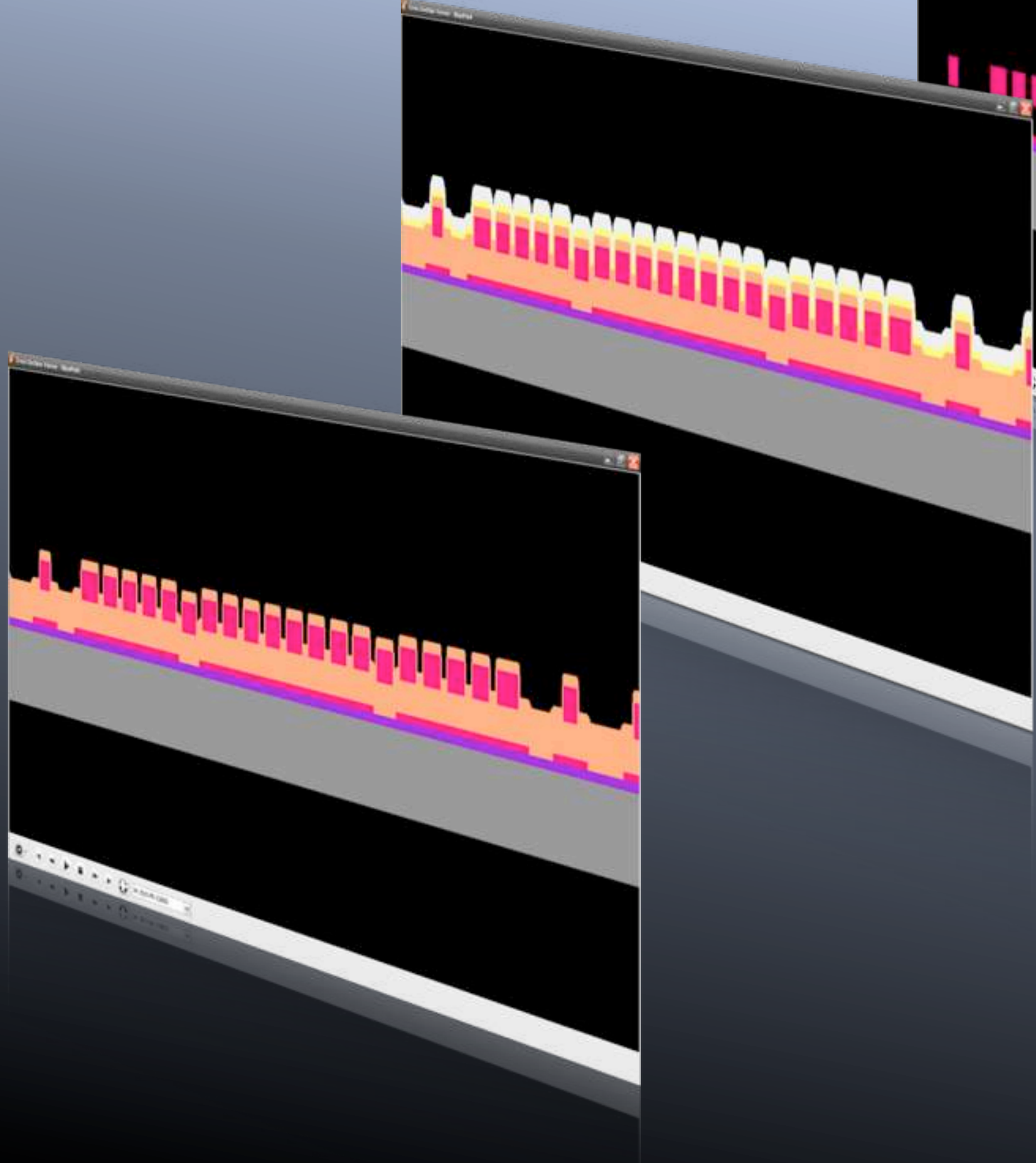
# Blueprint

## mems design editor



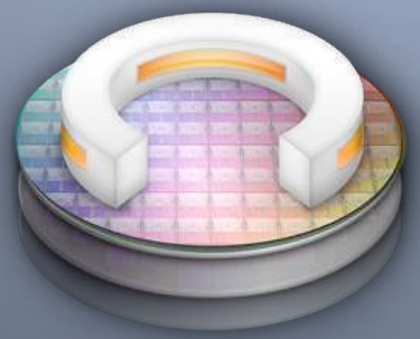
# Hexpresso

hex meshing in a jiffy

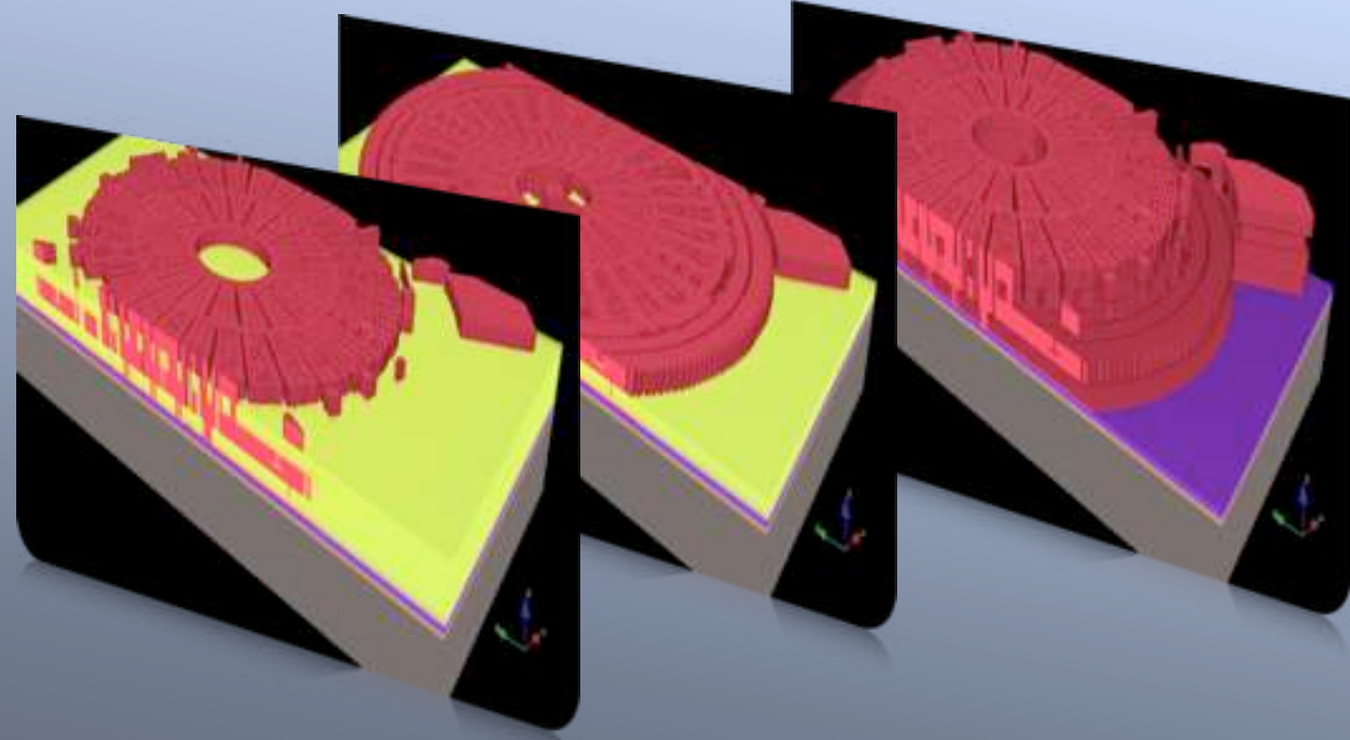


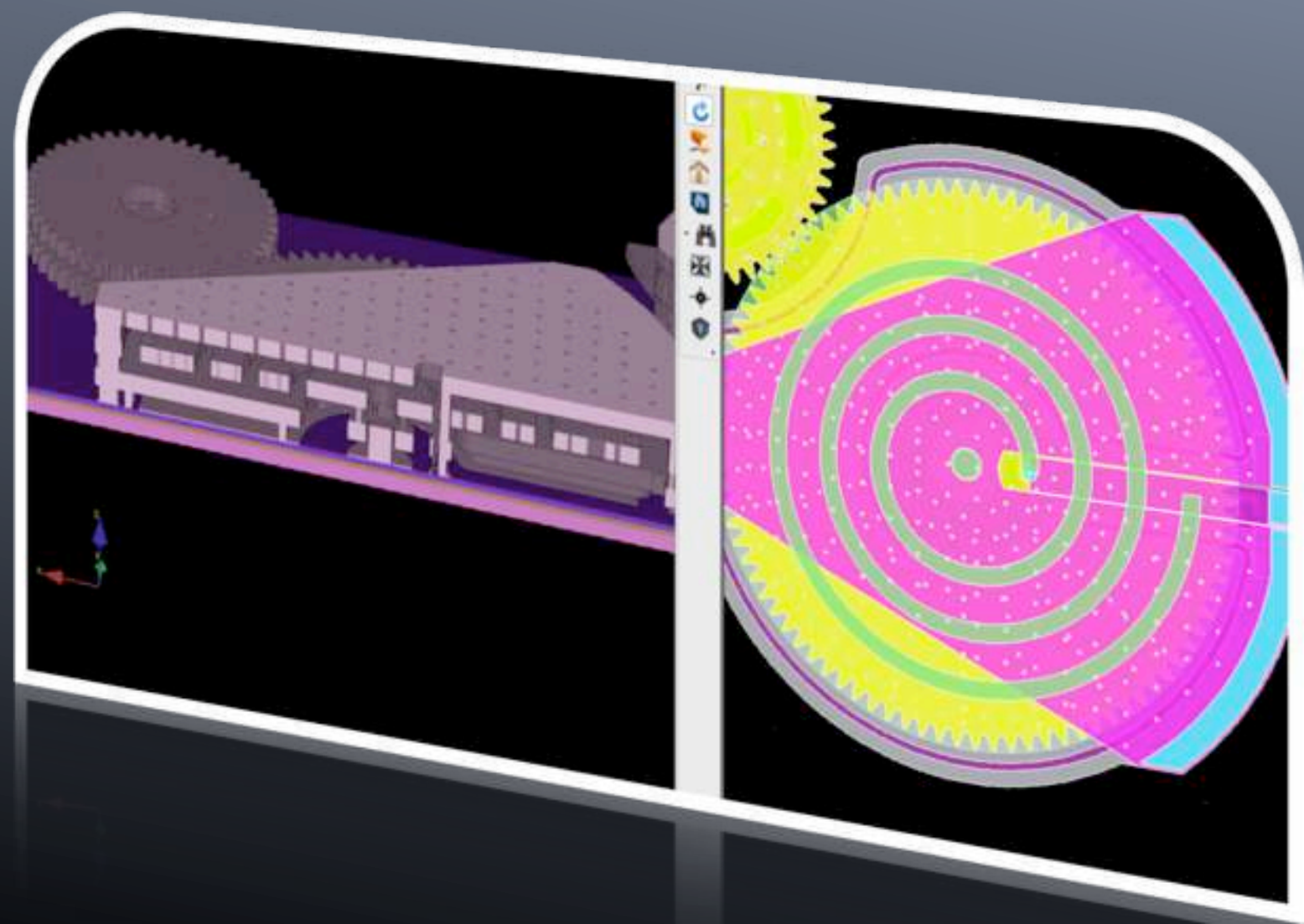
# CS Viewer

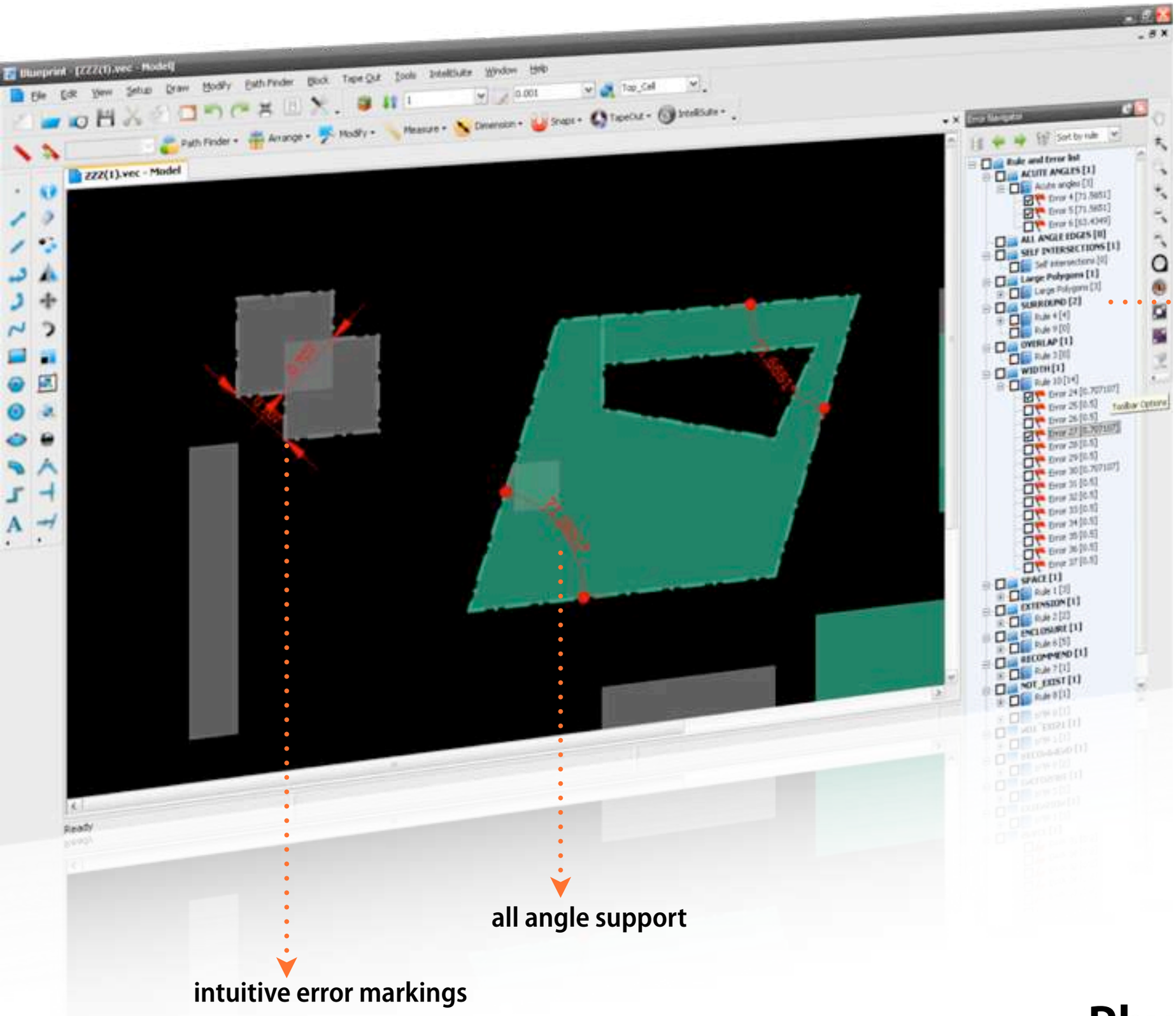
Step by step process visualization



# 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

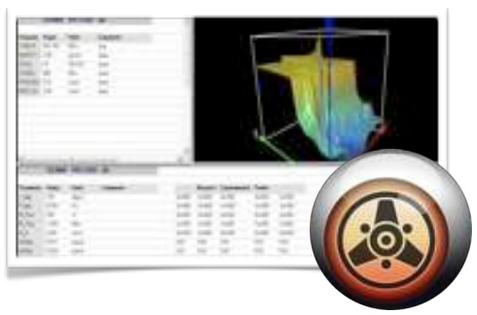
***Ab initio*** based etch modeling
wet and dry etch modeling

## Hexpresso

Automated hexahedral meshing engine for FEA/BEA model creation

# Clean Room capabilities (Process)

**Process capture**
Develop process traveller
Debug traveller
Create process databases



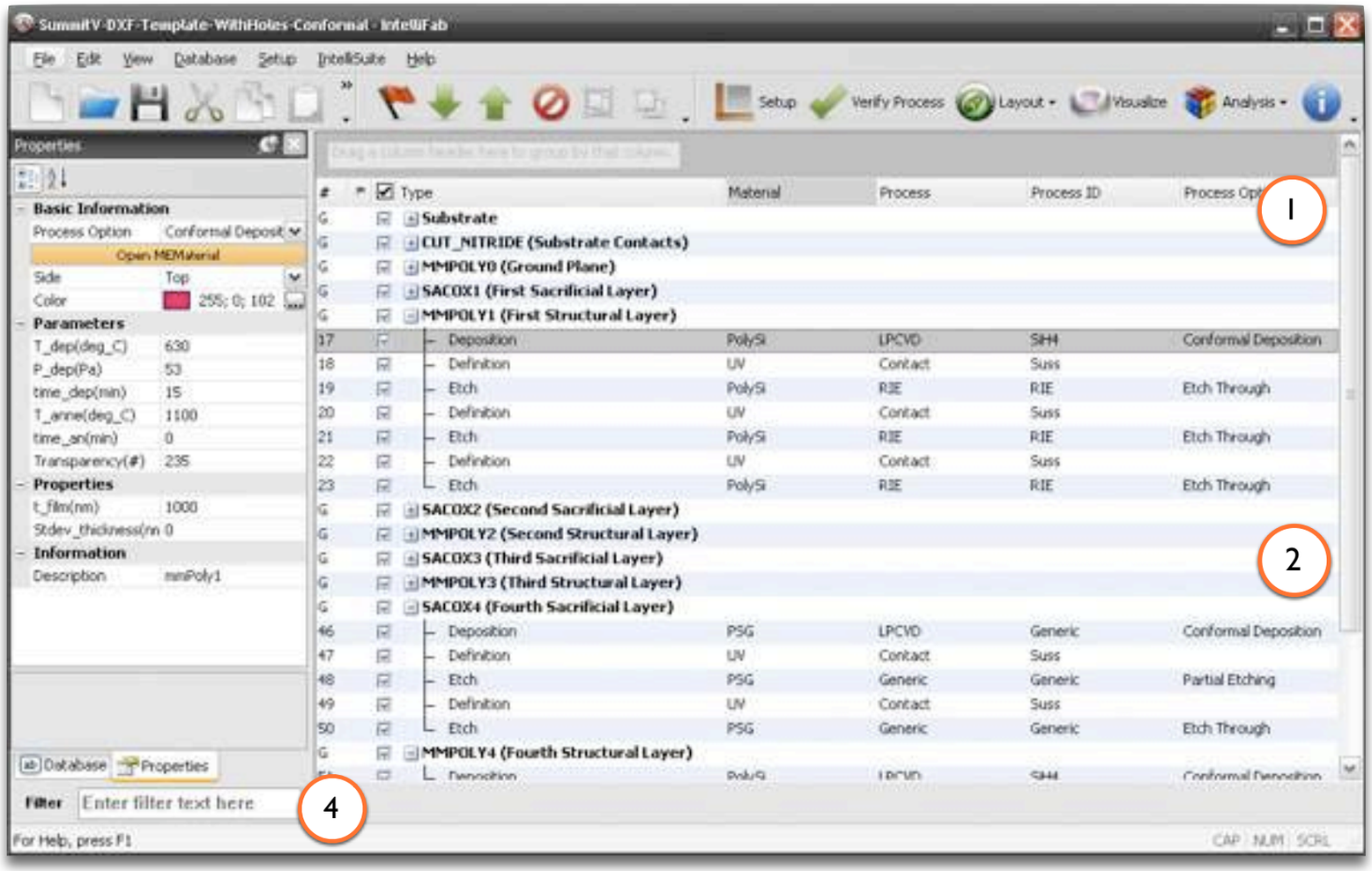
**Material databases**
Process correlated databases
Material properties

**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…

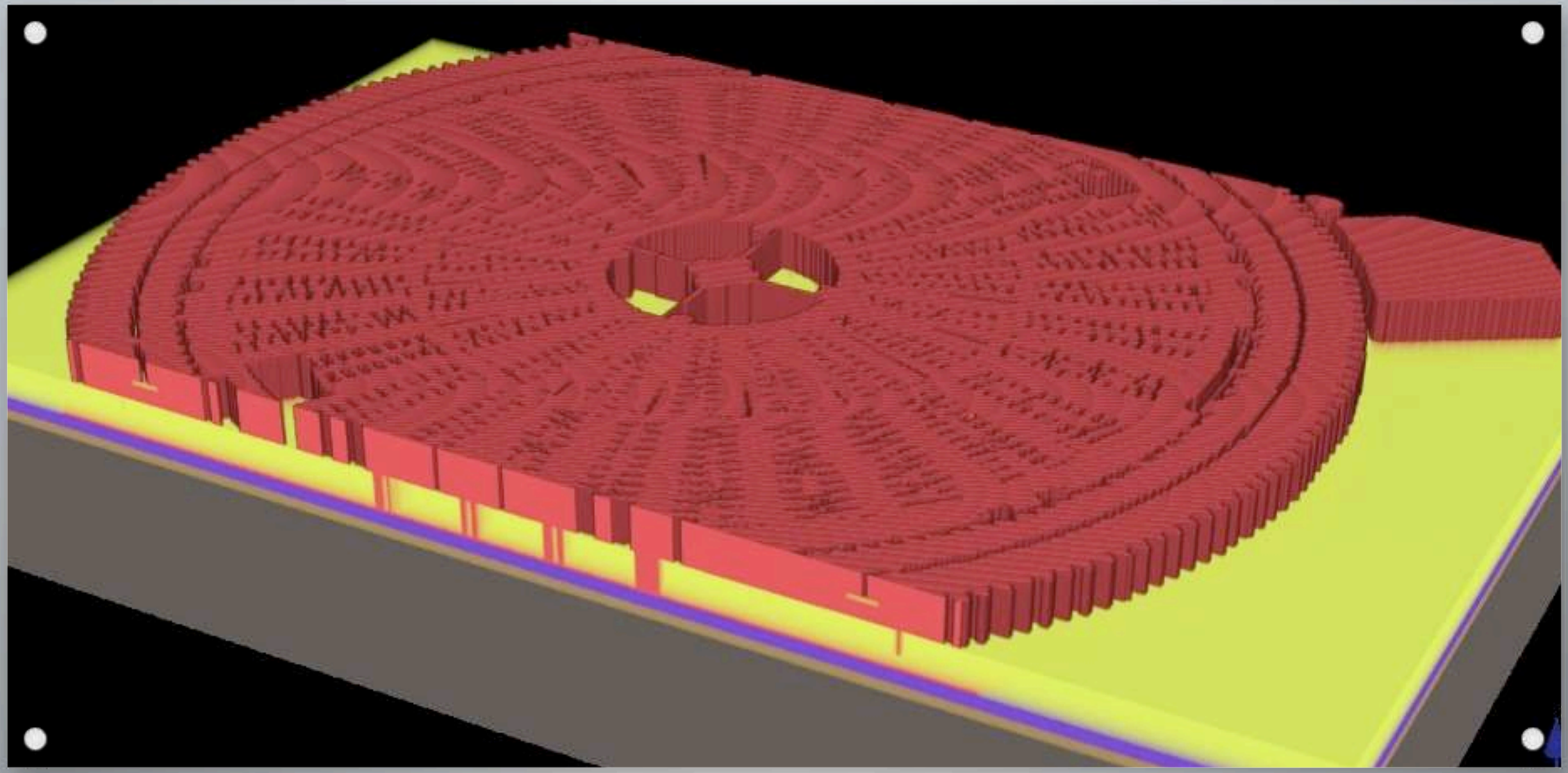
**Process Pane**
Enter process parameters, tolerances and visualization settings in a single consolidated pane




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

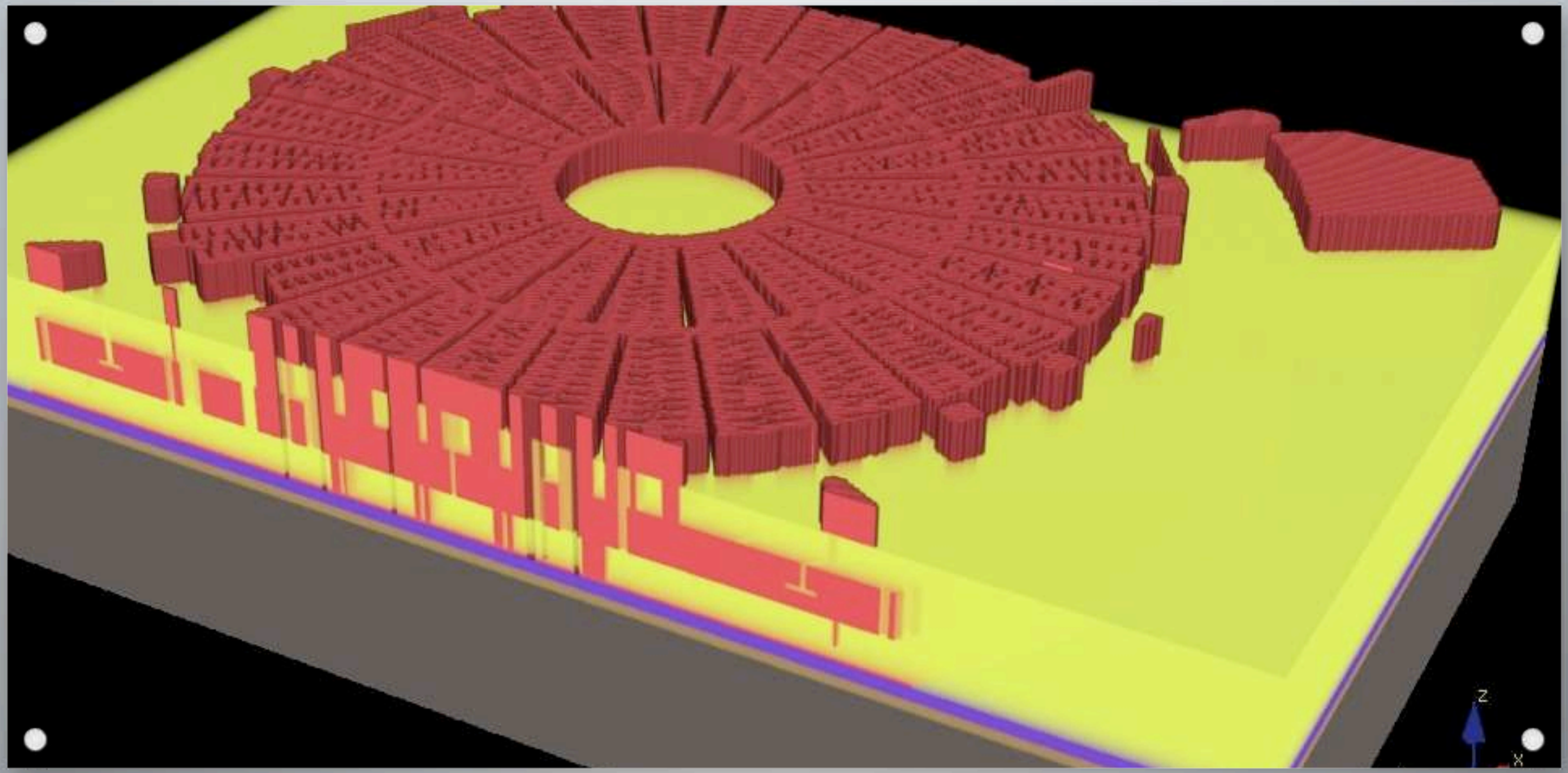
**Process Editor for MEMS**
IntelliFAB makes editing and organizing a process table quick and easy. Setup your virtual process traveller exactly as you would for a real foundry.

**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.



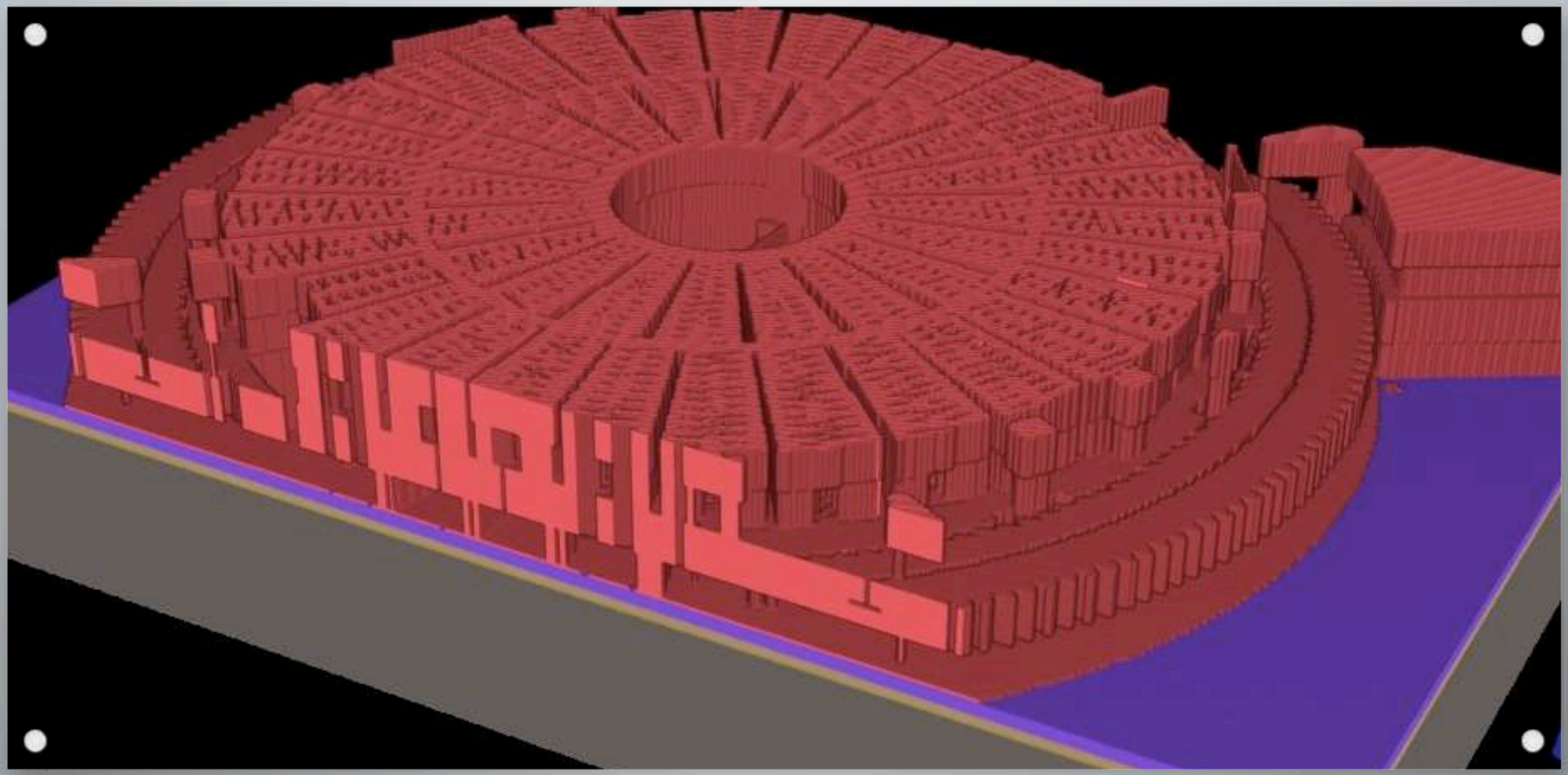
# Visualize Complex process flows

Courtesy, Prof Tim Dallas, Texas Tech




# Visualize Complex process flows

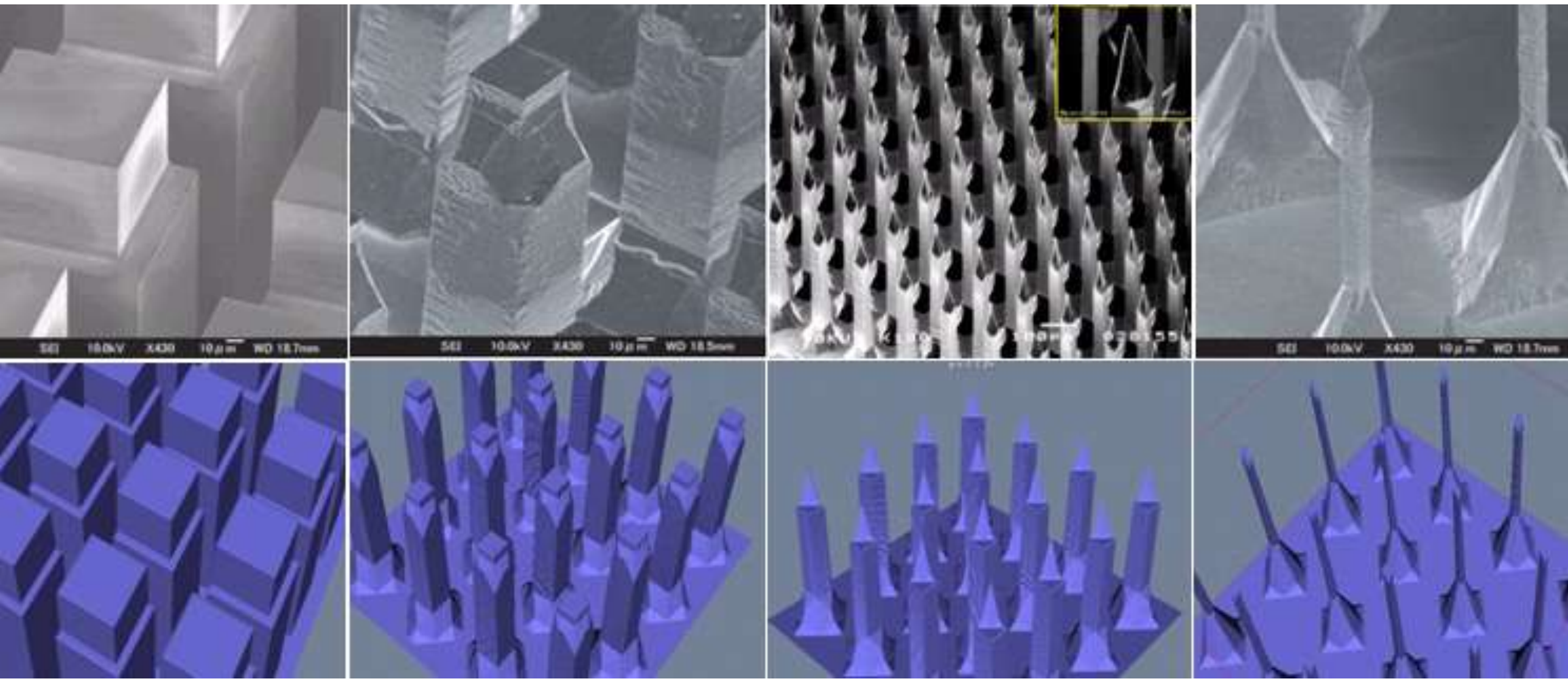
Courtesy, Prof Tim Dallas, Texas Tech



# Visualize Complex process flows

Courtesy, Prof Tim Dallas, Texas Tech

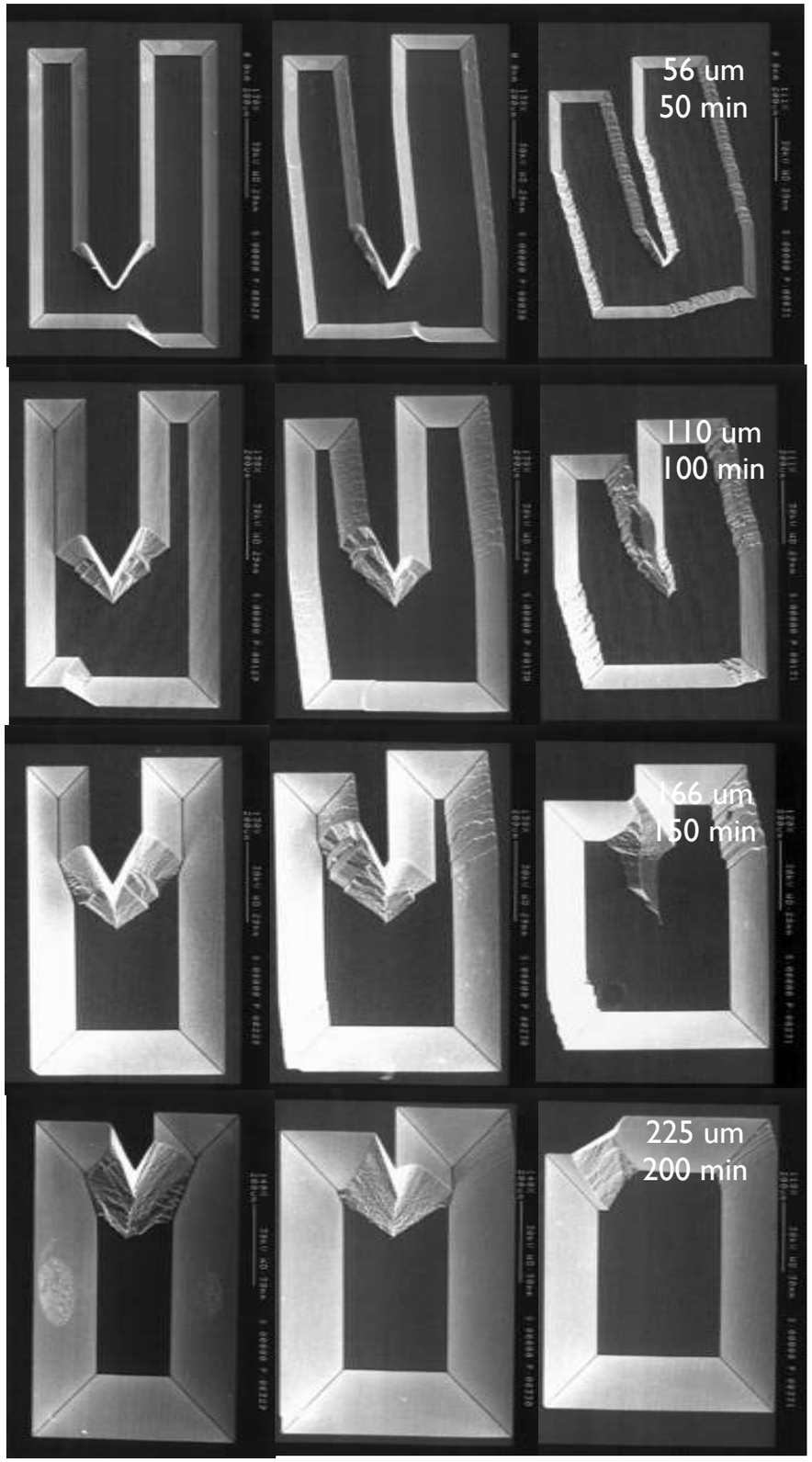
# Simulate composite MEMS processes



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

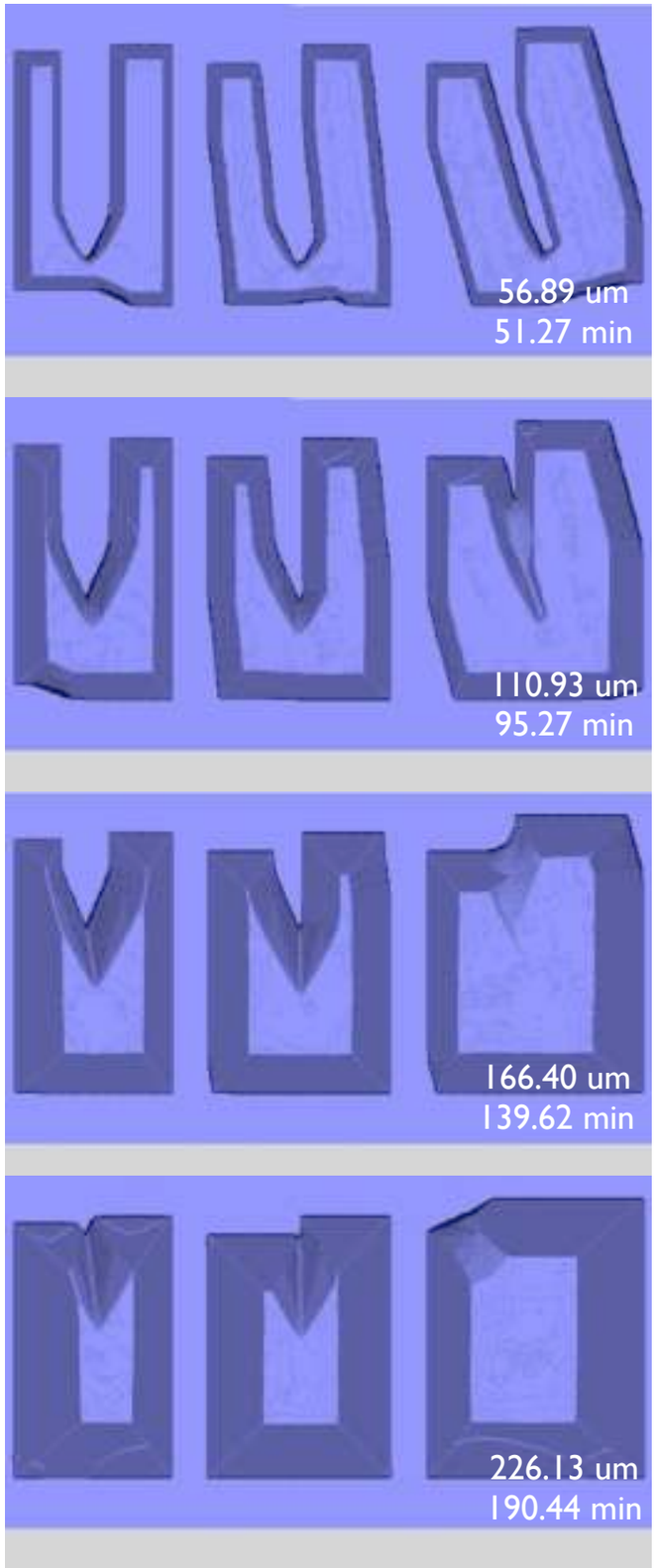
Composite processes, Shikida Mitsuhiro, J. Micromech. Microeng. 14

# Validate processes in design



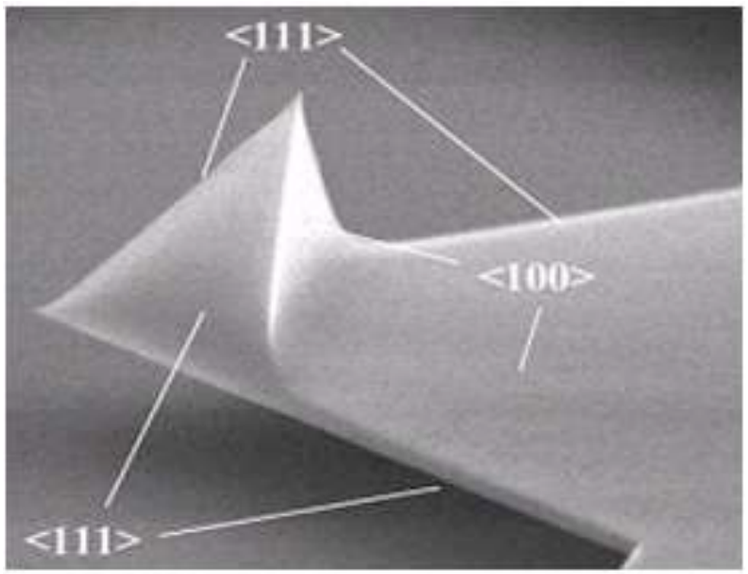

Measured

vs

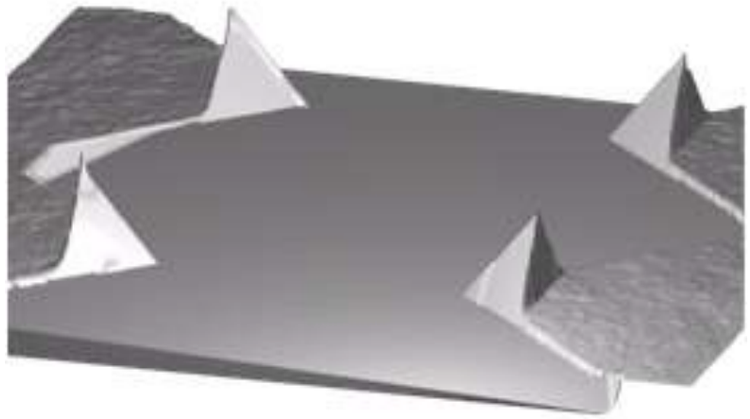


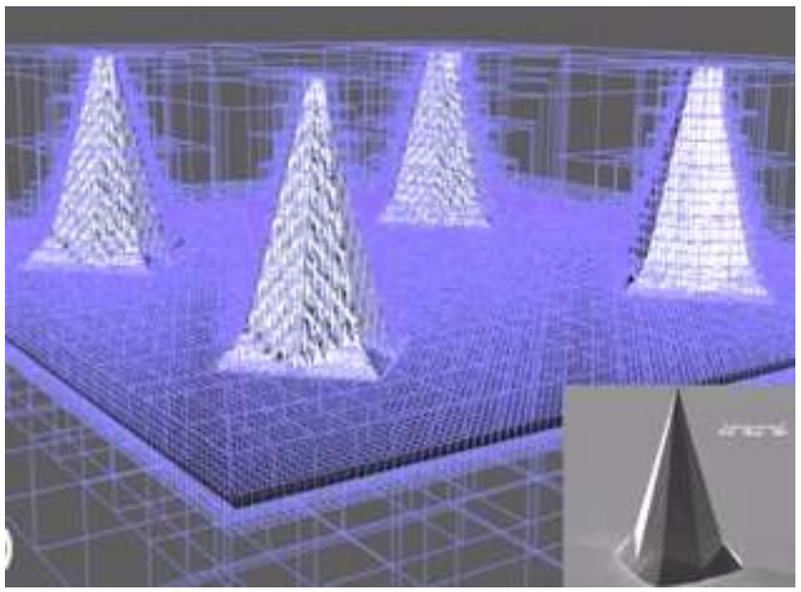

Modeled

# Higher order plane etching



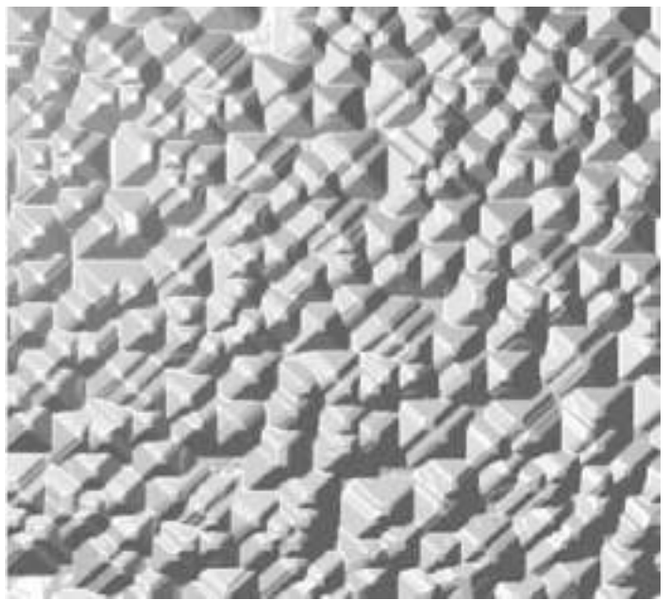

D. Saya, Sensors & Actuators A95 (2002)



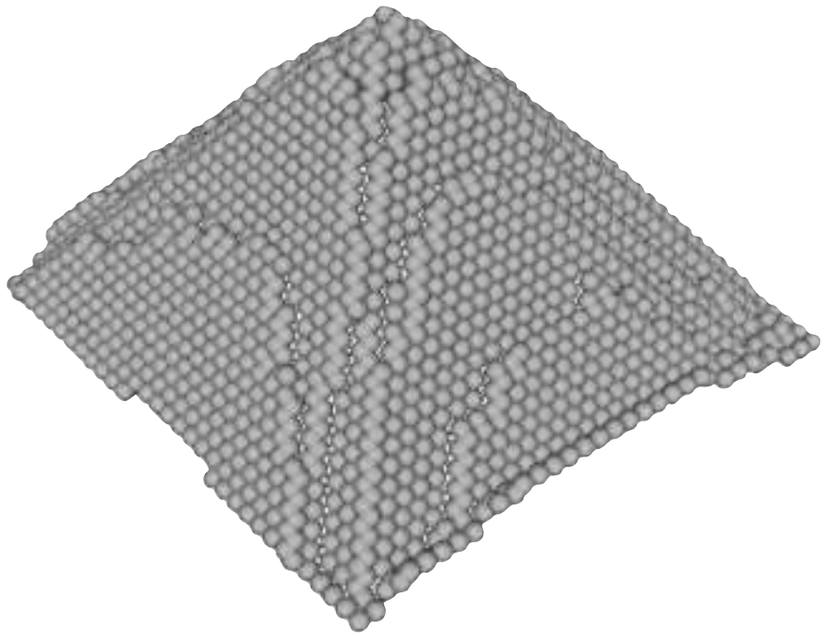


Simulation results

# Surface morphology prediction

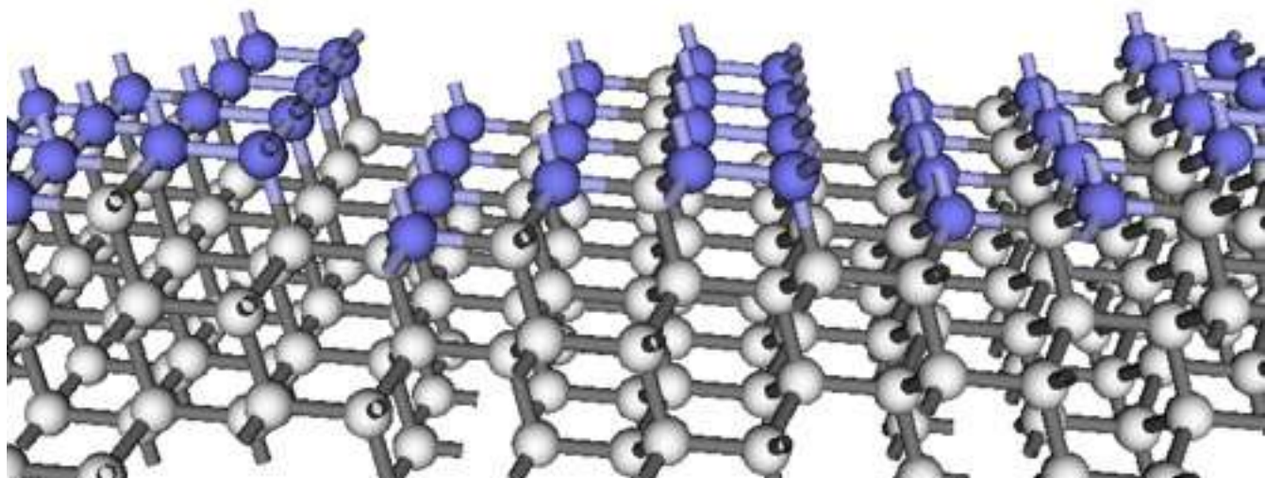


Pyramid like morphology on 100 Si
subject to wet anisotropic etching

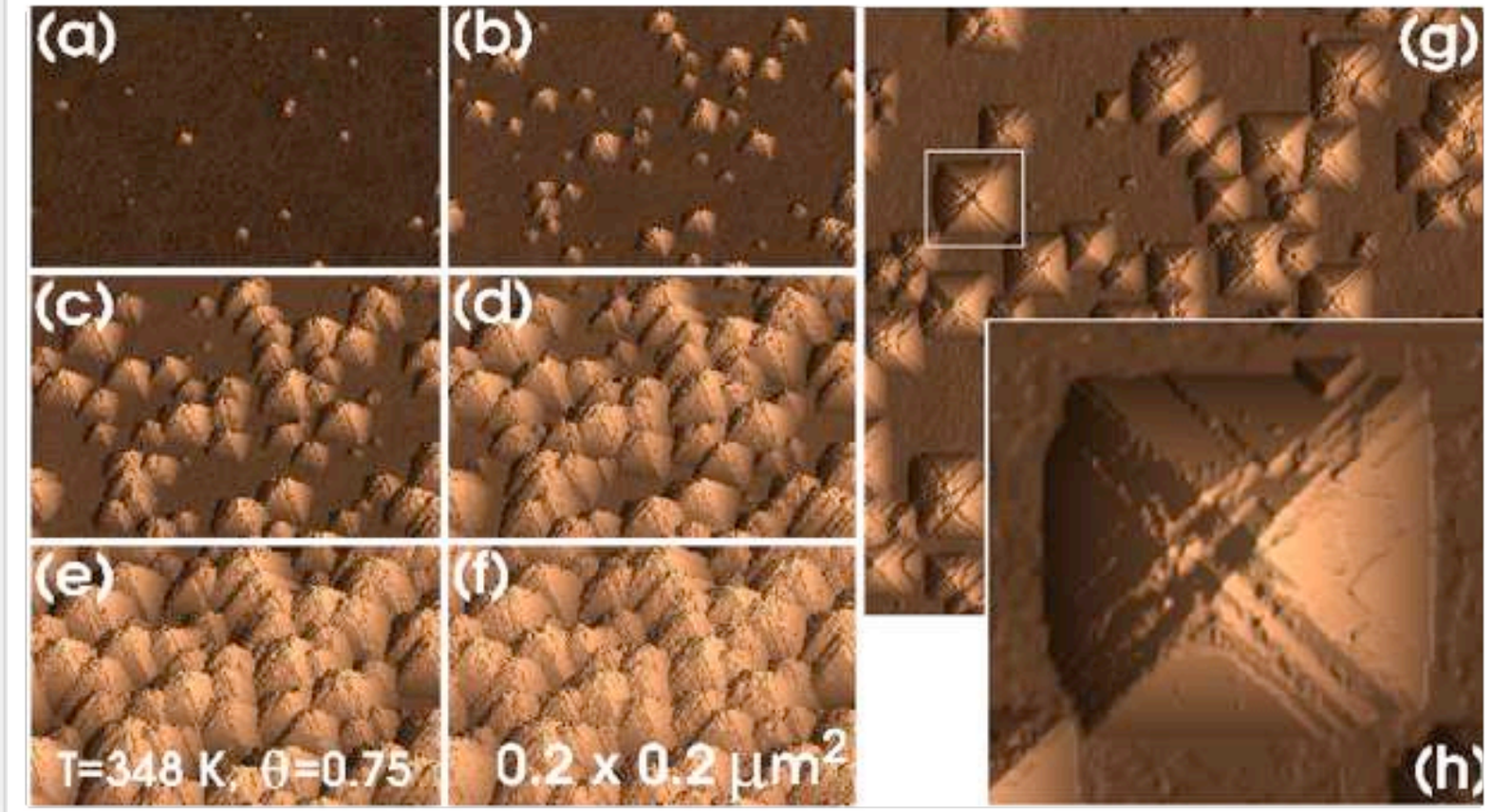


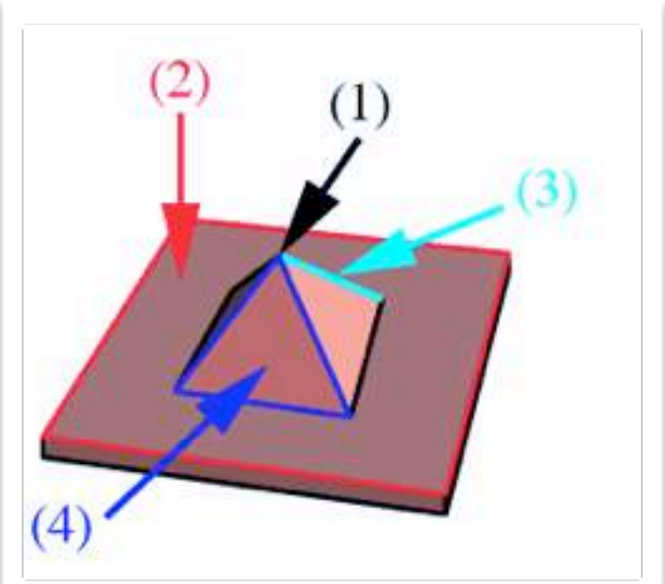
Simulation results predict pyramid formation

Arbitrary Cut Planes <533>
to understand the physics



# Surface morphology prediction

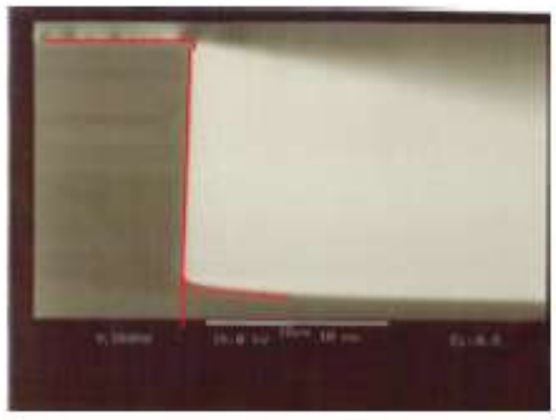


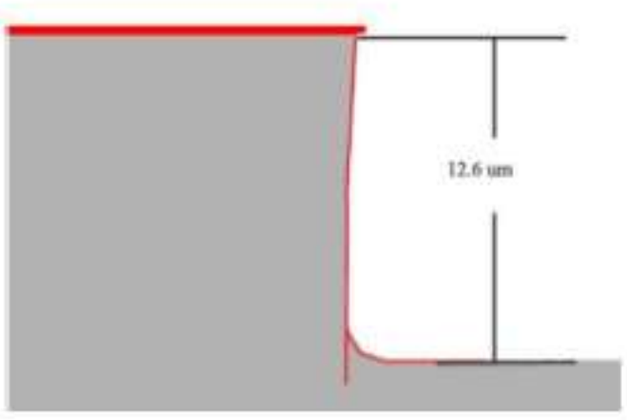



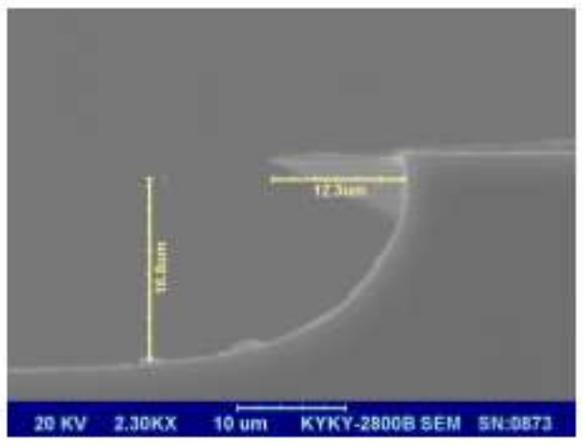

1 Micromasking of apex
2 Floor moves down fast
3 Edges are stable
4 Facets are very stable

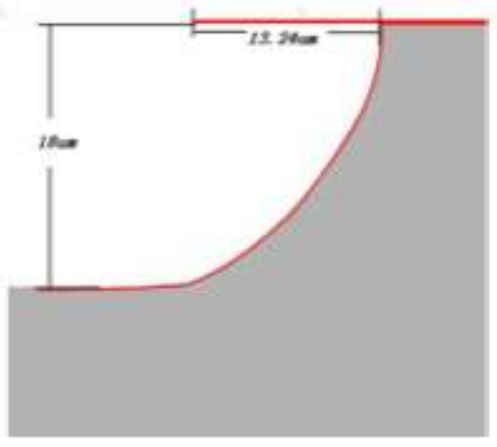
## Hillock formation prediction

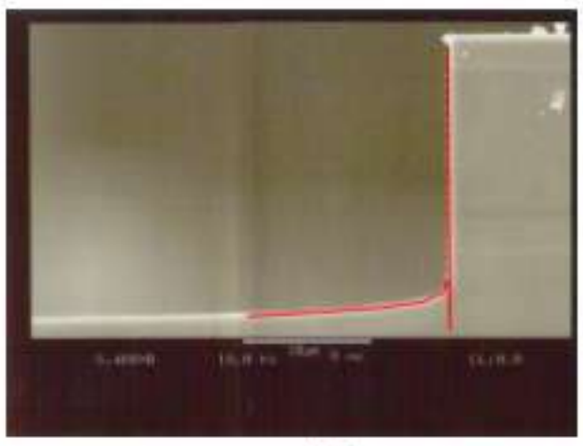
# DRIE Etch characterization experiments (1)

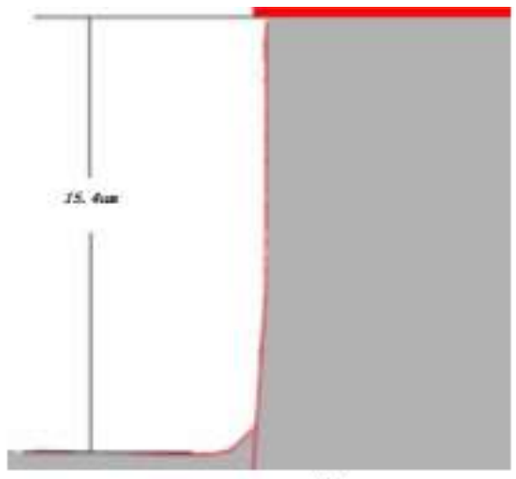


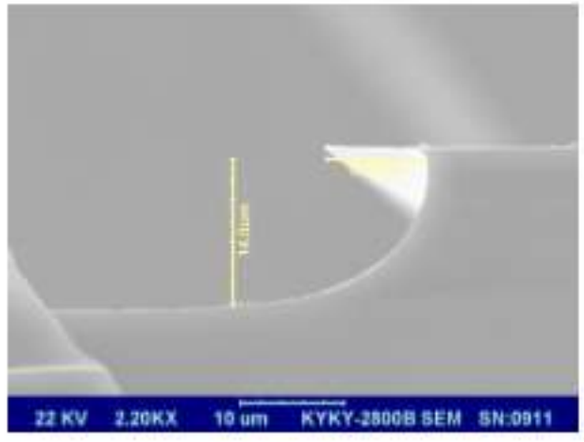


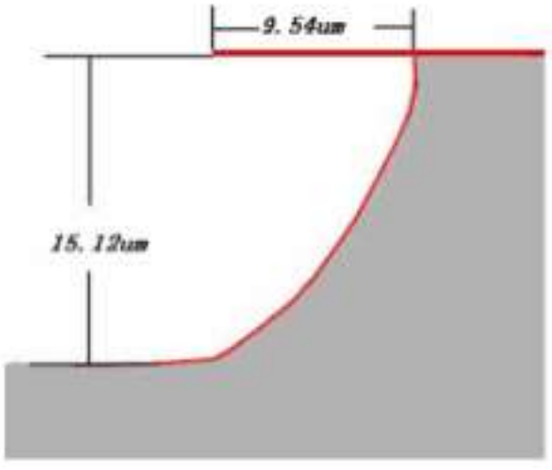



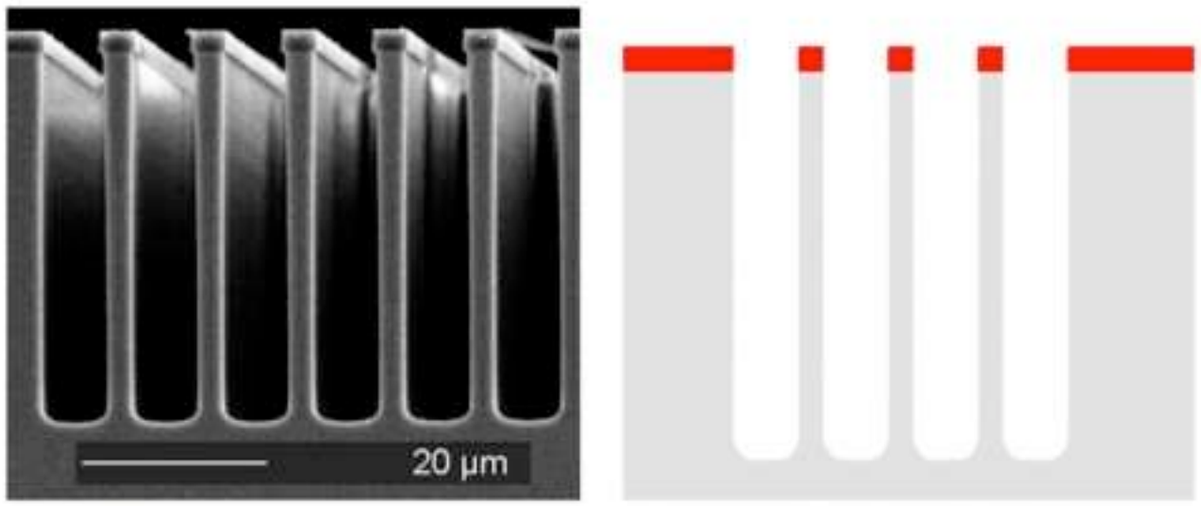





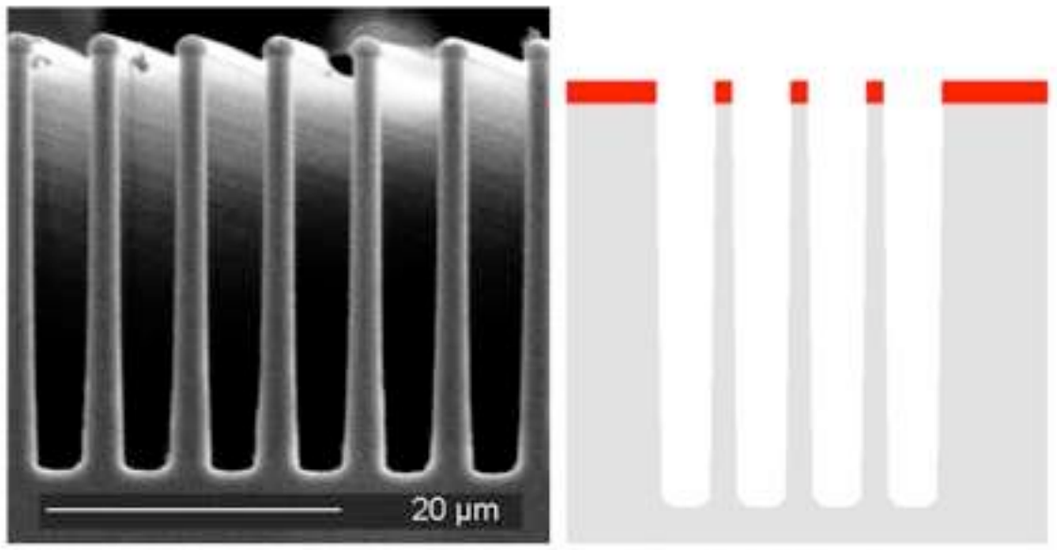



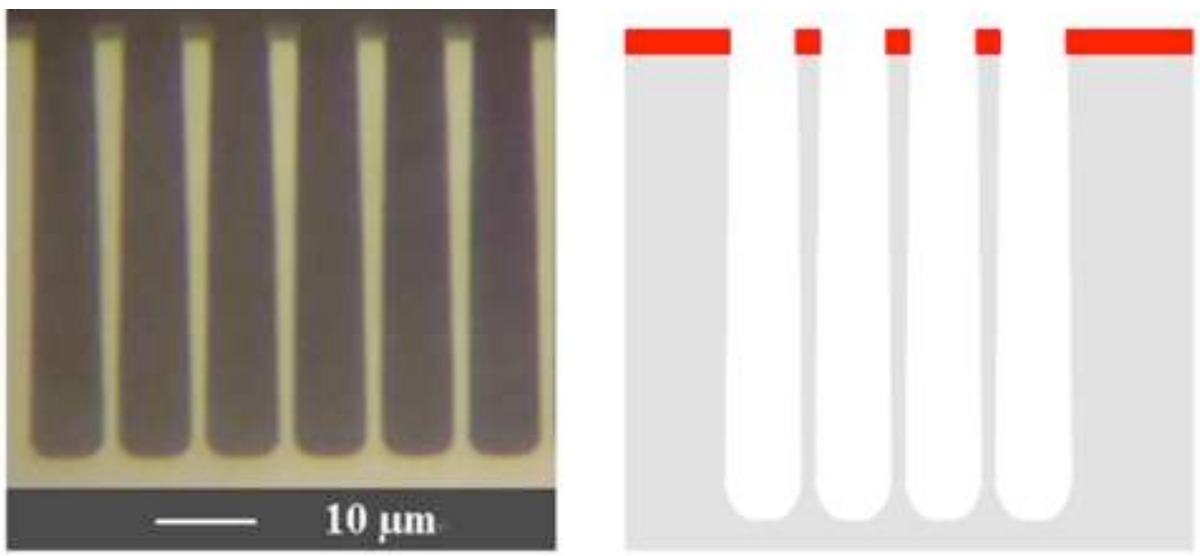
# DRIE Etch characterization experiments (2)



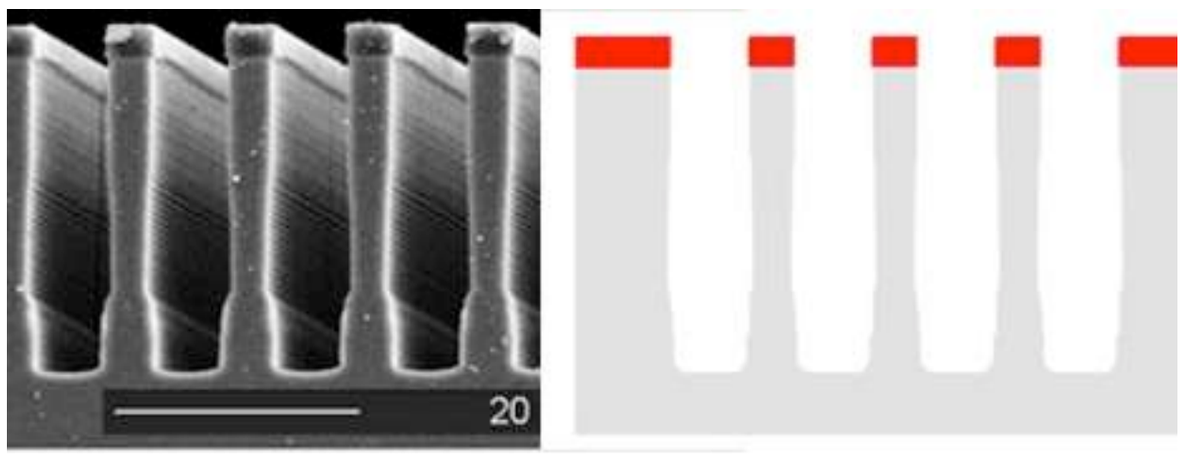

The experimental results of the etching. Comparison of etching 5 µm openings with an etch/dep cycle of 7s/7s.




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

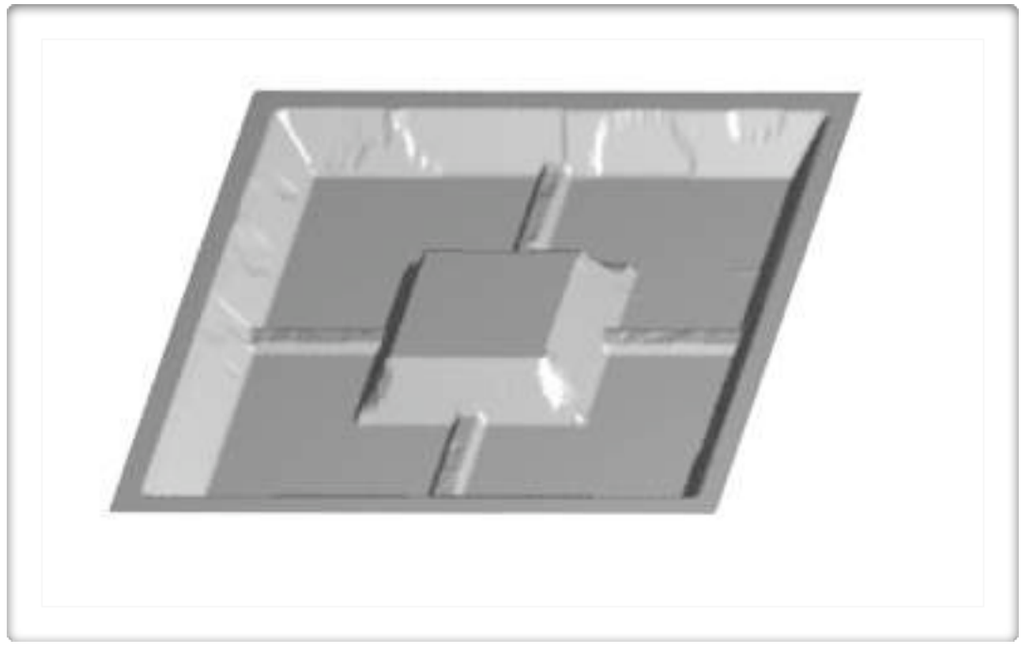


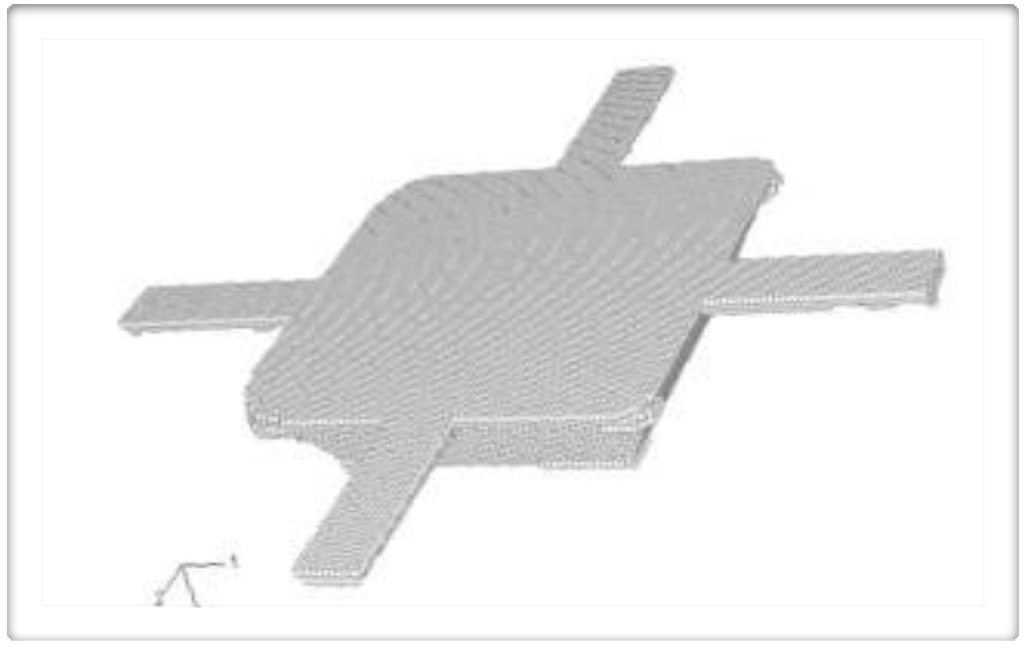

Comparison of etching a 5 µm trench with a 7s/8s cycle

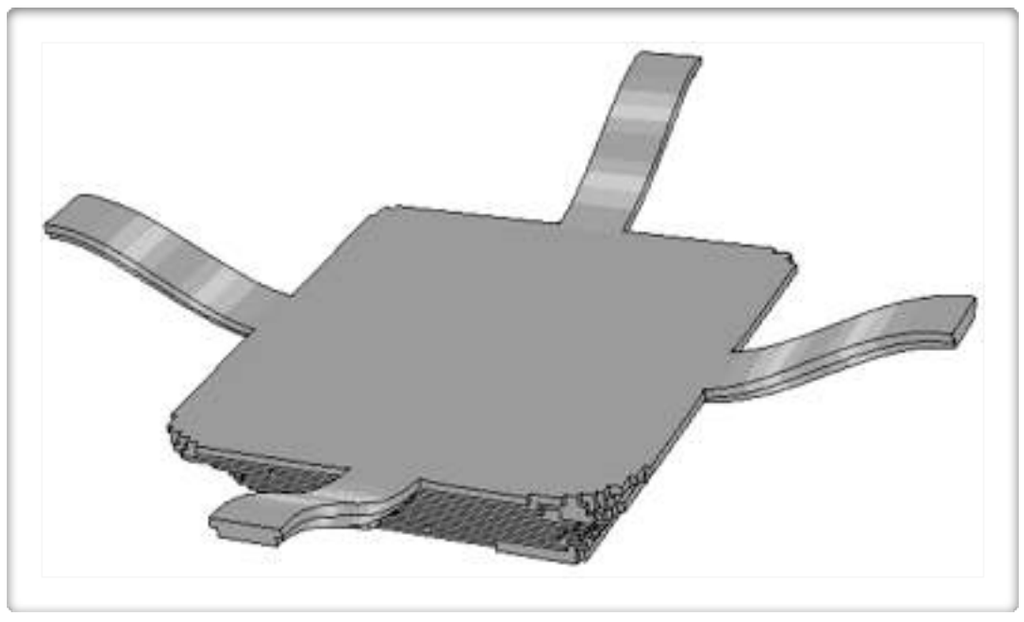


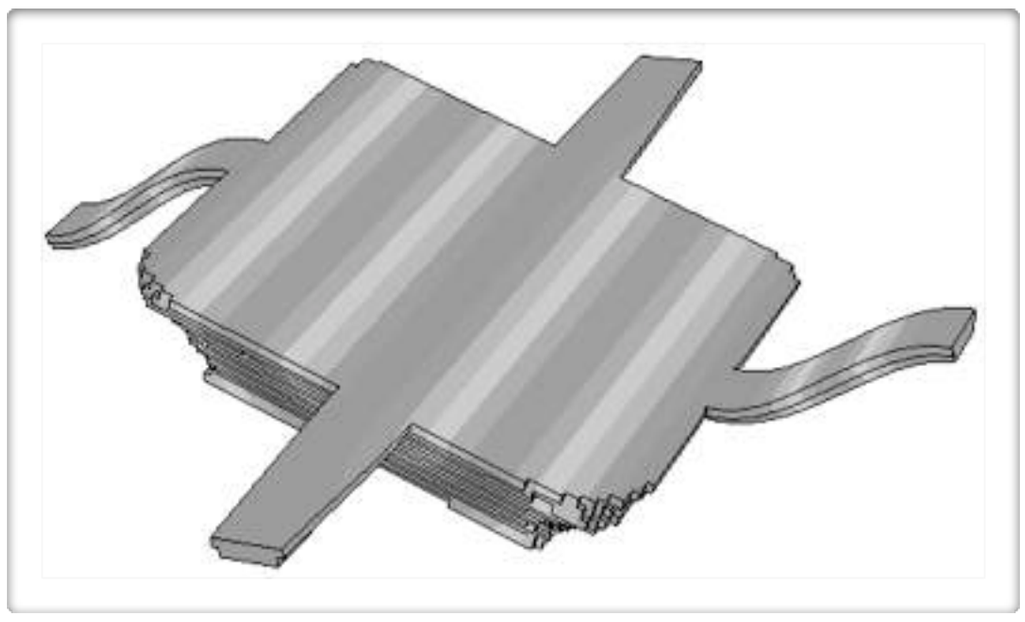

The experimental result of the etching of trenches using three etching steps with different etching/polymerization time configurations. 7s/7s, 9s/7s and 5s/7s are used sequentially, each for 5 minutes.

# Output to FEA

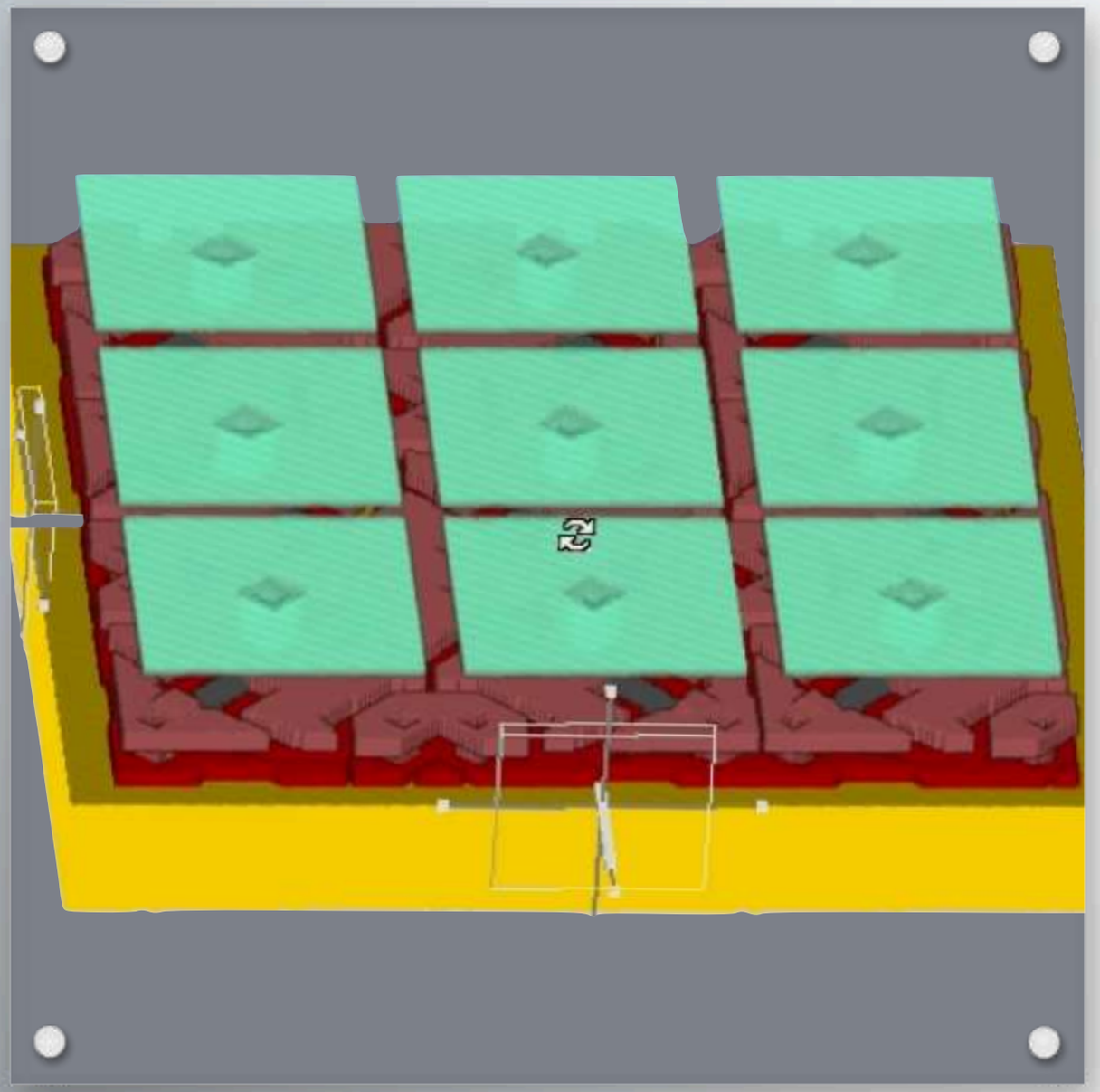


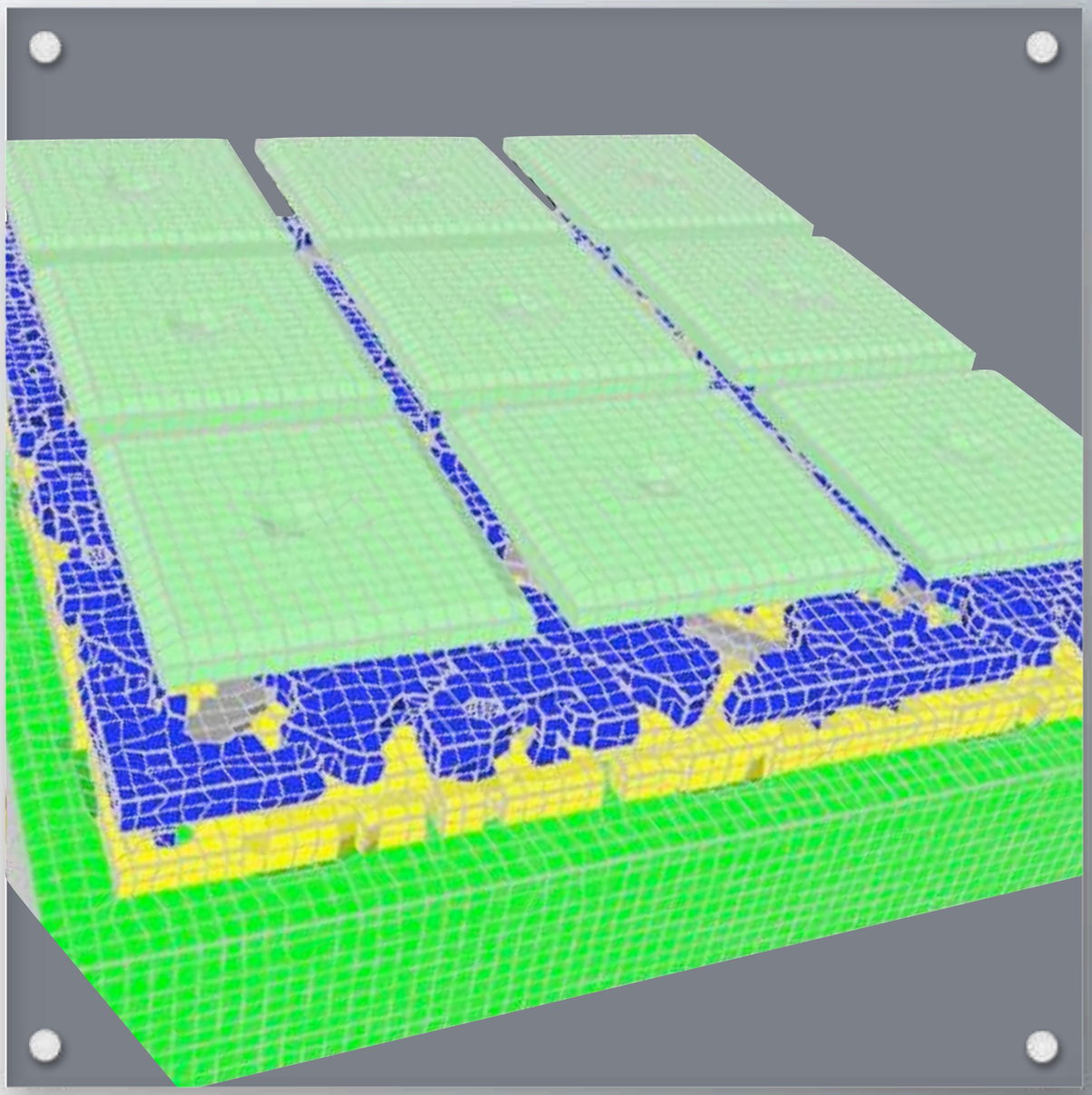






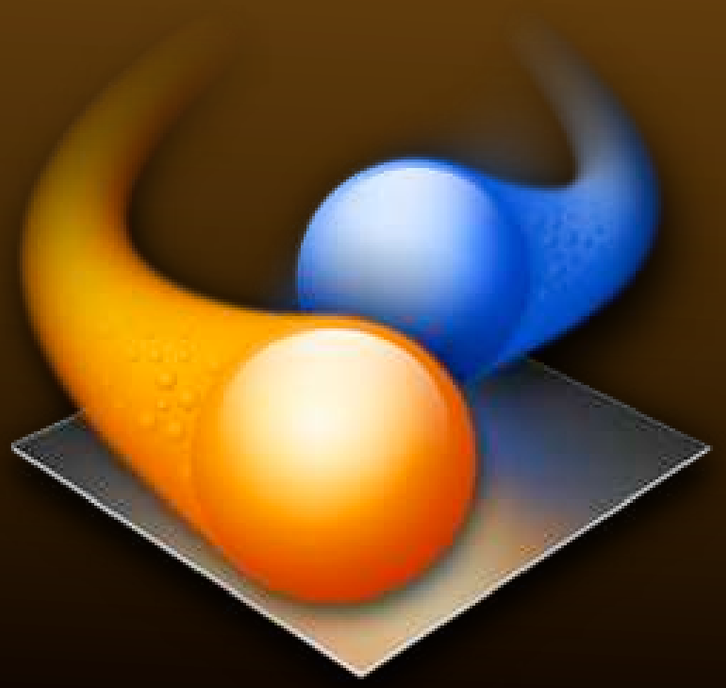
**Interface with analysis tools:** Direct export to IntelliSuite and other industry formats



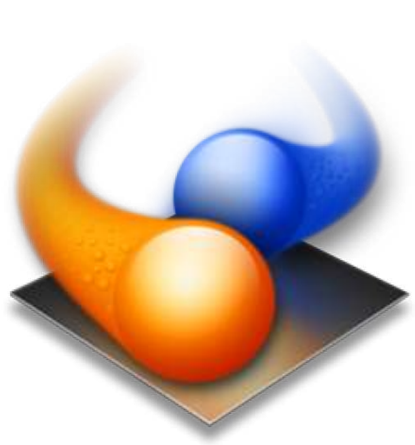


# PROCESS TO MODEL

# 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

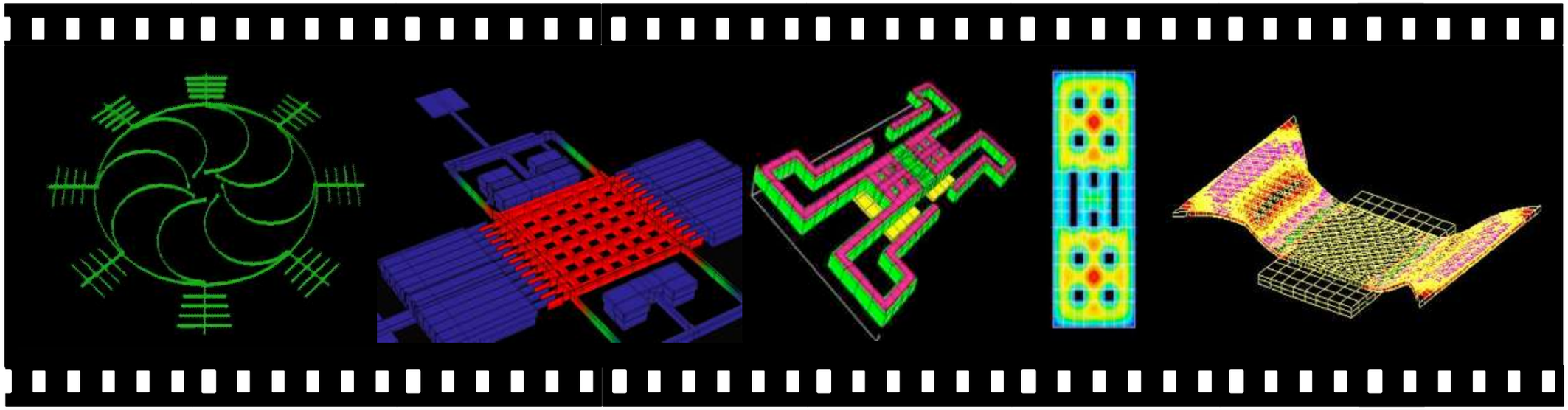
  Deal with large deformations, contact and post-contact without convergence issues

*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*

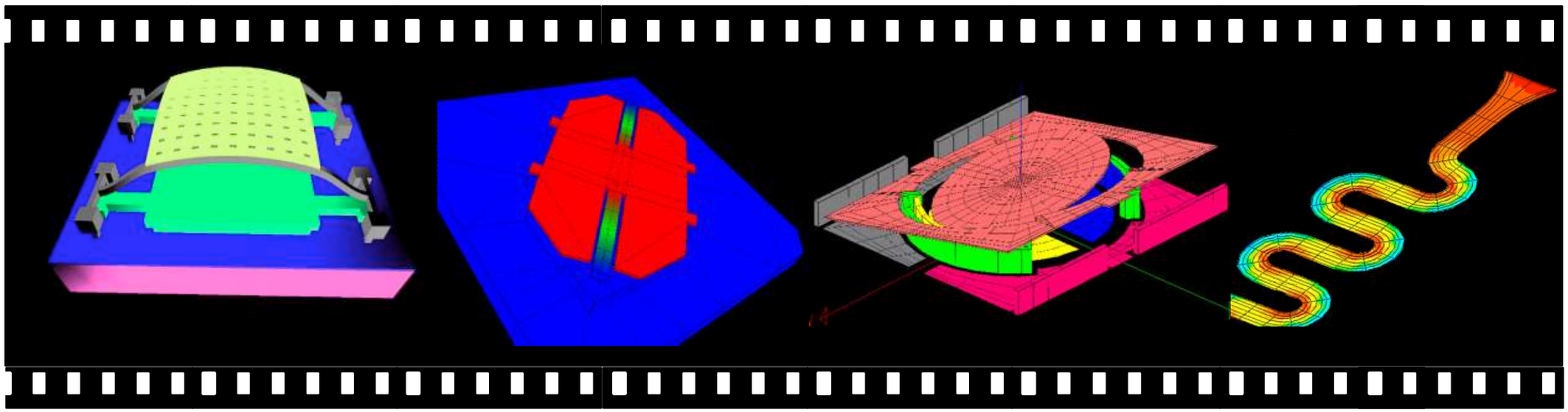


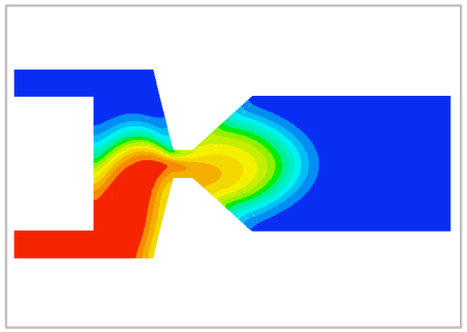
*Hitachi*
*RF Tunable Filter*

*NASA*
*Adaptive optics*

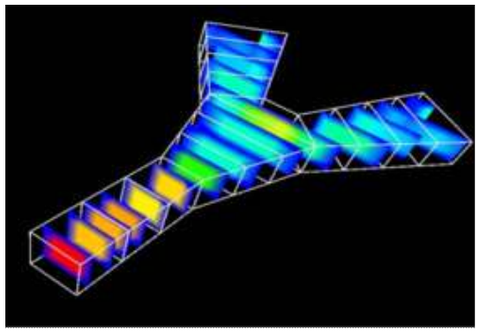
*Corning*
*3D Optical cross connect*

*NASA*
*Radiation detectors*

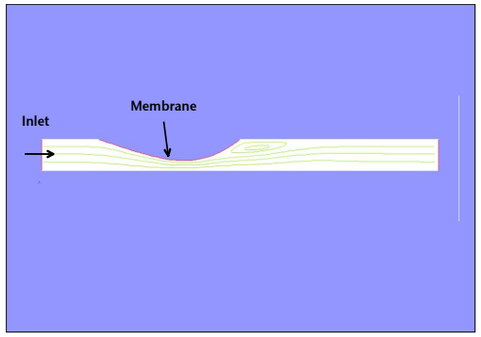




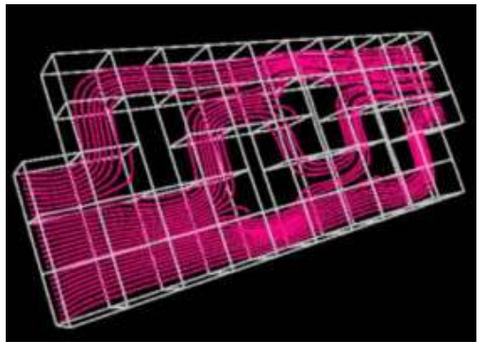
*Micro-mixing in a valve*
*Concentration gradient evolution*



*Flow mixing*
*Y combiner*

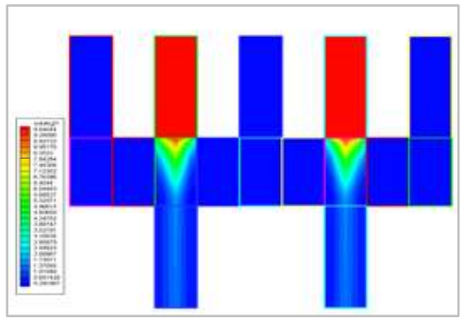



*Fluid Structure Interaction*
*Inlet flow - membrane interaction*

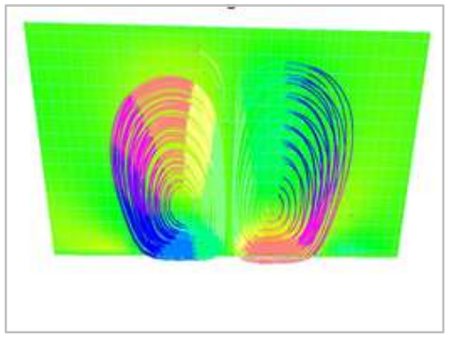


*Flow separation device*

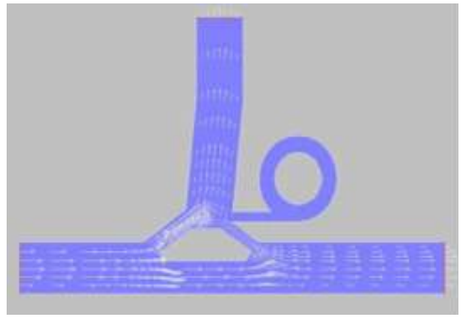
Microfluidics• Electrokinetics • Transport stochiometry • Heat transfer • Electro-Wetting on Dielectric (EWOD) • Digital droplet microfluidics • Free Surface Flow • Fluid Structure Interaction • Electrochemistry • Micro-mixing • Electrophoresis • Dielectrophoresis • Capillary flow and electro-separation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



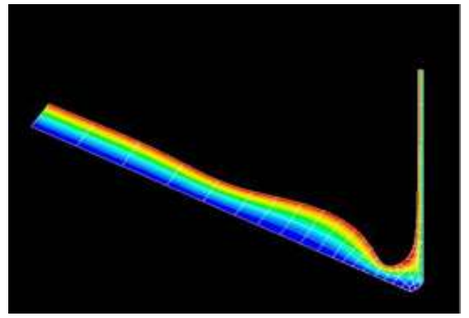
*Electrokinetics*
*Multiplex focusing*



*Electro-osmotic driven flow*
*Electrohydrodynamics for cooling*

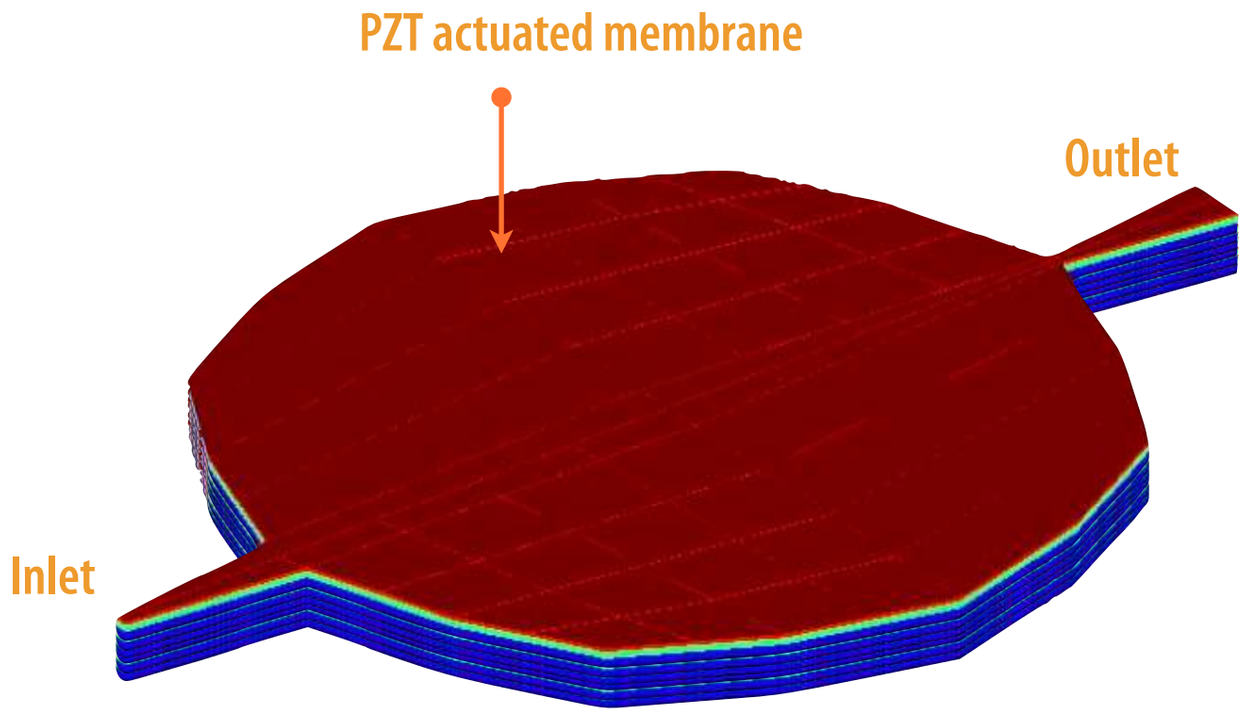


*Electrophoresis/Dielectrophoresis*
*High Frequency Waste separation*

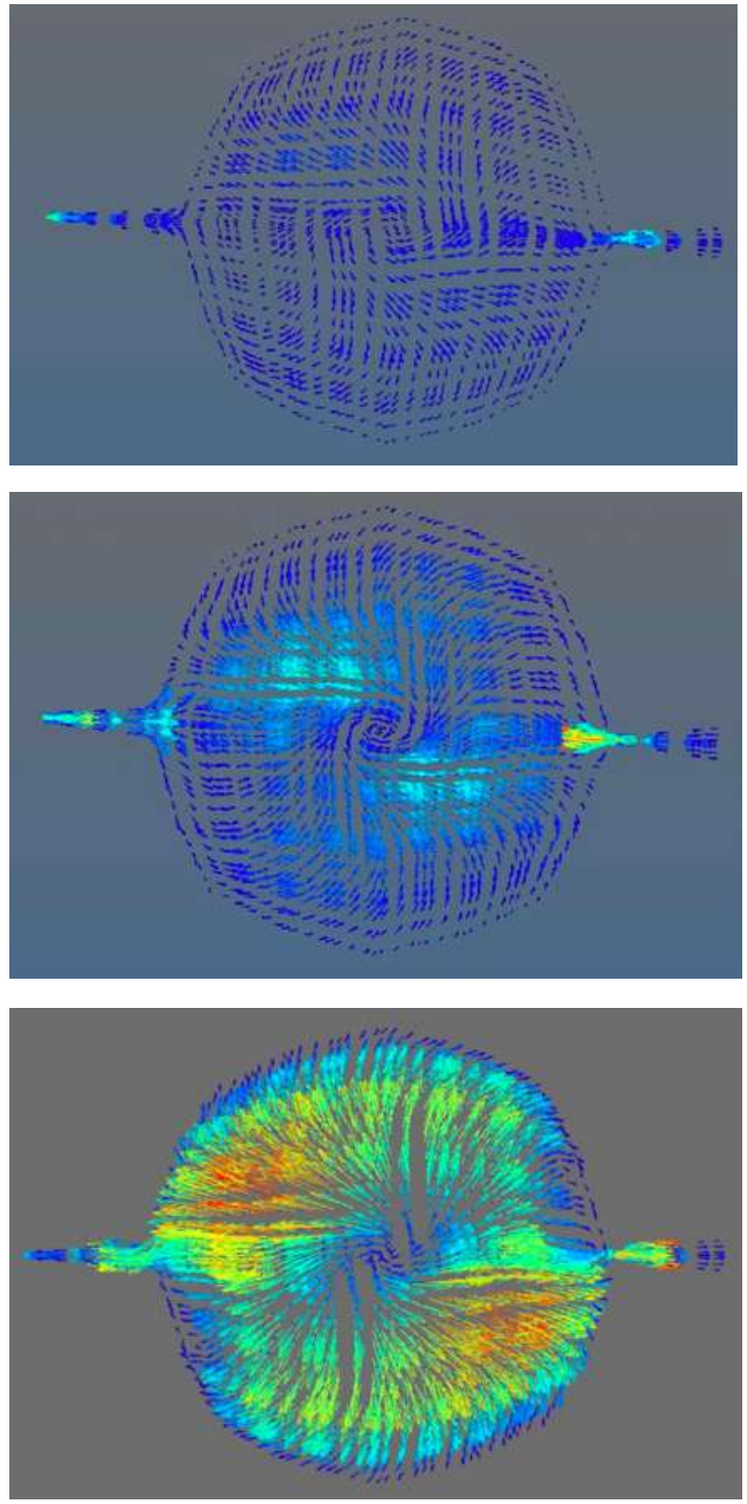


*Free surface flow*
*Slide coater*

# Advanced FSI

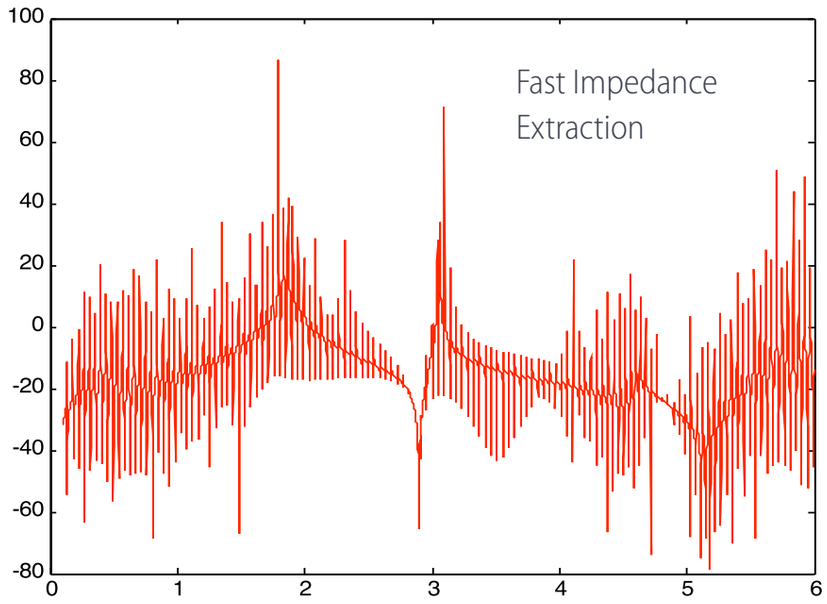


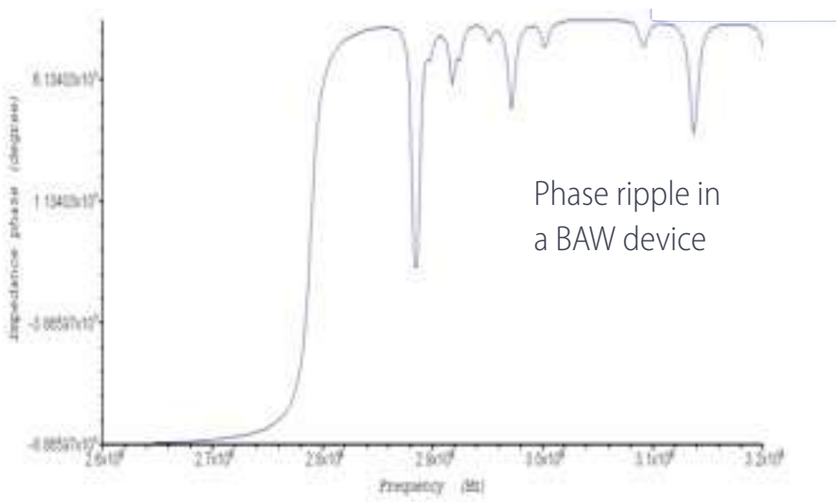

***Example***: Valveless piezoelectrically actuated micropump



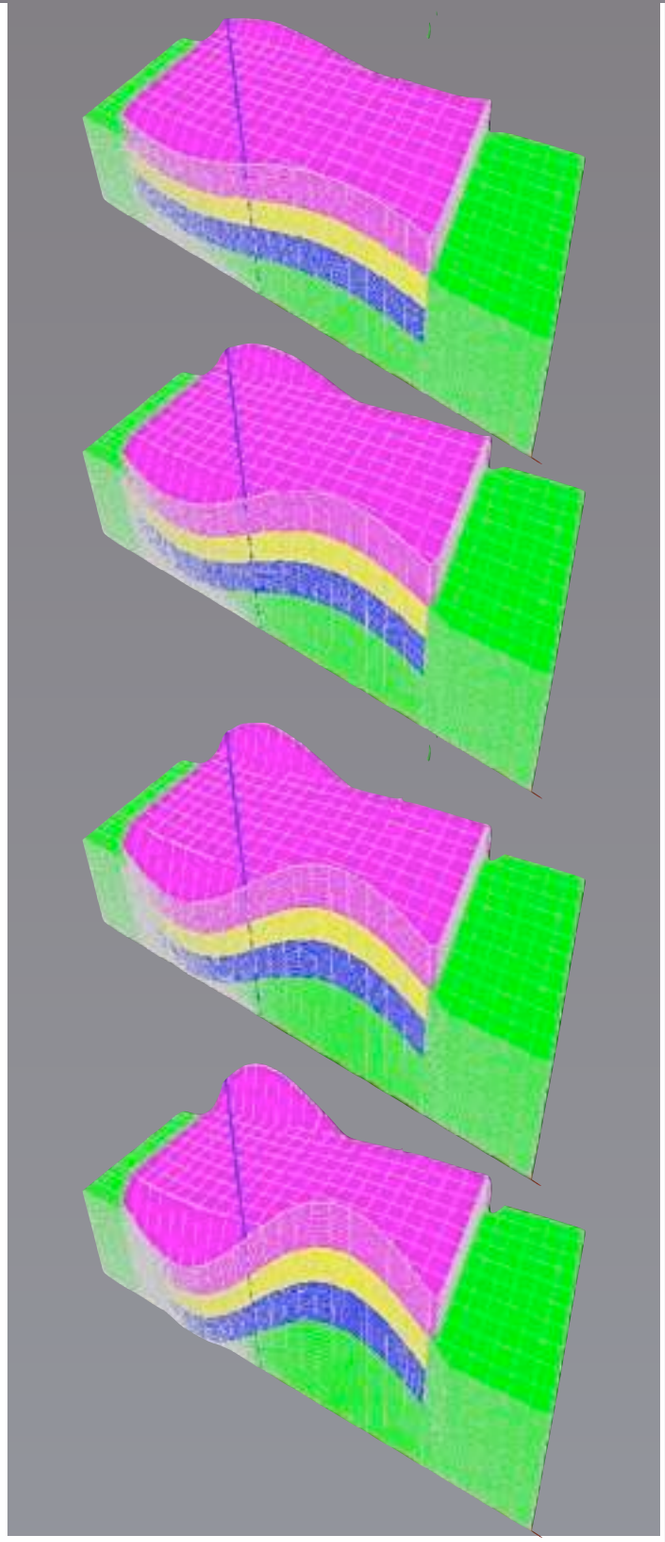
Flow evolution in a piezoelectric membrane micro pump

# Piezo-Acoustics



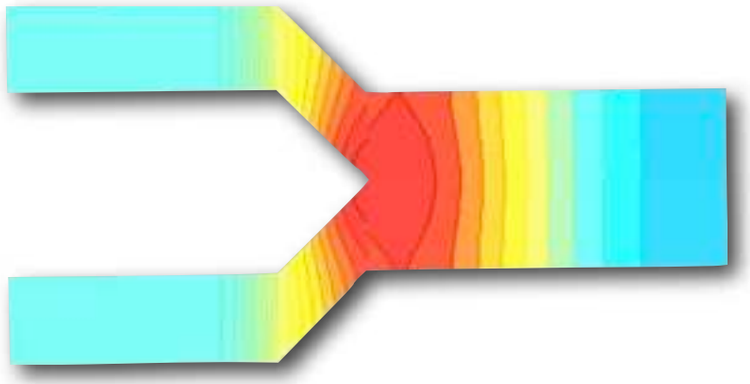




**1** **Multi-processor enabled BAW/SAW simulation**
Fast impedance and phase ripple calculations

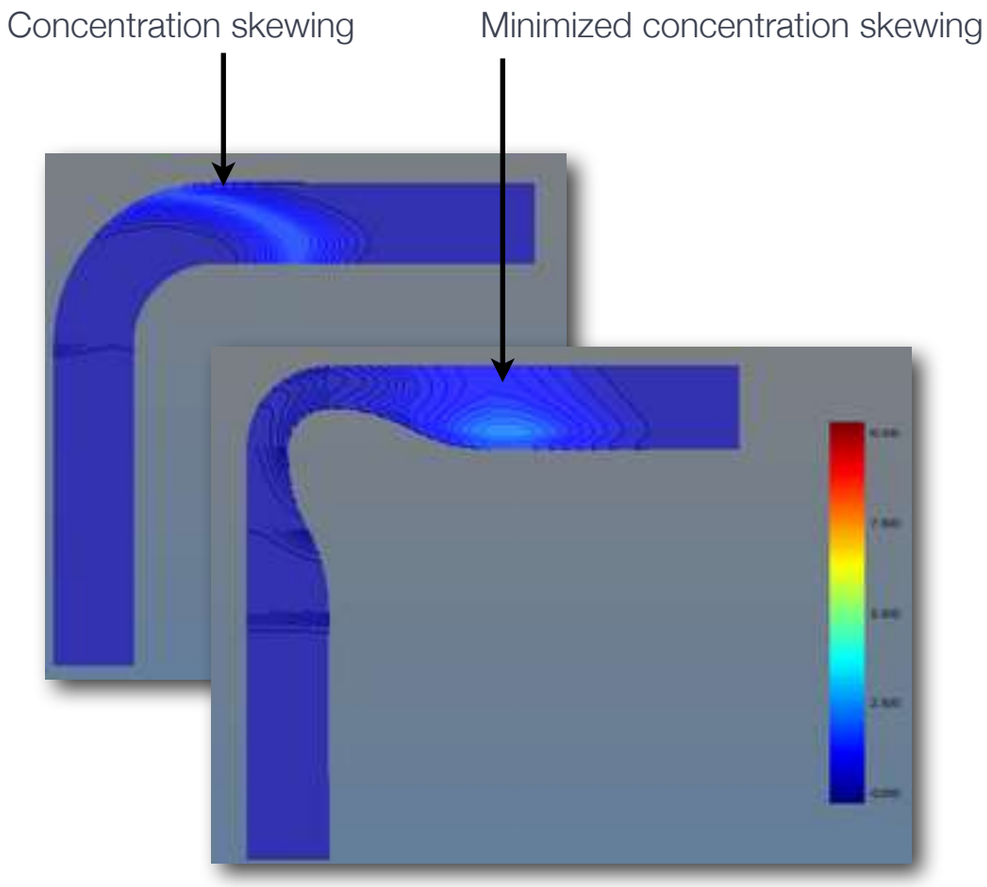


**2** Piezo-acoustic
wave generation

# Microfluidics



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

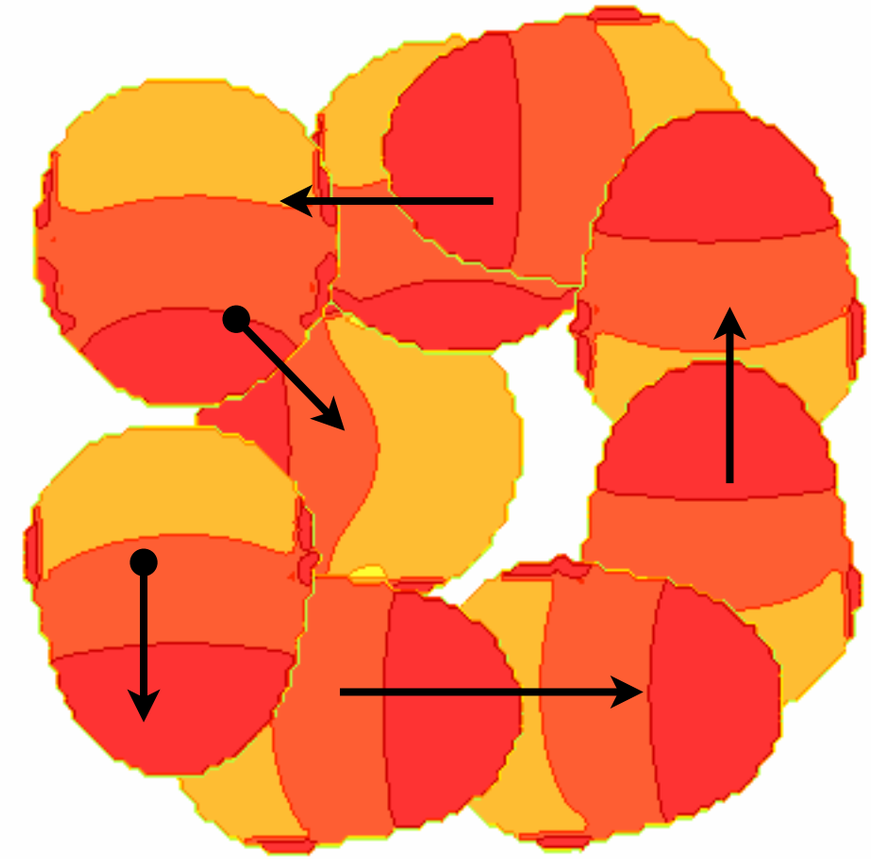



Enhanced ion drag calculations allows you to optimize elbow turns to minimize concentration skews

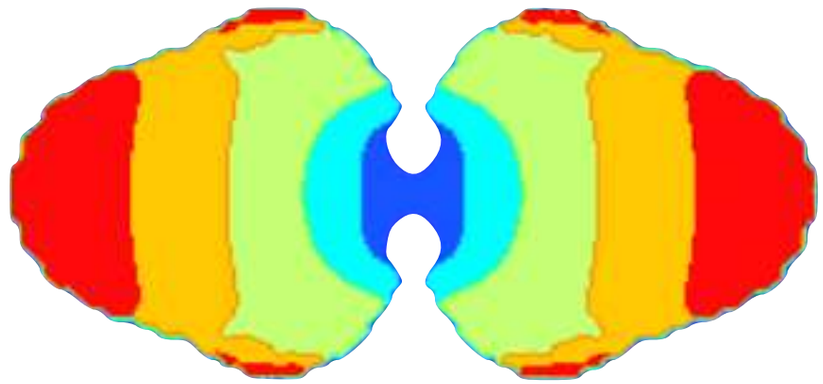
1 **Enhanced Chemical Reaction**
Microfluidics with enhanced transport kinetics

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

# Microfluidics



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

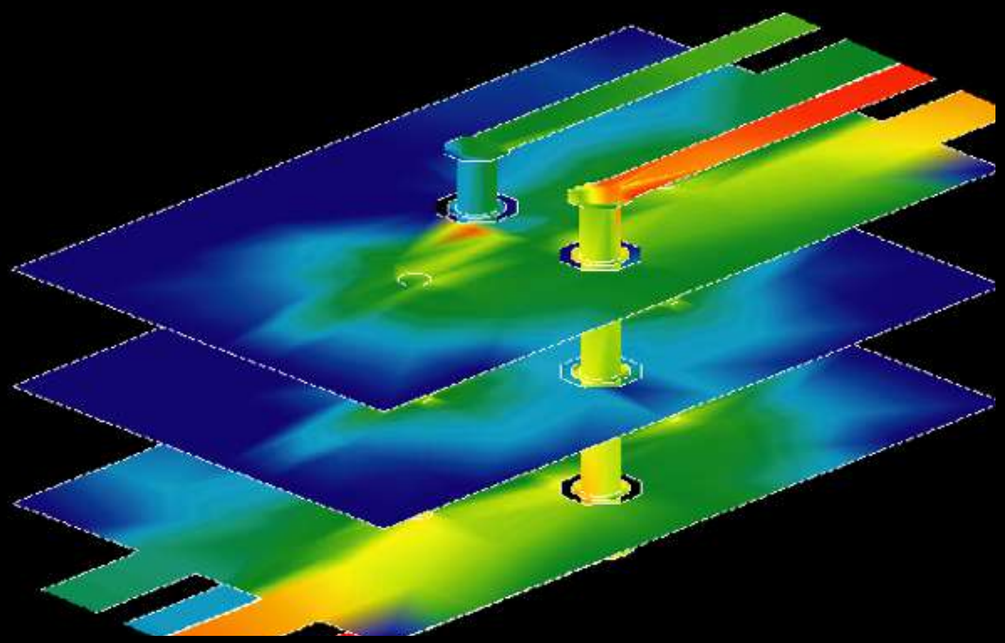


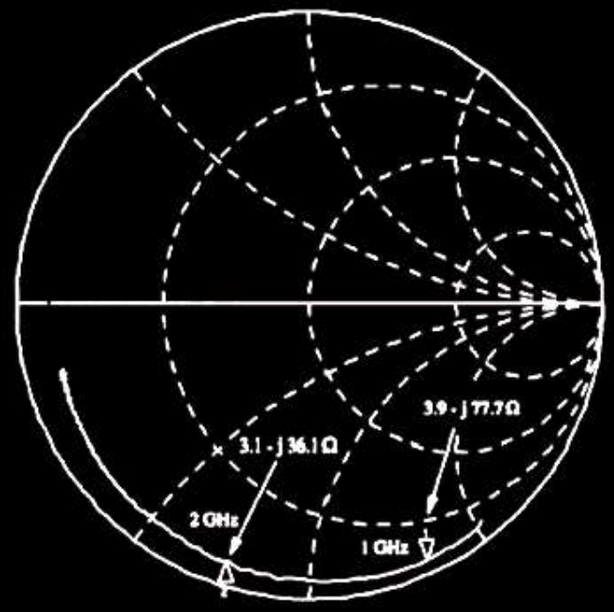
Droplet fission (top view)

3

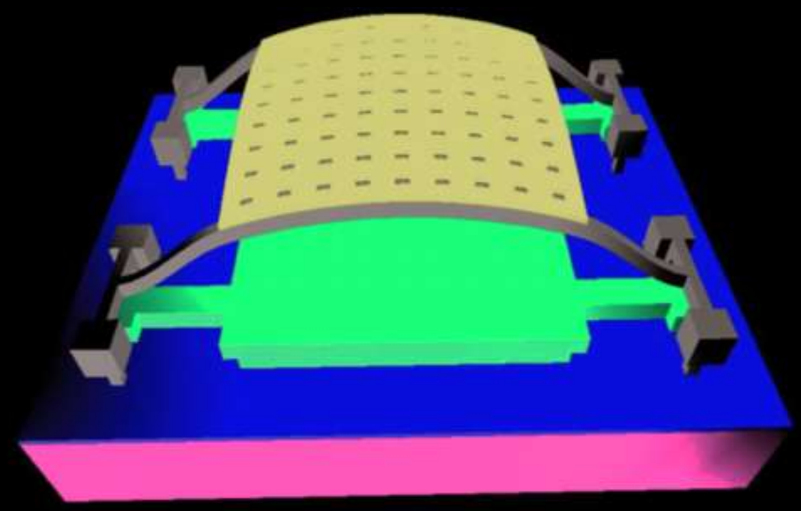
**Electrowetting on dielectric (EWOD)**
3D Electrowetting calculations

# 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)

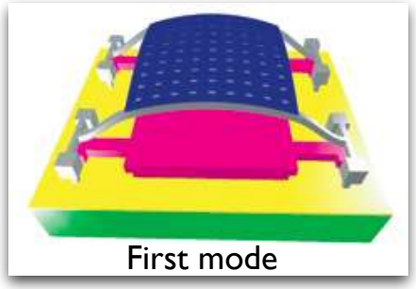
Other dissipation sources (thermoelastic damping (v8.6.1) and anchor acoustic losses (v8.6.2))

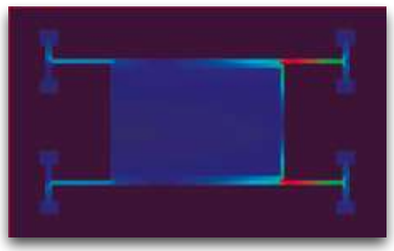
# System Model Extraction (SME)

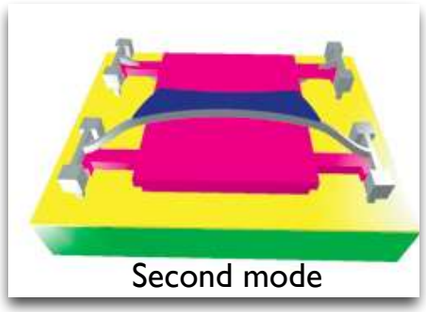
Capture strain energy associated with each mode

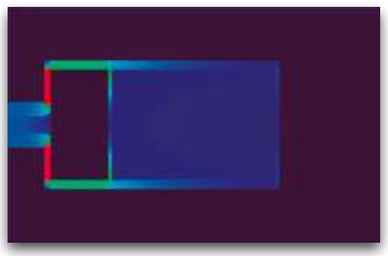
Capture electrostatic energy associated with each mode

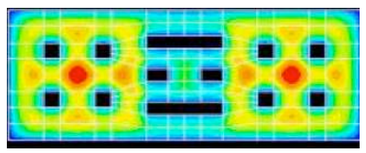
Capture fluid damping characteristics

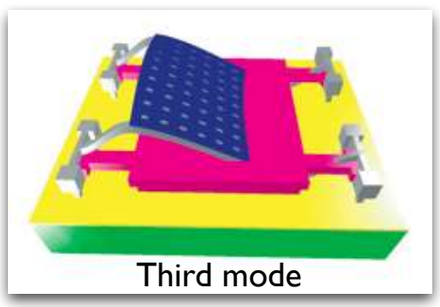

First mode

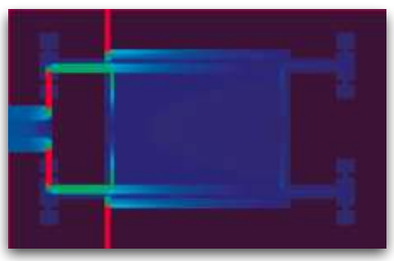



Second mode






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

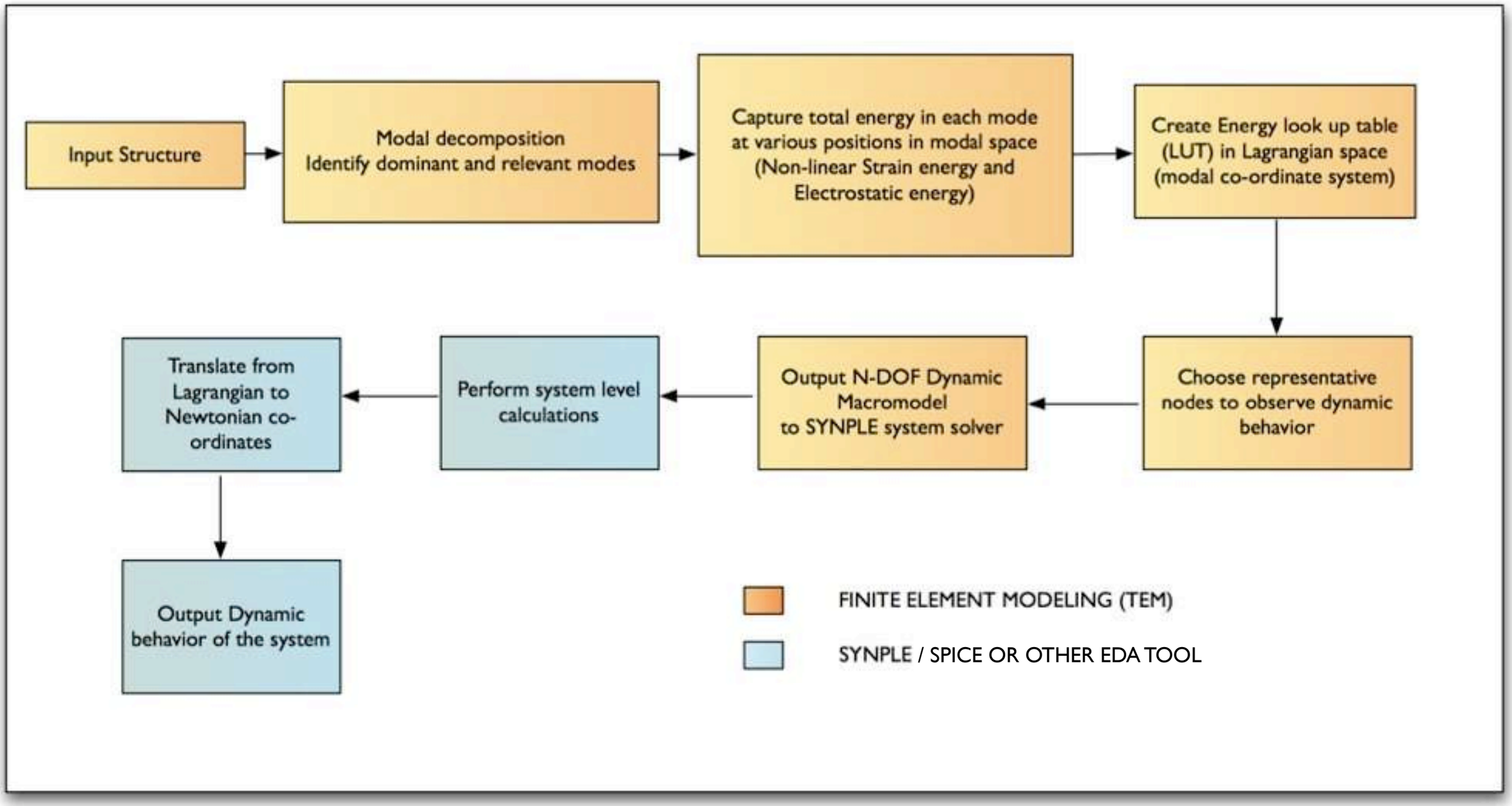
Hardware Description

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

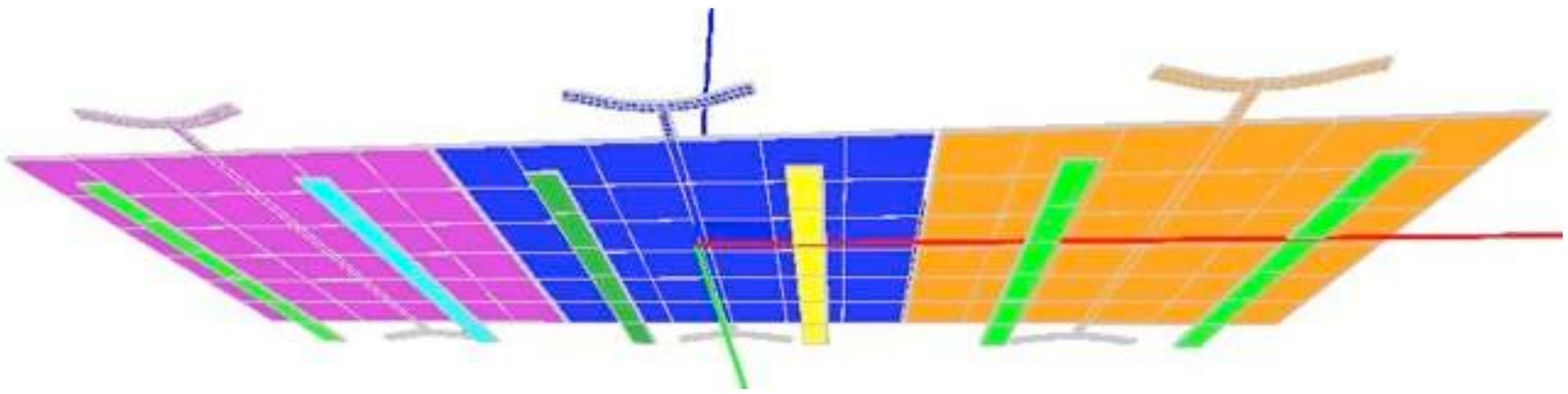
Ensure MEMS model used in circuit development is accurate

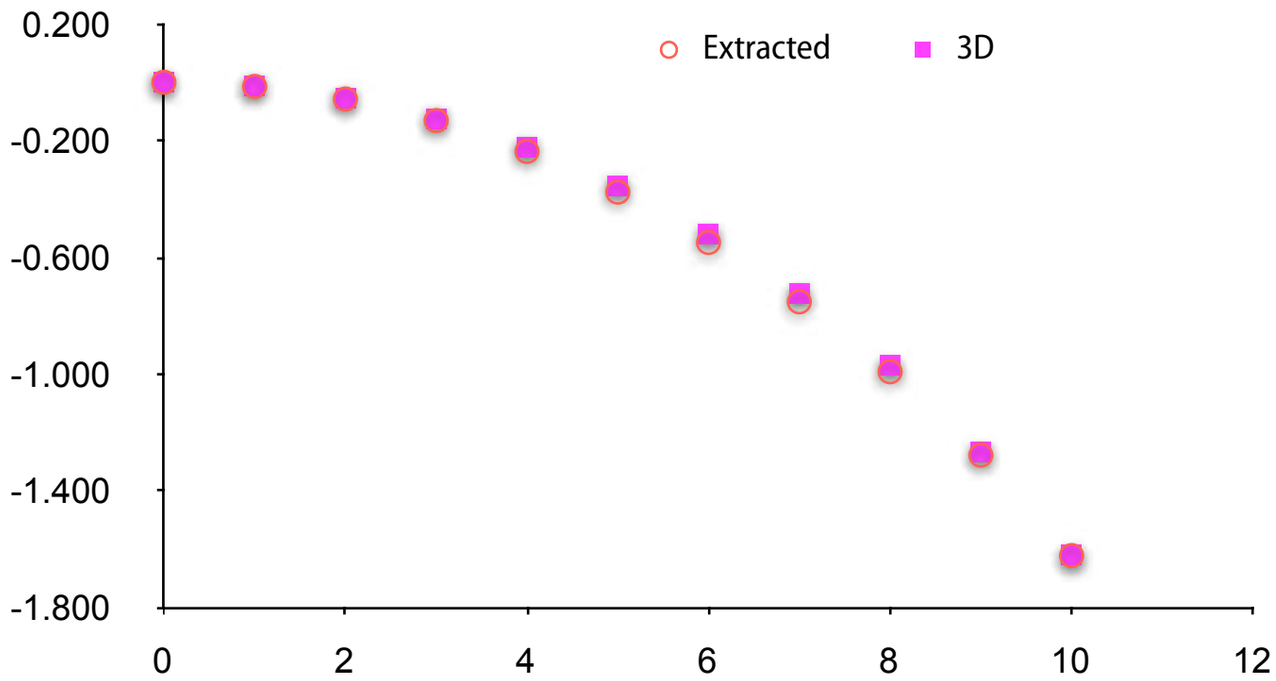
## Physical verification (‘Tape Out’)

Verify physical layout is consistent with Design Rules

Ensure design meets manufacturability criteria

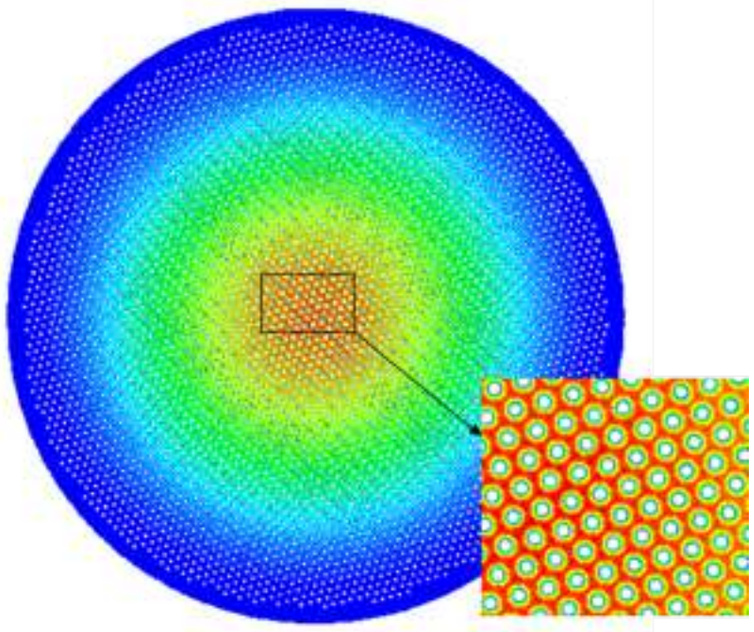
# Static model verification



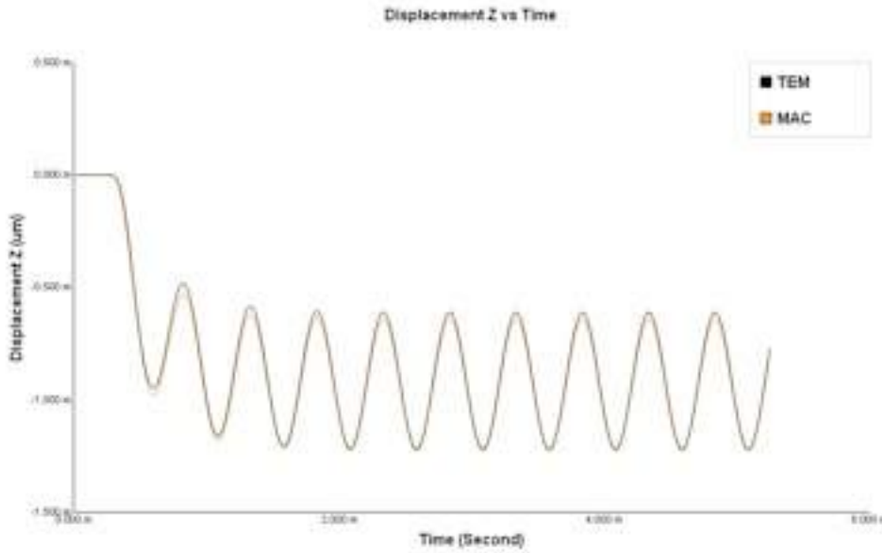



Pull-in: Schematic results vs Full 3D results

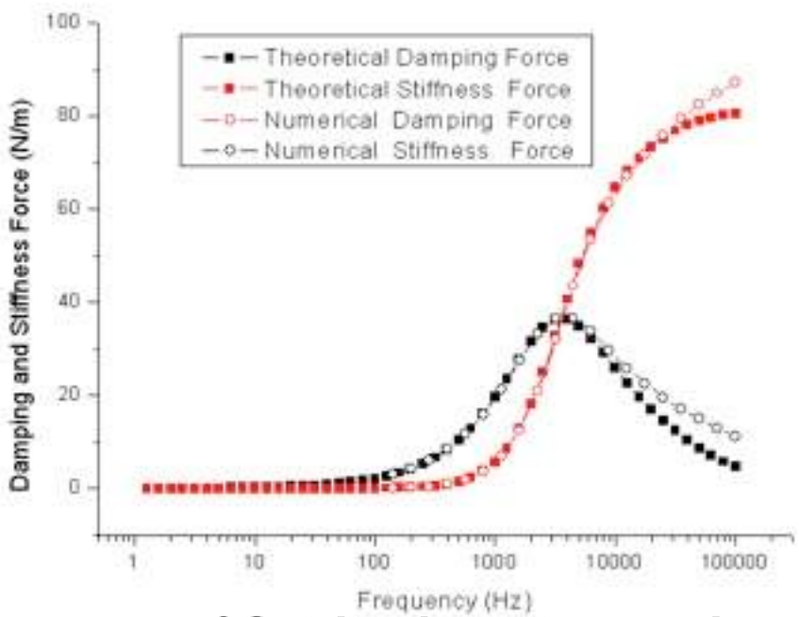
# Damping model verification



Perforated condenser membrane

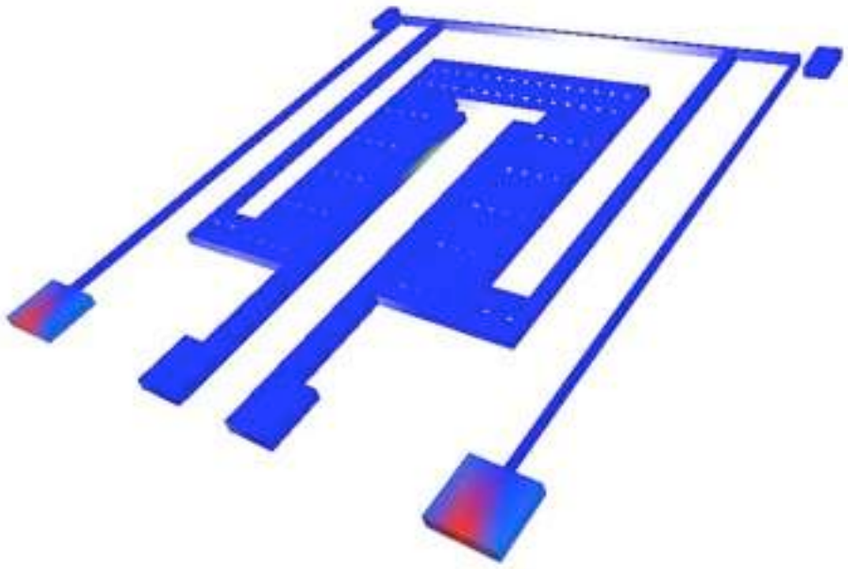


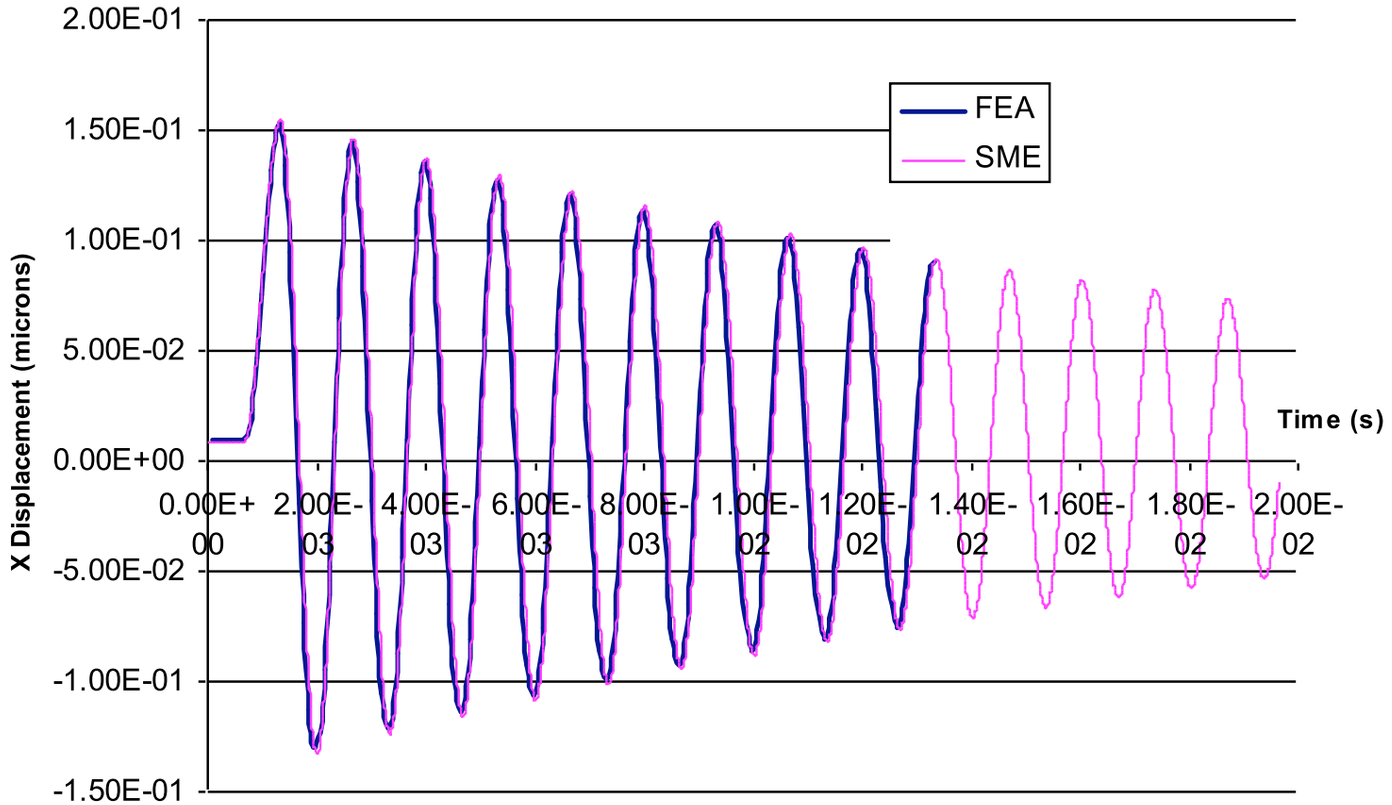

Full 3D (TEM) vs Macromodel comparison




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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