CAD Application to MEMS Technology

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Acknowledgment:
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Definition of Computer Aided Design in Microsystems Technology

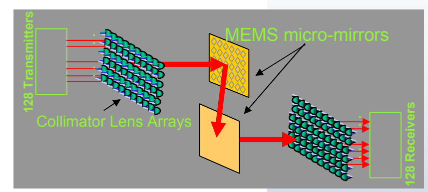
In MEMS technology, CAD is defined as a tightly organized set of cooperating computer programs that enable the simulation of manufacturing processes, device operation and packaged Microsystems behavior in a continuous sequence, by a Microsystems engineer.

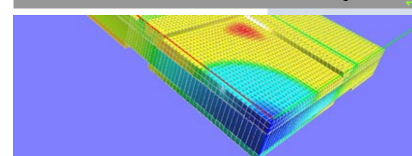
Commercially Available Software

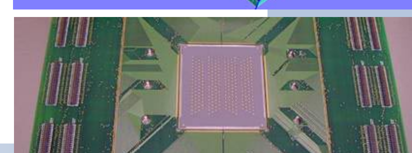
- Coventorware from Coventor
  - http://www.memcad.com
- IntelliSuite from Intellisense Inc. (Corning)
  - http://www.intellisense.com
- MEMS ProCAETool from Tanner Inc.
  - http://www.tanner.com
- MEMScap from MEMScap Inc.
  - http://www.memscap.com
- SOLIDIS from ISE Inc.
  - http://www.ise.com

MEMS CAD Motivation

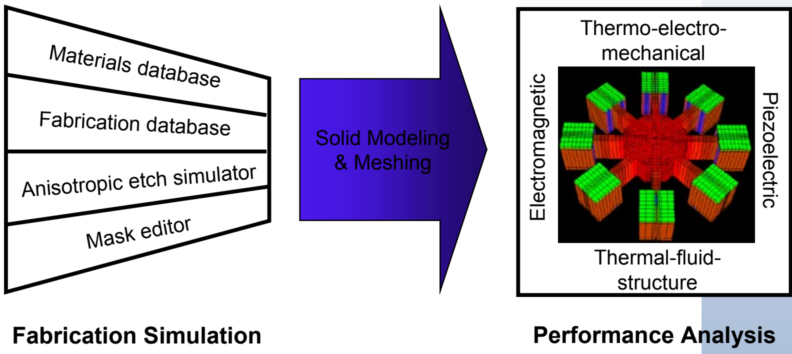
- Match system specifications
  - Optimize device performance
  - Design package
  - Validate fabrication process
- Shorten development cycle
- Reduce development cost







Example: IntelliSuite System



Model courtesy of Auburn University

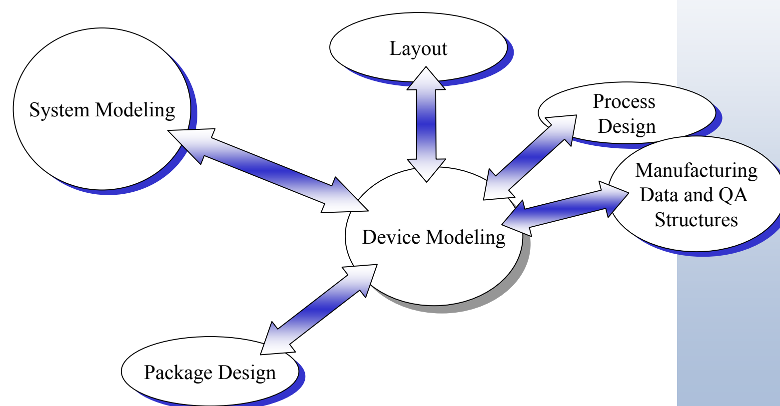
Example: IntelliSuite Advantages

- Design for manufacturability
  - Fabrication database
  - Thin-film materials engineering
  - Virtual prototyping
- Ease of use
  - Consistent user interface
  - Communication with existing tools
- Accuracy
  - MEMS-specific meshing and analysis engines
  - In-house code development
  - Validated by in-house MEMS designers
  - ISO certified for quality

The Design Process

- All systems have some common threads to their design
  - Device design
    - Design a manufacturable component
  - Package design
    - Design a practical package
  - System design
    - Design the system into which the device fits.
- Goal: concurrent design at these levels

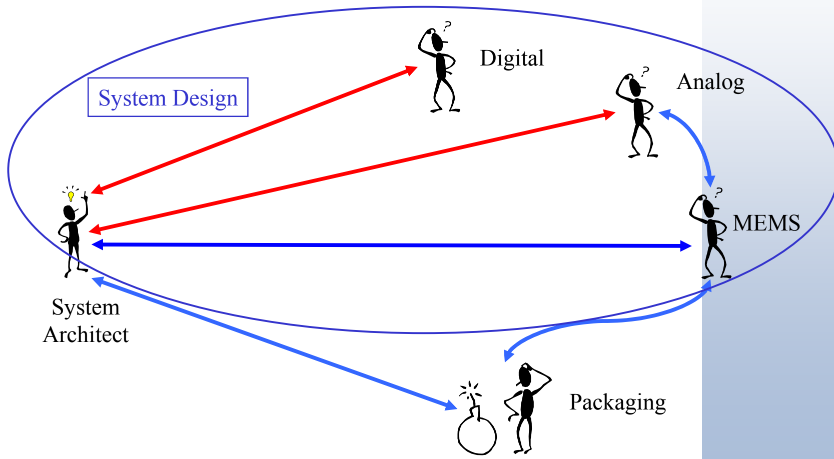
MEMS CAD System Flow



Types of MEMS Design

- Custom Level
  - Design New MEMS in New Process
  - Goal: A New MEMS component
- Semi-Custom
  - Design Existing MEMS in New Process
  - Goal: A Better MEMS component
- Standard/IP
  - Re-Use Existing MEMS and MEMS Process
  - Making Existing MEMS Available to IC level Designers to Build new systems

Who Designs?

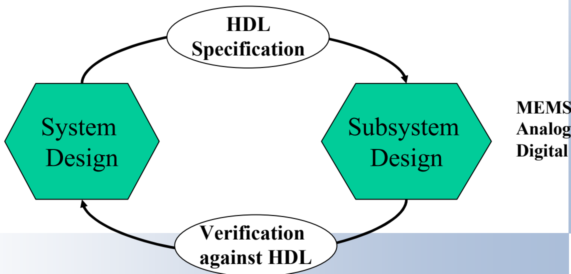


What is Top Down Design

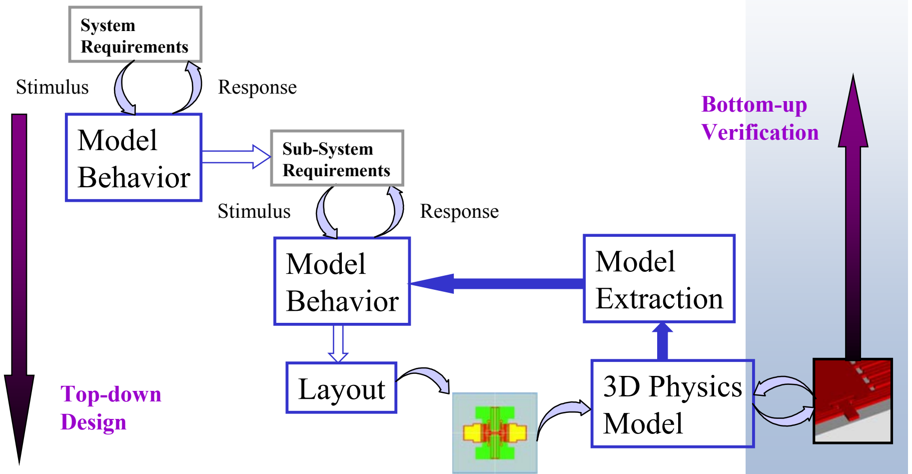
- System Architect
  - Designs and Simulates Mixed Technology System at a high level
- Subsystem Designers
  - Receive subsystem target specs in Hardware Description Language (HDL) form from SA
  - Design and pass back HDL model of realizable subsystem
  - Iterate with SA until realizable design is acceptable
- Top Down Design
  - Enables SA to make tradeoffs among subsystem design teams
  - Enables Design teams and SA to quantitatively communicate their goals and constraints

Implementing Top Down Design

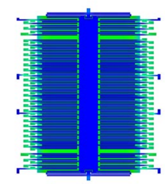
- Iterative design in each subsystem Implementing the Architect to Designer Loop
  - Behavioral Model to Layout (Design)
  - Layout to Behavioral Model (Verify)
- Enable Communication in the Design Team
- Interoperability (Composite CAD VHDL-AMS working group)



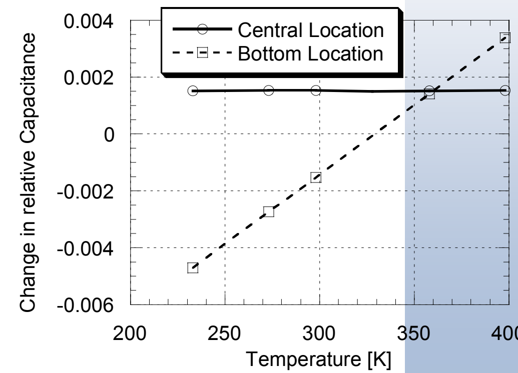
MEMS IC Design Flow



Cornering the Design Space



Simulated von Mises stress in Analog Devices ADXL76



Outline of the Task Sequence Accomplished by a CAD Tool

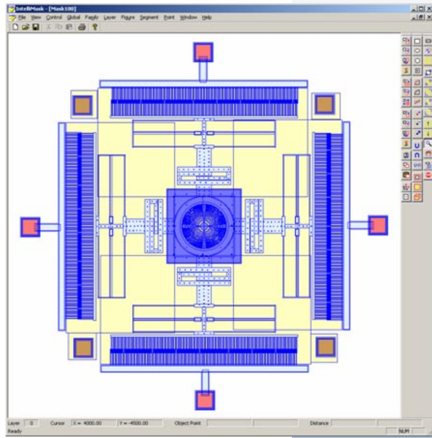
- Layout and process
- Topography simulation
- Boundaries, IC process results and Material properties
- Mesh generation
- Device simulation
- System-Level Simulation
- MEMS Control CAD

Layout and Process Resources

- First Resource: The Process Description of the interface and the driving circuitry:
  - Can be acomplished using a layout file editor (eg. CADENCE, http://www.cadence.comor L-Edit, http://www.tanner.com)
- Second Resource: The Process flow description file:
  - Relates a processing step to each lithography mask in the layout file
  - Can be optimized by using the MISTIC software from the University of Michigan (http://www.eecs.umich.edu/mistic/)

Layout Editor

- Layout process
  - Multi-layer mask sets
  - Cell hierarchy
  - Boolean operations
  - Curved shapes
- MEMS-specific features
  - Any-angle feature creation
  - Multi-copy by translation or rotation
- Links directly to process simulation and mesh generation
- Compatible with GDSII & DXF



Topography Simulation

- Goal: Obtain a realistic topography of the considered device by:
  - Realistically representing complex 2D and 3D structures to simulate the manufacturing process

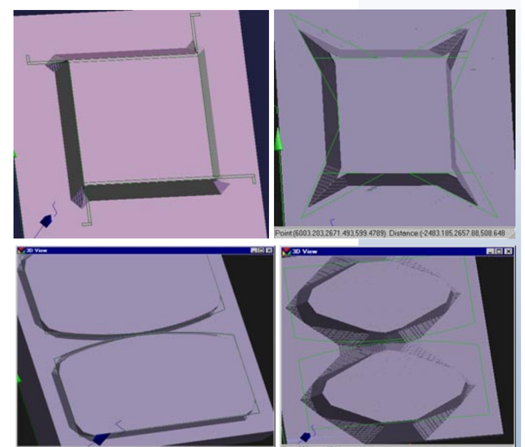
Process Simulation

- Document & validate process steps or process flows
- Model creation directly from fabrication process
- Link process & design to reduce prototype runs
- Process database
  - MEMS process steps
  - Standard foundry templates
  - Expandable for custom steps or templates

Model courtesy of the University of Windsor
SEM courtesy of IME Singapore

Anisotropic Etch Simulation (AnisE®)

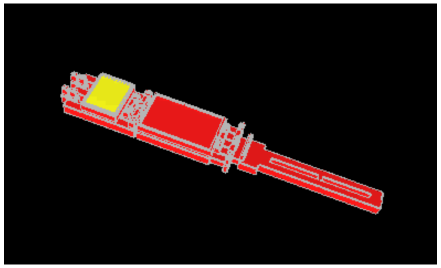
- Etch rate databases
- Single & double sided etching
- Multiple etch stops
- Real time etch visualization
- 3D geometry visualization
- Direct measurements of etch depths and feature sizes
- Study process deviations



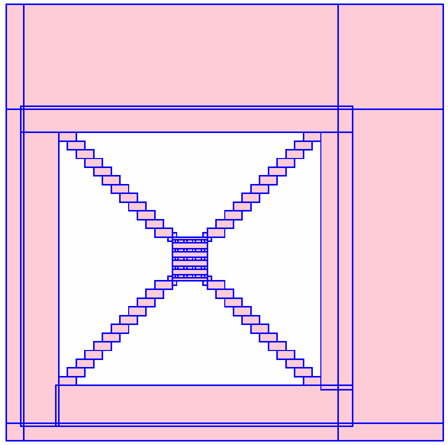
Above: Examples of corner compensation
Below: Rounded edge after 1 hour (left) and 5 hours (right)

Lower models courtesy of OptIC

Virtual Prototyping



Surface micromachining simulation



Anisotropic etch simulation

- Validate process
- Verify mask set
- View 3D geometry after each process step

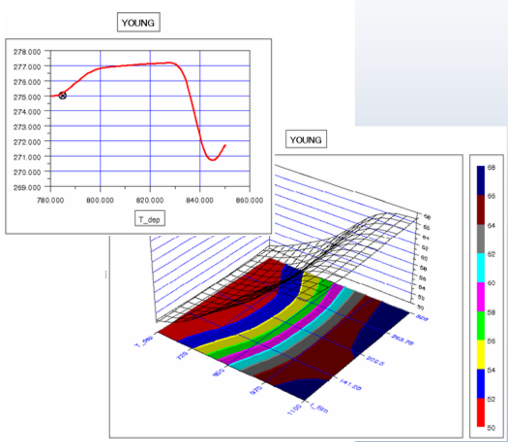
Model (left) courtesy of Tennessee Technological University

Boundaries, IC Process Results and Material Properties

- Description of the material interface boundary
- Dopant Distribution within each layer of the device
- Distribution of residual stresses
- Optimization of the Material Properties (eg. MEMCAD from Microcosm Inc.)

Thin-film Material Expertise

- Accurate material property estimation for device analysis
- Provide insight into material behavior
- Expandable for custom materials or processes
- Reduce number of materials characterization fabrication runs
- Increase device performance
- Improve yields



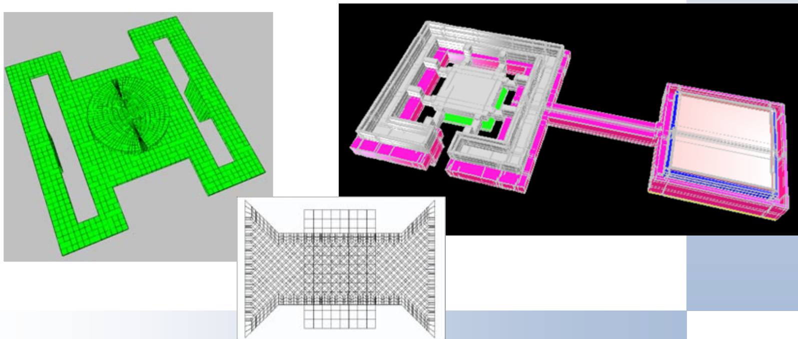
Young's Modulus variation in deposited layer due to process temperature and film thickness

Mesh Operations

- Generate a computational mesh for device simulation by either using boundary element methods or finite element methods or coupling of both

Automatic Mesh Generation

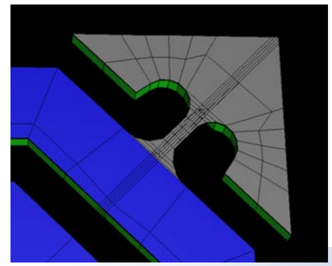
- From fabrication simulation
  - 3D model based on mask set and process sequence
  - Material properties transferred to analysis
- Import or export ANSYS, ABAQUS, PATRAN models

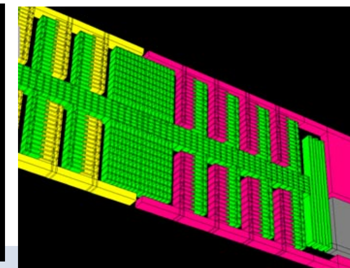


Models courtesy of the University of Windsor (left), Raytheon (center), and Tennessee Technological University(right)

Interactive Mesh Refinement

- Mesh optimization provides faster simulation times
  - 100% Automated or 100% user-driven
  - Local or global
- Mesh optimization results in greater accuracy
  - Independent refinement of electrostatic & mechanical





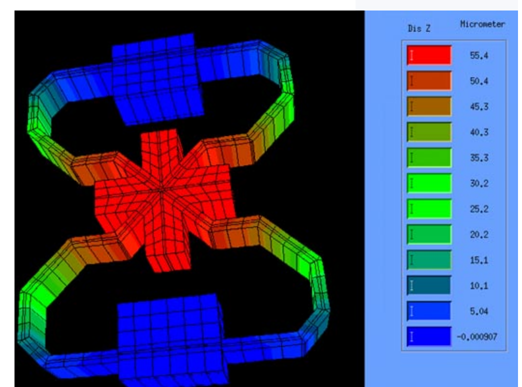
Model (right) courtesy of DSI, Singapore

Device Simulation

- Compute the coupled response of a MEMS device using numerical methods
- Also provide many coupling effect that MEMS rely on (eg. electromechanical, thermomechanical, optoelectrical, and optomechanical coupling behaviors)
- Extract behavioral models for system-level simulation.

Modeling of All Contributing Factors

- Process induced effects
  - Deformation
  - Stiffening
- Micro-assembly & post-contact behavior
- Coupled dynamic analysis
  - Frequency vs. voltage bias
  - RF switching time
- Macro-model extraction
- Electrostatic force vs. Displacement characterization
- Coupled boundary element & finite element analysis
- Large & small displacement theory
- 3D static & dynamic analysis

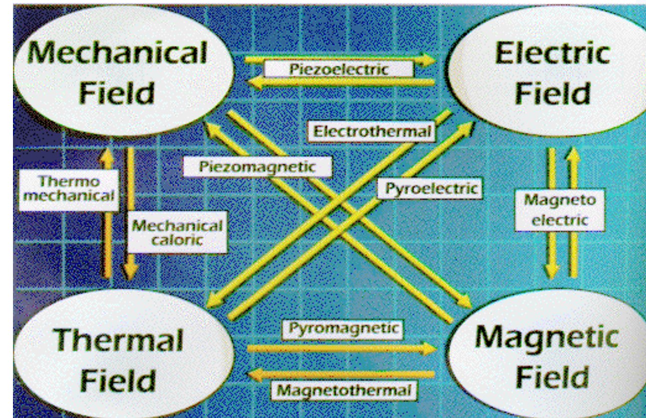


Model courtesy of Auburn University

3D Device Modeling

- Structural Mechanics (including contact)
- Electrostatics & Capacitance Extraction
- Thermo-mechanics
- Coupled Electro-Thermo-Mechanics (including contact)
- Thermal Flow Analysis
- Piezoresistive Devices
- Electro-Thermal Devices
- CFD for Compressible and Incompressible Flow
- Electrokinetics and Chemical Transport in Liquids
- Inductance (RL) and RL-Thermo-Mechanics
- Damping of complex structures Electrokinetic Switching for Chemical Transport

Coupling Effects

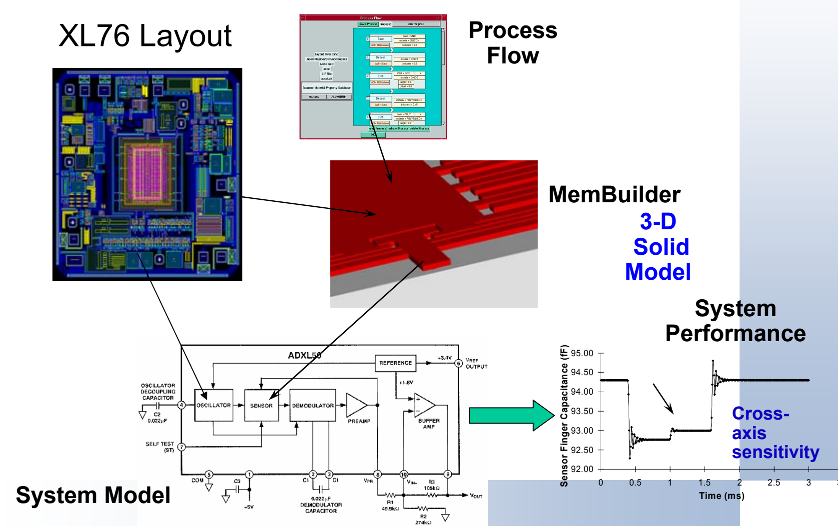


A. K. Noor and S. L Venneri, bulletin for the international association for computational mechanics, n°6, summer 1998

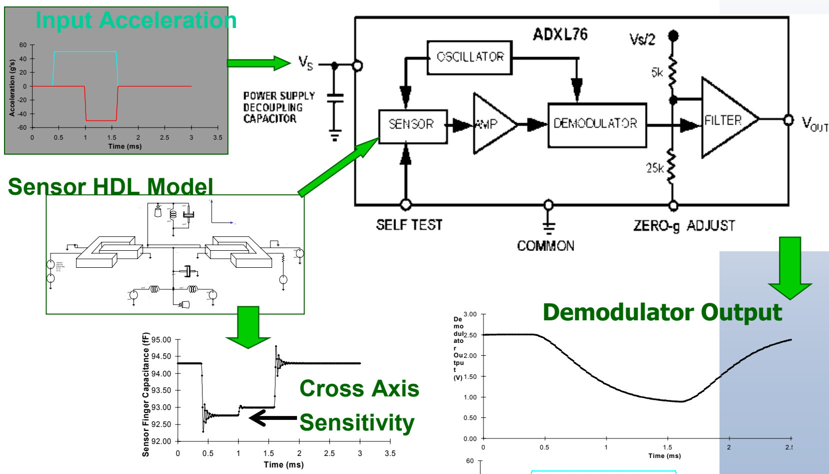
System-Level Simulation

- Conversion of a numerical matrix to an equivalent subcircuit
- Translate specific changes in device configuration, dimensions, and material properties into the circuit-equivalent behavioral model

Device to System

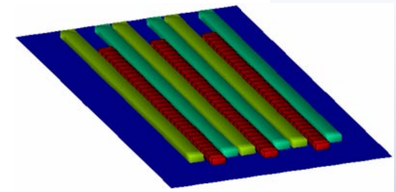


System Modeling

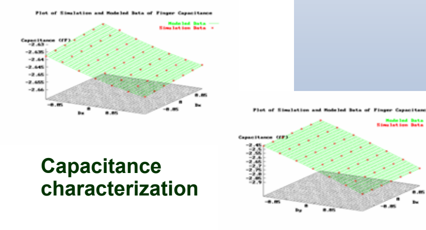


HDL (Macromodel) Generation from Device Modeling

- Extract from 3D model:
  - ***Auto Fit of Behavior Curves***
  - – Mechanical Spring
  - – Electrostatic Forces
  - – Mass
  - – Damping Coefficients
- Auto generation of 6-DOF HDL Model
- Industry standard system/circuit modeling tools: SABER, SPICE, Matlab, etc.

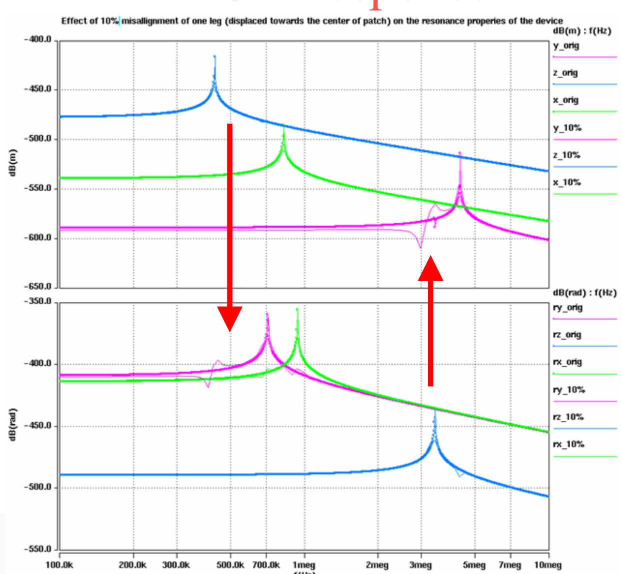


ADXL76 finger-cell 3D model

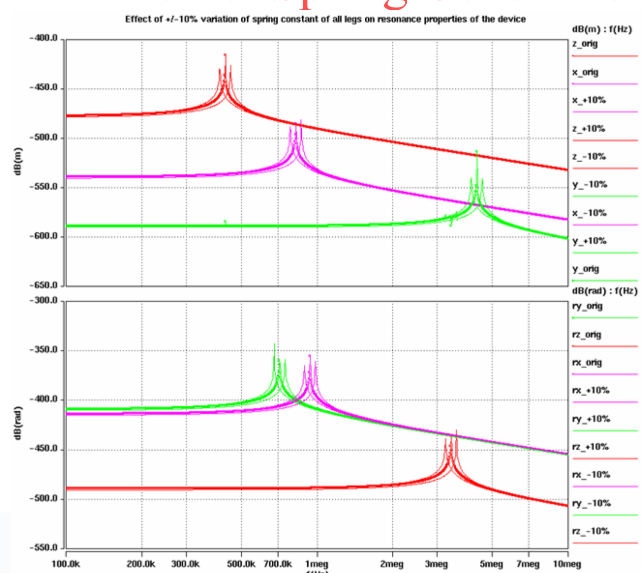


Capacitance characterization

Effect Of 10% Tether Misalignment On Response



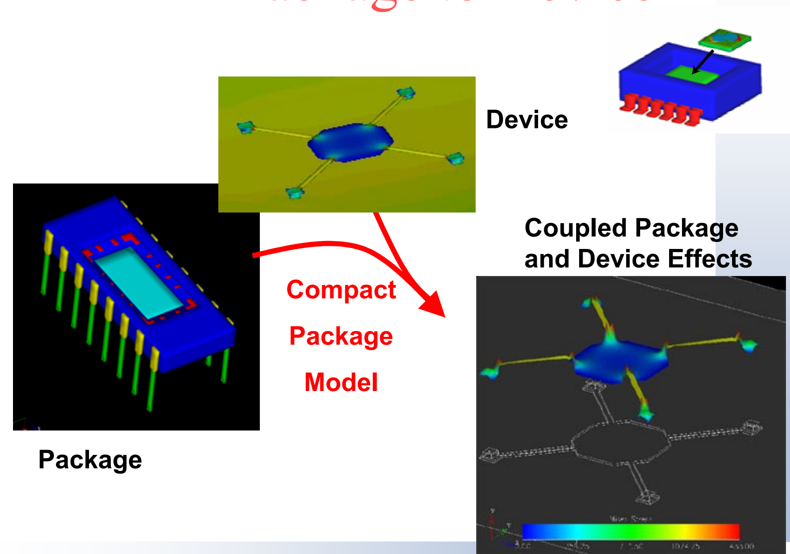
Effect Of A +/- 10% Variation Of Tether Spring Constants



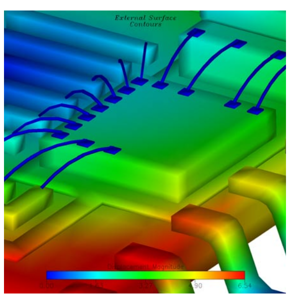
Packaging Simulation

- Automated package-device interaction simulation by:
  - Separating FEA of both the package and the device
  - Coupling the results through parametric behavioral package models (MEMCAD from Microcosm Inc.

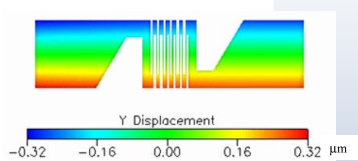
Package to Device



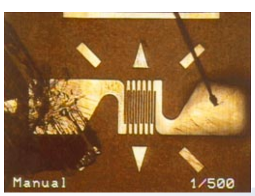
Package Model Calibration



Silicon die, wirebonds, and leadframe of plastic package



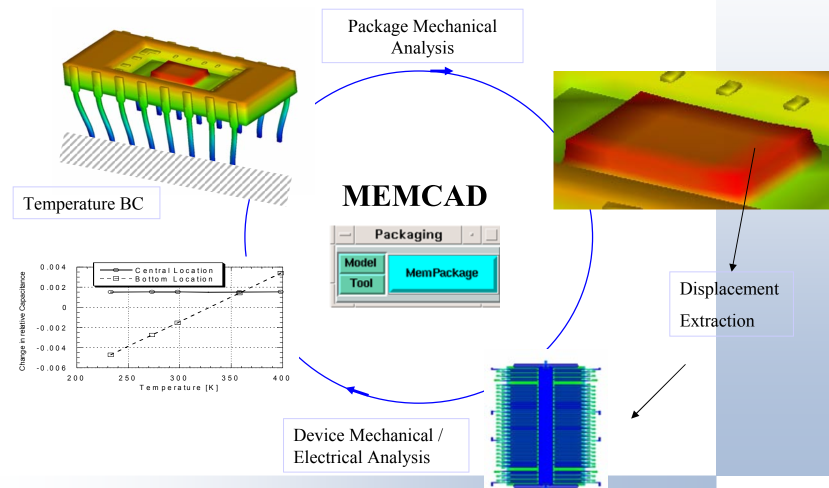
Displacement along the sensitive axis of the resistor element



Metal foil strain gauges

Potential distribution in the metal foil

Packaging Sensitivity Analysis



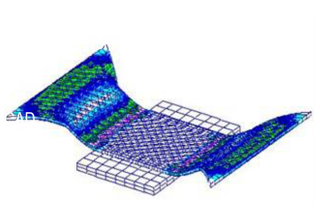
Summary

- MEMS/MST tools exist today.
- The Tools can support the design of RF devices and systems.
- The Design Process needs to support the integration of MEMS and ASIC subsystems.
- ALL players in the design process (Architect, Analog, Digital, MEMS, Package) must communicate.
- Communications are enabled by specific layers in the design tool set which allow models from one subsystem to influence the others.

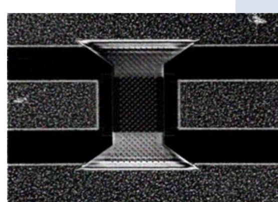
IntelliSuite Application Examples

Raytheon Systems

- RF switch
  – Corrugated geometry contact analysis
  – Electrostatically actuated



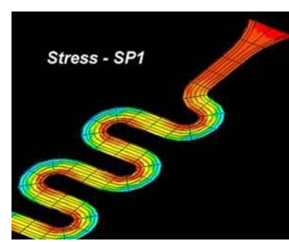
Device model



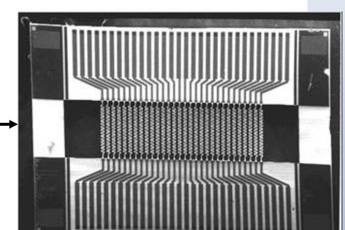
Fabricated device SEM

NASA

- Radiation detectors



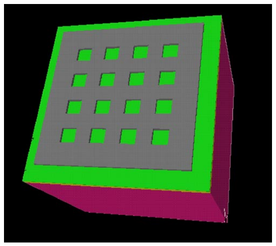
CAD – stress results

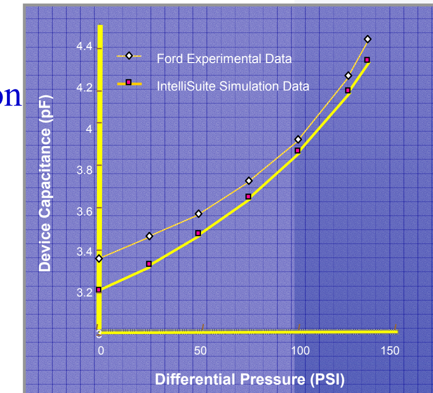


Fabricated array

Ford Microelectronics, Inc.

- Capacitive pressure sensor
  - Capacitance as a function of applied pressure



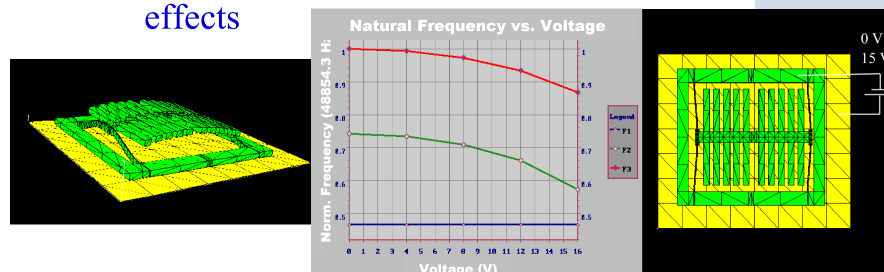


Comparison between IntelliSuite simulation and Ford's experimental results

*Ford Microelectronics, Inc. Colorado Springs, CO, *JMEMS*, June'96, p 98

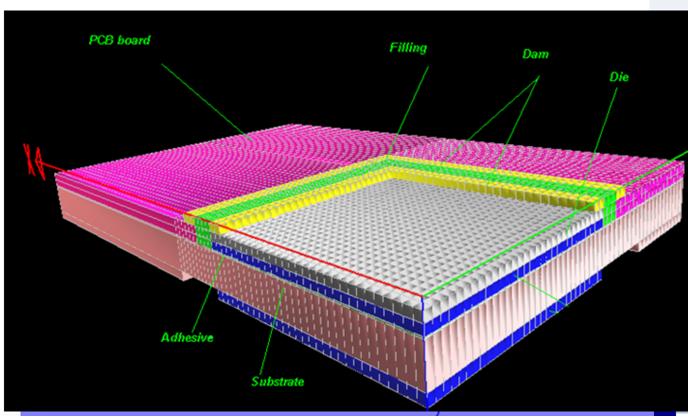
Gyro / Accelerometer

- Natural frequency shift
  - Electrostatic or thermal frequency tuning
  - Only 3D simulation available
  - Accounts for levitation & other 2nd order effects



Corning IntelliSense

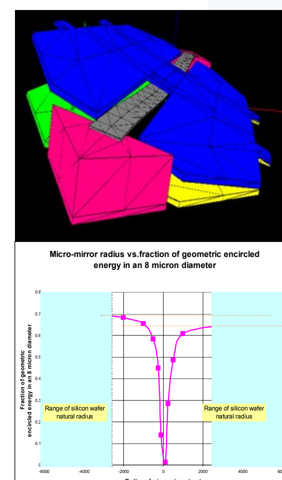
- Mirror array packaging analysis



IntelliSense Packaging Group

Integrate With System-level Design

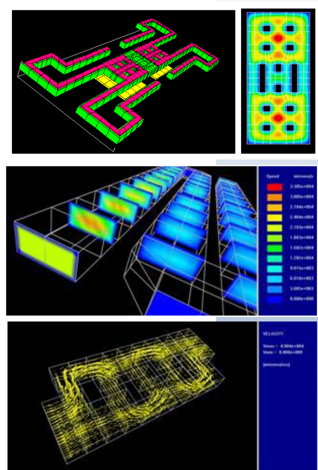
- Electro-mechanical output as input to optical model
  - 3D mirror profile
  - Maximum mirror angle
  - Jitter angle associated with mirror stability
  - Surface material



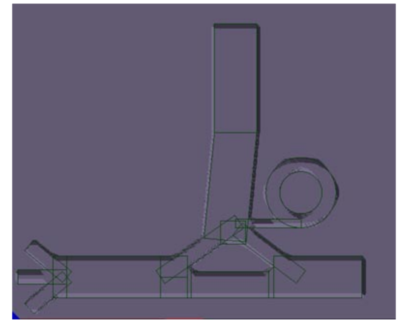
Model courtesy of NASA, Goddard Space Flight Center

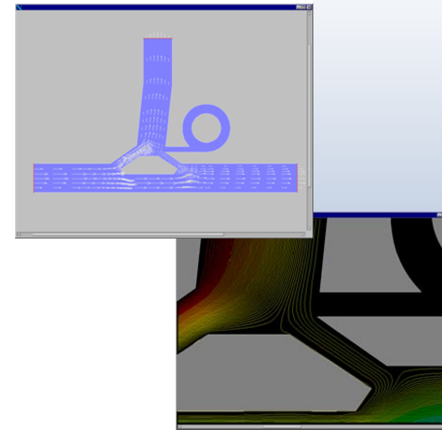
Fluidic analysis overview

- 3D Navier-Stokes solution
- Incompressible, laminar, single-phase flow
- Heat transfer
- Steady-state and transient
- Squeeze-film damping
- Electro-kinetic phenomena
  - Electro-osmosis
  - Electro-phoresis
- Finite element & finite volume solvers



Electrophoresis channels

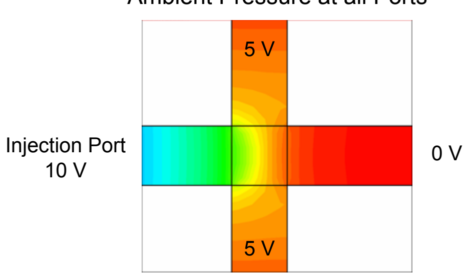




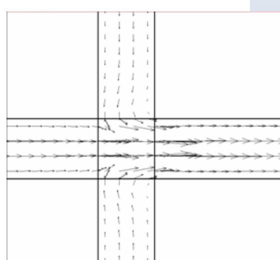
Electro-osmosis

- Cross-channel fluid flow

Ambient Pressure at all Ports



Pressure Plot



Vector Plot

Ref.: Patankar and Hu; *Analytical Chemistry, Vol. 70, No. 9, May 1, 1998*