MEMS Simulation and Mask Design

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ME 8254
MEMS Design
Design, A Tradeoff Iterative Process

- Find a solution that satisfies a set of requirements
- Some requirements may have conflicted requirements
- Trade-offs have to be made
- Performance may not the only goal. It is often traded off for manufacturability
Design, A Tradeoff
Iterative Process

Adapted from
Wu, UC Berkeley
The MEMS Overall System

Physical World

Sensor

Actuator

MEMS Transducers

Electronic Signal Processing, Computing Storage

Mechanical, Optical, ...

Electrical Signals
Design Issues

- Competition with both conventional technologies and other MEMS producers
- Manufacturability
- Cost

- Is MEMS the best solution?
- Does it have high impact?
- Does MEMS produce a paradigm shift?

- Real need for the market
- Who are the customers?
- Market size
- Market timing
- Mass or niche market?
- Technology available?
MEMS Design and Modeling

High-level simulations

System

Analytical, Macro-models

Device

Numerical, Finite-element,..

Designer Inputs

Physical

TCAD

Process

Simulation

Verification
## MEMS Design Process & Flow

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<th>System Requirements</th>
<th>Device Design</th>
<th>Implementation</th>
<th>Layout</th>
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<td>What technology to use?</td>
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<td>Verify system requirement</td>
<td>- Custom vs Foundry processes</td>
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<td>Loss</td>
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<td>- Materials (Si, single crystal, poly, ...)</td>
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<td>Power consumption</td>
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<td>- Process integration</td>
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<td>etc</td>
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<tr>
<td>System level simulation (e.g. optical simulation for optical systems)</td>
<td>Analytical models</td>
<td>Finite element method</td>
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<td>Macro models</td>
<td>Coupled domain FEM (MEMCAD, ANSIS, IntelliCAD, ..)</td>
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<td>Establish technology files</td>
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<td>Design rule checking (DRC)</td>
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<td>- Synthesis</td>
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<td>- Export to MEMS CAD</td>
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Other MEMS Design Issue

- Fabrication
- Testing
- Reliability
CAD for MEMS Design
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 microsystem engineer.
Commercial Software

- Coventor Suite/MEMCAD by Coventor Inc.
  - http://www.coventor.com
- Intellisuuite by Intellisense Inc.
  - http://www.intellisense.com
- MEMScap from MEMScap Inc.
  - http://www.memscap.com
- SOLIDIS from ISE Inc.
  - http://www.ise.com
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 accomplished using a layout file editor (e.g., CADENCE, http://www.cadence.com or 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
Topography Simulation

- Goal: Obtain a realistic topography of the considered device by:
  - Realistically representing complex 2D and 3D structures to simulate the IC manufacturing process
  - Can be accomplished using (among others):
    - IntelliCAD from Intellisense Inc.
    - ACES from the University of Illinois at Urbana
    - MenBuilder from Coventor Inc
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 material properties
Mesh Operations

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

- Meshless methods being developed
Device Simulation

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

- Development of automated algorithmic methods for designing and controlling large coupled groups of MEMS units
- Development of micromanipulation workcell to assemble automatically MEMS parts
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 (Coventor Suite)
Modeling Engineering Systems
We separate out modeling into three areas:

- 1) Mathematical Modeling
- 2) Numerical Modeling
- 3) Computational Modeling.

These are not really three distinct entities, but rather are related by the fact Mathematical Modeling is a subset of Numerical Modeling, and both Mathematical and Numerical Modeling are subsets of Computational Modeling.
It is important to note that each type of modeling has its advantages and drawbacks. Of course, the optimal goal of modeling is to attain the "best" simulation of a realistic physical system with the "least" amount of headache.

The "best" simulation is that it gives the most accurate description of physical behavior for a given system. It is critical to remember that when we model a system, we will never completely describe all the behavior of that system.
We must make assumptions as to what aspects of the system behavior are most important to "catch" in our model.

We often have to reach a compromise between the need to represent a system as accurately as possible with our ability to both create and solve our representation or model of the system.

Finally, always, always remember that no model is 100% accurate.
Mathematical Modeling

Mathematical modeling is the oldest basis for analyzing physical systems. Mathematical modeling involves describing the physics of a system by partial differential equations (PDE).

The PDE are developed by balancing fluxes on an infinitesimal element. By assuming this flux balance, we derive the standard elliptic PDE describing the physics of static systems and the hyperbolic PDE describing the physics of dynamic systems.
The assumptions we make are that the material is subject to a certain flux of energy, such as thermal, mechanical, etc.

Using only mathematical modeling requires that we solve the PDE analytically. Although the advantage of doing this is that we have a compact description of the physical field within the system, the drawback is that it is almost never possible to generate an analytical solution except for the simplest systems.

Physical systems have more complicated material distributions, more complicated domains, and more complicated boundary conditions which create very complicated analytical solutions.
Numerical Modeling

- Numerical modeling is a superset of mathematical modeling. Numerical modeling contains the original mathematical modeling descriptions, but *creates approximations* to mathematical model solutions.

- Well-known examples of numerical modeling include Fourier solutions to differential equations, Ritz methods and Runge Kutta time integration schemes. Numerical modeling essentially converts an analytical solution into an approximate algebraic solution to determine the unknown coefficients.
• Although numerical modeling is now integrated closely with the computer, many numerical approximation methods were developed starting in the late 18th century.

• In addition, numerical solutions to mathematical PDE were carried out well before the development of the computer, although the computer has obviously enhanced the use of numerical methods.

• Numerical methods really represent an advance in the processing portion of modeling. For instance, we can apply numerical solution methods for problems whose material, domain and boundary conditions we can describe by paper and pencil.
Computational Modeling

- Computational modeling represents the largest set of modeling techniques in our description.
- Computational modeling is based on the PDE description of physics from mathematical modeling, and also utilizes the solution approximations made in numerical modeling.
- What sets computational modeling apart from mathematical and especially numerical modeling is that now we must use a computer not only to solve our numerical approximation, we must also use other aspects of computing like computer graphics, visualization and imaging to set up our mathematical description.
Because of its intimate link to the computer, computational modeling involves the generation of software packages, which are specifically tied to computer hardware.

Advances in computational modeling come not only from applied mathematics, which is where the majority of advances come in mathematical and numerical modeling, but also from electrical hardware engineering and software algorithm development.

Much of the research in computational modeling actually involves ways to describe and set up the mathematical description of the problem, including defining the domain of the problem, the material distribution, and the boundary conditions.
Computational modeling is ubiquitous within engineering today. Finite element and finite difference software systems are used extensively to design and analyze products.

However, although these software systems, extensively based on the geometry paradigm we discuss next, have greatly enhanced the modeling process, they by no means are a utopia.

Modeling extremely complex systems still takes a significant amount of time, sometimes too long to be of use in making the product.

For biological tissues, the complexity of anatomy and tissue structure often make the traditional geometry paradigm of limited value. For this reason, the idea of image based CAE, proposed by a number of researchers, has taken hold in biomedical engineering, but is also taking hold in traditional engineering.
Finite Element Analysis and Design

Microsystems/MEMS Engineering
MEMS Modeling Levels

- Process level: reflecting fabrication steps and their effects on device geometry and materials properties
- Physical level: reflecting the response of the 3D device continuum (3D FEA)
- Device level: reflecting macro-model or low-order extracted models from physical models (simple spring elements)
- System level: reflecting system behavior integrating mechanics and electronics through behavioral model that can be simulated in Simulink and alike.
Mask Design and Fabrication
Both microelectronics and MEMS fabrication start with lithography.
The stencil used to repeatedly generate a design pattern on resist-coated wafers is called a mask.

The lithographic patterns printed on a wafer need to be as good as patterns on the mask.
Mask Type

- Binary Mask
- Proximity correction mask
- Phase shift mask
Binary Mask

- The pattern area is either clear or opaque
- The mask pattern design is the same as the desired pattern of the device
- May cause serrated edges and non-uniformity across the mask
Proximity Correction Mask

- Modify the mask pattern
- Final mask pattern may contain serifs at feature corners
Phase Shift Mask

- Add one 180° phase shift layer on a mask
- The feature size can be about 100 nm
- First was introduced in 1982. New software developed.
Mask Principal Parameters

- Pattern position accuracy
- Feature size control
- Defect and pattern fidelity
Pattern Position Accuracy

- It refers to the pattern alignment between two or more critical mask levels of a given set.
- It is important to know and measure the machine error that affects the pattern position accuracy.
Feature Size Control

- Critical dimension control (CD) is one/more features defined by a designer
- Three important parameters:
  1. The average value of a given critical dimension for the specified value.
  2. The uniformity of the critical dimension.
  3. The linearity of feature sizes down to some lower limits.
Defects and Pattern Fidelity

- Defects may be defined as extra or missing parts of a chromium film.
- Pattern fidelity covers many issues such as incorrect pattern shape. It is also defined by the pixel size used to write the pattern.
Mask Design

- Design sequence
- Design consideration
- An example - micromotor
Design Sequence

- Device design
- Pattern design
- Process design
- Drawing your mask pattern
Design Consideration

- Minimum feature size
- Pattern uniformly
- Positive/negative photoresist
- Alignment marks
- Bonding requires
An Example - Micromotor

- Electrostatic force
- Rotor: 120 μm in diameter
- Six masks process design
Mask for Micromotor
Exposure and Alignment Tool
Mask and Substrate Holder
Principle of Alignment
Alignment Mark

Test structures.

Arrows point to mark to make it easy to find.

Mask number.
Layer ID.
Scribe lane.

Alignment marks as they appear when drawn one above the other.

A very simple alignment design for two layers. (example only, not to scale)
Mask Design Tools

- AutoCAD
- L-edit
- Some simulation tools: MAMSCAD; Intellsense
- Link CAD
L-Edit Main Setting

- Technology file – store the preference layer name, layer number, screen color, internal units, ……
- Grid – basic mesh dimension variable, snap, ……
- Text – type text on your layout
- Format – GDSII, CIF, TDB, ……
Mask Making

- Pathway pattern transfer
- Emulsion mask and Chrome mask
- Fabrication tools and steps
Fabrication Procedures

- Substrate preparation
- Pattern writing
- Pattern processing
- Metrology
- Inspection for pattern integrity
- Cleaning
- Repair
- Pellicle attachment
- Final defect inspection
Mask Fabrication Tool

- High resolution printer
- Optical pattern generator
- E-beam writer