Hierarchical Design and Test of Integrated Microsystems

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Successful design of application-specific integrated microchips that can sense and actuate as well as compute and communicate requires hierarchical design methodologies and tools such as those presented here.

Digital design tools such as logic synthesis, semicustom layout, and behavioral simulation have drastically changed the digital IC design process, enabling design of complex "systems on a chip." The usefulness of such chips is limited in a world dominated by information that is not represented by zeros and ones. Overcoming these limitations has led to mixed-signal and mixed-domain technologies that monolithically integrate CMOS electronics with microelectromechanical systems (MEMS), leading to chips that can sense and actuate as well as compute and communicate.

In the 1980s, MEMS research into process technologies led to the development of micromechanical actuators, microfluidic pumps and valves, and various physical and chemical sensors, demonstrating the benefits of miniaturization in sensors and actuators. Recently, such devices have been monolithically integrated with electronics, resulting in integrated microsystems. Processes that ease the integration of MEMS with CMOS electronics now allow VLSI system designers to integrate micromechanical components into their microelectronic "systems on a chip." As a result, there is a growing need for CAD tools that shorten the design and development time for low-cost, low-volume microsystems that integrate tens to thousands of micromechanical components. Success in this area depends greatly on new design methodologies that allow complex microsystems of mechanical, electrical, thermal, fluidic, and optical components to be hierarchically represented and simulated. In addition, CAD tools capable of assessing and preventing faulty MEMS behavior are also necessary to ensure the end quality of complex MEMS-based products.

One relatively mature design area is the surface-micromachined suspended MEMS, as exemplified by the recent success of commercial microaccelerometers for automotive airbag deployment and digital mirror displays for high-fidelity video. The existence of accumulated design expertise, stable fabrication services, and electromechanical modeling tools has made the suspended MEMS technology a good candidate for initial development of design and test tools for MEMS. This article presents emerging results of an integrated mixed-domain design methodology similar to the mixed-signal design methodologies in the VLSI community. This methodology is based on a hierarchical mixed-domain design representation and includes a Spice-like nodal simulation environment, an "on-the-fly" component layout-synthesis module, a layout extractor for design verification, and a fault model generator for test methodology development.

Surface-micromachined suspended MEMS

The processing of microstructures has shared the same silicon-based technology used in IC fabrication over the last 40 years. Initial microstructures were fabricated in single crystal (or bulk) silicon. However, the
VLSI-motivated development of thin-film deposition, patterning, and etching steps in modern ICs led to the development of surface-micromachined structures. Surface micromachining is easier to integrate with electronics than bulk micromachining and has become the process of choice for integrated microsystems. Classical surface micromachining begins with the deposition of a silicon nitride layer for substrate passivation of the silicon wafer, followed by a polysilicon layer that is patterned and etched to define the interconnect needed for the device. A sacrificial layer (usually phosphosilicate glass) is then deposited and patterned to define anchor cuts. A conformally deposited structural polysilicon layer fills the anchor cuts and is then patterned and etched to define the microstructure. Additional sacrificial and structural layers are possible. A wet etch in hydrofluoric acid removes the sacrificial phosphosilicate glass layer and releases the resulting polysilicon structure. The MCNC Multi-User MEMS Processes (MUMPs) is an example of a polysilicon surface micromachining process.

As an alternative to polysilicon, 10 years ago, researchers began testing microstructures fabricated using CMOS interconnect layers. A CMOS-MEMS process that decouples the micromachining steps from the CMOS process flow has the advantage of low-cost fabrication of integrated MEMS and the capability to place multiple isolated conductors within suspended structures. The fabrication steps for a simple cantilever beam are illustrated in Figure 1. Prototype structures begin with the Hewlett-Packard 0.5-µm three-metal n-well CMOS process available through the MOS Implementation Service. Anisotropic reactive-ion etching of the dielectric layers precisely defines the structural sidewalls, with the top metal interconnection layer acting as an etch-resistant mask. Next, a nearly isotropic etch undercut the silicon substrate and releases the structure. Fourteen different composite structures can be made by using different combinations of the embedded metal layers and polysilicon. A scanning electron micrograph of a released composite beam with three metal conductors and polysilicon is shown in Figure 1d.

Suspended microstructures form a class of microstructures that is attached to the immobile silicon substrate through compliant flexures or rigid anchors. Suspended MEMS include commercial microstructures (such as accelerometers for automotive airbag deployment and digital mirror displays for high-fidelity video projection). This commercial interest in integrated suspended MEMS/chips and the need for a design and test methodology for increasingly complex designs motivate the development of CAD tools that focus on suspended MEMS.

Hierarchical design of MEMS

Currently, most system-level design involving MEMS-based integrated microsystems is accomplished by modeling each microelectromechanical component using a single behavioral entity, possessing no hierarchy in its representation. Knowledge of component function along with analytical macromodeling or macromodeling techniques developed around existing continuum simulation (e.g., finite-element

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**Figure 1.** The CMOS micromachining process flow: (a) after CMOS processing; (b) after dielectric reactive-ion etch for definition of structural sidewalls; (c) after isotropic silicon etch for structural release. (d) Cross section of a composite CMOS microstructural beam with three CMOS metallization layers and gate polysilicon embedded.
or boundary-element analysis) can be used to generate component-level macromodels for system-level simulation. These approaches capture physical effects with high accuracy, however, they require the creation of new models whenever there is a change in geometric parameters or topology, which slows design iteration. Essentially, these macromodels are behavioral views of a fixed layout view of the component, since there is no established method for general reuse of the macromodels. Conversely, there are no existing ways of synthesizing layout from the behavioral representation.

To facilitate the design of integrated microsystems, a hierarchical design representation of the MEMS components has been developed that is similar to existing mixed-signal design methodologies. The hierarchical nature of the design representation enables abstractions that accommodate the application-knowledgeable system designer, the MEMS component engineer, and the technology-conscious process/device engineer, yet enable the vital communication necessary for complex system design. This hierarchical nature is possible because the underlying layered batch-fabrication process limits the types of manufacturable microstructure geometries. Other hierarchical approaches to MEMS design have been proposed. A more complete survey is available in Fedder.6

Consider an integrated oscillator consisting of its MEMS and electronics components. The MEMS component of this oscillator has to behave like a resonator. One example of a microresonator is the folded-flexure resonator component in Figure 2a. The component is partitioned into functional elements as shown in Figure 2b: a shuttle mass, two symmetrical folded-flexure springs, and two comb drives. These functional elements are composed of reusable atomic elements, such as the anchor, plate, beam, and electrostatic gap shown in Figure 2c. This atomic element level is available in existing simulation environments enables a schematic representation of MEMS and provides a critical link between layout and behavioral simulation.

The realization of complex integrated microsystems that include several electronic and micromechanical components requires the use of parameterized behavioral models for the elements in the hierarchical representation. Models can be parameterized as a function of layout geometry (similar to MOS length and width), material parameters (similar to electron mobility), and operating environment. Modeling intervention during design iterations is required only when a designer insists on device topologies that cannot be constructed from parts in the library or if additional parameters are required. Tools for mixed-domain circuit simulation, synthesis, extraction, and test to support this hierarchy are discussed next.

Mixed-domain circuit simulation

As was the case for MEMS processing, circuit simulation of MEMS should take advantage of the extensive research in electronic circuit simulation. In electrical simulation, elements (parameterized with their geometry) are interconnected into a schematic that is subsequently net-listed for simulation via a matrix-based simulator derived from Kirchoffian theory and elemental models. The location of the elements is not important. In contrast to electrical simulation, the mechanical nature of MEMS components results in a coupling between the geometric parameters of each element and the layout position parameters.

Unlike early approaches to integrating mixed-domain behavior into Spice by translating the mechanical natures into electrical natures, our approach7 has taken advantage of modern analog hardware description languages such as VHDL-AMS and Verilog-A, which allow the use of nonelec-
electrical natures, similar to the work of Teegarden et al. In this context, a "nature" is an assignment of physical meaning to through variables and across variables in Kirchhoffian network theory. Force is the through variable and displacement is the across variable for the translational mechanical nature in this work. For the rotational mechanical nature, moment is the through variable and rotational displacement is the across variable. These natures are similar to the electrical nature in which current is the through variable and voltage is the across variable. Behavioral models of the mechanical (e.g., beam and plate) and electro-mechanical (e.g., gap) elements are then developed with separate electrical and mechanical terminals. These models are parameterized functions of the geometric parameters. As all suspended structures respond to inertial forces, each inertial element needs to have a terminal connected to the chip substrate to access the chip's translational inertial acceleration and rotational inertial velocity in the model. The force balance equation, which states that the sum of all forces acting on a body is zero, is enforced by the mechanical equivalent of Kirchhoff's current law. That is, the sum of all "branch forces" incident at a node is equal to zero. Behavioral models for the mechanical elements are based on the theory of structural analysis and for the electro-mechanical elements are based on analytical field solution coupled with parameter fitting from continuum analysis.

The mechanical nature of the elements implies that the element geometry and location are tightly related (mechanical interconnection occurs only by abutment). Using an iconified symbol view of each of the elements, a designer is able to put together a schematic of the MEMS and electronic elements in the system. The MEMS portion of the schematic has a one-to-one correspondence to the layout, which provides an intuitive interface for the designer. Coupling the schematic methodology with existing schematic capture tools that are compatible with electrical circuit analysis enables MEMS design to be quick and efficient.

The schematic representation of a "crab-leg" MEMS accelerometer is shown in Figure 3. The crab-leg suspension is a popular MEMS spring device, created by joining two beams at a 90-degree angle. Separate macromodeling of the complete accelerometer device is not necessary to conduct the simulation. In a manner analogous to circuit simulation, general models of the beams and gaps are interconnected in the net list to build hierarchically (and automatically) the device-level macromodel. A mechanical shaker test jig is
Figure 4. (a) Shaker test of the accelerometer using ac simulation. The external acceleration amplitude is 1 m/s² swept from 10 Hz to 100 kHz. (b) Transient response of displacement and output voltage to a pulse in external acceleration.

simulated by attaching an ac acceleration source to the external acceleration input of the mechanical plate element. CMOS electronics is used for the transresistance amplifiers that detect the displacement current in the comb drive sensors when the proof mass moves due to external acceleration. The ac simulation of the MEMS accelerometer component and the attached electronics component is shown in Figure 4a. The 6.4-kHz resonant frequency for this structure is within 1 percent of the value generated by finite-element analysis. The transient response to a 3-ms pulse in external acceleration is also shown in Figure 4b. The response is underdamped, and the voltage responds only to changes in acceleration, as expected.

The mixed-domain circuit simulation strategy allows capabilities such as transient analysis and integration of MEMS and electronics into a single simulation that cannot be performed in continuum simulators. Additionally, the layout-based schematic methodology provides an intuitive user interface to the designer that reduces design entry time by orders of magnitude compared to continuum simulation. The resulting environment—called NODAS, for Nodal Design of Actuators and Sensors—enables iterative design of integrated MEMS/electronics microsystems.²

MEMS component synthesis

As is the case with traditional VLSI, the MEMS components in an integrated MEMS/electronics design can come from fixed libraries, parameterizable libraries, or "on-the-fly" component synthesis. The large number and variety of performance specifications in a MEMS component minimize the usefulness of fixed libraries (mixed-signal system designers find the same limitations in fixed libraries for analog cells). Parameterizable libraries enable a device designer to rapidly generate a layout given a set of geometric parameters. While these libraries eliminate the manually intensive layout process required for physical design, a methodology based on parameterizable libraries still requires MEMS expertise for generating the geometric parameters from the performance specifications. Component synthesis, on the other hand, proves a flexible and extensible way to generate MEMS components.

Component synthesis involves rapid translation of design specifications (such as accelerometer sensitivity) into a design. This design is then translated into a layout using a parameterizable layout generator. This approach involves modeling the design problem as a formal numerical synthesis problem and then solving it with powerful optimization techniques. Although universal building blocks have not been discovered for MEMS, components frequently used in system designs can be easily identified. In the suspended MEMS area, reusable topologies include several kinds of accelerometers, gyroscopes, resonators, xy positioners, and micromirrors. Instead of redesigning these components each time a new system is proposed, system designers will benefit from synthesizers that tackle the routine design of frequently used components.

The process of modeling the design problem involves determining the design variables, the numerical design constraints, and the quantitative design objective. Let us consider a lateral capacitive accelerometer like the one shown in Figure 5. The accelerometer consists of a movable proof mass, suspended by two Y-shaped spring beams on both sides.
External acceleration causes the proof mass to move relative to the substrate, subject to restoring spring forces and the damping provided by the motion of air around the device. The suspension is designed to be compliant in the x direction of motion and to be stiff in the orthogonal direction (y) to keep the comb fingers aligned. Movable comb (rotor) fingers are attached to the proof mass. They are combined with the fixed comb (stator) fingers to form the sensing and actuation units. One of two voltages can be applied to the actuation unit to cause a net electrostatic force that pulls the proof mass in the desired direction. These actuation-unit fingers can be used for either self-test or force-feedback control. The sensing fingers form a capacitive bridge, which is modulated with voltage $V_m$ during sensing. The divider output is proportional to the difference in the capacitances and therefore to the proof mass position. This divider voltage passes through a buffer and is then demodulated to generate the final output voltage.

The lowest three lateral translational and rotational modes of the mass-spring-damper system are modeled by second-order equations of motion. The vertical mode and other higher-order modes are currently not modeled. The design variables include the geometric parameters of the Y-spring, proof mass, and comb elements, as well as the modulation voltage. Technology-driven design rules constrain the minimum geometries, such as beam widths and minimum spaces between structures. Maximum values of structural parameters are primarily constrained by possible sticking of the structural film to the substrate during sacrificial oxide etching.

The load seen by the sensing comb drive stemming from the integrated electronics is currently modeled as a parasitic capacitance ($C_{pos}$) that affects the operation of the capacitive bridge, as shown in Figure 5b. The functional specifications include accelerometer sensitivity to primary and cross-axis acceleration, the maximum and minimum detectable acceleration, and accelerometer bandwidth. The complete design problem is therefore represented as a constrained nonlinear optimization problem and solved by an off-the-shelf solver.

In addition to “on-the-fly” synthesis of layouts to meet desired performance specifications, MEMS synthesis can be used for design space exploration, as shown by the complete Pareto curve in Figure 6. The curve was generated by minimizing noise for several fixed values of sensitivity, with

![Figure 5.](image)

**Figure 5.** (a) Layout of the lateral capacitive microaccelerometer. The black areas indicate anchors between the polysilicon structure and the bottom layer. The rest of the structure is suspended 2 µm above the bottom layer. The actuation units are shown in a lighter shade than the rest of the structure. (b) The capacitive sensing interface is composed of the differential capacitance formed by the top and bottom stator fingers with the moving rotor finger (attached to the proof mass) and attendant electronics.

![Figure 6.](image)

**Figure 6.** Pareto curve showing the trade-off between sensitivity and noise. Increasing sensitivity results in the need for more sense fingers.
range > 10 g for all the designs. This curve allows the designer to determine the optimum device design from system constraints. As the required sensitivity increases, the number of sense fingers and the length of the fingers increase. Since the total accelerometer width is limited to 700 μm due to the sticking constraint, the increased finger length implies reduced proof mass width, which increases the total accelerometer noise due to Brownian motion. Since the designer tends to look for a high-sensitivity, low-noise design, one option can be to use electronic buffers to boost sensitivity. Coupling the curve of Figure 6 with a gain-noise plot for a buffer can lead to the optimal system design of an integrated MEMS/electronics chip.

Currently, the MEMS component synthesis focuses on the mechanical and electromechanical components, with simplified models of the interface electronics (i.e., fixed value of $C_{\text{on}}$) used to ensure that the MEMS to electronics transduction elements are optimally sized. Since the system designer will need to use alternate electronics specifications depending on the capabilities of the MEMS technology, it is envisioned that a more complete codomain synthesis tool can be developed by integrating MEMS synthesis with analog cell synthesis. Previous general-purpose approaches to analog synthesis have failed to make the transition from research to industrial practice. Our topology-specific tools are not general purpose and are aimed at enabling the vast numbers of electronic designers currently not experts in MEMS design to include MEMS devices in their application-specific systems.

**Layout extraction**

Extraction translates layout into a corresponding circuit representation (i.e., a net list). It enables verification of layout correctness against an existing circuit representation and provides an annotated circuit representation that can be evaluated via mixed-domain simulation to verify system behavior. Extraction involves determining the elements in the net list, as well as their connectivity. The elements can be extracted as fixed valued (e.g., plate has 1 μg mass) or as geometrically parameterized (e.g., square plate has length of 100 μm). The MEMS abstractions used for mixed-domain circuit simulation are based on geometrically parameterized behavioral models of the atomic elements. Extracting to match these parameterized models enables the reuse of the behavioral models and is the approach taken in this work. This is similar to device extraction in VLSI, where geometrical parameters for the MOS model are extracted from the layout. Unlike VLSI layout extraction, however, the features (shape, size, and position) of each layout rectangle are of utmost importance in recognizing the constitutive MEMS elements. Once the constituent MEMS elements are recognized, elements-specific extraction can be used as necessary.

General-feature recognition algorithms for surface-micromachined MEMS have been developed. As the rectangles that comprise the layout are generated by algorithms specific to the layout editing tools, the first step in any layout extraction involves creating a unique representation of the layout. Starting from an input layout in the Caltech Interchange Form, the rectangles in the layout are partitioned into a canonical representation, such that each rectangle (or cell) has only one neighbor on each side. The functionality of each of the cells is then determined by its shape, size, and connectivity. Nonstructural mask layers (such as those that define anchors) are used to obtain hints for possible functional uses for each of the cells. Cells that have only one side connected are cantilever beams and are considered to be fingers. Cells that are connected on opposing sides are considered to be beams. The canonical representation's partitioning algorithm results in multiple adjacent cells performing the same function. These multiple cells have to be combined to minimize the number of unnecessary nodes in the net list. Cell merging, first in the horizontal direction and then in the vertical direction, accomplishes this for the mass and anchor cells. The resulting net list directly corresponds to the atomic elements in the MEMS circuit representation for which behavioral simulation models have already been developed.

Higher-level functional-element models can be detected by processing the extracted net list. A functional-element library containing rules for detecting various springs (e.g., Y-springs, crab-leg, serpentine, and folded-flexure springs) and comb drives (e.g., linear, differential, and pedestal-based) has been developed. Finger orientation, region of occurrence, and geometrical parameters (length, width, and interfinger gap) are used to partition the set of recognized fingers, which are then analyzed for connectivity, resulting in the extracted comb drives. Spring detection is accomplished via a finite-state machine-based algorithm. Starting from a start state (always an anchor atomic element), the types of beams and joints determine transitions into the transition states and onto the final state, which indicates the type of spring detected. The joint transitions are classified according to the number of ports and the direction of rotation and provide the fundamental abstraction on which this FSM-based detection works. The FSM for each of the springs is created by reading in the description of the FSM from the component library. The connected sets of beams and springs obtained after the atomic recognition are then passed through each of these FSMs to recognize their type. Simulation-based verification using this level of extraction is a magnitude faster than at the atomic-element level and is seen as crucial for an iterative-design methodology.

A prototype implementation of the feature recognition for
element extraction and detection algorithms for functional-element extraction for rectilinear MUMPs layouts has been completed. As an example, an accelerometer layout, its constitutive elements, and its functional elements are recognized in Figure 7. Extraction algorithms enable the MEMS designer to easily link the layout view to the mixed-domain circuit representation needed for the verification of MEMS designs.

**Test**

We are developing generic fault models for capacitive inertial sensors and actuators that are fabricated using surface-micromachined technologies. Generic fault models are desirable because of their applicability to a wide range of devices. They also enable premanufacture evaluation, thus allowing test method optimization. One of our goals is to incorporate these fault models into our schematic-based MEMS simulator NODAS. This incorporation will essentially enable NODAS to perform as a fault simulator and thus will allow misbehavior analysis through simulation.

Faulty MEMS behavior can result from process contaminations that affect the structure and material properties of a given microstructure. For example, Figure 8 shows the scanning electron micrograph of a defective resonator. This particular resonator has two broken beams that may have resulted from the introduction of foreign particles into the fabrication process. Other unwanted structural or material properties can be caused by residual stress, process variations, stiction, or a combination of them. Currently, we are focusing on particles, since failures induced by these contaminations can be extremely difficult to detect.

We used process simulation to predict the effects that contaminations have on the physical geometries and material properties of surface-micromachined components. Figure 9 (next page) shows Caramel's output for different 2-µm contaminations occurring at different resonator locations and introduced at various steps of the MUMPs fabrication process. Finite-element analysis is then used to characterize the impact that structural defects have on the key operational parameters of the device. For example, Figure 10 compares the displacement properties of a defect-free resonator with one that has two adjacent comb fingers welded together, as shown in Figure 9b.

**Hierarchical Design and Test Methods** for suspended MEMS promise to shorten the development cycle to days and enable the design of more-complex integrated systems comprised of hundreds to thousands of micromechanical elements with microelectronics. Identification of reusable hierarchical representations of MEMS components into functional and atomic elements enables a structured design methodology similar to that used for VLSI microelectronics.

A mixed-domain circuit simulation environment enables rapid exploration and analysis of the design space for MEMS
MEMS synthesis is a powerful tool for building common components that can then be used in larger systems. Modules for the layout synthesis of microresonators and microaccelerometers have been developed, and progress is being made for other common suspended MEMS components. The use of functional-element models of the MEMS components instead of a numerical simulation is essential to minimize the computation time required to generate synthesized results via an iterative improvement algorithm.

MEMS layout extraction couples the intuitive layout view for MEMS design with the hierarchical MEMS representation. Heuristics for recognizing atomic elements (such as beams, plates, and gaps) in rectilinear MUMPs layouts have been developed. Algorithms for detecting functional elements (such as serpentine springs and differential comb drives) have also been developed. Extensions to other surface micromachining processes are simple. MEMS extraction enables two-fold verification of layout—first, by comparing the connectivity of the elements in the layout with the elements in the schematic and, second, by enabling behavioral simulation capability directly from MEMS layout.

A comprehensive testing methodology for surface-micromachined suspended MEMS is required to ensure that the designs generated using the above methods can actually be tested for the presence of manufacturing contaminations and extreme process variations. We are developing an understanding of the effect of manufacturing reality on the physical geometries and material properties of surface-micromachined components, which can then be used to create robust MEMS designs.

Finally, we envision a MEMS design environment in which the expert MEMS designer can rapidly iterate on ideas for MEMS designs, in the same integrated environment in which a system-level designer can use synthesized and custom-made MEMS components to develop monolithic mixed-technology chips for reliable, low-cost, low-volume commonplace applications. Such a design environment is essential for designs in which sensors and actuators need to be integrated on the same chip as the attendant electronic information processing capability.

Figure 9. Structural impact of three different contaminations. (a) Flexure beam. (b) Comb fingers. (c) Shuttle mass.

Figure 10. Comparison of defect-free frequency spectrum with the spectrum of a resonator affected by welded fingers.

components. Many existing suspended MEMS designs can be partitioned into discrete elements and devices (such as beam springs, plate masses, and electrostatic actuators) that are modeled as lumped-parameter elements. Conversely, new components can be created by connecting these lumped elements. A component-level simulation capability that can simulate novel interconnections of these MEMS elements with microelectronics enables the shortening of the integrated MEMS design cycle.
References


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