Hierarchical Design and Test of Integrated Microsystems

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Abstract

The advent of monolithic integration of mechanical structures with electronics has ushered an era in which microchips can sense and act as well as compute and communicate. The complex device, component and system design issues involving such integrated chips requires the development of new CAD representations, methodologies and tools. A suite of tools that simultaneously considers the mechanical and electromechanical nature in such microsystems with traditional electronics natures is presented. These tools are based on a design methodology that partitions the micromechanical and electromechanical components in a hierarchical fashion into low-level reusable elements. This mixed-domain circuit representation is combined with Kirchhoffian network theory for an integrated microsystem simulation environment. Behavioral models from this hierarchical representation are combined with optimization into a tool that generates microstructure layouts meeting specified performance criteria. A feature-recognition based extractor translates layout geometry into the mixed-domain circuit representation, enabling layout verification. Models that integrate the effects of process contaminations on a microstructure form the basis of a MEMS testing methodology.

Index Terms: MEMS, hierarchical circuit representation, nodal simulation, synthesis, extraction, testing methodology

1. Introduction

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 are limited in a world dominated by information that is not represented by 0s and 1s. 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.

MEMS research into process technologies in the 1980s led to 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 [1]. Processes that ease the integration of MEMS with CMOS electronics [2] 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 arti-

cle 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.

2. Surface-Micromachined Suspended MEMS

The processing of microstructures has shared the same silicon-based technology used in integrated circuit (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 [1] 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—PSG) 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 PSG layer, and releases the resulting polysilicon structure. The MCNC Multi-User Process Service (MUMPS) [3] is an example of a polysilicon surface micromachining process.

As an alternative to polysilicon, microstructures fabricated using CMOS interconnect layers was first explored ten years ago [4]. A CMOS-MEMS process that decouples the micromachining steps from the CMOS process flow [2], has the advantage of low-cost fabrication of integrated

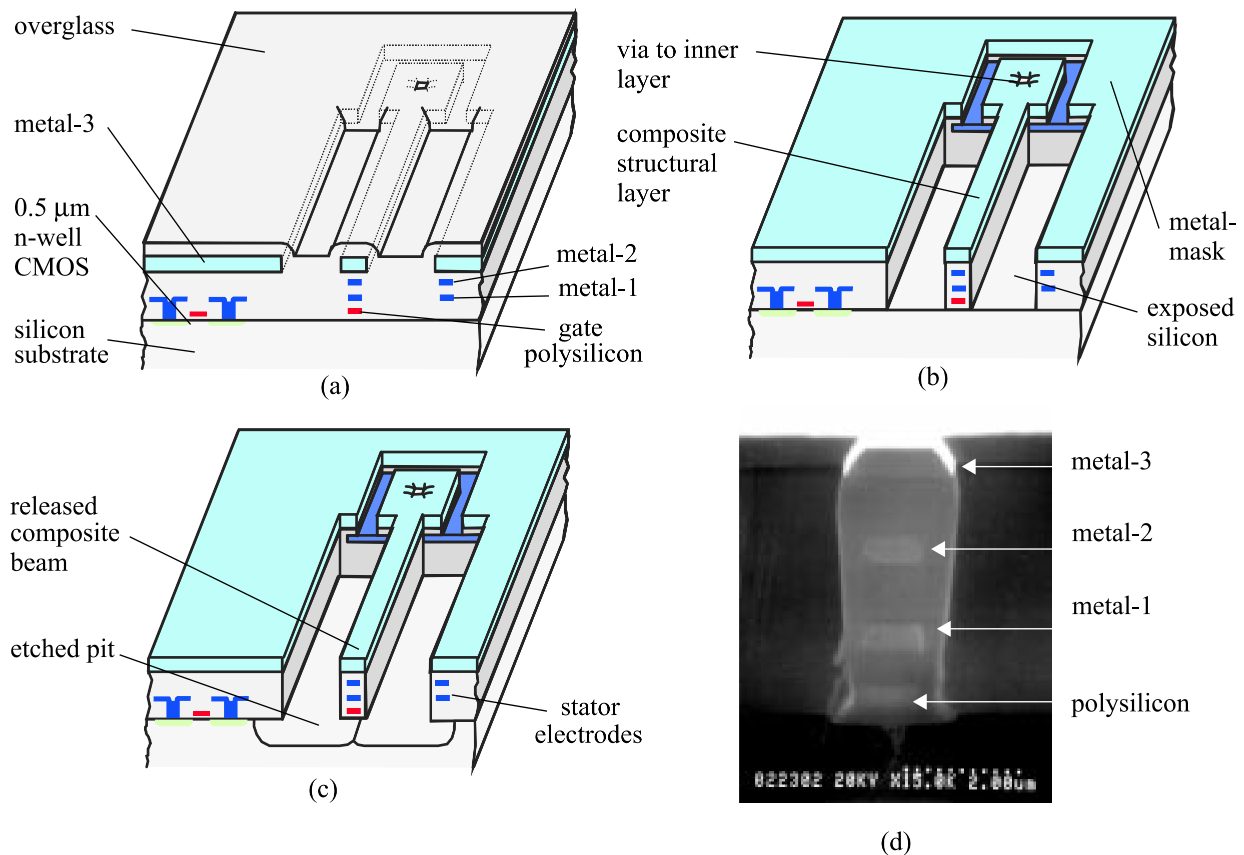

Figure 1: The CMOS micromachining process flow: (a) after CMOS processing; (b) after dielectric reactive-ion etch for definition of structural sidewalls; (c) after isotropic silicon etch for structural release. (d) Cross section of a composite CMOS microstructural beam with three CMOS metallization layers and gate polysilicon embedded.

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 (MOSIS). Anisotropic reactive-ion etching (RIE) 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 undercuts 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 scanned electron micrograph of a released composite beam with three metal conductors and polysilicon is shown in Figure 1(d).

Suspended microstructures are a class of microstructures that are attached to the immobile silicon substrate through compliant flexures or rigid anchors. Suspended MEMS includes commercial microstructures such as accelerometers for automotive airbag deployment and digital mirror displays for high-fidelity video projection [1]. This commercial interest in integrated suspended MEMS/electronics chips and the need for a design and test methodology for increasingly complex designs motivates the development of a CAD tools that focuses on suspended MEMS.

3. 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 or boundary-element analysis) [5] can be used to generate component-level macromodels for system-level simulation. These approaches capture physical effects with high accuracy, however, 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, which 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

comb drive

anchor

beam

folded flexure

gap

folded-flexure resonator

shuttle mass

plate

(a) (b) (c)

Figure 2: Decomposition of a folded-flexure resonator: (a) resonator component; (b) functional elements; and (c) atomic elements.

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 [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 2(a). The component is partitioned into *functional elements* as shown in Figure 2(b): 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 2(c). This atomic element level is analogous to circuit design where transistors, resistors, capacitors and inductors serve as the basic elements. All existing suspended MEMS designs can be partitioned into similar atomic elements. Conversely, new components higher up in the hierarchy can be formed from the lower-level elements, and these in turn can be used in even higher-level components and systems. Therefore, adding these atomic elements to the library of circuit elements (transistors and resis-

tors) available in existing simulation environments enables a schematic representation of MEMS and provides a critical link between layout and behavioral simulation.

Realization of complex integrated microsystems that include several electronic and micromechanical components requires the use of parametrized behavioral models for the elements in the hierarchical representation. Models can be parametrized as a function of layout geometry (similar to MOS length and widths), material parameters (similar to electron mobility), and operating environment. Modeling intervention during design iterations is only required 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 will now be discussed.

4. 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 (parametrized with their geometry) are interconnected into a schematic that is subsequently netlisted for simulation via a matrix-based simulator derived from Kirchhoffian theory and elemental models. The actual 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 approach [7] has taken advantage of modern analog hardware description languages such as VHDL-AMS and Verilog-A, which allow the use of non-electrical natures, similar to [8]. In this context, a ‘nature’ is an assignment of physical meaning to through and across variables in Kirchhoffian network theory. In particular, a translational mechan-

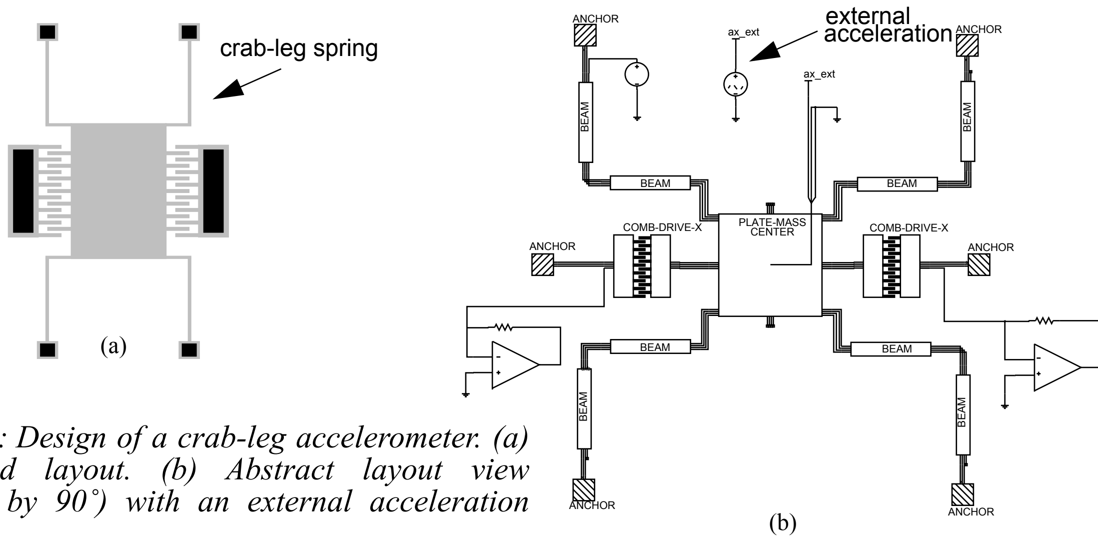

Figure 3: Design of a crab-leg accelerometer. (a) Simplified layout. (b) Abstract layout view (rotated by 90°) with an external acceleration source.

ical nature based on force as a through variable and displacement as an across variable, and a rotational mechanical nature based on moment as a through variable and rotational displacement as an across variable is used. 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 electromechanical (*e.g.*, gap) elements are then developed with separate electrical and mechanical terminals. These models are parametrized 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 theory of structural analysis and for the electromechanical 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 90°. 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 netlist to build the device-level macromodel hierarchically (and automatically). A mechanical shaker test-jig is 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 attached electronics component is shown in Figure 4(a). The 6.4kHz resonant frequency for this structure is within 1% of the value generated by finite element analysis. The transient response to a 3 ms pulse in external acceleration is also shown in Figure 4(b). The response is underdamped and the voltage only responds 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 con-

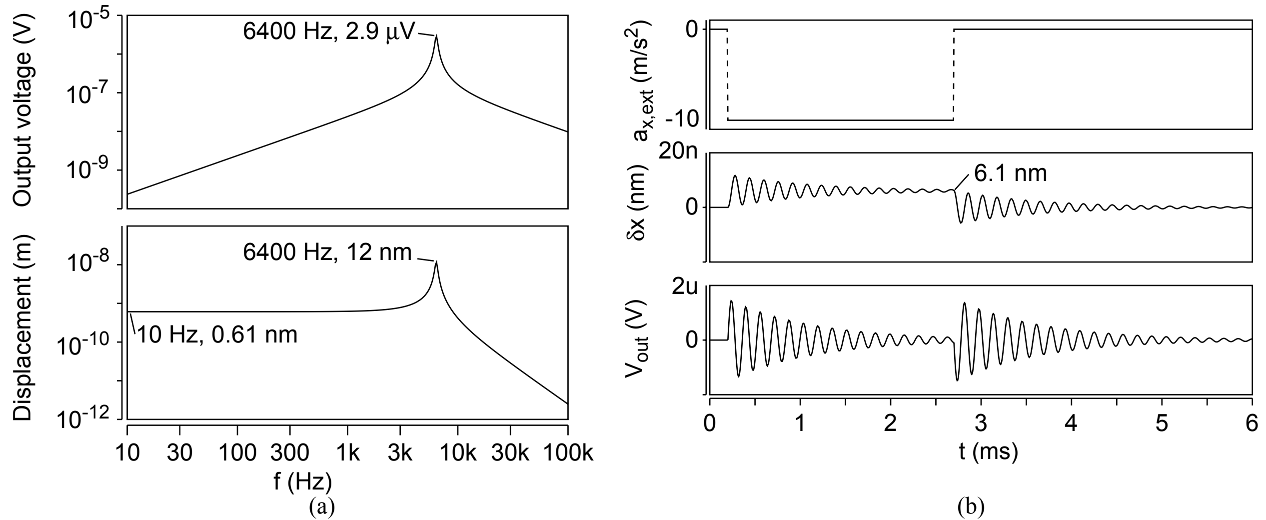

Figure 4: (a) Shaker test of the accelerometer using ac simulation. The external acceleration amplitude is 1 *m/s*^{2} *swept from* 10*Hz to* 100*kHz. (b) Transient response of displacement and output voltage to a pulse in external acceleration.*

tinuum simulation. The resulting environment, called NODAS for NOdal Design of Actuators and Sensors, enables iterative design of integrated MEMS/electronics microsystems [7].

5. MEMS Component Synthesis

As is the case with traditional VLSI, the MEMS components in an integrated MEMS/electronics design may come from fixed-libraries, parameterizable libraries, or from 'on-the-fly' component synthesis. The large number and variety of performance specifications in a MEMS component minimizes 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.

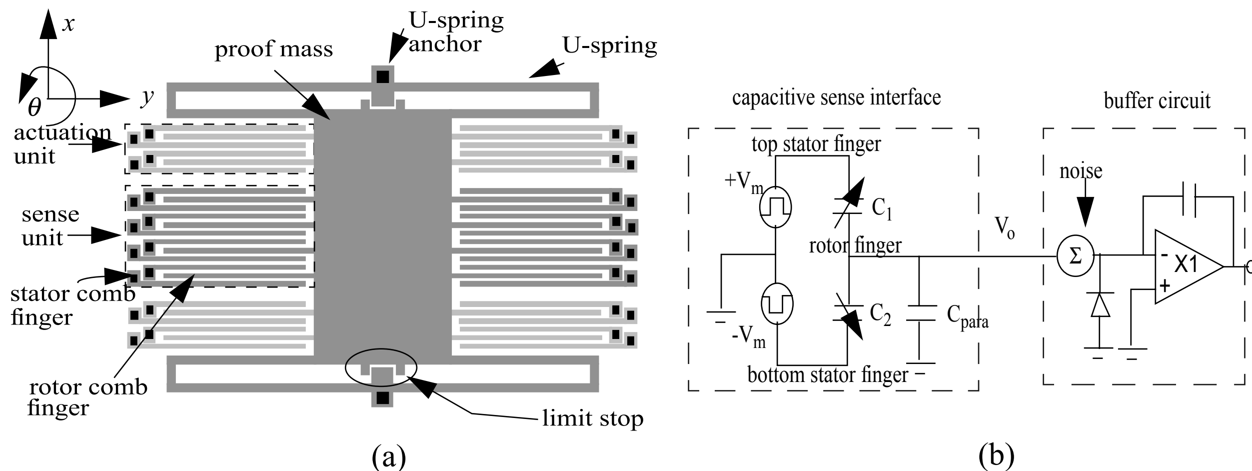

Figure 5: (a) Layout of the lateral capacitive microaccelerometer. The black areas indicate anchors between the polysilicon structure and the bottom layer. The rest of the structure is suspended 2 *μm above the bottom layer. The actuation units are shown in a lighter shade than the rest of the structure. (b) The capacitive sensing interface 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.*

Component synthesis involves rapid translation of design specifications (such as accelerometer sensitivity) into a design. This design is then translated into 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, x-y positioners, and micromirrors. Instead of redesigning these components each time a new system is proposed, system designers will benefit from synthesizers which 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. Lets consider a lateral capacitive accelerometer like the one shown in Figure 5. The accelerometer consists of a movable proof mass, suspended by two U-shape 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 [9]. The vertical mode and other higher order modes are currently not modeled. The design variables include the geometric parameters of the U-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 [3]. The load seen by the sensing comb drive stemming from the integrated electronics is currently modeled as a parasitic capacitance (C_{para}) that affects the operation of the capacitive bridge, as shown in Figure 5(b). 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 non-linear optimization problem, and solved by an off-the-shelf solver.

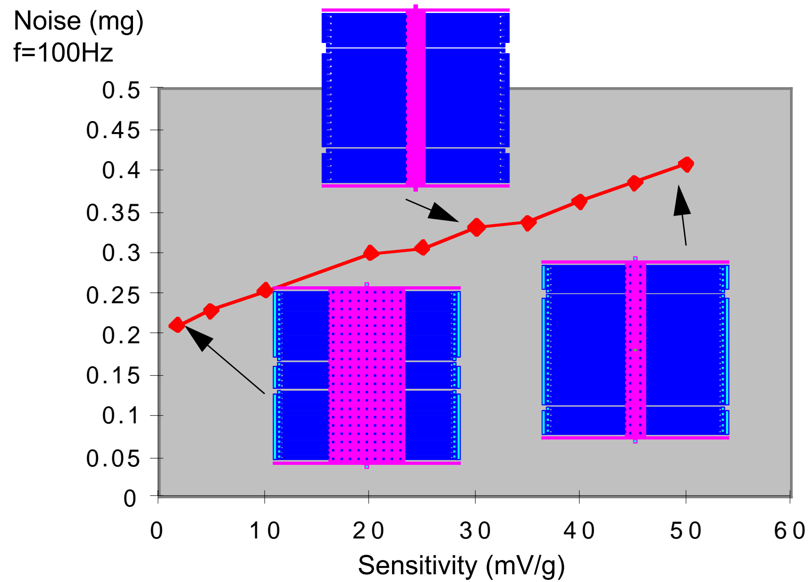

Figure 6: Pareto curve showing the trade-off between sensitivity and noise.

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 range > 10g 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 increases. Since the total accelerometer width is limited to 700µm, 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. The 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_{para}) 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 co-domain 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 into industrial practice. Our topology specific-tools are not general purpose and are aimed at enabling the vast numbers of electronics designers currently not experts in MEMS design to include MEMS devices in their application-specific systems.

6. Layout Extraction

Extraction translates layout into a corresponding circuit representation (*i.e.*, a netlist). It enables verification of layout correctness against an existing circuit representation, and provides an annotated circuit representation that can be evaluated via mixed-domain circuit simulation to verify system behavior. Extraction involves determining the elements in the netlist, as well as their connectivity. The elements can be extracted as fixed valued (*e.g.*, plate has 1μg mass), or as geometrically parametrized (*e.g.*, square plate has length of 100μm). The MEMS abstractions used for mixed-domain circuit simulation are based on geometrically parametrized behavioral models of the atomic elements. Extracting to match these parametrized 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 is extracted from the layout. Unlike VLSI layout extraction, however, the features (shape, size and position) of each layout rectangle is of utmost importance in recognizing the constitutive MEMS elements. Once the constitutive MEMS elements are recognized, element-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 CIF (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. Non-structural 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 netlist. Cell merging, first in the horizontal direction, and then in the vertical direction accomplishes this for the mass and anchor cells. The resulting netlist 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 netlist. A functional element library containing rules for detecting various springs (e.g., U-springs, crab-leg, serpentine and folded-flexure springs) and comb-drives (e.g., linear, differential, pedestal-based) has been developed. Finger orientation, region of occurrence, and geometrical parameters (length, width and inter-finger gap) is 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 (FSM) based algorithm. Starting from a start state (always an anchor atomic element), the type of beam and joint determines 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

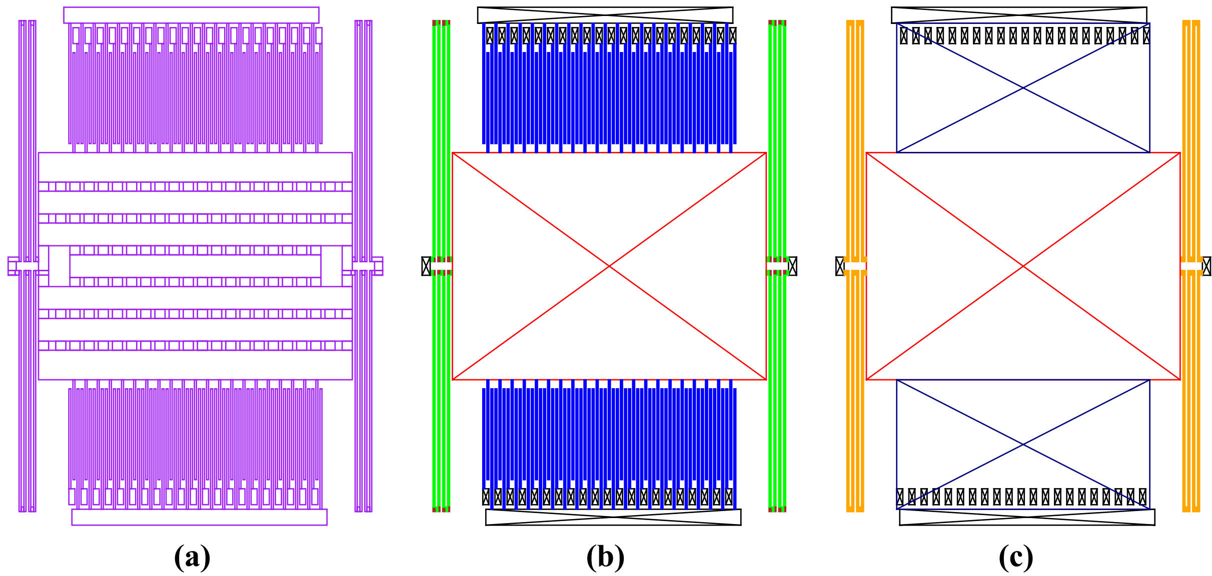

Figure 7: Accelerometer extraction showing (a) initial CIF layout, (b) recognized elements (anchors, plate, beams, joints, fingers, gaps), (c) detected functional elements (beams and joints as serpentine spring and fingers and gaps as differential comb-drive).

by reading in the description of the FSM from the component library. The connected sets of beams and springs obtained after the atomic recognition is then passed through each of these FSMs to recognize their type [10]. Simulation-based verification using this level of extraction is a magnitude faster than at the atomic element level, and is seen to be 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.

7. 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

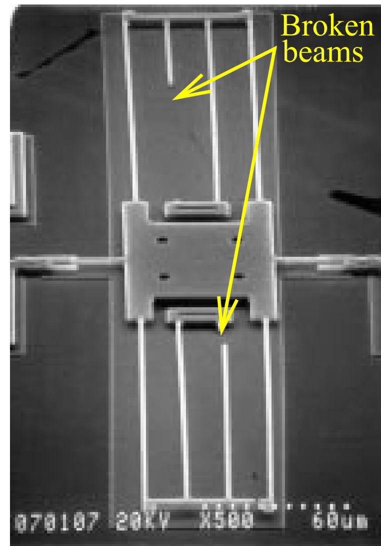

Figure 8: A single-finger comb drive resonator with broken flexure beams.

their applicability to a wide range of devices. They also enable pre-manufacture evaluation, thus allowing for test method optimization. One of the goals that we are working towards is the incorporation of 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 SEM of a defective resonator. This particular resonator has two broken beams which may be the result of 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 thereof. Currently, we are focussing on particles since failures induced by these contaminations can be extremely difficult to detect.

Process simulation is used to predict the effects that contaminations have on the physical geometries and material properties of surface-micromachined components [11]. Figure 9 shows CARA-

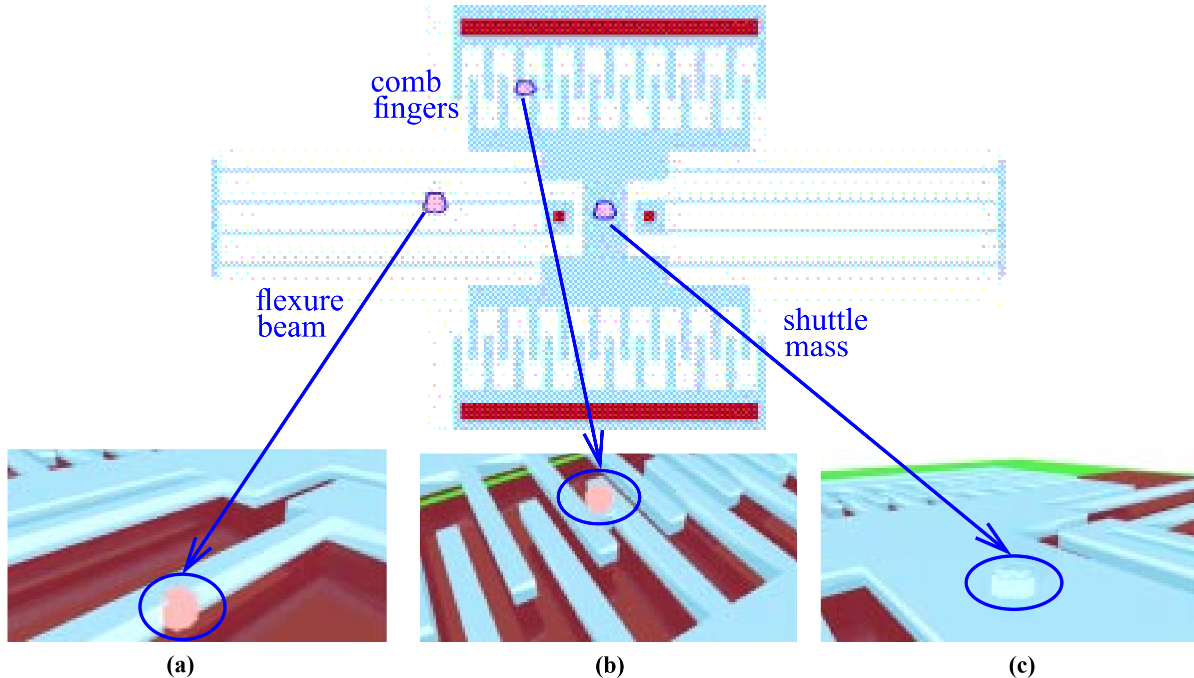

Figure 9: Structural impact of three different contaminations: (a) Flexure beam, (b) comb fingers, and (c) shuttle mass.

MEL's output for different 2 μm-size contaminations occurring at different resonator locations, introduced at various steps of the MUMPS fabrication process [3]. FEA 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 9(b).

8. Conclusion

Hierarchical design and test methods for suspended MEMS promise to shorten the development cycle to days, and enable 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.

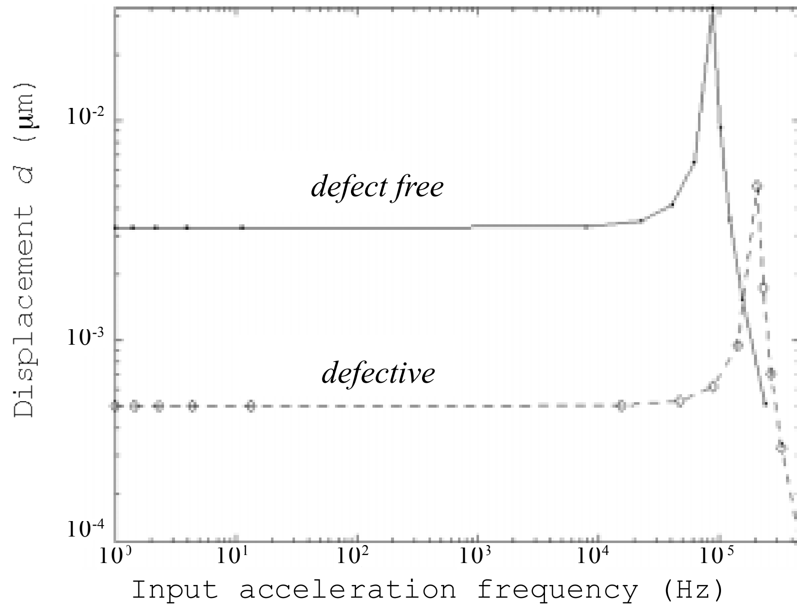

Figure 10: Comparison of defect-free frequency spectrum with the spectrum of a resonator affected by welded fingers.

A mixed-domain circuit simulation environment enables rapid exploration and analysis of the design space for MEMS 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 together 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.

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 in minimizing 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 is 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 where 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.

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