Evolution of Integrated MEMS Design Methodology

Nikolay Georgiev Delibozov, Rossen Ivanov Radonov and Marin Hristov Hristov

Abstract - **The long term impact of MEMS technology will be in its ability to integrate novel sensing and actuation functionality on traditional computing and communication devices enabling the ubiquitous digital computer to *interact* with the world around it. The design and verification of such integrated systems will occur at the system level, driven primarily by the application [1]. Therefore application-driven system level design methodologies are needed to ease the integration of the digital area to the real world using mixed area technologies.**

Keywords - **MEMS design methodology, integrated MEMS design, MEMS CAD**

I. Introduction

Low-cost MEMS designs are targeted for high-volume applications such as the automotive accelerometers, gyroscopes and pressure sensors, or consumer ink-jet print heads. Today, custom MEMS design involves designers that need to be experts in MEMS processing, MEMS device design, system integration, as well as the final application [1]. Reducing these development costs requires an integrated MEMS design methodology that formalizes the communication between the process, device, system and application areas, and exploits the expertise in each area.

Once available, it will enable the successful design of *Application Specific Integrated Microsystems* (ASIMs) and advance the commercialization of MEMS in the various application areas where MEMS sensors are ideally suited [1]. To meet the needs of rapid design of low-volume custom MEMS, an integrated MEMS design methodology must: support a wide class of MEMS designs; be extensible to handling new MEMS design concepts; support a wide variety of MEMS fabrication techniques; fit into existing VLSI design flows; and, have the capability to evaluate integrated system designs.

A. Design Methodology

The design methodology is focused on assembled micromechanical systems. The class of assembled MEMS devices (including accelerometers, gyroscopes, and pressure sensors for automotive markets; micropositioners for data storage; resonators, RF filters, variable capacitors for communication systems; micromirrors for optical data processing systems; and acoustic and ultrasonic transducers) has significant application variety and complexity [1]. The decomposition of electrostatically actuated assembled MEMS designs into perforated plates, beam springs of various topologies (*e.g.*, folded-flexure, crab-leg flexure), electrostatic air-gaps and anchors, is exemplified in Figure 1.

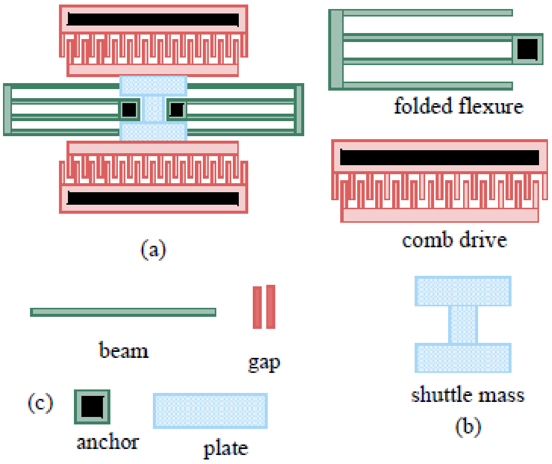

Figure 1: Decomposition of a folded-flexure resonator: (a) component-level folded-flexure resonator; (b) functional elements include comb drive and folded flexure; and (c) atomic elements include plates, beams, gaps and anchors.

The composition of complex topologies by interconnecting simple elements and the use of parameterized behavioral models for simulation are analogous and compatible with VLSI design [1]. This enables the leveraging of design environments already in common use in VLSI design, and simulation of cross-area effects arising from integration, leading to seamless insertion of MEMS into an application-specific design flow. This modular methodology depends on a variety of abstractions and representations.

B. Design and Process Aspects

Design of complex integrated MEMS, like any other engineering design problem relies on two fundamental principles, *divide and conquer* to simplify the design problem, and *iteration* to optimize the design. Applying these principles to MEMS requires consideration of the relevant representations for MEMS [1].

MEMS Xplorer is a flexible, powerful, easy-to-use CAD tool for the design and analysis of micro-electromechanical systems (MEMS). It offers an integrated solution for the design process that shortens development time while providing designers reliable analysis for manufacture [2].

B.1 Representations of the Design

The physical representations linking process sequences, material properties, mask layout into a 3D structural view for continuum prediction of behavior. The mask layout (or physical layout for device fabrication) and 3D structural views (with a mesh for continuum simulation) are the first two of the primary design representations in MEMS, as shown in Figure 2(a) and (b). For an entire decade, MEMS CAD research is focused on methodologies based on these representations [1].

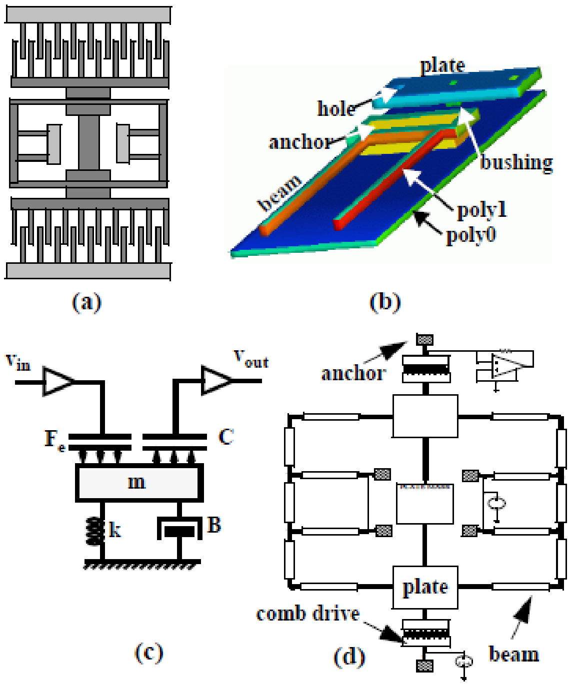

Figure 2: MEMS Design Representations of a micromechanical resonator filter with electromechanical transducer at input and output (a) layout, (b) 3D model (of portion of layout), (c) equation-based behavioral schematic, and (d) MEMS "circuit" schematic.

As MEMS research evolved from microstructure to microsystem design, a lumped-parameter representation (Figure 2(c)) was imported from classical electromechanics. This view, a behavioral schematic in Figure 2(c), is really a set of analytical equations that capture device performance as a function of device geometry. The final, and most recently introduced representation is that of the MEMS "circuit" schematic of Figure 2(d) [1]. It is based on extending VLSI-style circuit simulation to MEMS, by identifying the commonly used MEMS circuit elements, parametrizing them by their geometric design variables and material properties, and developing models for them that are compatible with differential algebraic equation solvers within the circuit simulation tools.

B 2. System-level Tools

MEMS Xplorer provides system-level design capability through fully hierarchical schematic capture and behavioral level simulation of MEMS devices with electronics and packaging [2]. A library of composable MEMS models is included parameterized by process parameters, material properties and device dimensions. The models are represented with mechanical, thermal, magnetic, fluidic, optical, and electro-static areas. MEMS models are represented in high level behavioral languages, SPICE, C-code, or data tables.

B 3. Foundry Modules

These models enable targeting of specific process technologies, provide process-specific device intellectual property, and are fully integrated with SoftMEMS' tool to ensure process compatibility and manufacturability with the world's leading MEMS foundries Figure 3 [2]. Foundry modules include mask and device design rules, mask layer descriptions, device descriptions for extraction, process parameters and material properties, and foundry fabrication process sequence descriptions.

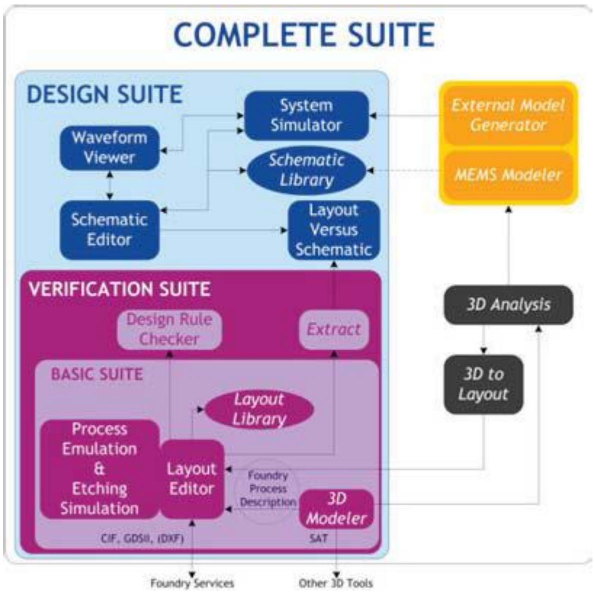

Figure 3: Complete suite process tehnologies

B 4. 3D Solid Modeler

3D Solid Modeler creates a 3D view of a MEMS device from a selected area and fabrication process description. An easy to use Technology Manager allows users to enterbfabrication process step and sequences as well as material properties [2]. Surface and bulk micromachining process steps such as material deposit, etch, mechanical steps are supported. The 3D model may be scaled, and a subset of mask layers may be selected for view. Modeler can be viewed with rotations, zooms, preset views, step-by-step display of the fabrication sequence, and can be animated to show process sequences.

B 5. Bottom-up and Top-down Design

The nature of design implies design hierarchy. The primary approach to traversing this hierarchy in MEMS had been bottom-up [1], with the aim of encapsulating the MEMS design as a fixed macromodel for system design (similar to hard-IP or discrete design). The limitation of bottom-up design is the barrier to design optimization at the lowest levels of the hierarchy. In contrast, a top-down design approach provides a level of transparency to the entire design hierarchy allowing design customizations for application-specific needs. In both top-down and bottom-up design, the primary language of communication between layers of a design hierarchy are the system (i.e., the level immediately above) and the sub-system (i.e., the current level) *design specifications*.

C. Translators between various design views

For translation up and down the design hierarchy, translation between the various design views described in Figure 2 (symbol, behavioral model, schematic , layout, and 3D) are needed. By using a parameterized element library, support for translations between these representations are greatly simplified [1]. This paper focuses on the translations described by the arrows in Figure 4, with the element library in the center enabling the parameterization needed for custom design. Schematics are constructed using the symbol representation.

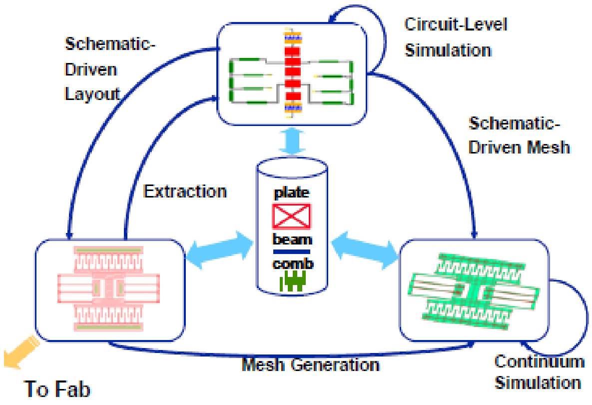

Figure 4: Integrated MEMS Design Methodology.

The models and the schematic representation are used to evaluate the design performance through circuit-level simulation. The schematic capture involves both the interconnection of symbols (design topology), and the geometry parameters of each symbol (component sizing) [1]. The designer can change design topology and element sizing and subsequently simulate the effect of these alterations using the behavioral models, thereby achieving the goal of iterative simulation-based design.

The top-down schematic-based simulation relies on models parameterized by the design geometry and material properties.

The design library can contain elements at several levels of the hierarchy. At the lowest level are the *atomic elements* such as beams, plates, gaps and anchors of Figure 1(c) [1]. These elements are chosen by three characteristics: they are often re-used (albeit sized by appropriate geometric parameters); they are modular (in the sense that they are decoupled from neighboring elements); and they can be accurately described by simple lumped parameter models.

I I. Conclusions

The use of an extendible library of elemental schematic symbols, behavioral simulation models and layout and mesh generators forms the core of the design methodology. The parameterized MEMS library is similar to a parameterized analog device library increasingly being available from semiconductor foundries as physical design kits. This MEMS library is process independent, and when coupled with process dependent technology abstractions, is able to support the coupling of custom-designed MEMS-enabled sensing and actuation with traditional electronics leading to application specific integrated microsystems.

III. Acknowledgement

This paper is financially supported by contract No. 122ПД0038-03

.

REFERENCES

[1] T. Mukherjee. *MEMS Design and Verification*, Carnegie Mellon University, 2003.
[2] http://www.eecatalog.com/sensors

N. Delibozov is with the Department of Microelectronics, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: n.delibozov@ecad.tu-sofia.bg

R. Radonov is with the Department of Microelectronics, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: Rossen.Radonov@ecad.tu-sofia.bg

M. Hristov is with the Department of Microelectronics, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: mhristov@ecad.tu-sofia.bg