Microelectromechanical Systems (MEMS) Design and Design Automation Research at Duke University

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1 ABSTRACT

This paper presents an overview of microelectromechanical systems (MEMS) research being conducted at Duke University. The Duke University MEMS research program encompasses initiatives in both application design and design automation. These two areas serve synergistic and complementary roles: application design provides relevant challenge problems for design automation and design automation, in turn, provides computer-based modeling and analysis for application design. Together, MEMS design and design automation research at Duke University address a wide array of technology for a broad user set. MEMS application design research involves explosives detection, cardiovascular ultrasound scanning, and micro drug infusion. MEMS design automation research involves visual component modeling, rapid performance analysis, and yield optimization.

Keywords: MEMS design, MEMS modeling, VHDL-AMS, and microelectromechanical systems.

2 INTRODUCTION

MEMS application design research is investigating how the capabilities of microelectromechanics can be used to reengineer sensor systems, improving both functionality and performance. The benefits of integrated circuit fabrication provide the basis for improved affordability, sensitivity, distributed processing, and reliability.

MEMS application design for explosives detection supports anti-personnel mine sweeping. Nanogram particle detection occurs by collecting particles on an array of temperature sensitive MEMS sensors and irradiating the particles with 3-5 micron wavelength infrared light. Explosive particles selectively absorb the infrared energy at approximately 1600 cm-1, decompose, and give off heat which can be detected. Prototype explosive detectors have been fabricated that do not absorb energy in the peak absorption bands of the explosives, thus allowing for selective particle heating without heating the sensor device itself.

MEMS application designs for biomedicine are supporting a new generation of miniature forward-looking mechanical sector scanners incorporating transducers above 20 MHz to enable intra-luminal ultrasound scanning of the cardiovascular system. Totally housed within a cardiac catheter, piezoelectric transducers are driven by tiny MEMS actuators operated by electrostatic forces combined with pivoting hinges to produce a sector scan. A normally closed, electromagnetic microvalve has also been fabricated for use in a drug infusion system. Microfabrication technologies of bulk micromachining and LIGA high aspect ratio machining and microassembly methods were used to attach the valve seat to precision machined components.

MEMS design automation, in concert with application designs, is focusing on system-level modeling and analysis. Component models are being developed at the circuit level of abstraction, using unified energy-based concepts that span both electrical and mechanical domains. Behavioral analog modeling styles are being studied using the hardware description language VHDL-AMS. Design tools address both front-end design for creating new MEMS applications and back-end design for improving existing MEMS applications.

Front-end MEMS design automation tools enable a highly interactive design environment. Design entry involves new visual modeling approaches for rapid domain-specific model definition, with subsequent generation of VHDL-AMS descriptions. The goal is to leverage the interoperability and linguistic advantages of hardware description languages by building visual component modeling technology on top of present textual component modeling technology. Fast performance analysis is investigating applications of macro-modeling and static evaluation techniques to microelectromechanical systems, as a more computationally efficient alternative to detailed circuit simulation.

Back-end MEMS design automation tools support statistical microelectromechanical fabrication process characterization and yield optimization. Back-end MEMS design automation tools target enhancing existing designs by improving their yield and, thus, commercial viability. Key material properties and process parameters that influence circuit function and performance are identified and their stochastic behavior is characterized. This technology information is used to improve manufacturing yield by design centering techniques.

3 DESIGN APPLICATIONS

MEMS design application research involves a wide spectrum of functions in diverse environments, ranging from explosives detection in harsh environments to precision drug infusion in medically controlled environments. A variety of transduction mechanisms are employed using both monolithic micromachining and discrete micromolding.

3.1 EXPLOSIVES DETECTION - PRECONDITIONING

In our efforts to make an explosive particle sensor, a silicon based MEMS (microelectromechanical systems) approach has been taken where we have the advantages of small size, quick response, and cheaper cost of fabrication. Our approach has been to detect explosive-laden soil particles which selectively accumulate at the surface of the ground. Detection is done in two steps: preconditioning and sensing.

Preconditioning uses air-borne ultrasound as a means for remotely stimulating the removal of trace particles loosely bound to the soil surface above the land mine, which enhances the amount of particulate matter for the sensor. The proposed system uses focused megahertz frequency air-ultrasound waves to loosen and remove small particles (< 100 mm) in much the same way that commercial "megasonic" cleaning systems remove particles using a liquid medium [5]. This approach combines the advantages of efficient particle removal, high throughput, and non-contact operation.

Micromachined ultrasonic transducers operate on the same principle as traditional electrostatic or capacitive ultrasonic transducers [3]. Two conducting plates are separated by an air gap, forming a parallel-plate capacitor structure. One of the plates is free to move, while the other one is fixed in place. When an electric field is applied across the plates, the electrostatic force causes the movable electrode to deflect towards the fixed electrode. Usually, a large DC bias voltage is applied along with the alternating signal voltage.

3.1.1 Transducer Design

We have adopted the micromachined transducer design developed at Stanford University[1]. In this design, a sacrificial silicon dioxide layer is first deposited on a highly doped silicon wafer. Then, a silicon nitride layer is deposited that forms the membrane and a thin gold layer to provide metalization for the top electrode. Small round holes are then etched through the metal/nitride layer to provide access to the underlying oxide. These holes are then used to wet etch a controlled amount of the oxide from beneath the nitride to create an air gap resulting in a circular membrane suspended above the silicon substrate.

Since there is relatively little freedom in choosing the membrane stress and density, the desired resonance is primarily achieved through designing the membrane radius. In this case, a value of 25 mm was chosen to provide a resonance in the range of 2-4 MHz using available processes.

After the resonant frequency, the air gap thickness is the most important factor affecting device performance. The maximum displacement at the center of the membrane is restricted by the thickness of the air gap which in turn limits the maximum acoustic output of the transducer at a given frequency. It is desirable for the air gap to be made as large as possible; however, increasing the air gap results in reduced coupling between the capacitor plates, requiring larger voltages to drive the transducer. On the other hand, coupling may be improved by reducing the thickness of the nitride layer. Hence, a trade-off must be established among maximizing the air gap while minimizing the membrane thickness and the required operating voltage. An air gap thickness of 2.0 mm and a silicon nitride membrane thickness of 4000 Åwere chosen.

3.2 EXPLOSIVES DETECTION - PARTICLE SENSING

It is known that in the vicinity of land mines, particulate matter of the explosives on the order of nanograms are present. The detection system adapted for this purpose makes use of silicon-based microelectromechanical systems (MEMS) for trace explosive particle detection. Our detection system makes use of the concept of bending of a bimetallic strip due to different thermal coefficients of expansion. The deflection arises when the bimetallic strip is subjected to heat, and both the materials that comprise the bimetallic strip have different coefficients of expansion. This deflection can be measured electrically or optically.

The particles in the vicinity of the land mine are collected onto an array of bimetallic cantilever beams (bimorph structure). In the nanogram range of particles, the explosives do not explode but rather deflagrate[6]. A source of optical radiative energy is supplied to the explosive particles in such a way that the sensor does not absorb the energy, but most of the energy is selectively absorbed by the explosive particulate. The wavelength of the energy source is chosen to lie in the peak absorption spectrum of wavelengths of the explosives so that all the energy is absorbed by the explosive. The top layer of the sensing bimorph is coated with a highly reflecting surface in order to reflect all the optical energy in that spectrum of wavelengths. The explosive particles, on absorbing the energy, deflagrate and release heat. The long wavelength heat thus released is absorbed by the cantilever beam through thermal conduction and the beam undergoes deflection.

3.2.1 Transducer Design

The bimorph structure consists of polysilicon and gold in a cantilever structure with thickness of 1.5 and 0.5 mm respectively. The air gap between the cantilever and the underlying ground is about 2 mm. Several designs are being evaluated. Individual cantilevers with different areas have been fabricated with lengths ranging from 50 mm to 200 mm and widths ranging from 20 mm to 100 mm. It is observed that longer and wider cantilever beams are subject to warping.

Due to the very small capacitance of one single beam, an array of beams was also fabricated in parallel which gave more capacitance and made detectability easier. This array consisted of hundreds of beams, each with an area of 75 X 35 mm^2. Since the measurement of capacitance becomes extremely difficult if the signal has to be taken off the die, a process where electronics would also be present on the same chip is being designed currently. Fabrication utilizes flip-chip die attachment of the MEMS bimorph arrays to a pre-fabricated electronics chip with differential amplifiers.

An important design parameter of the cantilevers is that they are highly reflecting due to the gold coating. This particular property gives rise to the selective nature of the cantilevers which do not deflect due to the heat of the light source which is used to ignite the explosive, but will deflect only due to the heat released by the explosive particles. This design assumption has been verified experimentally to be valid from the results of infrared (IR) spectroscopy performed on the die. The absorption is very close to zero percent over a very broad spectrum.

3.3 INTRA-LUMINAL SCANNER

Intra-luminal scanning involves the insertion into an artery of an ultrasound transducer on the tip of a catheter for imaging the cardiovascular system. Current systems are driven by a rotating wire inserted into the end of the catheter, which only allows for side scanning. We are developing a miniature catheter based forward-looking, mechanical sector scanner/transducer which utilizes a MEMS actuator for mechanical motion.

Our approach to develop the intra-luminal mechanical sector scanner is to use a linear actuator, the Integrated Force Array (IFA) developed at the Microelectronic Center of North Carolina (MCNC) [4]. The IFA is a large scale array of hundreds of thousands of microscopic parallel plate capacitor cells which are fabricated from a polyimide membrane using photolithography. When a voltage is applied, the cells contract due to electrostatic force. The IFA's used in our preliminary studies were fabricated from 2.2 mm thick polyimide. Each elementary capacitor cell is 30 mm wide x 2.2 mm thick x 1.7 mm high. Thus the gap between the plates is 1.7 mm. Each complete device contains 200,000 capacitor cells and measures 1 cm long x 3 mm wide x 2.2 mm thick. We have fabricated and tested prototype mechanical systems of polyimide films which serve as the substrate for the ultrasound transducer as well as the IFA, and which include microhinges to convert the linear motion of the IFA into a mechanical sector scan.

4 DESIGN AUTOMATION

To address the demanding challenges of the application designs involving microelectromechanics, Duke University is also pursuing research in automating the design

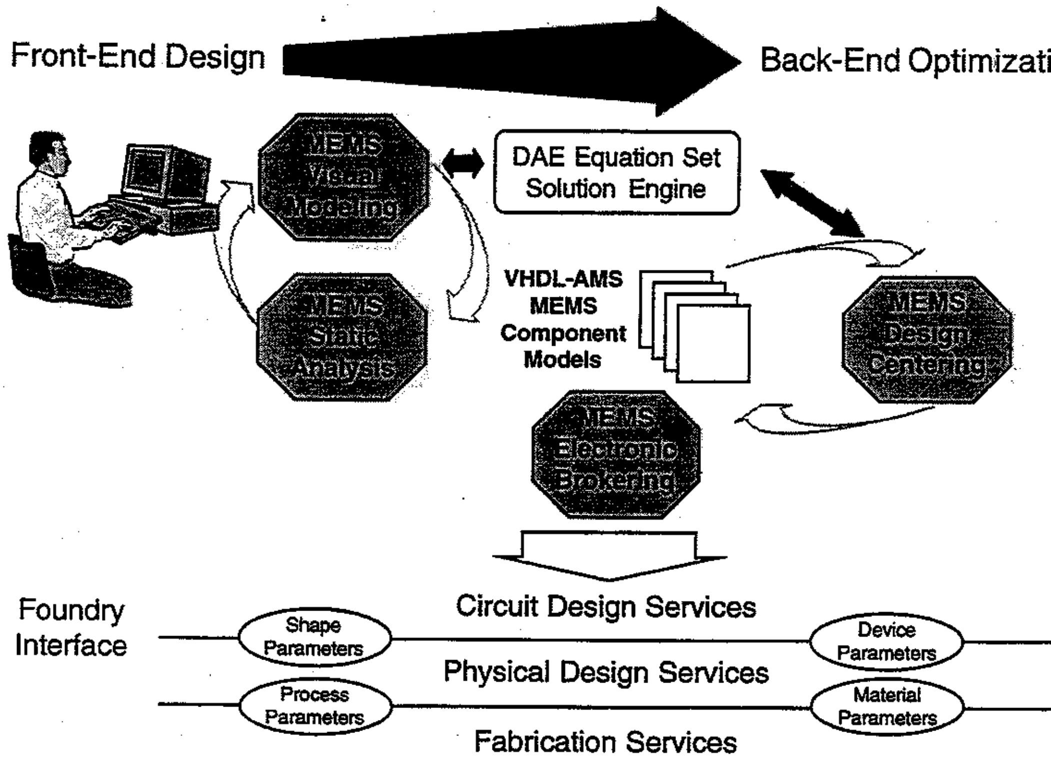

Figure 1: Duke University Design Automation Research

process. The Duke MEMS design automation system is shown in Figure 1.

For microelectromechanical systems technology to mature in a manner comparable microelectrical systems technology, "front-end" engineering processes, such as functional circuit design, must be decoupled from "back-end" production processes, such as physical implementation and fabrication. Such a decoupling allows partitioning the system development challenge into smaller, more manageable parts and compartmentalizing the associated complexity. Thus, all the details associated with fabrication need not be carried forward in addressing physical layout and geometry. Likewise, all the details of physical implementation need not be carried forward in addressing functional circuit design.

With this perspective, Figure 2 illustrates that the focus of the design automation research is to move microelectromechanical systems design to higher levels of abstraction to support modeling and analysis of increasingly complex applications. The design automation research is also aligned with major circuit-oriented computer-aided design (CAD) strategies, recognizing that significant work has been conducted in the general area of microelectrical systems and that the resulting technology base, composed of design and manufacturing processes, tools, and business practices, represents a relevant and meaningful precedent for establishing a comparable microelectromechanical technology base.

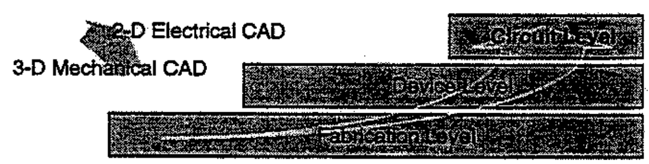

Figure 2: Duke University Design Automation Research Focus

4.1 VISUAL MODELING

MEMS visual modeling design capture research is investigating new graphical rendering techniques to enable direct manipulation of desired microelectromechanical system function and composition [7, 8]. The objective is to build the visual modeling capability on top the linguistics of the hardware description language VHDL with its recent extensions for analog and mixed signal modeling, referred to as VHDL-AMS.

MEMS VHDL-AMS modeling practices and models, being developed in cooperation with Carnegie Mellon

University, seek to promote establishing foundry interfaces via component design reuse and parameterized back-annotation to physical shape and layout processes and tools. This research recognizes that model availability is a pressing concern for microelectrical systems and is expected to be an even greater concern for microelectromechanical systems because of the additional degrees of design and implementation freedom associated with the mixed disciplines of electrical and mechanical systems.

Design is an abstract process of creating and refining information primarily constituted as design models. Design models capture in a computable form the actions of design processes and, as such, serve as the primary record of intellectual expertise and experience. Thus, design models form the "fuel" that drives tools that, in turn, drive microelectromechanical system engineering. Unified, hierarchical abstractions of microelectromechanical systems characterized by differential and algebraic equations (DAE) are being investigated using the energy-based scheme shown in Figure 3 [12].

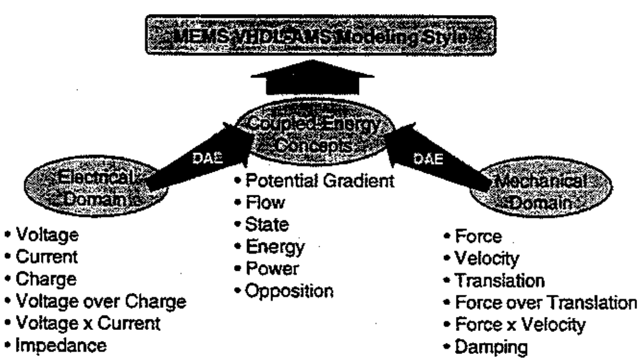

Figure 3: Energy-Based Microelectromechanical Modeling Representations

4.2 ELECTRONIC BROKERING

Electronic brokering research is investigating how to combine the powerful technologies of the world-wide-web and VHDL-AMS modeling to promote the establishment of an intellectual property infrastructure for microelectromechanical systems (MEMS). Electronic computer-aided design technology development provides a relevant and meaningful precedent, as the design automation industry is rapidly and aggressively moving to formalize and institutionalize notions of intellectual property of logic design and associated models. Electronic brokering research seeks to promote similar advances for microelectromechanical reusable component models.

An electromechanical component model library accessible via the Internet-based World-Wide-Web (WWW) will accelerate the distribution of component models and modeling styles and the creation of additional web sites and freeware. A pilot version, called VHDL/VHDL-AMS Annotated Library and On-Line Repository (VALOR), is being tested locally at Duke University.

4.3 RAPID PERFORMANCE ANALYSIS

Rapid performance analysis research is seeking to develop efficient analysis techniques to contain the evaluation complexities of multiple domains and curtail the demands of detailed process and device simulation that are major challenges for microelectromechanical systems. The rapidly escalating complexity of future microelectromechanical system specifications and component models places substantial limits on the use of conventional simulation techniques. Even the present complexities of Very Large Scale Integrated (VLSI) circuits are stressing the practical capabilities of simulation, evidenced by the active commercial development and industry standardization of static timing analysis and formal Boolean comparison tools.

The objective of the rapid performance analysis research is to exploit the hierarchy often found in microelectromechanical circuits to introduce macro-models tuned for a particular analysis. Subcircuits are identified, element couplings are discerned, and aggregate system performance is assessed. Metrics of timing, frequency response, energy consumption, and operating range are being investigated.

4.4 DESIGN CENTERING

Design optimization builds on current evaluation capabilities of numerical equation solution engines and characterization studies of tribological phenomena to promote new design centering capabilities. The objective is to understand the influence of first-order sensitivity gradients of physical and process parameters on circuit function and to develop associated "circuit hardening" techniques.

MEMS design centering research, being developed in cooperation with MCNC MEMS Technology Application Center, is investigating strategies for determining nominal values for circuit parameters to "center" the circuit in its performance space to minimize potential drifts caused by variances in physical implementation and fabrication process [10]. Design centering maximizes the stability of a circuit function in response to changing layout and/or process parameters. Design centering identifies the layout and process factors that most effect circuit function and develops design practices and techniques to negate the potential destabilizing effects. The result is a circuit that remains "centered" within its function space, despite manufacturing and operating variances. Design centering is an important technology for microelectromechanical systems because foundry implementation processes are relatively immature and thus wide variances can be expected in layout and fabrication parameters. Designing to minimize the detrimental effects of the variances will make microelectromechanical systems easier to build and foundry services more affordable to develop.

5 SUMMARY

In this paper, we have presented a brief summary of the research being conducted at Duke University in the area microelectromechanical systems (MEMS). A sample set of application design and design automation research efforts were presented. The wide array of MEMS application design research is driving associated design automation research to adopt a "systems" focus, working on circuit level abstraction and analysis techniques.

At Duke University, microelectromechanical systems is one of several mixed-signal, coupled-energy, or composite systems being investigated. Several interesting microelectrofluidic system research projects are also being pursued. The long-term objective is to understand the modeling and analysis principles of coupled-energy systems to develop the ability to perform co-design of composite systems illustrated in Figure 4 [11, 9].

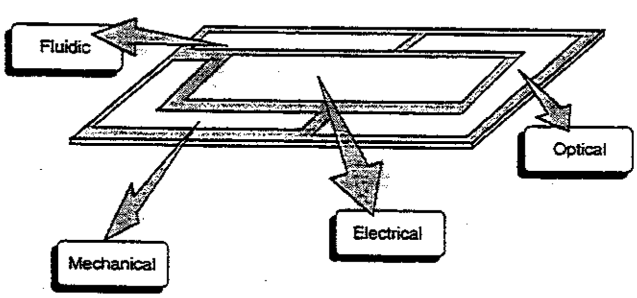

Figure 4: Coupled Energy Co-Design

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