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Fabless Prototyping Methodology for the Development of SOI based MEMS Microgripper

H. M. Usman Sani, Shafaat A. Bazaz, and Nisar Ahmed

***Abstract*—**In this paper, Fabless Prototyping Methodology is introduced for the design and analysis of MEMS devices. Conventionally Finite Element Analysis (FEA) is performed before system level simulation. In our proposed methodology, system level simulation is performed earlier than FEA as it is computationally less extensive and low cost. System level simulations are based on equivalent behavioral models of MEMS device. Electrostatic actuation based MEMS Microgripper is chosen as case study to implement this methodology. This paper addresses the behavioral model development and simulation of actuator part of an electrostatically actuated Microgripper. Simulation results show that the actuator part of Microgripper works efficiently for a voltage range of 0-45V with the corresponding jaw displacement of 0-4.5425µm. With some minor changes in design, this range can be enhanced to 15µm at 85V.

***Keywordss*—**MEMS Actuator, Behavioral Model, CoventorWare, Microgripper, SOIMUMPs, System Level Simulation

I. INTRODUCTION

MICROSYSTEMS and MicroElectroMechanical Systems (MEMS) are characterized by the interaction of microscale components operating on different physical domains. The investigation of such complex systems demands the modeling and simulation of single components as well as the overall system simulation. CAD tools play a vital role in the development of MEMS and Microsystems design and analysis.

Modeling of MEMS devices can be categories into four levels: *Process Level*, *Physical Level*, *Device Level*, *System Level* in order of bottom-up approach same as we carry out in Microelectronics. Fabrication steps are simulated/emulated in the sequence required for the given design to obtain a proper physical model at process level while 3D numerical solutions for underlying dynamic equations are obtained to understand the internal operating behavior of MEMS device at physical level. Optimizing the device performance by investigating its extracted reduced order model (ROM) is performed at device level while at system level, constituent components of the MEMS are integrated to study the dynamic behavior of the complete system under the given operating conditions [1]–[2].

Process level is rigorously related to fabrication process simulation. The 3D model of a MEMS device can be generated by using a process definition, an associated material properties database and a designer created 2D layout. Process level is necessary to proceed ahead to physical level simulation. ANSYS, COMSOL, CoventorWare Analyzer based on Finite Element Methods (FEM) are usually used at physical level to find the 3D solution. These simulations take very long time to execute even in days and weeks. This elongates the design cycle time and increases computational cost. Reduce Order Modeling (ROM) can be used to overcome above mentioned problems [3]–[4] but optimization at device level is a cumbersome task [5].

Finally the System level suggests the less time consuming but efficient simulation. The additional advantages are parameters adjustment and the integration of electronics with the MEMS devices and hence a complete Microsystem can be analyzed in a single simulation environment [6].

A. Fabless Prototyping Methodology for MEMS Devices

The concept of Fabless Prototyping Methodology is introduced in this paper as shown in Fig. 1 including various MEMS design tool. The design specifications include selection of prototyping process, device dimensions, etc. An analytical model is developed on the basis of these design specifications. The analytical model is based on basic formulae and theories analyzed in Matlab. On the basis of these initial results, device specifications are proposed. These device specifications are then used in creating layout of device in any Layout Editor. Design Rule Check (DRC) is necessary to verify the device geometrical properties with respect to prototype process, making the design feasible for fabrication. In case there is any error after running DRC, it should be removed without having any major change in device features otherwise new results should be obtained for modified design.

In the next phase, behavioral model is created in CoventorWare's Architect. Results obtained from the analysis of these behavioral models are then compared with the analytical results. If these results are close to each other then one should proceed to physical level simulation and/or finally

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device fabrication. In case of mismatch in results obtained from behavioral models and analytical model, there may be two possibilities: either there is some deficiency in behavioral model development or the proposed design is not valid. In first case, one should redevelop the behavioral model and then analyze it. In the second case, one should re-design the proposed design under given design specifications or change the prototyping process.

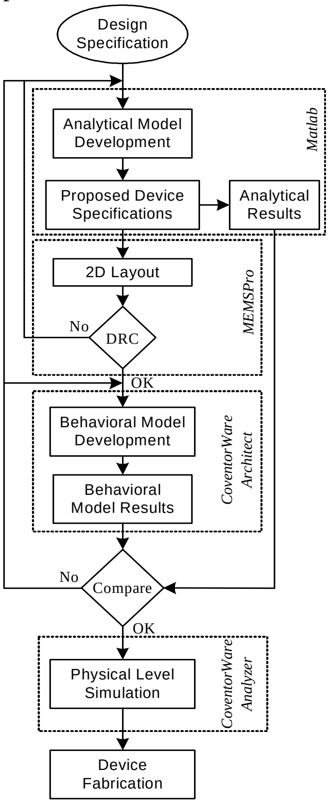

Fig. 1 Fabless Prototyping Methodology for MEMS devices

B. Behavioral Modeling & Simulation

In mid nineties, system level modeling and simulation of MEMS devices was based on Nodal Analysis. Nodal Simulation of MEMS devices includes electrical equivalent circuits to represent mechanical structures and then creating the behavioral models of mechanical structures for a system level simulator such as MATLAB or Hardware Description Language (HDL) enabled circuit simulator such as Cadence Spectre and Synopsys Saber. Tilmans demonstrated that electrical equivalents of mechanical structures could be created and can be quickly analyzed in SPICE [7] as HDL-enabled circuit simulators were not available at that time. Force-Voltage analogy was used to demonstrate modeling and simulation of comb-finger resonator. SUGAR was developed at UC Berkeley [8]. In SUGAR, behavioral models of basic elements such as beams, electrostatic gaps, and simple circuit components such as resistors, capacitors, voltage sources, etc. were created as Element Stamps compatible with Matlab implementation of nodal analysis. NODAS was developed at Carnegie Mellon University [9]–[10]. Behavioral models of basic elements were coded in Verilog-A and Cadence Spectre is used as system level simulator.

G. Lorenz and R Nuel at Bosch [11]–[12] developed basic MEMS behavioral models in the MAST HDL language that could be simulated in Synopsys Saber. Lorenz later used these MEMS models to implement CoventorWare Architect [13]. Various MEMS devices including Gas Sensors [14], Accelerometers [15], etc. are implemented in CoventorWare Architect. Hardware Description Languages can be directly used to implement MEMS device modeling and simulation [16]-[18] or can be used with reduced order FE models of MEMS devices [19].

In this paper we implemented behavioral modeling based system level simulation of actuator part of Microgripper in CoventorWare Architect.

II. CASE STUDY: MICROGRIPPER ACTUATOR

Microgripper are the devices which are used to perform pick and place operation for micrometer size objects. An electrostatic actuation based Microgripper was designed in a commercially available surface micromachining SOIMUMPs Process [20] by this research group [21].

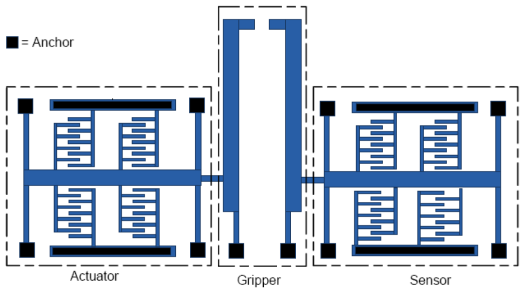

Fig. 2 Basic schematic of Electrostatically actuated Microgripper integrated with Force sensor [26]

The Microgripper shown in Fig. 2 consists of 3 basic parts: Actuator, Gripper, and Sensor. When a voltage is applied at the comb drives of actuator part, a force of attraction is produced according to the relation:

$$F_N = \frac{N.n}{2}\varepsilon\frac{tV^2}{d} \qquad (1)$$

Where N is number of comb drives, n is number of gaps in single comb drive, t is thickness of device layer, V is applied DC voltage, d is separation between rotor comb fingers and stator comb fingers. This force of attraction is finally transferred to the Gripper's arm through central beam which is supported by four parallel flexures. These four flexures not only provide support to the hanging structure of central beam but also bring back the central beam to the original position when applied voltage at comb drives is removed. Gripper part consists of two flexures connected in series to provide high flexibility for Gripper arm movement. The total spring constant for all flexures of actuator (or sensor) part was calculated as:

$$k = 4\frac{Ew_f^3 t}{l_f^3} + 3\frac{EI_b I_u}{(l_b^3 I_u + l_u^3 I_b)} \quad (2)$$

Where E is modulus of elasticity, w_f and l_f are width and length of flexures respectively, I_b and I_u are moments of inertia for bottom and upper spring respectively, and l_b and l_u are lengths of bottom and upper spring respectively.

Our aim is to analyze the performance of this designed Microgripper before fabrication for the proof of concepts. As per our proposed designed methodology, shown in Fig. 1, initial model is developed based on Matlab simulation and applying design rules to develop 2D layout of the design using SOIMUMPS process [20]. In this paper, we present the behavior model development in CoventorWare Architect.

A. *Behavioral Model of Microgripper's Actuator*

CoventorWare Architect has a library for behavioral models of various basic elements such as beams, comb drives, rigid plate, flexible plates, etc. Any complex MEMS structure can be decomposed into its basic constituents. These constituents are joined together in Saber Sketch environment to form a complete MEMS device. Electronics circuitry can also be integrated with the constructed MEMS device in the same schematic to analyze the complete Microsystem.

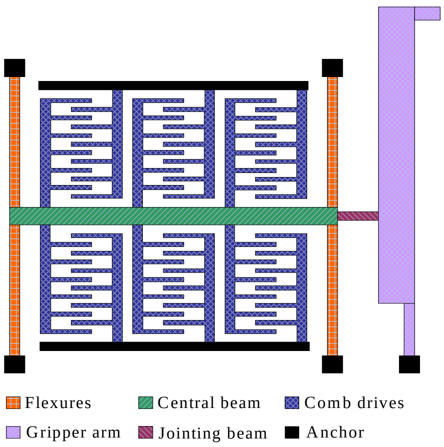

Fig. 3 Basic schematic of actuator part of Microgripper [26]

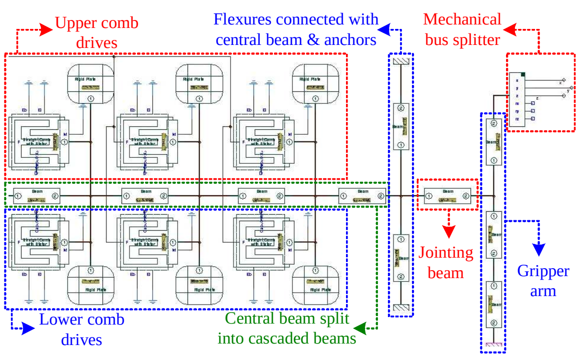

Fig. 4 Schematic of Microgripper actuator part with comb drive in Saber Sketch

Fig. 3 illustrates the geometrical structure of actuator part of Microgripper. This actuator part is then decomposed into its three basic building blocks: beam, comb drive, and rigid plate. *Straight Beam model*, *Straight Comb with Stator model* and *Rigid Plate model* are available in Coventor Parts Library [6]. The mathematical description of these behavioral models was discussed in [11]–[12].

Fig. 4 shows the schematic of actuator part of the Microgripper created in Saber Sketch. The central beam is split into many beam elements. At the joint of each beam element, a rigid plate containing moveable fingers of comb drive is connected. An ideal DC voltage source is connected between moveable fingers and fixed fingers. The parameters of actuator structure are given in Table I.

TABLE I
COMBDRIVE AND MECHANICAL STRUCTURE PARAMETERS WITH THEIR VALUES FOR ACTUATOR PART OF MICROGRIPPER

Parameter	Value	Parameter	Value
Fixed finger width	3µm	Length of central beam	630µm
Moveable finger width	3µm	Width of central beam	20µm
Anchor width	5µm	Length of lower spring	300µm
Finger pitch	12µm	Width of lower spring	15µm
Finger tip anchor gap	10µm	Length of upper spring	300µm
Finger tip plate gap	10µm	Width of upper spring	68µm
Comb drive spacing	4µm	Length of gripper arm	2470µm
Length of flexures	500µm	Width of gripper arm	68µm
Width of flexures	10µm	Device Layer	*SOI*

III. SIMULATION RESULTS

Fig. 5 shows the 3D model extracted from the Saber Sketch schematic, shown in Fig. 4, in Scene3D of Architect. The generation of this 3D model takes less than 2 minutes on a 2.80GHz dual core processor with 4GB of RAM. Fig. 6 is the displacement vs. voltage plot giving a comparison of analytical results of [21] and behavioral modeling based system level simulation. The voltage is swept from 0 to 45 volts with 5 volt step and displacement observed at gripper jaw is 0 to 4.5425µm. Time taken by the DC transfer analysis is 35.37 seconds which is relatively very small as compared to FEA of same structure.

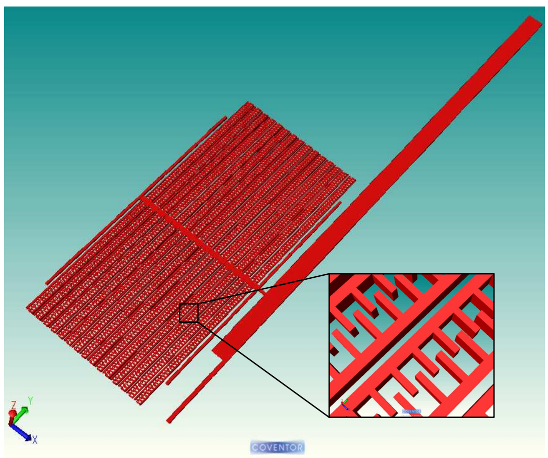

Fig. 5 Extracted 3D model of actuator with comb drives in Scene3D of Architect

Although this Microgripper was designed to operate up to 85V with a corresponding jaw displacement of 15μm [21] but due to the improper design of jointing beam (the beam which joints the central beam with the gripper arm), the central beam motion is not purely in x-axis, there is also some displacement of central beam in y-axis. Due to this small displacement of central beam in y-axis, the displacement of moveable fingers is also not purely in x-axis especially at the far ends from central beam. This causes a collision of moveable fingers and fixed fingers. Due to this collision, the solution of the system does not converge during DC transfer analysis in Saber for voltages higher than 45 volts and returns an error. This problem could not be found during Matlab analysis by [21]. This fact can also be observed in the plot shown in Fig 6. At 45 volt, the system level curve is steeper than the analytical curve because at this voltage distance between moveable fingers and fixed fingers is less than 3μm due to the tilting of central beam. This cause an increase of force of attraction between comb fingers and finally a collision of fingers occur if we slightly increase the input voltage. This situation is depicted in Fig. 7.

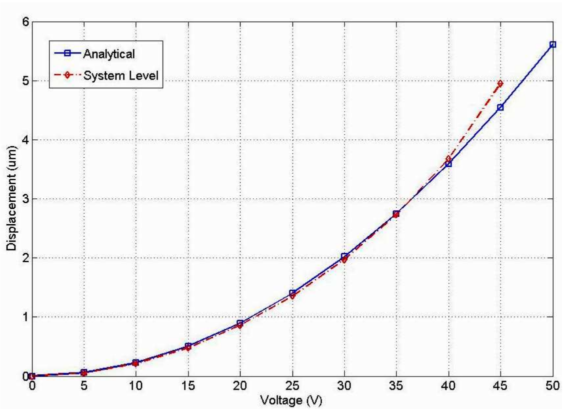

Fig. 6 Comparison of analytical result [26] and behavioral modeling based system level simulation

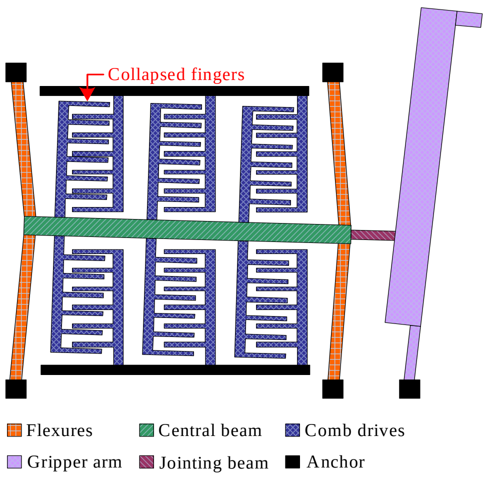

Fig. 7 Collapsed comb fingers due to the tilting of central beam

This problem can be solved by optimizing the width and length of jointing beam. Another solution is to engrave this jointing beam into the central beam to provide guard walls as proposed by Beyeler *et al* [22].

IV. CONCLUSIONS

The concept of Fabless Prototyping Methodology is presented with its partial implementation on Microgripper's actuator. System level simulation based on behavioral modeling is performed in CoventorWare's Architect module. These simulation results shows that the actuator part of Microgripper works efficiently for a voltage range of 0-45V with the corresponding jaw displacement of 0-4.5425μm although it was designed for 0-85V with the corresponding jaw displacement of 0-15μm. If we further increase input voltage, the fingers of comb drive will be collapsed. This phenomenon is observed without doing computationally expensive FEA. This also proves the usefulness of Fabless Prototyping Methodology, where the designer can detect the anomalies in the design using less expensive behavior modeling techniques.

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REFERENCES

[1] Stephen D. Senturia, "CAD challenges for microsensors, microactuators and microsystems", Proceedings of the IEEE, vol. 86, No. 8, 1998, pp. 1611-1626.
[2] Shafaat Ahmed Bazaz, "Design Methodology and Modeling Strategies for MEMS", Bulletin of Canadian Society of Mechanical Engineers, Sept. 2003.
[3] Rana I. Shakoor, Shafaat A. Bazaz, Y. Lai, M. M. Hasan, "Comparative Study on Finite Element Analysis & System Model Extraction for Non-Resonant 3-DoF Microgyroscope", The 2008 IEEE International Behavioral Modeling and Simulation Conference , September 25-26, 2008, San Jose, California, USA.
[4] Xiezhao Lin, Zichen Chen, Ji Ying, "Macromodeling of the Electrostatically Actuated Rectangle Plate Based On Modal Projection", International Conference on Mechatronics and Automation, August 5-8, 2007, Harbin, China.
[5] Q. Jing, "Modeling and Simulation for Design of Suspended MEMS", Ph.D. Thesis, Carnegie Mellons University, 2003.
[6] CoventorWare ARCHITECT, version 2008, Reference: MEMS and Microsystems System-Level Design, Coventor. Inc.
[7] H. A. C. Tilmans, "Equivalent circuit representation of electromechanical transducers: II. Distributed-parameter systems", Journal of Micromechanics Microengineering (7 No. 4), pp. 285-309, December 1997.
[8] J. V. Clark, N. Zhou, S. Brown and K.S. J. Pister, "MEMS Simulation Using SUGAR v0.5", Solid-State Sensors and Actuators Workshop, Hilton Head Is., SC, June 7-11, 1998, pp. 191-196.
[9] Q. Jing, T. Mukherjee and G. K. Fedder, "Schematic-Based Lumped Parameterized Behavioral Modeling for Suspended MEMS", International Conference on Computer Aided Design, San Jose, CA, Nov. 10-14, 2002.
[10] G. C.Wong, G. K. Tse, Q. Jing, T. Mukherjee, G. K. Fedder, "Accuracy and Composability in NODAS", IEEE Int. Workshop on Behavioral Modeling and Simulation, San Jose, CA, October 7-8, 2003.
[11] Neul R, Becker U, Lorenz G, Schwarz P, Haase J, Wunsche S, "A Modeling Approach to Include Mechanical Microsystem Components into the System Simulation", Proceedings of Design, Automation and Test in Europe, 23-26 Feb. 1998, pp. 510-517.
[12] G. Lorenz, R. Neul, and S. Dickmann. "Modeling of electrostatic MEMS components", International Conference on Modeling and Simulation of Microsystems, San Juan, April 1999, pp. 128- 131.

[13] G. Lorenz and R. Neul, “Network-Type Modeling of Micromachined Sensor Systems”, Int. Conf. on Modeling and Simulation of Microsystems, Semiconductors, Sensors and Actuators, Santa Clara, CA, April 6-8, 1998.
[14] G. Uma, M. Umapathy, L. Baby Vidhya, M. Maya, T. Sophia, K. Tamilarasi, "Design and Analysis of Resonant Based Gas Sensor", Sensors Applications Symposium, Atlanta, GA, 12-14 Feb. 2008, pp 119-121.
[15] A. Manut, M. I. Syono, "Effects of Mechanical Geometries on resonance Sensitivity of MEMS Out-of-Plane Accelerometer", IEEE International Conference on Semiconductor Electronics, Kuala Lumpur, 2006.
[16] Chenxu Zhao, Leran Wang and Tom J. Kazmierski, "An efficient and accurate MEMS accelerometer model with sense finger dynamics for applications in mixed-technology control loops", IEEE Behavioral Modeling and Simulation Conference, September 20-21, 2007, San Jose, CA.
[17] O. Leman, A. Chaehoi, F. Mailly, L. Latorre , P. Nouet, "Modeling and system-level simulation of a CMOS convective accelerometer", Journal of Solid-State Electronics, Vol. 51, 2007, pp1609-1617.
[18] O. Leman, N. Dumas, F. Mailly, L. Latorre, P. Nouet, "An approach to integrate MEMS into high-level system design flows", 6th International IEEE Northeast Workshop on Circuits and Systems and TAISA Conference, Montreal, QC, 22-25 June 2008, pp 273-276.
[19] Michael Schlegel, Fouad Bennini, Jan E. Mehner, Göran Herrmann, Dietmar Müller, and Wolfram Dötzel, "Analyzing and Simulation of MEMS in VHDL-AMS Based on Reduced-Order FE Models", IEEE Sensors Journal, Vol. 5, No. 5, October 2005, pp 1019-1026.
[20] Keith Miller, Allen Cowen, Greg Hames, and Busbee Hardy, "SOIMUMPs Design Handbook", Revision 4.0, MEMSCAP. Inc.
[21] Kinnan Amjad, Shafaat A. Bazaz, Yongjun Lai, “Design of an Electrostatic MEMS Microgripper System Integrated with Force Sensor”, The 20th IEEE International Conference on Microelectronics, Sharjah, 14-17 Dec., 2008.
[22] Felix Beyeler, Adrian Neild, Stefano Oberti, Dominik J. Bell, Yu Sun, Jürg Dual, Bradley J. Nelson, "Monolithically Fabricated Microgripper With Integrated Force Sensor for Manipulating Microobjects and Biological Cells Aligned in an Ultrasonic Field", Journal of Microelectromechanical Systems, Vol.16, No.1, Feb. 2007, pp 7-15.