Design and Simulation of Micro-Cantilever Beams for variable capacitor

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ABSTRACT
Micro-electro-mechanical systems (MEMS) is the integration of mechanical and electrical components that can sense the environment, process and analyze information, and respond in order to control the environment for some desired outcome. MEMS are nowadays becomes increasingly popular due to their high isolation and low insertion loss.The capacitance values of MEMS-based variable capacitors and tuning range are too small, typically less than a few pF. The work presented in this paper involves design, simulation and application of micro-cantilever beam as a variable capacitor. The device consists of array of cantilever beam with variable length, suspended over a bottom electrode. By applying a voltage between the electrodes, the electrostatic force pulls the beams in one-by-one realizing a digital increase in capacitance. The change in length of the beam influences the pull-in voltage while the effect of beam width on the pull-in voltage is negligible.

General Terms
MEMS, Micro-machining, Micro-cantilevers Beam

Keywords
Digital Variable Capacitor, RF MEMS, MUMPS

1. INTRODUCTION
The MEMS based switches and capacitors are the most important components for RF applications. They have a mechanical structure that isolates the control circuit from the signal circuit, and a mechanical inertia that prevents modulation of the capacitance value by RF signal, and provides good linearity. There are two basic types of MEMS capacitors. One is the gap-tuning variable capacitor using two parallel plates horizontally positioned, and has a limited tuning distance up to a third of the gap [1].
The other one is the area tuning variable capacitor typically using a comb-drive structure which is normally made by deep reactive ion etch [2, 3]. Both configurations have limited capacitance values, tuning ranges and difficulty of precision control of capacitance, thus limiting their applications. Attempts have been made to increase the capacitance and tuning range by various designs and technologies, and substantial progress has been achieved such as the combination of thermal and electrostatic actuator [4], two gap tuning, etc. [5,6], but problems still remain with these designs. There is a need to provide variable capacitors that are able to provide fixed values of capacitances for digital circuit applications [7–10].

This paper represents the design and simulation of a new type MEMS based, digital variable capacitor. Micro-cantilevers are the most simplified MEMS based devices, which can act as a physical, chemical or biological sensor by detecting changes in cantilever bending or vibrational frequency. The technology is based upon changes in the deflection property induced by environmental factors in the medium in which a micro-cantilever is immersed. The structures were fabricated through the Multi-User MEMS Processing Service (MUMPS) provided by MEMSCAP. The devices consist of a multi-cantilever beams with variable length, width and constant thickness anchored over the substrate, which consists the bottom electrode. By applying a voltage between the two electrodes, the electrostatic force pulls the beams in one- by-one in the array, which gives digital increase in capacitance. Coventor Ware is used to simulate and analyze the behavior of the device. Coventor Ware supports both system-level and physical design approaches. The system-level approach involves use of behavioral model libraries with a high-speed system simulator. The physical approach starts with a 2-D layout and involves building a 3-D model, generating a mesh, and simulating using FEM or BEM solvers. Finally, the verified 2-D layout can be transferred to a foundry for fabrication.

The nonlinear electrostatic force gives rise to the well-known pull-in phenomenon that causes beams or diaphragms to collapse on the ground if the applied voltage exceeds a certain limit namely the pull-in voltage. Accurate determination of the pull-in voltage is a critical parameter in the design of MEMS devices. The finite element method (FEM) is often used for modeling the pull -in phenomenon and has been implemented in various commercial MEMS simulation software.

2. MICRO-CANTILEVER STRUCTURE
2.1 Schematic and operating principle
A micro-cantilever is simplest micro-electromechanical system structure that can easily be micro-machined. It is a projecting structure that is supported at one end and carries a load at other end or along its length.

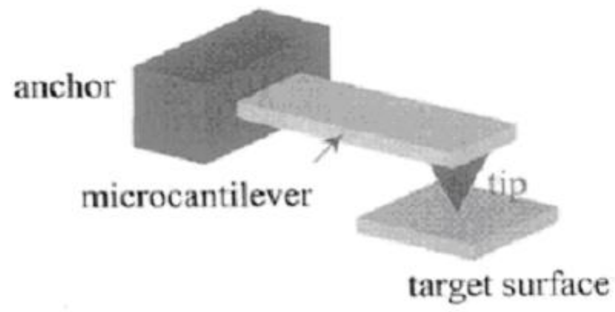


Figure 1: Schematic of Micro-cantilever Structure

The fundamental actuation principle behind electrostatic actuation is the attraction of two oppositely charged plates. When a DC voltage is applied across the plates causes an electrostatic pull-down force and consequent reduction of the air gap, resulting in change in capacitance. Thus, micro-cantilever beams can act as a variable capacitor.

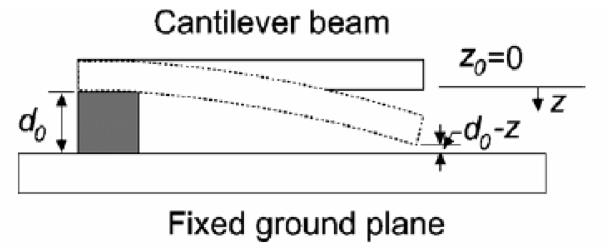


Figure 2. The electrostatic force about the zero deflection point

When the potential voltage is applied between the bottom and the top electrodes, an electrostatic force is generated thus pulling in the cantilever beam. Further increasing in number of cantilever with variable length for application of voltage, the longest cantilever beam will snaps down firstly, and form a capacitor with a thin insulator between the electrodes, leading in to step increase in capacitances. Further increase of voltage pulls the second cantilever beams realizing the step increase in capacitance, ignoring the fringe effect and assuming the cantilevers are parallel to bottom electrode. If the applied voltage increased beyond the pull-in voltage, the resulting force will overcome the elastic restoring force and will cause the movable plate to collapse on the fixed ground plane and the device will be short circuited. This phenomenon is known as pull-in.

2.2 Fabrication

In the present work, array of cantilever beams were fabricated using the three layers polysilicon surface micro-machining PolyMUMPS process. In this process polysilicon is used as a structural layer and silicon dioxide is used as a sacrificial layer. The sacrificial layer is etched out by dry etching process using hydrogen fluoride, which results to release the array of cantilever beams. A layer of gold was deposited

above the top polysilicon layer, which acts as the top electrode for characterization. Figure3 shows the SEM (Scanning electron microscopy) photograph of the fabricated array of cantilever beams. From fig., it is clear that the array of cantilever beam is released successfully.

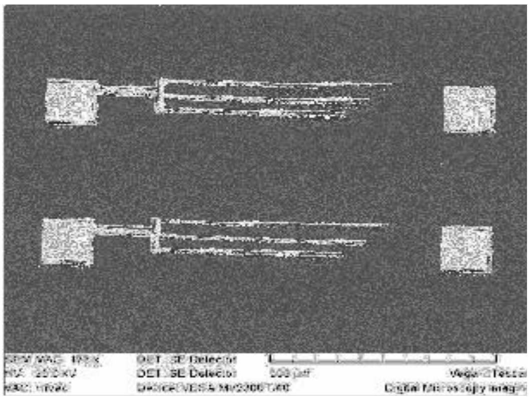


Figure 3. SEM photograph of released micro-cantilever

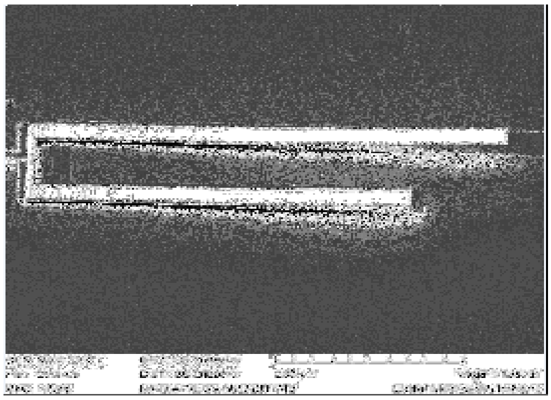


Figure 4. SEM photograph of released micro-cantilever beams

3. SIMULATED RESULTS

CoventorWare supports both system level and physical designs approaches. The system-level MEMS designs can be used to generate 2-D layout for physical level verification. The physical approach starts with 2-D layout and involves 3-D models, generating a mesh and simulating. The 3-D model for cantilever beam is shown in figure 5.

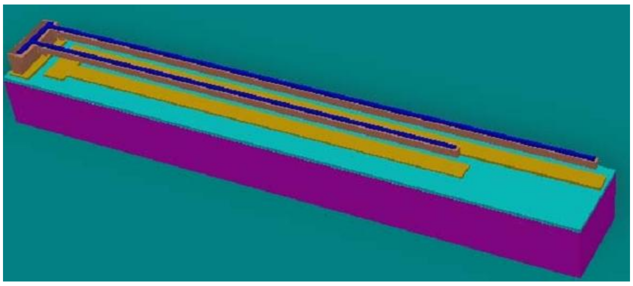
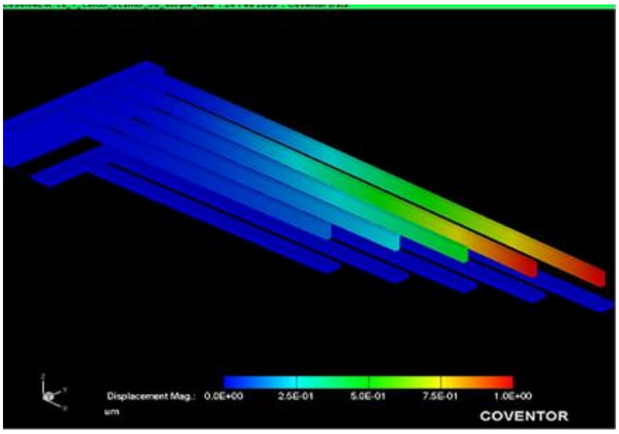
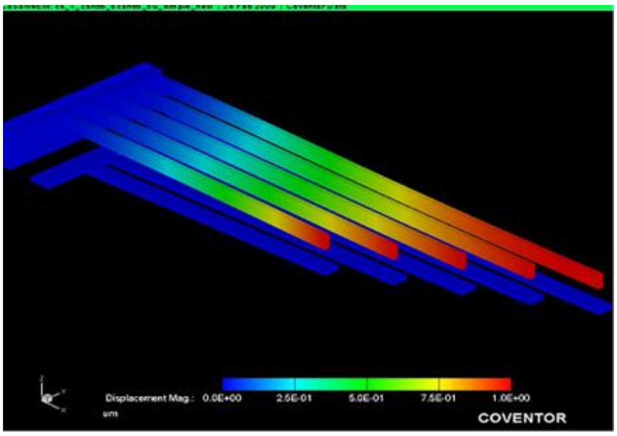


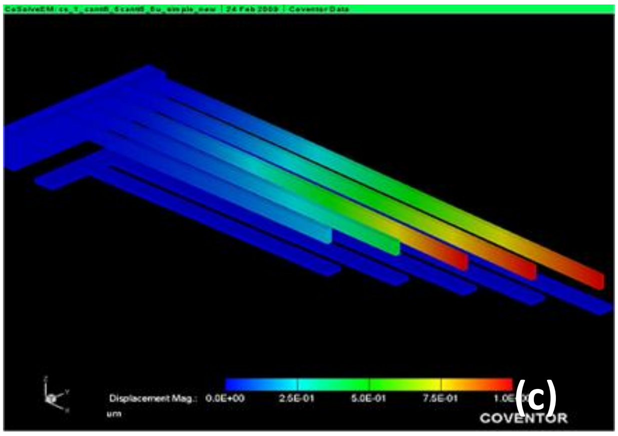
Figure 5: 3-D solid model of cantilever beam

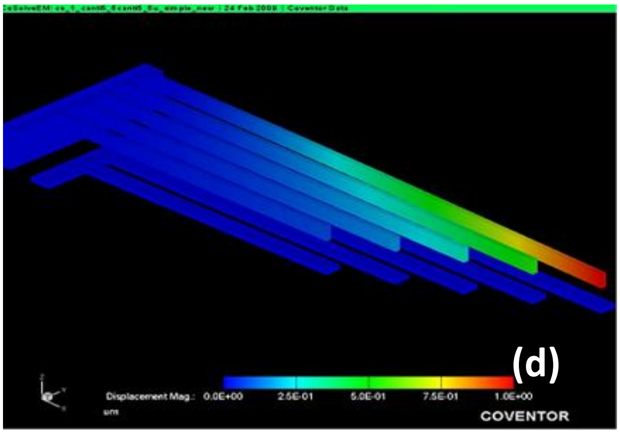
CoventorWare is also used for user to perform a wide variety of simulations on any MEMS structure and can provide significantly accurate results using Finite Element Method (FEM). All of the simulations are performed using the MemElectro Solver, Mechanical Solver and CoSolve EM



solver. Following are some simulated results:







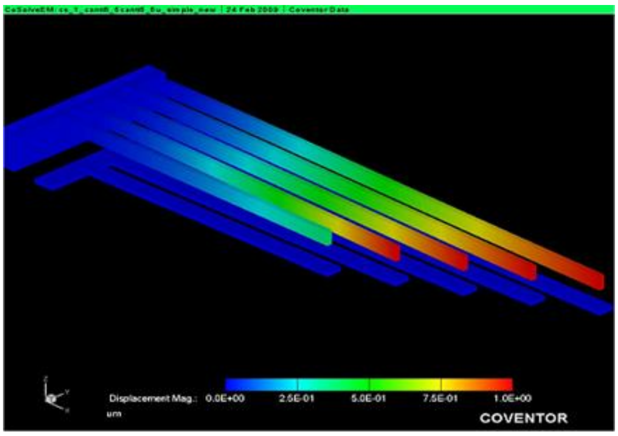


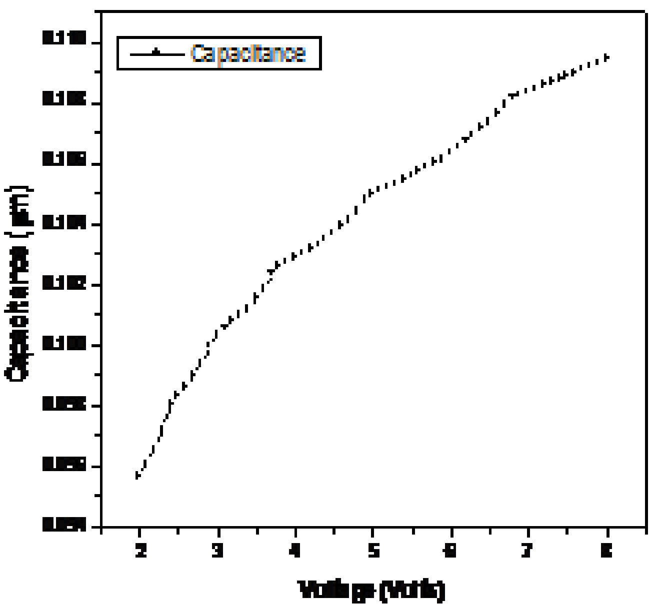
Figure 6. 3-D view showing pull-in analysis for an array of five cantilevers beam from (a) to (e)

Length of the cantilever beams	Pull-in voltage (volts)	
	Simulated	**Theoretical**
L=500µm	2.4	2.45
L=450µm	3.0	3.02
L=400µm	3.8	3.82
L=350µm	4.9	5.0
L=300µm	6.7	6.81

Table 1. Pull-in voltages at different lengths of cantilevams

3.1 Pull –in Analysis

From following analysis it is found that the deflection is more at the tip of the cantilever beam and increases with increase in DC bias voltage, which reduces the gap between the top and bottom electrodes. The slope of maximum deflection increases, as the voltage increases and finally approaches infinity when it reaches pull-in voltage. Beside this, maximum deflection is also larger for longer beam. This relationship is linear at low voltage and becomes increasingly nonlinear when the voltage applied is increased. Change in length of the beam influences the pull-in voltage while the effect of beam width on the pull-in voltage is negligible.



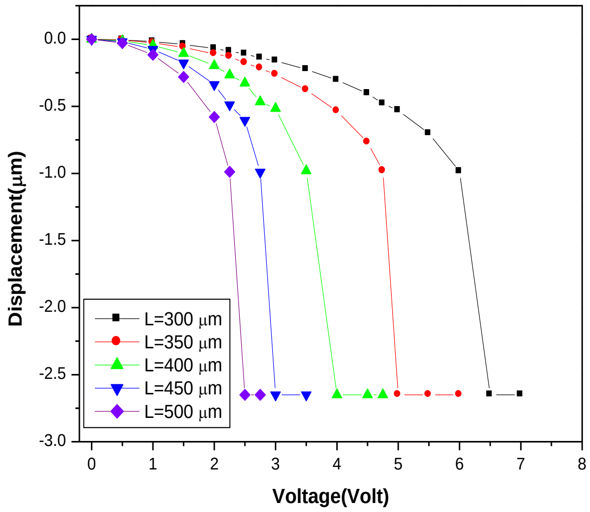


Figure 7. Displacement vs. Voltage Curve

3.2. Capacitance Analysis

From these Figures it can be seen that the capacitance is increases with increasing DC bias voltage, and when voltage is reached equal to the pull-in voltage then there is a sudden rise in capacitance occurs. The capacitance increases linearly with voltage, but there is a sharp increase in capacitance at the pull-in voltage and beyond that it again linearly increases with voltage.

Table 2. Capacitance at Pull-in voltage for different kinds of cantilevers

Different Lengths of Micro-cantilever with width 5µm	Capacitance at pull-in voltage (pF)	Different Lengths of Micro-cantilever with width 8µm	Capacitance at pull-in voltage (pF)	Different Lengths of Micro-cantilever with width 20µm	Capacitance at pull-in voltage (pF)
L=500µm	0.07818	L=500µm	0.09804	L=500µm	0.08627
L=450µm	0.07967	L=450µm	0.10039	L=400µm	0.09100
L=400µm	0.08122	L=400µm	0.10260		
L=350µm	0.08280	L=350µm	0.10483		
L=300µm	0.08502	L=300µm	0.10795		

4. CONCLUSION

In this paper, MEMS based digital variable capacitors with multicantilevers were analyzed and designed.The length found to have a great influence on the pull-in voltage. In contrast to that of a single plate capacitor, the capacitance increases in step with the bias voltage, indicating that the cantilever beams are individually pulled-in. The voltage interval for individual beams to be pulled-in is not a constant, but varies from beam to beam. The magnitude of the first step rise in the capacitance is too large to correspond to a single cantilever beam. Digital variation in capacitance was realized from capacitors with multi-cantilevers. But it is difficult to pull-in more than 10 cantilevers, and most of cantilevers stick on the substrate
when the voltage is off.Future work of characterization is in progress.

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