Effect of Nonlinear Structural Stiffness on the Response of Capacitive MEMS Devices

M. Shavezipur*,[1], P. Nieva*,[2], A. Khajepour*,[3], and S. M. Hashemi**

* Department of Mechanical and Mechatronics Engineering, University of Waterloo,
200 University Ave. W., Waterloo, ON, N2L 3G1, Canada,
[1] mshavezi@engmail.uwaterloo.ca, [2] pnieva@uwaterloo.ca, [3] akhajepour@uwaterloo.ca
**Department of Aerospace Engineering, Ryerson University,
350 Victoria St., Toronto, ON, M5B 2K3, Canada, smhashem@ryerson.ca

ABSTRACT

The effect of flexibility and initial curvature of moving plates in parallel-plate MEMS capacitors are investigated. A parallel-plate-based MEMS tunable capacitor with extended tunability and linear capacitance-voltage (*C-V*) response is introduced. The design combines the flexibility and curvature of the electrode with an array of mechanical stoppers to increase the overall stiffness of the device as the actuation voltage increases. The plate's curvature and the location of the stoppers are tailored to provide a smooth *C-V* curve with high linearity and fairly constant sensitivity throughout the working range. ANSYS® FEM simulations and experimental results of capacitors fabricated with PolyMUMPs demonstrate a notable improvement in the linearity of the *C-V* response comparing to that of a conventional parallel-plate capacitor. The proposed technique can also be applied to capacitive pressure and temperature sensors and electrostatic actuators to enhance their performances.

Keywords: Linear capacitor, residual stress, nonlinear stiffness.

1 INTRODUCTION

MEMS technology has demonstrated significant growth in past decade and different devices and integrated circuits such as sensors, micro-actuators and micro-mirrors with superior performances have been introduced. Electrostatically actuated capacitive MEMS elements are among the most used devices in different areas such as tunable capacitors [1,2], capacitive sensors [3] and out-of-plane actuators [4]. They have simple structures, small sizes and low energy loss and fit in many applications including RF engineering and automotive and aerospace industries. However, their coupled electrostatic-structural governing equations result in limited working ranges and nonlinear characteristic curves. In electrostatically actuated devices like micro-actuators and grippers and tunable capacitors, the structural instability after pull-in limits the working range of the device. On the other hand, nonlinear relation among displacement, capacitance and external actuation generates nonlinear responses in capacitive pressure, temperature and displacement sensors that results in low sensitivity in a part of their working ranges.

Earlier work by the authors [5,6] demonstrated that utilizing geometric nonlinearities such as segmented electrodes (with lumped flexibility) and a set of optimized mechanical stoppers can results in structural stiffening, which in turn improves the tunability and linearity of the *C-V* response in MEMS tunable capacitors. In this research, a simpler approach, combining electrode flexibility and nonlinear stiffness, is developed and demonstrated to reduce the nonlinearity of the responses of MEMS capacitive devices. In the present study, the application of the proposed design methodology for parallel-plate tunable capacitors parallel-plate tunable capacitor is demonstrated, due to their simple fabrication and post-processing (i.e. release and packaging). However, numerical and ANSYS FEM simulations show that the proposed technique is equally applicable to MEMS capacitive pressure and temperature sensors and out-of-plane actuators.

A conventional parallel-plate tunable capacitor is simply made of two electrodes, one is suspended by a set of supporting beams modeled as linear mechanical springs [7] and the other one is fixed to the substrate. When bias voltage, *V*, is applied, the electrostatic force obtained from

$$F_e = \frac{\varepsilon_0 A V^2}{2g^2} \tag{1}$$

deforms the spring-like beams and changes the air gap. Here, *A* is the area of the electrodes, *g* is the gap in between and ε_0 is the permittivity of air. The air gap is obtained from the equation of static equilibrium:

$$\frac{\varepsilon_0 A V^2}{2g^2} - k_{eq}(g_0 - g) = 0 \tag{2}$$

where k_{eq} represents the stiffness of all supporting beams and g_0 is the initial gap between electrodes. The capacitance is then obtained from:

$$C = \frac{\varepsilon_0 A}{g} \tag{3}$$

The tunability of conventional parallel-plate capacitors is limited to 50%, because as the voltage increases, the electrostatic force overcomes structural resistive force and structural instability occurs at pull-in. Moreover, due to nonlinear coupled electrostatic-structural governing equations (2) and (3), the capacitance-voltage (*C-V*) response is nonlinear. Low tunability and highly nonlinear response are two main drawbacks of MEMS parallel-plate capacitors. While many novel designs with higher tunabilities ranging from 100% to over 1700% are proposed in the literature (for example see [8,9]), the linearization of response of parallel-plate capacitors has not received enough attention [5-7,10,11].

In this paper, the effects of flexibility and initial curvature of moving plates on the performance of tunable capacitors are investigated. A simple structure that uses a set of mechanical stoppers to control the displacements of the moving electrode is proposed to linearize the *C-V* response and improve the maximum tunability. The plate curvature and location of stoppers can be easily optimized to provide a smooth *C-V* curve with high tunability and fairly constant sensitivity throughout the working range.

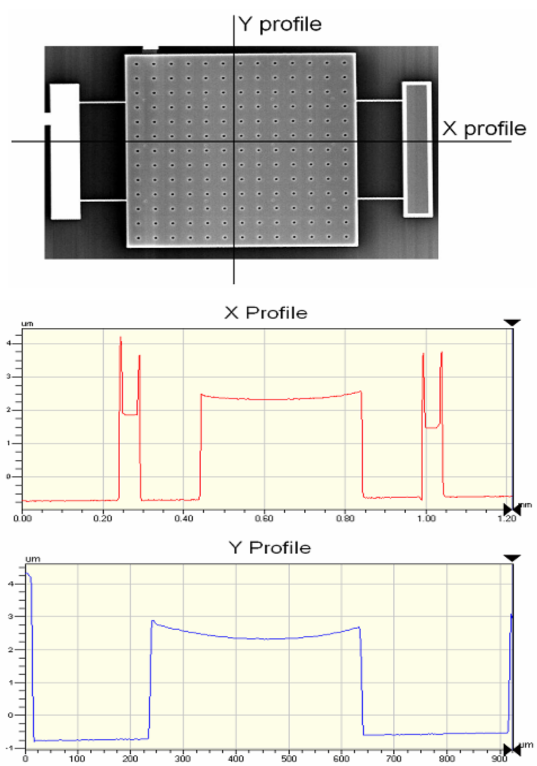


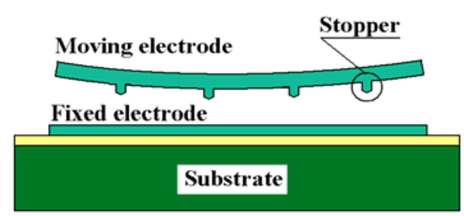
Figure 1: The curvature of moving electrode obtained using a WYKO NT1100 Optical Profiler.

2 CAPACITOR DESIGN AND FABRICATION PROCESS

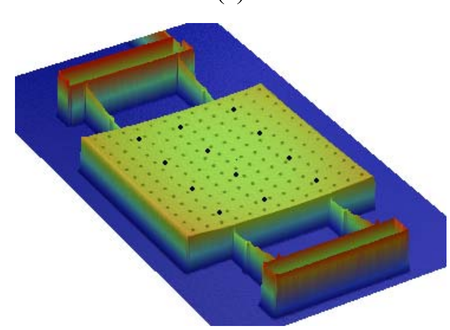
Conventional models for parallel-plate capacitors, equations (1) to (3), assume that the moving electrode is rigid and remains flat as the bias voltage increases. This model predicts a complete contact between electrodes (or between the moving plate and the dielectric layer deposited on the top of fixed electrode) as the pull-in occurs. This means that there should be no more tunability if the DC voltage passes the pull-in voltage. However, the reported tunabilities obtained after pull-in suggest that the assumption of flat and rigid moving electrode is not always valid, since a linear region in *C-V* responses of different designs after pull-in is observed [8,9]. While the curvature and flexibility of moving electrodes are known as negative factors that reduce the maximum tunability, it is possible to exploit them to enhance the *C-V* response as follows.

To employ the flexibility of the moving electrode and its initial curvature for improvement of *C-V* response, a parallel-plate capacitor fabricated using PolyMUMPs [12] and presented in Figure 1 is proposed. As shown in this figure, the plate has a slight curvature in two perpendicular directions. Because the supporting beams are located at two sides of the moving electrode, different curvatures in two directions are obtained. When a DC voltage is applied, the moving electrode is displaced due to deformation of supporting beams which can be considered as a rigid-body displacement. It is also deformed because of distributed electrostatic load. Up to the pull-in, the rigid-body mode of displacement is the dominant cause of capacitance change; however, after pull-in the vertical movement of the plate is stopped and the capacitance changes because the deformation of moving electrode continues.

To prevent direct contact between two electrodes and extend the tuning range of the capacitor beyond pull-in, DIMPLE mask in PolyMUMPs is used to fabricate a set of mechanical stoppers under the moving plate. DIMPLE mask is used to etch Oxide1 (sacrificial) layer and when the polysilicon layer is deposited, it create a small tooth under the moving electrodes, as depicted in Figure 2-a. The locations of stoppers are shown in Figure 2-b as black dots.



(a)



(b)

Figure 2: (a) The mechanical stopper created under the moving plate using DIMPLE mask in PolyMUMPs. (b) The location of stoppers (black dots) in a fabricated capacitor.

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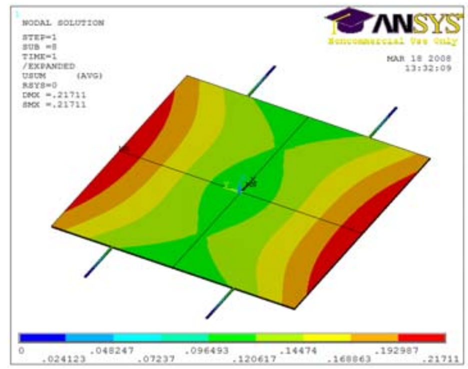
An FEM simulation is performed to investigate the behavior of the proposed design. ANSYS® ESSOLV command is used to iteratively solve the electrostatic and structural equations. SOILD122 and SOLID186 are used to mesh electrostatic and structural physics, respectively. The results of ANSYS simulations are presented in Figure 3-a and 3-b. The curvature of the moving electrode is same as that of capacitor shown in Figures 1 and 2. To study the effect of different initial stress, the minimum air gap between two electrodes has been changed and the corresponding ΔC-V responses are plotted and compared in Figure 4. Smaller gaps are corresponding to higher initial stress and for the sake of simplicity of the simulations, the plate's curvature is considered to be the same. This may generate small error in the capacitance values; nonetheless, the trend of C-V curves is not affected. As displayed in this figure, when the initial stress increases and the air gap reduces, a smoother C-V response is obtained and the highly sensitive region near pull-in is eliminated. Moreover, because the structural stiffness of the capacitor gradually increases, the linearity of the C-V curve and the overall tunability increase. In this design, the pull-in occurs when the moving electrode touches the fixed one at its corners. It is also observed that as the initial gap decreases, the tunability of the capacitor is also reduced, due to the fact that the capacitance jump in preliminary pull-in is eliminated.

To quantitatively express the level of linearization, the coefficient of linear correlation between capacitance and voltage is considered as the linearity factor, LF [5-7,13]:

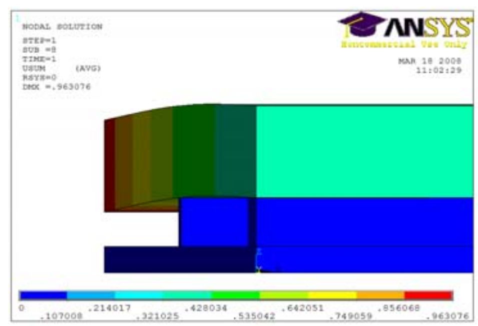
$$LF = \frac{n\sum C_i V_i - \sum C_i \sum V_i}{\sqrt{[n\sum C_i^2 - \left(\sum C_i\right)^2][n\sum V_i^2 - \left(\sum V_i\right)^2]}} \quad (4)$$

LF for an ideally linear C-V response is 1.0 and for that of a conventional parallel-plate capacitor is 0.865. The advantage of the defined linearity factor is that it does not depend on the initial capacitance, the pull-in voltage or number of voltage samples. For capacitors with minimum gap of 1.15 μm, 0.95 μm and 0.85 μm, presented in Figure 4, the linearity factor is 0.984, 0.987 and 0.993, respectively, displaying a notable improvement compared to the conventional design.

To verify the applicability of the proposed design, the fabricated capacitors are tested using Agilent E4890A Precision LCR meter. Identical capacitors from four released chips were tested and their tunability-voltage (ΔC-V) responses are compared to those of a conventional capacitor and ANSYS® simulations in Figure 5. As displayed in this figure, the experimental results are consistent with ANSYS simulations and smooth curves with high linearity are obtained. The linearity factor, LF, for capacitors of Chips #1, #2, #3 and #4 are 0.997, 0.996, 0.990 and 0.995, respectively. Comparing the response of the same capacitor without stoppers (conventional) with new design reveals that in absence of mechanical stoppers, the moving plate collapses on the fixed one at pull-in because of the rigid-body mode of the displacement, where in case of new design with stoppers, the rigid-body displacement is stopped at a preliminary pull-in and then the deformation mode plays a major role in changing the capacitance. As explained before, it is also observed that this technique delays the final pull-in as the conventional capacitor faces pull-in at $V < 2$ V where in the new design pull-in happens at $V > 7.0$ V.



(a)



(b)

Figure 3: ANSYS simulations of a capacitor with initially curved moving electrode; (a) Deformations of the electrode; (b) Local contact of stoppers and the fixed electrode.

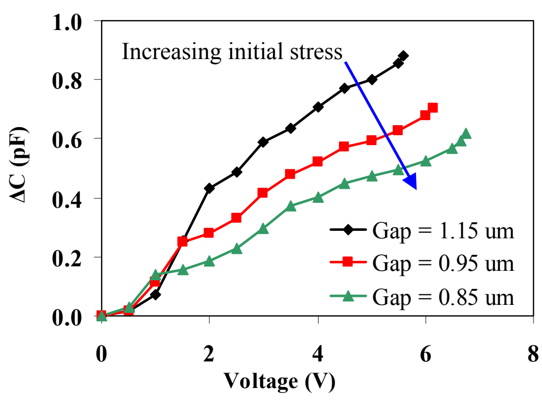


Figure 4: ANSYS simulations showing the C-V response of capacitors with different initial air gaps (initial curvature is assumed to be fixed).

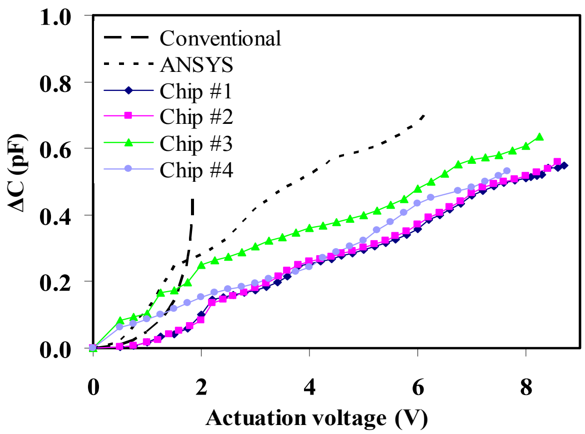


Figure 5: Tunability-voltage (ΔC-V) responses of four identical capacitors with mechanical stoppers obtained from experiments compared to that of a conventional capacitor and ANSYS® simulations.

3 CONCLUDING REMARKS

The effects of flexibility and electrode curvature on performance of MEMS capacitors were investigated and a linearly tunable capacitor was introduced. The design advantageously combines the flexibility and curvature of the moving electrode with an array of mechanical stoppers to increase the linearity of the *C-V* response. ANSYS simulations and experimental results verify the applicability of the proposed design technique. Although only tunable capacitors were discussed in this paper, analytical and FEM simulations show that similar approach, a combination of electrode curvature, structural nonlinear stiffness and shape optimization can be used to enhance and linearize the characteristic responses of pressure and temperature sensors and electrostatic actuators.

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