Electrostatic Actuation of Variable Capacitor

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***Abstract* – The are many cases were having as variable capacitor can be beneficial. Such cases include oscillators, tunable filters, and phase shifters. In this paper I propose a variable capacitor that can used whose variance is not dependent on the drive voltage of the capacitor itself but on a different drive voltage of an electrostatic actuator. The benefit of this is that it prevents noise from the capacitor drive voltage from effecting the overall capacitance. Then the performance of the variable is capacitor is analyzed based on the structure of the electrostatic actuator.**

1. INTRODUCTION & BACKGROUND

1.1 Electrostatic Actuation

Electrostatic actuation uses an attractive/repulsive Coulomb force between charged bodies in order to move a physical structure. It usually consists of two electrodes, with one of the electrodes being the physical structure, separated by a small distance (< 10 μm). A voltage, called the drive voltage, is applied to the fixed electrode, causing the second electrode to deform, depicted in Figure 1 [1]. When the drive voltage is taken away, the second electrode returns to its original state.

The main benefits of using electrostatic actuation include having simple design making it compatible with most MEMS manufacturing processes, low power consumption, high speed operation, and well understood physical behavior due to various electrical parameters. However, some of the drawbacks is that its susceptible to malfunctioning due to particulates due to small gaps, requires high voltages, and is normally only able to drive small actuation distances.

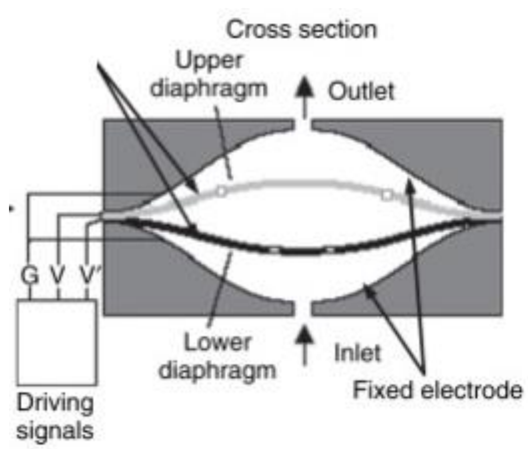

Figure 1: Diagram of Electrostatic Actuator

1.2 Parallel Plate Capacitor

In MEMs structures, a parallel plate capacitor (PPC), is usually comprised of a fixed plate electrode on the wafer surface and a top plate electrode suspended above the fixed plate as depicted in Figure 2 [2]. The top plate structure is made so that it may move vertically but not laterally. A drive voltage V_d is then applied to the top plate while the fixed plate is made ground. This causes an electrostatic force between the plates with a magnitude equal to

$$F_e = \frac{1}{2}\frac{\varepsilon A V_d}{d^2}$$

with ε being the electrical permittivity, A being the effective area of capacitor plates, and d being the original vertical distance between the plates [2]. This electrostatic force will cause the vertical distance between the plates to decrease, and thus increase the capacitance equal to

$$C = \frac{\varepsilon A}{d}$$

until the system reaches equilibrium. Thus, the capacitance of this PPC can be tuned based on the driving voltage. However, this structure does not allow for a controller of capacitance such that capacitance can changed interpedently of its drive voltage.

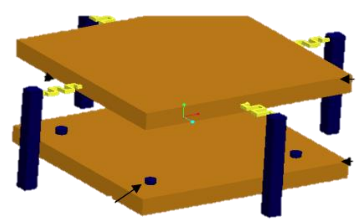

Figure 2: Diagram of Parallel Plate Capacitor

1.3 Purpose of Project

The purpose of this project is to design a MEMs structure that combines both an electrostatic actuator, and PPC in order to create a system that provides use to a multitude of devices and overcomes the downfalls of each component. The electrostatic actuator will be used in order to independently control the capacitance of PPC. The goal is to create a structure that is simple in design and easy to manufacture so that in can be incorporated in larger devices, and to be able to vary the capacitance of the PPC by a significant amount.

2. Concept & Approach

2.1 Structure Conceptual Design

The MEMs structures I am proposing is an electrostatic actuator that consists of a cantilever beam sandwiched in between two curved electrodes and attached to the end of the beam in the top plate of PPC with the fixed plated located below it on the wafer surface.

The curved electrodes will have V_d applied to them while the cantilever beam will be attached to ground on the wafer through an anchor. This will make the top plate of the PPC act as a ground plate, and thus the V_d for PPC will be applied to the bottom fixed plate.

When the voltage is applied to the curved electrodes, this will cause the cantilever beam to deform laterally above the wafer towards one of the electrodes. This deformation also causes the top plate to move and thus the effective area of the PPC to decrease and along with it, the capacitance of the PPC. A conceptual diagram of this event is depicted in Figure 3.

2.2 Actuator: Curved Electrodes

As mentioned before, electrostatic actuators are typically only used in cases where small displacements are being used. However, using a curved electrode structure developed by Legtenberg, et. al., large displacements (> 10 µm) can be accomplished [3]. A diagram of the structure is shown in Figure 4. The curved electrode allows for the pull in voltage, V_{pull} due to the difference in voltage between the electrode and beam, to still be effective but also give ample space for the beam to deform.

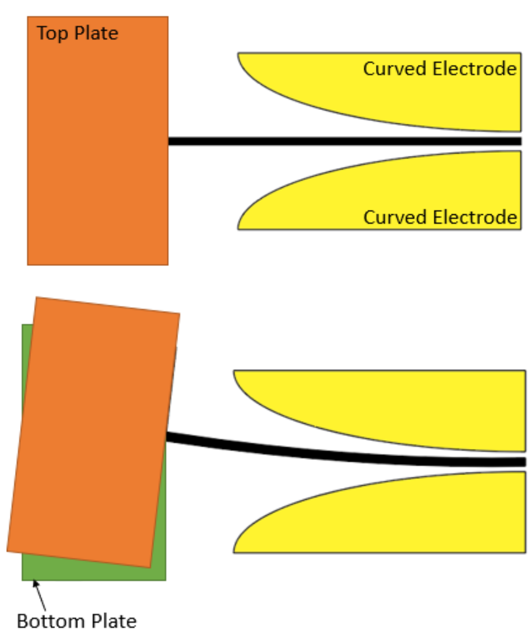

Figure 3: Conceptual Diagram of Proposed Microstructure

2.3 Parallel Plate Capacitor Variance

Since normally PPC vary their capacitance by changing the original distance between the two plates, careful attention is usually needed to discuss the pull in effects of voltage difference between the top and bottom plates. However, since the focus is looking at the change in effective area while keeping the distance between the two plates constant, the voltage pull in effects will not be discussed since they will be constant among all tests. The effects that can occur between the PPC and the electrostatic actuator being in proximity to each other are also going to be considered negligible since in all designs, the space between both will be relatively large.

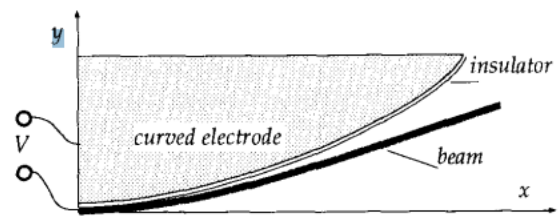

Figure 4: Depiction on Cantilever Beam Bending w/ Curved Electrode

3. Design & Analysis

3.1 Structure Shape & Size

The base line shape and size of the microstructure is shown in Figure 5a. As seen, the variable values are L =500 µm, δ_{min} = 10 µm, δ_{max} = 101.0711 µm, h = 2 µm, t = 2 µm, and the bottom plate of the PPC is 102 µm x 102 µm, and the top plate is 100 µm x 100 µm. A cross sectional view is shown in Figure 5b. The curve of the electrodes follows the path $s(x) = \delta_{max}\left[\frac{x}{L}\right]^n$, where n =2 for the base line structure. Both of the curved electrode pads are 50 µm x 50 µm, while the pad for the bottom plate of PPC is 40 µm x 40 µm and the pad for the cantilever beam is 40 µm x 70 µm.

3.2 Structure Design

Both curved electrodes have a dielectric layer of Silicon Nitride in order to electrically isolate them from each other as from the cantilever beam. The electrodes will be raised to the same height level as the cantilever beam by using 3 anchors on each. Pads for each electrode are made in order to provide voltage to either when desired. For convenience, a pad is attached to the cantilever beam to act as an anchor as well as provide a drive voltage if needed. The bottom plate of the electrode is covered in a dielectric layer of Silicon Dioxide with a permittivity of $\varepsilon = 2.568 * 10^{-17}\ \frac{F}{\mu m}$. This electrically isolates the bottom plate from top plate of PPC.

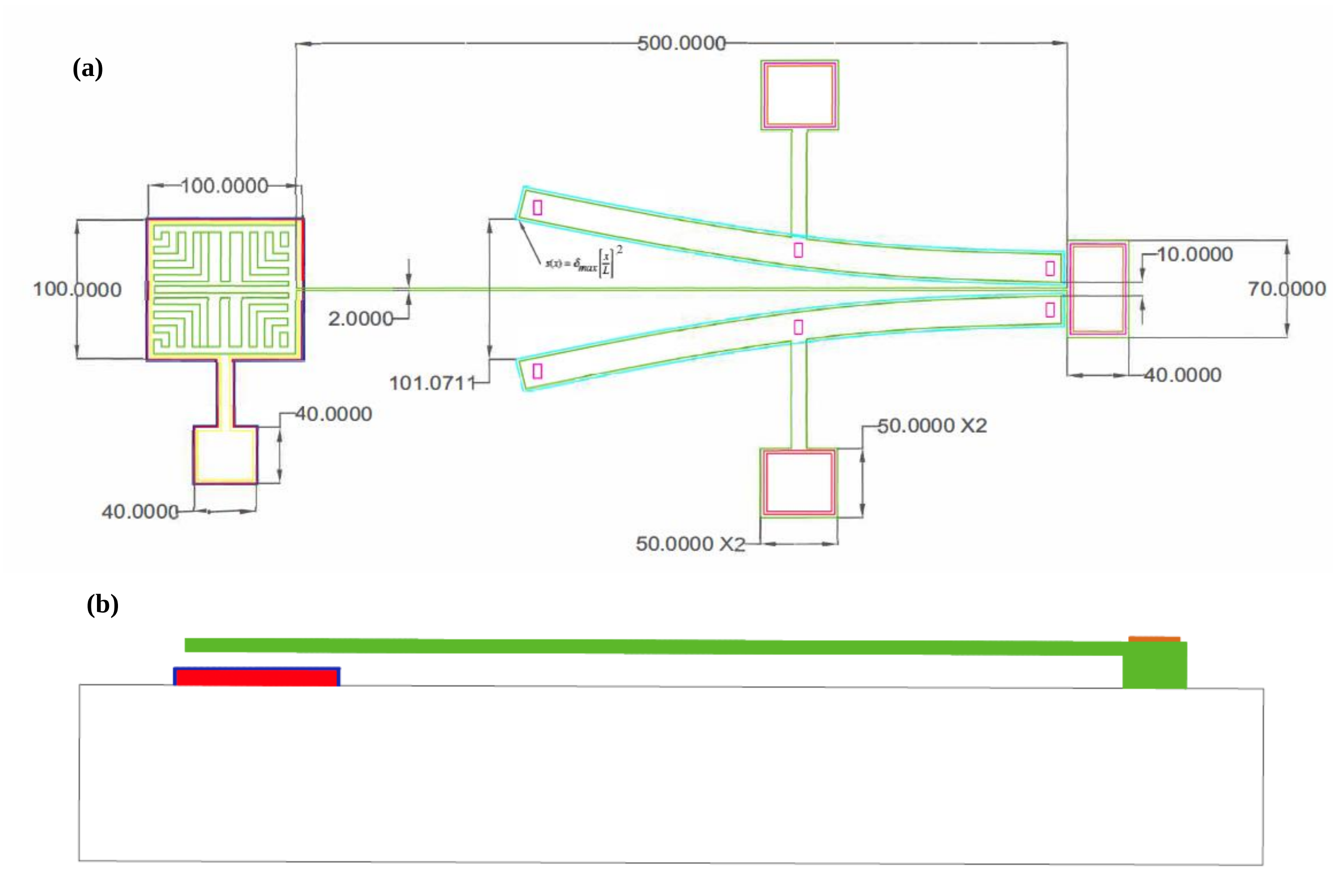

Figure 5: (a) Dimensional Drawing of Microstructure. (b) Cross Sectional View Along Middle of Microstructure.

3.3 Numerical Analysis

From Legtenberg work, it is deduced that the deflection profile of the beam can be calculated using the following equation [3]:

$$\delta(x) = cx^2\ (6L^2 - 4Lx + x^2)$$

The constant c here is determined experimentally. The values for this kind of actuator with different values of n that defines the electrode shape were found by Legtenberg, et. al. and are presented in Table 1 [3].

Table 1: Values of c for varying values of n

n	c [$* 10^7\ m^{-3}$]
0	7.63
0.5	7.66
1.0	7.56
1.5	6.88
2.0	5.54

Now knowing the displacement of the beam end, the top plates center location, and rotation angle are known. Capacitance is calculated using the following equation [2]

$$C = \frac{\varepsilon A_{eff}}{d}$$

where $\varepsilon = 2.568 * 10^{-17}\ \frac{F}{\mu m}$ for the permittivity of PPC, $d = 2.8\ \mu m$ based on the fabrication process discussed later, and A_{eff} is calculated using the bboxOverlapRatio() function in MATLAB, and the area of the top plate is $1000 \mu m^2$.

3.4 Experimental Setup

For performing the calculation results presented later, the drive voltage for the electrostatic actuator was held constant at 40 V, in order to prevent unstable deformation from the cantilever beam. No drive voltage in the PPC was assumed with all calculations.

The capacitance at steady state, once the beam stops moving after drive voltage applied, was calculated for varying lengths of the beam from 300 μm to 500 μm, and for different profiles of electrodes with n = 0.5, 1.0, 1.5, 2.0.

4. Fabrication Process

The manufacturing process being used to generate the MEMs structure is surface micromachining. Figure 6 depicts each mask used for each layer in the structure. The following steps are used to manufacture the structure.

I. Deposition & etching of SiO_2

A 0.1 μm of SiO_2 is thermally oxidized on top of the silicon wafer. Then using mask 1, the SiO_2 is etched.

II. Deposition of Cr & 1st Photoresist

0.1 μm seed layer of Cr is deposited to help adhesion of Al later on. 5 μm layer of photoresist (PR) is deposited on top of Cr.

III. Etch 1st PR

Etch with UV light the 1st PR layer using mask 2

IV. Deposition of 1st Al

Deposit 2 μm of Al with physical vapor deposition (PVD), using mask 2 again but bright instead.

V. Remove PR & Cr Seed Layer

Place in HCl bath for short period to remove PR and CR layers not under Al. Some of Al will remove, so account for this in previous step.

VI. Grow Oxidation Layer

Grow a 1 μm oxidation layer on top of the Al using mask 3.

VII. Deposition & Etch of PSG Layer

Deposit 5 μm PSG, then flatten using Chemical Mechanical Polishing (CMP). Then etch anchors using mask 4.

VIII. Deposition & Etch of 1st Polysilicon

Deposit 2 μm of polysilicon and dry etch using mask 5

IX. Deposition & Etch of Si_3N_4

Deposit 1 μm of Si_3N_4 and dry etch using mask 6.

X. Deposition & Etch of 2nd PR

Deposit 5 μm of PR and UV etch using mask 7

XI. Deposition of 2nd Al

Deposit 2 μm of Al with PVD and using mask 7 but bright instead.

XII. Remove PR & PSG

Bathe in HCl solution for short period to remove PR, and then bathe in HF solution to remove rest of sacrificial PSG.

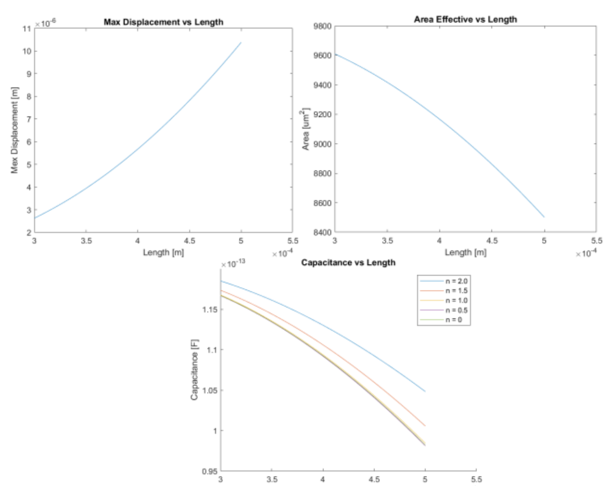

Figure 7: (a) Displacement Results. (b) Effective Area Results. (c) Capacitance Results

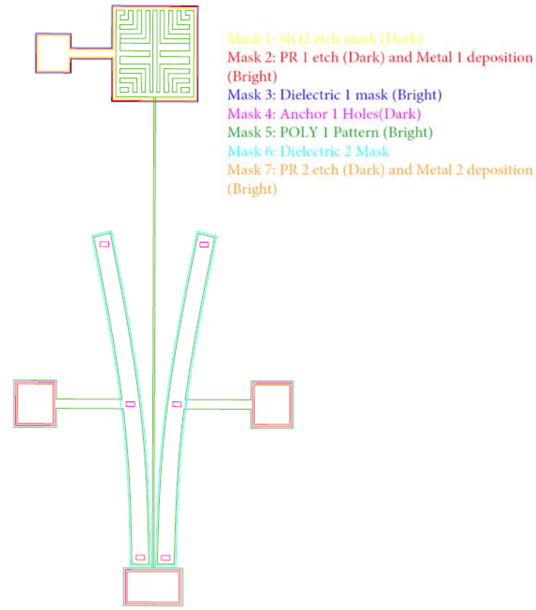

Figure 6: Mask Diagram for Manufacturing Process

5. Expected Results

5.1 Deflection and Effective Area

After performing calculation based on the equations presented in section 3, the max displacement of the beam and the effective area of the PPC vs the length of the cantilever beam is presented in Figure 7a and 7b, respectively. As expected, the max deflection increases as the length of the beam increases, and the effective area decreases as the length of the beam increases. The curves depict a parabolic path which is consistent with the deflection equation presented earlier.

5.2 Capacitance vs Electrode Curve

The capacitance at steady state was calculated using the equations presented in Section 3, and the c values determined by Legtenberg, et. al. for different values of n [3]. The results are presented in Figure 6c. Of notice is that for lower values of n, the capacitance is lower than for higher values of n, and this difference also increases as the beam length is increased.

6. Conclusion

From the results it is seen that varying the length of cantilever beam has some effect on the steady state capacitance of the PPC but that variance is very minimal. Future work that can possibly show higher variances is looking at parameters including drive voltage of the electrostatic actuator, the gap distance between the electrodes of the actuator, and, the thickness of the cantilever beam. In order to get more accurate results as well, the pull in effect of the PPC can be accounted for as well since this also changes the distances between the two plates and thus the capacitance of the PPC,

7. References

[1] H. Kim, K. Najafi and L. Bernal, "Gas Micropumps" in Comprehensive Microsystems, Amsterdam, The Netherlands:Elsevier, pp. 273-299, 2008.

[2] Sonje, Manoj. (2011). *Design and Simulation Analysis of Mems Parallel Plate Capacitor Models for Voltage Conversion and Power Harvesting*, [Unpublished bachelor’s thesis]. University of Missouri – Columbia

[3] R. Legtenberg, J. Gilbert, S. D. Senturia and M. Elwenspoek, "Electrostatic curved electrode actuators," in Journal of Microelectromechanical Systems, vol. 6, no. 3, pp. 257-265, Sept. 1997, doi: 10.1109/84.623115.