MEMS Comb Drive Gap Reduction Beyond Minimum Feature Size: A Computational Study

Ndu Osonwanne[1] and Jason V. Clark[1,2]

[1]School of Electrical and Computer Engineering, [2]School of Mechanical Engineering, Purdue University
West Lafayette, IN 47906
[1]nosonwan@purdue.edu, [2]jvclark@ecn.purdue.edu

Abstract: In this paper we present a method to reduce the comb drive gap in micro electro mechanical systems (MEMS) beyond the minimum fabrication feature size. The benefit of reducing the gap space between comb drive fingers is to increase its sensitivity to changes in capacitance due to displacements. The minimum feature size of standard fabrication foundries is 2 microns. To reduce the gap beyond a minimum feature size, we propose that the comb drive fingers be initially disengaged to facilitate the fabrication of gaps without conventional limits. Post-fabrication assembly however required to electrostatically translate the stator to engage the comb fingers. Previously, researchers have investigated using engaged variable finger widths; however, compared to what we propose, the previous method results in a jump in the electrostatic force and non-passive sensing. Through modeling and simulation, we examine various stator translation configurations, and comb drive instability due to the smaller gap size.

Keywords: gap reduction, sensitivity, pull-in phenomenon, vertical instability

1. Introduction

The comb drive, though the most widely used electrostatic actuator and sensor in the MEMS industry, has several design limitations [1]. Positioning of the comb fingers with substantial gap limits the amount of force that can be exerted on the comb fingers and its sensitivity to capacitance changes. We model the comb drive with anchors to minimize this gap, thereby increasing effective capacitance read by the device and thus the accuracy and precision of measurement. Comb drive actuators traverse in the vertical and lateral direction. Vertical comb drive actuation is particularly useful for applications requiring small device size, low drive voltage and large vertical displacements[2].

Among the capacitance-based sensors and actuators, the comb drive is the most common [3]. It is activated by electrostatic actuation and relies on the theory of parallel-plate capacitors, where the parallel-plates are an array of comb fingers – a key part of the comb drive [3]. Having comb fingers come in with smaller gap, gives much larger capacitance readouts and reduces the noise ratio, especially for very sensitive device applications. The capacitance level being extremely high above the noise floor, results in better accuracy for capacitive sensing.

There have been several methods attempted to optimize the comb-drive. For instance, Naraghi et al. have developed a method to increase the net force output by comb drives with clamped tethers, which also improves the accuracy in calculation of the applied force [4]. A vertical comb drive actuator with thin, high-aspect ratio comb fingers that are self-aligned, offset and fabricated with small gaps (≤ 2μm) is presented by Carlen et al. in [2].

The present work discusses methods to improve the performance of comb-drives post-fabrication using various configurations employing pull-in phenomenon due to electrostatic force for vertical displacement of the comb-fingers beyond minimum feature size. From our research, we find that reducing the gap leads to more accurate device measurements given stronger forces and capacitive sensitivity.

The rest of the paper is organized as follows: In Section 2, we discuss the governing equations showing the relationship between gap space of the comb fingers and the electrostatic forces and changes in capacitance of the device. We discuss how gap reduction occurs due to bigger electrostatic forces after the comb fingers are initially engaged. In Section 3, we present our methods and simulation of COMSOL models for comb drive gap reduction. Sections 4, 5 and 6 cover our results, discussion and conclusions respectively.

2. Theory and Governing Equations

The comb fingers of the MEMS comb drive are dominated by both direct and fringe electrostatic fields which enable the electrostatic actuation. Direct parallel plate electrostatic force are more powerful than the fringe field forces acting on the movable comb fingers [5]. The fringe fields can be neglected for analysis purposes. The vertical motion of comb drive structures occurs when a potential difference or external force is applied between stationary and movable comb fingers, thus establishing asymmetric electric field lines around the moving finger [2]. The asymmetric electric field lines result in displacement of the movable comb fingers. To better understand the interaction of electrostatic forces in the comb fingers, we first examine the theory of parallel-plate capacitors. The basic equation for capacitance is given as:

$$C \equiv \frac{Q}{V} = \frac{\varepsilon A}{g} \qquad (2.1)$$

Equation 2.1 is a good approximation, where most of the capacitance is due to charges that accumulate on the comb fingers, neglecting the fringe fields. As illustrated in Figure 1, *g* is the gap between comb fingers -- vertically, *A* is the shaded area of the overlapping comb fingers, and ε is the permittivity of the material.

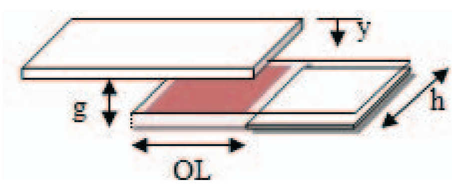

Figure 1. Partial cross-section showing overlapping area of two comb fingers.

The electrostatic force between the comb fingers or plates can be determined as a partial derivative of the energy stored, *U* with respect to the co-ordinate in the direction of the force [5]. For the vertical displacement, with respect to the y-direction, the electrostatic force is give as:

$$F_y = \frac{\partial U}{\partial y} = \frac{\partial\{(1/2)CV^2\}}{\partial y} = \frac{\partial\{(1/2)[\varepsilon A/g]V^2\}}{\partial y}$$

$$F_y = \frac{\partial\{(1/2)[\varepsilon A/(g_o - y)]V^2\}}{\partial y}$$

Here, *y* in the numerator is the only variable, thus:

$$F_y = \varepsilon A V^2 \frac{\partial\{1/(g_o - y)\}}{\partial y}$$

Hence:

$$F_y = \varepsilon A\, V^2 [1/(g_o - y)^2] \qquad (2.2)$$

As the displacement of the comb drive across the vertical direction *y* gets larger and larger, the nonlinear $(g_o - y)^2$ function of equation 2.2 becomes much bigger and we get a very large electrostatic force, F_y.

However, for the lateral displacement, *A* varies in the +x direction. Taking the partial derivative with respect to the x-direction, we have:

$$F_x = \frac{\partial\{(1/2)\,\varepsilon\,[h\,(OL + x)/g_o]\,V^2\}}{\partial x}$$

where OL is the overlap which increases in the x-direction, so the area is given by [h * (OL + x)] Thus,

$$F_x = \frac{(1/2)\,\varepsilon\, h\, V^2}{g_o} \qquad (2.3a)$$

Equation 2.3a is really just for one side of the comb finger. Taking into consideration forces from both top and bottom sides of the parallel-plate capacitor or comb finger, we have:

$$F_x = \frac{\varepsilon\, h\, V^2}{g_o} \qquad (2.3b)$$

Note however, that the force in equation 2.3b is not a function of displacement. If we reduce the gap between comb fingers in the y-direction we get a force that is several magnitudes greater, but changing gap space in the x-direction results in the same force.

In this paper, we use this vertical instability to our advantage, where initially disengaged comb fingers are fabricated on the anchor at less than 2 microns gap in order to make contact when the comb drive is first engaged due to really large attractive electrostatic forces, F_y. This way the device is made to perform much better using various stator configurations that enhance the comb drive.

3. Methods

In our simulation, we use a limited number of comb fingers for simplicity purposes. We draw on the MEMS module in COMSOL Multiphysics®, using the plane-stress mode in 2D, to simulate displacement of the comb-fingers. Modeling with too many comb fingers results in a lot of computer memory use and meshing; to compensate for the fewer comb fingers used, we increase the force on the comb fingers proportionately.

The capacitance and electrostatic force on parallel-plate capacitors, the comb fingers, are highly nonlinear. Beyond an equilibrium point, the comb fingers of the movable and fixed plates stick together as the gap closes and the electrostatic force keeps them in place. This electrostatic instability is known as pull-in [5]. Thus, when the vertical displacement increases, the distance between the comb fingers goes to zero as the electrostatic force becomes exceptionally large. A lock mechanism can be used subsequently to clamp the structure.

We provide several models of tentative comb drive configurations to foster the pull-in phenomenon that reduces the gap between comb fingers. The anchors have auxiliary comb fingers designed to make contact when the comb drive is first engaged. Flexure beams are used on the main comb fingers to enable the comb drive spring back in place. Ideally, there is no vertical instability due to pull-in on the primary comb fingers, but only on the auxiliary comb fingers on the supporting anchors.

Figure 2 shows a simplistic representation of the comb drive with comb fingers on anchors at both ends of the structure. After creating mesh and solving in COMSOL, we see the displacement on the comb fingers due to the electrostatic forces. The models shown include a gap-closing actuator mounted on the anchors that are several orders of magnitude stronger than the actuation from the primary comb fingers of the comb drive. The idea is for these auxiliary comb fingers to close permanently while the rest of the comb drive is allowed to engage repeatedly. Several methods can be used to implement this: either applying a voltage to get the comb fingers of the anchor or gap-closing actuator past the point of instability, or fabricating with gap space less than 2 microns.

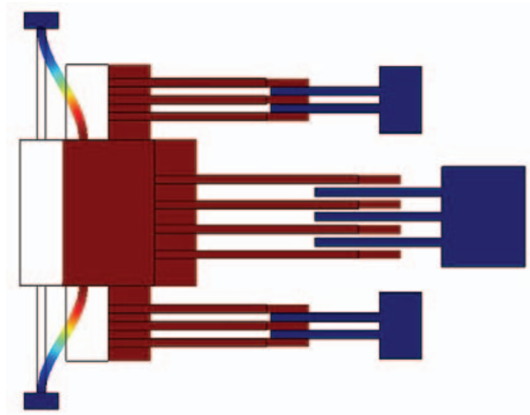

Figure 2. Simple COMSOL model for comb drive with comb fingers also attached to anchors.

Notice that the gap space between the comb fingers on the anchors on both ends are smaller than that of the rest of the comb drive and the space closes up when the fingers come together and overlap. The vertical electrostatic forces on the comb finger plates are much larger here and cause the comb fingers to stick at these ends. Before being engaged, the comb fingers at the anchor ends are not touching and the tips are apart. Electrostatic pull-in phenomenon occurs after the fingers are engaged, as the gap spaces are well below 2 microns. When additional external voltage is applied, the comb drive would be engaged more fully beyond the current position.

Another configuration of the comb drive with anchors for gap reduction is presented in Fig. 3

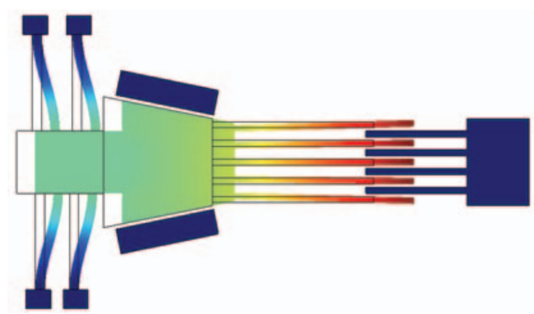

Figure 3. Alternative model for comb drive with anchors for gap reduction.

In the model of Figure 3, the comb drive glides alongside the anchors, with the flexure beams to pull it back in place. The anchors are positioned by the sides of the comb drive at an angle keeping a small distance between the plates, such that the electrostatic interaction between the capacitive plates enable the comb drive structure to exert more force for the comb fingers to interlock with smaller gap space. The anchors help keep the comb drive structure firmly in place, due to larger electrostatic forces between capacitive plates with little distance apart.

4. Results

Minimizing the gap between comb fingers implies that less potential difference is needed to do the same amount of work. From equation 2.1, when gap space g decreases, the effective capacitance of the comb fingers increase as more charge is stored on the plates. Also, from equations 2.2 and 2.3, the forces exerted on the comb fingers are inversely proportional to the gap space, consequently less applied voltage is needed for comb finger displacement.

We analyze the effects of applying additional external voltages, ranging from 0 Volts to 25 Volts. Figure 4 below shows the exponential relationship between the electrostatic force acting vertically on the comb fingers as a result of gap reduction when external voltage is applied.

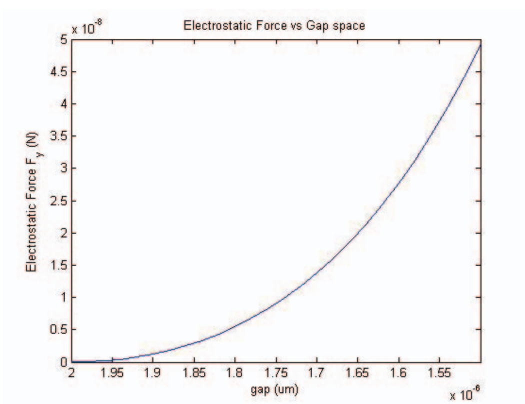

Figure 4. Graph illustrating exponential increase in electrostatic forces acting vertically on the comb fingers as gap space reduces

Furthermore, figure 5 shows the difference in electrostatic force per applied external voltage, for comb fingers fabricated with even smaller gap spaces. The figure compares the electrostatic force acting vertically between comb fingers fabricated for 2, 1.5 and 1 micron gap space. For comb drives fabricated with smaller gap space, little incremental voltage changes lead to substantial deflection of the comb fingers; so there is more displacement of comb fingers with less voltage.

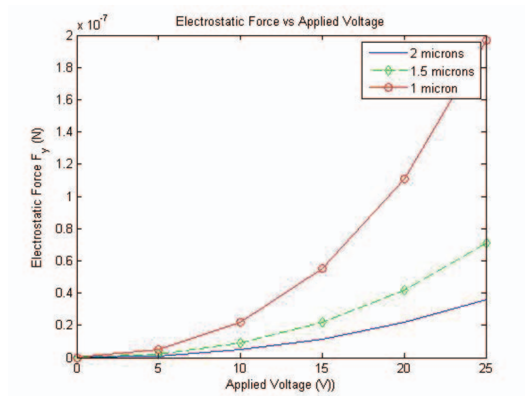

Figure 5: Electrostatic force versus applied voltage for different comb finger gap spaces: 2 microns, 1.5 microns and 1 micron, showing increasingly exponential relationship with smaller gap space.

Moreover, with reduced gap space, the comb drive is more sensitive to changes in capacitance, as seen in Figure 6 below. Changes in capacitance per unit gap space shows an exponential relationship as well, implying better sensitivity as higher capacitance readings result in improved signal to noise ratio of the device.

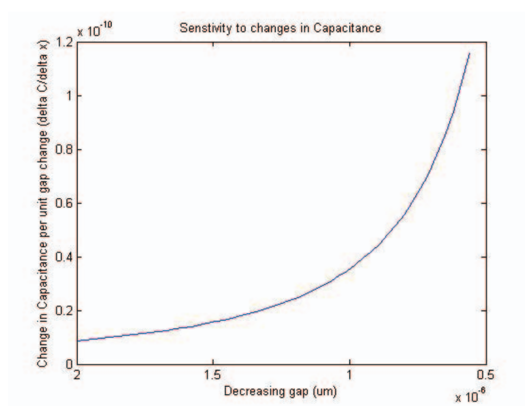

Figure 6. Increasing sensitivity to changes in capacitance with decreasing gap space.

The figures illustrated not only show the exponential increase in electrostatic force as the comb finger gap reduces, but also the increased sensitivity to capacitance changes.

5. Discussion

MEMS comb drives are frequently used for electrostatic capacitance sensing [5]. For comb fingers with reduced gap, the capacitance of the plates change by larger amounts as the structure is deflected. Having larger sensitivity to changes in capacitance will improve the device sensing. Moreover, undesirable stray capacitances known as parasitic capacitances often interfere with capacitance sensing [5]. If the magnitudes of the stray capacitances are greater that the nominal and dynamic capacitance of the device, it may cause errors in sensing [5]. Although the stray capacitances may be minimized by shielding and good layout practices, the parasitic capacitances may limit the charging and discharging of the comb finger plates and affect the sensing. Thus, it is beneficial to have reduced gap space between comb fingers as this gives larger capacitance readouts with smaller displacements, much higher than the noise from stray capacitances, to greatly improve accuracy in sensing. MEMS comb drives use capacitive sensing in measuring physical variables such as acceleration or pressure [5].

6. Conclusions

In this paper, we presented the use of comb drive instability due to smaller gap size between comb fingers to better improve the device accuracy in measurements. For capacitive sensing, the comb fingers with reduced gap have vertical electrostatic forces several orders of magnitude greater than that of comb fingers with 2 microns gap. The resulting increase in capacitance of the comb finger plates makes them more precise for capacitive sensing.

7. References

[1] J.V. Clark, "Electro Micro-Metrology," *PhD Dissertation, U.C. Berkeley*, Fall 2005, pg. 120.

[2] E.T. Carlen, K-H Heng, S. Bakshi, A. Pareek and C.H. Mastrangelo, "High Aspect Ratio Vertical Comb-Drive Actuator With Small Self-Aligned Finger Gaps", *Journal of MEMS*, Vol. 14, No. 5, October 2005, pg 1057

[3] I.P.F. Harouche, and C. Shafair, "Simulation of shaped comb drive as a stepped actuator for microtweezers application", *Sensors and Actuatos*, A 123-124 (2005), pg 540-546

[4] M. Naraghi, and I. Chasiotis, "Optimization of Comb-Driven Devices for Mechanical Testing of Polymeric Nanofibers Subjected to Large Deformations", *Journal of MEMS*, Vol. 18, No.5, October 2009, pg 1057

[5] Allen, James J., "Micro electro mechanical system design" 1st ed. 2005, CRC Press, ISBN 0-8247-5824-2, pg 273-293