Optimizing the Performance of MEMS Electrostatic Comb Drive Actuator with Different Flexure Springs

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Abstract: A new design of electrostatic comb drive actuator is presented in this paper by using different spring designs and with different folded beam lengths. An increased displacement of lateral comb drive actuator will subsequently be accomplished with the same actuation voltage. Stress distribution over different spring designs are simulated by COMSOL 3.5a using a standard comb drive with 4 movable comb fingers and device displacement could reach up to maximum of 2.85µm at a constant driving voltage of 130V. With increase in flexure length from 220µm to 280µm, displacement and capacitance increases from 1.063µm to 2.85µm and 327pf to 352pf respectively at 130V.

Keywords: MEMS, Electrostatic Comb Actuators, Spring Designs, Large displacement, Low actuation voltage, COMSOL 3.5a.

1. Introduction

Comb drive actuator is one of the most common electrostatic actuator used in MEMS applications. It uses both electrostatic energy from a DC voltage applied between the moving & fixed comb drive structures, and the mechanical restoring force provided by the spring structure [1]. Comb drive actuators have been used as resonators, electromechanical filters, optical shutters, micro grippers and voltmeters. These have also been used as the driving element in vibromotors and micromechanical gears [2]. It is desirable in comb drive to achieve large displacements at low actuation voltages. The well known electrostatic micro-actuators include side drive silicon micro-motor, wobble micro-motor, comb drive micro-actuator and out of plane diaphragm micro-actuator [3].

Comb Drive actuators consist of two interdigitated finger structures, where one comb is fixed and the other is connected to a compliant suspension. The driving voltage between the comb structures causes the displacement of the movable fingers towards the fixed fingers by an attractive electrostatic force. The position of the movable finger structure is controlled by a balance between the electrostatic force and the mechanical restoring force of the compliant suspension. Mechanical forces are generated through spring structures. So besides electrostatic forces, mechanical forces also play a very important role. Mechanical forces are directly depending upon the stiffness of the flexures. By changing these flexures, mechanical forces also changes. It is very important to find the flexure compatibility for large deflections at low actuation voltage. In the present work, different flexures of electrostatic comb drives are simulated for large displacements.

2. Designing of Actuator with Different Flexure Springs

A typical Comb-Drive considered in this study is shown in Figure 1. It consists of movable and fixed combs. The fixed comb is anchored to the base and movable plate is supported by a spring through a shuttle mass plate. Different types of spring designs have been applied in comb-drive actuators. Simulation for different 2D structures is done by using COMSOL 3.5a as it provides advanced methods of solving moving boundaries with FEM.
The basic structure consists of 5 fixed and 4 movable combs attached to different flexure spring having 7µm distance between the comb fingers.

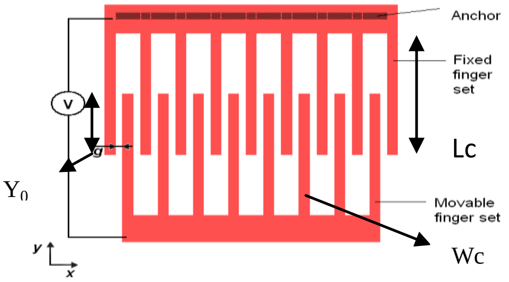

Figure 1. Comb Drive Actuator

The capacitance of comb drive is [1]:

$$C = \frac{2n\varepsilon_0 t(y_0 + y)}{g} \quad (1)$$

where, t is the thickness of comb finger, y_0 is the initial overlap, y is the comb displacement and g is the gap spacing between movable and fixed combs. The design parameters of comb drive are shown as Table.1.

Table 1. Specifications for designing of comb actuator

Dimensions of Actuator	
1) Comb length (Lc)	30µm
2) Comb Width (Wc)	3µm
3) Gap between moving comb and fixed combs (g)	7µm
4) Overlapping area (y0)	20µm
5) Spring length(Ls)	280µm
6) Spring width (Ws)	2µm
7) Gap between spring legs (Lg)	19µm
8) Thickness of Actuator (t)	2µm
9) No. of Moving combs (n)	4

The lateral electrostatic force (Fel) in y direction [4]can be expressed as:

$$\text{Fel} = \frac{1}{2}\frac{\partial C}{\partial y}V^2 = \frac{n\varepsilon_0 t}{g}V^2 \qquad (2)$$

Where, V is the applied voltage between the movable and fixed combs. The displacement, y (along the y-axis), of the movable plate as a function of applied force is:

$$y = \text{Fel} / K \qquad (3)$$

$$y = \frac{n\varepsilon_0 t V^2}{Kg} \qquad (4)$$

where y is the displacement, covered by the movable comb finger from its initial overlap position in positive y-direction when an electrostatic field, Fel is applied on it and K is the mechanical stiffness of the flexure spring. The suspension spring (beam or cantilever) must be flexible enough in the direction of the actuation. Increasing the beam stiffness will require large electrostatic force to cause the deflection and consequently require higher driving voltages. A general formula for calculating the stiffness [4] is:

$$K = 2Et[\frac{W}{L}]^3 \qquad (5)$$

Where: E is the Young Modulus for Polysilicon, W is the width and L is the length of cantilever. For choosing a suspension there are usually four main characteristics to watch: the spring constant, the compliance in the other directions (it needs to be low to keep the motion in the desired direction), the tolerance to internal stress (long beam may buckle during fabrication) and its linearity during large deformation. In this section the following spring designs will be discussed; clamped– clamped beams, a crab-leg flexure and the folded-beam flexure. The basic material used for the design is Polysilicon. Table 2 shows the properties of Polysilicon which are used for the design.

Table 2. Properties of Polysilicon.

Properties of Polysilicon	
Property	Parameters
Young’s Modulus	$160e^9$[Pa]
Poission’s Ratio	0.22
Density	2320[kb/m^3]
Thermal Expansion	$2.6e^{-9}$[1/k]
Relative Permittivity	4.5

A. Fixed-Fixed Beam

It is also called Clamped – Clamped beam. An electrostatic comb drive using Fixed-Fixed flexure is shown in Figure 2. Fixed-Fixed flexure has a very stiff non-linear spring constants because of the extensional axial stress in the beam which produces non linear effects. Due to non linear effects, stiffness increases with increasing deflection. They also have a very high stiffness ratio. The axial displacement along the x-axis can be found directly from Hooke’s law and the lateral displacement along the y-axis is obtained from small deflection theory [2].

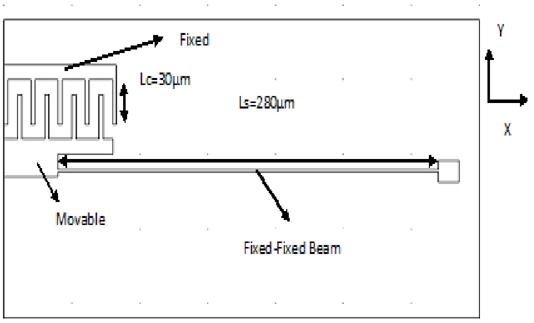

Figure 2. 2D model of Comb drive with clamped-clamped flexure beam and their specifications.

Due to electric potential electrostatic forces are produced in both X and Y directions. Figure 3 states that by applying voltage difference between the comb structures, movable comb is moved towards the fixed comb by an attractive electrostatic force.

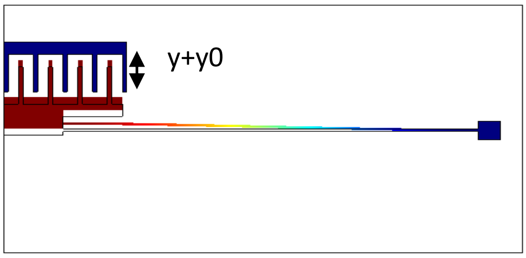

Figure 3. Change in overlapping area of comb fingers i.e. (y0+y)

Displacement can be verified by equation 4 which shows that displacement (y) is directly proportional to the square of the driving voltage and other terms remains constant.

B. Crab Leg Flexure beam

A novel variation of the fixed-fixed flexure is the crab-leg flexure. This flexure is used to reduce the extensional axial forces. A sketch of a comb drive using crab-leg flexure is shown in Figure 4.

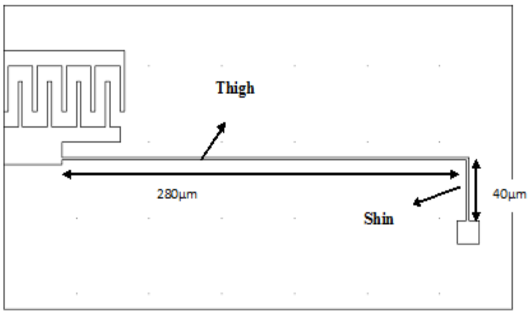

Figure 4. 2D model of Comb drive with crab leg flexure and their specifications.

In crab leg flexure thigh section is introduced to minimize the peak stresses in the flexure. This design has a shin length of 40µm and thigh dimensions equal to our previous clamped-clamped beam example that is 280µm, has a stiffness ratio that is already several orders of magnitude smaller.

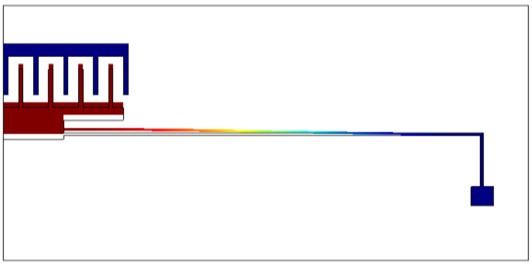

Figure 5. Displacement in 2D model at 200V

Because of thigh section this design gives large displacement at low driving voltage as compared to clamped-clamped beam. The drawback of this type of actuator is that it needs a high voltage to generate the large displacement and force. In order to reduce the actuating voltage, another design has been proposed.

C. Folded Flexure beam

Folded flexure is another design which offers a good compromise of linear behaviour to an extent in the desired y-direction and added stiffness in the undesired x-direction. The problems associated with the remaining stresses are also minimized because the trusses that connect the beams allow for the contraction and elongation while the beams are anchored at the centre. This suspension beam is flexible and particularly suitable for that process where there is a risk of buckling that means it will stand large internal stress, as those appearing during surface micromachining. It avoids lateral instability during actuation.

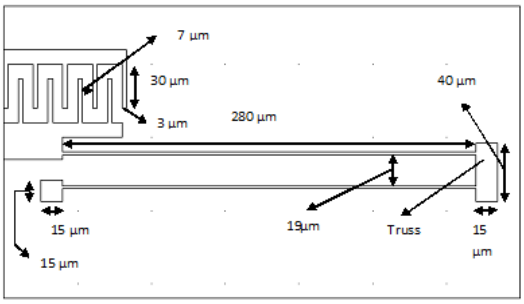

Figure 6. 2D model of comb drive using folded flexure and their specifications.

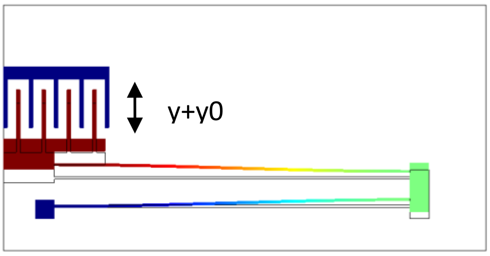

Figure 7 shows the change in overlapping area of comb fingers using folded flexure.

Using Polysilicon as the structural material the maximum actuation voltage, the total capacitance and displacement across the comb fingers, finger overlap between the comb fingers and the force across the combs of different flexure beams are shown in Table 3.

Table 3. FEM simulation results of different flexures

Parameters	Fixed-Fixed	Crab Leg	Folded Flexure
Voltage (V)	460	200	130
Displacement (µm)	5.9	4.0	2.85
Capacitance (pF)	417	372	352
Finger overlap (µm)	6	4	3
Force (N)	0.085	0.015	0.0056

3. Comparison among Fixed-Fixed, Crab Leg and Folded Flexure Beams

Low actuation voltage for large deflections is required to remove the pull in process and side (axial) instability. In support of this, it is necessary to find which flexure is more compatible for giving large deflections at low driving voltage.

Table 4. Comparison of different flexures at a constant voltage

Parameters	**Different Flexures**		
	Fixed-Fixed	Crab leg	Folded Flexure
Voltage (V)	130	130	130
Displacement (µm)	0.92	1.156	2.85
Force (N)	0.0050	0.0052	0.0056
Capacitance (pF)	326	328	352

Now at a constant voltage the variation of comb drive displacement, force and capacitance for different flexures is shown in Table 4.

In clamped-clamped flexure, only one cantilever beam is used. Its stiffness is very high and produces high extensional forces and because of extensional axial stress in the beam it gives non linear spring constant. This stiffness and peak stresses can be reduced by using a thigh section in crab leg flexure. Crab leg flexure gives linear characteristics for small deflections and not suitable for large deflections. Then Folded Flexure beam is introduced in which two cantilever beams are connected in parallel by using a truss. Each end of the flexure is free to expand or contract in all directions. It reduces the development of axial forces. It offers large linear deflection range. The stiffness ratio for small deflections is equal to the stiffness ratio of a clamped-clamped beam. This design is therefore very suitable for large deflection actuators. So in this study it is seen that folded flexure beam is best suitable for large deflections at low actuation voltage and this is shown in Figure 8.

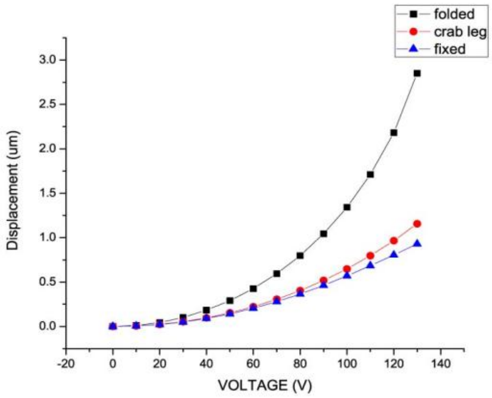

Figure 8. The variation of comb drives displacement for different flexures at low driving voltage.

4. Folded Flexure Length with Displacement

As the length of folded flexure spring (L) increase, its stiffness K decreases “(5)” and consequently displacement of the comb increases “(4)”. We analyzed our Comb Drive model at different flexure lengths for a given voltage 130V and found that as the flexure length increases, comb displacement increases as shown in Figure 9. Secondly, we also studied the effect of voltage on the comb displacement. A shown in “(4)”, increase in voltage increases the comb displacement. The results are shown in Figure 10. Table 5 shows the effect of folded flexure length with respect to the displacement, total capacitance and the force across the combs at a constant actuation voltage.

Table 5. Comparisons based on different Folded Flexure Lengths

Number of Moving Fingers	4 fingers		
Spring Length (Ls)	280	250	220
Voltage (V)	130	130	130
Displacement (µm)	2.85	1.704	1.063
Capacitance (pF)	352	336	327
Finger Overlap (µm)	3	2	1
Force (N)	0.0056	0.0052	0.0050

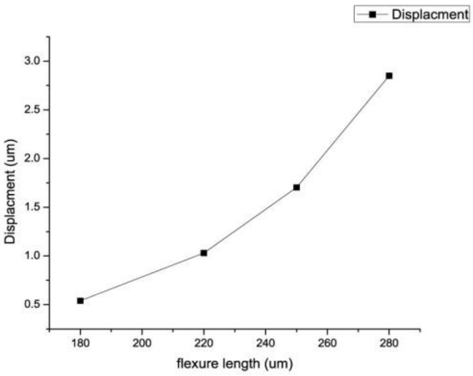

Figure 9. The variation of Comb Drive displacement versus Flexure length

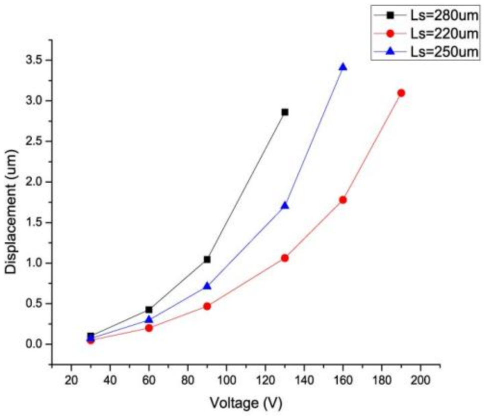

Figure 10. The variation of Comb Drive displacement versus the driving voltage for several folded flexure spring designs; all designs have a folded-beam width 2µm and beam thickness 2µm.

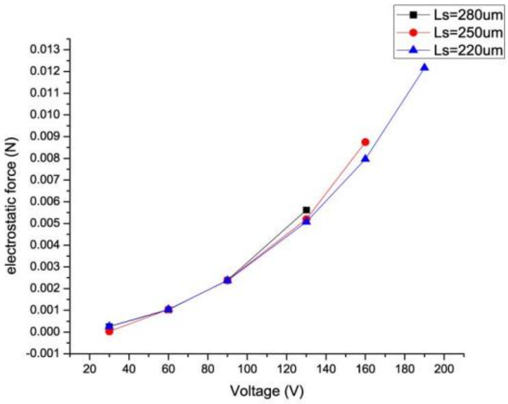

Figure 11. Electrostatic Force vs. Driving Voltage for different Folded-Flexure Lengths

5. Results

According to table 4 it is observed that folded flexure spring gives better results for large deflections at low driving voltages. It reduces the development of axial forces offers large linear deflection range. Stiffness reduces which increases the flexibility. It avoids lateral instability during actuation. Figure 9 demonstrates that higher flexure length shows better displacement and force across the combs at lower actuation voltage.

6. Conclusion

A Comb Drive actuator is a basic actuation device of MEMS. MEMS applications often require large force, large displacement, low-power, and energy-efficient actuators. In this work different spring designs of an electrostatic Comb-Drive are studied and its effects on actuation using Polysilicon which could be used as microtweezer. The spring stiffness in actuation direction is shown to decrease with the increase of the comb drive folded flexure length. Since the decrease in spring stiffness results an increase in comb drive displacement. Stiffness produces a direct relationship between the applied voltage and the displacement covered by the finger. From the results it can be concluded that folded flexure spring is a key factor for optimization of the Comb-Drive due to its low stress, low stiffness, high sensitivity and low spring constant.

7. Acknowledgment

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