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MEMS Electrostatic comb actuators with different configurations: A comparison of structure design and materials using COMSOL 3.5a

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Abstract

In this paper different electrostatic comb designs are compared on the basis of structure and materials. Large displacement comb actuators at low actuation voltage should employ large number of comb fingers, reduced distance between the combs and by increasing the width of the fingers. Silicon has been the dominant mechanical materials for MEMS fabrication. However, other materials such as glass, ceramics, polymers and metals are equally useful at this scale and they have also been used as structural materials with great success. COMSOL Multiphysics 3.5a is used for the designing purpose as it offers Finite element analysis to prove the concept of controlled displacement of the movable comb fingers, achieved by prescribing the amount of electrostatic force generated by the device.

Keywords: Electrostatic comb actuators, large displacement, Low actuation voltage, Comb fingers, MEMS, Finite element analysis.

I. Introduction

The micromachining technology that emerged in the late 1980's can provide micron sized sensors and actuators. . Such machines are called Micro-electro-mechanical systems which consist of both mechanical devices and electrical devices. Actuators are used for the transformation of non-mechanical input energy into mechanical output energy. There are many types of micro actuation mechanisms, most commonly used are piezoelectric, magnetic, thermal, SMA, electrochemical, electrostatic actuation[1,2] . Electrostatic actuation is one of the most common force generation schemes. The well known electrostatic micro-actuators include side-drive silicon micro-motor, wobble micro-motor, comb drive micro-actuator, out of plane diaphragm micro-actuator. Comb drive actuators are used for large displacement at low driving voltage and are used as resonators, electromechanical filters, optical shutters, micro- grippers [2, 3, 4].

In recent years, silicon and poly-silicon are the major structural materials as it is used in IC processing and it has excellent mechanical, electrical properties and can be further modified by doping but more structural materials need to be incorporated into MEMS devices. Materials such as polymers, glass, ceramics and metals are equally useful at this scale and they have also been used as structural materials with great success. The presented work discusses some of the structural and materials comparisons. Materials having smaller young's modulus than poly-silicon like polyimide and copper are considered for getting large displacement, low actuation voltage electrostatic comb actuators [2, 6, 7].

II. Designing of actuator based on different structures and materials

Capacitance based actuators have been extensively used in MEMS devices. A typical rectangular shaped comb drive design requires simple fabrication steps and it is characterized by low power consumption. Most commonly used comb drive actuators consist of interdigitated finger structure, where some comb fingers are fixed and the others are connected to complaint suspension. Applying a voltage difference between the comb structures will result in a deflection of the movable combs due to the developed electrostatic force which provides the actuation in the direction of the length of the comb fingers [4,7,8].

The basic structure consists of 5 fixed and 4 movable combs attached to folded flexure spring having 7µm distance between the comb fingers..

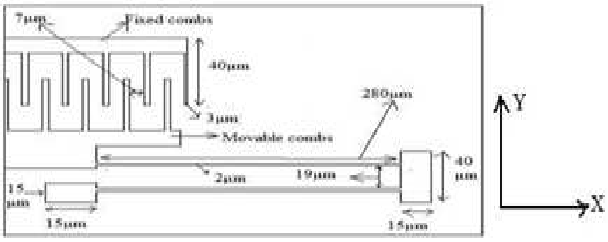

Figure.1 The actuators having 4 movable and 5 fixed comb fingers and their specifications.

The fixed fingers are grounded and the voltage is applied on the movable combs as shown in Figure.1.

The specifications used for the designs are shown in Table.1 for the comparisons the number of comb fingers and the distance between them are varied.

DIMENSIONS OF ACTUATORS	
GEOMETRY	VALUE
COMB LENGTH (l)	40µm
COMB WIDTH (w)	3µm
GAP BETWEEN MOVINGS & FIXED COMBS (d)	d µm
OVERLAPPING AREA (A)	20µm
SPRING LENGTH (k_1)	280µm
SPRING WIDTH (k_w)	2µm
GAP B/W SPRING LEGS (k_g)	19µm
THICKNESS OF ACTUATOR (t)	2µm
NO. OF MOVING COMBS	n

Table.1 shows the specifications used for designing of the comb actuator.

Applying voltage difference between the comb structures will result in a deflection of the movable comb structure by electrostatic forces which causes change in area between the combs i.e. (y + y□□) as shown in Figure.2, as the overlapping area changes, the capacitance between the fixed and movable combs changes.

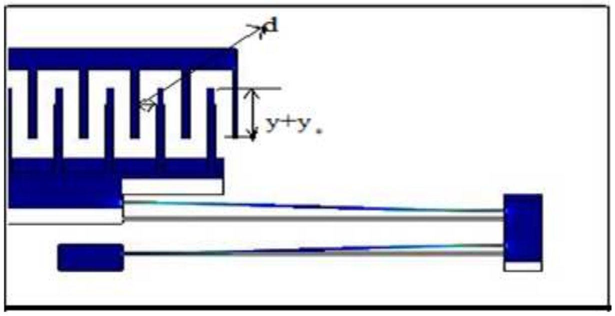

Figure.2 shows the change in overlapping area of comb fingers i.e (y + y□)

The change in capacitance can be expressed as:

$$C = \frac{2n\underset{\circ}{\varepsilon}h(y + \underset{\circ}{y})}{d} \qquad (1.1)$$

Where, *n* is the number of combs, ε□ is the dielectric constant in air, *h* is the height of the comb fingers, *y*□ is the initial comb finger overlap, *y* is the comb displacement and *d* is the gap spacing between the comb fingers. The lateral electrostatic force in the y-direction can be expressed as:

$$F_{el} = \frac{1}{2}\frac{\partial C}{\partial y}V^2 = \frac{n\underset{\circ}{\varepsilon}h}{d}V^2 \qquad (1.2)$$

Where, *V* is the applied voltage between the movable and fixed combs.

As shown in Eq.1.1 and 1.2 the number of combs and the thickness of combs are directly proportional to the electrostatic force so, if the number of combs is increased there is increase in capacitance as well as the electrostatic force. Large deflection comb drive actuators at low driving voltages should employ large number of comb fingers. If the distance between the comb fingers is decreased then also the electrostatic force and the capacitance between the fixed and movable combs gets increased [2,7,15].

The basic material used for the design is Polysilicon. Table.2 shows the properties of Polysilicon which are used for the design.

PROPERTIES OF POLYSILICON	
PROPERTY	EXPRESSION
YOUNG'S MODULUS	$160e^9$[Pa]
POISSION'S RATIO	0.22
DENSITY	2320[kg/m^3]
THERMAL EXPANSION	$2.6e^{-9}$[1/k]
RELATIVE PERMITTIVITY	4.5

Table.2 shows the properties of Polysilicon.

- Firstly, by decreasing 7µm spacing to 1µm spacing between the 4movable and 5 fixed combs as shown in figure. 3.
- By increasing the number of combs i.e 9 movable combs having 7µm distance between fixed and movable combs as shown in figure.4.
- Then by decreasing the distance 7µm to 1µm for 9 movable comb structures as shown in figure.5.

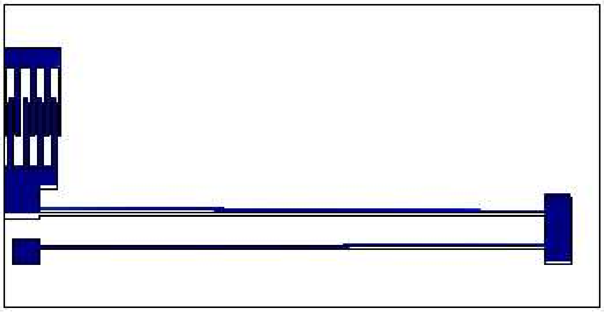

Figure.3 shows the design having 4 movable and 5 fixed comb fingers having 1µm spacing.

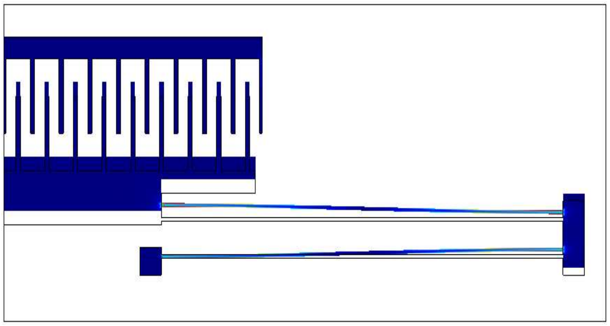

Figure.4 shows the design having 9movable and 10fixed comb fingers having 7µm spacing.

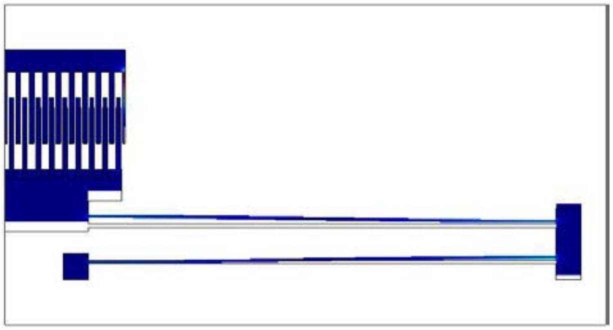

Figure.5 shows the design having 9 movable and 10 fixed comb actuator having 1µm spacing.

Using Polysilicon as the structural material[10,11] for different structural designs as shown in Figures 2,.3,4,5; the maximum actuation voltage, the total capacitance and displacement across the comb fingers and the force across the combs is compared which is shown in Table.3

POLYSILICON				
No. Moving fingers	4 fingers		9 fingers	
Gap b/w fingers	d=1µm	d =7 µm	d = 7µm	d =1µm
Max. Voltage (V)	80.1	700.1	201	80.1
Displacement (µm)	2.411	8.132	7.719	4.080
Capacitance $(cap * 10^{-3})$ (µF)	1.858	0.4402	0.8595	4.413
Force (µN)	0.399	1.7902	0.8043	1.019

Table.3 shows the maximum actuation voltage, displacement, total capacitance and the force across the combs when Polysilicon is the structural material.

On decreasing the distance between the fingers it is seen that the actuation voltage gets decreased and when the number of combs is increased, suitable deflection can be seen across the combs at lower actuation voltage.

For further comparisons polyimide and copper is considered as the structural material respectively. Polymers need to have suitable elastic moduli to support the deformation initiated by MEMS devices; excellent overall dimensional stability, long-term environmental stability, biocompatible and thus useful for many medical devices. It has excellent flexibility and resistance to weather, fungus, solvents, water and chemicals. The main requirements for structural polymer are mechanical stability and low material costs. The most well developed thermosetting polymers for structural use in micro systems are SU8 and Polyimide They both have excellent thermal and mechanical properties. Polyimide being a ductile material and having small elastic modulus which is 50 times smaller than Polysilicon it can tolerate large strains before fracture. For large displacement, low actuation voltage actuators polyimide is a useful material as it is light in weight, highly flexible, excellent thermal stability and resistant to heat and chemicals[5,10,11,12,14]. The properties used for designing are shown in Table.4 and further the comparisons are shown for different design structures using Figures. 2, 3, 4, 5 is shown in Table.5.

Properties of Polyimide	
Property	Expression
Young's Modulus	$3.1e^{9}$[Pa]
Poisson Ratio	0.35
Density	1300[kg/m^^{3}]
Thermal Expansion	$25*10^{-5}$[1/k]
Relative Permittivity	3.5

Table.4 shows the properties of polyimide used for designing.

POLYIMIDE				
No. Moving fingers	4 fingers		9 fingers	
Gap b/w fingers	d=1µm	d=7µm	d =7µm	d =1µm
Max. Voltage (V)	10.2	100	30.1	10.2
Displacement (µm)	2.188	8.105	8.7107	3.735
Capacitance $(cap * 10^{-3})$ (µF)	1.809	0.4395	0.8842	4.312
Force (µN)	0.005164	0.1808	0.176	0.0128

Table.5 shows the comparisons based on different design structures.

When polyimide is the structural material for the design, suitable deflection across the combs can be observed at lower actuation voltage if, the number of comb fingers are increased and the distance between the comb fingers is decreased.

Copper is amongst the metals which is conductive in nature and has smaller young's modulus in comparison to Polysilicon [10, 11, 16] as shown in Table.6. It is one of the materials which can be worked upon and can be used as functional material in the field of MEMS.

Properties of Copper	
Property	Expression
Young's Modulus	$120e^{9}$[Pa]
Poisson Ratio	0.36
Density	8960[kg/m^^{3}]
Thermal Expansion	16.5*10^{-6}[1/k]
Relative Permittivity	1.5

Table.6 shows the properties of Copper.

Using copper as functional material and comparing different design structures as shown in Table.7, it is observed that the maximum voltage gets decreased as the number of combs is increased and the distance between them is decreased.

COPPER				
No. Moving fingers	4 fingers		9 fingers	
Gap b/w fingers	d=1µm	d=7µm	d=7µm	d=1µm
Max. Voltage (V)	69.1V	741V	210.8	70.1
Displacement (µm)	2.4013	11.683	11.176	4.119
Capacitance $(cap * 10^{-3})$ (µF)	1.864	0.4881	0.9507	4.274
Force (µN)	0.28907	2.0844	0.8880	0.860

Table.7 Comparisons based on different structural designs.

III. Results

According to the comparisons shown above it is observed that polyimide having smaller young's modulus in comparison to copper and Polysilicon shows better displacement and force across the combs at lower actuation voltage. Further the comparisons show that on increasing the number of combs and decreasing the distance between them also shows better output at lower actuation voltage.

IV. Conclusion

Low power consumption is is highly desirable not only for economic reasons, but also for heat generation considerations. Large deflection comb actuators at low driving voltage should employ structures with large amount of comb fingers and minimum distance between the comb fingers. This designed structure can be mainly used as a microtweezer actuator for application in areas such as biological sample handling. Polysilicon is an attractive material for high strength applications. For MEMS, materials like metals, polymers, and ceramics can provide the opportunity to create flexible MEMS structures. Microscale actuators can also make use of the low modulus of the structural materials like aluminium, polymers etc. Low actuation voltage, large displacement, high speed is highly desirable for MEMS applications so, lot of work can be done in context to these factors by working upon structural parameters or material parameters. In spite of the great benefits of using commonly used material such as silicon, it is not always true that they are the best choice for structural applications in micro-systems.

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