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Simulation of Curl Compensation in MEMS Micromirror

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Abstract. This paper reports a design to compensate overlapping area reduction in MEMS Micromirror. The electromechanical behavior of a 300x300 μm mirror actuated by electrostatic comb drive is simulated by CoventorWare^{TM}. The interdigitated fingers are 240 μm long and 20 μm wide separated by 20 μm gap. The displacement of the mirror is compared when the frame of stator is released and fixed. The simulation shows that released-frame stator produces more displacement in z direction than fixed-frame stator by the factor of 3 when 50V DC voltage is applied. The improvement in micromirror actuation is as a result of the increase of overlapping area provided by curl compensation with released-frame approach. Therefore, the released-frame design is a promising method to reduce input voltage and enhance efficiency of electrostatic comb drive micromirror.

1. Introduction

Interdigitated comb drive has been widely used for electrostatic actuation, capacitive position sensing and frequency tuning. They have become an integral part of many MEMS devices. Micromirror is an application that uses the comb drive to actuate the movement. The moving part is rotor and fixed part is stator. Most of micromirrors are made of thin-film materials. It is well known that it is difficult to achieve large flat thin-film mirrors with large tilt range due to the residual stress in the thin-film structure. Residual stress is a tension or compression which exists in the bulk of a material with no an external load applied. Unlike the lateral comb drives, the stator and rotor comb fingers of the comb drive do not lie in the same plane due to residual stress, and therefore large electrically actuated out-of-plane displacement is achieved. Out-of-plane comb finger actuation and sensing in vertical mechanism has been implemented in a 3-axis microstage and a lateral-axis vibratory gyroscope [4].

The main problem of out-of-plane curling of comb drive is that the overlapping area between fingers is reduced and hence higher applied voltage will be required to produce necessary displacement. Out-of-plane curling associated with the composite structural layer can be compensated to the first order through a curl matching technique [1]. In another approach, out of plane motion is compensated by a comb drive design with vertical angled offset of the comb fingers [2]. Moreover, a novel large vertical-displacement electrothermal-actuation mechanism has been proposed to maximize overlapping between curling finger [3]. The new design realizes the uneven stator and rotor comb fingers by using the curling of multilayer thin-film beams was also reported [5].

In this work, released-frame stator is designed to reduce the curling effect due to residual stress. To study the movement of mirror, commercial simulation program, CoventorWare^{TM}, is used to emulate the characteristics of the device when the voltage is applied.

2. Micromirror Design

The 300x300 μm square-shaped mirror described in this paper is fabricated by Multi-Users MEMS Process (MUMPS$^{®}$). The multi-layer stacks of 3.5 μm-thick mirror and associated comb drive are fabricated by POLY1 and POLY2 stacking layers. The interdigitated fingers are 240 μm long and 20 μm wide separated by 20 μm gap. There are 5 fingers on each side of rotor and 6 fingers on each stator. Figure 1 shows the 2D layout of the micromirror. The residual stress and stress gradients of polysilicon thin-film cause fingers to curl out of plane.

In normal design, rotor fingers and stator fingers will curl in opposing directions as shown in figure 2(a). The proposed curl compensation technique is to release frame of the stator and fix the two ends of frame as shown in figure 2(b). It takes advantage of good matching to increase overlapping area.

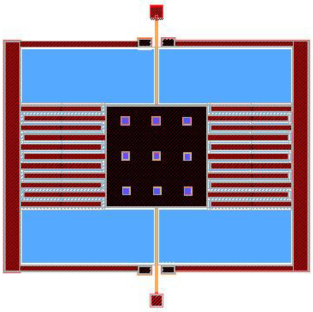


Figure 1. The 2D layout of the micromirror.

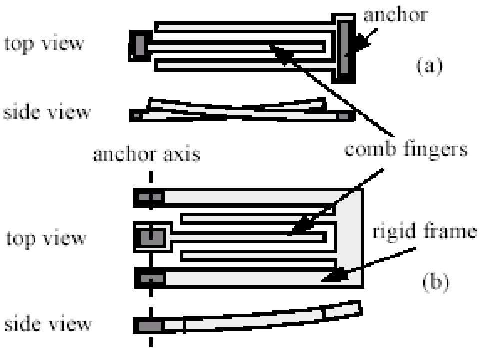
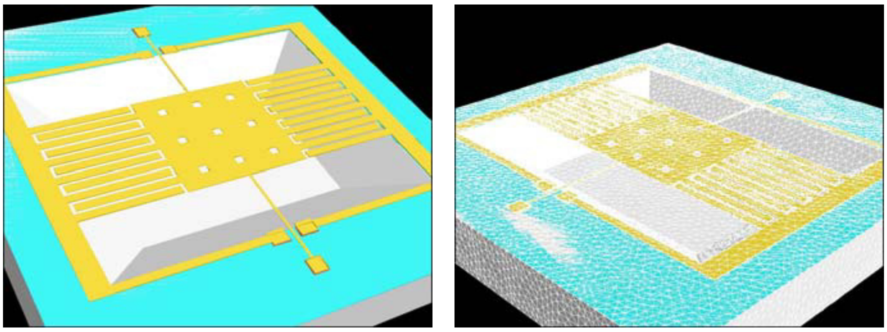


Figure 2. (a) fixed-frame stator (b) released-frame stator [1].

CoventorWare^{TM}, commercially available finite element analysis software, is used to simulate the device to find the relationship of displacement and input voltage. From the layout, three dimensional model is generated as shown in figure 3(a). There are three polysilicon layers in the simulation, POLY0, POLY1 and POLY2. The nitride and oxide layer is neglected. Material properties of MUMPS layers that were used to fabricate our micromirror (run#58) are partly provided by memscap [6], which is shown in table 1.



(a) (b)

Figure 3. The 3-D model of Micromirror before and after meshing.

Table 1. Material properties of MUMPS run 58 [6]

Film	Thickness (A)	Standard Deviation (A)	Sheet Resistance (Ohm/sq)	Resistivity (Ohm-cm)	Stress (MPa)
Nitride	6,000	261			119, Tensile
Poly0	5,104	48	29.30	1.50×10^{-3}	34, Compressive
Oxide1	20,174	593			
Poly1	19,845	220	13.56	2.69×10^{-3}	13, Compressive
Oxide2	7,440	242			
Poly2	15,083	203	23.35	3.52×10^{-3}	18, Compressive
Metal	5490		0.05	2.80×10^{-6}	33, Tensile

Then tetrahedron mesh is applied with element size of 10 µm. The structure after meshing is shown in figure 3(b). The speed and quality of simulation depend on type of mesh and size. If finer mesh is applied, it would take unacceptably longer time for calculation.

3. Mathematical formulation

In order to estimate the performance of the curled comb drive, the electrostatic force must be calculated. The electrostatic force in the z-direction, F_{ez}, is given by [5]

$$F_{ez} = \frac{1}{2} N_g \left(\frac{dC}{dz} \right)_z V^2 \tag{1}$$

where C is the sidewall capacitance per comb finger, N_g is the number of comb-finger gaps and V is the applied voltage. Assuming forces with the same magnitudes but in opposite direction on each end of the mirror (which will not be the case for the metal layers with different thickness), the resulting moment of the mirror, M_e, about its support beam is

$$M_e = 2F_{ez} \left(\frac{a}{2} \right) = F_{ez} a \tag{2}$$

where a is the length of the mirror side that is normal to the axis of rotation. The elastic recovery torque, M_r , of the torsion beams (with width w, length l, and thickness t) is found from

$$M_r = k_\theta \theta = \left(\frac{2\beta G w t^3}{3l} \right) \theta \tag{3}$$

where k_θ denotes the torsional spring constant of the torsion support beams, β the correction factor, θ the mechanical deflection angle, and G the shear modulus of elasticity in N/m^2. Applying force balance concept, the voltage required for angular displacement of θ is

$$V(\theta) = \left(\frac{\theta_{rad} k_\theta}{\frac{1}{2} N_g a \left(\frac{dC}{dz} \right)_{\frac{1}{2} a \sin\theta}} \right)^{\frac{1}{2}} \tag{4}$$

4. Simulation Results

The simulated displacements of fixed-frame and released-frame stator designs are shown in table 2. It can be seen that the released-frame stator produces more displacements in y and z direction than that of fixed-frame stator when 50 V (DC) voltage is applied.

Table 2. Displacements in x, y and z axis when 50V (DC) voltage is applied.

	Maximum Displacement (micrometers)		
	x-axis	y-axis	z-axis
Fixed-frame stator	2.260×10^{-2}	7.364×10^{-3}	-6.452×10^{-3}
Released-frame stator	2.260×10^{-2}	1.616×10^{-2}	-1.965×10^{-2}

The displacement in x-direction of the fixed-frame stator and released-frame stator are the same (~0.02 μm) because the force is approximately balanced in x direction. The z-axis displacement of curl compensated released-frame structure is approximately higher than that of fixed-frame by the factor of 3. This is because released-frame structure can produce more force in z-direction according to equation (1). The displacement characteristics of fixed-frame and released-frame structures are simulated as a function of applied voltage from 0 to 80 V as shown in figure 4. The displacement is calculated at an end of comb drive finger where deflection is at maximum. It can be seen that the magnitude of displacement in z-direction increases exponentially as a function of applied voltage for both fixed and released frame comb drive structures. In addition, the displacement begins to increase rapidly at a threshold voltage above 20V and 40V for released-frame and fixed-frame stators respectively. However, the displacement in x-direction increases slowly at a function of an applied voltage. Furthermore, the x-axis displacements of fixed-frame and released-frame stators are nearly identical except at low voltage. Therefore, released-frame stator produces more movement in the desired z-direction than fixed-frame stator but it does not generate additional movement in x-direction.

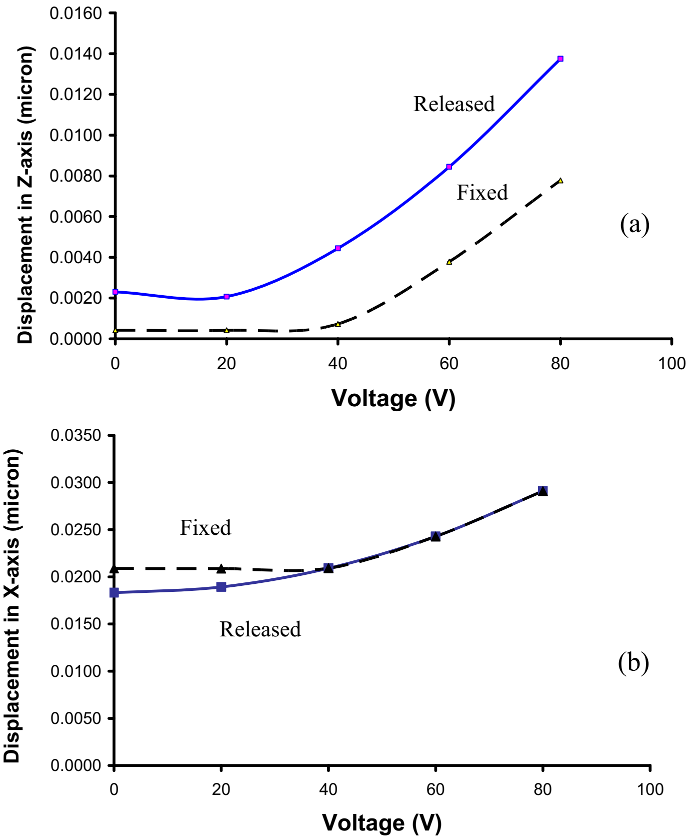


Figure 4. Displacement in (a) Z-axis and (b) X-axis versus applied voltage of electrostatic comb drive.

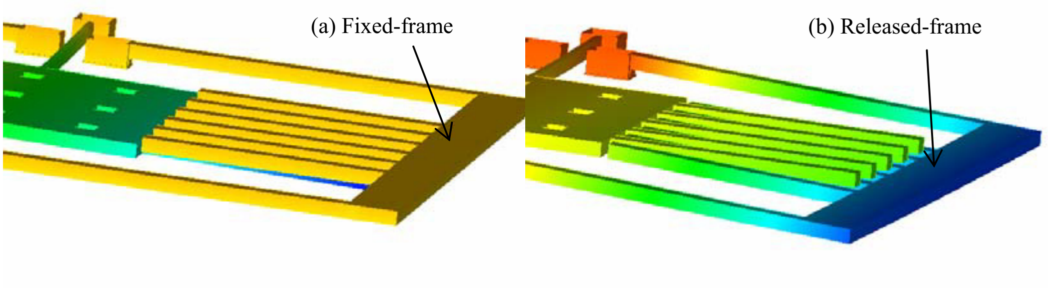


Figure 5. Simulated structures of (a) fixed and (b) released-frame stator.

The 3D simulated structures of fixed and released-frame stator are illustrated in figure 5. From the figure 5(a), it can be seen that the mirror is bending downward while the stator is planar because it is anchored to the substrate. On the other hand, both rotor and stator are curling downward due to compressive residual stress in polysilicon layers in figure 5(b). In addition, it can be inferred that the released-frame structure can create more movement than the fixed-frame stator because of larger overlapping area. The overall operation of the micromirror with released-frame design is demonstrated in figure 6. In this illustration, the mirror is slightly turning to the right because of positive electric field is applied on the right stator.

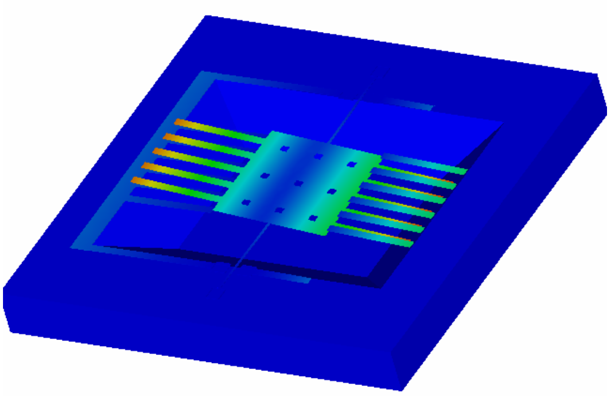


Figure 6. The overall operation of the micromirror with released-frame design.

5. Conclusion

The electromechanical behaviour of a 300x300 μm mirror actuated by fixed-frame and released-frame electrostatic comb drive is simulated by CoventorWare. It was found that released-frame stator produces more displacement in y and z direction than fixed-frame stator by the factor of 3 when 50V DC voltage is applied. The improvement in micromirror actuation is as a result of the increase of overlapping area provided by curl compensation with released-frame approach. Therefore, the released frame design is a promising method to reduce input voltage and enhance efficiency of electrostatic comb drive micromirror. Furthermore, this technique can be generally applied for other MEMS applications such as optical switch, accelerometer and gyroscope to enhance efficiency of the devices.

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