The Design and Simulation of a Novel Out-of-plane Micro Electrostatic Actuator

C. Tsou, S. L. Huang, T. S. Lai, and H. C. Li

Feng Chia University, Taichung, Taiwan, cftsou@fcu.edu.tw

ABSTRACT

This paper presents a mechanism of developing a novel out-of-plane micro electrostatic actuator that capable achieves a large out-of-plane deflection. The performance of the actuator is evaluated and simulated by MEMCAD software. Analysis results indicate the design of using the novel U-shape suspension beam and electrostatic actuation mechanism permit a large rotations motion by way of increasing the electrode numbers. Moreover, stable rotational motion can be achieved by varying the dimensions of electrode and gap spacing. This design advantage brings the possibility of developing other 3-D structures for on and out-of-wafer applications such as optical switch or display.

Keyword: out-of-plane, actuator, optical switch, MEMS

1 INTRODUCTION

MEMS technology based to fabricate microsensors and microactuators on silicon wafer has advanced rapidly development rapidly over the past decade and can be used to interact with environment. In many applications, micro actuators can perform useful work in consonance with the environment conformable to a command or a control signal. For example, electrostatic optical microswitch can be used for fiber telecommunication applications. In addition, scanning micromirrors of commercialized has been used for projection display or digital signal process [1,2].

Recently, numerous techniques has been explored to develop out-of-plane microactuators with a large displacement or large rotation angle such as: 1) the employment of thermal effect on a single-layer or multi-layer suspension beam [3,4]; 2) the usage of magnetic force generated by coils via around the ferromagnetic [5,6]; 3) the utilized of electrostatic vertical comb drive actuator [7]. Typical, each type of actuation mechanism has its advantages and disadvantages. Specifically, electrostatic actuators are extremely low power and have fast response times, but have lower output force. In the applications of those microactuators, one of the most important actuators is perhaps in the area of free-space optics with micromirror; after all, it does not take much force to bend a beam of light. Therefore, the free-space optic devices fabricated using IC fabrication methods can readily take advantage of electrostatic actuation. However, the electrostatic actuation, which is widely used in MEMS actuators, can't always match the desired range of force and displacement simultaneously under the constraints of practical micro systems. Consequently, the development and the implementation of electrostatic micro actuator capable of actuating a large out-of-plane deformation or a rotation angle in MEMS still pose many challenges.

In order to achieve large out-of-plane rotation angle, a novel out-of-plane micro electrostatic actuator was designed and simulated in this work. The diagram of this proposed actuation mechanism is shown in Fig. 1. When an opposite couple force (or distribution force) with equivalent magnitude applied on the post individually as shown in Fig. 1(a), the suspension beam will be deformed and it will become bending upward as shown in Fig. 1(b). According to the schematics shown in Fig. 1, an actuation method can be realized by way of the attraction force between the charged bodies to bend the nonconductive suspension beam of which it can be fabricated using microfabrication processes. Therefore, with an appropriate dimension design and the fabrication of MEMS techniques, our proposed micro actuator can provide a large out-of-plane deflection and it is suitable for driving rotary free-space optic devices in the future.

2 DESIGN CONCEPT AND ANALYSIS

The design concept and schematic structure of proposed micro actuator is illustrated in Fig. 2. This novel microactuator comprises two metal electrodes, U-shape torsional beam with isolation property, and a suspension flat. In this design, the actuation mechanism is made active through a high-aspect-ratio parallel-electrode and U-shape torsional beam of which this beam is fixed in part to the substrate and from which this beam gives rise to flexures to

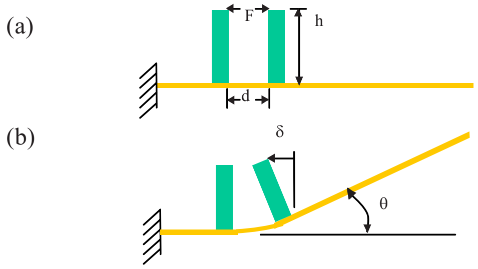


Figure 1: The diagram of the novel actuation mechanism.

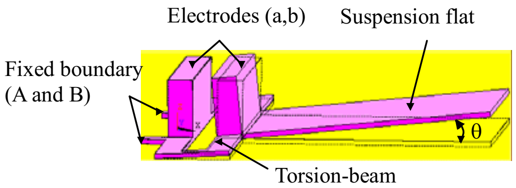


Figure 2: Schematic structure of the proposed out-of-plane electrostatic actuator.

provide torsional rigidity. Utilizing coulombic attraction force between pair electrodes to exert force when the voltage is applied on them, this suspension flat can rotate an angle θ in an out-of-plane direction since the U-shape torsion-beam is twistedly deformed by electrostatic force. When the electrostatic force raised is equal to the torsion stiffness of U-shape torsional beam, an equilibrium position of the suspension flat can be attained at the given voltage. Consequently, by varying the dimensions of electrode and the geometry of U-shape torsional beam, the characteristics and the performance of the electrostatic actuator can be predicted and applied on microsystem.

Fig. 3 shows a schematic view of the microactuator, which includes two electrodes, U-shape torsion-beam, and the needed parameters for analysis. In order to conveniently model the electrostatic torque, Fig. 3 can be simplified and presented as Fig. 4, where T_e is the torque produced by electrostatic force, $L_e(=2L)$ is the equivalent length of torsional beam, and boundaries A and B are the fixed areas. In addition, assuming electrode is undeformed. Therefore, with the electrostatic force being equal to the torsion stiffness of U-shape torsional beam, the relationship between voltage V and torsion angle θ is given by Eq. (1) [8],

$$V = \left\{ \frac{\dfrac{2Ewt^3\theta^2}{L_e\varepsilon X(1+\nu)}\left[\dfrac{1}{3}-0.21\dfrac{w}{t}\left(1-\dfrac{w^4}{12t^4}\right)\right]\theta}{\dfrac{h\theta}{d-h\theta}+\ln\left(1-\dfrac{h\theta}{d}\right)} \right\} \tag{1}$$

where E is the elastic modulus, υ is Poisson's ratio , and ε is the dielectric constant of free space. As illustrated in both Fig. 3 and the equation just mentioned above, one can vary design parameters such as L, t, w, h, X, and d to obtain the relationship of the rotate angle θ of micro actuator with respect to the applied voltage V. As a result, a reasonable structural scheme can therefore be designed and acquired.

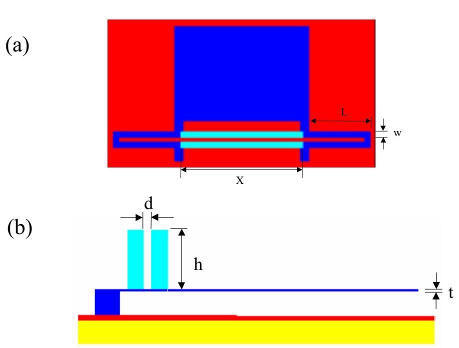


Figure 3: Schematics of the (a) top (b) lateral view of the micro actuator with dimensional parameters.

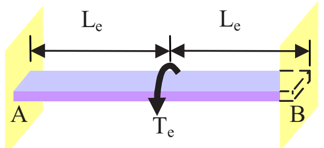


Figure 4: A simplified schematic representation of micro actuator.

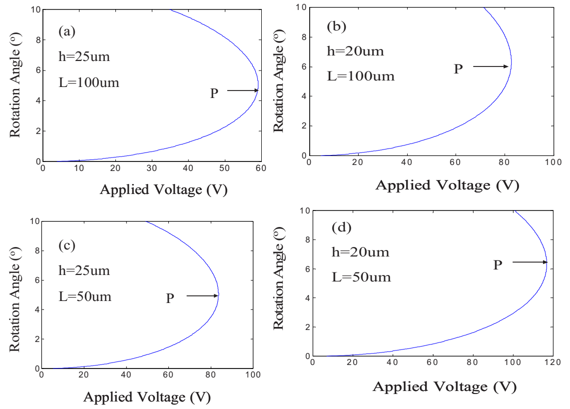


Figure 5: Variation of the rotation angle of the micro actuator versus with applied voltage.

Assuming the material of U-shape torsional-beam is manufactured by using thermal oxidation growth and its material properties of elastic modulus (E) is 72 GPa and its Poisson's ratio (υ) is 0.17. Also, the critical dimensions of the electroplating metal electrode and torsional beam of the proposed electrostatic actuator are as follows, X=200 μm, h=20 and 25 μm, L_e=100 and 200 μm, w=10 μm, t=1 μm, and gap d=5 μm. Based on the equation (1), the results of analysis regarding the tilt angle θ and various applied voltage V are shown in Fig. 5. As indicated in Fig. 5 (a)~(d), due to the fact that the voltage at which the restoring spring force of torsion-beam can no longer balance the attractive electrostatic force, the pull-in instability will occur at p point. Thus, before the pull-in position of p point, with the increase of applied voltage, the maximum actuation angle for all cases is approximately in the range of 4~6 degree. Besides, the normalized pull-in position of 0.44 was obtained from our novel designed microactuator with difference gap spacing.

According to the results of the analysis described above, one approach to increasing the actuation angle is to increase the gap spacing d or to reduce the electrode height h. However, higher operation voltage is required for both scenarios. A second approach is to increase the gap spacing d and electrode height h simultaneously, but, unfortunately, it becomes even more difficult to manufacture high-aspect-ratio metal electrode using microfabrication. Thus, in order to attain a large rotation angle at a reasonably low applied voltage, one most advantageous solution to this problem is to connect multi-electrodes to achieve large rotation angle. For details of this approach, it will be discussed in the following section of MEMCAD simulation.

Additionally, the deformation configuration of Fig. 1

indicates that the tilt angle θ is approximately equal to $Sin(\delta/h)$. However, gap-closing actuators are limited to either small motion or to bistable optional because large motion can lead to “pull-in” instability in which the actuator snaps are closed. The analytical results obtained from Fig. 5 indicated that the maximum operation tilt angle before pull-in instability is equal to $Sin(0.44d/h)$. To enhance the operation function of our designed microactuator, an isolation layer such as SiO_2 or SiN_3 was deposited on electrodes not only to prevent the short circuit but also to be used as a stopper when pull-in is taking place, thus further obtaining a more operational tilt angle being equal to $Sin(d/h)$.

3 SIMULATION AND DISCUSSION

The theories used in this paper with respect to the equation mentioned above have not considered the following two effects: 1) fringing effect of electrostatic fields, 2) the bending deformation and the displacement of U-shape torsional beam. To verify the simplified approach we suggested in terms of actuator design as proposed and outlined in Fig. 4, we compare the outcomes from the mathematical calculations with respect to the results obtained from both analytical calculations and MEMCAD simulations using typical design parameters and material properties. By comparing MEMCAD simulation results to the analytical results, the material properties are the same for both cases, and the dimensions of the micro actuator model are X=200 μm, h= 25μm, L=100 μm, w=10 μm, t=1 μm, and gap d=5 μm. The simulation results are shown in Fig. 6. First, the graphical view of 3-D and lateral deformation of our proposed actuator is shown in Fig. 6(a) after its being applied with a voltage of 65 V. Second, the relationship between different applied voltage and its corresponding rotation angle θ is shown in Fig. 6(b). As shown in Fig. 6(a), this actuator can provide an out-of-plane deflection and can be used to raise the attached flat to achieve rotating an angle. Further, as indicated in Fig. 6(b), the pull-in voltage is approximately 65 V, and the rotation angle is increased with the increment of various applied voltage.

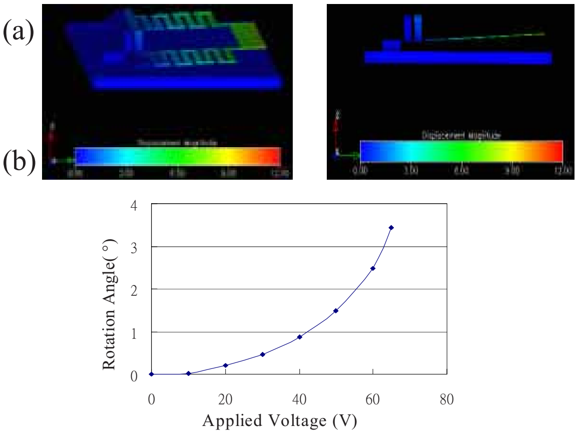


Figure 6: (a) The 3-D and side view of the deformation with an applied voltage at 65V. (b) the variation of the rotation angle versus with applied voltage.

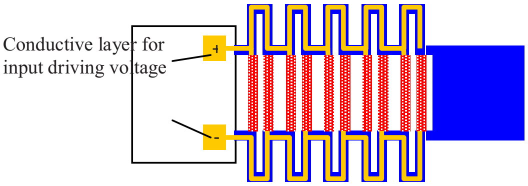


Figure 7: Schematic top view of the arrangement of the multi-electrodes.

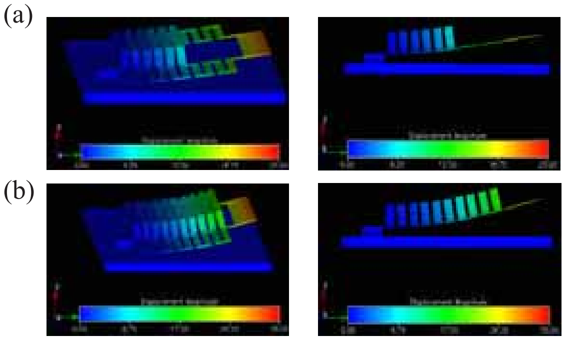


Figure 8: Typical simulated deformation of the micro actuator for the number of (a) six and (b) ten electrodes respectively.

By comparing the results presented in Fig. 5(a) and Fig. 6(b), it can be seen that the rotation angle from the simulation results is slightly different from those of the calculated ones. It is to be believed that the difference mainly originates from the torsional beam of which it produces both in-plane and out-of-plane motion to reduce the gap spacing d when activated by electrostatic force. Consequently, according to the equation of $\theta_p \approx Sin(0.44d/h)$, the decreasing of gap spacing will reduce the amplitude of maxima tilt angle. Hence, the pull-in voltage of MEMCAD simulation is less than that obtained from Eq. 1.

In this study, the major design targets are to obtain a large out-of-plane deformation or rotation angle. Based on the simulation process mentioned above, these targets can

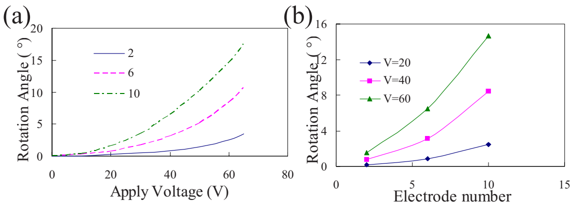
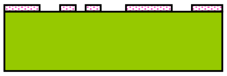
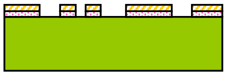


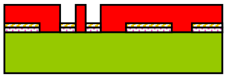
Figure 9: Typical simulated rotation angle of the micro actuator for varying electrode numbers and applied voltage.



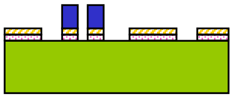
(a) Deposited Si3N4 and then patterned



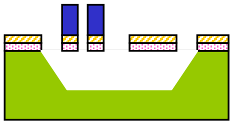
(b) Sputtered Cr-Au and then patterned



(c) A thick PR is deposited and patterned



(d)Electroplating Ni and then removes PR



(e) Silicon anisotropic wet etching

Figure 10: The proposed fabrication process for fabricating the novel microactuator.

be achieved by increasing the numbers of electrode. The arrangement of electrodes and the layout of the conducting layer to each electrode for applying voltage are shown in Fig. 7. To be specific, Fig. 8 exhibits the view of 3-D plus the lateral deformation of actuator using the number of six (three-pairs) and ten (five-pairs) electrodes with an applied voltage of 65V. Fig. 9 displays the relation between the rotation angle and the applied voltage. As shown in Fig. 8 and Fig. 9, at the same applied voltage, the rotation angle increases with the increase of electrodes number. In addition, Fig. 9(b) illustrates that the magnitude of rotation angle is approximately proportional to the number of electrodes. This result demonstrates that the idea of using multi-electrodes design is feasible in getting large out-of-plane deformation or rotation angle.

4 PROPOSED FABRICATION PROCESS

This research also proposes a process using bulk micromachining and high aspect ratio electroplating Ni to fabricate microactuator. This process starts with a <100> oriented single crystal Si wafer. The fabrication process outlined in Fig. 10 is described in detail below. (a) A thin Si_3N_4 with low residual stress is deposited on the Si substrate and then patterned. This nitride film acts as a structure layer of U-shape torsion-beam and serves as an etch mask for the bulk-etch process. (b) Cr-Au is sputtered and then patterned to form both electrical pads and conducting leads for connecting individual electrode as well as to act as electroplating seed layer. (c) A thick PR is deposited and patterned to expose the electroplating area of electrode. (d) Nickel is electroplating onto a seed layer to act as a structural layer of electrode and then PR is removed. (e) Finally, the exposed single-crystal silicon is etched using anisotropic wet etching (KOH) process to complete the device.

5 CONCLUSION

This paper proposes a new design structure of fabricating an electrostatic driven micro actuator capable of producing a large out-of-plane rotation angle. For applications, this novel design of micro actuator may be used to provide larger operating range or to act as a micro optical switch, optical display. Moreover, it can be fabricated using microfabrication processes. According to our analysis and simulation, this designed actuator can achieve large out-of-plane deflection actuation via connected multi-electrodes on U-shape suspension beam. Concurrently, the parameters that influence the design limitation and the performance of the micro actuator have been studied. In summary, it can be seen from this work that a proper design of the dimensions of the U-shape beam and electrode is essential to the success of performing our proposed micro electrostatic actuator. Furthermore, this optimal structure can be obtained by varying geometric dimensions to enhance its performance.

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