Development of scanning micromirror with discrete steering angles

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Abstract. This paper describes the development of a new MEMS-based optical mirror, which can perform optical switching (or scanning) function with discrete reflection angles in an out-of-plane configuration. The device is fabricated through the Deep Reactive Ion Etching (DRIE) process on silicon-on-insulator (SOI) wafer, followed by wafer dicing and assembly with two metalised glass dies. The MEMS mirror can be tilted under electrostatic force between the opposite electrodes embedded on SOI and glass structures. The most outstanding feature of this MEMS mirror is the discrete and therefore, reliable tilting angles, which generated by its unique mechanical structural design and electrostatic-driven mechanism. In this paper, the concept of the new scanning mirror is presented, followed by the introduction of device design, mechanical simulation, microfabrication process, assembly solution, and some testing results. The potential applications of this new MEMS mirror include optical scanning, optical sensing (or detection), and optical switching.

1. Background

All-optical switching systems, which employ bulk mechanically-actuated optical components and MEMS devices, are emerging. Such systems utilize electromagnetic, piezoelectric and electrostatic actuators to physically move prisms, mirrors and portions of optical fibers to switch signals transmission between optical fibers.

One kind of MEMS micromirror uses bi-state switching method: non-reflective state and reflective state. In the non-reflective state, the mirror is out of the optical path to allow the light passing through. In the reflective state, the mirror is moved, or flipped, into the optical path to re-route the light beam by reflection.

Another kind of MEMS mirror executes the light switching using scanning method. The micromirror is tilted along single or multiple axes to deflect the light beam in multiple directions. This kind of micromirror using such scanning mechanism has good potential in high fiber port count switching or beam scanning as compared to the bi-state mirror, where an overwhelming number of mirrors might be required. However for scanning mirror, the reflection angle has to be precisely controlled to ensure the required switching is achieved with low coupling loss [1-3]. Positioning and
controlling units are usually required to be integrated in such cases, which limit the switching time and accuracy. The mechanical reliability of such scanning mirror is also easily affected by vibration or mechanical shocks due to unstable structures commonly adopted, such as gimbaled rings and fold-up mirrors.

In this paper, we present a new scanning MEMS mirror with precision control of scanning angle without the complexity of position sensing and control servo; good reliability under vibration or mechanical shock; and scalability in achieving $1 \times N$ ($N > 4$) switching capacity.

2. Working Principle

An optical mirror system with multi-axis deflection is designed. This MEMS-based sandwich-like device includes a flat mirror body and at least two actuation units. Figure 1 depicts the basic working principle of the MEMS mirror system.

![Figure 1. The basic working principle of the mirror.](image)

The mirror (M) with its two actuators (A1/A2 and C1/C2) are shown in figure 1 (a). Each actuation unit includes 3 electrodes: a floating electrode between two fixed electrodes. The opposite fixed electrodes, A1/A2, C1/C2, are anchored on two parallel planar substrates. Two floating electrodes, A and C, are linked with the mirror through hinges (H1, H2). Without any actuation, the system is under Idle state: A (or C) are seating in the middle of the gap between A1/A2 (or C1/C2). Under actuation, one fixed electrode is charged by DC voltage, and an electrostatic force is generated between it and its corresponding floating electrode, that pulls the floating electrode moving towards it. When the two actuators are actuated in a complementary way, as shown in figure 1, the mirror is rotated through the pivot crossing the center of the mirror. The initial gap H between the floating plate and fixed electrodes dominates the range of mirror rotation, as shown in figure 1 (b), under a “pull-in” phenomenon. [4] “Pull-in” means when the DC voltage increases and reaches a threshold, the floating electrodes will snap down towards the fixed electrode and reside on it firmly until the voltage is released. A particular tilting angle, $\theta$, shown in figure 1(b), can then be achieved, which is largely determined by the geometrical setting of the structure. In practice, an incoming light beam will be reflected by the mirror surface in accordance with an angle of $2\theta$. 

![Figure 2. Multi-Axis Torsional Mirror, Exclusive of the Upper Substrate.](image)
Extending from the basic concept depicted in figure 1, a multi-axis implementation can be configured, as illustrated in figure 2. It includes one mirror (M), four actuators (A, B, C and D) and those hinges linking the mirror, substrates and actuators. The number of scanning orientations can be further increased by allocating more actuators.

Two actuation modes can be employed in the 4-axis system as shown in figure 2. The 1st actuation mode is to activate two opposite units, e.g. A/C or B/D, while keeping the other two units in idle. The mirror is rotated round one axis, x or y, as depicted in figure 2. The 2nd mode is to activate the four units simultaneously. Two adjacent units, A/B, pull their floating electrodes upwards, while the other two units, C/D, pull their floating electrodes downward, and therefore the mirror rotates along axis $\xi$ (or $\eta$ on the contrary), as marked in figure 2. Table 1 lists out all the actuation configurations. 00 stands for the idle state. 01, 02, 03 and 04 belong to the 1st actuation mode. Others belong to the 2nd mode.

|   | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 |
|---|----|----|----|----|----|----|----|----|----|
| A | 0  | +  | -  | 0  | 0  | +  | -  | +  | -  |
| B | 0  | 0  | 0  | +  | -  | +  | -  | 0  | 0  |
| C | 0  | -  | +  | 0  | 0  | -  | +  | -  | 0  |
| D | 0  | 0  | 0  | -  | +  | -  | +  | 0  | 0  |

### 3. Mechanical Simulation

Mechanical modeling and simulation of the mirror behavior under electrostatic forces has been performed using Ansys™ to verify the feasibility of the proposed mirror concept. The floating electrodes are assumed to be in full contact with the corresponding fixed electrodes in this simulation as the mechanical boundary conditions. The design is symmetrical around the mirror center. The dimensions used in the simulation were set based on typical silicon MEMS fabrication processes.

![Figure 3. ANSYS™ simulation: mechanical movement of tilting mirror.](image)

Figure 3 (a) shows the close-up view of the mirror model under the 1st actuation method. Mirror is rotating along the Y-axis, as depicted in figure 2. While figure 3 (b) shows the rotation state of the mirror under the 2nd actuation mode. All the results showed no significant curvature on the mirror body, which is paramount for its function as an optical scanning element. Similar results were achieved in other simulations also.

We performed comprehensive simulations using Coventorware™ to analyze various mirror designs. Two different geometrical configurations, type “+” and “Φ”, were used in the arrangement of supporting springs vs. electrodes, which were shown in figure 4 (a) and (b), respectively.
As shown in figure 4 (a), with “+” type, the mirror is linked with electrodes through one pair of springs and linked with anchored substrate through another pair of springs. While for “Φ” type shown in figure 4 (b), the electrode is linked with mirror at one end and linked with substrate at the other end. Such arrangement can significantly reduce the chip space compared with “+” type, which is important for allocating more than 2 actuators. Figure 5 showed the realization of the two types in device layout.

4. Device Realization
To enable the function of mirror tilting, the design of fabrication process has to make sure each actuator comprised one floating electrode and two corresponding fixed electrodes (upper one and bottom one) with embedded dielectric layers in between. All the electrodes need to be controlled individually by applying DC voltage and has to be routed out individually to the bonding pads, which must be convenient for packaging.

A sandwiched structure was employed in the device realization process. It comprises an SOI structure, which acts as the substrate for fabricating all the moving parts, e.g. mirror, floating electrode and supporting springs; and two metalized glass structures for building the upper and bottom fixed electrodes. Three wafers, consisting of one SOI and two glass wafers, were then fabricated individually through the MEMS process, then go to wafer dicing into dies. Subsequently the SOI die and glass dies were stacked and assembled to be an integrated device, MEMS mirror. Each device is made up of 3 dies coming from the three wafers. Figure 6 shows the fabrication process flow.
(a) Deep Reactive Ion Etching (DRIE) on both sides of SOI wafer with 110 μm-thick top silicon layer [5].

(b) Over etching of the buried oxide layer for the release of the bottom block of silicon.

(c) Wet etching of glass to form recess with 10 μm depth; metallization on glass surface, patterning, deposition of dielectric layer for insulation. Two glass wafers are fabricated using the same process flow but with different photomasks for metal patterning. The control pads (metal) for all the electrodes, i.e. two glass dies and the SOI die are all made on the top surface of the bottom glass wafer.

(d) The three wafers are diced into different sizes, respectively. The glass die with upper electrodes is diced into the identical size with that of the released back silicon block shown in (a), so that it can be self-assembled to the SOI die without the need of precision alignment. The glass die with bottom electrodes is then diced into a size bigger than that of the SOI die.

Figure 6. Fabrication process flow.

As shown in figure 6 (d), the floating electrodes made from SOI are seating between their corresponding fixed electrodes on top and bottom glass dies, and isolated with dielectric layer in between. In practical, the top glass wafer can be pre-perforated to open a through hole in the central zone so that the optical beam can go in, be reflected by the tilting mirror and go out. For better optical reflectivity, the mirror surface can also be coated with gold or aluminum through the evaporation process.

Figure 7. Stacking contact scheme for electrical wiring.
The electrical wiring of the electrodes from SOI die and the 2 glass dies is realized through the stacking contact during assembly. For applying voltage to the electrodes on top glass, the SOI die serves as interconnection media between top and bottom glass dies through the conductive silicon layers. The top silicon layer of SOI was cut into several electrically-isolated zones, as shown in figure 7. The electrode on top glass is then linked to certain separated zones on the SOI top layer through direct contact with metal lines outside the recess area on the top glass die. The contact area is labeled as “T” in figure 6 (d). Through layout design, such zone eventually contact with electrodes Et on the bottom glass die, which acts as the control pad of the electrode on the top glass die. Meanwhile, the connected zone with floating electrodes and mirrors is linked with some other electrodes on the bottom glass, Eb, through direct contact, which acts as the control pad of the silicon (mobile) parts. The contact pad of bottom electrode, labeled as Eb, is directly wired out from the recess on the bottom glass die. In practice, conductive paste is applied on the contact area to improve reliability.

5. Results and Discussion

Nine different device designs were realized through microfabrication. The size of SOI dies is about 4 × 4 mm², including all the moving structures and also serving as the electrical contact media for top glass to bottom glass. In all the designs, the mirror is round in shape with a diameter of 100 μm and thickness of 110 μm, which is identical with that of the top silicon layer of SOI wafer. The top glass die is 2 × 2 mm² in size, which is equal to the size of released block of back silicon layer of SOI wafer. This arrangement is for the self-assembly between top glass die and SOI die. The bottom glass die, which holds the control pads for all the electrodes on the three dies, is 5 × 5 mm², the final size of the device after assembly.

Figure 8 (a) and (b) show the optical microscopy images of SOI dies under two different designs after MEMS fabrication process. In device A, the floating electrodes are 100 × 100 μm² and are located 80 μm away from the nearest edge of the mirror. The width of the spring linking the floating electrode and mirror is 5 μm. The narrowest part of supporting spring between mirror and anchored substrate has a width of 2 – 3 μm. In device B, the distance between floating electrode and mirror is 40 μm. They are linked through a 2 μm-wide spring.

Electrical validation has been done on the assembled devices. The mirror can be successfully driven upon the pull-in of the floating electrode under electrostatic force generated between opposite electrodes. In general, the pull-in voltages measured are between 50 and 100 volts. The tilting angle for the mirror in device A and B shown in figure 8 is approximately 6º and 12º, respectively.

6. Conclusions
In this paper, we present the development of a unique structure for micromirror based on MEMS technology. Good application potentials can be expected due to its unique features as listed below:

- Accurate control of mirror orientation: in this structure, the mirror is always seating into a pre-determined position upon actuation. No sensor or control servo is required for position tuning.
- Anti-vibration property: the mirror is constrained by at least two complimentary actuators. It is less susceptible to external vibration in comparison with conventional torsional mirrors.
- Extendibility to larger scale scanning: the 4-axis scheme shown in figure 2 is extendable in terms of scanning scale by adding on more actuators, which means more deflection orientations can be realized through multi-axis mechanism.

Other than serving as the switching element in telecommunications, more applications in chemical/bio-medical measurement and scanning laser system are feasible with this 3D MEMS mirror, which shows good potential in terms of mechanical stability and reliability.

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References
[1] Chu P B, Lee S S and S. Park 2002 *IEEE Communications Magazine* pp 80-87
[2] Bishop D J, Giles C R and Austin G P 2002 *IEEE Communications Magazine* pp 75-79
[3] Wang Z F, Cao W Q and Shan X C et al 2004 *Sensors and Actuators A* 114 pp 80-87
[4] Rocha1 L A, Cretu1 E and Wolffenbuttel1 R F 2004 *J. of Micromech. Microeng.* 14 pp 37-42
[5] Marxer C and de Rooij N F 1999 *IEEE J. of Lightwave Technology* 17 pp 2-6