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DEVELOPMENT OF SCANNING MEMS MIRROR WITH NEW ASSEMBLY STRUCTURE

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ABSTRACT

This paper introduces the development of a new MEMS-based optical mirror, which performs optical scanning function with discrete reflection angles in an out-of-plane configuration. The device was fabricated through Deep Reactive Ion Etching (DRIE) process on silicon-on-insulator (SOI) wafer, followed by assembly with two metalised glass dies. The optical mirrors can be tilted by electrostatic forces between the opposite electrodes on the SOI and glass dies. The most outstanding performance that can be expected from the device is the discrete and therefore, reliable tilting angle of the mirror, which is guaranteed by its unique mechanical structure and the electrostatic-driven mechanism. In this paper, the working principle of the new MEMS mirror was presented, followed by the introduction of device design, mechanical simulation, microfabrication process, assembly solution, and some testing results. The potential application of this new MEMS mirror is for light beam scanning or optical sensing (detection).

1. INTRODUCTION

The electrostatic force is a commonly used actuation method for scanning micromirrors, which is usually generated from a fixed electrode on the substrate and a movable one associated with the scanning mirror. The mirror deflection depends on the voltage applied between the fixed and movable electrodes. A deformation sensor and a control servo are usually required to displace the mirror to the desired position with the required tilting angle. The accuracy of such positional (or angular) control is dependent on the sensitivity of the deformation sensor and the performance of servo circuit. Therefore, the response time and torsional accuracy, which are paramount to the coupling loss and crosstalk of the switching element, are largely dependent on the performance of such sensors and circuits. The mechanical reliability of such scanning mirror is affected by vibration or mechanical shocks due to unstable structures commonly adopted, such as gimbaled rings and fold-up mirrors. [1-3]

In this paper, we present a new scanning mirror based on MEMS technology with precision control of scanning angle without the complexity of position sensing and control servo. Based on the sandwich-like mechanical structure, good reliability under vibration or mechanical shock can be expected. A unique die-to-die assembly structure is also introduced, which is critical in realizing the mirror function.

2. DESIGN OF NEW SCANNING MEMS MIRROR

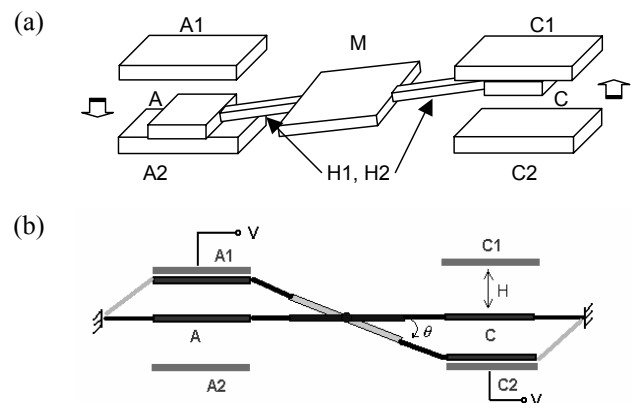


Fig. 1 Basic Working Principle of Scanning Mirror

An optical mirror system with multi-axis deflection is designed to perform light beam scanning with discrete deflection orientation. Fig. 1 depicts the basic working principle of the optical mirror system. The mirror (M) and two actuators are shown in Fig. 1 (a). Each actuator includes a floating plate (electrode) and two fixed electrodes. The opposite electrodes, A1/A2, C1/C2, are anchored on two parallel planar substrates. Two floating plates, A/C, which are made of conductive material, are used as electrodes under actuation and linked with the mirror through hinges (H1, H2). Without applying voltage, the actuators are in their idle state; A/C are seating in the middle of the gap between A1/A2 and C1/C2, respectively. Upon actuation, one electrode of the actuator is charged by DC voltage, thus electrostatic force is generated and pulls the floating plate. When the two actuators are actuated in a complementary way, as shown in Fig. 1 (b), the mirror is rotated through the pivot

crossing the center of mirror. The initial gap H between the floating plate and fixed electrodes dominates the range of mirror rotation, as shown in Fig. 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.

When the opposite floating plates are pulled upwards and downward, respectively, under individual control, a particular tilting angle, θ , shown in Fig. 1(b), can be achieved and stabilized when plate A and C are firmly attached with the substrates by very strong electrostatic force. In practical, an incoming light beam can be reflected by the mirror surface in accordance with an angle of 2θ .

Based on the concept depicted in Fig. 1, a multi-axis torsional mirror can be designed, as illustrated in Fig. 2. It includes one mirror (M), four actuators (A, B, C and D) and hinges that link the mirror, substrates and actuators. Each actuator has two actuation states. The floating plate can be pulled towards the upper or lower substrate. The fixed electrodes are located on the substrates and thin layers of dielectric material are coated on the surface of electrodes to avoid short circuit with floating plate when they are attached.

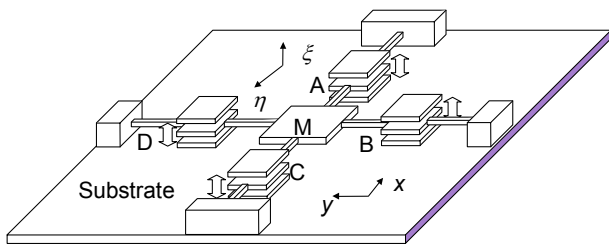
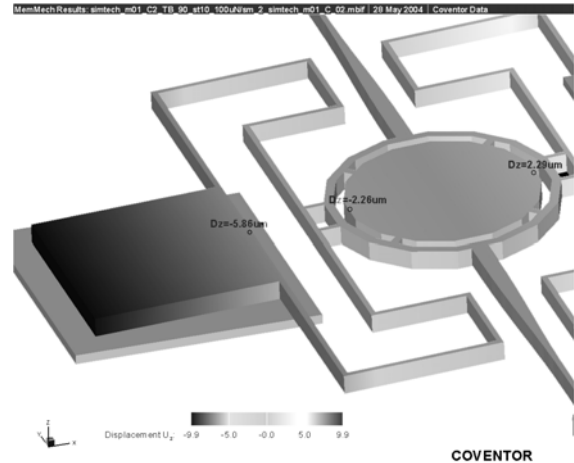


Fig. 2 Multi-Axis Torsional Mirror, Exclusive of the Upper Substrate

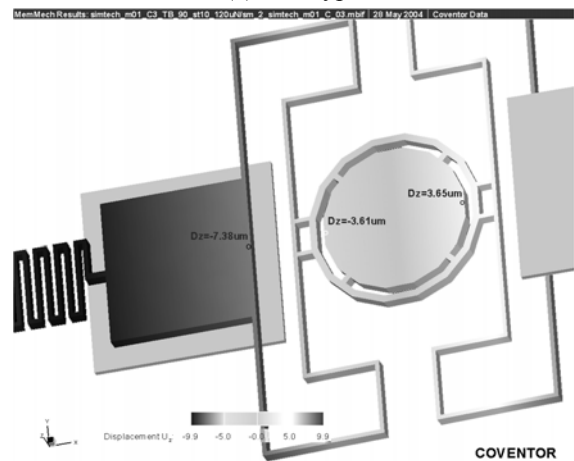
The number of tilting orientations can increase by adding the number of actuators. There are two methods (or modes) of actuation can drive the present mirror system. In the 1st actuation mode, only two opposite actuators, e.g. A&C or B&D as shown in Fig. 2, are actuated. The other two actuators are kept in idle. Under this mode, the mirror is rotated round one axis (x or y) as depicted in Fig. 2. In the 2nd actuation mode, all the four actuators are driven simultaneously. Two adjacent actuators, e.g. A&B, are pulling the floating plate upwards, while the other two plates, e.g. C&D, are pulling the floating plate downwards. Therefore the mirror rotates along axis ξ or η , as marked in Fig. 2. In total the mirror has 8 tilting states apart from the original state, and each state contributes one deflection orientation.

3. MICROFABRICATION AND ASSEMBLY

Comprehensive modeling and simulation associated with various geometrical design of mirror structure has been done on CoventorwareTM. Two different geometrical configurations, type “+” and “ Φ ”, were used for positioning the supporting springs vs. electrodes as shown in Fig. 3 (a) and (b).



(a) “+” Type



(b) “ Φ ” Type

Fig. 3 COVENTOR simulation: 2 configurations of spring vs. electrode

In type “+”, the mirror is linked with electrodes by one pair of springs and linked with anchored substrate through another pair of spring. While in type “ Φ ”, each electrode is linked with mirror at one end and linked with anchored substrate at the other end. This “ Φ ” type structure can significantly save chip space compared with “+” type. This is important for multiple-orientation scanning by using more than big number (more than 4) of actuators.

Through the simulation, the geometrical design of mechanical parts was optimized, especially for the shape

and dimension of springs. In the final design we used for fabrication, the displacement of actuator (floating electrode) under pull-in condition can be largely (more than 90%) converted into the deflection of mirror plate.

A 3-layer sandwiched structure was employed in device realization, which composed of a SOI structure for making all the moving parts, e.g. mirror, floating electrode and supporting springs, and two metalised glass structure for building upper and bottom electrodes. The three wafers, e.g. one SOI and two glass wafers were fabricated individually through MEMS process in wafer level, and then went to wafer dicing process and assembly. Each micromirror device is made up of 3 dies coming from the 3 wafers. Fig. 4 shows the fabrication process flow.

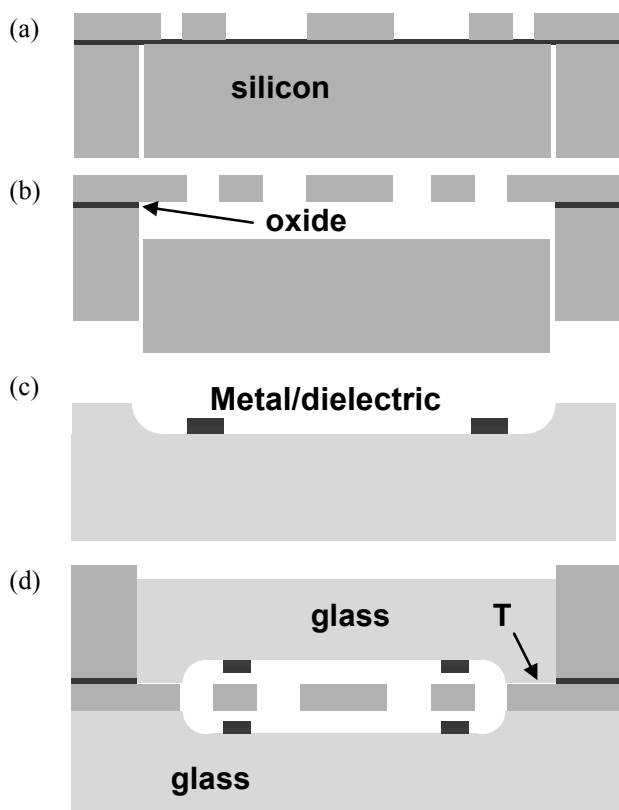


Fig. 4 Fabrication process flow

The fabrication started from DRIE process on both sides of SOI wafer, which has top silicon thickness of 110 μm , as illustrated in Fig. 4(a). [5] Through over etching of the buried oxide layer, as shown in Fig. 4(b), the bottom block of silicon was released. On the other hand, wet etching process was taken on two glass wafers to form recess with 10 μm depth, as shown in Fig. 4(c), followed by metallisation, patterning, and deposition of dielectric layer for insulation. Two glass wafers were fabricated under same process flow but with different photomask for metal patterning, as illustrated in Fig. 4(d). The three

wafers were then diced into different sizes. The glass die with upper electrodes was diced into identical size of the released back silicon block, so that it could be easily assembled to the SOI die with precise alignment.

As shown in Fig. 4 (d), the floating electrodes on SOI were seating between their corresponding fixed electrodes on top and bottom glass dies with dielectric layer in between. In practical, the top glass wafer will be pre-perforated 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 be coated with gold or aluminum through evaporation process.

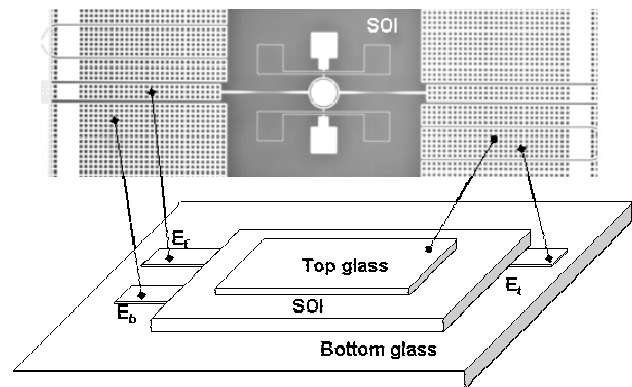


Fig. 5 Stacking contact scheme for electrical wiring

The electrical wiring of the electrodes from the SOI die and the two glass dies was realized by the stacking contact applied during die assembly. In order to apply voltage to the electrodes on top glass, the SOI die serves as interconnection media between top and bottom glass through the conductive silicon substrate. The top silicon block of SOI was divided into several electrically-isolated zones by through etching, as shown in Fig. 5. The electrode on top glass is linked with certain separated zones on SOI through direct contact with metal pads outside the recess area, as labeled "T" in Fig. 4(d). Through proper layout design, such zones eventually contact with electrodes E_t on bottom glass, which acts as the control pads of the electrodes on the top glass die. Meanwhile, the connected zone with floating electrode and mirrors are linked with other electrodes on bottom glass, E_f , through direct contact, which acts as the control pad of the silicon parts. The contact pad of bottom electrode, labeled as E_b , is directly wired out from the bottom recess. In practice, conductive paste can be applied on the contact areas before assembly to achieve better connection.

After fabrication, different device designs have been realized. The size of SOI dies is about $4 \times 4 \text{ mm}^2$, which include all the moving structures and also serve as the electrical contact media for top and bottom glass dies. In all the designs, mirror is in round shape with 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 in size of $2 \times 2 \text{ mm}^2$, which is equal to the size of the released block of back silicon layer of SOI wafer. This arrangement is for the self-alignment during the assembly with top glass die and SOI die. The bottom glass die, where located the control pads for all the electrodes on the three dies, is $5 \times 5 \text{ mm}^2$, which equals to the final size of micromirror device after assembly.

Fig. 6 shows the optical microscopy image of SOI dies under different designs after microfabrication process. In device (a), the floating electrodes are with size of $100 \times 100 \text{ }\mu\text{m}^2$ and allocated $80 \text{ }\mu\text{m}$ away from the nearest edge of the mirror. The width of spring between floating electrode and mirror is $5 \text{ }\mu\text{m}$. The narrowest part of supporting spring between mirror and anchored substrate has a width of $2\text{-}3 \text{ }\mu\text{m}$. In device (b), which represents the “ Φ ” type design illustrated in Fig. 3(b), the distance between mirror and floating electrode is $40 \text{ }\mu\text{m}$, which are linked through a $2 \text{ }\mu\text{m}$ -wide spring. Device (c) represents the “+” type design with 4 actuation units.

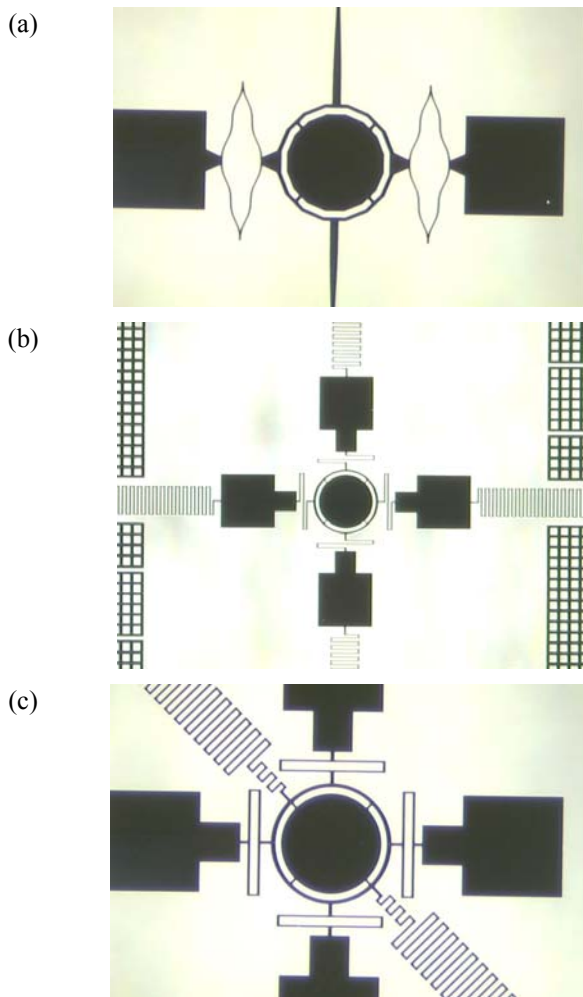


Fig. 6 Optical microscopy images of fabricated mirror devices (close-up view of the SOI part)

Electrical test has been done on the assembled devices with all the nine designs by applying DC voltage. The mirror can be successfully driven upon the pull-in of the floating electrode under electrostatic force generated between opposite electrodes. The pull-in voltages measured out are in general among $50\text{-}100$ volts. The tilting angle for device A and B shown in Fig. 6 is approximately 6° and 12° , respectively.

4. CONCLUSION

In this paper, we present the development of a unique structure for micromirror based on MEMS technology. Accurate control of mirror orientation can be expected due to the structural design. The mirror is always driven into a pre-determined tilting position upon actuation. No sensor or control servo is required for position (or angle) tuning. The mirror can perform good anti-vibration property because that the mirror is constrained by at least two complimentary actuators. It is less susceptible to external vibration in comparison with conventional torsional mirrors. The micromirror device can be extended into larger scale scanning 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, applications in chemical/bio-medical measurement and scanning laser system can also be expected with the integration of this 3D MEMS mirror, which shows good potential in terms of mechanical stability and reliability.

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