# A Low-Voltage Two-Axis Electromagnetically Actuated Micromirror With Bulk Silicon Mirror Plates and Torsion Bars

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## ABSTRACT

In this paper, a new micromirror structure has been proposed and fabricated. The proposed micromirror is electromagnetically actuated along two-axis at low voltage using an external magnetic field. The mirror plates and torsion bars are made of bulk silicon and the actuation coils are made of electroplated copper. The maximum deflection angles have been measured as ±4.35° for x-axis actuation and ±15.7° for y-axis actuation. The actuation voltages are below 4.2V for x-axis actuation and 1.76V for y-axis actuation, respectively.

## INTRODUCTION

There are many applications of micromirrors that require large deflection angles and mechanically robust structures such as optical switch [1], optical scanner [2], projection display [3], etc. Most of the micromirrors reported to date have used electrostatic force actuation [4-6]. In the case of electrostatic actuation, the actuation voltage is high (>100V) to acquire the deflection of a required angle and it is relatively difficult to have mechanically robust mirror structures because the torsion bars have to be thin to have a low spring constant. On the contrary, electromagnetic actuation can induce a large force with a lower voltage but require large power consumption [7].

In this work, we used an external magnetic field to acquire large force at low voltage and low power consumption. This large force actuation enables the micromirrors to be fabricated in a stable microstructure using bulk silicon. To obtain a stable microstructure, the proposed structure uses bulk silicon for torsion bars and a mirror plate. This structure requires low operating voltages by using an external magnetic field. In addition to that, electromagnetic actuation enables bi-directional motion, so that torsion bars are subjected only to torsional motion but not to bending motion. This can make a stable actuation possible. Previously, micromirrors using an external magnetic field have been reported; however, they only allow one-axis actuation [8-9]. In this paper, a two-axis magnetically actuated micromirror has been proposed, fabricated, and demonstrated using bulk silicon.

## DESIGN AND SIMULATION

The proposed micromirror actuates with Lorentz force using an external electromagnetic field as shown in Figure 1. The proposed micromirror structure consists of a mirror plate, frames, cantilever type actuators and coils. The cantilever type actuator is connected to the frames using lifting bars. The mechanical structure is made of silicon. The coils are electroplated copper integrated on the mirror plate and cantilever type actuators. There are two types of actuators, x-axis actuator and y-axis actuator. The x-axis actuator is implemented in the cantilevers on the outside of the mirror plate and the y-axis actuator is integrated on the mirror plate.

The operating direction of the micromirror is determined by the direction of the current flowing in the coils on the mirror plate and the cantilever actuator as shown in Fiure 2. Among this coils, only the coils perpendicular to the magnetic field induce Lorentz force. In the case of x-axis actuation, the coils on the mirror plate induce Lorenz force. The coils which flow a current, I1, induce a upward force, F1, while the coils which flow a current, I2, induce a downward force, F2. These forces enable the mirror plate to rotate along the y-axis with inner torsion bars as a centeral axis. In the case of x-axis actuation, the coils on the cantilever actuators induce Lorentz force. The coils which flow a current, I3, induce a upward force, F3, and this force lifts up the pair of cantilevers. The lifted cantilevers accordingly lift the frame.

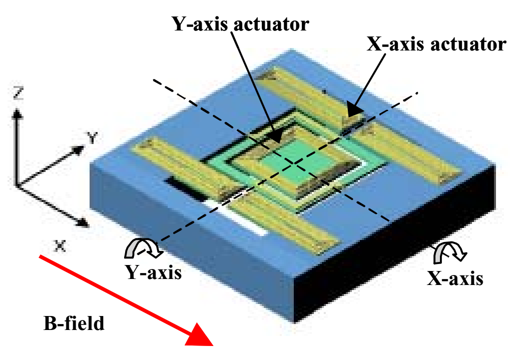



***Figure 1***. *Shemetic diagram of the proposed micromirror.*

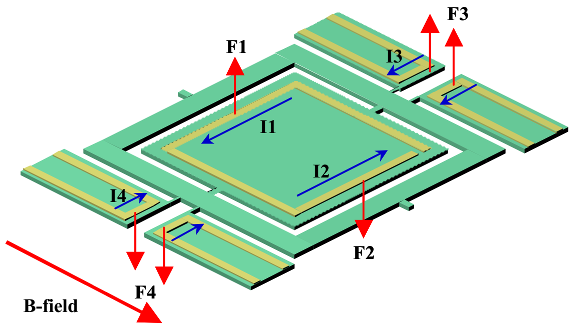
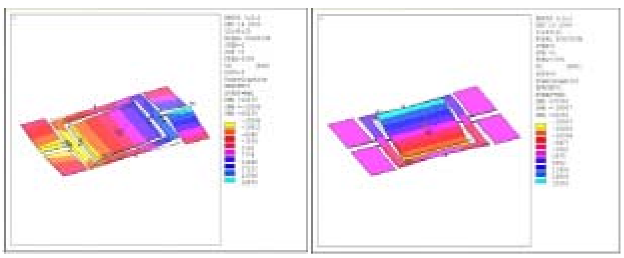



***Figure 2***. *Operating principle of the proposed micromirror.*



*(a)* *(b)*

***Figure 3***. *Simulation results using ANSYS: (a) x-axis actuation, (b) y-axis actuation.*

The other pair of cantilevers move downward by the Lorentz force, F4, induced from a current, I4, which flows in the opposite direction of I3, and this makes the frame move downward the frame. From this cantilever actuation, the frame rotates along x-axis with outer torsion bars as a central axis. Figure 3 shows the actuation modes of each direction simulated using ANSYS 5.3. The resonant frequency of x-axis actuation is 5.369kHz and that of y-axs actuation is 3.391kHz, respectively. This resonant frequencies allows this micromirror to be operated in sub-milliseconds.

## FABRICATION

The fabrication processes of the proposed micromirror are shown in Figure 4. Starting material is an SOI wafer with top silicon of 5µm and buried oxide of 1µm. The thickness of the top silicon determines the thickness of the proposed micromirror directly. Mirror frames and mirror plates are defined at the top silicon by RIE (Reactive Ion Etching) using thermal oxide as an etch mask (Figure 4 (b)). Then, Cr/Cu is deposited for a seed metal layer for electroplating. Next, bottom copper coils are electroplated as shown in Figure 4 (c). The 5µm-thick copper coils are electroplated using 10µm-thick AZ9260 photoresist as a mold. After electroplating the bottom copper coils, photoresist is coated for scrificial layer to make an air gap and patterned for contact. Then, another copper layer is deposited as a seed layer.

***Table I.*** *Dimension of the proposed micromirror*

| | X-axis actuation | Y-axis actuation |
|---|---|---|
| Mirror plate | 800µm × 800µm | |
| Torsion-bar length | 100 µm | |
| Torsion-bar height | 10µm(silicon 5µm +Cu coil 5µm) | |
| Lifting-bar length | 50 µm | |
| Lifting-bar width | 20 µm | |
| Coil width | 10µm | |
| Coil height | 5µm | |
| Resonant frequency (simulated) | 5.369kHz | 3.391kHz |

With photoresist as a mold, bridge metal is electroplated as shown in Figure 4 (d). Using the buried oxide as an etch stop, silicon is etched from the backside in KOH with silicon nitride as an etch mask (Fig. 4 (e)). After removing the buried oxide, the mirror and frame are released as shown in Figure 3 (f).

Figure 5 shows the SEM pictures of the fabricated micromirror. Figure 5 (a) shows the side view of the fabricated micromirror and Figure 5 (b) shows the top view. Air bridge metal lines are seen at the cross point of the coils and there are four metal pads used for x-axis and y-axis actuation inputs. Metal lead wires are electroplated on the torsion bars for electrical connection. The total thickness of the torsion bars will be the addition of top silicon thickness and lead wire thickness, which is about 10 µm. These thick torsion bars enable mechanically-stable operation under the large electromagnetic force induced from an external magnetic field. The detailed dimensions of the fabricated structure are summarized in Table I.

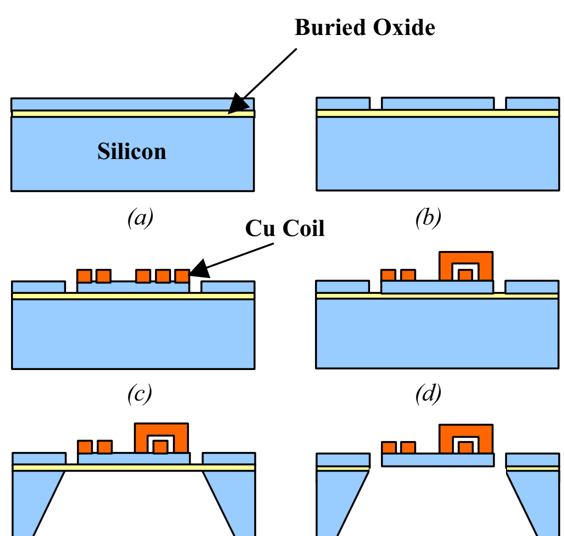
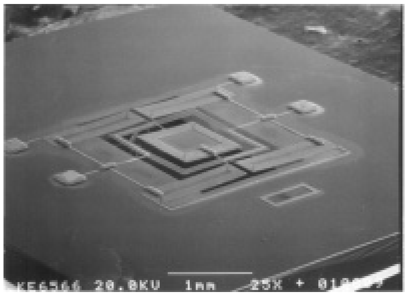
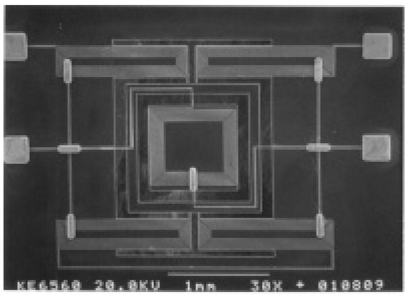



***Figure 4***. *Process flow of the proposed structure: (a) Starting wafer, (b) Mirror structure define by dry etch, (c) Bottom Cu coil electroplating, (d) Air bridge coil electroplating, (e) Si anisotropic etch in KOH, (f) Buried oxide removal.*



*(a)*



*(b)*

***Figure 5**. SEM pictures of the fabricated mirror structure: (a) side view, (b) top view.*

## MEASUREMENT AND RESULTS

To measure deflection angles, current is applied to the copper coil. The diced micromirror is mounted on a PCB board and the metal pads on the mircromirror and PCB board are connected with bonding wires. The actuation current is applied to the micromirror via the PCB board. External magnetic field is applied using a pair of permanent maganets as shown in Figure 6. The micromirror mounted on the PCB board is inserted between the permanent magnets in a way to apply a magnetic field parallel to the x-axis of the micromirror as shown Figure 1. The measured external magnetic field intensity is 0.16T(=1600Gauss) at the actuation point.

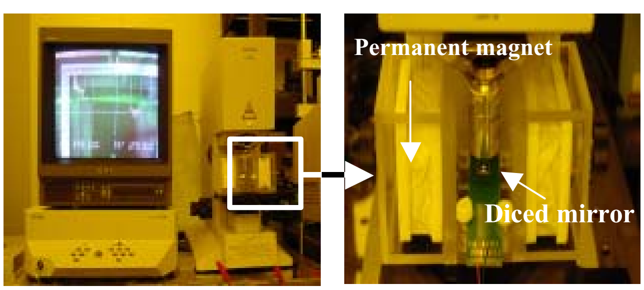



***Figure 6**. Measurement setup: (a) Displacement measured using 3D profiler (Keyence VF-7500), (b) Permanent magnet setup.*

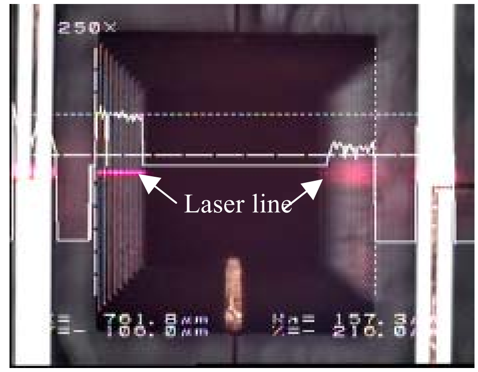
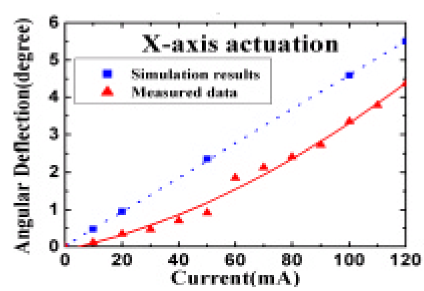
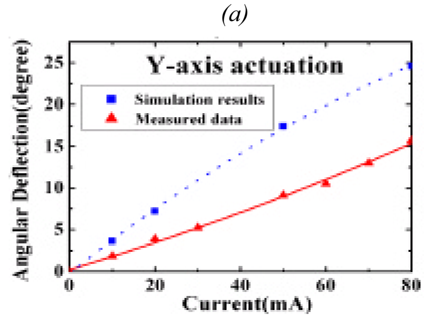



**Figure 7**. Picture of the rotating micro mirror using a 3D profiler

The 3D laser profiler is used to measure rotational angles of the actuated micromirror. The used laser profiler is a Keyence VF-7500. This laser profiler scans sample surface with a focused laser beam and displays a 3D profile as shown in Figure 7. To measure the actuation angle, the mirror plate is scanned with a focused laser line from the 3D profiler and the actuation angle is obtained by measuring the difference in height between the left side and the right side of the mirror plate. As a result of rotation, the laser line on the left of the mirror is in focus and that on the other side is out of focus and seen blurred as shown in Figure 7. Rotation angle can be also confirmed from the dimensional change in the sidewall of the mirror plate.




*(a)*




*(b)*

***Figure 8**. Measured deflection angle as a function of applied current: (a) x-axis actuation, (b) y-axis actuation.*

*Table II*. *Experimental results of the fabricated micromirror*

| | X-axis actuation | Y-axis actuation |
|---|---|---|
| Magnetic Field | 0.16Tesla | |
| Actuation Angle | 0 ~ ± 4.35° | 0 ~ ± 15.7° |
| Actuation Current | 0 ~ 120mA | 0 ~ 80mA |
| Actuation Voltage | 0 ~ 4.2V | 0 ~ 1.76V |
| Maximum Power | 50.4mW | 14.1mW |

Angular deflection is measured by applying a constant current. Figure 8 shows the measured angular deflection of the micromirror as a function of applied current for x-axis and y-axis actuations, respectively, compared to the simulation results. The simulation results of angular deflection are obtained using ANSYS 5.3.

In the case of x-axis actuation, the maximum deflection angle has been measured as 4.35° at the applied current of 120mA and the actuation voltage of 4.2V. The total resistance of the colis on the cantilever type actuator is 35Ω and power consumption is 50.2mW. In the case of y-axis actuation, the maximum deflection angle has been measured as 15.7° at the applied current of 80mA and the power consumption of 14.1mW. Therefore, the total maximum power consumption is about 64.5mW for two-axis simultaneous actuation. Table II summarizes the characteristics of the fabricated micromirror.

## CONCLUSTIONS

We have proposed and fabricated a new two-axis actuated micromirror. This fabricated micromirror operates electromagnetically using an external magnetic field. The maximum actuation angle has been measured as 4.35° at 120mA for x-axis actuation and 15.7° at 80mA for y-axis actuation, respectively. The actuation voltages are below 4.2V for x-axis actuation and 1.76V for y-axis actuation, respectively. Total maximum power consumption is 64.5mW and simulated resonant frequencies are 5.369kHz for x-axis actuation and 3.391kHz for y-axis actuation, respectively. The fabricated micromirror has demonstrated large deflection angles at low voltage and low power consumption. The robust torsion bar structure formed by bulk silicon allows the proposed micromirror to stably operate at high frequencies. The actuation angle of the y-axis actuation can be increased by optimizing the dimension of lifting bars through the further work.

## ACKNOWLEDGEMENTS

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