A Micromirror Device with Tilt and Piston Motions

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ABSTRACT

A newly developed micromirror device that possesses two rotational (tilt) and one displacement (piston) degrees of freedom has been designed and fabricated by using surface micromachining technology. The device consists of a micromirror, four vertical thermal-actuator arrays and four torsion bars that connect the mirror and the actuator. The vertical thermal actuator has the capability to elevate from its origin position. To demonstrate the feasibility of the vertical thermal actuator, various layouts and sizes has been designed. The present device was fabricated through the Multi-User MEMS process (MUMPs). When the controlled signal is applied to any two adjacent thermal-actuator arrays of the device, the remain two thermal actuator arrays and torsion bars will act as the supporting beams that allow the micromirror to experience rolling or pitching motion. On the other hand, by applying controlled signals to all four thermal-actuator arrays synchronously, the micromirror would elevate vertically. Note that different rolling or pitching angle of the micromirror can be archived by designing the locations of the torsion bars with vertical thermal actuators. Through the process, a compact, extremely light in weight, potentially low cost, and operating in very low voltage (<10V) micromirror device with various applications can be obtained.

Keywords: Micromirror, Thermal Actuator, Rolling and Pitching Degrees of Freedom, MEMS, MUMPs.

1. INTRODUCTION

Various micromirror devices based on MEMS technology have been fabricated and demonstrated in the past two decades. In 1992, Texas Instrument has developed the DMD (Digital Micromirror Device)[1] for laser projection television technology. The device consists of a series of micromirror arrays, the tilt motion of the micromirror that creates the scanning effect was operated using electrostatic force. In 1995, Silicon Light Incorporation has successfully designed and manufactured the so-called GLV (Grating Light Valve)[2] that can be used to grating the light for the application such as high definition television. Unlike DMD with tilt motion, the micromirror array of the GLV that is also driven by electrostatic force is operating on vertical direction. However, one may notice that most of the existing micromirrors have only possessed either piston or tilt motion. Thus, for the purpose of surface or space scanning/projection, micromirror arrays with specific tilt/vertical motion need to be carefully designed.

2. DESIGN

In order to obtain a micromirror device that has multiple degrees of freedom (DOF), the schematic concept of these DOF is given in Fig. 1. In Fig. 1, the micromirror could have rolling motion if we apply vertical actuation on the right or left two corners of the micromirror. Similarly, the micromirror would experience pitching motion if the forces were applied at the

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top or bottom two corners. Finally, the micromirror would produce vertical movement if we apply forces at four corners synchronously. One may notice that the major success of the present concept is highly relied on the development of the vertical actuation. To achieve this goal, a vertical thermal actuator based on the lateral thermal actuator [3] is designed. Unlike the design in reference 3 that the "hot arm" and "cold arm" are fabricated in the same process layer with different cross-section areas, we re-designed the "hot arm" and "cold arm" in different layers with different cross-section areas through multi-layers deposition and sacrificial layer technology process. Figure 2 shows the vertical thermal actuator layout. When the vertical thermal actuator is driven at a fixed electrical voltage, the current is running from the hot arm to the cold arm. From of the joule-heat principle, the hot arm would obtain more electric power than the cold arm. Thus, these two arms would give different thermal expansion. In another words, the hot arm would produce more thermal expansion (displacement) than the cold arm. By connecting the tips of the hot arm and cold arm, the actuator would produce a displacement at the tip. In order to gain the inside of the designed vertical thermal actuator, in later section, we used ANSYS to analyze the characteristics of the vertical thermal actuator. Note that in the case of increasing the actuating force, we could connect several vertical thermal actuators in parallel to form an actuator array.

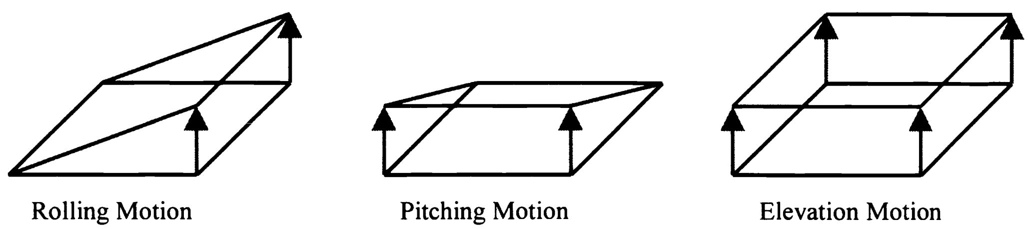

Figure 1 Schematic of the Micromirror Device with Multiple DOF

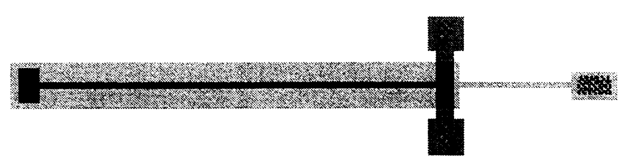

Figure 2 Layout of the Vertical Thermal Actuator

3. FABRICATION

The multiple DOF micromirror device we designed using the surface micromachining technology that is publicly available through MCNC/ Multi-User MEMS Process (MUMPs)[4]. The process consists of three-layer polysilicon for structure layers, two PSG layers for sacrificial layers, and gold layer for electrical contact or optical reflective surface layer. Figure 3 shows the process' cross-section view and Table 1 lists the thickness relative to each process layer. The present device consists of a micromirror and four vertical thermal-actuator arrays. The layout of the design is given in Fig. 4. In Fig. 4, if the device is driven by the right or left thermal-actuator arrays, the micromirror yields the rolling motion. And if the device is driven by the top or bottom thermal-actuator arrays, the micromirror will create the pitching motion. Finally, if the control signals are applied at all four thermal-actuator arrays synchronously, the micromirror will produce vertical displacement. Note that the different rolling and pitching angles can be archived by alternating the area of the micromirror and the location of the torsion bars that is attached to both the micromirror and the thermal-actuator array. The vertical thermal actuators are fabricated with 2 μm polysilicon (POLY1) in cold arm and 1.5 μm polysilicon (POLY2) in hot arm. The mirror (200 μm $\times$ 200 μm in area) is fabricated with 2 μm thickness (POLY2+GOLD). The torsion bars are fabricated using the POLY2 layer. By applying control signals to different thermal-actuator arrays, the micromirror device is able to produce rolling angle, pitching angle and vertical displacement.

Layer	Thickness(μ m)
Gold	0.5
Poly2	1.5
2nd Oxide	0.75
Poly1	2.0
1st Oxide	2.0
Poly0	0.5
Nitride	0.6

Table 1 MCNC/MUMPs Process Layers and Thickness

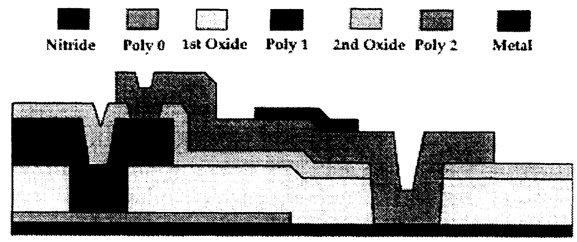

Figure 3 MCNC/MUMPs Process Cross-section View

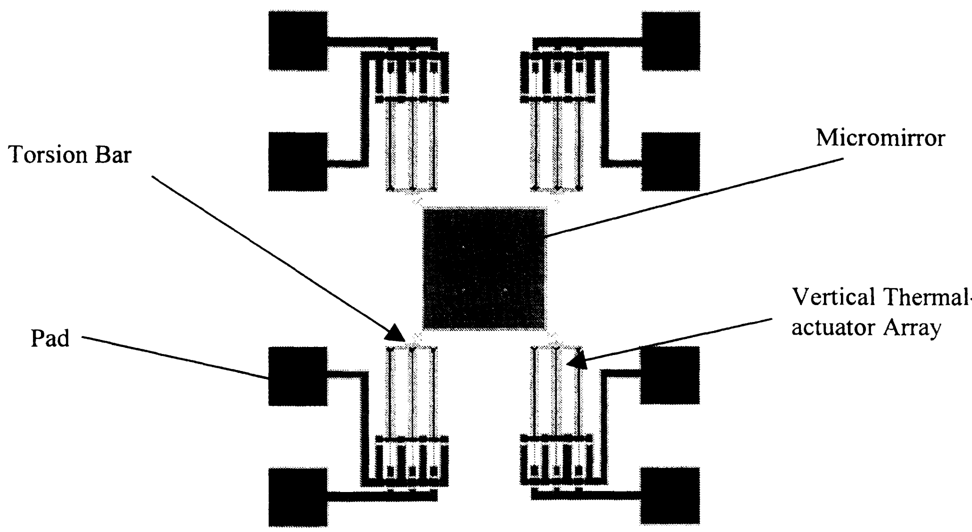

Figure 4 Layout of the Multiple DOF Micrmirror

4. SIMULATION

In order to predict the performance of designed micromirror device, we used the finite element method based ANSYS software to analyze the device. First, we use electro-thermal-mechanical coupled field function to predict the performance of the designed vertical thermal actuator. Upon obtaining the model of the actuator, a voltage from DC 0 ~ 8 V is applied to the pads. Figure 5 shows the animated displacement of the vertical thermal actuator when we applied DC 5V. Here, we observe that the displacement at the tip of actuator is about 6 μ m. The relation between the applied voltage and the corresponding vertical displacement is given in Fig. 6. With the basic vertical thermal actuator, we then proceed to form the micromirror device. As shown in Fig. 7, for the piston motion, the mirror would elevate as we increased the applied voltage. The maximum vertical displacement is 10.4 μ m with applied voltage equal to DC 8V. For the tilt motion as shown in Fig. 8, with DC 8V, we obtained approximately 7 μ m at forces activated end. One may notice that the vertical displacement in piston motion is greater than tilt motion. This is due to the fact that the forces for tilt motion need to sustain both the weight of the mirror and the stiffness from the supported bars.

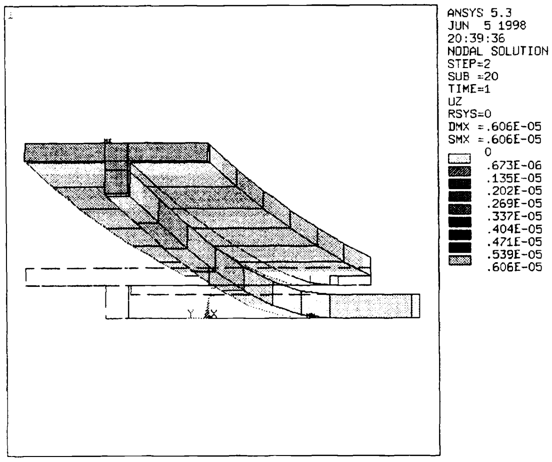

Figure 5 Simulation Result of Vertical Thermal Actuator

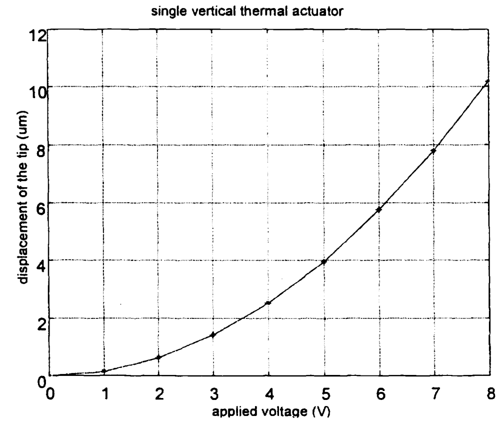

Figure 6 Applied Voltage Vs. Displacement

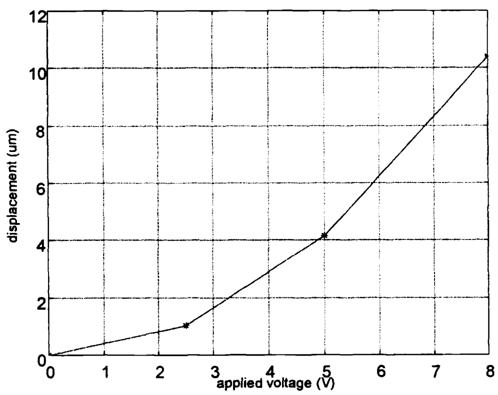

Fig. 7 Applied Voltage Vs. Displacement for Piston Motion

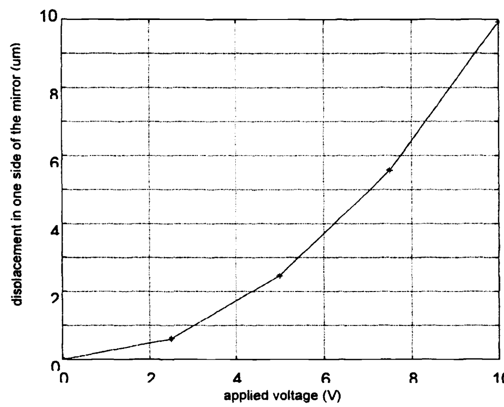

Fig. 8 Applied Voltage Vs. Displacement for Tilt Motion

5. EXPERIMENT

The final fabricated micromirror devices are shown in Fig. 9 and 10. Fig. 9 has demonstrated the movement of the vertical thermal actuator. Here, the upper one is driven with a DC 5V and the bottom one is remained unloaded. Because of the depth of focus from the microscope, we can clearly see the movement of the upper actuator that has vertical displacement. Although not reported here, various dimension of vertical thermal actuators have been designed, fabricated and tested. Fig. 10 shows the designed micromirror device after we completed the release process. In order to test the micromirror device, a measurement system is assembled. Fig. 11 shows the schematic diagram of the measurement system. A He-Ne laser beam with diameter of 3 mm was de-magnified by lenses L1 (with focal length of 84 cm) and L2 (with focal length of 5 cm) which formed a telescopic structure. The diameter of the condensed beam was ~180 μm. Thus, the size of the condensed laser beam can match with the size of the vibration mirror (~200 μm) and is still a collimated beam. The condensed beam was incident on the vibration mirror and then reflected. In addition, a screen with a scale ruler was placed on the track of reflecting beam and was used to measure the scanning angle. When the distance between the vibration mirror and the screen d is known, the scanning angle can thus be written as,

$$\Delta\theta = \frac{\Delta x}{2d}$$

where Δx is the shift-distance of the laser spot on the screen when the driven signal is applied on the vibration mirror. In the present experiment, we measured the scanning angle as a function of the driven frequency (a sinusoid wave at DV 8 V). The result is given in Fig. 12. From Fig. 12, we observed that when the driven frequency is lower than 200 Hz, we have obtained the maximum scanning angle at 2.5 degrees. The corresponding vertical displacement at the actuation end is about 8μm which is closed to the numerical simulated result at 7 μm. Note that the scanning angle is consistently decreased to 0.4 degree as we increased the driven frequency from 100 Hz to 10K Hz. However, a peak angle at 1.3 degree is observed as the driven frequency reached 19K Hz. We interpret this frequency as the resonate frequency of the micromirror device for the tilt motion for the reason that the system consisted of thermal (1st order system) and mechanical (2nd order system) characteristics. As the frequency is increased, the frequency from thermal effect gradually falls behind the frequency from the mechanical effect that causes the scanning angle to decrease. As the driven frequency keep on increasing to a certain frequency that excites the resonate frequency of the mechanical supported torsion bars. Although not shown here, similar result is also obtained for the piston motion. Note that different scanning angles can be obtained by varying the size of the mirror.

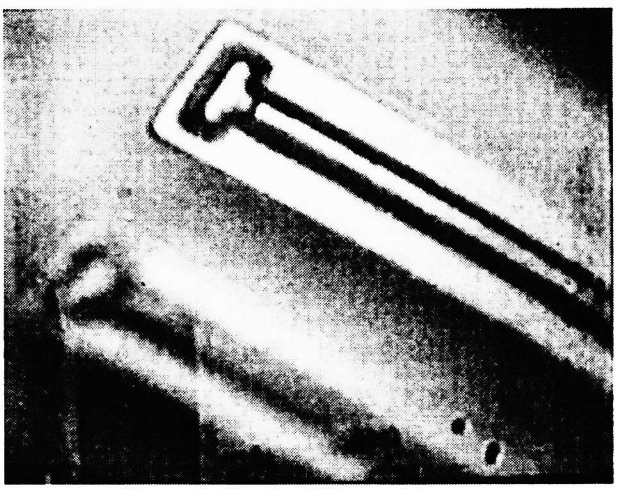

Figure 9 Vertical Thermal Actuators

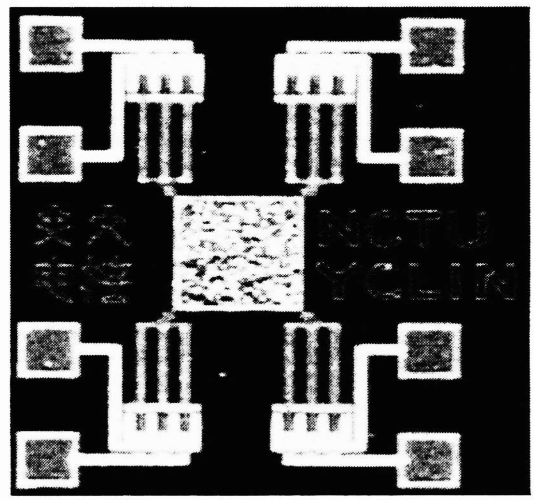

Figure 10 The Micromirror Device

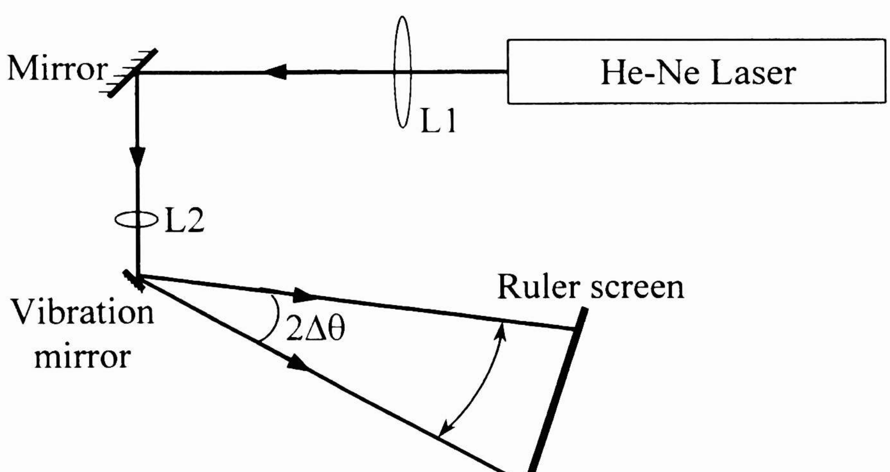

Figure 11 Schematic Diagram of the Measurement System

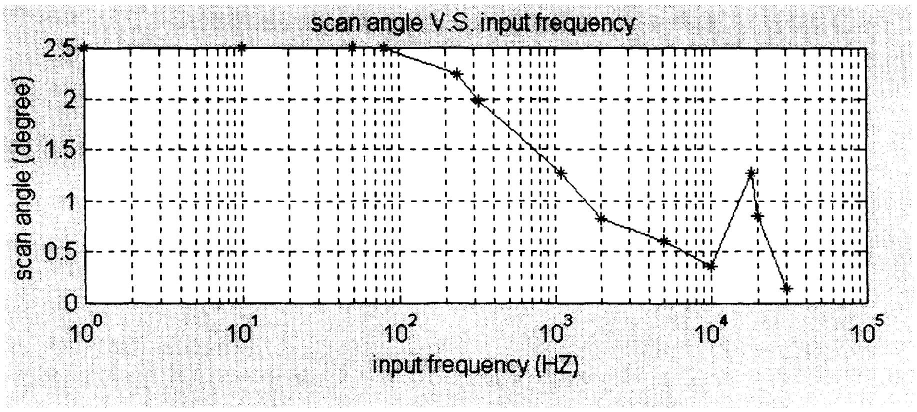

Figure 12 Frequency Vs. Scanning Angle (DV 8V)

6. CONCLUSION

A micromirror device that possesses multiple DOF has been designed and fabricated by using surface micromachining technology (MUMPs). The device consists of a micromirror, four vertical thermal-actuator arrays and four torsion bars that connect the mirror and the actuator. To demonstrate the feasibility of the vertical thermal actuator and the micromirror device, numerical simulations and realistic fabrication have been carried out. Experiments have indicted that the present designed matched closely with the numerical simulations. Through the designed, a compact, extremely light in weight, potentially low cost, and operating in very low voltage (<DC 10V) micromirror device is obtained. Note that, these devices can be used to form an array with independent controlled micromirrors. These micromirror arrays can be used for bar-code scanner, three-dimensional projector and optical display.

7. REFERENCE

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