LOW VOLTAGE AND PULL-IN STATE ADJUSTABLE DUAL-SERVO-SCANNING-MIRROR

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Abstract –*This paper reports a new dual-servo-scanning-mirror, which makes use of thermal and electrostatic driving principles. By tuning loading of the thermal and electrostatic actuator individually, one can increase the scanning-angle of the mirror.*

INTRODUCTION

Micromirrors are becoming more and more relevant, particularly for the display and telecommunication industry [1-7]. Usually, large continuous scan ranges are required to achieve high-resolution display or high channel count optic multiplexers. In addition, low voltage is desired to reduce the cost of drive electronics. Some elegant devices have been proposed to achieve this goal, e.g. [2,10,12]. However, because of the constraints on the geometry associated with mirrors and electrostatic actuators, it is still challenging to achieve large static tilting-angle from large mirrors with low driving voltage [3-7]. This paper reports on the first investigation to design, build and characterize an electrostatic and thermal dual-servo-scanning micromirror for reflective optical switching or scanning.

DESIGN OF THE DUAL-SERVO-SCANNING MIRROR

The dual-servo mirror is shown in Figure (1). The thermal and the electrostatic actuators are connected to the mirror through torsional springs. Figure (2) shows the scanning electron microscope (SEM) image of the torsion spring.

Thermal Actuator

The chevron thermal actuator consists of 32 symmetric thermal expansion members at an angle of 14.5degrees. Each of them has a length of 230μm. Tapered thermal expansion members have been used to improve the thermomechanical performance [8]. They are narrow near the edge (2.8 μm) and wide at the center (5.5um). The members are laminated from MUMPs poly1 and poly2 to create 3.5μm tall structures that increase the thermal force and prevent out-of-plane buckling. These members are heated by current from electrical contact pads anchored to the substrate. When thermal stress pulls a cold linkage beam, connected from the thermal actuator to the electrostatic actuators, the mirror undergoes upward tilting.

Electrostatic Actuator

The electrostatic actuator consists of four bimorph beams, composite of poly2 and gold, 250μm length and 23μm width. The residual stress within the beam curls the beam upward from the substrate, which yields a gradually ascending gap between the beam and substrate from the clamped edge. This kind of gap design can provide relatively large displacement [9]. The mirror also performs as a part of the electrostatic actuator that has large surface area, 250 by 250μm size, connected to the curved beam with an extended soft spring to decrease the driving voltage. An applied voltage tilts the mirror downward. The mirror is composite of poly1, embedded oxide2, poly2 and gold. A sandwiched oxide layer provides the thickest freestanding structure, which increases the moment inertia of the mirror, thus improving the mirror flatness under thermal residual stress generated from the microfabrication process.

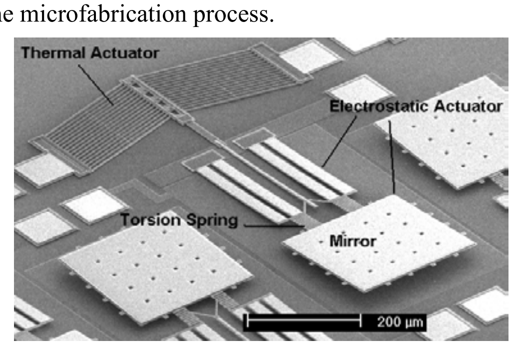

Figure 1: The dual-servo mirror

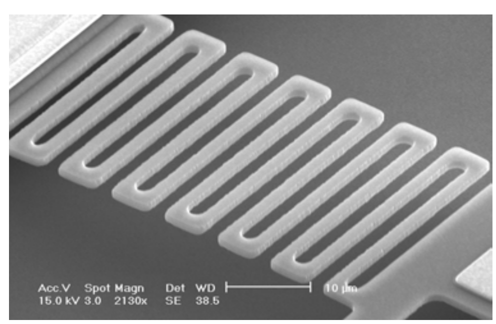

Figure 2: The extended torsion spring

MECHANICAL PERFORMANCE

Switch Characteristic

Three different driving modes have been investigated: thermal mode, electrostatic mode and dual-servo mode. The thermal actuator drives the curved bimorph beam up and the electrostatic actuator drives it down. Associated with these two movements, the mirror can sweep out larger optic angles than in single mode actuation. The DC switch characteristic is plotted in Figure (3). Under the thermal mode, the mirror can tilt up 5.5° with power input of 764mW. Under the electrostatic mode, the mirror can snap down 3.5° with only 6.2 volts. By controlling the thermal and electrostatic actuator individually, we can increase the scanning optic degree up to 18°. We observed natural resonance frequency at 416Hz under the thermal actuated cycle, Figure (4). It is very close to the theoretic estimation (see below). Electrostatic actuators with lower pull-in voltage, which are more close to the substrate at the initial point, show more squeeze film damping. After 4.9×10^{7} (49 millions) cycles under resonance in the thermally actuated mode no fatigue has been observed.

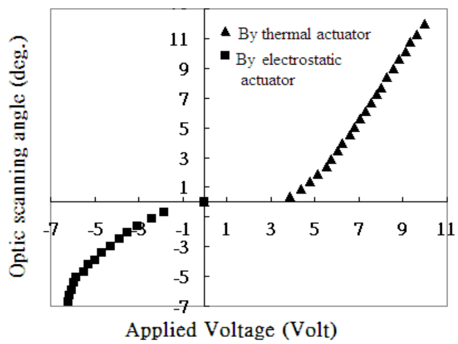

Figure 3: The DC switch characteristics

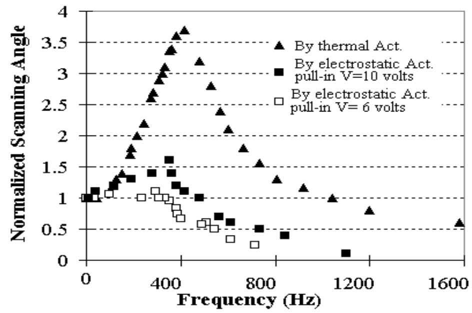

Figure 4: Frequency response by using the thermal and electrostatic actuator to drive the mirror. The measured natural frequency is 416Hz. The electrostatic actuator with lower pull-in voltage shows more squeeze film damping.

Dual-servo-scanning Mode

The static tilting characteristic of the mirror under dual-servo-mode can be found in Figure (5). By adjusting the voltage on the thermal actuator we can control the pull-in voltage of the electrostatic actuator, see Figure (6).

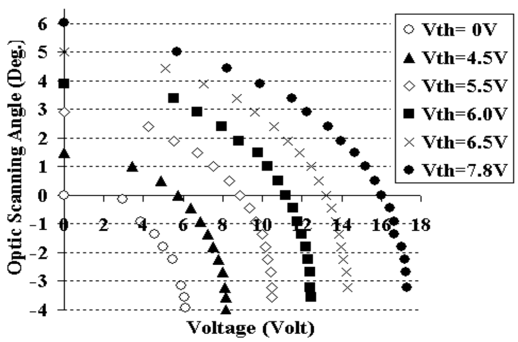

Figure 5: The switch characteristics under the dual-servo-scanning mode (Vth = thermal voltage)

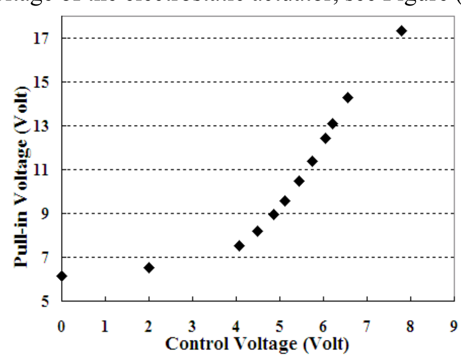

Figure 6: Control (thermal) voltage vs. pull-in voltage

NATURAL FREQUENCY ANALYSIS

Assuming the springs are ideal torsion springs (linear, mass can be neglected), the natural frequency of this system will be a function of the spring constant of the torsion spring and the mass of the mirror. The torsional spring constant is represented in equation (1). With the equivalent moment of inertia of the mirror (2), we can estimate the natural frequency of the mirror (3).

$$k_\theta = 2GJ\ /\ L \qquad (1)$$

$$I_{eq} = M_m R^2 + I_m \qquad (2)$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{I_{eq}}{k_\theta}} \qquad (3)$$

Here k_θ is the spring constant of the torsion spring. G is the elastic shear modulus of polysilicon. J is the torsion constant of each spring. L is the effective length of each torsion spring. I_{eq} is the equivalent polar moment of inertia of the mirror. M_m is the mass of the mirror. R is the distance from the center of the mirror to the end of the torsion spring. f_n is the natural frequency. The natural frequency of the system obtained from this approximation is 427 Hz. It is very close to the test result of 416 Hz.

CONCLUSION

We achieved large optical scanning angles with low voltages (<10V) for a large MEMS mirror. The dual-servo-system also demonstrated adjustability of the electrostatic pull-in voltage and the squeeze film damping with an electrothermal actuator. A comparison of this mirror to some of the published micromirrors is listed in Table 1.

Table 1 Micromirror

Device (Actuation technologies)	Mirror Size	Voltage (Volt)	Max. static angular deflection (deg.) (before pull-in)	Fabrication Processes	Ref.
Dual-servo mirror	250×250μm	10	(9)	PolySi MUMPs	This work
Hidden vertical comb-drive	137×120μm	6.0	(11.8)	SUMMiT-V (1μm minimum feature)	[2]
Dual-mode comb	100×300μm	20	(1.87)	PolySi surface micromachining	[3]
Rotational comb	500×700μm	90.0	(10)	DRIE on SOI	[4]
Solder self-assembled electrostatic mirror	250×250μm	150.0	11	PolySi MUMPs	[5]
Electrostatic actuation + 4-bar mechanism	500-2000μm square	100.0	(16)	CMOS, DRIE Wafer Thinning	[6]
Angular comb drive	r=1000μm	110.0	(3.4)	DRIE on SOI	[7]
Bent-beam actuation	100×90μm	50.0	14	Surface + Bulk (DRIE)	[10]
Digitally positioned micromirror	120×120μm	15.0	(7)	PolySi MUMPs	[11]

"()" means the mirror can be driven to both directions (clockwise + counterclockwise).

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