Micro-optical Components for a MEMS Integrated Display

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This paper summarizes the results from our previously published researches on reflective and transmissive optical switches for MEMS integrated display systems. They include a dual-servo-scanning mirror and a transmissive zigzag electrostatic micro-optical switch. It also introduces a new process for making a microlens array. These are three key components for a MEMS display system.

I. Introduction

Today, Cathode Ray Tube (CRT) and Liquid Crystal Display (LCD) are the two mainstream display technologies. Plasma display panels (PDP) are thinner than CRT displays and brighter than LCD with good contrast ratio, contributing to the rapid growth in the wall display market. However, each display technology can address only a limited market segment, according to its characteristic advantages and limitations. Microelectro-mechanical display systems are attracting a lot of attention because of their potentially low power consumption, higher contrast ratio and cost effectiveness [1]. Several optical MEMS based display technologies have been proposed such as DLP [2], GLV [3], IMod [4], Gyricon [5] and LCOS [6]. Among these technologies, the major challenge in commercialization of MEMS displays is the cost of the production and packaging. Thus, the next generation of MEMS displays must include key components developed for the improvement of device performance and the reduction of manufacturing costs. This paper summarizes the results from our previous published papers on reflective [7] and transmissive [8] optical switches, as well as microlens arrays for MEMS integrated display systems. They are three key components for MEMS, including:

1) a dual-servo-scanning mirror, which makes use of thermal and electrostatic driving principles for low voltage large static tilting-angle reflective optical switching or scanning;
2) a transmissive zigzag electrostatic micro-optical switch (TMOS);
3) and a process for making microlens arrays without expensive processing costs for fabrication.

The prototypes of reflective and transmissive optical switches are fabricated in the Cronos MUMPs® foundry process.

II. Dual-Servo-Scanning Mirror

Micromirrors are one of the critical components for the display and communication industries. Usually, large controllable scan ranges are required to achieve high-resolution displays or high channel count optic multiplexers. In addition, low voltage is desired to reduce the cost of drive electronics [9,10]. However, because of the constraints on the geometry associated with mirrors and electrostatic actuators, it is still challenging to achieve a large static tilting-angle from large mirrors with low driving voltage. [11-14]. The dual-servo mirror shown in Figure 1 has a thermomechanical in-plane microactuator (TIM) and an electrostatic actuator, which can drive the mirror in two opposite directions, upward and downward to increase the scanning angle. The thermomechanical actuator has tapered members [15] for better performance. When current heats these members, the thermal expansion force pulls the electrostatic actuator and the mirror upward. The electrostatic actuator consists of four bimorph beams curled by residual stress from the MUMPs process with gradually ascending gap between the beam and substrate. The mirror performs as part of the electrostatic actuator; it has large surface area connected to the curved beam with torsional springs to increase the driving force. Three different driving modes have been investigated: thermal mode, electrostatic mode and dual-servo mode. Under the thermal mode, the optic scanning angle has an almost linear relationship to input power. The mirror can tilt up 5.5° (optical scanning angle = 11.0°) with power input of 764mW. Under the electrostatic mode, the mirror can snap down 3.6° with only 6.2 volts. By controlling the thermal and electrostatic actuator individually, we can increase the optical scanning angle to 18° (Figure 2). We observed natural resonance frequency = 416Hz, which agrees with the theoretic approximated value [7]. After 4.9×10^{7} (49 million) cycles under resonance at 6.1 volts in the thermal mode, no fatigue has been observed. By controlling the voltage of thermal actuators, one also can adjust the pull-in voltage of the electrostatic actuator (Figure 3).

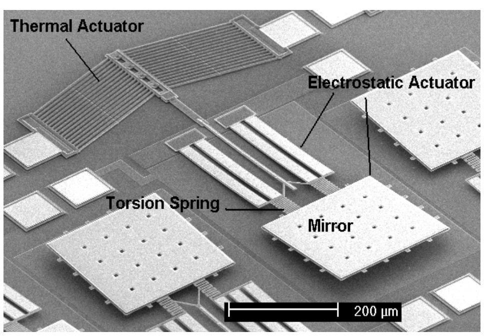


Fig.1 The dual-servo mirror.

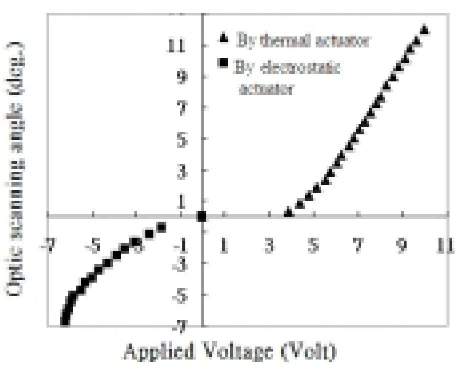


Fig.2 DC switch characteristics.

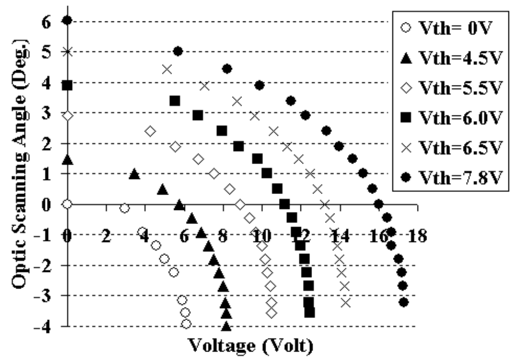


Fig.3 The switch characteristics under the dual-servo-scanning mode (Vth = thermal voltage).

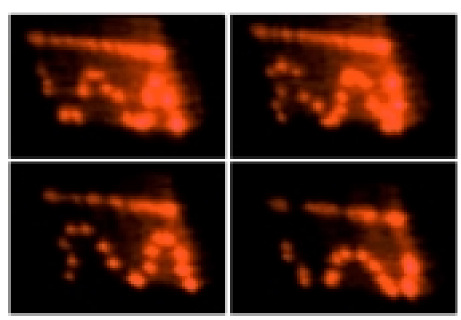


Fig.4 Some simple patterns displayed on screen by dual servo mirror.

By driving this mirror and a coil actuated mirror under raster-scanning mode with time-modulated laser by Labview controlled circuits, one can generate some simple patterns (Figure 4) on a screen (10×10 pixels).

Reflective technologies for MEMS displays usually have high space efficiency. Reflective MEMS projectors [2] work well in dark places such as movie theaters and dim conference rooms. MEMS transmissive micro-optical switch (TMOS) technology does not require a polarized plate, thus it can reduce the optical loss and yield a bright, power saving display. It also can totally block the light by fully opaque shutters to create black pixels with very good contrast ratio. Actuators for a transmissive display cannot share their working space with the light path; otherwise they may block the light. Thus, it is very difficult to design a transmissive optical switch for a highly space efficient (high pixel density) display. However, the particularities of transmissive micro-optical switches, i.e., low optical absorption and loss, make them very attractive to next generation display technologies.

III. ZIGZAG TRANSMISSIVE ELECTROSTATIC MICRO-OPTICAL SWITCHES

Transmissive micro-optical switches (TMOS) have great potential for optical networks [16-19] but current designs are generally too space-consuming for these applications. Thus, the critical design challenges are small size, large shutter motion, good optical contrast, low optical loss and high switching speed. We developed zigzag TMOS for a MEMS integrated display system (Figure 5) to simultaneously achieve these design goals. Each TMOS represents one pixel with 150µm×150µm spacing in a display module. The optic switch (Figure 6) consists of an electrostatic "zigzag" actuator pair, overlapping shutters and a miniaturized optical tunnel; its geometry is determined from the diffraction spot size and the numerical aperture of the microlens system. The zigzag actuator makes efficient use of the available space by simultaneously increasing

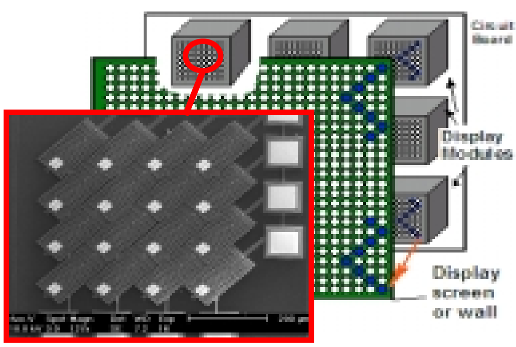


Fig.5 The space-efficient transmissive optical switch is at the heart of our integrated MEMS optical display system.

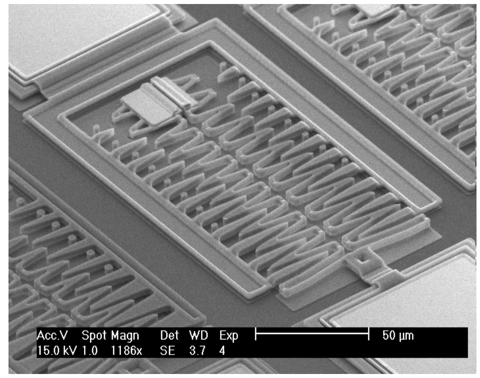


Fig.6 SEM of one TMOS confined to 108µm × 188µm area. It consists of dual zigzag actuators; each one takes 47µm × 160µm of space.

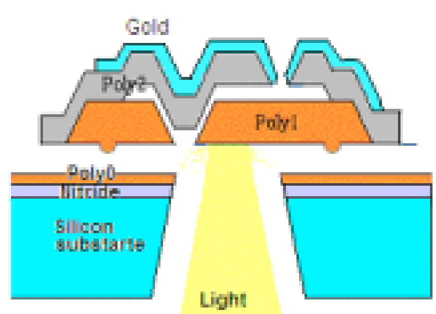


Fig.7 The cross-section of a shutter made from Poly1, Poly2 and Gold. The optical tunnel is dry etched by DRIE and RIE for light transmission focused from a microlens.

the driving force and decreasing the spring stiffness to increase the deflection. The shutters driven by the zigzag actuator (Figure 7) are made from overlapping polysilicon, covered with a 0.5µm gold layer as the opaque material. The prototypes were fabricated in Cronos MUMPs®, with post-processing, which included backside mechanical and chemical polishing, double-side-aligned DRIE based optical tunnel etching, 49% HF sacrificial oxide removal and supercritical point drying. The process ended with PECVD (C_3F_6) hydrophobic fluorocarbon polymer coating to reduce in-use stiction and to provide electrical isolation.

A pair of zigzag actuators controls an 18µm×22µm opening at 38-130V with large controllable static displacement, depending on the zigzag geometry and zigzag electrode thickness combinations [8] (Figure 8). We observed natural frequencies up to 18.6 kHz. Optical test results showed that the shutter can effectively turn the light beam on and off with very good contrast ratios (Figure 9).

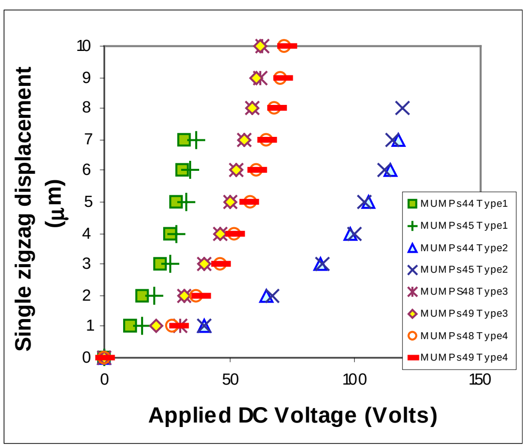
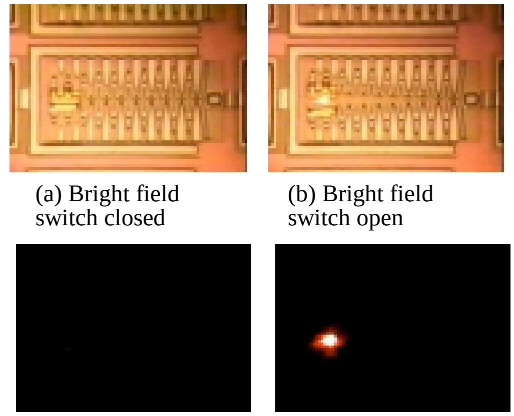


Fig.8 Experimental results show the displacement of zigzag actuators immediately before pull-in.

To reduce the optical loss and scattering, the light will be focused through a microlens array before being modulated by TMOS.



(a) Bright field switch closed (b) Bright field switch open

(c) Dark field switch closed (d) Dark field switch open

Fig. 9 Optical test results show that TMOS can achieve near-ideal contrast ratio.

IV. MICROLENS ARRAY

Microlens arrays are critical optical elements in the field of microdisplays, communications and datastorage systems. There are various methods that can produce microlens arrays including etching [20], reflow [21], microjet [22], and micromolding [23] methods. Among these methods, one of the biggest challenges is to produce a micolens array with high surface coverage ratio. The coverage ratio is defined as the total lens coverage area vs. total array area. A higher surface coverage area implies lower optical loss and higher focusing efficiency. We present a time-multiplexed plasma-etching method which achieves fabrication of paraboloidal mirrors as molds for high surface coverage microlens arrays by choosing the appropriate opening and spacing of the etching windows with carefully controlled timing [24]. Each array consists of 70×70~100×100 micromolds for lens arrays.

The time-multiplexed plasma-etching scheme of the mold, which includes two SF_6 plasma etch steps and one oxygen plasma etch step, is shown in Figure 11. Unlike deep reactive ion etching (DRIE), there is no passive cycle in this process, thus, there is no scalloping encountered on silicon

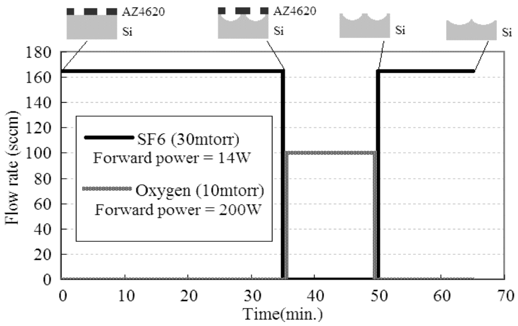


Fig.10 Time-multiplexed plasma-etching scheme.

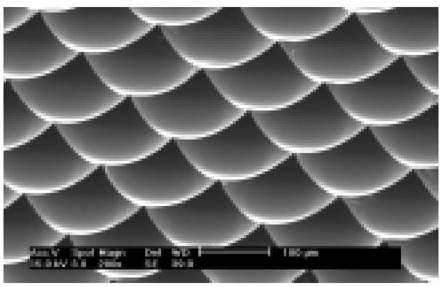


Fig.11 The silicon mold made from time-multiplexed plasma-etching.

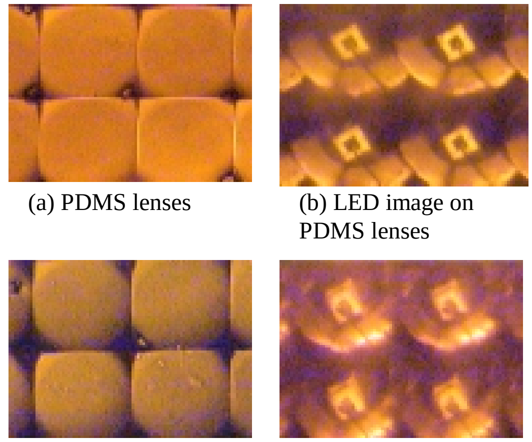
sidewalls. A smooth surface can be obtained for molding.

The first master mold for microlens arrays is duplicated from the time-multiplexed plasma-etched silicon mold by two step micromolding process of Reprorubber from Flexbar Machine Corp. Reprorubber is a non leaching or outgassing casting material. This metrology-grade casting material can reproduce molds with zero shrinkage.

After the rubber-master mold is ready, various optical polymers or resin such as PDMS, SU8 resin or other UV curing polymers can be applied on top of it to fabricate a polymeric microlens array. A comparison of these lens materials is listed in Table 1. The results are shown in Fig.12.

Table 1. The optical index of molding materials

Molding Material	PDMS	SU8	Norland Optical Adhesive
Optical Index	1.4-1.6	1.6 – 1.8	1.54-1.56



(a) PDMS lenses (b) LED image on PDMS lenses

(c) UV cured lenses (d) LED image on UV cured lenses

Fig.12 Microscopic images of molded microlenses.

V. Conclusion

A dual-servo-scanning mirror, a transmissive zigzag micro-optical switch and a new process of making a microlens array have been introduced. They are key components for MEMS display systems. Future work will be integrating these components into a complete system.

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References

[1] C. W. Mclaughlin, “Progress in projection and large-area displays,” *IEEE Proceedings*, vol. 90, no. 4, pp. 521-532, April 2002.

[2] L. J. Hornbeck, “Digital light processing for high-brightness, high-resolution applications,” *Electronic imaging, projection displays III*, 10-12, February 1997.

[3] R.W. Corrigan, D.T. Amm, C.S. Gudeman, “Grating light valve technology for projection displays,” *International Display Workshop*, Kobe, Japan, Paper Number LAD5-1, 9, December 1998.

[4] S. Bains, "Micromechanical display uses interferometric modulation," *Optical engineering report SPIE*, no. 199, July 2000.
[5] http://www2.parc.com/dhl/projects/gyricon/
[6] http://www.schott.com/digitalprojection/english/products/technology/lcos.html
[7] K. Wang, K. F. Böhringer, M. Sinclair, "Low Voltage and Pull-in State Adjustable Dual Servo Scanning Mirror." *The 5th Pacific Rim Conference on Lasers and Electro-Optics CLEO/Pacific Rim*, Taipei, Taiwan, December 2003.
[8] K. Wang, K. F. Böhringer, Mike Sinclair, Gary Starkweather, "Highly space-efficient electrostatic zigzag actuator for transmissive micro-optic switches." *Transducers'03*, Boston, USA, pp. 572-575, June 2003.
[9] D. Hah, S. Huang, H. Nguyen, H. Chang, J. Tsai, and M. C. Wu, "Low voltage MEMS analog micromirror arrays with hidden vertical comb-drive actuators", *Solid-State Sensor, Actuator and Microsystems Workshop* Hilton Head Island, South Carolina, June 2-6, pp.11-14, 2002.
[10] Y. Xie and C. T. Nguyen, "A low-voltage tiltable microplatform using bent-beam actuation", *Solid-State Sensor, Actuator and Microsystems Workshop*, Hilton Head Island, South Carolina, pp. 329-332, 2002.
[11] U. Krishnamoorthy, K. Li, K. Yu, D. Lee, J.P. Heritage, O. Solgaard, "Dual-mode micromirrors for optical phased array applications", *Sensors and Actuators*, vol. 97-98, pp. 21-26, 2001.
[12] O. Tsuboi, Y. Mizuno, N. Koma, H. Soneda, H. Okuda, S. Ueda, I. Sawaki and F. Yamagishi, "A rotational comb-driven micromirror with a large deflection angle and low drive voltage", *Proceedings of the IEEE MEMS, Las Vegas, NV*, pp. 532-535, 2002.
[13] J. H. Smith, S. S. Nasiri, J. Bryzek, M. Novack, J. B. Starr, H. Kwon, A. F. Flannery, D. L. Marx, Z. Chen, and E. Sigari, "1200 mirror array integrated with CMOS for photonic switching: application of mechanical leveraging and torsional electrostatic actuation to reduce drive voltage requirements and increase angular tilt", *Solid-State Sensor, Actuator and Microsystems Workshop*, Hilton Head Island, South Carolina, pp.378-379, 2002.
[14] D. Hah, S. Huang, H. Nguyen, H. Chang, J. Tsai, and M. C. Wu, "A scanning micromirror with angular comb drive actuation", *Conference on Optical Fiber Communication, Technical Digest Series*, vol.70, pp. 544-547, 2002.
[15] M. Sinclair and K. Wang, "Folded and Tapered-Beam Thermal Actuator", *SPIE Smart Sensors, Actuators, and MEMS*, Canary Islands, 2003.
[16] J.D. Grade, H. Jerman, T.W. Kenny, "A large-deflection electrostatic actuator for optical switching application", pp. 97-100, *Sensor and Actuator Workshop*, Hilton Head Island, June 4-8, 2000.
[17] G. Perregaux, S. Gonseth, P. Debergh, J. P. Thiebaud, H. Vuilliomenet, "Arrays of Addressable High-Speed Optical Microshutters", *Proc. IEEE MEMS*, pp. 232-235, 2001.
[18] J. Li, Q.X. Zhang and A.Q. Liu, Advanced fiber optical switches using deep RIE (DRIE fabrication), *Sensors and Actuators A*, vol. 102, pp. 286-195, 2003.
[19] M. Hoffmann, P. Kopka, T. Grob and E. Voges, "Optical fibre switches based on full wafer silicon micromachining", *J.micromech. microeng.*, vol. 9 , pp. 151-155, 1999.
[20] M.B. Stern T.R. Jay, Dry etching for coherent refractive microlens array, *Opt. Eng.* vol.33, pp.3547-3551, 1994.
[21] Y. Lin, C. Pan, K. Lin, S. Chen, J. Yang and J. Yang, "Polyimide as the pedestal of batch fabricated micro-ball lens and micro-mushroom array," *MEMS 2001 14th IEEE Int. Conf.*, pp. 337-340, 2001.
[22] S. Moon, N. Lee and S. Kang, "Fabrication of a microlens array using micro-compression molding with an electroformed mold insert", *J. micromech. microeng.*, vol. 13 , pp. 98-103, 2003.
[23] S. Moon and S. Kang, "Fabrication of polymeric microlens of hemispherical shape using micromolding" *Opt. Eng.*, vol 41, pp.2267-2270, 2002.
[24] K. Wang, K.F. Böhringer, "Time-multiplexed plasma etching of high numerical aperture paraboloidal micromirror arrays." *The 5th Pacific Rim Conference on Lasers and Electro-Optics CLEO/Pacific Rim*, Taipei, Taiwan, December 2003.