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 \cite{1}. Several optical MEMS based display technologies have been proposed such as DLP \cite{2}, GLV \cite{3}, IMod \cite{4}, Gyricon \cite{5} and LCOS \cite{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 \cite{7} and transmissive \cite{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\textsuperscript{®} 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 \cite{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 $4.9 \times 10^7$ (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).
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 150×150 µm 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 (C₃F₆) 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).

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 microlens 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 SF₆ 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.8 Experimental results show the displacement of zigzag actuators immediately before pull-in.](image1)

![Fig. 9 Optical test results show that TMOS can achieve near-ideal contrast ratio.](image2)

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

(c) Dark field switch closed (d) Dark field switch open
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>
<thead>
<tr>
<th>Molding Material</th>
<th>PDMS</th>
<th>SU8</th>
<th>Norland Optical Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Index</td>
<td>1.4-1.6</td>
<td>1.6 – 1.8</td>
<td>1.54-1.56</td>
</tr>
</tbody>
</table>

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.

ACKNOWLEDGEMENT

The authors acknowledge the support from Microsoft Research and from the National Science Foundation (REU). The authors would like to thank Gary Starkweather for his helpful discussion.

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