Introduction to Micro-Electro-Mechanical Systems (MEMS) with Emphasis on Optical Applications

Adisorn Tuantranont and Victor M. Bright

NSF Center for Advanced Manufacturing and Packaging
of Microwave, Optical, and Digital Electronics (CAMPMODE),
University of Colorado at Boulder, CO, USA 80309-0427
Adisorn.Tuantranont@colorado.edu (e-mail); Tel: (303) 735-1763; Fax: (303) 492-3498

ABSTRACT -- Micro-Electro-Mechanical Systems, or MEMS, are integrated micro devices or systems combining electrical and mechanical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from micrometers to millimeters. These systems can sense, control and actuate on the micro scale, and function individually or in arrays to generate effects on the macro scale. This paper presents an overview of MEMS technology with emphasis on optical applications. Applications of MEMS devices vary in many fields from automotive transducers, biomedical technologies, communication systems, robotics, aerospace, micro-optics, industrial sensors and actuators. The applications of MEMS in optics include display systems, optical switching, optical communication, optical data storage, optical processing and interconnection, and adaptive optics. Examples of micro-optical components and systems are described in this paper.

KEY WORDS: MEMS, MOEMS, micromachining, micro-optics, sensor, actuator

บทคัดย่อ -- ระบบจุลภาคไฟฟ้า - เครื่องกล (MEMS) คือประดิษฐ์กรรมขนาดไมโครมิเตอร์ซึ่งรวมส่วนประกอบของระบบไฟฟ้าและเครื่องกลเข้าด้วยกัน ระบบจุลภาคไฟฟ้าเครื่องกลสร้างโดยอาศัยเทคโนโลยีการผลิตวงจรทรานซิสเตอร์ซึ่งมีขนาดตั้งแต่ไมโครมิเตอร์ถึงมิลลิมิเตอร์ ระบบดังกล่าวนี้สามารถตรวจวัด,ควบคุมและกระตุ้นในระดับต่ำและสามารถทำงานทั้งในแบบอิสระหรือแบบขบวนเพื่อให้มีผลในระดับสูงขึ้น บทความนี้กล่าวถึงภาพรวมของเทคโนโลยีระบบจุลภาพไฟฟ้า-เครื่องกลและการนำไปใช้ประโยชน์โดยเน้นการใช้ประโยชน์ทางด้านแสง การใช้ประโยชน์ของระบบนี้สามารถใช้ได้ในหลายสาขา อาทิ เทคโนโลยียนตกรรม เทคโนโลยีการแพทย์ชีวภาพ เทคโนโลยีระบบสื่อสาร ระบบหุ่นยนต์ ระบบอากาศยาน เป็นต้น การใช้ประโยชน์ทางด้านแสงสามารถนำไปสร้างระบบการแสดงผล ระบบการสับเปลี่ยนทางแสง การสื่อสารด้วยแสง การเก็บข้อมูลด้วยแสง การประมวลและเชื่อมต่อข้อมูลด้วยแสง รวมทั้งการปรับปรุงภาพทางดาราศาสตร์ ในบทความนี้ได้อธิบายถึงตัวอย่างของอุปกรณ์และระบบขนาดเล็กเกี่ยวกับแสง

คำสำคัญ -- ระบบจุลภาคไฟฟ้า - เครื่องกล, ระบบจุลภาคไฟฟ้าเครื่องกลทางแสง, กลจักรขนาดเล็ก, อุปกรณ์ขนาดเล็กเกี่ยวกับแสง, อุปกรณ์ตรวจวัด, อุปกรณ์กระตุ้น

1. Introduction

Trend toward smaller size, higher performance, and greater functionality for electronic devices is made possibly by the success of solid-state microelectronics technology. In the late 1980s, the silicon Very-Large-Scale-Integrated (VLSI) design and manufacturing was developed for use in field of Micro-Electro-Mechanical System (MEMS)[1]. This field is called by a wide variety of names in different parts of the world: micro-electro-mechanical systems (MEMS), microsystem technology (MST), micromechanics, and micro total analysis systems (μ-TAS) etc. These systems interface with both electronic and non-electronic signals and interact with non-electrical physical world as well as the electronic world by merging signal processing with sensing and/or actuation. Instead of dealing only electrical signals, MEMS also deals with moving-part mechanical elements, making miniature systems possible such as accelerometers, fluid-pressure and flow sensors, gyroscopes, and micro-optical devices. MEMS are designed using computer-aided design (CAD) techniques based on VLSI and mechanical CAD tools and typically batch-fabricated using VLSI-based fabrication process [1]. The commercial available surface and bulk micromachining such as Multi-User-MEMS process (MUMPs) at MCNC and MOSIS service respectively are widely used to fabricate prototype MEMS devices due to their low cost and short turn-around time. Post-processing such as cavity etching, silicon bonding and flip chip soldering can be applied to produce the more complex mechanical structures for suitable applications. An early application of MEMS was in the field of microsensor and microactuator for measuring or driving position, pressure, velocity, acceleration, force, torque, flow, magnetic field, temperature, gas composition, humidity, pH, fluid ionic concentration, and biological gas/liquid-/Molecular concentration. Some applications have been successfully commercialized in market such as thermal inkjet printer, automotive accelerometer, and high-resolution display projector.

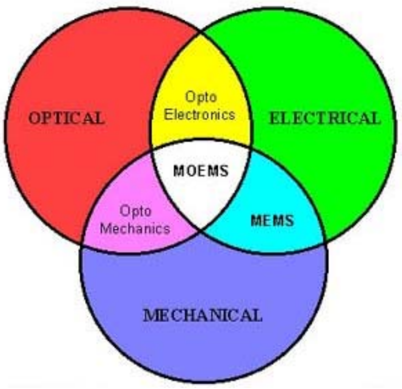

Figure 1. Schematic diagram shows interdisciplinary field of MOEMS

MEMS is also widely used to fabricate micro optical components or optical systems such as deformable micromirror array for adaptive optics, optical scanner for bar code scanning, optical switching for fiber optical communication etc. This special field of MEMS is called 'Micro-Opto-Electro-Mecha-nical Systems (MOEMS)'. This interdisciplinary field has to combine knowledge in optics, electronics, and mechanics to design and fabricate devices as shown in Fig.1.

2. Fabrication Technology

Batch IC fabrication technology is used to fabricate mechanical microstructures such as beam, spring, diaphragms, orifices, grooves, gears, linkages, and complex mechanical suspended flexure. MEMS devices can be divided into two fabrication classes: Surface micromachining and bulk micromachining.

2.1 Surface micromachining

Surface micromachining is an additive fabrication technique that involves the building of devices on the top surface of substrates. Specific structure parts of a device are encased in layers of a sacrificial material during fabrication process. The structural parts are released by chemical etchant dissolving of the sacrificial layers. Surface micromachining can be used to fabricate not only relatively conventional mechanical structure such as beams or diaphragms, but also more sophisticated ones such as gears, linkages, and micro-motors. Commercial polycrystalline silicon surface micromachining processes such as MUMPs (Multi-User-MEMS-Process) and SUMMiT (Sandia Ultra-planar Multi-level MEMS Technology) are available for prototyping MEMS designs. Multi-levels of doped or undoped polysilicon layers are used to form the mechanical structures and silicon dioxide layers are used as the sacrificial material. The schematic layout diagrams of MUMPs and SUMMiT surface micromachining fabrication were shown in Fig. 2 [2]. Electrostatic micromotor fabricated by surface micromachining was shown in Fig.3.

2.2 Bulk micromachining

Bulk micromaching is a subtractive fabrication technique that uses the substrate to form mechanical structure of MEMS devices. The single crystal substrate is etched in anisotropic

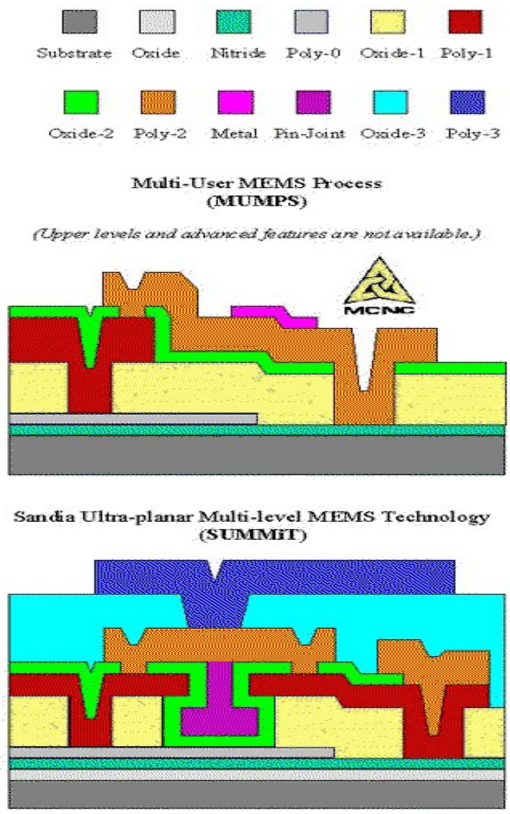

Figure 2. Surface micromachining fabrication (MUMPs and SUMMiT)

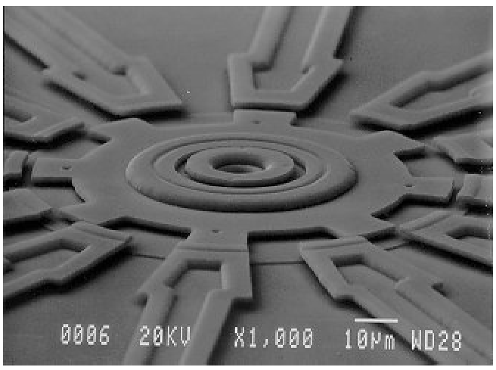

Figure 3. Electrostatic micromotor fabricated by MUMPs: diameter is 80 µm. (Courtesy of MCNC) (For reference, human hair diameter is 70-80 µm)

etchants such as potassium hydroxide (KOH) or ethylene-diamine pyrocatecol (EDP) along given crystal planes. The process is based on the fact that anisotropic etchants etch the <100> and <110> crystal plane significantly faster than the <111> crystal planes. In a <100> silicon substrate, anisotropic etching proceeds along <100> plane but practically stop etching at <111> plane, making a 54.7 degrees angle slanted wall in the etched cavity. The final size of etched cavity is controlled by the etch-mask opening or heavily boron-doped silicon etch-stop. Under-etching occurring where etch masks are misaligned with <110> direction can be used to fabricate suspended microstructure. The Miller indices indicated the plane of silicon crystal was shown in Fig.4. Fig. 5 shows the cavity anisotropic-etched by EDP.

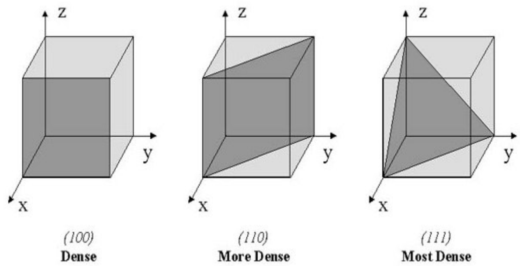

Figure 4. The Miller indices of silicon crystal plane

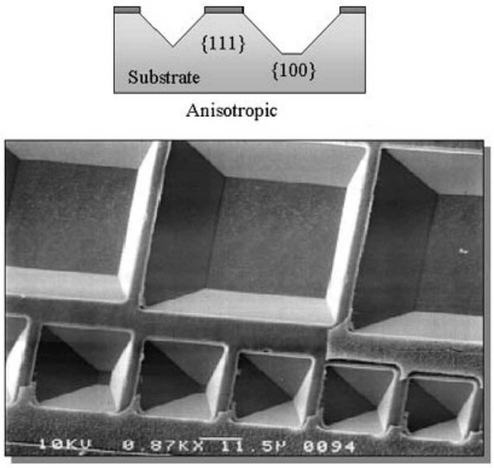

Figure 5. The etched cavity from anisotropic etching: cavity size ranges from 10-100 µm. (Bulk micromachining)

The design of MEMS device is limited by planar geometry of IC fabrication process. Three-dimensional structure or high aspect ratio (height to width) is difficult to fabricate by conventional IC process. The x-ray photolithography technique (LIGA) was developed to fabricate high aspect ratio structure over 100. Microgear and motor fabricated by LIGA were shown in Fig.6.

Post-fabrication processes such as bonding or flip chip soldering permit a silicon substrate to be attached to another substrate to provide added design flexibility and packaging possibility.

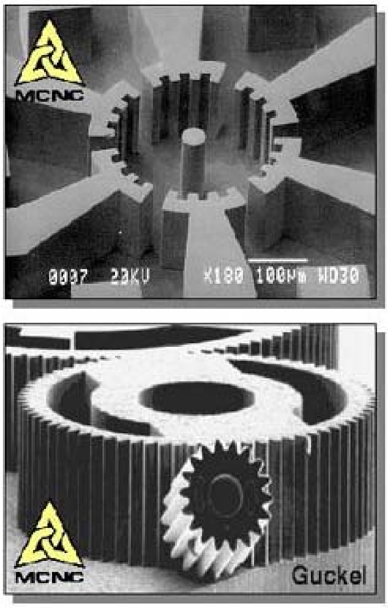

Figure 6. Micromotor components fabricated by high aspect ratio LIGA. Stator (upper figure) and rotor(lower figure). (Courtesy of MCNC)

3. Computer-Aided Design for MEMS

Computer-Aided Design and Engineering programs (CAD and CAE) have been recently developed to assist MEMS design easier. In MEMS technology, the design complexity is compounded by intimacy between mechanical and electronic performance.
Several commercially available software tools such as L-EDIT, Cadence, and MEMCAD can provide the layout tool for MEMS design. The MEMS-specific tools that are integrated into an environment where complete structural, as well as operational, analysis such as MEMCAD, CAEMEMS, and IntelliSuite have used to be design verification tools (e.g., solid modeling, finite element analysis, discretization, and visualization). These software tools have also proven useful for modeling a variety of parameters (e.g., displacement, stress, electric field, magnetic field, temperature, and fluid velocity) under a wide variety of conditions. Fig. 7 shows computer-users interface of MEMS CAD tool available in market.

Finite-element analysis (FEA) is one very powerful technique to model a variety of static and dynamic phenomena for a complex microstructure. Among them are mechanical stress-strain distribution, thermal distribution, frequency response, fluid flow, electromagnetic field and resonant frequency. Several commercially available software packages such as Ansys, Nastran, Cosmo, and Abaqus provide sophisticated modeling capabilities.

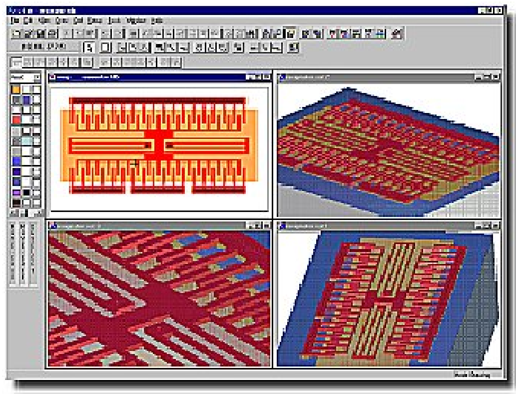

Figure 7. MEMS CAD tool for design, layout, and simulation (Courtesy of Tanner EDA)

4. Microactuators, Microsensors and Microsystems

4.1 Microactuator

Microactuators are component that converts energy into appropriate action capable of producing micron-scale motion. Microactuators can be classified into two classes: rigid microstructure and deformable microstructures. Rigid-type microactuators such as micromotors provide displacement and force through rigid-body motion [1].

Deformable microstructures such as beams and diaphragms provide displacement and force through mechanical deformation. Currently, the microactuation methods in common use are electrostatic, electromagnetic, piezoelectric and thermal. Fig.8 shows deformable mirror driven by electrostatic mechanism.

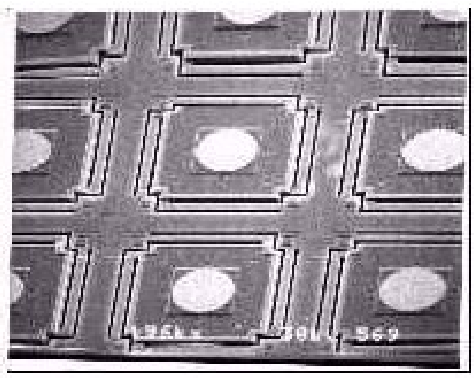

Figure 8. Electrostatic deformable micromirror array [4]

The electrostatic actuation uses the nature of electrostatic force provided by parallel plate capacitor structures or comb-finger structures. The attractive and repulsive forces generated by electric charge distribution are used to convert electrical to mechanical energy. The electrostatic actuated devices (e.g., micromirror array, microswitch, scanner, microshutter, micromotor) are widely used in varieties of fields. Fig.9 shows the commercially available micromirror array for display projection developed by Texas Instrument, USA.

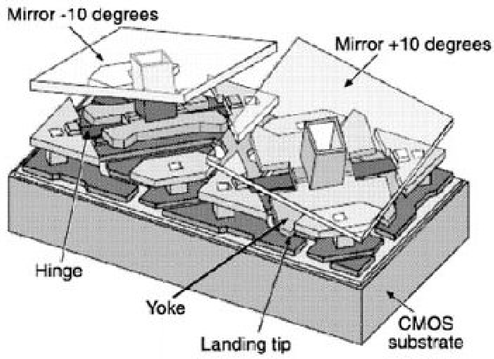

Figure 9. Texas Instrument's micromirror display projector (Courtesy of TI DSP)

Electromagnetic actuator has been demonstrated in conjunction with both mechanical classes of microactuators but electro-magnetic systems prove difficult to micromachine using planar IC processes. The high aspect ratio micromachining method such as LIGA is required to build the three-dimensional structure of magnet and solenoid. Magnetostatic micromotor was shown in Fig.10. Electrostatic actuator dominates in the development of actuators in microworld because of its simpler and more compatible with IC fabrication.

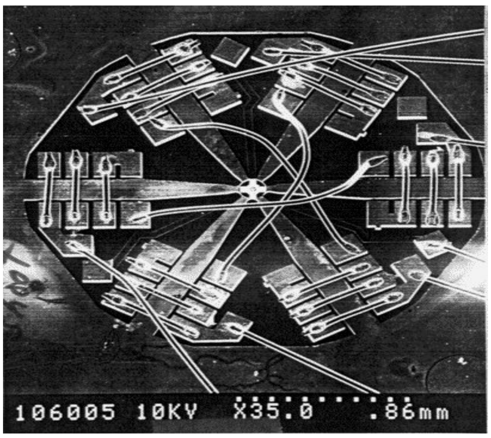

Figure 10. Magnetostatic micromotor. (Courtesy of UW Madison)

Another form of microactuation is based on the piezoelectric effect [5]. This material exhibits deformation of crystal when voltage is applied. Therefore, piezoelectric films can be used to provide actuation in a variety of applications such as valves, pumps, and positioning devices. Typical piezoelectric thin films now used in microactuator technology are zinc oxide (ZnO), lead zirconate titanate (PZT), and polyvinylidene fluoride. Of these materials, PZT has the largest piezoelectric coefficient. Thermal actuator uses bimorph structure that there is thermal coefficient of expansion mismatch between two layers of materials to generate force or motion. The bimorph structure can provide deformations in the lateral or normal to the plane of substrate. In general, thermal microactuators have a slow response time (on the order of tens of milliseconds) and high power consumption (on the order of tens of milliwatts). Electrostatic microactuators can be much faster (with response time measured in microseconds), and consume far less power but less force or motion generated.

4.2 Microsensor

Microsensors are component that converts one form of energy into another and provides a usable energy output in response to a specific measurable input. Due to the micro-scale size of microsensors, less invasive, high accurate/sensitive, and low cost/weight sensor can be achieved. The smart sensor fabricated by IC processes can integrate with CMOS electronic circuits on the chip to handle, switch, or amplify the signal. Several kinds of microsensors are successful in the market such as pressure sensor, flow sensor, thermal sensor, gas/chemical sensor, accelerometer, and immunosensor. The commercially available integrated accelerometer for automotive air bag system developed by Analog Devices was shown in Fig.11.

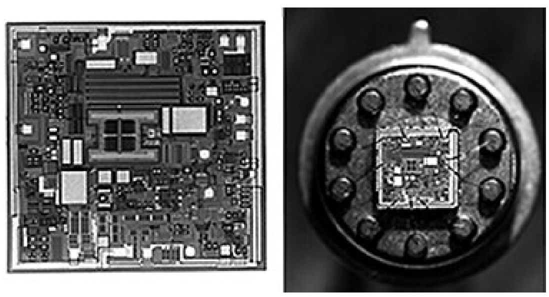

Figure 11. Integrated accelerometer and packaged device. (Courtesy of Analog Devices)

5. MEMS for Optical Applications

Micro-Opto-Electro-Mechanical System (MOEMs) is a specific field of MEMS that includes the knowledge in fields of optoelectronics and optics to create the micro-optical components and systems. Some micro-optical components recently fabricated at University of Colorado, Boulder, Colorado have been described and demonstrated as follow [6].

5.1 Piston micromirrors

One of the most useful MOEM components is the electrostatically actuated piston mirror. This device takes advantage of the planar nature of the surface micromachining process and the ease to form parallel plate capacitor structures by sacrificial layers releasing. The segmented or membrane deformable micromirrors have been fabricated. The upper plate of the structure can be metallized to create a moving mirror. The lower plate was used as an underlying addressable electrode. When a voltage is applied between the two plates, an attractive electrostatic force is developed and balanced by the restoring mechanical force of the flexures that suspend the mirror over electrode. The phase of incoming light modulated by mirror deflection can be controlled by applied voltage between two electrodes. Fig.12 shows one element of micromirror array.

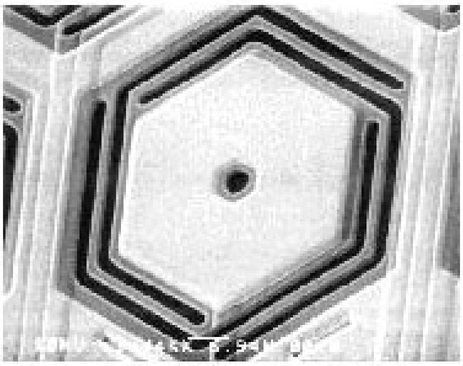

Figure 12. Element of segmented deformable micromirror

Bulk micromachining process is another way to fabricate micromirror array that micromirror and CMOS circuit can be integrated on the same chip. Thermal bimorph actuator was used instead of electrostatic actuator to actuate the mirror in vertical direction. The larger deflection stroke can be achieved with trade off in lower modulated frequency. The bulk micromachining micromirror array was shown in Fig.13. Applications of deformable micromirror array include active aberration correction for atmosphere's turbulence compensation or free space optical communication systems. The schematic diagram of wavefront compensation for aberration correction was shown in Fig.14. The incoming wavefront was phase-modulated by up/down movement of micromirror element.

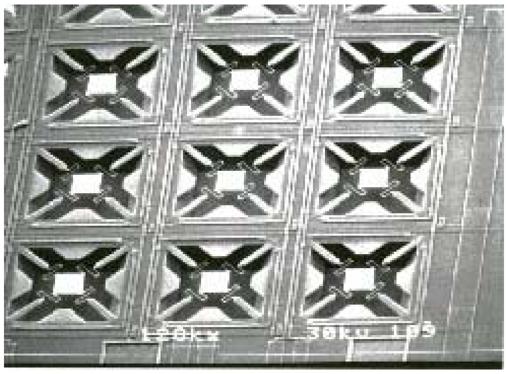

Figure 13. Micromirror array fabricated by bulk micromachining

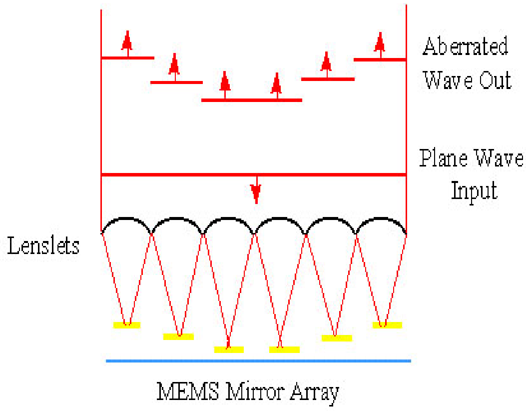

Figure 14. Aberration correction

5.2 Gratings

Optical grating is another optical element that can be easily fabricated in surface micromachined polysilicon. The optical grating is an optical element that serves to periodically modulated the phase or the amplitude of the incident wave. The grating consists of repetitive arrays of polysilicon line suspended over substrate by flexure which individual line was electrostatically moved perpendicular to the plane of substrate to diffract light of a particular wavelength at a designed angle. The electrostatic grating, shown in Fig.15, has an active area of 500 µm × 500 µm with 2 µm lines spaced 4 µm center-to-center. The array of grating line is moved perpendicular to the plane of the substrate to change the phase relationship between light reflected off the grating lines and substrate. This grating is designed to be able to modulated optical intensity by shifting power from the zero diffracted order to the ±1st diffracted orders.

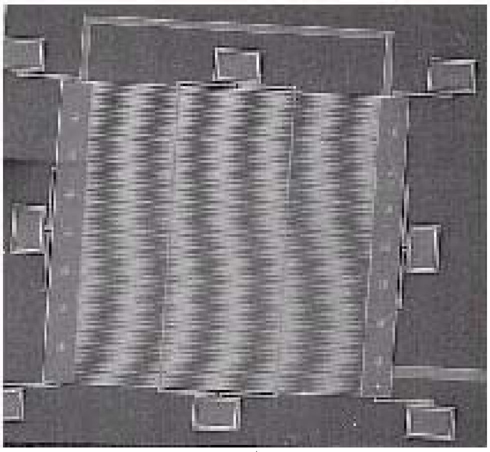

Figure 15. Micro-optical grating

5.3 Fresnel Lenses

Since surface micromachining uses materials with uniform layer thickness, it is not possible to design curved refracting lenses: however, Fresnel lenses can be fabricated easily. Fresnel lens consists of an array of polysilicon circular rings increasing in width and spacing toward the center. An example of a 7 order Fresnel lens is shown in Fig.16. The plate is 200 μm tall and locks into place. The slider attached at the left lifts the plate. The bottom of lens plate is hinged so it can be flipped up into the light path. The Fresnel lens on substrate can be used to collimate laser light from laser diode. The schematic diagram of microhinge is shown in Fig.17

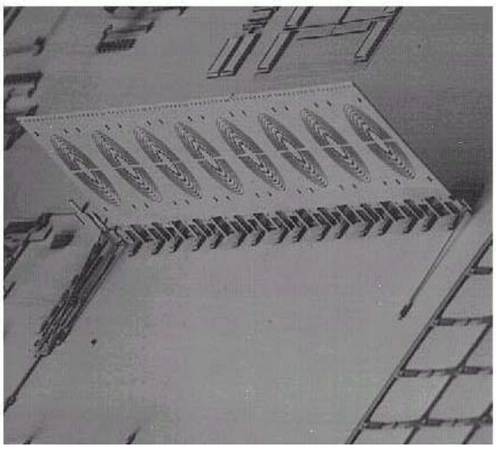

Figure 16. Micro-Fresnel lenses.

5.4 Optical Scanner

Optical scanner is another optical component successfully demonstrated for commercial market. The scanner consists of hinged mirror plates connected to thermal actuator arrays, which can move 10 μm laterally on substrate. The lateral thermal actuator consists of a narrower polysilicon hot arm connected to a wider polysilicon cold arm.

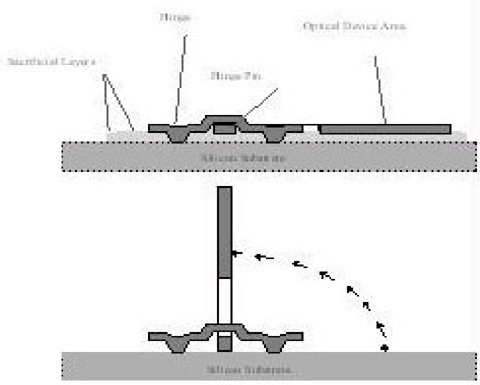

Figure 17. Schematic diagram of micro-hinge for flip-up structure

When the current is applied to them, the higher current density in the hot arm causes it to heat and expand more than the cold arm. This causes the actuator tip to move laterally in an arcing motion towards the cold arm side as shown in Fig.18. Typical dimensions of thermal actuator are: 'hot' arm 2.5 μm wide, 240 μm long; 'cold' arm 16 μm wide, 200 μm long and gap between both arms 2 μ m wide.

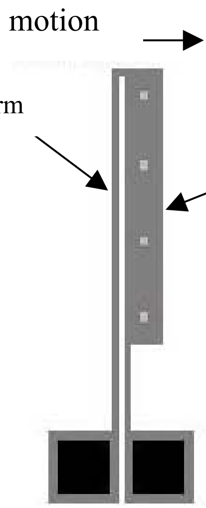

Figure 18. Thermal actuator (Heatuator).

The coated gold mirror surface is 75μm square (for reference , the diameter of human hair is about 70-80 μm). An etch hole has been cut in the center of the mirror to ensure that the mirror is completely released during the sacrificial oxide etch. The mirror is connected to the substrate with two substrate hinge, and to the actuator array with a self-locking tether. The lock and key mechanism consists of a key hole in the bottom of the mirror plate with awide opening at the top and narrow opening at the bottom. The tether end is tapered into a triangularshape which slightly overhangs the bottom of the keyhole. Below the triangular tip, slots are cut into both sides of tether, corresponding to the size of the narrow bottom of the keyhole. As a hinged plate is rotated off the substrate, the tether slide into the keyhole. The actuator array is used to set the angle of the mirror plate for beam steering, or it could be used to move continuously, to create a scanning mirror with a large scan angle. The 15.7° maximum deflection angle is observed [6]. Micro-optical scanner for bar code scanning or display projection was shown in Fig.19.

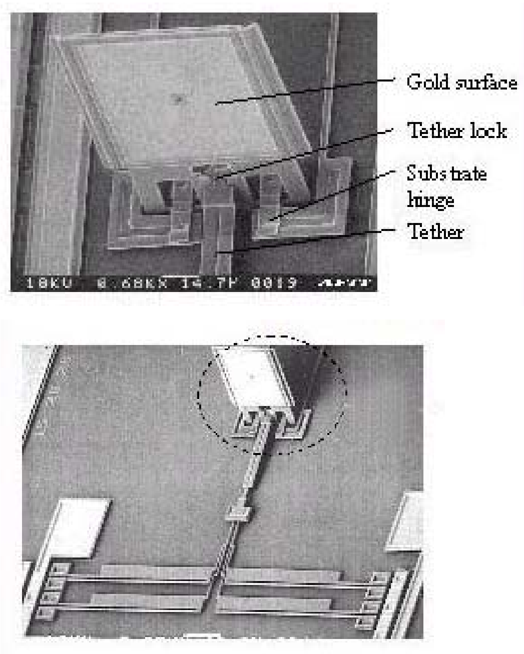

Figure 19. Micro-optical scanner

Rotate mirror plate is another mechnism for scanning the optical beam. Fig.20 shows a flip-up mirror attached to rotary stepper motor, which is driven by an array of thermal actuator. The 200 μm sector gear on the base allows the 180° of positioning. Mirror is 185 μm wide and 200 μm tall.

5.5 Corner Cube Retroreflector

So far only single device have been described; however, more complex systems can be developed. One of the most interesting optical components is a corner-cube retroreflector (CCR). A CCR has three mutually hinged, stand-up gold plated mirrors. One hinged mirror is positioned and modulated with a thermal actuator array, in the same manner as the scanning mirror. The other hinged mirror is held by a slotted locking plates to fix the position of mirror.

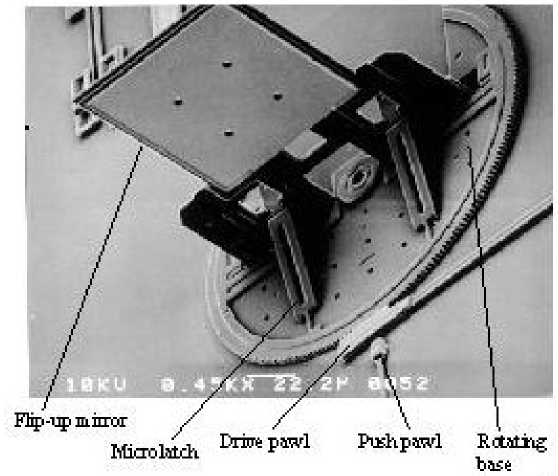

Figure 20. 180 degree scannong mirror

As shown in Fig.21, CCR system has a static gold mirror on the substrate and two perpendicular, mirrored walls. This mirror arrangement will reflect light back in the direction of its incomimg path, and is commonly used in roadside reflectors. The CCR can be used for line-in-sight optical communication

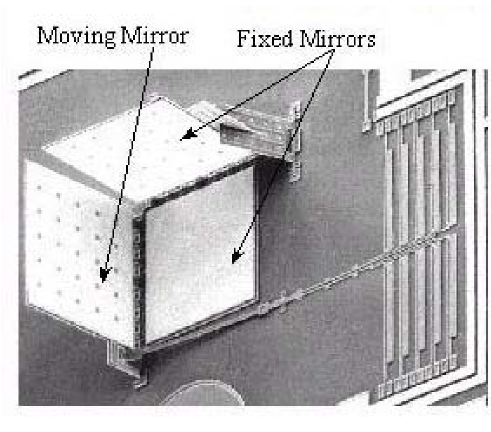

Figure 21. Micro-corner cube retroreflector

The previously described optical components can be combined to form a micro optical bench as shown in Fig.22. A vertical cavity surface emitting laser (VCSEL) is used as a laser light source. The laser beam is emitted perpendicular to the substrate and reflected by 135° mirror. The beam is

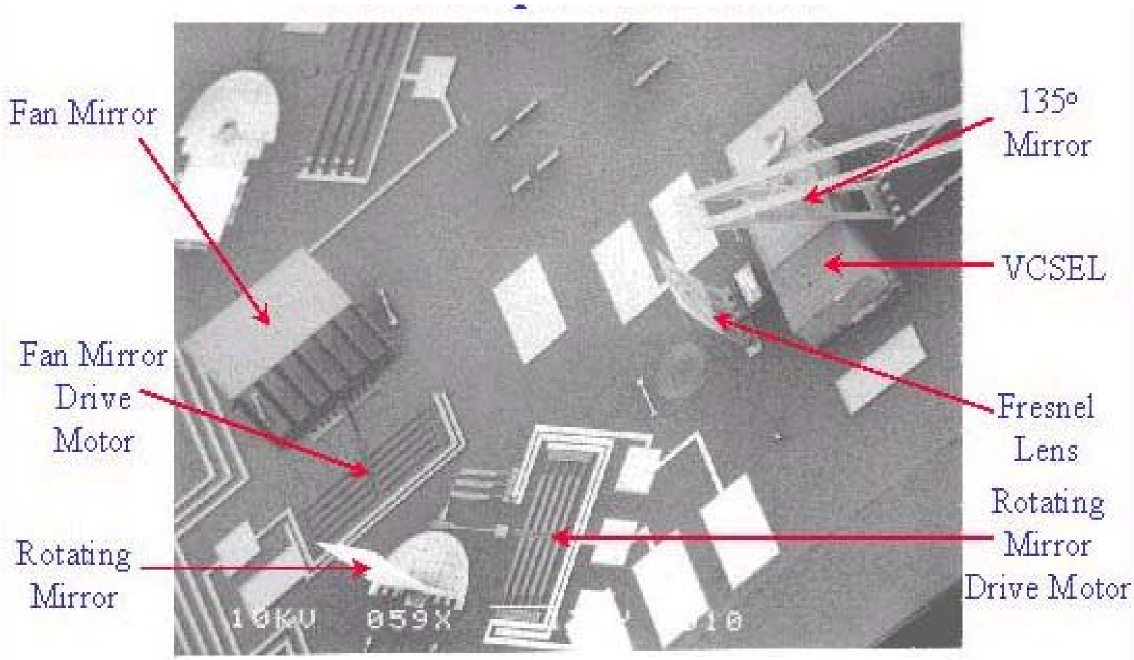

Figure 22. Micro-optical bench for display projection system

collimated by Fresnel lens and scanned in two dimensions by rotating micromirror and fan mirror. This micro optical system is proposed as low cost laser scanner or bar code scanner [7].

6. Conclusion

MEMS proves to be a promising technology for future sensors and actuators. Trend to decrease size, enhance performance, and lower the cost of transducer in market is made possibly by the success of MEMS technology. Fabrication technique has to be developed further to support the increasing MEMS industry. MEMS has merged several fields of knowledge to create a micro-scale device by using today available IC fabrication technology. Discussions of MEMS technology, fabrication tool, MEMSCAD tool, and MEMS applications for sensor and actuator concentrated on micro-optics applications have been presented in this paper.

Acknowledgement

Thank you M. A. Michalicek for nice MEMS pictures and V. Thiantamrong for typing and Thai translation.

Reference

[1] M. Mehregany, "Micro-Electro-Mechanical Systems," *IEEE Circuit and Devices,* July 1993 pp. 14-22.

[2] M. A. Michalicek, "Introduction to MEMS," *CU MEMS web* 1998

[3] US National research council, "Micro-Electro-Mechanical System: Advanced materials and fabrication method," *National Academic Press*, Washington, D.C. 1997.

[4] A. Tuantranont, V. M. Bright, W. Zhang and Y.C. Lee, "Flip chip integration of lenslet arrays on segmented deformable micro-mirrors," *SPIE* Vol. 3680, pp. 668-678, 1999.

[5] M. Madou, "Fundamentals of microfabrication," *CRC Press*, New York, 1997.

[6] V. M. Bright, J. H. Comtois, J. R. Ried, and D. E. Sene, "Surface micromachined micro-opto-electro-mechanical systems," *IEICE Trans. Electron,* Vol.E80-C, No.2 February 1997, pp.206-213.

[7] V. M. Bright, "Surface micro-machined optical systems," *Course material 1998*.

Adisorn Tuantranont received the B.S. in Electrical Engineering (Control Eng.) from King Mongkut Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand, in 1995 and the M.S. in Electrical Engineering (Lasers & Optics) from University of Colorado at Boulder in 1998. He is pursuing the Ph.D. degree in Electrical Engineering at University of Colorado at Boulder and working in Optoelectronic Computing Systems Center (OCS) and Center for Advanced Manufacturing and Packaging of Microwave, Optical and Digital Electronics (CAMPmode). During his master degree, he was working for Prof. Kristina M. Johnson and Prof. Y. C. Lee. Research interests include the Alignment of Liquid Crystal by Obliquely Evaporated SiO_x method, flat screen liquid crystal display and optical modulator. For his Ph.D. degree, he is currently working for Prof. Victor M. Bright in Micro-Electro-Mechanical System Laboratory (CU-MEMs Lab). His current researches specify in MEM Deformable Micromirror for optical beam steering and shaping, microlens array for optical interconnect, and micromirror for laser resonator and high power application.