Advanced MEMS for Photonics

M. C. Wu, P. R. Patterson, D. Hah, M.-C. M. Lee, S. Huang, and J.-C. Tsai

Electrical Engineering Department & California NanoSystem Institute (CNSI)
University of California, Los Angeles
Los Angeles, CA 90095-159, (310) 825-6859

Micro-electro-mechanical-systems (MEMS) is a key enabling technologies for many new all-optical network elements in next-generation photonic networks. With intensive efforts from industry in the last five years, many of these new photonic MEMS components have now moved from research laboratories into commercial reality. Examples include 2D [1] and 3D [2] MEMS optical switches, and wavelength-division-multiplexed (WDM) optical add-drop multiplexers (OADM) [3]. In the meantime, research laboratories continue to develop newer photonic MEMS components and technologies. In this talk, we will review the state of the art of photonic MEMS components and systems, and describe the development of new photonic MEMS research at UCLA.

There are a wide variety of photonic MEMS devices. Figure 1 shows the requirements of scanning micromirror devices in terms of their complexity (number of MEMS components) and optical resolution (number of resolvable spots). Projection display devices such as TI's Digital Micromirror Devices (DMD) required a large number of pixels (~ 10^6) but two digital states for each mirror. Scanning display or imaging applications require a small number of devices with very high resolution (> 1000 resolvable spots per axis). It is interesting to note that the state-of-the-art scanning devices fall on a straight line defined by a constant number-resolution product. As the technology progresses, this product may increase over time.

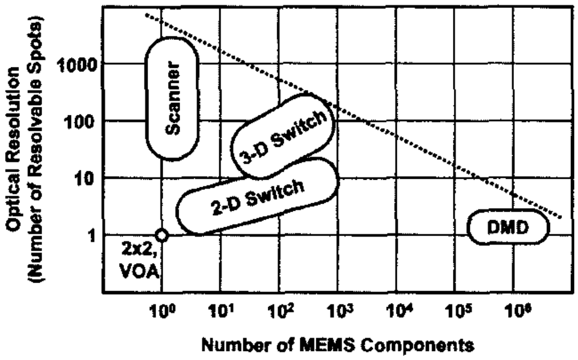

Figure 1. Technology road map of scanning-type photonic MEMS devices. The state-of-the-art devices fall on a constant number-resolution product line.

We will describe three different types of MEMS devices that are currently being developed at UCLA. The first one is a large scanning mirror with large scan angle for optical imaging applications. We have proposed and demonstrated a novel angular vertical comb (AVC) drive actuator [4]. The AVC actuators have higher force density than the conventional parallel-plate type actuators. This enables us to achieve large scan angle, low actuation voltage, and high resonant frequency. It also eliminates the pull-in phenomena and can fully utilize the entire scan range. The AVC scanner is fabricated on a single-layer silicon-on-insulator (SOI) wafer. The self-aligned comb fingers are patterned in a single etching process and no critical alignment is needed. Figure 2 shows the scanning electron micrograph (SEM) of a 1-mm-diameter AVC scanner. The movable comb is tilted upward while the stationary comb remains in the substrate plane. The angular comb drive offers several advantages over the staggered vertical comb (SVC) drive fabricated on two-layer SOI wafers [5]. First, the maximum scan angle of AVC drive is equal to the initial tilt angle of the movable comb, and is 50% larger than that achievable by SVC drives. Second, the self-aligned process minimizes the asymmetry of comb fingers and increases the threshold of lateral instability. A prototype AVC scanner has been fabricated on a 25-μm-thick SOI wafer. The movable comb fingers are assembled by the surface tension force of molten photoresist [6]. The resonant frequency of the device is 1.4 kHz. At resonance, a scan angle of ±18° is achieved. Our theoretical models show that the performance can be further improved by using SOI wafer with thicker device layer, and increasing the number of comb fingers.

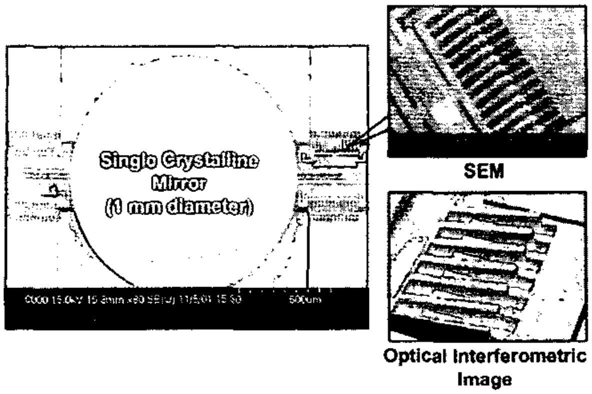

Figure 2. Scanning electron micrograph of a 1-mm-diameter scanning micromirror with angular vertical comb (AVC) actuator. The top inset shows the close-up view of the AVC. The movable comb was assembled by surface tension. The bottom inset shows the interferometric image of the AVC measured by WYKO profiler.

The second device is a linear array of analog micromirrors for MEMS WDM Router applications [7]. The micromirror array needs to satisfy the following requirements: high fill factor along the array direction is needed to achieve a "flat-top" spectral response with minimum gap between WDM channels; large continuous scan range is needed to increase the number of spatial (fiber) channels. In addition, low voltage operation is important to reduce the power consumption and increase the reliability of the devices. We have proposed a novel analog micromirror device with hidden vertical comb drive actuators. The schematic of the analog micromirror device is shown in Fig. 3. High fill factor (91%) is achieved by placing the actuators and springs under the mirrors. Vertical comb-drive actuators are used to reduce the operating voltage and extend the linear scan range. Unlike conventional parallel-plate type electrostatic actuators, the comb-drive actuators do not suffer from the pull-in effect and can fully utilize the entire scan range (24° optical). The vertical comb-drives also have higher electrostatic torque, which enables low voltage operation (6V).

The micromirror array was fabricated by SUMMiT-V (Sandia Ultra-planar Multilevel MEMS Technology-V) process. The SUMMiT-V process has four structural polysilicon layers and four sacrificial oxide layers, which are ideal to implement our micromirrors. In addition, the top two polysilicon layers are deposited on chemical-mechanical-planarized (CMP) oxide layers so that underlying topography will not replicate on the top layers. This feature is critical for fabricating vertical comb-drive actuators underneath the flat micromirrors. The spring and the mirror are made of poly1 and poly4, respectively. The movable fingers are made of poly3 and the fixed fingers are made of laminated poly1 and poly2. After fabrication, the mirrors are released in HF for 45 minutes at room temperature. Cr/Au is deposited by maskless e-beam evaporation to increase the mirror reflectivity. Electrical isolation between electrodes was achieved by incorporating overhang structures. Figure 4 shows the interferometric image of a 1x10 analog micromirror array. Thanks to the CMP process, smooth and flat mirror surface are achieved. Excellent uniformity (<± 3.2%) was observed in the scanning characteristics of the array. The crosstalk between adjacent mirrors was measured to be below 20 dB. The resonant frequency of the device is 3.4 kHz.

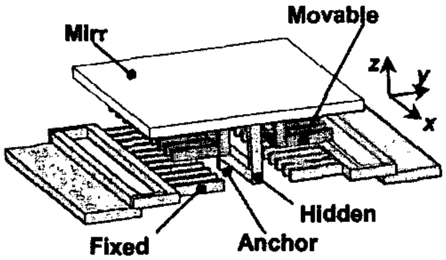

Figure 3. Schematic of analog micromirror with hidden vertical comb drive actuator.

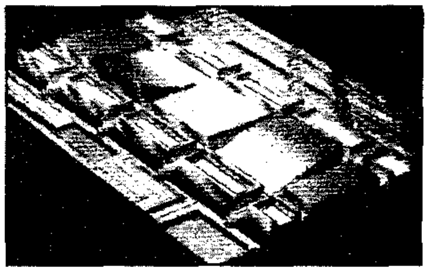

Figure 4. Interferometric image of the analog micromirror array with high fill factor.

The third device is a nano-electro-mechanical (NEM) photonic crystal (PC) switch [8]. Photonic crystals have the ability to confine light propagation within small volumes for specific frequency ranges, known as photonic bandgaps (PBG). Switching in PC can be achieved by moving one or a few photonic atoms due to the large index contrast and the tight optical confinement. Therefore, combining NEM actuation with PC confinement can produce extremely compact nanoscopic optical switches.

We have designed and fabricated a one-dimensional (1D) photonic crystal ON-OFF switch on a SOI wafer. Figure 5 shows the schematic structure of the switch. The PC structure is sandwiched between an input and an output waveguide. An NEM actuator enables us to switch between two different PC structures. In the "REFLECTION" state, the photonic crystal consists of two photonic atoms and it forms a broadband reflection filter (from 1.0 μm to 2.1 μm wavelength). Light will be reflected back to the input waveguide. In the "TRANSMISSION" state, the gap between the two photonic atoms is filled with silicon, thus forming a "defect" which has a transmission resonance centered at 1.55 μm. The pass bandwidth is around 70 nm. Connected to a NEM actuator, the PC between the waveguides can be switched between either one of these structures. This allows us to control the flow of light as it passes along the waveguide.

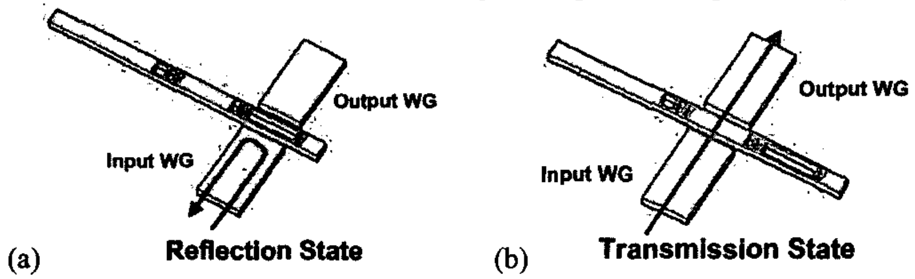

Figure 5. Schematic of 1D MEMS photonic crystal ON-OFF switch: (a) Reflection state; (b) Transmission state.

A prototype device was fabricated on an SOI wafer with 1.5-μm-thick device layer. SOI was chosen due to its flat, single crystalline surface and low residual stress of single crystal, which is more reliable for the nanofabrication. We have developed a fabrication process that combines electron-beam direct write and optical lithography to pattern both small and large features. All structures were created in one etching step and are self-aligned. The minimum feature in the photonic crystal structure is 110 nm. Precise control of lateral undercut is very important. The device is released in a supercritical dryer. The SEM of the finished device is shown in Fig. 6. The device was tested using a 1.55μm laser to couple light into the waveguide via a lensed fiber. The peak wavelength at TRANSMISSION state was measured to be 1.56 μm, which is very close to the design wavelength of 1.55 μm. An extinction ratio of 11 dB was obtained. Higher extinction ratio could be achieved with single mode waveguide and polarization control. The temporal response is shown in Fig. 7. The switching time is less than 0.5 msec.

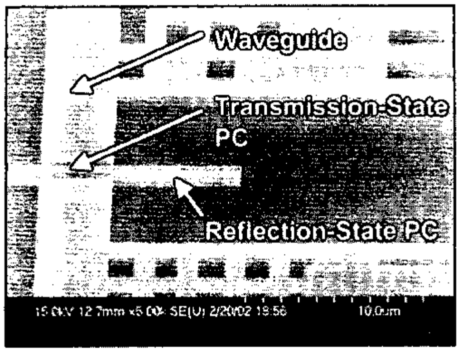

Figure 6. SEM of MEMS photonic crystal switch. The minimum feature is 110 nm.

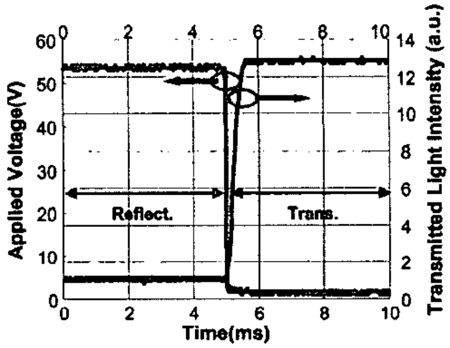

Figure 7. Temporal response of the MEMS photonic crystal switch. The switching time is about 0.5 ms.

In summary, we have presented an overview of current state of the art of the photonic MEMS devices and their requirements. We have also described three photonic MEMS devices at three different length scales: a 1-mm-diamter scanning micromirror, a 120-μm-wide analog micromirror array, and a NEM photonic crystal switch with a minimum feature of 110 nm. In all cases, MEMS is a key enabling technology for reconfigurable photonic circuits. The projects at UCLA are sponsored by DARPA #DAAH01-99-C-R220, #N66001-00-C-8088, #MDA972-00-1-0019, NSF #BES-0119494, and Agilent Technologies through California MICRO program.

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