OPTICAL MEMS FOR ADAPTIVE OPTICS APPLICATIONS

Yves-Alain Peter, Emily Carr, Justin Mansell, Olav Solgaard
Stanford University, E.L. Ginzton Laboratory
450 Via Palou, Stanford CA 94305-4085, USA
yap@ieee.org

Abstract

We report on the design, fabrication and applications of different kinds of deformable mirrors based on optical MEMS, which could gain importance in the future for adaptive optics applications. Optical MEMS versatility of fabrication allowed to demonstrate large optical fiber switches, and large arrays of segmented mirrors.

INTRODUCTION

During the past decade, many Optical Micro Electro Mechanical Systems (Optical MEMS) have been developed [1]. Although very powerful, most of them have relatively simple functionality. Many of these systems are now in a commercialization stage [2, 3]. The challenge for future Optical MEMS is to be smarter and/or smaller. Smart Optical MEMS are being developed in telecommunication applications where a system has to adapt its function to the surrounding conditions (temperature, atmospheric perturbations, misalignments, etc...) [4, 5].

Optical MEMS has contributed to telecommunication systems over many years. From simple optical elements like micro-mirrors [6] or microlenses [7, 8] to optical switches [9, 2], many of these systems are now commercially available. More complex optical switches have also been widely developed. Vertical micromachined mirrors, with digital (up and down) positions are used to switch light. A 2-dimensional approach involving an array of N^2 on/off vertical micro-mirrors (digital cross-bar switch) [10] enables the interconnection of NxN channels. This approach is well suited for up to 32x32 cross connections. Beyond this number, the system suffers from losses due to the divergence of the optical beam [11]. In order to address more interconnections (up to 1000x1000), a 3-dimensional approach is needed. In this case, an array of 2N mirrors having each N positions (analog beam-steering switch) have been demonstrated [12] and is now commercially developed [3]. Larger number of interconnects can even be efficiently addressed, using simple optical MEMS [13]. However, packaging, as well as alignment tolerances makes the practical realization of such systems difficult.

Applications like free space optical telecommunication and targeting require smarter systems, able to adapt to changing conditions (e.g. atmospheric perturbations, temperature, mechanical stress, etc...). Adaptive optics is particularly well suited to respond to these requirements. Adaptive optics is used for many years in astronomical applications to correct for aberrations in the atmosphere. Conventional adaptive mirrors are complex, large in size and expensive [14]. They are not suited for integration into a micro-electro-mechanical system. Recently, micro-electro-mechanical deformable mirrors (MEM-DM) have been developed using silicon micromachining. Three types of MEM-DM are currently being pursued: continuous face sheet mirrors backed by individual actuating elements, microfabricated membrane mirrors and segmented mirrors.

CONTINUOUS FACE SHEET MIRRORS BACKED BY INDIVIDUAL ACTUATING ELEMENTS

Continuous face sheet mirrors backed by individual actuating elements, as shown in Fig. 1, have been demonstrated to be particularly well suited for high power laser applications [15]. The good surface quality leads to good reflectivity, which is very important for high power applications. In addition, they have very low static distortion.

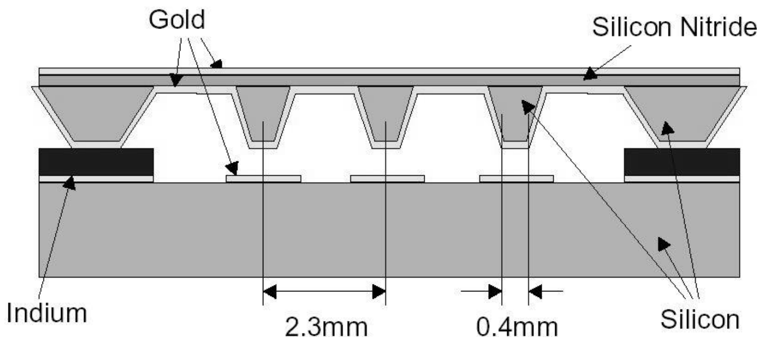

Figure 1: Schematic drawing of a continuous adaptive-optics mirror backed by individual actuating elements [15].

MICROFABRICATED MEMBRANE MIRRORS

Microfabricated membrane mirrors have high optical efficiency and a very good potential for aberrations correction, while keeping small dimensions. These properties make them very suitable for optical fiber switching applications. Such a microfabricated membrane mirror, see Fig. 3, has been used to optimize the coupling efficiency of an optical fiber switch for more than 3000 interconnects [5]. Figure 2 shows the optical system, which has two functions. First, it images a singlemode source fiber onto another singlemode receiver fiber (coupling function). Second, it deflects the beam by moving the lens laterally to address one of the receiver fibers (switching function). The adaptive membrane mirror is fabricated by bulk silicon micromachining at the T.U. Delft [14] (see Fig. 3). Electrostatic deflection is generated by 37 electrodes disposed under the membrane in a hexagonal array.

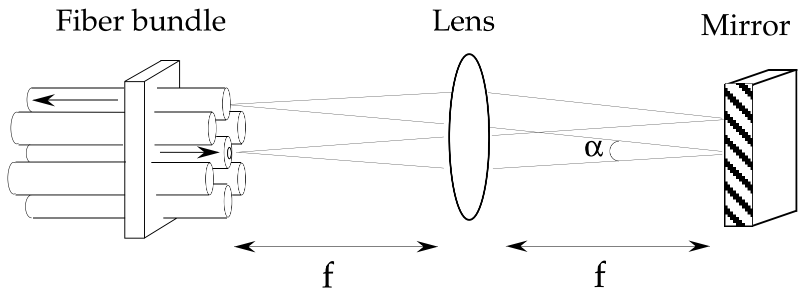

Figure 2: Schematic setup of the free space optical switching system. The source fiber is imaged ($4f$ system) onto one of the receiver fibers by moving the lens laterally.

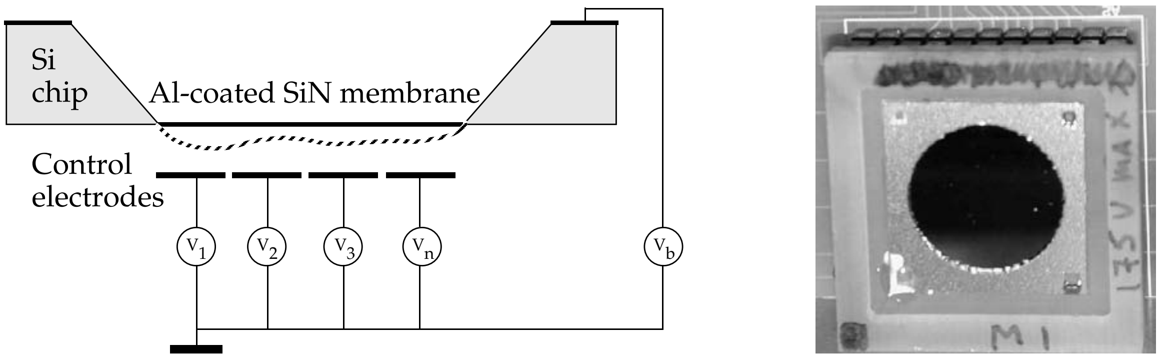

Figure 3: Schematic and photograph of the micromachined deformable membrane mirror. The membrane has a diameter of 15 mm and a thickness of $d < 1$ μm. The surface of the membrane is coated with a 0.2 μm thick reflective aluminum layer. Its active area has a diameter of 12 mm.

SEGMENTED MIRRORS

Segmented mirrors are fast, due their small size. Typically, a single pixel is 100μm aside. Their reliability, small size, light weight and ease of fabrication make them particularly well suited for free space optical telecommunication (e.g. satellite to satellite communication, satellite to earth communication or plane to earth communication). Basically, air turbulence and atmospheric perturbations are generating optical aberrations. The wavefront is distorted to such a point that the data is lost. For this reason, we need a fast device, able to restore the initial wavefront. A deformable mirror, made of many segmented micro-mirrors, is able to correct for these aberrations, and provides an almost perfect wavefront. Such a device need to meet challenging specifications, such as fast response time (typically 10 μs) and very high surface quality (better than $\lambda/50$). In addition to these specifications, the device needs to be scalable to 1000x1000 pixels in order to have a large enough aperture. Such a large matrix of mirrors can be realized using standard surface silicon micromachining. It is however much more difficult to integrate the electronics under the mirror array. For this reason, we choose to develop the mirror array separately from the electronics layer. The mirror array and the electronics are combined in a final fabrication step.

The mirror array is fabricated by silicon surface micromachining. In a first step, we used the Multi User MEMS Process (MUMPS®) having three polysilicon layers, called *poly0, poly1 and poly2*, and two oxide layers, called *1st oxide and 2nd oxide*. The electronics chips is also fabricated using the MUMPS®) process, but could as well be a CMOS chip. Figure 4 shows the different layers of both chips. The electrodes are patterned in the first polysilicon layer (poly0) and the third polysilicon layer (poly2) forms the pads on the electrode chip. The mirror are patterned in the second polysilicon layer (poly1), and the actuator in the third polysilicon layer (poly2) of the mirror chip. Once both chips are done, we bond them together, using the metallic bond

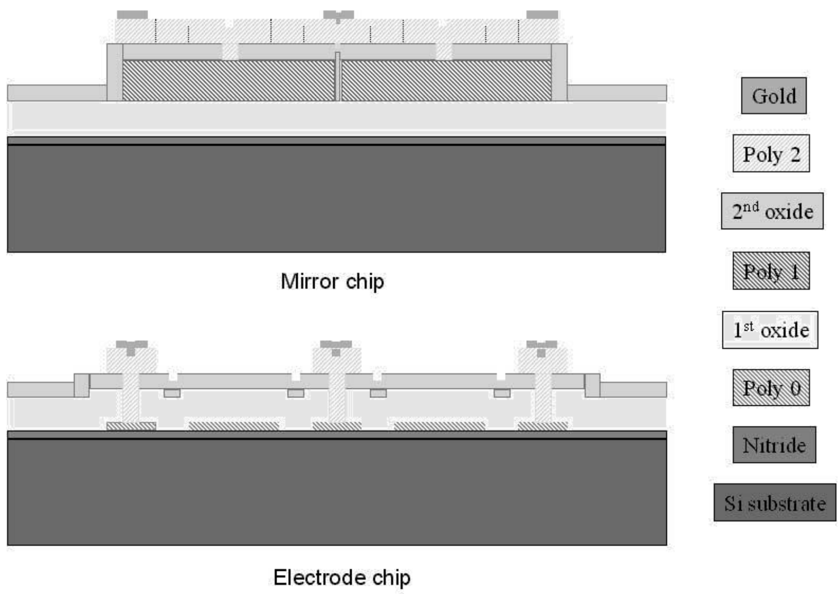

Figure 4: Process flow for the fabrication of the mirror chip and the electrode chip using MUMPS®).

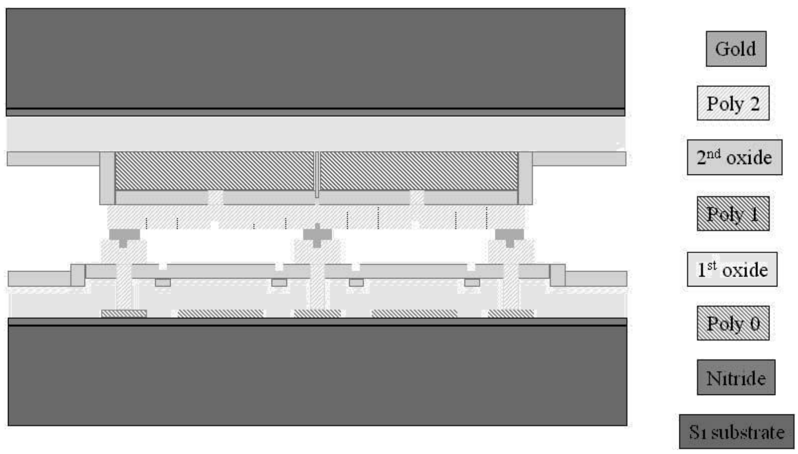

Figure 5: Schematic of the mirror chip bonded upside down onto the electrode chip.

pads (gold). A pressure of 1 MPa and a temperature of 300°C is applied using a flip chip bonder. Figure 5 shows the two chips bonded together. The device still needs to be released. The oxide layers are etched away in 49% HF, followed by rinsing in DI water. In order to prevent the structure from sticking, we dry the device using a Critical Point Drying process (CPD), using liquid CO_2. Figure 6 shows the final structure. Figure 7 is a solid model of one mirror pixel, showing the electrode, the

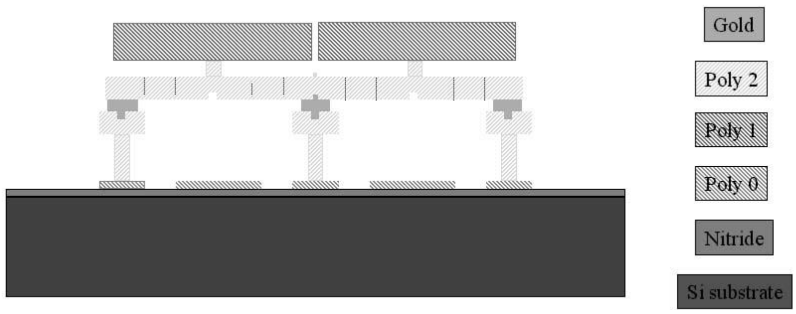

Figure 6: Schematic of the final structure after the release of the oxide layers.

actuator and the mirror. Figure 8 is an optical microscope photograph of a part of a segmented mirror. We see some light deformations, which are due to the stress of the polysilicon layer. In order to improve the surface quality, next generations of mirrors will be patterned in single crystal silicon.

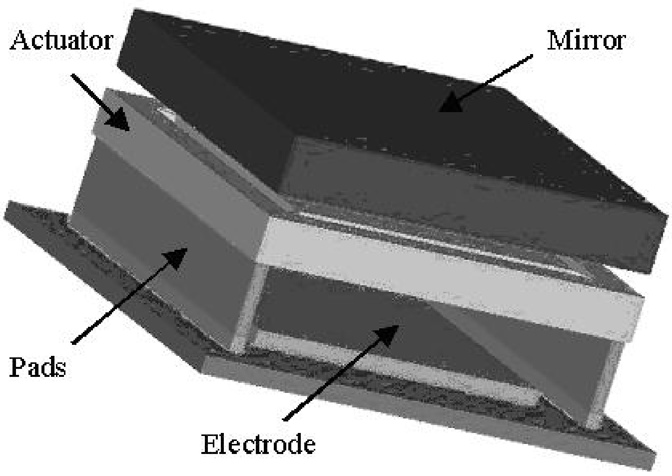

Figure 7: Solid model of one mirror pixel. The mirror stands above the actuator, which is connected to the electrode chip using Au bonding.

The segmented mirrors described above have only piston motion capabilities. This is sufficient to correct for aberrations in a wavefront. However, free space optical telecommunication requires also a targeting functionality. It would then be beneficial to add a 2D-tilt function to each pixel of the segmented mirror. In order to generate large tilt with as little displacement as possible, we investigate compliant structures.

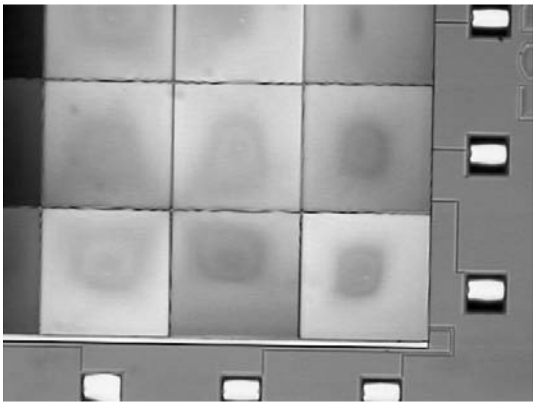

Figure 8: Optical microscope photograph of a segmented deformable mirror (4x4 matrix). Each pixel is 400 μm x 400 μm.

Figure 9 shows a solid model of a simulated tip/tilt pixel mirror. The edge of the mirror is actually moving more than any part of the actuator layer.

Figure 9: Simulation of tilt in an individual mirror of the adaptive optics array, The 5 stationary electrodes under the actuator layer enables piston motion and tilt on two axes.

CONCLUSION

We have presented three different adaptive optical MEMS. Applications were as diverse as high power lasers, optical fiber switching and free space optical telecommunication. Each system needed a specific type of deformable mirror in order to meet the respective requirements. Optical MEMS prove to have the versatility to generate such devices. Large fiber optic switches, as well as large arrays of segmented mirrors have been presented.

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