Micromachined Silicon Deformable Mirror

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Abstract

A new silicon deformable mirror design is presented which provides high reflectivity, an optical quality continuous surface, and high intensity handling capability. Its features make it useful for a wide range of devices including telescopes, lasers, and photolithographic systems. The mirror architecture is similar to commercial electrostrictive deformable mirrors. A focus corrector built using this architecture exhibited 2.25 microns of actuation at the center through the application of 100v corresponding to a radius of curvature of –2.4m. A 30μm thick 1cm diameter silicon mirror exhibited its first mechanical resonance at 2.7kHz. A mirror coated with 100nm of gold was shown to be able to withstand 100 kW/cm^2 of continuous wave 1064nm intensity for 10 minutes without observable degradation. An active mode-matching experiment was performed showing that 99.5% of a Nd:YAG beam could be coupled to a finesse 4000 ring cavity.

Keywords: micromachined, deformable mirror, adaptive optics, silicon mirror, electrostatic actuation.

1. Introduction

The need to propagate high power laser beams through distorting media while preserving the wavefront quality is a requirement of many projects today including the Laser Interferometer for Gravitational Wave Observation (LIGO) project. In particular, for LIGO, the requirement is to correct for thermally induced beam distortions without inducing additional loss or scatter on the beam. In this paper we report progress toward a silicon crystal based deformable mirror that has potential for low cost and high performance because of the application of lithographic processing techniques developed by the integrated circuit industry to single crystal silicon.

Single-crystal silicon is often used as the substrate for mirrors for high-power lasers because it can be polished and coated to handle high power. The integrated circuit industry has spent a great deal of time and effort in developing silicon. Currently 12" diameter silicon wafers are being produced. The thermal conductivity of silicon is 157 W/mK which is 3.4 times that of sapphire and 200 times that of fused silica. As a further benefit of silicon, micromachining technology has been well established as an avenue for fabrication of complex devices integrating electrical, mechanical, and optical capability.[1] The marriage of optics and silicon micromachining has proven to be very fruitful in the last several years[2,3]. Several groups have demonstrated that silicon micromachining can be used to make deformable mirrors,[4,3] but the micromachined mirrors presented thus far have had a variety of drawbacks including low power handling capability, low reflectivity, high scatter loss, and unusual influence functions.

We present here the application of silicon micromachining technology to a deformable mirror design. The approach is versatile enough to address many of the applications of adaptive optics including atmospheric compensation and high-power laser wavefront correction, and yet simple enough to be compatible with mass fabrication technology and, in the future, to be low cost.

2. Background

During the early days of adaptive optics, many researchers investigated deformable mirror characteristics that would be best for aberration compensation.[5] A variety of characteristics were deemed important for the performance of the deformable mirror including influence function shape and crosstalk, actuator throw, linearity, bandwidth, and surface quality. Recently, other characteristics have become important including power handling for high power lasers, scalability for larger telescopes, and reduced complexity and cost.

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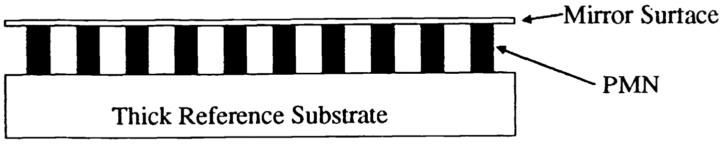

Figure 1 - Schematic depiction of a traditional deformable mirror. The top plate is the reflective surface. It is supported by an array of electrostrictive actuators which sit on a thick base for support.

Following early progress in deformable mirror development by Itek in 1973,[6] progress slowed until micromachining techniques were applied to the problem. **Figure 1** shows, in a schematic form, the basic design of the early deformable mirrors. The Itek design offered more than $10\mu m$ of throw, excellent surface quality, influence functions close to the ideal shape, and low adjacent channel crosstalk. However, the early deformable mirrors were costly to scale with an approximate cost of $1000 per actuator.

Micromachining techniques have been explored by many groups to improve deformable mirror technology. The micromachined designs offer the potential to be scalable and cost effective. The micromachined mirrors created at JPL[9] and Delft[3] have excellent surface quality and curved influence functions, but the influence functions have high crosstalk and the mirrors to date have not demonstrated high power handling capability. Bifano[4] used a surface micromachined technique to achieve a poly-silicon micromachined deformable mirror which had curved influence functions, low crosstalk, and a 66kHz resonance frequency. The surface of the mirrors was a polysilicon layer which was not polished to optical quality and had holes in the surface for the release step. The upper layer of polysilicon was about 60% reflective due to the uncoated surface being used as the mirror. The segmented mirrors created at Wright-Patterson Air Force Base[7] and the Air Force Research Laboratory on Kirtland Air Force Base[8] offered about 1.5 microns of throw, but the influence functions were tip/tilt and piston only. Further, the reflective surface, although improved due to a planarization step, was full of the release holes, discontinuities, and print-through errors. Cowan demonstrated that the mirror segments could withstand 4W of average power in a helium gas environment, but the performance in vacuum or room air was worse.

The demand by the LIGO project for excellent beam quality and active control of the laser wavefront led us to explore a new silicon-based deformable mirror approach. Single-crystal silicon was chosen as the substrate because of its excellent mechanical properties, high thermal conductivity, ability to be polished and coated, and the availability of micromachining technology for fabrication. Making a continuous membrane insures a curved influence function. Lithographic definition of the actuators and the use of integrated circuit mass-fabrication techniques provides scaling and the potential for low cost.

3. Design

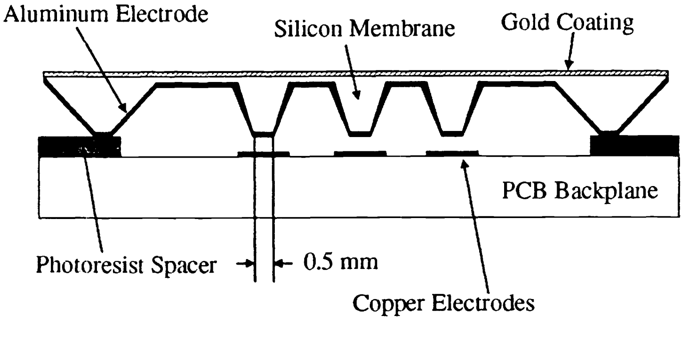

Figure 2 - Cross-sectional view of a schematic of the silicon deformable mirror design. The mirror is formed by etching away the back of a silicon wafer, coating the back side with aluminum for conductivity, coating the front with gold for reflectivity, and mounting it above an array of electrostatic pads to actuate the membrane.

The deformable silicon mirror design we have investigated is illustrated in Figure 2. The deformable mirror is comprised of two components. The first is a continuous silicon surface that has been polished to optical quality and coated with gold or a dielectric stack for high reflectivity. The back side has an array of silicon pillars formed by anisotropic silicon etching with potassium hydroxide (KOH) or tetramethyl ammonium hydroxide (TMAH). Anisotropic etching along the <411> crystallographic planes forms pillars with side walls that are angled at 76.4 degrees.[9] The pillars are coated with a thin layer of aluminum that is used as an electrical contact for the electrostatic deformation. The second component is an elect7rostatic pad array, which can be made by patterning metal on a silicon wafer or by patterning copper on a printed circuit board. The spacer between the membrane and the electrodes can be made from a variety of materials such as silicon dioxide or hard-baked photoresist, or can be etched into the surface of the wafer recessing the electrodes. The mirror and the electrostatic pad array, are bonded together. For an all silicon design, this can be done with silicon fusion bonding or eutectic bonding. If the electrostatic pad array is created on a printed-circuit board, epoxy can be used to bond the two elements.

There are several advantages to this design. The reflective surface is highly polished before the fabrication and coated with gold or a dielectric to create a high quality reflective surface. Gold coatings are sufficient for many applications, but in the future dielectric coatings will be required for projects like LIGO to minimize loss and the resulting thermal distortions. The coated surface can be sealed in a layer of deposited silicon nitride to protect it during the processing. The influence of the electrostatic pads is isolated to the tips of the pillars, which are in turn attached to the silicon mirror membrane. This provides influence functions more like the traditional deformable mirrors. Finally, the design is completely mass fabrication compatible.

4. Fabrication

The mirror fabrication begins with a silicon wafer which is coated with a thin layer (40nm) of low stress silicon nitride on both sides. Shipley 1813 photoresist is spun onto both sides of the silicon wafer and soft baked. The silicon nitride on the back of the wafer is patterned using photolithography and plasma etching to open a few test windows on the edges of the wafer. The photoresist is stripped in acetone and the wafer is put into 33wt.% KOH at 80C for 10 minutes etching pits in the silicon about 10 microns deep. The wafer is then coated again with photoresist and patterned using photolithography. The silicon nitride is then etched away using a plasma etch forming the etch windows for the remaining KOH etching. The photoresist is stripped from the wafer in acetone and it is put into the KOH until the initial windows become transparent indicating that the membranes are about 10 microns thick. The wafer is then rinsed and cleaned in a piranha etch (4:1 sulfuric acid to hydrogen peroxide). Finally the nitride is etched away from both sides using a plasma etch. The backside is coated with aluminum to make an electrical contact to the pillars on the backside.

The silicon mirror membrane is then mounted on a printed circuit board (PCB) with epoxy. The PCB is coated with a one-micron layer of photoresist to prevent the electrodes from shorting. A five-micron thick layer of photoresist is used as a spacer between the membrane and the electrodes. The electrical contact between the membrane and the PCB is made with conductive epoxy or conductive grease. In the future a silicon substrate patterned with the electrostatic pads will allow for more precise control of the spacing between the pads and the pillars. This will allow for a better bond and better quality control over a larger range of temperatures.

5. Results

Circular mirrors 1cm in diameter and 1.8cm in diameter were fabricated. The results presented here are for the 1cm diameter mirrors unless otherwise indicated. The pillars were arranged in a hexagonal pattern with the spacing between the pillars being 2.05mm. The top of the pillars that formed the electrode on the mirror were 500 microns on a side. The backside surface of the silicon mirror membranes was rather rough even with vigorous (280rpm) stirring during etching. The etch also was somewhat uneven as the etch termination windows on one side of the wafer opened prior to those on the opposite side. The time difference was about 3 minutes and therefore about 3 microns of deviation from edge to edge of the 3" wafer. In the future a boron etch stop or a SOI wafer can be used to control the etching.

Several mirrors were built with 10μm thick membranes using the technique documented above. The first mirror was 1cm in diameter. It had only a single electrode behind an array of 7 pillars in a hexagonal pattern with a spacing of 2.05mm. This mirror was built as a focus corrector. The second mirror, with a diameter of 1.8cm, had an array of 7 electrostatic pads behind an array of 7 pillars with a separation of 4.1mm.

The response of both mirrors was tested with a Shack-Hartmann wavefront sensor. The single electrode response was measured in the configuration shown in Figure 3. A 20x beam expanded helium-neon laser illuminated a beam splitter. The beam then reflected from the deformable mirror, the beam splitter, and was transmitted through a 2x telescope before entering the Shack-Hartmann wavefront sensor.

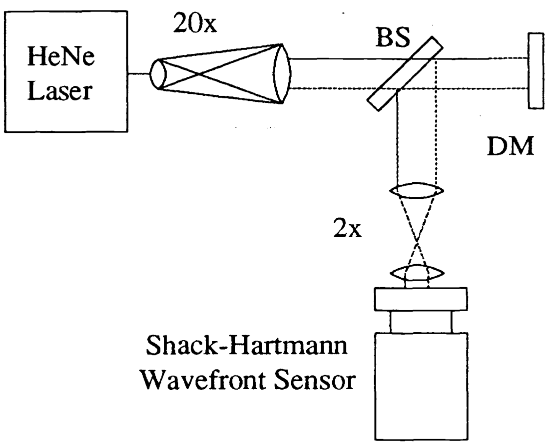

Figure 3 - Experimental setup used to test the deformable mirrors.

The deformation versus applied voltage at the center of the focus corrector relative to the edge is shown in Figure 4. The deflection with respect to applied voltage followed a parabolic dependence that is consistent with electrostatic force actuators. The Shack-Hartmann wavefront sensor measured a mirror deformation of 2250nm at 100V, which corresponded to a measured radius of curvature of -2.4m.

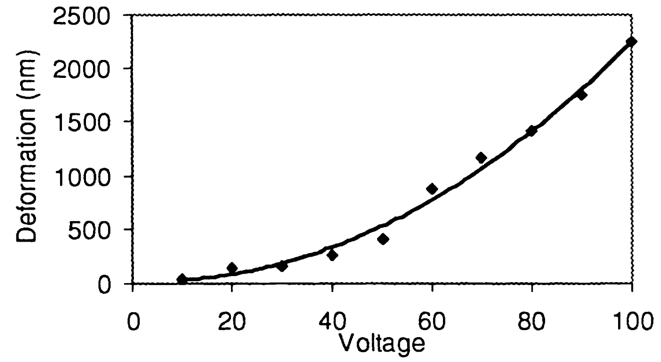

Figure 4 – Deformation to the applied voltage of the 1cm diameter, 10μm thick, silicon deformable mirror.

The seven element deformable mirror was characterized in a configuration similar to that shown in Figure 3. A 3X telescope was used to reduce the membrane image to fit into the wavefront sensor. The influence functions of this mirror were characterized by applying voltage to each of the electrostatic pads. Each of the six actuators 4.1mm from the center moved approximately 63nm and the center actuator created a 100nm of deformation for 155V of applied potential. The amplitude of the influence function of the six surrounding actuators at 4.1mm from the center of the actuator is 36nm corresponding to an adjacent channel coupling of 57%.

The temporal response of the a variety of deformable mirrors was measured with a square wave potential from 0V to 100V. The step response measured in room air for a 10 μm thick silicon mirror membrane 1cm in diameter showed ringing at a frequency of 950Hz. The step response for the 1cm diameter 30μm thick membrane exhibited a resonant frequency of 2.7kHz corresponding to a deformation of 275nm. A membrane 1.8cm in diameter and 30μm thick had a resonant frequency of 1.02kHz. These resonance frequencies were a bit lower than those used in atmospheric adaptive optics, but would be acceptable for other applications such as thermal lensing compensation. A higher resonance frequency could be obtained by making the membrane thicker or by modifying the deformable mirror architecture.

Mirrors built with 20 μm and 30μm membranes were coated with 100nm of gold for enhanced reflectivity. The power handling capability was tested by illuminating the mirror with 1064nm CW Nd:YAG laser focussed to a 50 micron spot radius. Two different membranes were tested and both withstood 8W of power, corresponding to an intensity of more than 100kW/cm^2, for 10 minutes.

6. Application - Active Mode Matching

Figure 5 shows the experimental setup used to demonstrate the mirror's performance as an element to actively control mode matching to a resonant cavity. A non-planar ring oscillator (NPRO) Nd:YAG laser was circularized and transmitted through a Faraday isolator. A half-wave plate and polarizer pair was used to attenuate the beam. An electro-optic modulator added high frequency FM sidebands onto the laser beam which are used for RF locking the laser to the Fabry-Perot ring cavity. The laser was carefully mode matched to the cavity, which is called a "mode cleaner" because it filters the spatial mode of the laser by reflecting all the light that is not in the TEM$_{00}$ mode. The mode cleaner consists of two flat mirrors and a 1m radius of curvature mirror with a round trip distance of 40cm. The cavity waist is 371μm and the finesse is approximately 4000.

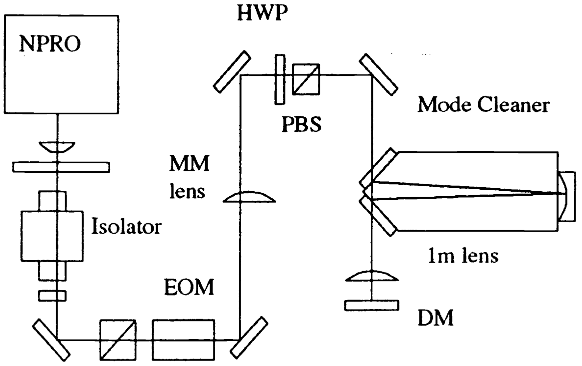

Figure 5 - Setup of the active mode matching experiment. (MM lens = mode-matching lens, DM = deformable mirror, EOM = electro-optic modulator, HWP = half-wave plate, PBS = polarizing beam splitter)

To test deformable mirror active mode matching, the deformable mirror was actuated to maximize the light transmitted through the cavity as indicated by minimizing the light reflected from the angled cavity mirror. Figure 6 shows the normalized reflected intensity as a function of the potential applied to the deformable mirror. More than 99.5% of the light was mode matched to the mode cleaner cavity. The remaining 0.5% which was reflected is probably a result of wavefront distortion due to aberrations in the lens or aberrations in the deformable mirror.

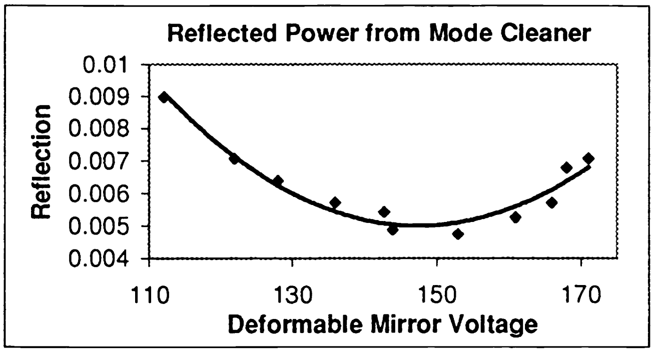

Figure 6 – The amount of light reflected from the optical cavity versus the voltage applied to the deformable mirror. Active control of mode matching achieved 99.5% coupling efficiency to the Fabry Perot cavity.

7. Conclusions

We have presented here preliminary tests of an all-silicon deformable mirror. The mirror has a continuous surface, lithographically etched pillars actuated by electrostatic force, and is compatible with conventional silicon processing. The focus corrector was shown to be tunable from a flat position to a radius of curvature of -2.4m with 100V. The seven-actuator mirror had influence functions with crosstalk of 57%. The design concept is compatible with scaling to silicon wafer diameters of 30cm and to large numbers of actuators.

In the future, we plan to improve the fabrication process. We expect that slight modification to the architecture will reduced crosstalk, improve actuator response, and increase the resonance frequency. We will explore thickness control of the mirror by using an epitaxial layer of heavily boron-doped silicon or silicon-on-insulator (SOI) wafers for an etch stop.

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[1] K. E. Petersen. "Silicon as a Mechanical Material". Proc IEEE. Vol. 70. pp. 420-457. (1982)

[2] Lin, L.Y.; Lee, S.S.; Pister, K.S.J.; and Wu, M.C. "Micro-machined micro-optical bench for optoelectronic packaging". Proceedings of LEOS '94. pp. 219-20.

[3] Gleb Vdovin and P.M. Sarro. "Flexible mirror micromachined in silicon". Applied Optics. Vol. 34, No. 16. June 1, 1995.

[4] Bifano, T.G. et al. "Continuous-membrane surface-micromachined silicon deformable mirror". Optical Engineering, May 1997. vol.36, no.5, p. 1354-60.

[5] Robert K. Tyson. Principles of Adaptive Optics (2nd Edition). Academic Press, 1998.

[6] Louis C. Marquet and John Hardy. "Historical Review of Adaptive Optics Technology". SPIE Proc. 141.

[7] William D. Cowan *et al.* Surface micromachined silicon mirror design presented during this SPIE conference.

[8] M. Adrian Michalicek *et al.* Surface micromachined silicon mirror design presented during this SPIE conference.

[9] Roberto Dizon, Hongtao Han, Armistead G. Russell, and Michael L. Reed. "An Ion Milling Pattern Transfer Technique for Fabrication of Three-Dimensional Micromechanical Structures." Journal of Microelectromechanical Systems. Vol 2, No. 4. Dec. 1993. Pp. 151-159.