Single-Crystal-Silicon Continuous Membrane Deformable Mirror Array for Adaptive Optics

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Abstract

We present a single-crystal-silicon (SCS) continuous membrane deformable mirror array with applications as a corrective adaptive optics element for space-based telescopes. The continuous membrane is made from a thin silicon-on-insulator (SOI) layer with good optical surface quality. The membrane is able to deform locally by 125nm at 100V with a resonance frequency of 25kHz.

Introduction

In this paper we present a single-crystal-silicon continuous membrane deformable mirror array with electrostatic actuation for applications in adaptive optics [1, 2]. Adaptive optics used to correct for atmospheric distortion requires large strokes of up to several microns. In space-based telescopes, where atmospheric distortion is a non-issue, imperfection of the optical system is the main reason for image degradation. Under these conditions, short-stroke programmable adaptive optics can correct for imperfections in the optical elements, such as local defects of a few nanometers to large curvature flaws of several hundred nanometers, and for mis-alignments without the prohibitively high cost of having to replace the components. In such systems continuous face-sheet mirrors, as described in this paper, are more suitable than segmented mirrors since these types of mirrors add to the degradation by lower fill-factor and diffraction.

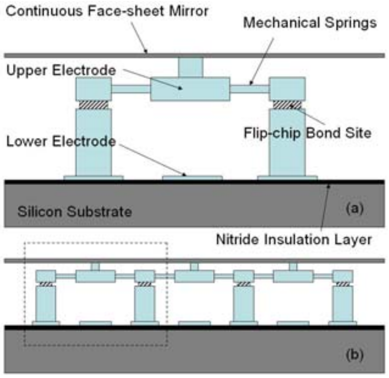

Figure 1. (a) Cross-section diagram of a single deformable mirror pixel. (b) Cross-section diagram of an array

Design and Fabrication

Our approach to the fabrication of continuous membrane MEMS mirrors differ from earlier reported methods [3,4,5,6] in that we fabricate the electronics and MEMS on different wafers and combine these with flip-chip bonding [7]. The advantage of this approach is that the MEMS and electronics can be optimized independently and separate foundries can be used for each. In particular, the electronics can be made in a standard foundry without the extra complexity that is associated with direct integration of MEMS. Just as important, this method also allows the fabrication of the top membrane using a sufficiently flat low-stress SCS device layer.

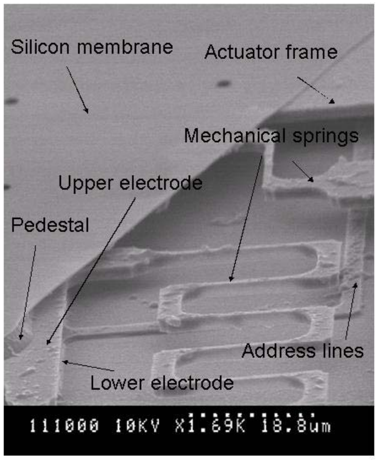

Figure 2. SEM of a pixel with the membrane partially removed to show the underlying structure

The diagrams in Fig. 1 show the structure of the deformable mirror. Figure 1(a) shows the cross-sectional view of a single pixel and Fig. 1(b) shows three elements of an array. Figure 2 shows a SEM of the structure. The upper electrode, membrane and spring structures are all at the ground potential and the bottom electrodes are individually addressed for control of the array. A potential applied between the two electrodes pulls the membrane towards the substrate by parallel-plate actuation.

The fabrication for the MEMS and electronics wafers is done separately and flip-chip bonded together (Fig 3.). The top membrane is a 300nm SOI (silicon-on-insulator) device layer. The pedestal that links the membrane and upper electrode plate is formed by a 2.0μm poly via that also forms the upper electrode and mechanical spring layer. As shown in Fig. 1(b), the mechanical springs are attached to the frame of the actuator and to the upper electrode. The upper and lower electrode areas are both 50μm x 50μm. The 3.0μm gap between the upper and lower parallel plate electrodes is determined by the 2.0μm thick poly layer offsets made on the electronics chip and gold bond layers of 0.5μm. Wiring lines and lower electrodes are formed on the lower poly layer. The

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MEMS chip and electronics chip is flip-chip bonded and released by isotropic silicon etching using XeF_2 and oxide etching using HF. The chip is finally dried by a critical-point-dryer (CPD).

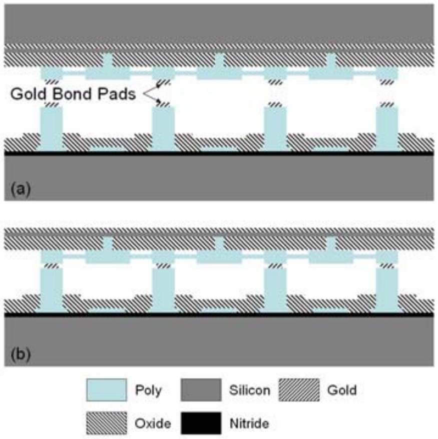

Figure 3. Flip-chip bonding and release of the MEMS and electronics chips

Device Characterization

The surface profile of the mirror array using a Wyko optical profiler is shown in Fig. 4. The center 1.0mm x 1.0mm area has a 5x5 array of active pixels with a pitch of 200µm. The outer 2 columns have dummy pixels that bound and support the upper membrane. The radius of curvature of the un-actuated mirror is 0.23m in the x-direction and 1.14 m in the y-direction. Stress in the poly actuator layer is believed to be cause of the curvature. This maybe resolved using a nitride/poly actuator layer to compensate for the stresses. The total surface roughness of the array with the curvature term removed is 19nm. The largest contribution to the roughness is the pedestal attachment to the upper membrane, which causes a bump in the membrane with a height of ~7nm.

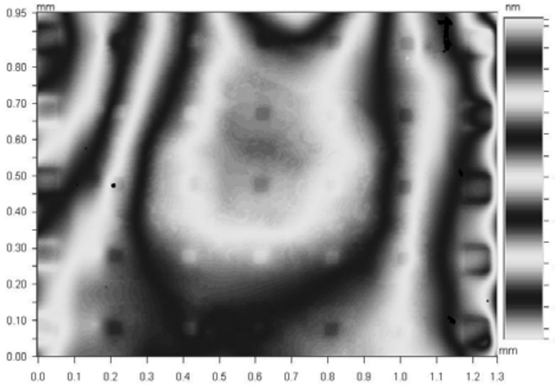

Figure 4. Surface profile of continuous AO array (measured using a Wyko optical profiler) x-profile curvature: 0.23m (center-to-edge height <700nm), y-profile curvature: 1.14m

Static deflection measurements show that the membrane deforms ~125nm at 100V (Fig. 5(a)) and closely matches simulated data. Figure 5(c) plots the cross-section of a pixel under varying potential. The plot shows that at 200µm pitch there is very little cross-talk <10%. Figure 5(b) shows the frequency response of a pixel measured using a fiber-interferometer and spectrum analyzer. The actuators were driven at 60sinωtV using an Intellite high-voltage MEMS driver. The response showed a resonance frequency of 25 kHz and a Q of 1.7. This is close to the simulated value of 27 kHz for the fundamental piston mode. The relatively low Q is expected to be due to squeezed-film damping of the continuous membrane.

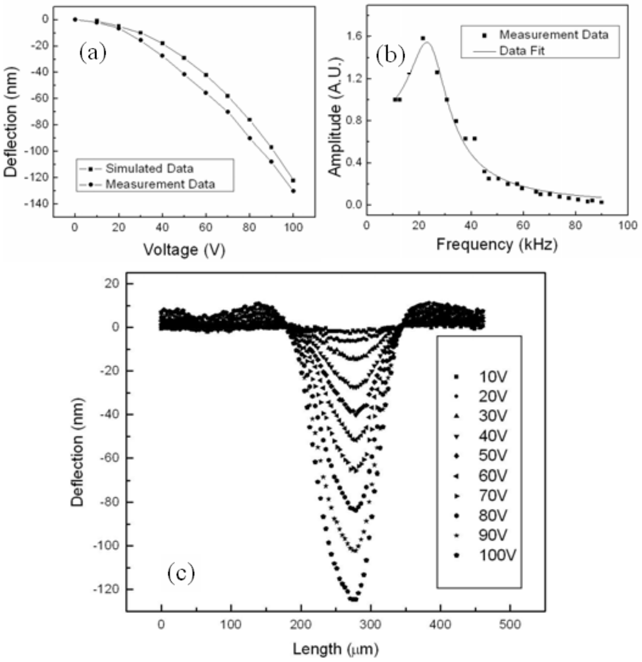

Figure 5. (a) Static deflection measurements (b) Frequency response (c) Static deflection cross-section at various actuation voltages

Conclusion

We have designed and fabricated a SCS continuous membrane deformable mirror array capable of ~125nm deformation at 100V. The 5x5 mirror array has a pitch of 200µm and surface roughness of 19nm. We expect that this type of device can be scaled with varying membrane thicknesses to be optimized for specific ranges in deformation from a few nanometers to microns as required by specific applications.

References

[1] P. Krulevitch et al, "MOEMS spatial light modulator development at the center for adaptive optics", *Proceedings of SPIE*, 4983, 227 (2003)

[2] Y.A. Peter et al, "Optical MEMS for adaptive optics applications", *First Int. Sympsium on Integrated Optoelectronics at the 201st Meeting of the Electrochemical Society, Philadelphia*, 361 (2002)

[3] T.G. Bifano et al, "Continuous-membrane surface-micromachined silicon deformable mirror", *Opt. Eng*., 36, 1354 (1997)

[4] J. Mansell, R.L. Byer, "Micromachined silicon deformable mirror", *Proceedings of SPIE*, 3353, 896 (1998)

[5] E.H. Yang, D.V. Wiberg, "A wafer-scale membrane transfer process for the fabrication of optical quality, large continuous membranes", *JMEMS*, 12, 804 (2003)

[6] P. Kurczynski et al, "Electrostatically actuated membrane mirrors for adaptive optics", *Proceedings of SPIE*, 4983, 305 (2003)

[7] Y.A. Peter, E. Carr, O. Solgaard, "Segmented deformable micromirror for free-space optical communication", *OMEMS*, 197 (2002)