A Wafer Transfer Technology for MEMS Adaptive Optics

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ABSTRACT

Adaptive optics systems require the combination of several advanced technologies such as precision optics, wavefront sensors, deformable mirrors, and lasers with high-speed control systems. The deformable mirror with a continuous membrane is a key component of these systems. This paper describes a new technique for transferring an entire wafer-level silicon membrane from one substrate to another. This technology is developed for the fabrication of a compact deformable mirror with a continuous facet. A 1 μm thick silicon membrane, 100 mm in diameter, has been successfully transferred without using adhesives or polymers (i.e. wax, epoxy, or photoresist). Smaller or larger diameter membranes can also be transferred using this technique. The fabricated actuator membrane with an electrode gap of 1.5 μm shows a vertical deflection of 0.37 μm at 55 V. The proposed technique has the following benefits over those previously reported: 1) No post-assembly release process (e.g. using HF) is required, and no wax, photoresist, or epoxy is used for the transfer purpose 2) The bonded interface is completely isolated from any acid, etchant, or solvent, which ensures a clean and flat membrane surface. 3) It offers the capability of transferring wafer-level membranes over deformable actuators.

BACKGROUND

The term "Adaptive Optics" refers to optical systems, which remove the blurring of images to compensate for optical distortions introduced by the medium between the object and its image. Turbulence in the Earth's atmosphere causes blurring of astronomical images. In an analogous manner, internal imperfections and fluids in the eye cause blurring of images striking the retina. The use of adaptive optics allows ground based telescopes to see clear images as if they were in space, and these techniques dramatically sharpen images of the retina. In order for an optical system to approach its diffraction limit, it is necessary to correct the wavefront of the incoming light so as to remove distortions that deviate the system from the ideal. A deformable mirror is a reflecting element that compensates for wavefront distortions with its array of actuators that push and pull at the mirror. The development of new technologies is essential in wavefront correction devices. Thus, the inclusion of a compact Micro Electro Mechanical Systems (MEMS) deformable mirror technology has much potential for advancing compact adaptive optics systems.

Micromachined designs have been developed by several research groups to improve the deformable mirror technology and offer the potential to be scalable and cost effective. Segmented mirrors [1-3] have been fabricated with individual pixel tip/tilt capability, but a continuous mirror surface is required for astronomical adaptive optics applications. Micromachined continuous membrane deformable mirrors have been fabricated by Delft [4] and JPL [5] although the previous JPL design was substantially more rudimentary in approach than that described in this paper. Both approaches provide excellent surfaces but the mirror membranes have high inter-actuator coupling between individual pixels. An electrostatically actuated surface micromachined deformable mirror [6] has been demonstrated. This micromachined deformable mirror has a continuous mirror backed by parallel plate actuators embodied within the Multi-User MEMS Processes (MUMPs). Being restricted to the MUMPS process results in design limitations and marginal surface quality, which in turn limits the applicability of this approach.

High contrast imaging applications call for optical quality continuous mirror surfaces. A continuous membrane has the advantage that it does not cause scattering by edge diffraction of the reflected beam, thus increasing the imaging sensitivity for imaging and spectroscopic applications. Such membranes also ensure smooth and continuous phase variations across the mirror surface. Therefore, a new design for the materials, structures, and fabrication methods to meet the requirements of imaging astronomical and visual adaptive optics is necessary. To satisfy this requirement, a novel concept is being pursued at JPL to develop a MEMS deformable mirror with a continuous membrane. In order to realize this concept, a sheet of optical quality single crystal silicon (with surface area greater than $1 cm^2$) should be transferred onto deformable membrane actuators. Batch transfer techniques to transfer devices or thin films over dissimilar wafers have been previously demonstrated [7-10]. Some of these techniques are capable of transferring multi-layered structures, but the transfers have succeeded only for localized devices. Wafer level transfer techniques have also been developed, which involved adhesives and/or molding materials [11, 12]. These techniques are not suitable for multi-layer or reliable transfer because adhesives often have residues over the transferred membrane surface, hindering subsequent post process required to complete the transfer. Thus, a new wafer-level transfer technique has been developed as a reliable process for the fabrication of a MEMS deformable mirror.

MEMBRANE TRANSFER PROCESS

A 1 μm thick corrugated polysilicon membrane was transferred onto an electrode wafer to show the feasibility of the proposed technique. The transferred corrugated membrane with underlying electrodes constitutes an electrostatic actuator array for deformable mirrors.

A Silicon-On-Insulator (SOI) wafer and a silicon wafer are used as the carrier and electrode wafers, respectively. Figure 2 shows the fabrication sequence for multi-layered wafer-level membrane transfer. A 0.5 μm thick oxide is thermally grown on both sides of the wafers. Then Ti/Pt/Au metallization is deposited and patterned to form the electrode array on the electrode wafer. The carrier wafer is patterned and etched to define a 5.0 μm deep corrugation profile. A 1 μm thick polysilicon film is deposited on the carrier wafer after thermal oxidation (Figure 2 (a)). Cr/Pt/Au metallization is deposited subsequently over the photoresist patterns on both wafers for the lift-off process. A thin indium layer is then deposited on both wafers. Since the indium layer uniformly wets the Au layer, the Au acts as a "substrate" for hermetic bonding, which is a critical step for the subsequent etch process. Indium instantly oxidizes in air, and the oxidized indium does not provide hermetic bonding. Thus, the indium deposition process is followed by the deposition of a 0.01 μm thick Au to prevent indium from oxidation. The deposited metal layers for bonding are patterned using a lift-off process.

The carrier wafer is subsequently bonded to the electrode wafer. An EV aligner and a thermo-compression bonder were used to align and bond two patterned wafers, respectively. The bond chamber is pumped down to $1X10^{-5}$ Torr before pressing down two wafers. A piston pressure of 4 KPa is applied at 156 °C in a vacuum chamber to provide a complete hermetic sealing (Figure 2 (b,c)). The substrate of the SOI wafer is etched in a 25 wt % TMAH bath at 80 °C until the buried oxide is exposed (Figure 2 (d)). A Teflon fixture is used to protect the backside of the wafer pair as well as their bonded interface. The exposed oxide is then removed by using 49 % HF droplets after an oxygen plasma ashing (Figure 2 (e)). The SOI top silicon layer is etched away by using an SF_6 plasma to define the corrugation profile, followed by the HF droplet etching of the remaining oxide. An oxygen plasma is then used to remove possible residues on the membrane surface. The wafer-level silicon membrane transfer is completed at this stage (Figure 2 (f)). The SF_6 plasma with a shadow mask selectively etches the polysilicon membrane if the transferred membrane structure needs to be patterned (Figure 2 (g)). The 2^{nd} layer membrane transfer process onto a deformable membrane actuator arrays (Figure 2 (h)) is currently under development.

CHARACHTERIZATION

Fig. 2 shows SEM photographs of a 1 μm thick membrane, which has been successfully transferred onto an electrode wafer. The gap between the membrane and the electrode substrate is very uniform (+/- 0.1 μm across a wafer diameter of 100 mm, provided by optimizing the bonding control). A WYKO RST Plus optical profiler was used to measure the static deflection and the surface profile of transferred membranes. The fabricated polysilicon actuator with an electrode gap of 1.5 μm shows a vertical deflection of 0.37 μm at 55 V (Fig. 4). The surface profile of a transferred single crystal silicon membrane was measured and compared with that of a typical silicon wafer (Fig. 5). Figs. 6 (a) and (b) show the power spectral density data of surfaces of a transferred silicon membrane and a silicon wafer, respectively. The surface quality of a transferred membrane is comparable to that of a typical silicon wafer. This shows that an optical quality deformable mirror can be obtained if wafer with an optical quality surface is used for the transfer, since the transferred membrane is a replica of the carrier wafer.

CONCLUSIONS

A new wafer-level silicon membrane transfer technique for developing a MEMS deformable mirror with a continuous membrane has been demonstrated by fabricating and testing an electrostatic actuator array. A 1 μm thick silicon membrane, 100 mm in diameter has been successfully transferred without using adhesives or polymers (i.e. wax, epoxy, or photoresist), thus avoiding residues and/or cracks and ensuring a clean mirror membrane. A more comprehensive characterization of successive membrane transfers thereby onto a deformable membrane actuator array is under development. A larger stroke design is also being incorporated to provide the enabling technology for adaptive optics for astronomical applications (e.g. segmented space telescopes).

This technique can be applied to many MEMS devices such as electrostatic actuators, optical connectors, and RF switches as well as deformable mirror (deformable mirror) technologies. The JPL's deformable mirror is targeted for insertion into high contrast astrophysical imaging with the advantages of applying MEMS technology in ultra miniaturized and high-precision components for adaptive optical subsystems.

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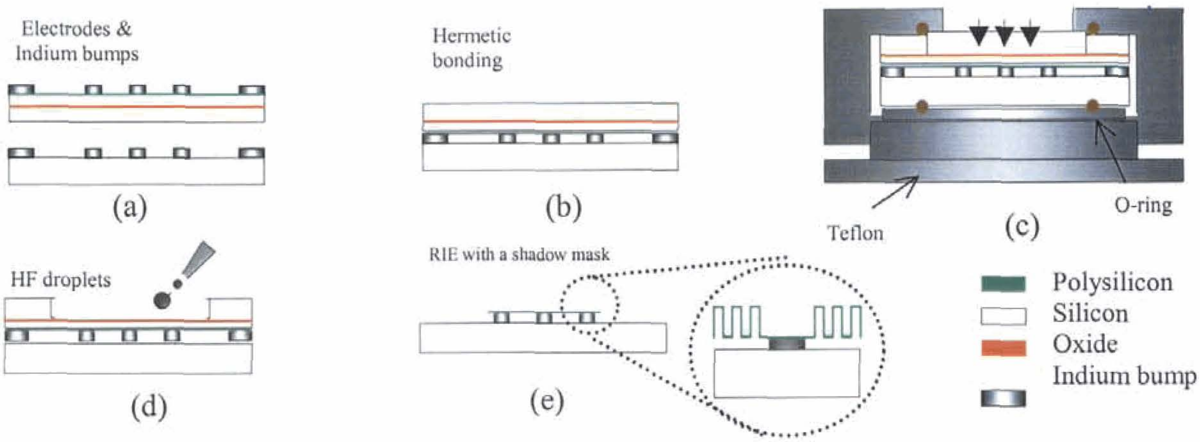
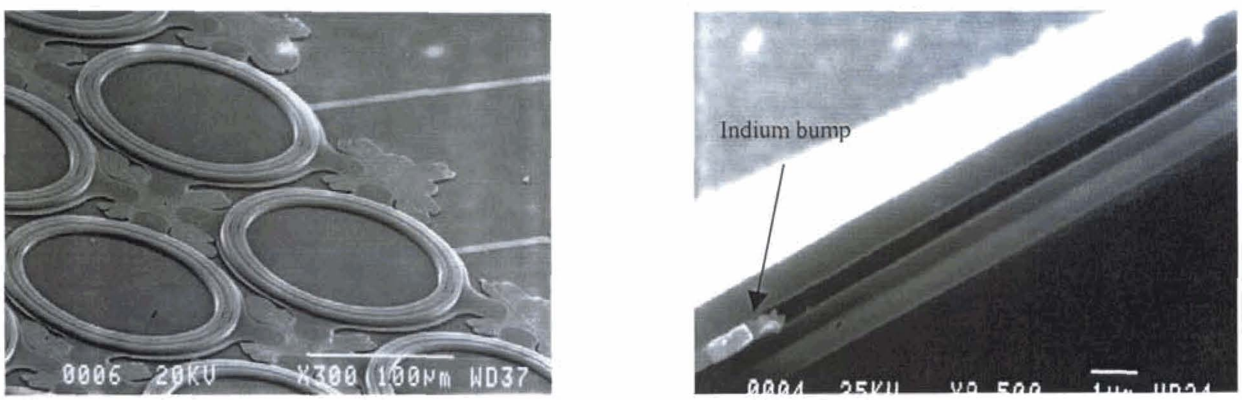


Fig. 1 The membrane transfer process for the fabrication of the high stroke MEMS deformable mirror. The successive layer transfer process is identical with the first layer transfer process except for the use of a shadow mask to place Indium bumps over deformable actuators. (a) Polysilicon deposition, electrode definition & Indium evaporation. (b, c, d) Bonding & etching. (e) Defining actuator membrane. (f) Successive layer transfer.



(a) (b)

Fig. 2 The SEM photographs of the transferred membranes. (a) The transferred corrugated membrane actuators. (b) The cross sectional view of a transferred membrane.

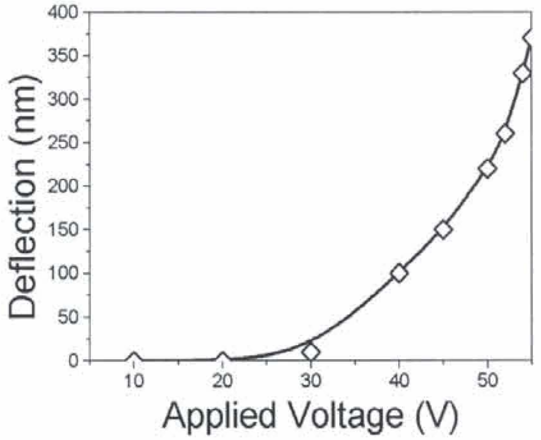


Fig. 3 The deflection characteristic of a transferred polysilicon membrane actuator.

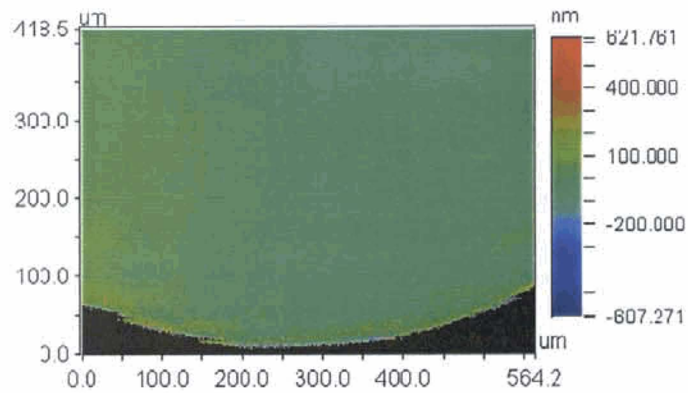
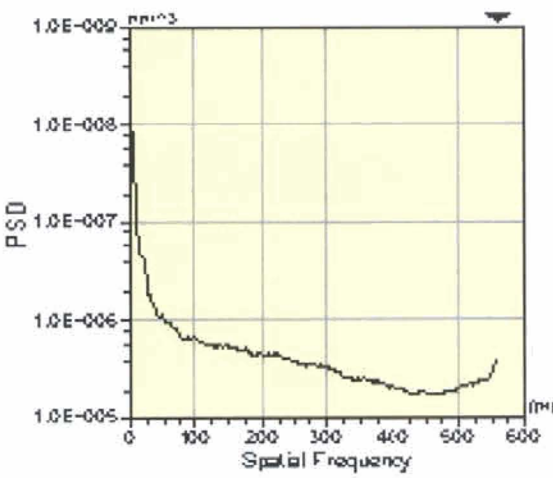
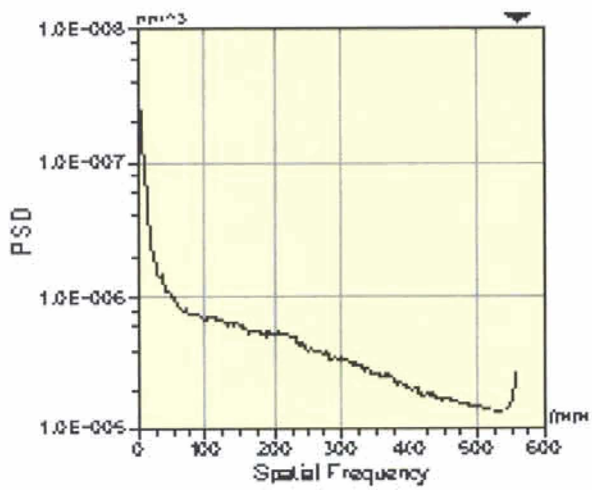


Fig. 4 The surface profile of a transferred single crystal silicon membrane.



(a)



(b)

Fig. 5 The Y average power spectral density data of the silicon surfaces.
(a) A transferred silicon membrane. (b) A silicon wafer.