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SHORT COMMUNICATION

Deformable Membrane Mirror for Wavefront Correction

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ABSTRACT

Deformable or adaptive mirrors are used in modern adaptive optics systems for direct correction of the aberrations in the light wavefront. Conventional deformable mirrors used for this purpose are expensive electromechanical devices. Deformable membrane mirror fabricated using microelectromechanical systems (MEMS) technology is a low cost, compact adaptive optical element for correction of the lower-order optical aberrations such as defocus and astigmatism. In this paper, important aspects of device design and simulation, fabrication techniques, and test results are discussed.

Keywords: Deformable membrane mirrors, adaptive mirrors, wavefront correction, micromachined deformable mirrors, microelectromechanical systems, adaptive optical systems

1. INTRODUCTION

Deformable or adaptive mirrors[1,2] are an integral part of modern adaptive optics systems, which are being used to adapt for compensating the optical effects introduced by the medium between the object and its image. Under ideal circumstances, the resolution of an optical system is limited only by the diffraction of light waves, which is never achieved in practice because atmospheric and telescope errors distort the spherical wavefront, creating phase errors in the image-forming ray path.

In an adaptive optics system, these effects are compensated leading to appreciably sharper images, better contrast and detection of fainter objects in astronomy. This is achieved by real time compensation of the turbulence-induced aberration using a wavefront sensor to detect the wavefront phase aberrations, and dynamically compensating these aberrations by reflecting or transmitting the wavefront by an active element such as deformable mirror working in a closed loop. The shape of the mirror is changed such that the aberrations in the distorted wavefront are reduced after reflection from the mirror, thus, improving the quality of the source image obtained with the camera.

A deformable mirror in combination with a wavefront sensor and real-time controller can be used to modulate the spatial phase of an optical wavefront. Piezoelectric deformable mirrors have been used as an active element but are heavy and expensive and require high driving voltage. Deformable mirrors based on microelectromechanical system (MEMS) technology using silicon micromachining provide an inexpensive, low power, compact, high performance alternative to piezoelectric mirrors. These are electrostatically-driven and consume low power, thus reducing the cost of drive circuitary. In addition, these devices are light-weight and can be packaged in an IC type of package with pin connections.

The emergence of MEMS-based deformable mirrors is likely to extend the field of adaptive optics, from its roots in astronomical imaging systems to the commercially important areas of laser-based communications, biomedical imaging, laser welding, and terrestrial imaging. In this paper, developmental steps of a micromachined adaptive mirror are presented.

2. DEVICE STRUCTURE AND PRINCIPLE OF OPERATION

Figure 1 shows a schematic of a micromachined deformable mirror. The device consists of a silicon chip mounted over a substrate, which is glass or a PCB holder. The chip contains silicon nitride membrane fabricated by silicon micromachining technique. The silicon nitride membrane is coated with aluminum or gold and acts as a thin, elastic, electrically conducting and reflecting mirror surface. The PCB contains the control electrode structure, spacer, and connector. It also serves as the mirror package. Bias voltage

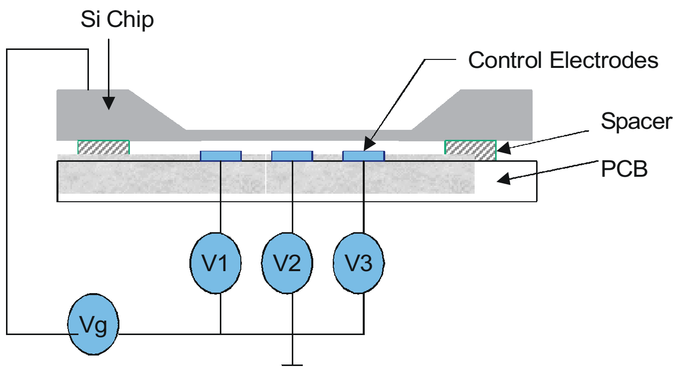

Figure 1. Schematic of a micromachined deformable mirror.

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is applied to the membrane, which is flexible to correct the wavefront shape. This mirror can have one or more shape control channels/electrodes depending on the application requirement. In an adaptive optical system a distorted wavefront enters the system and gets reflected from the deformable mirror. The wavefront sensor then measures the wavefront. Control voltage to different electrodes is adjusted to change the shape of the membrane in such a way that the amount of aberration in the beam is reduced after reflection from the mirror. This improves the quality of the source image obtained with the camera.

The electrostatic actuators are constructed with electrodes deposited on the ground plane over which the mirror is affixed. When voltages are applied between the bottom electrodes and the mirror membrane, the electrostatic force pulls down the membrane, modulating the shape of the mirror surface. The desired mirror deflection can be achieved by application of appropriate voltages to the electrodes.

The electrostatic forces between the membrane surface and control electrodes determine the deflection of the mirror surface, i.e. the shape of the membrane. The deflection of the membrane surface is generally nonlinear wrt the control voltages. Individually, each electrode channel changes the surface profile of the membrane. All channels can also be coupled together to form the overall modulation of the mirror surface shape within the fixed boundary.

This is a continuous membrane mirror system designed to ensure smooth and continuous variations across the mirror. Two others types of mirror systems used in adaptive optics are segmented mirrors and hybrid mirrors. But the present system design has the advantage that there is almost no diffraction of the reflected beam.

3. DESIGN AND SIMULATION

A simple model of a parallel-plate capacitor, where the lower plate is fixed and the upper plate is movable, can approximate the problem of the membrane deflection under

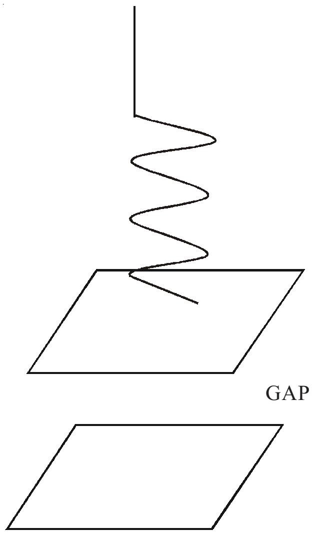

Figure 2. Diagram of parallel plate capacitor model.

applied voltage. Figure 2 shows the model of this voltage-controlled electrostatic actuator. The electrostatic force[3] must be matched by the spring force given by:

$$F = Q^2/2\varepsilon A = V^2 A\varepsilon/2d^2 = kz$$

where, F is the electrostatic force, Q is the charge on the plate, A is the area of the plate, V is the applied voltage, d is the gap between the membrane and the fixed electrode, k is the spring constant, and z is the displacement of the movable plate of membrane.

$$z = V^2 A\varepsilon/2kd^2$$

The expression for k in case of square diaphragm[4] of size l and thickness t is given by:

$$k = E.t^3/\alpha l^2$$

where, $1/\alpha = 0.0138$

Using this expression, displacement of the membrane can be determined for different values of gap d, membrane thickness t and applied voltage to bottom electrodes. The results using this model are shown in Figs 3 and 4 where mirror deflection is plotted as a function of applied voltage in the range 10 –110 V. In Fig. 3, effect of membrane thickness on deflection is shown. The deflection is increasing with the increase in voltage but the increase is higher for low values of membrane thickness thus indicating greater flexibility. In the case of gap variation (Fig. 4) increase in deflection

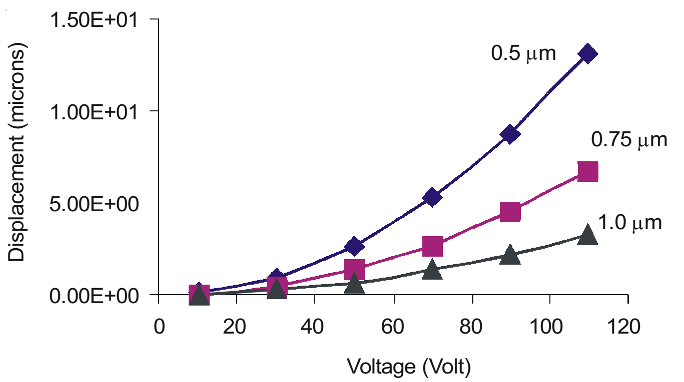

Figure 3. Displacement versus voltage (for different values of membrane thickness, gap ~50 µm, plate area ~1 cm x 1 cm).

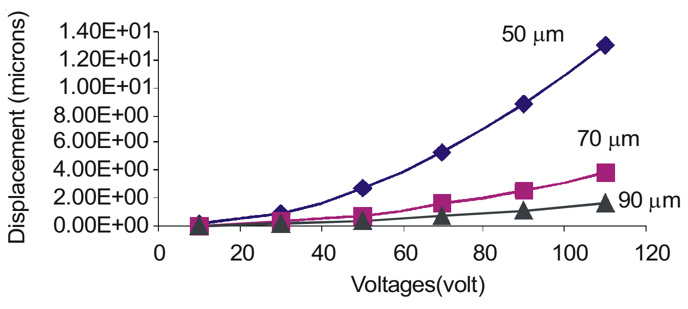

Figure 4. Displacement versus voltage (for different values of gap, membrane thickness ~1 µm, plate area 1 cm x 1 cm).

Table 1. Natural frequency for different membrane sizes and thickness

Nitride thickness (μ)	Natural frequency for 5 mm × 5 mm membrane (Hz)	Natural frequency for 10 mm × 10 mm membrane (Hz)
0.5	277	63
0.8	443	152
1.0	547	241
1.2	691	348
1.5	831	435

with voltage is higher for lower gap value. These parameters are the main device design parameters and fixed by the technological limitations and the particular application.

These results are based on a simplified model where both the plates are of the same size. In the actual device electrodes are of much smaller size than the deformable top membrane. Analytical solution is not possible in this case. Therefore mirror response was simulated using FEM with ANSYS software. Natural frequency was calculated for different membrane size and thickness (Table 1). As listed in the table, natural frequency of the deformable membrane was found to decrease with the increase in area and increase with the increase in thickness. Figures 5 and 6 show the deflections obtained on application of voltage (50 V) for the two membrane sizes: (1) 5 mm × 5 mm, (2) 10 mm × 10 mm mounted over a single bottom electrode. Maximum deflection obtained was 2.79 μm in the first case and 5.77 μm for the larger size device. Deflection was found to be maximum at the center of the mirror. Mirror response for multielectrode structure has also been calculated and results will be published elsewhere.

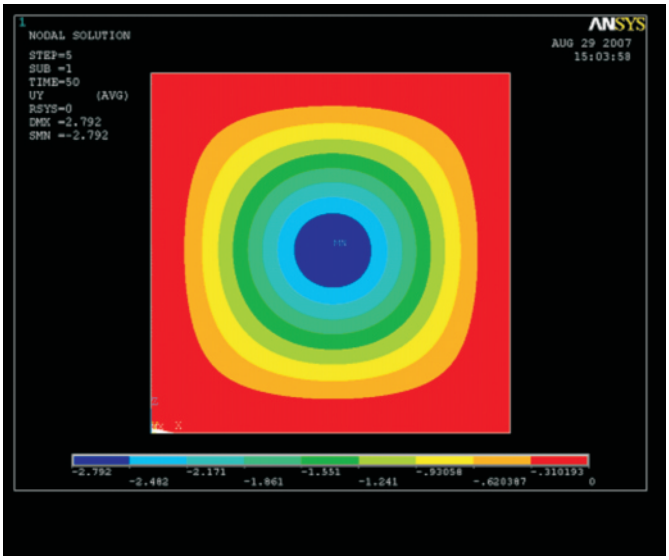

Figure 5. Deflection of mirror membrane at 50 V (size 5 mm × 5 mm, thickness 1 μm).

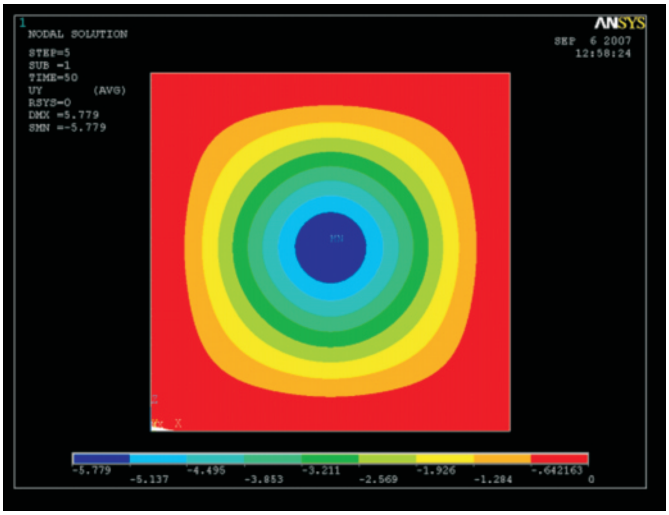

Figure 6. Deflection of mirror membrane at 50 V (size 10 mm × 10 mm, thickness 1 μm).

4. FABRICATION

The device geometry has been shown in Fig.1. Silicon nitride has been chosen as the membrane material because of its good mechanical properties and its compatibility with both bipolar and CMOS processes. Low stress, mechanically strong silicon nitride film of ~0.8-1 μm thickness is deposited on a (100) double side polished silicon wafer. The entire wafer was etched using silicon bulk micromachining with anisotropic etching. Figure 7 shows the photograph of silicon nitride membrane. The membrane surface was coated with 0.4 μm *Al* layer (deposited in a vaccum coating unit) to make it reflecting to serve as the mirror. The wafer was cut into chips containing one mirror each and each mirror was mounted on the substrate containing the bottom metal electrodes fabricated using standard photolithography techniques. The multielectrode structure fabricated for control is shown in Fig. 8. Complete packaged device is shown in Fig. 9.

5. RESULTS AND DISCUSSION

Initial measurements were done on the samples prepared by mounting the metallised mirror membrane on single electrode and four electrodes structures, respectively. The deflection in the membrane was measured with the optical

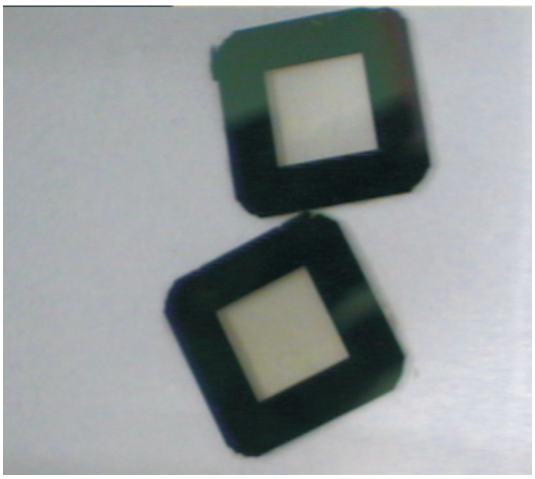

Figure 7. Free standing silicon nitride membranes (1 cm × 1 cm) obtained using bulk micromachining.

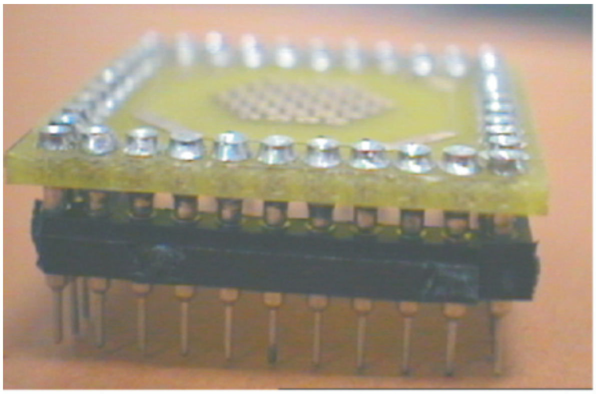

Figure 8. Multi electrode structure for mirror control.

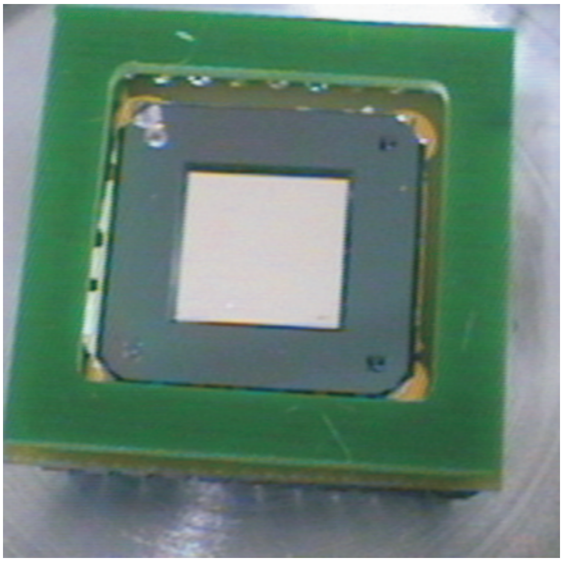

Figure 9. Top view of packaged adaptive mirror.

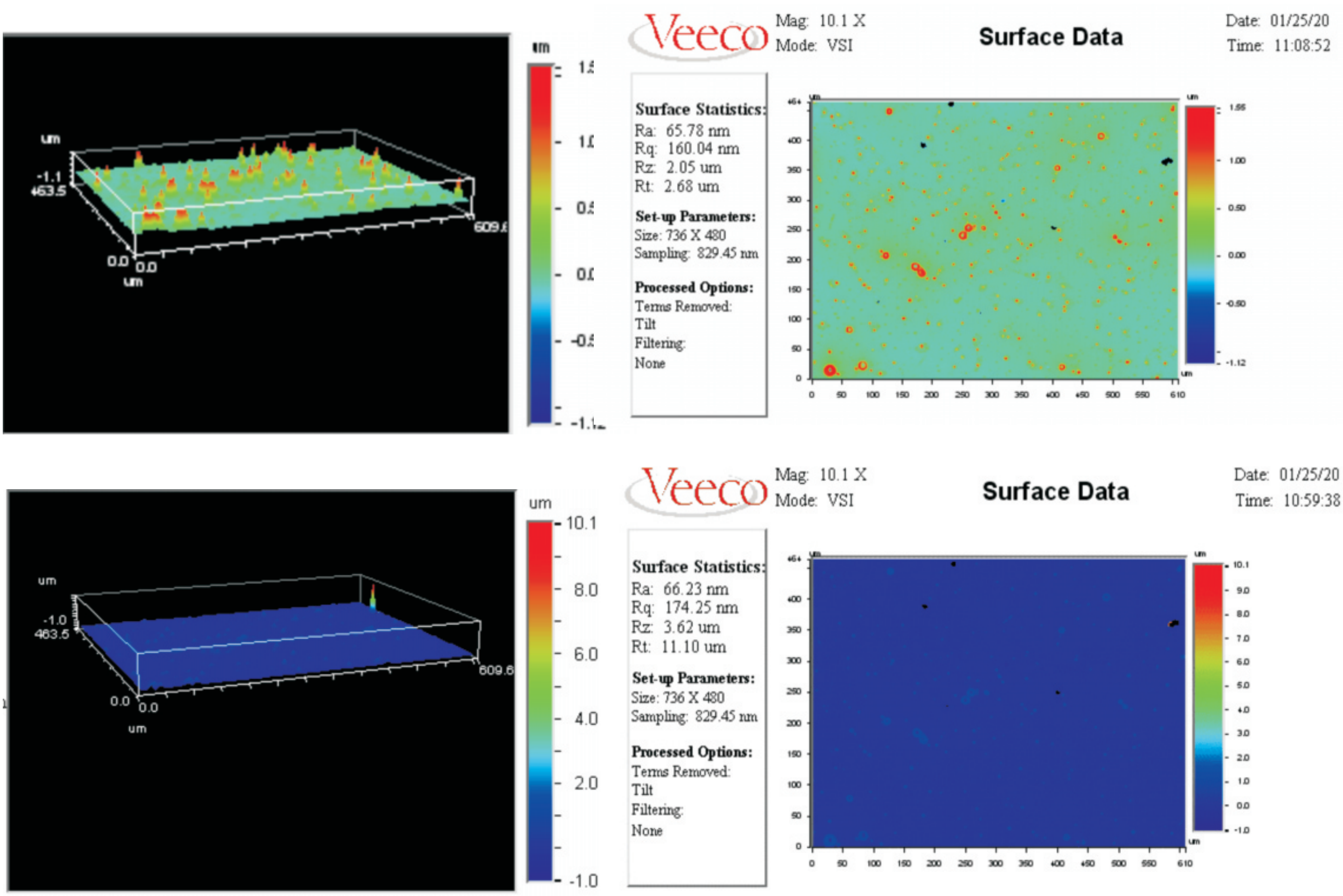

Figure 10. Measurement of deflection of deformable mirror in the *z*-direction.

profiler at Veeco-India Nanotechnology Laboratory at JNCASR. Deflection of >2 μ was observed in the vertical direction (Fig. 10}. The nitride membrane remained was intact and did not break during measurements.

6. CONCLUSION

Important development steps for fabrication of membrane deformable mirror have been described and initial test results have been reported.

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Contributors

Dr (Mrs) Amita Gupta obtained her PhD (Solar Cells) from BITS, Pilani. She worked as Assistant Lecturer at BITS and at IIT Delhi as Research Associate before joining DRDO as Scientist C in 1982. She has contributed in development of various semiconductor devices: *p-i-n* diodes, quadrant detectors, semiconductor fuse, porous silicon, and its applications, vibration sensors, and development of MEMS Technology. Her work on porous silicon was recognized internationally (published in *Encyclopedia of Advanced Materials*). She visited Moscow under a joint program with GPI and Moscow State University. She has published more than 50 papers in various journals and conference proceedings. Presently, she is working as Scientist G at Solid State Physics Laboratory (SSPL), Delhi, and her work area includes development of deformable mirrors, design and simulation of MEMS devices, biosensors, and microfluidic systems.

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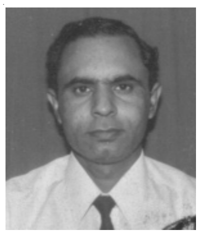

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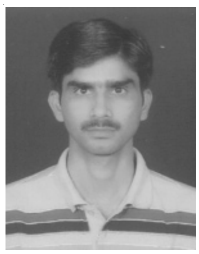

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