Static and Dynamic Optical Metrology of Micro-Mirror Thermal Deformation

C.R. Forest*, P. Reynolds-Browne**, O. Blum-Spahn*, J. Harris**, E. Novak**, C.C. Wong*,
S. Mani*, F. Peter*, D. Adams*

* Sandia National Laboratories[1], Albuquerque, NM, cforest@mit.edu
** Veeco Instruments, Inc., Tucson, AZ, tbrowne@veeco.com

ABSTRACT

Metrology of MEMS can provide feedback for accurate modeling of thermal-mechanical behavior and understanding of thin film properties. Towards this end, measurements of the thermal-mechanical response of a micro-mirror design have been performed using interferometry. The thermal mechanical response of a 500 μm diameter mirror is induced with spot heating using a 100 μm diameter infrared laser at optical powers up to 1.5 W. The transition between elastic and plastic deformation is observed. Amplitudes of elastic and plastic deformation up to 120 nm and 3 μm are measured, respectively. Optical heating is then cycled in the elastic regime, permitting a novel application of stroboscopic interferometry. Results indicate that heating and cooling of the micro-mirror occurs over approximately 2.2 ms, as measured with a temporal resolution of 0.14 ms. Deformation amplitude is proportional to optical power, and depends on micro-mirror surface coating.

Keywords: stroboscopic interferometry, optical profilometry, MOEMS, optical switch, thermo-mechanical

1 INTRODUCTION

Accurate and repeatable metrology of micro-electro-mechanical systems (MEMS) is vital to their widespread application. Metrology provides feedback for design and manufacturing process improvement which leads to predictable, reliable performance. Since MEMS usually contain moving parts, the capability to measure dynamic behavior is also useful. Such applications include the characterization of vibration amplitudes, frequencies, and mode shapes, for example. The observation of mechanical responses at these length scales can lead to new understanding of thin film or micro-mechanical properties for better modeling of these phenomena.

1.1 Integrated micro-switching system

A two-position micro-optical switch is being developed at Sandia National Laboratories for surety applications. This system features an optical shutter, a vertical cavity surface emitting laser (VCSEL), and a photodetector. The optical shutter, shown in Figure 1, is a 500 μm diameter gear with an off-axis thru-hole. Its angular position is controlled by an electrostatic comb drive as shown in Figure 2. The device is fabricated by surface micro-machining technology (SUMMiT™ process).

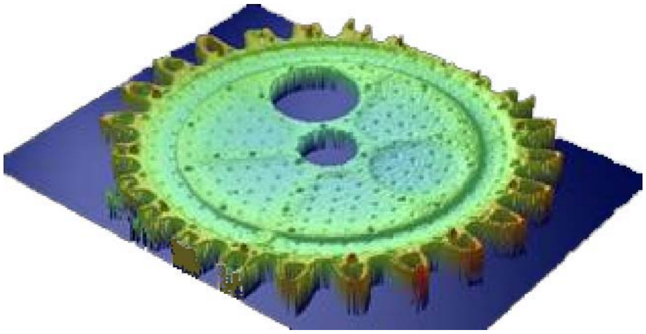

Figure 1: The optical shutter is a polysilicon gear, fabricated using micro-machining technology.

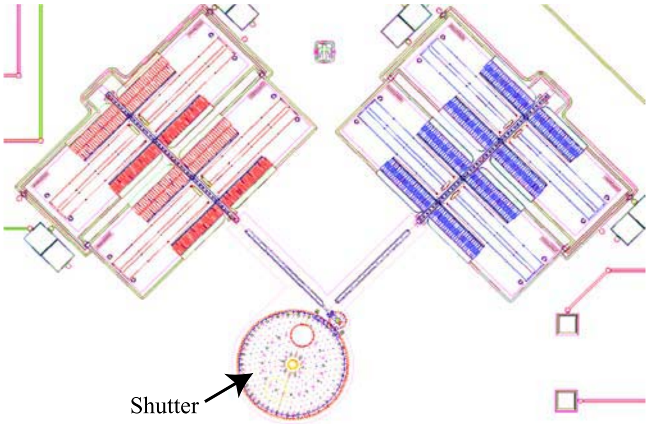

Figure 2: An electrostatic comb drive enables angular rotation of the shutter.

In the original design [1], incident radiation from the laser passes directly through the off-axis hole and through a via in the underlying substrate to the detector. In the alternate switch state, the shutter is rotated to block the path of the incident radiation to the detector. Further design modification has led to utilization of the shutter as a micro-mirror as well. In this configura-

---

[1] Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

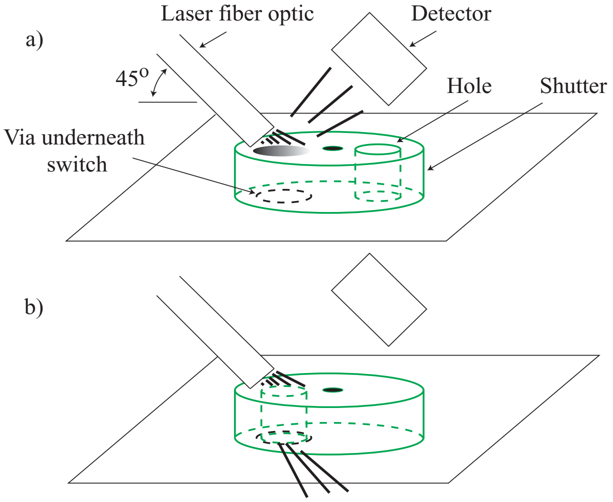

Figure 3: (*a*) Switch in the "on" position–incident laser radiation is reflected from the switch to the detector. (*b*) switch in the "off" position allows light to pass through.

tion, incident radiation reflects from the shutter's mirror surface to the detector as shown in Figure 3*a*. Figure 3*b* illustrates the "off" position, in which rotating the gear 180° allows the radiation to pass through the off-axis hole and through a via in the underlying substrate. The design modification is desirable since physical gear absence results in an "off" switch state.

Under these operating conditions, the VCSEL emits radiation for a period of tens of seconds before the shutter is rotated to the "off" position. For this duration, radiation incident on the mirror surface is partially absorbed, subjecting the shutter to localized spot heating. The resulting thermal expansion and deformation creates undesirable mechanical and optical performance, such as spurious reflections or binding between the shutter and its hub, which can prevent rotation. Understanding the heat transfer model for this system is crucial to mitigating these concerns. A thermo-mechanical heat transfer model in which absorbed radiation results in predictable deformation can be used to redesign the switch to prevent binding by minimizing deformation or moving deformation to an area where there is no performance impact [2]. Empirical data is required to generate this model. Therefore, we have pursued metrology of the deformed switch. This work, specifically, concerns the measurement of elastic and plastic thermally-induced deformation of the optical switch as a function of time and incident optical powers in order to create and validate a suitable heat transfer model.

2 OPTICAL SWITCH EXPERIMENTAL APPARATUS

For these experiments, a simple apparatus was devised to induce the optical shutter thermal response. A semiconductor laser operating at 832 nm was connected to a multimode optical fiber. The bare fiber core was then positioned over the micro-mirror at 45° angle of incidence with a three axis translation stage, thus replicating the illumination scheme for the actual optical switch. The shutter actuator was not included since only the "on" position was of interest–the shutter angular position in which local spot heating occurs. This configuration resulted in an approximately 100 μm spot size on the 500 μm diameter micro-mirror. Experiments were performed with both "bare" and gold-coated polysilicon micro-mirrors. This 500 Å thick gold coating was applied to increase surface heat conduction. Using a variable power op-amp, the optical power incident on the micro-mirror could be varied from 0–1.5 W.

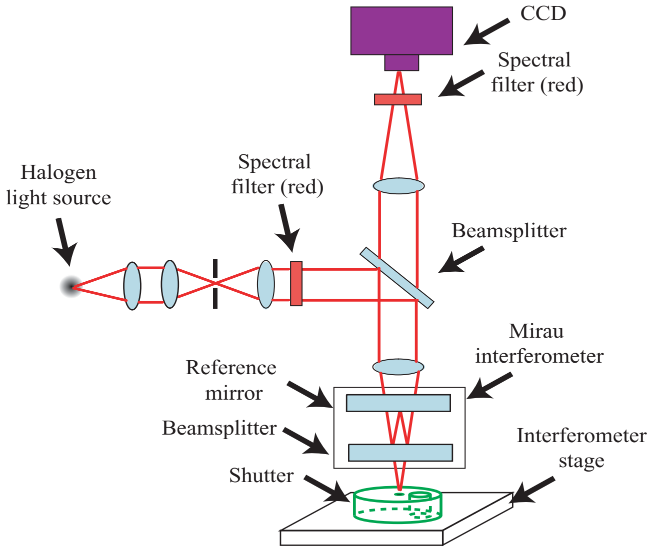

Figure 4: The Wyko optical profilometer uses a Mirau interferometer to measure the shutter at 10× magnification. The spectral filters reduce the bandwidth and protect the CCD array during the thermal measurements.

3 MEASUREMENT OF THERMAL DEFORMATION

To measure the thermal deformations, a Wyko optical profilometer (Veeco Instruments, Inc., NT3300 and NT 1100), utilizing a Mirau interferometer, was selected for its high spatial resolution, accuracy, and repeatability. The experimental apparatus was placed on the profilometer stage as shown in Figure 4. The instrument's CCD array was protected from the laser's intense infrared radiation by a narrowband red filter, matched to the instrument's source illumination.

3.1 Static measurements

Measurements of the switch were taken before heating and after the switch thermal response had reached

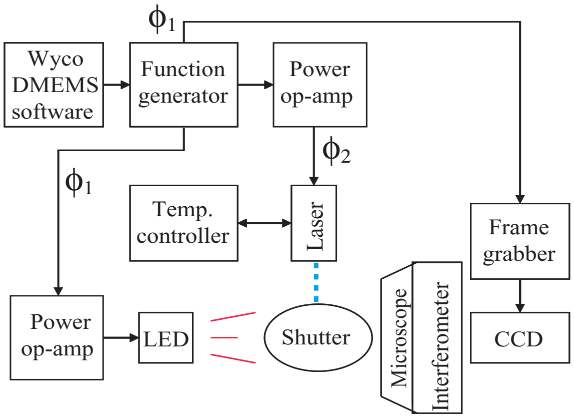

Figure 5: The function generator, controlled by Wyco software, sends drive square wave signals to the frame grabber and LED with phase ϕ_1 for image capture. A phase shifted square-wave (ϕ_2) of the same frequency is sent to the laser to induce thermal deformation.

steady state to determine the threshold optical power for plastic deformation and corresponding deformation amplitude. These static tests provided the boundary conditions for a purely elastic thermal response. The test procedure was as follows: a measurement of the room-temperature mirror surface was taken; optical power was set to 100 mW; a measurement of the heated, deformed mirror was taken while the laser was on. This cycle was repeated for increased optical powers for both the bare polysilicon and gold-coated mirror samples.

3.2 Dynamic measurements

The interferometer setup was modified to capture the mirror thermal deformations as they occurred. These dynamic measurements were performed using stroboscobic interferometry [3]. A schematic of the system is shown in Figure 5. As the name of the technique implies, pulse square-wave signals were used to drive the laser, CCD frame grabber and illumination. The phase of the laser heating, ϕ_1, was varied constantly with respect to the phase of the image capturing (frame grabber and illumination), ϕ_2. Both signals have the same frequency. This resulted in a set of data which fully recorded the mirror heating/cooling cycle. For these measurements, square wave drive signals at 20 Hz and 50% duty cycle were used. The phase shift, $\Delta\phi = \phi_1 - \phi_2$, was initially zero and was incremented by 1 degree per cycle. A higher signal frequency could have been used, up to a limit at which the laser would be cycled off before the mirror is heated to steady-state temperature and deformation. Smaller phase shift steps could also have been implemented if more temporal resolution of the transient behavior were desired.

For data integrity, the heating/cooling cycle in this stroboscopic interferometry measurement must be repeatable. Towards that end, results from the static measurement experiments were used to set the laser power below the threshold for plastic deformation. Thus, the purely elastic thermal response of the micro-mirror could be cycled thousands of times without residual mirror damage. Both optical power and mirror design (bare or gold-coated) were varied to study the dynamic thermal response.

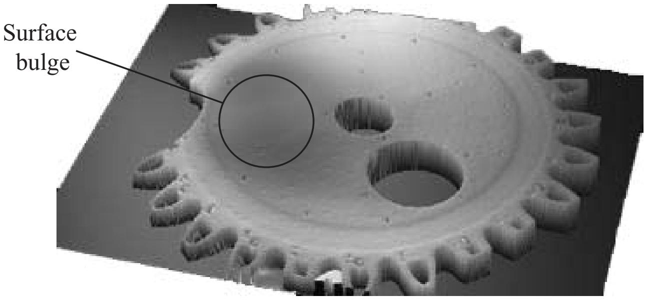

Figure 6: Optical shutter physically deformed by locally heating with an infrared laser. Compare with Figure 1. Data absence at left edge of shutter caused by optic fiber obstruction of profilometer.

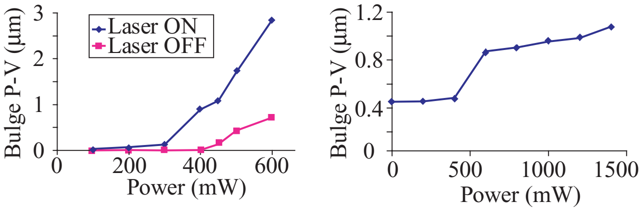

Figure 7: Static micro-mirror peak-valley (P-V) deformation for bare polysilicon (*left*) and gold-coated (*right*). Measurements taken with laser on, then off, for various optical powers.

4 Results and discussion

The static and dynamic experiments were performed to characterize the shutter thermal response. An interferometric image of a micro-mirror deformed elastically by spot heating is shown in Figure 6. A characteristic bulge on the surface is caused by local thermal expansion. The bulge amplitude for optical powers tested (0–1.5 W) ranged from 10's of nanometers to 3 μm.

Results from the static measurements are presented in Figure 7. As the bare polysilicon mirror is subjected to laser powers greater than 400 mW, the bulge present during heating does not entirely disappear after laser cessation. A micro-structural analysis of this plastically deformed region reveals recrystallization, indicating that melting has occured. Bulge P-V, measured with the laser on, was up to 150 nm for the elastic region and increased to over 3 μm for plastic deformation of the bare polysilicon mirror.

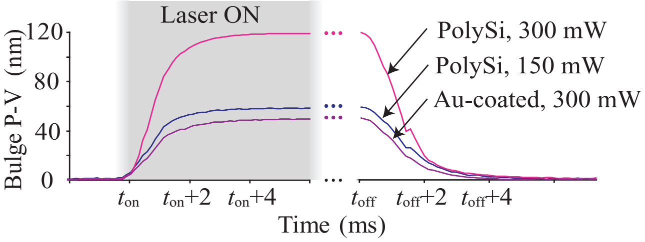

Figure 8: Experimental heating and cooling measurements, captured with stroboscopic interferometry. The bulge peak-valley (P-V) is proportional to incident power and depends on micro-mirror surface coating.

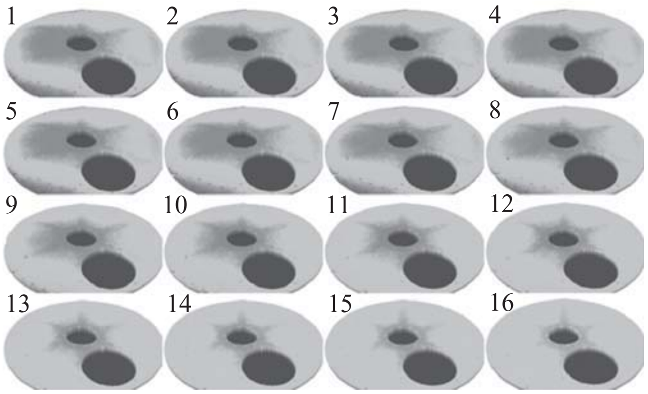

Figure 9: Sixteen images of a bare polysilicon micro-mirror over a span of 2.2 ms (resolution = 0.139 ms) illustrate transient cooling behavior following laser cessation.

For the gold-coated micro-mirror, optical powers up to 1.5 W over an approximately 8000 μm^2 area failed to produce plastic deformation. Notably, however, the surface area of the bulged region was more than twice as large as for the bare polysilicon micro-mirror due to increased thermal conduction on the gold-coated surface. For this gold-coated mirror, elastic deformation increased nearly linearly with optical power, from 0.45 μm with no optical power to 1.1 μm at 1.5 W. Results from these static measurements indicate that the optical power on the bare polysilicon micro-mirror should be kept below 400 mW for the dynamic measurements to keep the deformation purely elastic.

The dynamic measurements were then performed. This technique permitted the observation of micro-mirror heating and cooling which occured over time scales of a few milliseconds. Results are shown in Figure 8. The heating and cooling cycles were measured at 150 mW and 300 mW for polysilicon, and at 300 mW for the gold-coated micro-mirrors. The bulge P-V is proportional to optical power, and agrees with the previous static measurements. Clearly, the gold coating distributes energy more and reduces the P-V deformation as compared with the polysilicon data. The time required to heat and cool the mirrors to steady-state is approximately 2 milliseconds.

Along with this quantitative analysis, qualitative images were captured for the heating and cooling of the devices. Figure 9 shows the transient cooling of a bare polysilicon mirror. The laser is completely off after 0.3 ms (frame 3), and thus energy is solely leaving the mirror, primarily by conduction to the underlying substrate via the hub [2]. Thus, stroboscopic interferometry has permitted the characterization of the dynamic thermal response of the micro-mirror.

5 CONCLUSIONS

For both the silicon and gold-coated mirrors, exposure to infrared radiation from a laser produced a steady-state deformation after approximately 2 ms. This thermal-mechanical behavior has been measured using interferometry, including a new application of stroboscopic interferometry. Results indicate that for the elastically deformed regime, deformation is proportional to optical power. Gold-coating reduced the P-V deformation for the same optical power and prevented plastic deformation for powers up to 1.5 W. In contrast, the bare polysilicon mirror was plastically deformed at powers greater than 400 mW. Amplitudes of deformation ranged from 10's of nanometers to microns for both the bare polysilicon and gold-coated mirrors.

These measurements provide a characterization of the micro-mirror thermal response that will be used to improve the design and analysis of this device. Issues such as how the heat can be better distributed, and how deformation can be reduced in critical locations such as the bearing hub can be better understood and solved.

These novel observations of repeatable, transient MEMS thermal response provide an essential contribution to understanding the heat transfer mechanisms in these thin films. Thermal-mechanical analysis software can be validated and improved by comparison with these experimental results. There are numerous other applications in which dynamic metrology (i.e., stroboscopic interferometry) of thermal-mechanical behavior could be useful, such as bolometers and temperature sensitive safety mechanisms.

REFERENCES

[1] A.D. Oliver, F.J. Peter, M.A. Polosky, ”Microsystems based on surface Micromachined Mechanisms,” Proceedings of IEEE, Sensors, (2002)

[2] C.C. Wong, S. Graham, ”Investigating the Thermal Response of a Micro-Optical Shutter,” IEEE/ASME Itherm2002 (2002)

[3] E. Novak, D. Wan, P. Unruh, M. Schurig, ”MEMS metrology using a strobed interferometric system”, ASPE Winter Topical Meeting, (2003)