Micromirrors for High Power CW Lasers

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Abstract

This paper describes the key findings of a project that was undertaken to develop multi-layer dielectric coated optical micromirrors that could be used with high-power CW laser radiation. Silicon micromirrors of different dimensions and with different designs of multi-layer coatings were compared in terms of planarity, surface roughness and optical reflectivity. It was found that the planarity of the mirrors was influenced by the internal stresses in the different coating materials, but that this could be controlled by optimal design of the coating layers. A simple model of this effect was constructed; the model agreed very well with experimental findings. The micromirrors were exposed to 1W CW radiation at 1550nm wavelength - this radiation was produced from an optically amplified semiconductor laser. Over 99% reflectivity was achieved without any damage to the mirrors.

Kewords: micromirrors, multi-layer dielectric optical coatings, high power optical coatings

Introduction

Scanning MEMS micromirrors can be integrated with high power bulk or fibre lasers to realise compact systems for remote sensing. Systems which can apply scanning mirror/fibre laser integrated modules include LIDAR, laser range finding, active imaging and target illumination. For these applications, the micromirrors have to withstand the high optical powers emitted from fibre or other high power laser systems. For example a CW fibre laser with an output power of 1W generates an incident power density on the mirror surface of 36 MW/m^2 when the fibre-to-mirror separation is 1 mm. With bulk optic scanners which are currently used, specialist thin film optical coatings resistant to high optical power densities can be routinely deposited onto the reflecting optical surface of the scanner. However, the deposition of such high optical power coatings onto micromirrors requires further investigation before scanning micromirrors can be considered as a substitute for bulk-optic scanners. Such micromirrors are relatively thin – a silicon-on-insulator MEMS micromirror can vary in thickness from 10 μm to around 85 μm. Compared to this range of thicknesses, a high power multilayer dielectric coating can range in thickness from 3 to 10μm (dependent on the number of coating periods), and often such optical coatings have an internal stress. Differences in internal stress and thermal characteristics between the dielectric coating material and the micromirror films can lead to departures from planarity of the reflecting surfaces or localized distortions of the mirror surfaces. A study has been undertaken to investigate these issues. The micromirrors used in this study were exposed to 1W CW radiation at 1550nm wavelength – this radiation was produced from an optically amplified semiconductor laser. The overall aim was to identify dielectric coating technologies and materials that could be successfully deposited on mechanically thin mirrors, and

to subsequently investigate the optical and mechanical characteristics of such coated micromirrors.

Design and fabrication of micromirrors

Micromirrors were designed for fabrication using SOIMUMPs, a commercial foundry process provided by the MEMSCAP Inc MEMS foundry. The process begins with 100 mm diameter, n-type, double-side polished silicon-on-insulator (SOI) wafers. Wafers with a 25 μm silicon layer, a 1 μm oxide layer, and a 400 μm substrate layer were used, and processed as follows. First, the silicon is patterned with the first mask level, "SOI", and etched. Next, a protective material is deposited on the front face, and then patterning of the back side of the wafer is achieved using the second mask level, "TRENCH". A deep reactive ion etching (DRIE) step is used to etch these features completely through the substrate layer. A hydrofluoric acid releasing process follows, allowing silicon structures on top of the trench hole to be completely released since the acid removes the oxide. Finally, a metal layer, consisting of 50 nm Cr+ and 600 nm Au, is deposited and patterned using shadow masking technique. This mask layer is called "METAL". The wafers are then diced using a scribe and break method. A selection of "built-in" micromirrors of differing lateral dimensions were produced for the investigation. All micromirrors were designed to have square reflecting surfaces.

Surface profile measurements – no dielectric coating

Profile measurements of the micromirrors were made using a Veeco NT1100 surface profiler which is a non-contact optical profiler using the principle of white-light interferometry. This tool can measure both global surface profiles as well as localized profiles and surface roughness over a region of a few tens of microns square. All the data points in the various graphs in this paper relating to the curvature of the micromirrors show the deflection of the mid-point of the mirror. A *minus* sign indicates a mid-point deflection *below* the plane of the substrate (i.e a concave surface) while a *positive* value indicates a mid-point deflection *above* the plane of the substrate (i.e a convex surface).

Figure 1 shows optical surface profile measurements for 25 μm thickness built-in mirrors. Mirrors have been tested from three different chips. Profile traces show that this range of micromirrors initially have a concave profile.

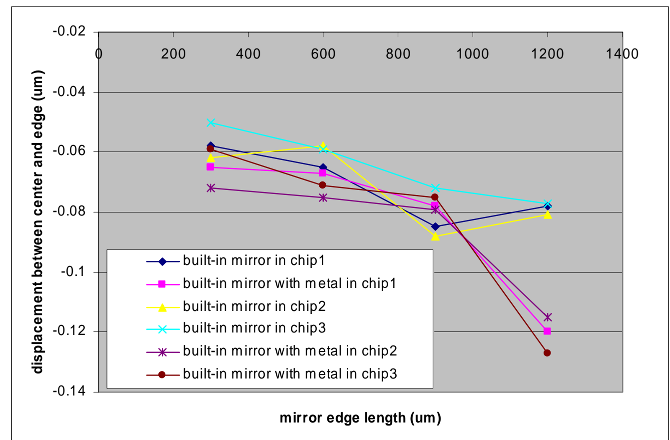

Figure 1. *Surface measurements of the built-in 25 μm micromirrors on 3 different chips before dielectric coating*

From Figure 1 it can be seen that:

(a) increasing the size of the mirrors producing higher central deflection of the micromirrors

(b) at the largest size (1200 μm) the gold coated silicon mirrors have a significantly higher central deflection than their uncoated silicon counterparts. The gold coated mirrors have an average deflection around -120 nm while the uncoated silicon mirrors have an average deflection around -78 nm.

(c) at the smallest size (300 μm) the gold coated silicon mirrors have a slightly higher central deflection than their uncoated silicon counterparts. The gold coated silicon mirrors have an average deflection

of around -68 nm, while the uncoated silicon mirrors have an average deflection of -58 nm.

Optical reflectivity measurements

Optical reflectivity measurements were undertaken using an amplified 1550 nm semiconductor laser with variable output state-of-polarisation. The amplification was achieved using a fibre amplifier. After optical amplification 1 Watt of radiation was delivered from the fibre amplifier output. The light was then coupled into an adjustable fibre polariser which has the capability to achieve both S and P states of polarisation. The fibre polariser used could typically achieve linear polarisation with 40dB suppression of the orthogonal state. The high-power laser output from the fibre polariser had a spot diameter of 10.5 µm. The output beam was uncollimated, and its diameter increased in accordance with Gaussian beam propagation. The linearly polarised output beam was incident at an angle of 45 degrees onto all the micromirrors which were tested. This meant that all beams were deflected by 90 degrees when reflecting from the micromirror surface. The overall distance from the fibre output to the micromirror surface was typically 1 mm – this generated a spot size of 188 µm on the micromirror surface, and a corresponding power density of 36 MW/m^2 on the micromirror surface. The distance from the micromirror surface to the optical power meter was 3 mm. All reflectivity measurements were referenced to an initial power measurement of the fibre laser output before insertion of the micromirror. It was noted that there was less than 1% fluctuation in power during the duration of each set of reflectivity measurements. The overall measurements reported here are accurate to around 2%. Table 1 presents reflectivity measurements for silicon and gold-coated silicon mirrors of 25 µm thickness. The theoretical results, also for 45 degrees incidence angle, were obtained using the software tool IMD v 4.1.

	Reflectivity (s-polarization) %		Reflectivity (p-polarization) %	
25 um mirrors without dielectric coating	Experiment	Theory	Experiment	Theory
Built-in silicon membrane	50.5	64.1	27.1	28.4
Built-in silicon membrane with gold	98.6	98.8	98.4	97.9

Table 1 *Measured and theoretical reflectivities of 25 micron thick mirrors*

Dielectric coating design

Dielectric coatings were designed and optimised to have high reflectivity at a centre wavelength of 1550 nm for a laser beam with an angle of incidence of 45 degrees. In a standard high reflection stack (L H)^N L, thickness L is λ/4 @1550nm of SiO_2 (refractive index n = 1.448); thickness H is λ/4 @1550nm of Nb_2O_5 (refractive index n = 2.208); N represents the number of periods, where each period has a thickness of L + H. Figure 2 shows the overall transmittance of an N = 8 stack.

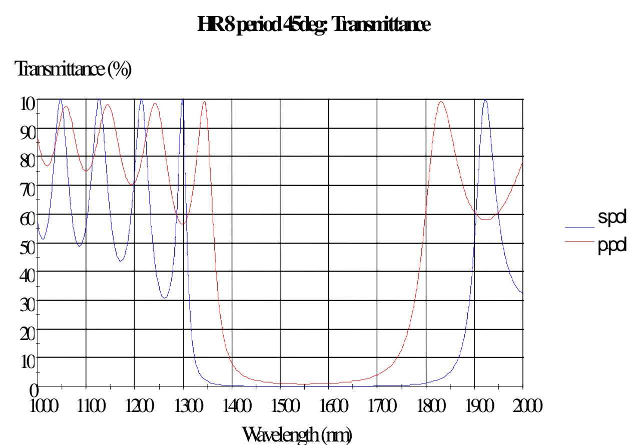

Figure 2. *The calculated transmittance at 45° angle of incidence (L H)^8 L*

Figure 3 shows that the stress is fairly substantial at this thickness. The total deposition time for an 8 period coating was around three and a half hours.

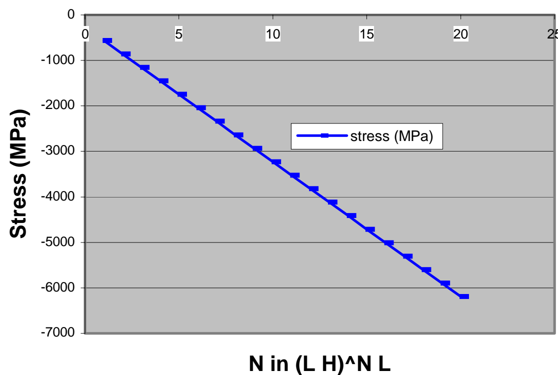

Figure 3. *The dependence of coating stress on period number N (-ve stress = compressive)*

Surface profile measurement: dielectric coated micromirrors

Figure 4 shows optical surface profile measurements for 25 μm thickness built-in mirrors. Mirrors have again been tested from three different chips. Profile

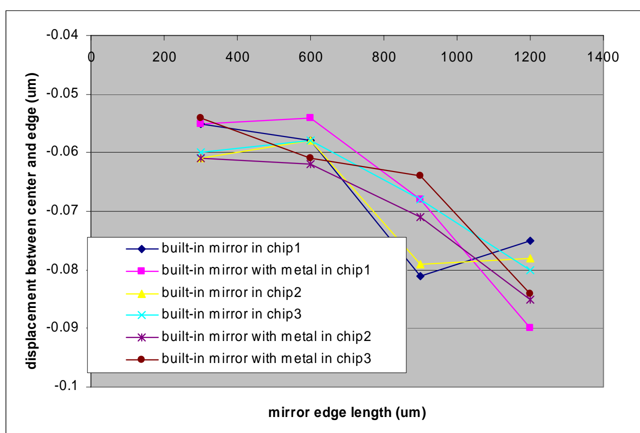

Figure 4. *Surface measurements of the built-in 25μm micromirrors on 3 different chips after 8 periods dielectric coating*

traces show that this range of micromirrors retain their original concave profile after dielectric deposition. From Figure 4 it can be seen that:

(a) increasing the size of the mirrors produces higher central deflection of the micromirrors

(b) at the largest size (1200 μm) the dielectric plus gold plus silicon mirrors have a slightly higher central deflection than their dielectric plus silicon counterparts. The first category has an average deflection around -86 nm while the second category has an average deflection of around -77 nm

(c) at smaller sizes (300 μm) the dielectric plus silicon mirrors have a slightly higher central deflection than their dielectric plus gold plus silicon counterparts. The first category has an average deflection of around -61nm (best two readings) while the second category has an average deflection of around -55 nm (best two readings)

Optical reflectivity measurements:dielectric coated micromirrors

Reflectivity measurements were undertaken following the procedure described earlier. Table 2 presents reflectivity measurements for the dielectric plus silicon and dielectric plus gold plus silicon mirrors of 25 μm thickness. The theoretical results were obtained from the software tool IMD v 4.1.

	Reflectivity (s-polarization) %		Reflectivity (p-polarization) %	
25 um mirrors with coating 8 period 45 degree optimized	Experiment	Theory	Experiment	Theory
Built-in silicon membrane	99.2	99.9	98.1	99.2
Built-in silicon membrane with metal	99.2	99.9	98.1	99.9

Table 2. *Measured reflectivities of 25 μm thick mirrors (dielectric coated)*

Conclusions

The main conclusions of this research are:

(a) thin "built-in" silicon micromirrors of 25 μm thickness can be successfully coated with gold films or multilayer dielectric stacks (of alternate Nb_2O_5 and SiO_2 layers) to obtain high-reflectivity (>99% with a measurement error of around 1-2%) micromirrors having less than 5 nm roughness measured by phase shift interferometry

(b) both the gold film and dielectric stack deposited on the micromirrors can withstand 1W of CW radiation (power density 36 MW/m^2) at 1550nm without any sign of optical damage – there is no adverse effect on the performance of the gold film or dielectric stack just because they are coated onto thin silicon layers of the type used in MEMS technology

(c) coatings of gold and dielectric on the silicon micromirrors changes the geometry of the reflecting surfaces because of thin film stresses. Simple mechanical modelling (not presented here) has allowed us to model the topologies of the coated silicon test structures. The results of the models match the measured profiles of coated silicon test structures very well, so the impact of the coating is deterministic

(d) changing the number of periods in the dielectric stack can be used as a mechanism for controlling the profile of micromirrors

(e) there is good repeatability in surface topology between mirrors of identical designs fabricated on different silicon chips.

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