TIME-MULTIPLEXED-PLASMA-ETCHING OF HIGH NUMERICAL APERTURE PARABOLOIDAL MICROMIRROR ARRAYS

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Abstract – This paper presents a time-multiplexed plasma-etching method for high numerical aperture paraboloidal micromirrors. By designing the appropriate opening and spacing of etching windows, one can fabricate micromirror arrays with varying focal lengths within one batch.

INTRODUCTION

Curved micromirrors, including various existing deformable micromirrors, e.g. [1-3], have many applications in micro-opto-electro-mechanical systems (MOEMS), such as communication or data storage devices. Since the deformable mirrors usually have limited numerical aperture (NA), spherical aberration and residual stress uniformity problems, static paraboloidal micromirrors still can be a very promising candidate for MOEMS applications. An ideal paraboloidal mirror has no spherical and chromatic aberration. It can be integrated into a solid immersion mirror for near-field optics, such as the read-head of a near-field ultra-high-density data storage system, e.g. [4-5]. However, highly precise fabrication and mass production technologies are critical issues for practical applications. In this study, we propose a time-multiplexed plasma-etching method for high numerical aperture paraboloidal micromirror arrays, Figure 1. By designing the appropriate opening and spacing of etching windows, one can fabricate various paraboloidal micromirror arrays (Each array consists of 70×70~100×100 micromirrors, NA: 0.44~1.92.) simultaneously on a substrate within one batch with carefully controlled timing.

FABRICATION

We have developed a time-multiplexed plasma-etching process for paraboloidal mirror arrays using an OXFORD Plasmalab System100. The process starts from 4" single-crystal-silicon <100> wafers (n-type, resistivity between 1 and 2 Ω-cm), coated by a hard-baked 9µm thick AZ4620 photoresist mask for plasma etching. It consists of physical and chemical etching. The profile is controlled by gas flow rates, pressure, forward power, temperature and the power of inductively coupled plasma (chuck temperature was at -15℃, ICP always equal to 2000W). The time-multiplexed plasma-etching scheme of the mirror is shown in Figure 2. The first step was started from a 35-minute SF6 plasma etch, which formed isotropic trenches in the silicon substrate. The second step consisted of 15-minute oxygen plasma cleaning, which was used to remove the AZ4620 mask from the substrate, then followed by another 15minute non-directional SF6 plasma etch to produce the paraboloidal cavity (Figure 1). Unlike deep reactive ion etching (DRIE), there is no passive cycle in this process, thus, there is no scalloping encountered on silicon sidewalls. Smooth surfaces were produced for mirror surfaces.
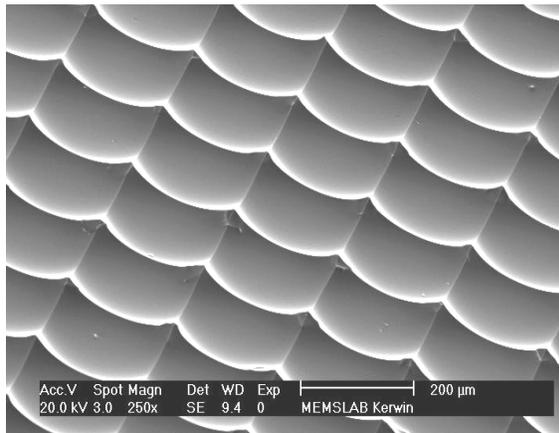
Figure 1: The paraboloidal micromirrors
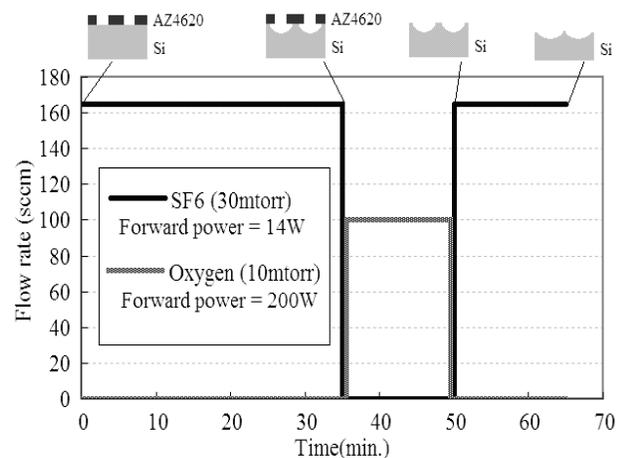
Figure 2: Time-multiplexed-plasma-etching scheme

After the plasma etching was complete, the paraboloidal concave shape can be coated with aluminum for visible light reflection or gold for infrared reflection. Various paraboloidal micromirror arrays were fabricated simultaneously on the same substrate by different etching openings and spacings.

EXPERIMENTAL RESULTS AND DISCUSSION

Different sizes of circular openings and spacings have been designed and tested through this process; their features are listed in the first column of Table 1 (e.g., "s125r20" represents a circular opening array, the radius is equal to 20μm, center to center spacing is equal to 125μm.) To quickly gauge the optical properties of the mirror, it is useful to observe the condensed filament image directly from the focal plane under an optical microscope. The experimental setup of the optical testing is shown in Figure 3. The image of the filament observed through a charge-coupled device (CCD) camera is placed in the second column of Table 1. From the relation between the magnifying power of the optical system and the image analysis unit connected to the CCD camera, one can estimate the focus of these mirrors. However, the detailed three-dimensional profiles of the mirrors, shown in Table 1, are both checked and characterized by SEM and surface profiler (TENCOR/P15 surface profiler, minimal step size: 1Å, best horizontal resolution: 0.5μm). Figure 4 shows the top view of the surface scanning result of mirror (s200r50); the black line represents the cross-section position of the curve fitting data.

Table 1: Experimental and curve fitting results of different spacing/opening designs

Spacing (s) & Radius(r) (μm)	Microscope image 200X	SEM	Surface profiler P15	r/s ratio	Polynomial curve fitting function $Z= A(X-B)^2 + C$	Focus (μm)	NA
s125r20				0.16	A = 0.0032 B= 0.0000 C =0.0000 RS = 0.991	78.1	1.28
s125r40				0.32	A = 0.0017 B = 0.0000 C = 0.0000 RS = 0.993	147.0	0.68
s200r20				0.1	A = 0.0048 B = 0.0000 C = 0.0000 RS = 0.980	52.1	1.92
s200r40				0.20	A = 0.0030 B = 0.0000 C = 0.0000 RS = 0.993	83.3	1.2
s200r50				0.25	A = 0.0021 B = 0.0000 C = 0.0000 RS = 0.993	119.0	0.84
s200r60				0.30	A = 0.0016 B= 0.0000 C = 0.0000 RS = 0.985	156.3	0.64
s200r70				0.35	A =0.0011 B =0.0000 C =0.0000 RS = 0.999	227.3	0.44

The curve fitting used least squares fitting of the scanning data from P15 surface profiler by second order polynomials, $Z= A(X-B)^2 +C$. The curve fitting results are shown in the sixth column of Table 1, Figure 5 and Figure 6. After the curve fitting, since B and C are very small and can be ignored, the polynomial can be rewritten as a parabolic function. $Z= AX^2$ has a focal point at (X=0 , Z=1/(4A)) with very good RS value. Here, RS is the R-Squared indicator. These results demonstrated that these concave mirrors have paraboloidal surfaces.

SUMMARY

We report a time-multiplexed plasma-etching technology for micromirror arrays. Based on this dry etching process, one can produce paraboloidal micromirrors (NA: 0.44~1.92) by selecting the appropriate spacing and r/s ratio, Figure 7. The condensed micromirror arrays have short focal length that can be employed in near-field optical applications. They also can be masters for microlens array molding. Compared to re-flow produced microlens arrays [6], this method will yield higher space-coverage lens arrays.
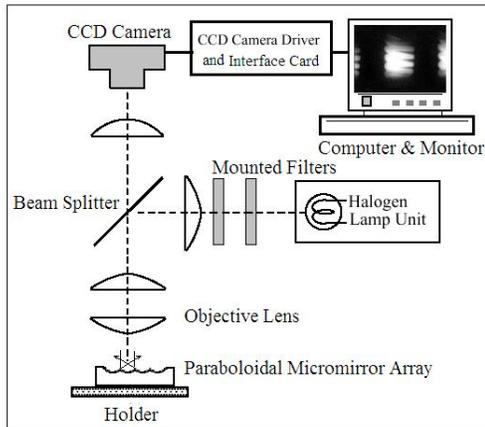
Figure 3: Experimental setup for optical testing
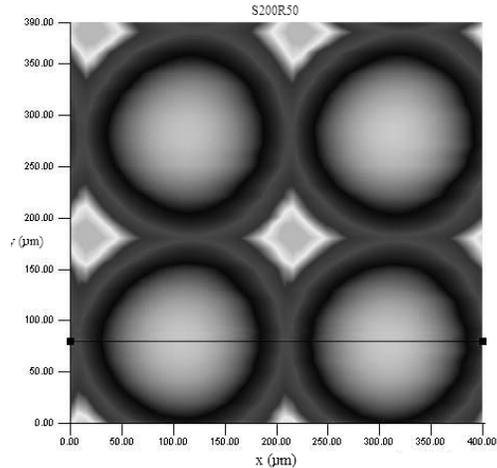
Figure 4: The concentric contour map of the paraboloidal micromirror (s200r50)
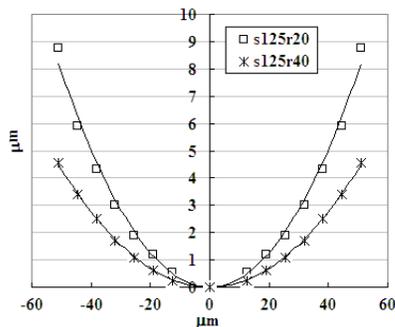
Figure 5: The curve fitting results of s125 series paraboloidal micromirror
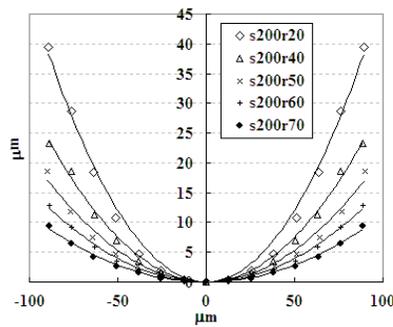
Figure 6: The curve fitting results of s200 series paraboloidal micromirror
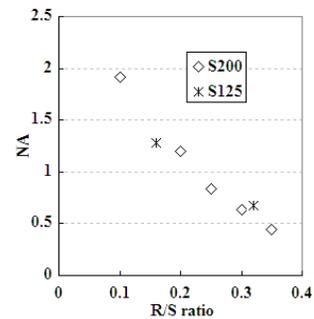
Figure 7: Numerical aperture can be adjusted by r/s ratio

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