Fabrication of Aspheric Micro-Lens Mold with High Aspect Ratio

— Method to Form Small 3D Structures with an Arbitrary Aspheric Surface
and High Aspect Ratio —

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Keywords : Small-Form-Factor Optical Disk Drives, Optical pickup, Aspheric micro-lens, Micro-lens mold, DRIE, Micro-loading effect

The optical pickup of Small-Form-Factor Optical Disc Drive (SFFODD) requires a micro-objective with an effective pupil diameter of 500 μm and a profile composed of two aspheric surfaces. The first surface of the micro-objective consists of a convex shape whose height is over 150 μm . However, it is difficult to fabricate the mold for the first surface with an arbitrary aspheric surface and high aspect ratio using conventional techniques. Therefore, we propose here a new method to fabricate an aspheric micro-lens mold with high aspect ratio. Figure 1 shows the principle of our method. The fabrication sequence is as follows.

(a) Multiple holes are formed in a silicon substrate by DRIE through a mask layer that has multiple circular apertures with different sizes. Due to the micro-loading effect, the depth of these holes increases as the sizes of the corresponding apertures increase.

(b) RIE for isotropic etching is performed through the first mask layer to remove the sidewalls of the above-mentioned holes with different depths, and a concave shape like a crater is formed by merging these holes together.

(c) The first mask layer is removed, and the above-mentioned crater is expanded by isotropic etching using a second mask layer with a larger aperture than that of the crater. In this process, the surface becomes smoother.

After these processes, the surface of the mold is oxidized to harden it, and a carbon film is formed on it to peel off the lens material easily.

Fig. 1. Process flow of proposed method

Fig. 2. 4x2 micro lens mold array

To design the mask pattern to form an arbitrary aspheric surface, we carried out experimental evaluations of the micro-loading effect. We also evaluated the methods to smooth the surface. Then we designed the mask pattern to form an aspheric micro-lens mold and fabricated a micro-lens mold array, as shown in Figure 2, for the prototype. Figure 3 plots the designed and measured sectional profiles of a crater on the first prototype after expanding and smoothing. The designed depth was found to be fabricated well. However, as it gets farther from the center, the measured profile deviates more from the designed one. We presumed that the apertures located in the area corresponding to the outer section of the lens caused the error in the profile for the first prototype. Therefore, we redesigned the pattern of first mask layer for the second prototype. The redesigned mask layer has multiple apertures with the smallest size outside the area where the crater is formed. The crater was formed using different depths between each hole in this area and the holes with the smallest apertures. With this design, the error between the designed profile and the measured one improved, as shown in Figure 4.

Fig. 3. Sectional profile of first prototype lens mold

Fig. 4. Sectional profile of second prototype lens mold

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The optical pickup of our Small-Form-Factor Optical Disc Drives (SFFODDs) requires a micro-objective whose profile is composed of two aspheric surfaces. However, it is difficult to fabricate a micro-objective with an arbitrary aspheric surface and high aspect ratio using conventional techniques. We propose here a new method to fabricate an aspheric micro-lens mold with high aspect ratio. This method uses the micro-loading effect in Deep Reactive Ion Etching (DRIE) and isotropic Reactive Ion Etching (RIE). The micro-loading effect is a phenomenon that leads to different etching depths depending on the aperture size of the mask layer used in etching. We fabricated an aspheric micro-lens mold for the prototype by using the proposed method after experimental evaluations of the micro-loading effect for a feasibility study. The profile of the first prototype was slightly different from the designed one according as the distance from the lens center increase. The profile error of the second prototype was reduced by using a mask that had multiple apertures with the smallest aperture located outside the area where the crater was formed. Our proposed method was found to be effective for fabricating a micro-lens mold with an arbitrary aspheric surface and high aspect ratio.

Keywords : Small-Form-Factor Optical Disc Drives, Optical pickup, Aspheric micro-lens, Micro-lens mold, DRIE, Micro-loading effect

1. Introduction

Small-Form-Factor Optical Disc Drives (SFFODDs)⁽¹⁾ are expected to be used as new storage devices in the next generation because they have many advantages, such as small size, removability, mass productivity of ROM content, and low cost archive media.

We have designed Compact Flash (CF) compatible SFFODDs and developed an optical pickup⁽²⁾ and swing arm type actuator⁽³⁾ for our SFFODDs. The optical pickup required a micro-objective with a profile composed of two aspheric surfaces. The micro-objective is too small to be fabricated by conventional machining using turning tools. Resist reflow, gray-tone lithography, the glass flow process,⁽⁴⁾ and Reactive Ion Etching (RIE) using a micro-loading effect⁽⁵⁾ are also familiar techniques to form small three-dimensional (3D) structures such as a micro-lens or its mold. However, it is difficult to form small 3D structures with an arbitrary aspheric surface and high aspect ratio using these techniques. In this paper, “aspect ratio” means height to diameter ratio of the lens surface.

In this paper, we describe our development of a new method to fabricate an aspheric micro-lens mold with high aspect ratio.

2. Micro-Objective

Figure 1 shows our optical pickup for SFFODDs, and the micro-objective⁽²⁾. The optical pickup requires a micro-objective with an effective pupil diameter of 500 μm and a profile composed of two aspheric surfaces. The first surface of the micro-objective consists of a convex shape whose height is over 150 μm , and the second surface consists of low convex and shallow concave shapes. The fabrication sequence is as follows. The first surface is formed by molding. Then the second surface is formed by stereo-lithography and RIE⁽⁶⁾.

However, the mold for the first surface is too small and deep to fabricate by conventional machining using turning tools. Moreover, it is difficult to fabricate a small 3D structure with an arbitrary aspheric surface and high aspect ratio using conventional techniques, as described in introduction. Therefore, we have

Fig. 1. Optical pickup and micro-objective for SFFODDs.

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developed a new method to fabricate an aspheric micro-lens mold with high aspect ratio.

3. New Method

3.1 Principle We propose a new method to fabricate the micro-lens mold for the first surface of the micro-objective using the micro-loading effect in SF₆-based Deep Reactive Ion Etching (DRIE) and isotropic RIE. The micro-loading effect is a phenomenon that leads to different etching depths depending on the aperture size of the mask layer used in etching. It has already been reported that a micro-loading effect in isotropic RIE⁽⁵⁾ was used to fabricate a small 3D structure such as a micro-lens with a low aspect ratio. However, it is difficult to fabricate the micro-lens mold with an arbitrary aspheric surface and high aspect ratio by using this conventional method. In contrast, our new method can allow us to fabricate it. Figure 2 shows the principle of our method. The fabrication sequence is as follows.

(a) Multiple holes are formed in a silicon substrate by DRIE through a mask layer that has multiple circular apertures with different sizes. Due to the micro-loading effect, the depth of these holes increases as the sizes of the corresponding apertures increase.

(b) Isotropic RIE is performed through the first mask layer to remove the sidewalls of the above-mentioned holes with different depths, and a concave shape like a crater is formed by merging these holes together.

(c) The first mask layer is removed, and the above-mentioned crater is expanded by isotropic etching using a second mask layer with a larger aperture than that of the crater. In this process, the surface becomes smoother.

After these processes, the surface of the mold is oxidized to harden it, and a carbon film is formed on it to peel off the lens material easily.

3.2 Feasibility study To design the mask pattern to form an arbitrary aspheric surface, we carried out experimental evaluations of the micro-loading effect, using Test Element Group (TEG) with multiple pattern areas (2.5 mm × 5.5 mm), under the etching conditions given in Table 1. The results are shown in Figures 3 and 4. The etched depth increases as the sizes of the corresponding apertures increase logarithmically, as shown in Figures 3. This is the micro-loading effect in DRIE. Figure 4 shows etched depths at 75 minutes of DRIE only and the depths at 45 minutes of isotropic RIE after 75 minutes of DRIE for various

aperture sizes. It was found that the micro-loading effect in isotropic RIE must be taken into account.

3.3 Smoothing We evaluated three methods to smooth the surface by TEG used in the experimental evaluations of the micro-loading effect. Figure 5 shows the surface topography of TEG after smoothing test. The surface was smoothed by isotropic RIE for 15 minutes in method 1, and by isotropic wet etching for 30 minutes in method 2. In method 3, it was smoothed by isotropic wet etching for 30 minutes after anisotropic wet etching for 10 minutes. The isotropic RIE was performed in the same conditions as shown in Table 1. A mixed aqueous solution of HF, HNO₃, and CH₃COOH was used in the isotropic wet etching, and an aqueous solution of 40% KOH was used in the anisotropic wet etching. Figure 5 shows the surfaces for method 1, method 2, and

Fig. 3. Etched depth in DRIE vs. aperture diameter.

Fig. 4. Etched depth in DRIE (75 min.) and in isotropic RIE (45 min.) after DRIE (75 min.) vs. aperture diameter.

Fig. 2. Process flow of our proposed method.

Table 1. Etching conditions.

	DRIE	RIE
SF ₆ Flow rate (sccm*)	120	100
Source power (W)	1000	900
RF power (W)	110	20
SF ₆ : C ₄ F ₈	7 : 4	-

*sccm : standard cubic centimeter per minute

Fig. 5. Surface roughness for three smoothing methods.

method 3. These arithmetical mean surface roughness (Ra) were measured, on a diagonal line of each TEG pattern area, by non-contact 3D measurement system (NH-3 from Mitaka Kohki Co.,Ltd.). We selected method 2 to enlarge the crater and smooth its surface because it easily produced the smoothest surface (Ra 70 nm). It is not, however, sufficient because the surface of the micro objective requires Ra 40 nm. It is necessary to improve it in future work.

4. Design and Prototyping

4.1 First prototyping After evaluating the fabrication methods described in chapter 3, we designed the mask pattern to form an aspheric micro-lens mold and fabricated a micro-lens mold for the prototype. The multiple circular apertures formed in the mask layer for DRIE and isotropic RIE were designed so that the sizes became larger as the apertures were located closer to the center section of the lens. The resolution of the photo lithography determines the smallest size of the apertures in the outer section. We designed the mask pattern based on the depth of the apertures with the smallest size.

Firstly a crater with a rough surface was formed by DRIE and isotropic RIE. Figure 6 shows the cross section of it after removing the first mask. Then it was enlarged and the surface was smoothed by isotropic wet etching and oxidized to harden it.

Figure 7 shows a fabricated 4×2 micro-lens mold array for the prototype. The diameter of mold is $40 \mu\text{m}$ larger than that of the lens, shown in Figure 1, for the difference between the estimated rate of side-etching and the actual one. It is, however, tolerable because carbon is overcoated onto the surface to peel off the lens material easily in molding.

Figure 8 plots the designed and measured sectional profiles of a crater on the first prototype after enlarging and smoothing. The dotted line shows the profile designed to satisfy the optical properties (numerical aperture, aberration, etc.) and the size which the micro-objective requires. The solid line shows the profile

measured by stylus profiler (KLA-Tencor). The designed depth was found to be fabricated well. However, as it gets farther from the center, the measured profile tends to deviate from the designed one.

4.2 Second prototyping We presumed that the error in the profile of the first prototype can be removed by changing the apertures in the outer section of the lens. Therefore, we redesigned the pattern of first mask layer for the second prototype, as shown in Figure 9. The redesigned mask layer has multiple apertures with the smallest size in not only the outer section of the lens but also whole patterning area exclude the lens area. The shallowest holes are formed outside the area by DRIE through the mask layer. The crater is formed by isotropic RIE and isotropic wet etching using these holes and the multiple holes with different depth in the area.

Figure 10 plots the designed and measured sectional profiles of a crater on the second prototype after enlarging and smoothing. The profile error of the second prototype was reduced. However, the measured profile was slightly different from the designed one in the position where the distance from the center was more than $130 \mu\text{m}$. We think that it is possible to overcome this problem by adjusting the location of the multiple apertures.

Fig. 8. Sectional profile of first prototype lens mold.

Fig. 6. Cross section of crater after removing first mask (before expanding and smoothing).

Fig. 7. 4×2 micro-lens mold array.

Fig. 9. First mask pattern for second prototype.

Fig. 10. Sectional profile of second prototype lens mold.

5. Conclusion

We have proposed a new method to fabricate an aspheric micro-lens mold with high aspect ratio for the micro-objective required for the optical pickup of our SFFODDs. This method uses the micro-loading effect in DRIE and isotropic RIE. We fabricated the micro-lens mold for the prototype using our proposed method and evaluated the sectional profile of the prototype mold. We found that our proposed method was effective for producing a micro-lens mold with an arbitrary aspheric surface having a high aspect ratio profile. This method can also be applied to fabricate other small 3D structures. We will form the aspheric micro-objective for the optical pickup of our SFFODDs using the prototype mold in our future work.

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