3-Dimensional Microstructure Fabrication using Multiple Moving Mask Deep X-ray Lithography Process

Member Osamu Tabata (Ritsumeikan University)
Student-Member Kouichi Terasoma (Ritsumeikan University)
Non-member Norihiro Agawa (Minolta Co., Ltd)
Non-member Kouji Yamamoto (Minolta Co., Ltd)

An advanced technology using a multiple moving X-ray mask deep X-ray lithography (M^3DXL) to realize various microstructures with inclined or free shape side wall, namely 3-dimensional microstructures, was proposed. The side wall shape of a PMMA microstructure fabricated by deep X-ray lithography has been controlled by moving X-ray masks in parallel with the PMMA substrate during X-ray exposure. In order to demonstrate the feasibility of this M^3DXL technology, various microstructures were successfully fabricated; (1) conical shape and truncated conical shape microstructures with height of 100 - 300 µm and a diameter of 0 - 310 µm and (2) grooves with saw shape cross section with depth of about 30 µm and width of 100 - 150 µm.

Key Words: Microstructure, Fabrication, Mask, X-Ray, Lithography

1. Introduction

Microstructures with height of over a few hundreds µm have been widely applied to various micro-systems, micro-sensors and micro-actuators. LIGA process, that utilizes the X-ray beam radiated from a synchrotron source for lithography process, is one of the promising technologies for fabrication of these microstructures. The microstructures with vertical side wall with height of over a few hundreds µm and a minimum pattern size of less than 1 µm, so called HARMST (High Aspect Ratio Micro Structures) have been successfully realized by the LIGA process.

The feature of the conventional deep X-ray lithography process for HARMST including LIGA is the verticality of the side wall. In other words, the fabrication freedom in Z-direction is limited. Therefore, if a microstructure with curved wall such as an X-ray transmission lens with parabolic thickness variations was required, a quasi 3-dimensional microstructures was adopted [1]. These microstructures that have been possible to realize by the conventional LIGA have several limitations as follows. (1) It is a quasi 3-dimensional structure due to the verticality of the side wall. (2) The maximum depth is limited to about 1 mm in the case of our SR source [2]. (3) It is difficult to modify the side wall shape without changing the mask pattern. However, there are few reports on fabrication technology of microstructures with inclined or free shape side wall, namely non-quasi 3-dimensional microstructures. If it becomes possible to realize non-quasi 3-dimensional microstructures using X-ray beam lithography, a lot of new application fields will open for LIGA technology.

One possible approach toward this goal is a control of an X-ray absorber cross-sectional shape used for X-ray mask, because the side wall shape of a microstructure can be defined according to that of X-ray absorber of the mask. However, there are following two weak points for this method. (1) The required absorber height of X-ray mask for LIGA is high compared to that of an X-ray mask for ULSI X-ray lithography, and an X-ray mask fabrication technology with arbitrary cross section absorber over a mask area of a few cm square with enough accuracy has not established yet [3]. (2) It is difficult to slightly modify the cross sectional shape of a microstructure without changing the mask pattern. The other possible approach is an inclined exposure [4, 5]. In this approach, an X-ray mask and a PMMA substrate are aligned to an incident X-ray with a certain angle and rotate. With this technology, microstructures with inclined side wall can be realized, but it is not possible to control the curvature of the side wall.

In this paper, we propose M^3DXL (Multiple Moving Mask Deep X-ray Lithography) process technology to realize a sophisticated 3-dimensional PMMA microstructure by controlling the side wall inclination and curvature. The concept of the X-ray exposure process with multiple moving mask overcomes above mentioned limitations of the previous technologies. An X-ray mask for M^3DXL is easier to fabricate compared to the previous approach, since a conventional X-ray mask fabrication technology with vertical side wall absorber can be applicable. The side wall shape of the fabricated microstructure can be modified without changing a mask[6].
Therefore, by combining M³DXL technology with subsequent electroplating and molding process, it is possible to greatly expand the application fields of conventional LIGA. Principle of the M³DXL technology, constructed X-ray exposure systems for one mask and two masks configurations, and preliminary experimental results and simulation results are presented.

2. Principle of multiple moving mask technology

M³DXL process utilizes the dependency of a PMMA processing depth on irradiation energy of X-ray to realize a 3-dimensional microstructure. The required procedure is a method to obtain the irradiated X-ray energy distribution corresponding to the desired cross section of a 3-dimensional microstructure. A basic concept of a multiple moving mask technology is explained using two fabrication processes with one mask and two masks configurations.

As a first example, an operation principle of the multiple moving mask technology using one mask configuration for fabrication of a conical shape PMMA groove is explained. If the X-ray mask with circular window pattern is moved circularly at a constant moving velocity, the resultant radiated X-ray energy distributes over a PMMA substrate as shown in Fig. 1. The distributed energy shows a constant value at the inner circular region. It decreases with increasing the diameter and becomes zero at the outside of the outer circle. Since the processed depth of the PMMA increases with increasing the absorbed X-ray energy into the PMMA, truncated conical PMMA groove microstructure is obtained.

A radiated X-ray energy $D$ at radius $r$ ($2r > d_{\text{mask}} - d_{\text{move}}$ for $d_{\text{mask}} > d_{\text{move}}$) at a sample surface is given by

$$\frac{D}{D_0} = \frac{1}{\pi} \cos^{-1}\left(\frac{D_{\text{move}}^2 + 4r^2 - D_{\text{mask}}^2}{4D_{\text{move}}r}\right)$$

(1)

where $D_0$ is total radiated X-ray energy, $d_{\text{mask}}$ and $d_{\text{move}}$ are diameters of the mask hole and the trajectory for mask movement, respectively. A radiated X-ray energy $D$ equals to $D_0$ for $2r \leq d_{\text{mask}} - d_{\text{move}}$ and equals to zero for $2r \geq d_{\text{mask}} + d_{\text{move}}$. For top and bottom diameters of the truncated conical shapes can be calculated by Eq.(1) with taking into account a dependence of fabricated depth on radiated X-ray dose energy.

A two masks configuration for fabrication of a saw shape cross section PMMA microstructure is explained as a second example. Figure 2 shows the two X-ray masks configuration with 200 µm line and space (L/S) pattern movable in the X-direction. Firstly, L/S patterns of the upper and the lower masks are aligned so as to make windows with width of 200 µm. Next, the windows width are narrowed by moving the upper mask at a constant speed until windows disappear. Next, the lower mask moves rightward quickly for 100 µm to make windows with width of 100 µm. The 100 µm window are then narrowed by moving the upper mask at a constant speed until windows disappear. Consequently, the microstructure with a saw shape cross section with widths of 200 and 100 µm can be realized by these procedures as shown in Fig. 2. A saw shape cross section with combination of different widths as shown in Fig. 2 can not be realized using one moving mask configuration.

The number of mask is not limited to two. By increasing the number of masks or freedom of movement and by changing a mask pattern and a trajectory of the mask movement, more complicated 3-dimensional structures can be realized.

3. Exposure system configurations

Figure 3 shows a configuration of a newly developed X-ray exposure system. A superconducting synchrotron radiation source "AURORA" was used as an X-ray source. The specifications of the SR source are as follows: the operation
Multiple Moving Mask Deep X-Ray Lithography Process

The beamline has been developed to carry out the hard X-ray deep lithography [2]. Since the X-ray beam energy is distributed within the exposure area of 5 mm x 30 mm, the substrate is scanned by a substrate X-Y stage to obtain uniform X-ray energy dose over the whole substrate area. The newly developed deep X-ray exposure system is composed of a mask stage, a substrate stage (Sigma KOKI Co., Ltd.) and an exposure chamber.

Figure 4 shows two types of mask stages. The mask stage for one mask configuration with X-Y movement is shown in Fig. 4 left. An X-ray mask and the PMMA substrate are vacuum-chucked to the mask stage and a substrate holder, respectively. The mask stage (Physic Instruments) has two piezoelectric actuators to scan the mask in X-Y plane. The each piezoelectric actuator has a stroke of 110 μm, a step resolution of 10 nm with closed loop control mode and resonant frequency of 500 Hz at an unloaded condition.

The mask stage for two masks configuration with X movement is shown in Fig. 4 right. It consists of two X-axis stages (MINI-40X, SIGMA KOKI Co., Ltd.) for X-ray masks movement and a substrate stage. Two X-ray masks are fixed at the corresponding mask stages and a PMMA substrate is fixed at the substrate stage.

4. Experiments

As a fundamental data to estimate the required X-ray dose energy to process the required depth, the dependencies of processing depth and irradiated X-ray energy without any membrane and through 75 and 150 μm polyimide membranes are measured. Commercially available pre-cast 800 μm thick PMMA sheets with molecular weight of 900 k and low stress were used. These data are also used for the simulation of the cross sectional shape fabricated by the multiple moving mask technology.

In order to show the feasibility of the moving mask
technology, deep X-ray exposure experiments of PMMA using the new exposure system have been carried out. For one mask configuration, conical shape microstructures were fabricated using X-ray masks with circular holes. The mask hole diameters ($d_{\text{mask}}$) of 30 and 210 $\mu$m and moving diameters ($d_{\text{move}}$) of 15, 30 and 100 $\mu$m were used. The frequency of the mask rotation was 300 rpm and a substrate moving speed was 1 mm/s. The X-ray dose condition was selected to obtain fabrication PMMA depth of about 200 $\mu$m. The gap between the substrate and the lower mask was set to 0.1 mm.

For two masks configuration, two saw shape microstructures with different saw widths of 100 and 150 $\mu$m were fabricated. The X-ray dose condition was selected to obtain fabrication PMMA depth of about 30 $\mu$m. The upper mask moving speed for a 150 $\mu$m saw width sample was set to 1.5 times as fast as that for a 100 $\mu$m saw width sample. The gap between the substrate and the lower mask was set to 100 $\mu$m and the gap between two X-ray masks was set to 3000 $\mu$m.

The X-ray mask is composed of a polyimide membrane with thickness of 75 $\mu$m and a composite X-ray absorber layer of Cu and Ni with thicknesses of 3 $\mu$m and 15 $\mu$m, respectively. In the following experiments, the X-ray mask absorber pattern is set to face the PMMA substrate. Therefore, in the X-ray exposure configuration with two masks, the PMMA substrate was irradiated through two polyimide membranes with total thickness of 150 $\mu$m.

After X-ray exposure, development of PMMA substrate was carried out using GG-developer [7] at 39 °C, 2 hours with stirring. The PMMA substrate was dipped to suspension liquid for 20 minutes for stabilize the dissolution reaction and followed by dipping to pure water for 10 minutes for washing out the chemicals. The processed depth was measured using optical microscope (HISOMET, UNION OPTICAL Co., Ltd.).

5. Results and discussions

![Fig. 5](image.png)  Dependence of fabricated depth on X-ray dose energy.

The dependencies of processing depth on the X-ray dose energy were measured at three different conditions, without mask, through one mask and through two masks. These conditions corresponding to the polyimide membrane thicknesses between the beam line and the substrate of 0, 75 and 150 $\mu$m, respectively. The measured data are shown in Fig. 5. The processed depth for a certain dose decreased with increasing the membrane thickness. The threshold value required to process the PMMA for polyimide membrane thicknesses of 75 and 150 $\mu$m are determined to be 0.4 and 0.6 A min by extrapolate the measured data, respectively.

![Fig. 6](image.png)  Photographs of the fabricated truncated conical shape microstructures.

![Fig. 7](image.png)  Calculated dose energy distribution and the cross-section of the PMMA microstructures shown in Fig.6B.

Figure 6 shows the photographs of the fabricated conical shape PMMA microstructures with depth of about 300 $\mu$m using the mask with a circular hole diameter ($d_{\text{mask}}$) of 210 $\mu$m and two different moving diameters ($d_{\text{move}}$) of 30 $\mu$m (Fig. 6A) and 100 $\mu$m (Fig. 6B). The top and the bottom diameters of the fabricated truncated conical shapes were calculated to be 240 and 180 $\mu$m for $d_{\text{move}} = 30 \mu$m, 310 and 110 $\mu$m for $d_{\text{move}} = 100 \mu$m. The obtained dimensions showed good agreement with these values. Figure 7 shows the cross-section of the PMMA microstructure shown in Fig.6B and the dose energy distribution calculated by Eq.(1). Using data shown in Fig.5, the cross-sectional shape of the PMMA microstructure can be predicted from the dose energy distribution. However, as stated later in this chapter, so the prediction accuracy is not enough that
their improvement is under investigation.

Figure 8 shows the dependence of cross-sectional shape of the PMMA microstructures for various moving conditions. A mask with $d_{\text{mask}}$ of 30 µm and moving diameters $d_{\text{move}}$ of 0 µm (Fig. 8A), 15 µm (Fig. 8B) and 30 µm (Fig. 8C) were used. From these preliminary experiments, it was confirmed that the inclination angle of the side wall of a PMMA microstructure can be controlled by this M'DXL technology.

Figure 9 shows the measured cross section of the processed saw shape microstructures with different saw widths of 100 and 150 µm. For comparison, the simulated results are also shown in Fig. 8. For the upper mask moving width of 100 µm, the processed width of 87 µm and depth of 36 µm were obtained. For the upper mask moving width of 150 µm, the processed width of 136 µm and depth of 34 µm were obtained. From these results, it is confirmed that the slope angle of the saw shape can be controlled by changing the moving width of the mask.

The measured and simulated results showed discrepancy among the verticality at the left hand side wall, the width of the saw shape pattern and the curvature of the slope. Since the minimum dose energy of 0.6 A min is required to process the PMMA for one mask configuration as shown in Fig. 5, the processed width for mask moving widths of 100 and 150 µm were predicted to be 60 and 110 µm, respectively. However, the measured widths were larger than these values. The calculated threshold value for PMMA processing from these results was 0.15 A min. We think that one of the reasons of this discrepancy between the threshold values obtained from Figs. 5 and 9 is related to the scattering at the absorber pattern edge.

The effect of the gap between a mask and a PMMA substrate was investigated next. For multiple moving mask exposure system, a gap is required between the mask and the substrate, and between two masks so as to allow the movement of masks. Due to the short wavelength used for X-ray exposure and the parallelism of X-ray, the influence of the gap is expected so small that the degradation of resolution is very small. The expansion angle $\theta$ (rad) of the X-ray beam is expressed by Eq. (2).

$$\theta = 0.51 \times 10^{-3}/E$$  \hspace{1cm} (2)

where $E$ is the energy of the synchrotron. By substituting the energy of 575 MeV for our SR source, the $\theta$ of $0.887 \times 10^{-3}$ was obtained. On the other hand, the diffraction effect $W$ (µm) can be calculated by Eq. (3).

$$W = (\lambda \cdot h)^{1/2}$$  \hspace{1cm} (3)

where $\lambda$ (µm) is the wavelength and $h$ (µm) is the distance between the absorber and a bottom of the processed groove. By substituting 5 Å for the wavelength corresponding to the
maximum X-ray energy of our exposure system, the $(\lambda)^{1/2}$ of 0.022 was obtained. Consequently, the maximum degradation of the resolution ($D_{\text{max}}$) is calculated by the following Eq. (4):

$$D_{\text{max}} = 0.022 (h)^{1/2} + 0.887 \times 10^{-3} h$$

By substituting 100, 1000, 3000 and 10000 µm for $h$, $D_{\text{max}}$ of 0.31, 1.6, 3.87 and 11.07 µm are obtained, respectively. Therefore, the observed discrepancy between the measured and simulated results about the verticality at the left hand side wall was thought to be mainly caused by this effect. However, it was difficult to predict the measured results with good accuracy. The reason of these discrepancies including the width of the saw shape pattern and the curvature of the slope should be clarified and is now under investigation from various points of view.

6. Conclusions

Microstructures with a conical shape, a truncated conical shape and a saw shape cross section were successfully realized using a M³DXL (Multiple Moving Mask Deep X-ray Lithography) technology. From the experiments, the feasibility of the M³DXL technology was confirmed. By adding a subsequent electroplating and mold technology to this M³DXL technology, a new powerful technology (M³LIGA) could be established. Based on these results, the simulation accuracy will be improved in the future.

Acknowledgements

The authors would like to thank Mr. Matsuzuka and Mr. Yamaji of Tabata Lab. for carrying out the experiments, Dr. Kato of Sumitomo Heavy Industry Co., Ltd. for his useful discussion and the member of Sugiyama Lab. and SR Center at Ritsumeikan University for their help in the LIGA beamline operation.

(Manuscript received November 22, 1999)

References