Lithography onto Surfaces of Fine-Diameter Pipes Using Rotary Scan-Projection Exposure

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A new rotary scan-projection exposure system was developed for replicating patterns with widths of around 100 μm. As the first step, a reticle was fixed steady on the reticle stage, and only specimen pipes were rotated. As a result, 100-μm line-and-space (L&S) patterns were successfully replicated on whole circumferences. Deviation 3 σ of the resist pattern widths was as small as 5 μm for the mean width of 100 μm. Next, a reticle with oblique L&S patterns was also scanned synchronously with the rotation of the specimen pipe. However, stitching of patterns doubly exposed at the start and stop parts of rotary exposure was difficult. Although large patterns with widths of 400 μm were successfully replicated on whole surface, 100-μm L&S patterns were replicated only on partial areas of the pipe surface. It was clarified that yaw alignment of the reticle, and alignment between the centers of chucked pipe and the rotation stage should be improved. By working on these subjects, the new system will be graded up further more.

Keywords: rotary exposure, scan-projection exposure, projection exposure, patterning onto pipes, synchronous scan

1. Introduction

Recently, lithography is often applied to patterning onto 3 dimensional materials in addition to conventional patterning onto flat materials such as semiconductor wafers. For this reason, it is strongly expected that simple and low-cost exposure systems and patterning processes for such use are developed. Lithography systems for patterning onto cylindrical materials such as pipes, wires, spindles, and rods are especially needed. To answer the requirement, various researches on developing lithography systems for replicating or delineating patterns on cylindrical materials were carried out [1-7]. The authors also developed laser-scan exposure systems onto fine wires and pipes with diameters of 40-500 μm [8-13]. It was demonstrated that very precise patterns were arbitrarily delineated on surfaces of such very fine cylindrical materials. In addition, fabrication processes of fine cylindrical micro-components such as coil springs and pipes with multi-holes were also developed [8-11] [13].

However, because patterns are delineated by moving and rotating materials for the laser beam, it takes long time to delineate complicated patterns. Accordingly, it is difficult to apply the system to patterning onto cylindrical materials with diameters of larger than 500 μm. In addition, if a laser beam is crossly scanned, the resist film coated on the material is doubly exposed at the cross points. Therefore, the resist is partially over-dosed, and it is worried that the partial changes of widths and profiles cause pattern defects. On the other hand, it is required to form complicated patterns easily with a low cost onto pipes with diameters of 1-2.5 mm for developing medical stents and special springs to cure curled nails.

For this reason, a new exposure system was developed here using a ultra-violet (UV) lamp source and a new scan-projection exposure scheme. In the new system, patterns on a conventional flat reticle are

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continuously replicated onto a cylindrical pipe or rod surface by synchronously giving a linear movement to the reticle and rotational movement to the cylindrical material and limiting the momentary exposure area in a narrow focused oblong. By using this scheme, exposure time is not influenced by the complexity of patterns.

A similar exposure system was once developed approximately 7 years ago [14, 15]. However, because the target object of the former exposure system was an axial micro-pump, and required patterns were very simple and large, patterning accuracy was not pursued. In this research, an exposure system with higher accuracy is aimed.

2. Development of Exposure System

Fundamental scheme of the newly developed exposure system is shown in Fig. 1. To replicate patterns on a reticle onto a round surface of pipe specimen, instantaneous exposure field on the pipe was limited to a narrow oblong area on the top surface. The oblong area was defined by placing a slit with a width of 0.8 mm just on the reticle. As a specimen, Ni-Ti alloy pipes with outer and inner diameters of 2.4 and 2.0 mm were used. Because the height of pipe surface changes depending on the curvature, and both outside parts are greatly defocused if the slit is wide, as shown in Fig. 2. The height difference $\Delta h$ between the top center of the pipe and the positions curved down to both outsides in the exposure field were calculated using the following Eqs. (1) and (2).

$$\Delta h = r(1 - \cos \theta) \quad (1)$$

$$\theta = \sin^{-1} \frac{b}{2r} \quad (2)$$

The calculation results are shown in Fig. 3. In the case of 0.8-mm slit, the maximum defocus at both field sides was calculated to be approximately 70 µm.

As a projection lens, a commercial camera lens for macro photography (Sigma, 50mm F2.8 EX DG MACRO) was used, and the projection ratio was adjusted to 1:1. The F-number of the lens was set at 2.8. The resolution and the depth of focus (DOF) were calculated to be approximately 4 µm and 46 µm, respectively. Although the calculated defocus for the 0.8-µm slit was larger than this DOF, it was judged that the defocus caused by the curvature did not prevent the successful replication of patterns with
widths far larger than the resolution limit.

As an exposure source, a UV lamp (Inflidge, UVB-300) was used. The exposure light was ejected through a rod lens unit for homogenizing the light flux. The peak wavelength was 365 nm.

At first, specimen pipes were held by a steel drill chuck directly attached to the rotation stage, as shown in Fig. 4(a). However, it was difficult to adjust the chuck center to the center axis of the rotation stage only by carefully combining them depending on their mechanical accuracy. In addition, because the drill chuck was supported as a cantilever, it was bowed down. For this reason, the drill chuck was changed to a small aluminum V-flat chuck, and a manual XY stage for adjusting the pipe center to the center of the rotation stage was added between the V-flat chuck and the rotation stage, as shown in Fig. 4(b).

3. Patterning Experiments

3.1. Choice of Resist

Patterning experiments were carried out using a positive resist of PMER P-LA900 PM (Tokyo Ohka Kogyo) and a negative resist of PMER N-CA3000 PM (Tokyo Ohka Kogyo). Each resist was coated using the dip method [8]. Resist thicknesses were controlled by changing the relative draw-up speed, as shown in Fig. 5. Here, they were coated in 8.5 and 16 µm thick, respectively, under the draw-up condition of 0.03 mm/s. In preparatory patterning experiments, it was found that the positive PMER P-LA900PM does not adjust to Ti-Ni pipes, and resist patterns often peeled off and shifted their positions here and there, as shown in Fig. 6. In addition, typical exposure time for replicating patterns onto the whole circumference of the pipe using PMER P-LA900PM was 245 s, and the time was much longer than that of 45 s using PMER N-CA3000 PM. From these results, it was judged that negative PMER N-CA3000 PM was preferable, and most of the experiments were carried out using PMER N-CA3000 PM.

3.2 Patterning of Circumferential Dense Patterns

Circumferential patterns in perpendicular to the pipe axis were replicated onto specimen pipes coated with 16-µm thick negative PMER N-CA3000 PM using a film reticle with 100-µm line-and-space (L&S) patterns. As the first step, the reticle was steadily fixed on the reticle stage, and only specimen pipes were rotated just 360°. Patterns replicated using
the drill chuck mechanically coupled with the rotation stage were shown in Fig. 7, and pattern widths measured at every 30° circumferential angle are shown in Fig. 8. The mean pattern width was 101 µm, and 3σ deviation was 9 µm. In comparison, photographs of patterns replicated after the chuck was changed to the V-flat one, and the specimen pipe center was aligned to the rotation stage center using the added XY stage are shown in Fig. 9. Measured pattern widths are shown in Fig. 10. The 3σ deviation was reduced to 5 µm. As a result of adjusting the rotation center of a pipe to the center of the rotation stage, the width homogeneity was much improved.

3.3 Patterning Using Synchronized Scan Exposure

Patterning characteristics of synchronized scan exposure were investigated next. Synchronizing with the rotation of a specimen pipe, a reticle with 45° inclined 100-µm L&S patterns was linearly scanned in the direction perpendicular to the pipe axis. The scan speed of the reticle was adjusted to move a distance equal to $\pi d$ during the pipe with a diameter of $d$ was rotated 360°. Because the pipe movement was controlled by the rotation angle, it was just rotated to the start angle when the scan of the reticle

![Measured pattern width](image)

Fig. 7. Patterns replicated on circumferential surface of pipe held by the drill chuck.

![Pattern width](image)

Fig. 8. Width homogeneity of patterns printed using the drill chuck. Mean pattern width was 101 µm, and deviation (3σ) was 9 µm.

![Pattern replication](image)

Fig. 9. Patterns replicated on circumferential surface of pipe held by the V-flat chuck.

![Width homogeneity](image)

Fig. 10. Width homogeneity of patterns printed using the V-flat chuck. Mean pattern width was 100 µm, and deviation (3σ) was 5 µm.
was stopped. On the other hand, it was found that stitching in the axial direction was difficult. The reticle was merely placed on the reticle stage, and the direction of patterns was not accurately adjusted. For this reason, patterns replicated at the stop point were not just stitched to the ones replicated at the start point in the direction parallel to the pipe axis. As a result, 100-µm L&S patterns inclined 45° were clearly replicated only at partial areas on the pipe surface, as shown in Fig. 11. The angles in the figure are the ones fixed for observing patterns, and differ from the angles for delineating patterns. The stitching errors were obviously shown at angles of 180-270°. However, because pattern shapes were partially degraded at angles of 30-90°, it was thought that defocus change accompanied by the pipe rotation also influenced the pattern degradation.

However, if the above mentioned stitching errors in the axial direction were possibly reduced to smaller ones far less than the pattern widths by using large 400-µm L&S patterns, the synchronous rotary scan-projection exposure was successfully carried out, as shown in Fig. 12.

### 4. Discussion on Subjects

It was clarified that stitching or super imposition of pattern images at start and stop points should be improved. Scan lengths of the reticle are only \( \pi d \approx 3-8 \) mm, because the target diameter sizes of the pipe are 1-2.5 mm. Accordingly, it is difficult to distinguish accurately the angle or direction of a reticle placed on the stage. It is probably possible to adjust the reticle pattern direction if a simple yaw-alignment stage is added for making the reticle rotatable in the horizontal plane. Once the reticle direction apt to stitch patterns replicated at start and stop points is found out by changing the reticle direction precisely using the yaw-alignment stage, patterns will be always stitched well, and clearly replicated on the whole circumference of specimen pipe, afterwards.

On the other hand, repeatability of pipe chucking should be investigated more closely. To reduce the unwilling defocus, fluctuations of pipe-center positions or top surface heights of pipes should be reduced. It is preferable that the positions of specimen pipes are always monitored using sensors.

### 5. Conclusion

A new rotary scan-projection exposure system was developed for replicating patterns onto Ni-Ti alloy pipes with outer and inner diameters of 2.4 and 2.0 mm, and fundamental patterning characteristics were investigated. As resists, positive PMER
P-LA900PM and negative PMER N-CA3000PM were compared. As a result, from viewpoints of adhesion performance to pipes and exposure time, the negative resist was mainly used.

At first, circumferential 100-μm L&S patterns were replicated by only rotating the specimen pipes, and fixing the reticle steady without scanning. As a result, patterns were successfully replicated onto whole circumferences of pipes. In addition, pattern width homogeneity was improved by precisely adjusting the pipe center and the rotation-stage center using a small XY stage added between the specimen chuck and the rotation stage.

Next, synchronous rotary scan-projection exposure was tried by linearly moving the reticle and rotating the pipe simultaneously. However, it was found that stitching of patterns replicated at start and stop points of the exposure was difficult, and patterns were wrongly superimposed or stitched. A yaw-alignment stage for precisely adjusting the reticle direction should be equipped to replicate finer patterns without stitching errors or image contrast degradation. In addition, the pipe position should be monitored and kept steady to improve the patterning repeatability and homogeneity.

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