Fabrication of Stent-Like Mesh Structures Using Synchronized Scan Rotation Lithography and Wet Etching

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Stent-like complicated cylindrical structures were made with pipes of stainless-steel SUS 304 using new lithography and wet chemical etching. In the new lithography, patterns on a flat reticle were printed on a pipe coated with a resist film by synchronously scanning the reticle linearly and rotating the pipe around the axis, and limiting the momentary exposure area on the top ridge of the pipe by placing an oblong slit on the reticle in parallel to the pipe axis. The patterned pipe was wetly etched in an aqueous solution of ferric chloride using the resist patterns as etching masks. Because the etching was progressed equally in all the directions from the resist pattern edges, masked parts under the resist patterns were also gradually etched from the pattern edges and undercut during the pipe was penetrated through the wall. Caused by the undercut, obtained mesh widths became narrower than the resist pattern widths. However, a stent-like mesh structure with widths of 108±12.4 (3σ) µm was decently fabricated by appropriately controlling the resist pattern width and the etching time. To attain higher accuracy in the future, cross section profiles of the mesh and relationship between resist pattern widths and mesh widths were discussed in detail.

Keywords: Synchronized scan rotation lithography, Lithography on a pipe, Stent, Wet etching, Chemical etching, Stainless-steel pipe

1. Introduction

Abnormal blood pressures and damages of blood vessels cause serious diseases, and often lead the patients to deaths. For this reason, treatments for these diseases are vigorously researched. As an effective treatment for degradation and damage of blood vessels, utilization of stents is being watched with keen interest [1-4]. Stents are medical components with cylindrical shapes used for supporting degraded or damaged blood vessels from inside, and various structures and fabrication methods of stents are proposed to supply trustworthy and inexpensive stents [5-8].

The authors have developed a new method for fabricating cylindrical micro-components using a novel lithography and wet etching [9-11]. In the method, stent-like patterns on a flat reticle are projected on a surface of a metal pipe with a thin wall and coated with a photosensitive resist film through a narrow oblong slit placed above the reticle by synchronously scanning the reticle and rotating the pipe. Because only patterns in the narrow oblong slit are momentarily projected on the pipe ridge where the surface is almost flat, reticle patterns are distinctly replicated on all over a pipe surface continuously by the synchronized scan and rotation. That is, during the plane reticle with stent-like mesh patterns is linearly scanned in perpendicular to the pipe axis, the pipe is rotated 360° around the axis.

Next, the pipe with resist patterns is chemically etched in an aqueous solution of ferric chloride. The resist patterns work as the etching masks, and the parts where the resist has been removed are dissolved in the etchant. Consequently, a stent-like mesh structure is obtained.
In this paper, width accuracy and homogeneity of stent-like structures fabricated by the new method are investigated in detail. In addition, influence of undercut phenomena in the wet etching process and relationship between the resist widths and mesh widths are discussed.

2. Fabrication process of stent-like structures

Stent-like mesh structures of stainless steel SUS 304 were fabricated using the processes shown in Fig. 1. At first, a resist was coated on a stainless steel pipe with an outer diameter of 2 mm, a thickness of 50 µm, and a length of 50 mm using the dip and draw-up method, as shown in Fig. 1(a). The pipe was a quasi-seamless one, and molded using the rolling draw-out method. The resist film was coated in 20-mm area from the pipe tip.

Next, stent-like patterns were printed on the resist film using the synchronized scan rotation lithography, as shown in Fig. 1(b). Resist was sensitized in the stent-like shapes by the exposure, and resist patterns were printed on the pipe surface after the development, as shown in Fig. 1(c).

Then, after the resist patterns were baked in an oven for increasing the adhesiveness, the pipe was etched in an aqueous solution of ferric chloride stirred by a propeller, as shown in Fig. 1(d). Because the pipe was etched at the parts where the resist film was removed by the lithography, a stent-like mesh structure with the resist patterns was obtained, as shown in Fig. 1(e). Finally, only the stent-like mesh structure was taken out after removing the resist patterns by dipping the specimen in a solvent, as shown in Fig. 1(f).

3. Resist patterning using synchronized scan rotation lithography

Stent-like patterns were replicated on a pipe surface coated with a resist using a handmade exposure system developed in the past research [12, 13]. The system is shown in Fig. 2, and the size was 600×450×935 mm³. Concerning exposure systems for printing or delineating patterns on a cylindrical specimen, various research results have been reported [14-18]. The authors have developed some systems also except the above mentioned ones [19-22]. However, the system used for this research had a large advantage that arbitrary intricate patterns were printable in a same exposure time without depending on the pattern density and complicatedness. In addition, patterns were printed without making doubly exposed parts. In the case
of pattern delineating systems using a laser or other exposure beams, it was difficult to delineate complicated patterns without crossing already delineated beam tracks.

As an exposure light source, a high-pressure mercury lamp (Inflidge UVB-300) was used. Projection lens was a camera lens (Sigma, 50 mm F2.8 EX DG MACRO). Patterns on a reticle were projected on a pipe by a magnification ratio of 1.13. As a resist, negative PMER N-CA3000 PM (Tokyo Ohka Kogyo) was used. The thickness was controlled to approximately 10 µm. In the synchronized scan rotation lithography, original patterns on a flat reticle were projected on a pipe surface through a narrow slit, and the specimen pipe was rotated 360° at a constant speed during the reticle was linearly scanned in a full span length. Consequently, the start and stop edges of the exposure field was exactly stitched. The stent-like mesh patterns were not allowed to be stitched with gaps, and it was thought preferable that the start and stop edges were slightly overlapped. From this point of view, a negative resist was preferable. In the case of positive resist, pattern shapes and widths of the parts exposed doubly by the overlapping were much deformed. However, in the case of negative resists, pattern shapes and widths of the parts exposed doubly by the overlapping were not deformed so much, because the sensitization was almost saturated if the patterns were printed under sufficient exposure-dose conditions.

Reticle patterns used in the research is shown in Fig. 3. The patterns were basically composed of 30 rhombuses arrayed 5 in the axial direction and 6 in the circumferential direction, and the rhombus corners were intentionally separated at 12 points for giving elasticity to the structure. Examples of patterns replicated on a pipe under the exposure time condition of 30 s are shown in Fig. 4. The patterns were observed from various rotation angles at 60° intervals. It is known that patterns at the rotation angle of 0° or 360° are smoothly stitched without notable changes of pattern profiles and widths. All the pattern edges of mesh parts were very smooth.

Next, resist pattern widths of mesh parts were measured. At first, pattern width distributions in the axial direction was investigated at the rotation angles of 10°, 70°, 130°, 190°, 250°, 310°. The measurement results are shown in Fig. 5. The mean

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**Fig. 3.** Reticle patterns of stent-like mesh structure.

**Fig. 4.** Resist patterns replicated on a stainless-steel pipe surface.

**Fig. 5.** Distribution of resist pattern widths in the axial direction.
width was 185.8 µm, and 3σ deviation was 11.1 µm. The axial length of the mesh structure patterns was 15 mm. Pattern width distributions in the circumferential direction was measured also at four positions of 0.75, 5.25, 9.75, and 14.25 mm from the mesh structure end. The measurement result is shown in Fig 6. The mean width was 186.4 µm, and 3σ deviation was 11.1 µm. From Figs. 5 and 6, it was found that the fluctuation of resist pattern widths was within 3σ deviation of 11.1 µm.

4. Wet etching of pipes in an aqueous solution of ferric chloride

Pipes with stent-like resist patterns in an axial span of 15 mm were etched one by one using the set-up shown in Fig. 7. A commercial etchant composed of 37-39% ferric chloride (FeCl₃) and 61-63% water (Sanhayato, H-1000A) was used. The etchant was kept at 40-45 ºC on a hotplate, and continuously stirred by a propeller at a rotation speed of 250 rpm. The etching time was adjusted between 22 and 25 min.

An example of the fabricated stent-like structure is shown in Fig. 8. It was clarified that the considerably intricate mesh structure was decently fabricated. Mesh widths of the stent were measured next at the same points where the resist pattern widths were measured. Mesh width distribution in the axial and circumferential directions are shown in Figs. 9 and 10, respectively. The mean mesh width for the measurement in the axial direction was 108.2 µm, and 3σ deviation was 11.4 µm. The mean mesh width for the measurement in the circumferential direction was 108.6 µm, and 3σ
deviation was 12.4 µm.

Though the mesh widths fluctuated a little, it was clarified that the fluctuations were within 3σ deviation of 12.4 µm in both the directions. The fluctuations should be reduced hereafter. However, the obtained width homogeneity would be decent as a result at the developing stage of the new method.

5. Discussion

When Fig. 5 and Fig. 9, and Fig. 6 and Fig. 10 were compared, respectively, the mesh widths of the stent-like structure were constantly narrower than the resist pattern widths. This width slimming was caused by the undercut during the wet etching. The pipe was etched at a same speed in all directions from resist pattern edges. For this reason, pipe walls covered by the resist patterns were etched also from the resist pattern edges to under the resist film, as shown in Fig. 11.

Because the pipe thickness was 50 µm, undercuts at the pipe surface get to more than 50 µm deep from both sides when the etching reached the inner wall. In fact, when the etching reached the inner surface of the pipe or the inner resist film, slightly remained parts near the inner surface were rapidly etched, and the opened parts were widened immediately. And, side wall shapes were stabilized when they became the gently inclined ones, as shown in figure. The mesh widths measured and plotted in Figs. 9 and 10 were the sizes of \( w_b \).

Therefore, the width difference between the resist patterns and stent-like mesh became a little smaller than the twice of the pipe thickness. The actual mean width difference was \( w_r - w_b = 186 - 108 = 78 \) µm. Therefore, if the undercut contour is a circular arc with a radius of \( r \), inclined part width \( w_i \) is calculated to be

\[
\begin{align*}
\frac{w_i}{2} &= r - \frac{w_r - w_b}{2} \\
&= \frac{\sqrt{r^2 + (w_r - w_b)^2} - w_r - w_b}{2} \\
&= \sqrt{50^2 + 39^2} - 39 \\
&= 63.4 - 39 \\
&= 24.4 \text{ (µm)} \\
\end{align*}
\]

This calculation result means that the mesh width at the pipe surface \( w_s \) becomes

\[
\begin{align*}
w_s &= w_b - 2w_i \\
&= 109 - 2 \times 24.4 \\
&= 60.2 \text{ (µm)} \\
\end{align*}
\]

Figure 12 shows a typical magnified view of the fabricated stent-like mesh structure. Though surface edge boundaries are unclear, and widths at the surface are not homogeneous, it seems that mesh widths remained at the surface without being etched are slightly smaller than the calculated value \( w_s \). However, the calculated \( w_i \) and \( w_s \) roughly consistent with the actually measured widths.

Next, relationship between the widths of resist pattern and etched mesh was investigated using the data plotted in Figs. 6 and 10. Because the resist pattern and etched mesh widths were measured at almost same points, it was considered that the influence of the resist pattern widths to the etched mesh widths might be inferred from the
relationship between both widths. The relationship is shown in Fig. 13. It was clarified that both widths had a positive correlation, and the mesh widths were obediently influenced by the resist pattern widths. The fluctuation of etched mesh widths for a same resist pattern widths are within ±8.5 µm, and rather smaller than the 3σ deviation of 12.4 µm obtained without considering the resist pattern width fluctuation. It was found necessary to improve the patterning accuracy of lithography in the first place. In addition, etching homogeneity should be improved some more.

6. Conclusion

Precision of a stent-like mesh structure of stainless-steel SUS 304 fabricated by a new method using synchronized scan rotation lithography and wet chemical etching was investigated in detail. By the new method, a considerably intricate stent-like mesh structure with a mean mesh width of 108 µm was obtained. Though the mesh widths fluctuated a little within 3σ deviation of 12.4 µm, the width homogeneity would be decent at the developing stage of the new method. They should be reduced step by step hereafter.

In the discussion, cross section profiles of the mesh parts were inferred, and width \( w_s \) at the outer surface and the width \( w_i \) of circular arc slopes were calculated to be 60.2 µm and 24.4 µm, respectively. Though actual mesh widths \( w_s \) at the outer surface were slightly narrower than the calculated value, the difference was not large.

On the other hand, it was found that the resist pattern widths and the stent-like mesh widths had a positive correlation, and the mesh widths were obediently influenced by the resist pattern widths. Patterning accuracy of the synchronized scan rotation lithography should be improved in the first place for obtaining more precise structures. In addition, etching performances should be improved some more.

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