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High-Aspect-Ratio Shape Replica Mold Fabrication Using Nanoimprinting and Silver Ink as Etching Mask

Keisuke Enomoto and Jun Taniguchi *

Department of Applied Electronics, Faculty of Advanced Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan; 8122507@ed.tus.ac.jp

* Correspondence: junt@te.noda.tus.ac.jp; Tel.: +81-3-5876-1440

Abstract: Effective high-aspect-ratio molds that minimize vacuum processes are becoming increasingly important for producing metalenses and other devices. To fabricate a high-aspect-ratio structure, a metal film must be used as a mask for dry etching, typically achieved via vacuum deposition. To avoid this vacuum process, we devised a method to develop an etching mask in the air using silver ink. The manufacturing method involved filling the mold with silver ink, baking it, removing silver from the convex parts of the mold with a polyethylene terephthalate film, and placing silver from the concave parts of the mold on top of the ultraviolet (UV)-cured resin using ultraviolet-nanoimprint lithography. The transferred pattern had silver on the convex parts, which was used as a mask for the oxygen dry etching of the UV-curable resin. Consequently, high-aspect-ratio resin shapes were obtained from three types of nano- and micromolds. Additionally, a high-aspect-ratio resin with silver was used as a replica mold to form a silver pattern. This process is effective and allows high-aspect-ratio patterns to be obtained from master molds.

Keywords: ultraviolet nanoimprint lithography; silver ink; replica mold; high-aspect-ratio pattern; reactive-ion etching



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1. Introduction

Metasurfaces and metalenses have recently attracted considerable attention [1–5]. A metasurface is an artificial medium (metamaterial) that achieves an arbitrary permittivity and permeability, and consists of periodically arranged structures that are small relative to the wavelength. Unlike metamaterials, which have a three-dimensional structure, metasurfaces have a two-dimensional structure. Thus, metasurfaces are easy to fabricate and suitable for mass production. Metasurfaces are two-dimensional structures with high aspect ratios. The aspect ratio is a shape factor expressed as the height divided by the linewidth or diameter. This is because the location at which the refractive index of the structure made of dielectric material changes from the refractive index of air in the gap requires a height equal to or greater than the wavelength of visible light. Nanoimprint lithography (NIL) has attracted significant attention for manufacturing metasurfaces [6–13]. NIL can be used to create slanted diffraction gratings for use in augmented reality (AR) glasses [14,15]. AR glasses are wearable devices whose lenses are displays that can project digital data, such as images. To achieve a wide viewing angle, the material for the slanted diffraction grating must have a refractive index of 1.7 or higher. Accordingly, an ultraviolet (UV)-curable resin containing nanoparticles of zirconia or titania was used. As UV-curable resins containing nanoparticles become brittle after curing, a transfer mold made of a soft resin should be used. Both soft resin molds and high-refractive-index materials are

available for metasurface fabrication. Therefore, a fabrication process for high-aspect-ratio molds needs to be developed. A high-aspect-ratio structure is usually defined as a structure with an aspect ratio that is greater than five.

The conventional processes for fabricating high-aspect-ratio nanostructures are as follows: The first method is electron-beam lithography (EBL), or NIL, for nanopatterning and successive dry etching processes (Figure 1a,b) [16–22]. Another method is metal-assisted chemical etching (MacEtch) (Figure 1c) [23–26]. Thus, EBL and NIL are suitable for the fabrication of nanopatterns. In the case of NIL, the residual layer must be removed by oxygen etching. A patterned resist is used for dry etching; however, it has a low etching selectivity for silicon substrates. Thus, a metal layer is usually deposited on a patterned resist surface, and the resist layer is then removed. This is the liftoff process. After obtaining the metal patterns, dry etching is performed (Figure 1b).

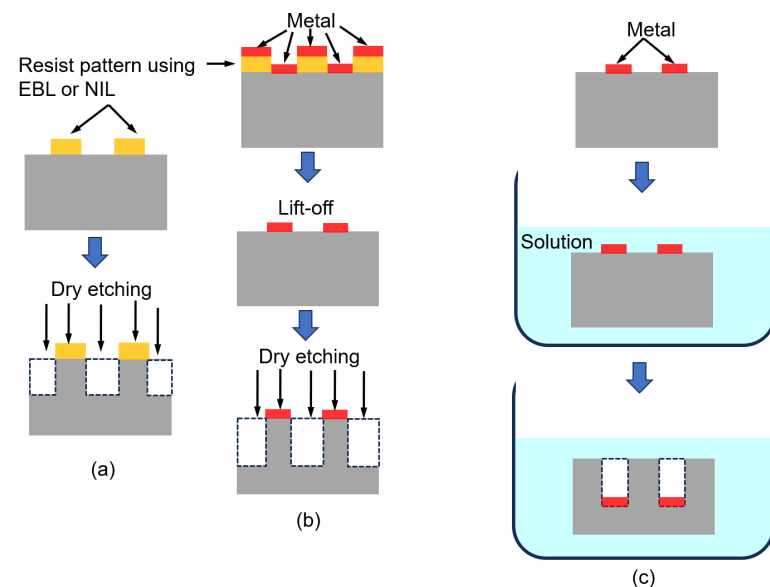


Figure 1. Conventional fabrication process for high-aspect-ratio patterns. (a) Resist patterns formed using EBL or NIL, with subsequent dry etching. (b) Metal liftoff and dry etching. (c) MacEtch.

The “Bosch process” is a method that can obtain a structure with a high aspect ratio. The Bosch process consists of a three-step cycle: Film deposition, bottom film etching, and silicon etching. In the deposition process, a passivation film is deposited on the sidewalls and bottom surface of the trench. In the bottom film etching step, the passivation film on the trench bottom is selectively etched. In the silicon etching step, only the silicon at the trench bottom, where the passivation film has been removed, is etched. This makes it possible to perform deep processing on substrates such as Si [27,28]. This method is also called deep reactive ion etching (DRIE). Thus, a high-aspect-ratio mold pattern is obtained. MacEtch also uses a metal layer. In this case, the metal acts as a catalyst for substrate etching. For silicon substrates, gold and platinum have high etching rates in a hydrofluoric acid solution. These techniques can be used to obtain high-aspect-ratio nanostructures. In this regard, several process steps are involved, particularly vacuum processing. To achieve an effective fabrication process, a method that uses minimal vacuum processing is required. Therefore, a process that uses silver ink instead of vacuum deposition to create a metal layer is effective. The formation of resin nanopatterns via NIL is also effective because EBL is a time-consuming vacuum process. By combining silver ink with NIL, a method was developed to create a resin replica mold with a high aspect ratio by placing a silver ink pattern on top of a transfer resin pattern and using the silver ink as an etching mask for oxygen reactive-ion etching (RIE). The advantages of this process are as follows: Only

one vacuum oxygen RIE process is used; therefore, the process is rapid. The selectivities of silver and resin are high; thus, a pattern with a higher aspect ratio can be obtained. This indicates that various aspect-ratio patterns can be obtained by changing the oxygen RIE conditions. After performing the oxygen RIE of the resin parts, this pattern can be used as a replica mold. Therefore, the developed process is effective and rapid for the fabrication of high-aspect-ratio replica molds. In this study, the transfer process of silver ink onto a resin top, oxygen RIE conditions, a fabricated high-aspect-ratio replica mold, and a UV-NIL transfer were examined.

2. Materials and Methods

2.1. Outline of Fabrication Process for High-Aspect-Ratio Replica Mold

We developed a method for filling a mold groove with silver ink and transferring it onto a UV-curable resin [29]. Our previous study dropped silver ink onto a nano-patterned hard mold made of silicon or quartz. In this study, silver ink was dropped onto a soft mold made of a UV-curable resin. This was done because we wanted to create a high-aspect-ratio mold with the same uneven shape as the master mold. Therefore, we needed to invert the shape twice with UV-NIL and drip silver ink onto the replica mold. In this study, this method was used to create a silver ink pattern on a UV-curable resin, followed by oxygen dry etching. An outline of the entire process is shown in Figure 2. First, the bottom of the mold groove was filled with silver ink (Figure 2a). Silver was sintered, and the UV-curable resin was dropped onto the mold. The support film was covered and pressed with UV-curable resin. Then, the UV film was exposed to UV light to cure the UV-curable resin (Figure 2b). After UV exposure, the UV-cured resin was removed from the mold, and silver ink was adhered to the top of the resin (Figure 2c). Sintered silver ink has high etching selectivity for polymer materials during oxygen RIE dry etching. As silver was passivated by ambient oxygen and became silver oxide, the polymer material became too weak for oxygen RIE [30]. Thus, the silver region acted as a mask for the oxygen RIE etching, and the polymer region was etched away (Figure 2d). This resulted in a higher aspect ratio of the pillar pattern than the mold groove depth. An advantage of this process is the formation of a silver mask region on the top of the pillar-shaped UV-curable resin. This indicates that the mold groove depth was obtained after UV-NIL, and the oxygen RIE process etched the residual layer region. Therefore, an effective increase in height was possible. By contrast, microcontact printing or nanoprinting methods form silver ink on a flat surface. In this case, dry etching is important to achieve a high-aspect-ratio pattern. In addition, the obtained high-aspect-ratio pattern, as shown in Figure 2d, can be used as a replica mold, although the silver region remains.

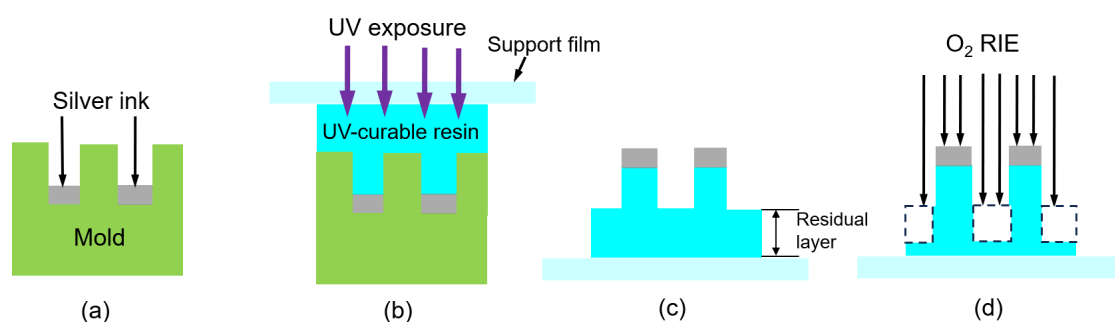


Figure 2. Outline of the fabrication process of the high-aspect-ratio replica mold. (a) Forming silver ink at the bottom of the mold. (b) UV-NIL process (c) and release. (d) Oxygen RIE etching of UV-curable resin parts, resulting in high-aspect-ratio pillar patterns.

2.2. Replica Mold Preparation

Three types of pillar-shaped silicon molds were used as the master molds. The first pattern was a microscale pillar-shaped mold with a diameter of 1.7 μm , a pitch of 3.3 μm , and a height of 6 μm . The second pattern was a nanoscale pillar with a diameter of 268 nm, a pitch of 500 nm, and a height of 250 nm. The third pattern was a line and space (L&S) pattern with a line width of 250 nm, a space width of 250 nm, and a height of 250 nm. All of the molds had a pattern area of 20 mm². To achieve a pattern with a higher aspect ratio, a pillar-shaped UV-cured resin pattern with silver ink is required (Figure 2c). Thus, hole-shaped replica molds were fabricated using UV-NIL. The UV-NIL process was performed as follows. First, a UV-curable resin, PAK-01-CL (Toyo Gosei Co., Ltd., Tokyo, Japan), was manually dropped onto the pillar-shaped Si master molds. These master molds were release-coated with the fluorinated material Optool DSX (Daikin Industries, Ltd., Osaka, Japan) and covered with a Cosmoshine A4300 polyester film (Toyobo Co., Ltd., Osaka, Japan). A glass slide was then placed on the film, and the glass slide and polyester film were exposed to UV light. After the resin was cured, the polyester film was removed from the Si master mold. Finally, hole-shaped replica molds were obtained, which required release coating. Figure 3 shows the release-coating process for the replica mold. First, chromium was deposited on the replica mold using conventional resistance wire heating and vacuum deposition (Figure 3a). After exposure to the atmosphere, chromium forms a chromium oxide layer on the surface, which couples with a fluorine-based release agent. This is because, if the release agent is directly applied to the UV-curable resin without Cr, the release property becomes weak [31]. The Cr-coated replica mold was then dipped in the release agent (1 wt.% Optool DSX) for 12 h (Figure 3b). After removal from the solvent, the replica mold was heated on a hot plate at 120 °C for 5 min (Figure 3c). Finally, the replica mold was rinsed with fluorine (Novec 7300, 3M Japan, Ltd., Tokyo, Japan) to complete the process (Figure 3d).

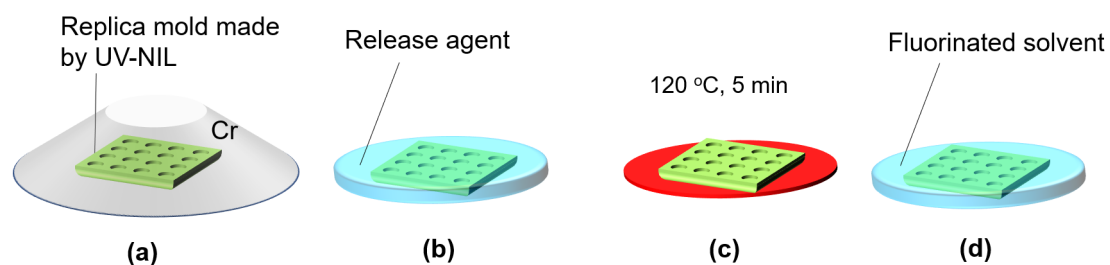


Figure 3. Release-coating process for the replica mold. (a) Deposition of Cr on the replica mold. (b) Dipping in the release agent. (c) Baking the replica mold. (d) Rinsing the replica mold.

2.3. Formation of Silver Ink on Top of UV-Curable Resin Pattern

Our group has developed a process of patterning silver ink on a UV-curable resin using a concave region of the mold. Further details are provided in the literature [29]. Here, we briefly describe this process. To form silver ink at the bottom of a hole pattern, silver ink (Smart Jet I, GenesInk Co., Ltd., Paris, France) was filled on the mold surface (Figure 4a), and it was thinned using a spin coater (Figure 4b). Smart Jet I is a low-viscosity silver ink developed for inkjet printing, with an inkjet resolution of approximately 40 μm . The firing temperature is 120–250 °C, and the resistivity is 2.5–17.5 $\mu\Omega\cdot\text{cm}$, depending on the firing temperature. The spin-coating conditions were an initial rotation speed of 500 rpm for 5 s and a main rotation speed of 3500 rpm for 60 s. After the silver ink was thinned, it was baked at 150 °C for 5 min (Figure 4c). After the baking, the silver ink solvent evaporated, silver was sintered, and both the top and bottom parts of the silver ink were reduced. Consequently, the top part of the silver became separated from the bottom

part. This separation is a key technique for obtaining the bottom part of the silver patterns. In this state, the silver ink in the top region was removed using a heated polyethylene terephthalate (PET, PET-6010, Takiron Co., Ltd., Osaka, Japan) film (Figure 4d) [32,33]. After removing the top region of the silver ink, the sintered silver remained at the bottom of the concave region of the mold (see Figure 2a). The top part of the silver pattern could not be used because the uniformity of the top region of the silver pattern was poor when silver ink was used [29]. However, the uniformity of the bottom part of the silver was good when the filling of the silver ink was sufficient. Thus, the bottom layer of the silver was used as a mask for oxygen dry etching.

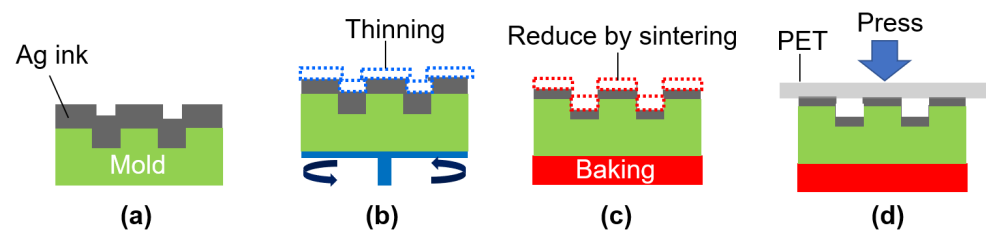


Figure 4. The formation process of the silver region at the bottom of the mold. (a) Filling of silver ink on the mold surface. (b) Thinning of the silver ink using a spin coater. (c) Silver ink baking. (d) Removal of the top part of the silver pattern.

Because the silver remains in the mold recesses, the subsequent process will be explained by referring to Figure 2. Subsequently, UV-NIL was performed on this mold, which had a silver pattern at the bottom (Figure 2a). A UV-curable resin (PAK-01-CL) was dropped onto the mold and covered with a support film (Cosmoshine A4300). The glass slides were then pressed for 1 min and exposed to UV light at 385 mJ/cm^2 (Figure 2b). After the UV-curable resin was cured, the support film was released from the mold. Consequently, a UV-curable resin with a silver pattern at the top part was obtained (Figure 2c). Oxygen dry etching was performed using these silver patterns as oxygen dry etching masks.

2.4. Oxygen Dry Etching Process and Fabrication of Silver Pattern Using High-Aspect-Ratio Mold

Oxygen dry etching was performed using inductively coupled plasma (ICP)-RIE equipment (EIS-700, Elionix Co., Ltd., Tokyo, Japan). The etching conditions were an RF power of 400 W, a bias power of 50 W, and an oxygen gas flow rate of 40 sccm. Under these conditions, the etching time was varied, and shape changes were observed using scanning electron microscopy (SEM; ERA-8800FE, Elionix Co., Ltd., Tokyo, Japan) (See Figure 2d). To confirm the remaining silver at the top part of the UV-cured resin after oxygen dry etching, scanning transmission electron microscopy (STEM, Tecnai F20X (FEI Co., Ltd., San Francisco, CA, USA)) and energy-dispersive X-ray spectroscopy (EDX; EDAX Genesis, Ametek, Co., Ltd., Nagoya, Japan) were performed.

Using the fabricated high-aspect-ratio mold, the silver pattern on the UV-curable resin was transferred in the same way as in Figure 2a–c. The transmittance of the transferred silver pattern on the UV-curable resin was measured using an ultraviolet–visible–near-infrared (UV–vis–NIR) spectrophotometer (SolidSpec-3700, Shimadzu, Co., Ltd., Kyoto, Japan).

3. Results

3.1. Fabricated High-Aspect-Ratio Mold Patterns

Figure 5 shows the fabricated high-aspect-ratio patterns. For comparison, the initial silicon mold shape and patterns before the oxygen dry etching (see Figure 2c) are also shown. To investigate the dependency on the etching time, one sample was used for each etching time; thus, multiple patterns with silver masks were prepared. The heights of the convex parts of the replicated patterns (Figure 5a,d,g) were lower than the initial

mold heights because of the shrinkage of the UV-curable resin [34]. After the oxygen dry etching, the height of each shape increased. For the L&S pattern, the height was 1.6 μm after 60 s of etching (Figure 5b), and 3.1 μm after 180 s of etching (Figure 5c). In this case, the top-line parts became sharper as the processing progressed. The aspect ratio after 180 s of etching was 12.4 ($3.1 \mu\text{m} \div 250 \text{ nm}$, the mold's line width). For the microscale pillar pattern, the height was 7.1 μm after 60 s of etching (Figure 5e), and 9.3 μm after 180 s of etching (Figure 5f). The aspect ratio after 180 s of etching was 5.5 ($9.3 \mu\text{m} \div 1.7 \mu\text{m}$, the mold's diameter). For the nanoscale pillar pattern, the height was 0.4 μm after 15 s of etching (Figure 5h), and 1.0 μm after 30 s of etching (Figure 5i). The aspect ratio after 30 s of etching was 3.7 ($1 \mu\text{m} \div 0.268 \mu\text{m}$, the mold's diameter). In our previous study, we showed that the top part of a convex UV-cured resin pattern was made of silver [29]. Each shape can increase the pattern height. Therefore, the silver layer on the convex UV-cured resin pattern acted as an etching mask for oxygen dry etching, and the residual layer of the cured UV-curable resin was etched (Figure 2d). Consequently, the initial pillar height and etched residual layer pattern, that is, the high aspect-ratio replica mold, could be obtained. However, for the L&S pattern, the top-line area sharpened with increasing etching time. This was confirmed using STEM-EDX.

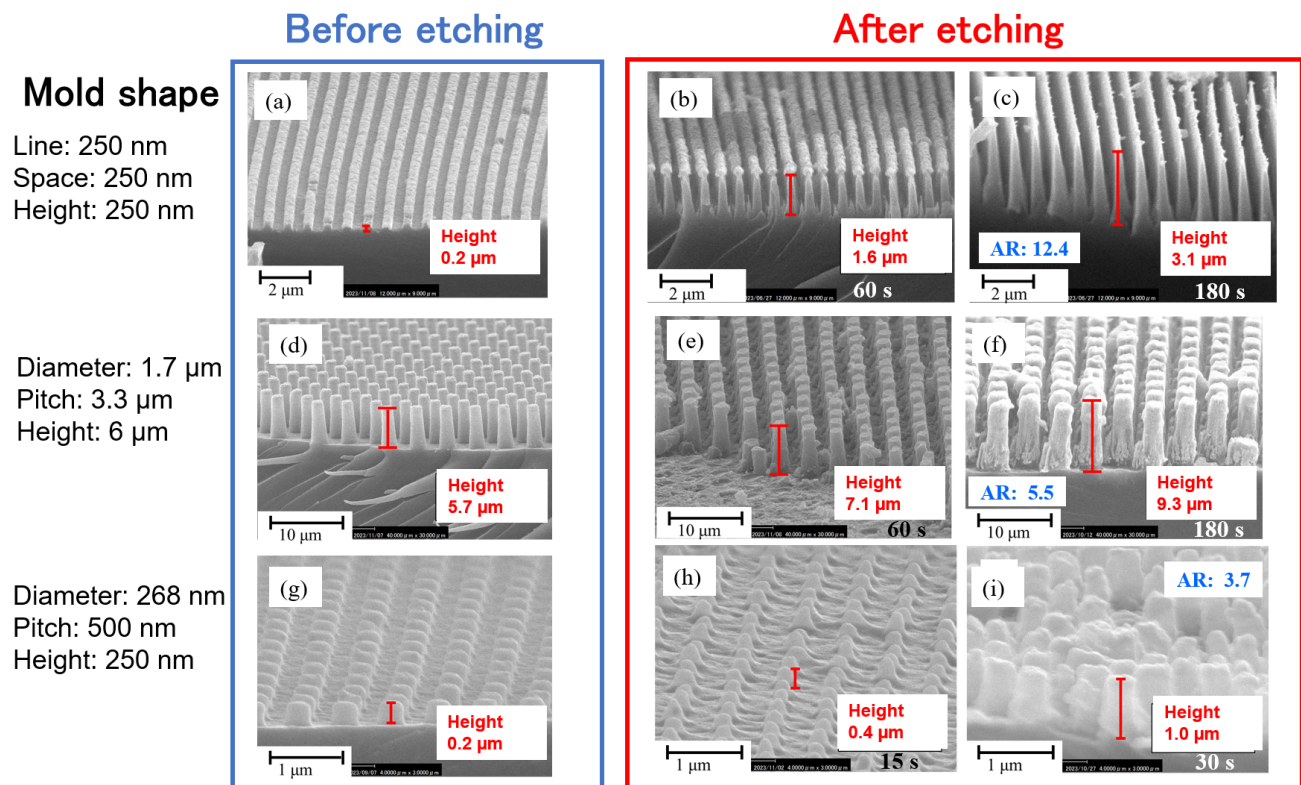


Figure 5. SEM photos before and after the oxygen dry etching of the silver-layer-capped concave patterns. L&S pattern before etching (a), after 60 s of etching (b), and after 180 s of etching (c). Micropillars shape before etching (d), after 60 s of etching (e), and after 180 s of etching (f). Nanopillars shape before etching (g), after 60 s of etching (h), and after 180 s of etching (i).

Figure 6 shows the SEM and STEM observations and elemental analysis of the L&S pattern after 30 s of etching. From a tilted angle view of the SEM photo and a cross-sectional view of the STEM photo, the height of the pattern was 0.6 μm (Figure 6a,b), which was lower than the height of 1.6 μm observed after 60 s of etching (see Figure 5b). SEM was performed first, followed by STEM and elemental analysis. Before the STEM observation, the pattern was embedded in the resin and prepared by cutting a thin slice that could be transmitted by STEM with a focused ion beam. The STEM image shows that the line widths

of the top parts were reduced from the line width of the original mold (250 nm). Therefore, the portion underneath the silver mask was removed by oxygen dry etching, resulting in undercutting. Bright spots and layers were observed in the STEM image (Figure 6b), which indicated metal elements. To clarify these aspects, high-angle annular dark-field (HAADF) STEM and elemental analysis with EDX were performed (Figure 6c). STEM-HAADF can be used to obtain elemental differences. In the HAADF image, two types of bright areas were observed. Therefore, the details were examined using EDX. The bright parts of the HAADF images are silver and chromium. Cr originated from the replica mold (Figure 3a). Silver was present at the top of the line, but it also existed at the bottom of the sidewall. This is believed to be because the silver at the top of the line fell to the side owing to undercutting.

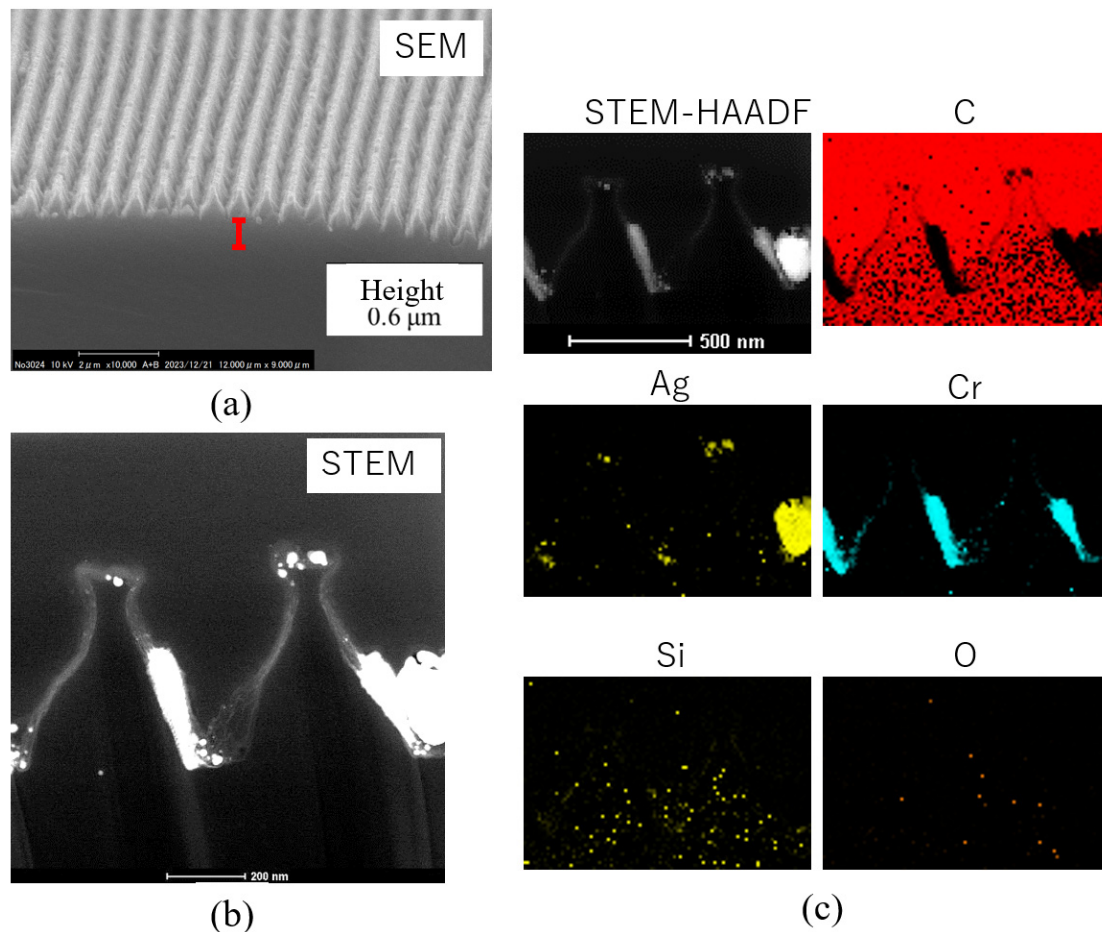


Figure 6. SEM and STEM observation of the L&S pattern after 30 s of oxygen dry etching. (a) Tilted-angle SEM photo, (b) cross-sectional STEM photo, (c) HAADF image, and elemental maps are shown.

In contrast, the UV-curable resin portion consisted of carbon (C in Figure 6c), oxygen (O in Figure 6c), and silicon (Si in Figure 6c). As shown in Figure 5, except for the L&S pattern, the patterns were processed almost vertically; therefore, in the case of the L&S pattern, the line width was narrow, and undercuts were likely to occur. To improve this, the etching anisotropy needs to be increased.

Subsequently, micropillars with the obtained high structure (Figure 5f) were used as replica molds to transfer the silver pattern.

3.2. Transfer of Silver Patterns Using Fabricated High-Aspect-Ratio Replica Mold

The fabricated high-aspect-ratio micropillar pattern (see Figure 5f) was used as a replica mold. Using this replica mold, the silver pattern was transferred in the same manner as in Section 2.3. Using the pillar-shaped pattern, a hole mesh-like pattern was

fabricated, which mimicked a hole mesh-shaped transparent electrode. The transferred hole mesh pattern is shown in Figure 7.

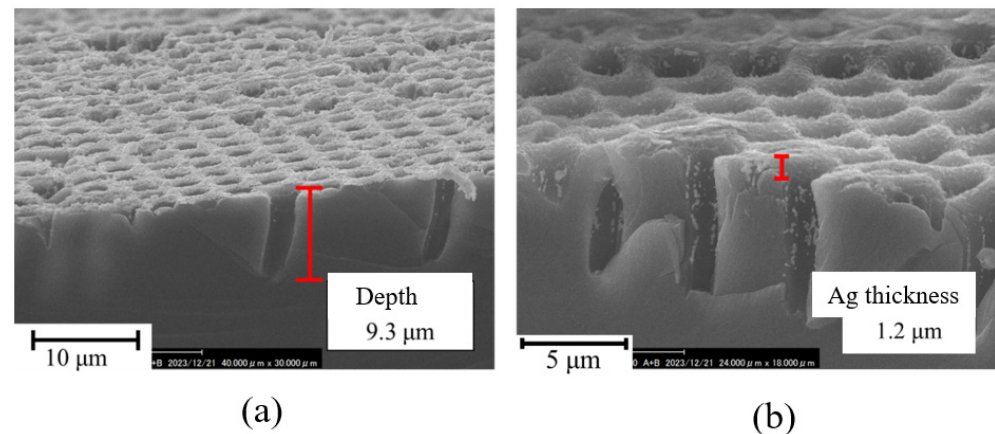


Figure 7. SEM observation of the transferred hole mesh pattern. (a) The tilted-angle view of the hole pattern. (b) The enlarged hole area.

As shown in Figure 7, a hole mesh pattern with a depth of 9.3 μm was obtained (Figure 7a). The enlarged view shows that a silver pattern of thickness 1.2 μm was formed on the UV-curable resin (Figure 7b). Consequently, a silver hole mesh pattern was obtained on the UV-curable resin. The transferred area was the same as that of the silicon mold (20 mm²). The resistance of the surface was 1.5 kΩ. Figure 8 shows the transmittance of the mesh-like silver hole patterns. For comparison, a 2 μm-thick sintered flat silver layer was formed on the polyester film (Cosmoshine A4300). This thickness was chosen because, in the enlarged view of Figure 5e, the thickness of the silver layer was measured to be 1 to 2 μm. Consequently, the transferred silver hole mesh pattern exhibited higher transmittance than the flat silver layer at wavelengths greater than 400 nm. However, a high transmittance of less than 300 nm was obtained for the flat silver layer. The silver layer created by firing the silver ink was a collection of silver nanoparticles with a diameter of several tens of nanometers, and these silver nanoparticles generated plasmon absorption of the color yellow [35]. In this state, when exposed to white light, the silver layer exhibited a complementary purple color. On the other hand, this coloring is also believed to occur in the pattern with holes. However, it is believed that there is less coloring because the thickness is small and the area of silver is small. This result is attributed to the microscale hole pattern, and it is believed that the transmittance can be improved by reducing the silver area.

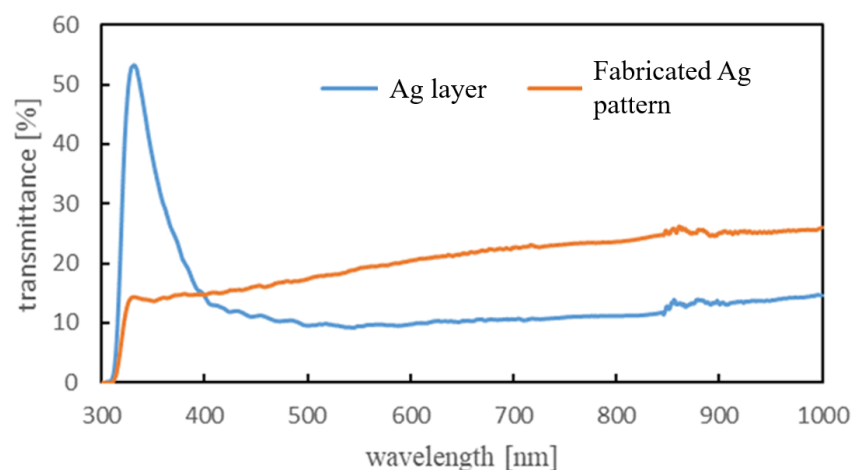


Figure 8. Transmittances of the silver hole mesh pattern on the UV-curable resin and flat silver layer.

4. Discussion

From Figure 5, the shape of the nanopattern was more disordered than that of the micropattern. This is because the height of the original mold was approximately 250 nm; therefore, the thickness of the silver film that served as a mask was small. Our previous study showed that the thickness of silver was approximately 100 nm for a nanomold with a depth of 250 nm [29]. The silver next to the side wall (see Figure 6, Ag element image) is also 100 nm thick, and the mask is believed to have approximately the same thickness. When the mold depth was 250 nm, filling and sintering with silver resulted in a thickness of approximately 100 nm; therefore, it was difficult to increase the thickness of the silver film. Therefore, the conditions for oxygen dry etching must be optimized. As shown in Figure 6, the linewidth of 250 nm after 30 s of etching narrowed to 100 nm because of undercutting. This is believed to have caused the silver layer on the top to fall off. Anisotropic processing can be used to prevent this phenomenon. For example, in this study, the bias power was 50 W; however, increasing this power is believed to strengthen the anisotropy. Increasing the bias power increases the ion acceleration voltage, resulting in anisotropic etching. However, increasing the anisotropy may cause the removal of the silver mask by sputtering, and it is believed that there is a tradeoff between the acceleration voltage and the mask selectivity. Therefore, it may be necessary to use ion-beam shower equipment instead of the ICP-RIE equipment. However, the processing conditions used in this study are optimal for ICP-RIE. To obtain even higher aspect ratios in nanopatterns, optimization is necessary, including that of the oxygen dry etching equipment; however, this is a topic for future research. DRIE and MacEtch are capable of producing high-aspect-ratio molds. However, when performing these processes, it is necessary to create fine patterns using EBL, NIL, etc. MacEtch requires a metal film, a lift-off process after forming a fine pattern, and the dry etching of the metal film using the fine pattern as a mask. In this way, when trying to obtain a metal nanopattern, a large number of manufacturing steps are required. In this method, the recesses of the mold are filled with silver ink. Then, it is baked, and the silver ink is used as a mask to etch deep into the UV-curable resin with oxygen RIE. Therefore, in addition to oxygen RIE, the NIL transfer and baking processes are required, which can be performed in the atmosphere. Thus, compared to MacEtch, it has the advantage of being easier to form metal films. In the case of DRIE, it is possible to process deep holes using fine resin patterns. Therefore, it is possible to omit the formation of a metal film. The advantage of this method compared to DRIE is the ability to use an existing mold. For example, after creating a mold with a high aspect ratio by DRIE, this method can be used to further improve the aspect ratio. In this way, this method can be further improved by using other high-aspect-ratio manufacturing methods. In addition, the etching depth in the developed method is expected to be about 10 μm , because the line width and diameter of the pattern are targeted to be smaller than a few microns. From the results in Figure 5, the etching speed when using oxygen gas for resin is calculated to be 0.8 to 1.6 $\mu\text{m}/\text{min}$. On the other hand, the etching speed of silicon in the Bosch process is over 3 $\mu\text{m}/\text{min}$, which is higher than the experimental result of this method [36]. This is partly due to differences in the output of the equipment, but even with this method, the etching time to obtain a depth of 10 μm is only about 10 min, so this etching time is sufficiently short to efficiently obtain a high-aspect-ratio pattern. Nanopatterns with aspect ratios of 10 or higher are advantageous for fabricating metalenses and metasurfaces. Cr is also observed in Figure 6. This is the chromium from the replica mold. Treatment is required to prevent the Cr from peeling off the resin. In this case, the use of a replica mold containing a mold-release agent was effective.

5. Conclusions

We devised an effective method for producing high-aspect-ratio molds using a master mold. To obtain a pattern with a high aspect ratio, a mask for dry etching, typically formed via metal deposition, is required. To eliminate the metal deposition process, silver ink was used as a mask for dry etching. After the mold pattern was filled with silver ink, it was baked. The pattern on top of the mold was removed with a PET film, and the silver at the bottom of the mold was scooped with UV-NIL to perform a transfer with a silver layer on top of the UV-cured resin. Using silver at the top of the pattern as a mask for oxygen dry etching to process the UV-curable resin, a mold with a higher aspect ratio than that of the original mold was fabricated. The lift-off process for the metal layer requires the formation of fine patterns and the removal of the resist. This process has the advantage of using a mold that has already been made, which reduces the number of steps. However, when performing metal film lift-off after transferring a fine pattern using nanoimprinting, the number of steps increases because the metal film is vapor-deposited after removing the residual layer after NIL transfer. Using the developed method, the 250 nm L&S pattern mold and 1.7 μm diameter mold were used with oxygen RIE to etch the UV-cured resin using silver as a mask for 180 s. This resulted in aspect ratios of 12.4 (250 nm L&S) and 5.5 (1.7 μm diameter). In this way, we were able to efficiently fabricate a mold with a high aspect ratio using the silver ink transfer process and oxygen RIE process. To use the high-aspect-ratio silver-capped micropillar pattern, the silver pattern was transferred in the same manner (see Section 2.3). As a result, a pattern with a hole depth of 9.3 μm and 1.2 μm thick silver layer on UV-curable resin was obtained. This pattern mimicked a hole mesh-shaped transparent electrode. A 1.5 k Ω surface resistance was obtained, along with higher transparency compared to a silver layer. The high aspect ratio mold thus fabricated was also capable of metal ink transfer, making it effective for fabricating metalenses and metasurfaces. To obtain a high-aspect-ratio shape with a line width on the order of several microns or a dot pattern, an etching depth of about 10 μm is required. The etching speed of the Bosch process is faster than that of this method, which etches resin with oxygen RIE using silver as a mask, but this method only requires about 10 min of etching time to obtain a processing depth of 10 μm , and thus, the developed method is also efficient for etching molds.

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