Fabrication of 3D micro/nanostructures using proximity effect between mask and resist

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Abstract

The variable proximity multi exposure technique in SR lithography is introduced. This technique provides to fabricate micro/nano gratings include Sub-wavelength gratings. The sub-wavelength gratings for antireflection were fabricated using this technique. Fresnel and Fraunhofer intensity distribution simulation for estimate the properly gap were performed. The simulation was done by the slit width of 150 nm and 250 nm, and the proximity gap was from 0 up to 100 µm. On the other hand, evaluation of proximity gap effect with conventional exposure was performed. We found the appropriate value of the gap for obtaining high contrast, and the gap for provide a taper. The experiment results were in agreement with the calculated result. T Then the multiple exposure with appropriate gap were performed and we were able to obtain the three dimensional sub-wavelength structures.

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Introduction

Many applications of optical elements (including diffraction optical elements) are recently wide employed. Therefore high efficiency, micro/nano parts for Micro Optical Electro Mechanical Systems (MOEMS) is needed, and the high precision and high aspect ratio Sub-Wavelength Grating (SWG) is also needed. So a fabrication technique of three dimensional structures for SWG using Synchrotron Radiation (SR) lithography is introduced. The SWG can provide a device with optical anisotropic and reflective index distribution on the surface of material by a simple section shape. SWGs can applicable for antireflection device, polarizing elements, guided-mode resonance filters, and high efficiency diffraction optical elements. The multifunctional optical elements with very high efficiency can be fabricated using the SWG for antireflection, because these can control the phase, polarization of light and wavelength of light simultaneously. A device is that of the two-dimensional arrangement which has the structure of a cycle shorter than a wavelength on the surface, such as shown in Fig.1. However several reports for fabricating SWG [1,2,3], there are few examples which manufactured directly on transparent resin with aspect ratio of over 1. It is possible to fabricate SWG directly on PMMA by our method.

On the other hands, there are some methods for fabricating three dimensional structures such as Plane pattern to Cross-section Transfer (PCT)[4], double exposure in deep x-ray lithography (D2XRL)[5]. Though, these methods are not suitable for fabricating SWGs, because of the mask and wafer distance (proximity gap). The schematic of allocation of mask and resist is shown in Fig. 2. While pattern replicating process, the influence of Fresnel diffraction on replicated resist patterns is a dominant factor limiting pattern resolution and line cross section shape which includes width and taper control in SR lithography. This influence is generally reduced by shortening the proximity gap and enlarging the mask contrast. Although X-ray absorber patterns are made as thick as possible, the mask contrast is also limited due to difficulties in high-aspect-ratio patterning. For this reasons, we have used a conventional X-ray mask with contrast of 3 that was made of a 0.5-μm-thick Ta absorber and a 2-μm-thick SiN membrane with critical dimension (CD) of 0.1 μm.

In order to make a taper shape, it is necessary to make a gray tone energy distribution in resist. So in order to manufacture the three-dimensional structure with high aspect ratio, it is necessary to fulfill simultaneously two contradicting conditions of attaching a gray tone with high contrast. Then we investigate two step exposures for attaching contrast and attaching a gray tone. When providing a gray tone, exposure is performed with detached gap by the same mask which used for attached contrast.

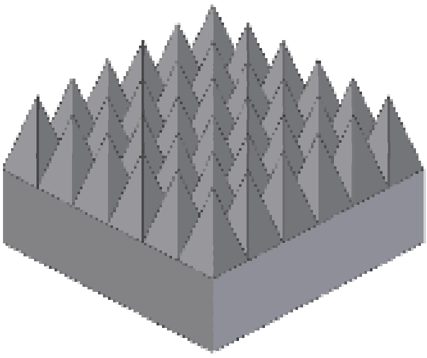

Fig. 1 Schematic of sub-wavelength structure

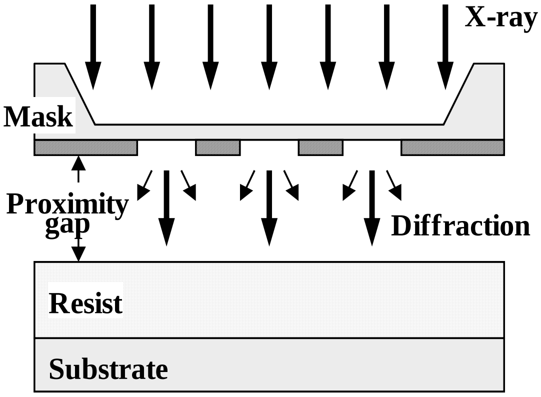

Fig.2 The allocation of Mask and Resist while X-ray exposure

Fabrocation Process

2.1 Conventional process

Process flow of fabrication is Fig. 3. Conventional lithography process is shown as the flow of (1), (2), and (a). First, PMMA resist is spin-coated on Si wafer-(1). Next SR X-ray was exposed to resist through the mask-(2). And finally resist was developed with GG developer. Then the structures are manufactured-(a), such as a line, cylinder, hole, and etc. We investigate in section 3

2.2 Process for micro/nano three dimensional structures

The process for micro/nano three dimensional structures is shown as flow of (1), (2), (3), and (b). In addition to (2), 2nd exposure is performed with detached gap as shown in (3). Then three dimensional shapes as shown in (b) are fabricated. We can repeat exposure process if necessary.

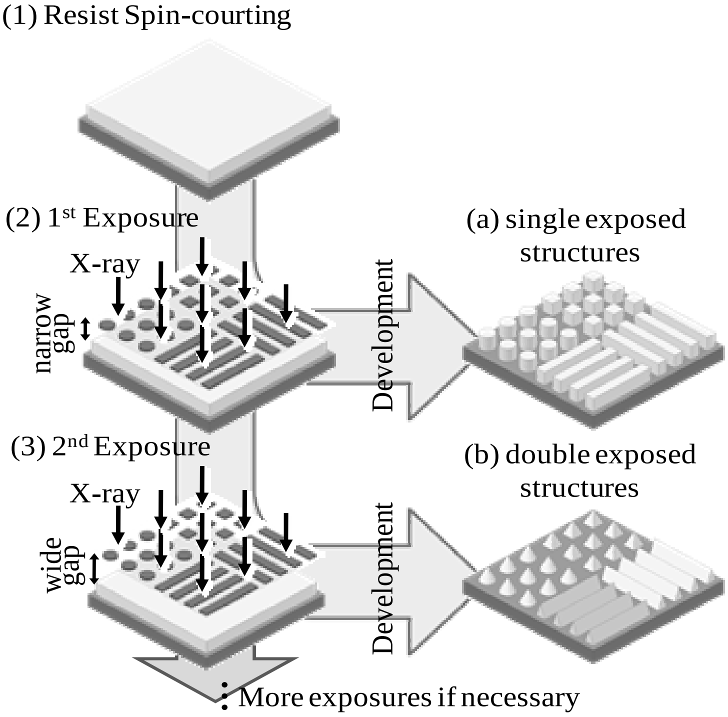

Fig. 2 The grating with 300 nm pitch

BLAZED GRATING

3. INVESTIGATION OF STRUCTURE TAPER AND CONTRAST

3.1 Simulation of proximity effect

The aerial intensity distribution was calculated for estimate the highest contrast. In principle, an optical image formation in proximity printing is described by Fresnel diffraction. In X-ray lithography an additional important factor is photoelectron blur, and the resulting aerial image is a convolution of these functions [6]. The Fresnel diffraction is described by the following expression;

$$I/I_0 = \frac{1}{2}\left\{\left[C(q_2)-C(q_1)\right]^2 + \left[S(q_2)-S(q_1)\right]^2\right\} \qquad (1)$$

$$C(u) = \int_0^u \cos(\pi t^2/2)dt \qquad (2)$$

$$S(u) = \int_0^u \sin(\pi t^2/2)dt \qquad (3)$$

Where, I/I0 refers to absorb correction term which is the ratio of I, integrated diffracted intensity and I0, incident X-ray beam intensity. C and S represent the Fresnel cosine integral and the Fresnel sine integral respectively, and qn is the position at a focul point [7]. This equation used for a calculation of the X-ray intensity at the cross-section of the structure.

The experiments were performed at Beamline-5 in AURORA storage ring of the SR center, Ritsumeikan University, Japan. The conditions of the storage ring are as following, the applied electron energy at the maximum current was 575 MeV and the wavelength of X-ray exposing on the resist ranged from 0.12 to 0.62 nm where the peak wavelength was 0.4 nm [8].

So the intensity distribution was caluculated with the wavelength of 0.1 nm to 0.6 nm and gap of 0 to 100 µm. The diffraction energy spectrum at the surface of resist without any influence was calculated from beam line parameters. The x-ray wavelength is between 0.1 nm to 0.6 nm at peak of 0.35 nm. The parameters used in exposure process is shown in Table 1.

Table 1 Parameters used in exposure process

Operating electron energy	575 MeV
Electron beam current	300 mA
Critical wave length emitted X-rays	1.5 nm
Beam line vacuum sealing window	1st 100 µm Be 2nd 200µm Be
Atmosphere of exposure chamber	0.85 atm He
Range of exposed wavelength	0.1 – 0.6 nm

The aerial intensity distribution map is shown in Fig. 4 for the slit width of 250 nm and Fig. 5 for the slit width of 150 nm, the gaps used in the simulation were from 0 up to 100 µm each. As shown in Fig. 4, we can obtain the maximum contrast where the gap distance was 55 µm. For the line width of 150 nm, we can also obtain the maximum contrast where the gap distance was 25 µm.

The contrast falls as it separates from these gaps of maximum contrast. In the gap less than the maximum contrast point that called proximity area, exposure contrast falls, though the inclination of a sidewall becomes high. On the other hand, in the gap more than maximum contrast point that is projection area, both exposure contrast and the inclination of a sidewall taper become low.

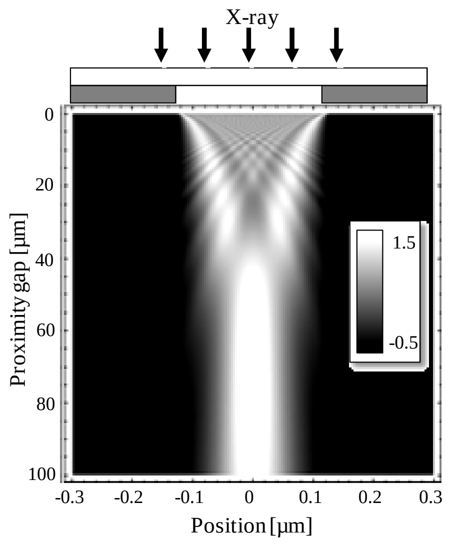

Fig. 4 Simulated air intensity distribution at slit width of 250 nm

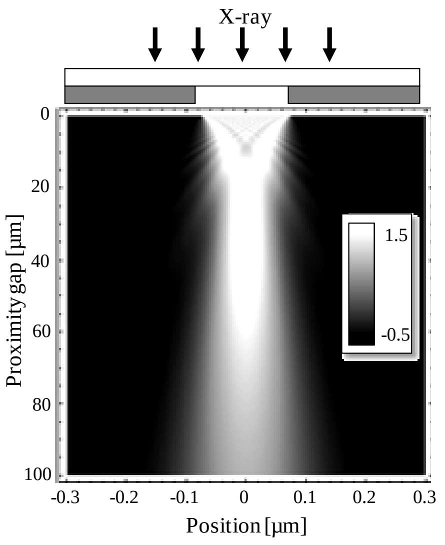

Fig. 5 Simulated air intensity distribution at slit width of 150 nm

3.2 Evaluation of development effect

First of all, the development effect to sidewall taper was estimated by conventional lithography process. The maximum taper in 250 nm Line-and-Space (L&S) with pitch of 500 nm when setting a gap to the 20 µm as possible as close proximity gap was investigated. The taper angle was evaluated, with amount of Dose, and developing time and temperature were changed.

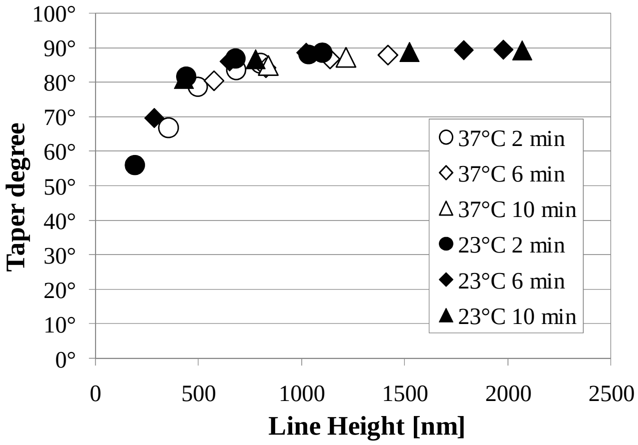

Fig. 6 Analysis of sidewall taper degree caused by development

Development temperature is estimated that 23 °C has higher sidewall taper angle than 37 °C. It has taper angles high about 2 degrees at each point. From Fig.5, it turned out that the processing depth and sidewall taper angle will become low, if the dose amount is low or developing time is short. It is depended on underexposure or underdevelopment. In order to make an inclination high angle and to obtain the processing depth, it turned out that the development temperature of 23°C and the developing time of 10 minutes are better.

3.2 Evaluation of proximity effect

Next, the proximity gap was changed and the relation with a taper angle was investigated. In these experiments, evaluation of 150 nm L&S besides 250 nm L&S was also performed, the proximity gap was performed by 20, 30, 45, and 60 µm, and every developing time was 10 minutes.

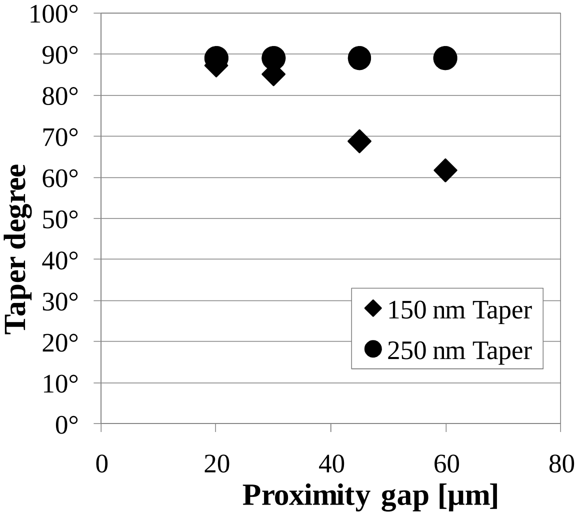

Fig. 7 Analysis of sidewall taper degree caused by proximity gap

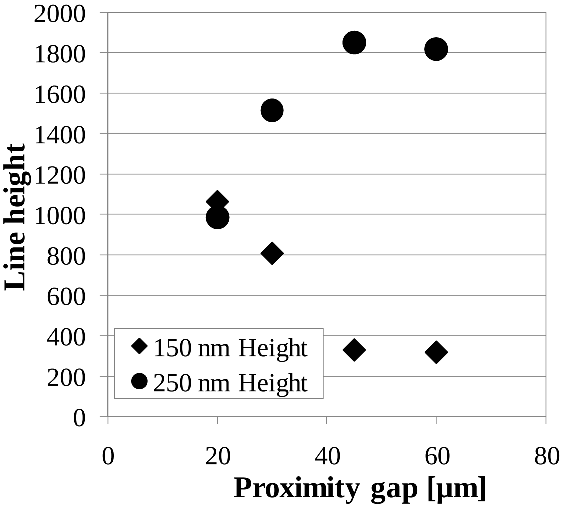

Fig. 8 Line height index for estimation of the contrast

As in the 250 nm L&S, sidewall taper was about 89° at every gap that is shown as Fig. 7. Although the peak of the processing depth is at the proximity gap of 55 µm, this is based on interference of diffraction. In the result of 20 µm gap, the form at the bottom of processing was superficial.

Similarly in 150 nm L&S, these which have a peak in 25 µm agree with the contrast result of interference calculated from the formula (1), respectively.
These results showed that the maximum contrast calculated in the simulation and experimental results were in agreement.

3.3 Mask pattern effect

To make sure the mask pattern effect, the conventional lithography processes were performed used a mask for fabricating the sub-wavelength structures. The critical dimension was 100 nm, so it was estimated that the maximum contrast is obtained with proximity gap of 16 µm. Even if maximum contrast was obtained with the proximity gap at 16 mm, proximity gap should be more than 20 µm in order to protect from breaking the mask membrane. The SEM photograph of X-ray mask used this process is shown in Fig. 9. However the Ta absorber was designed as square-shape, in practice each corners became rounded.

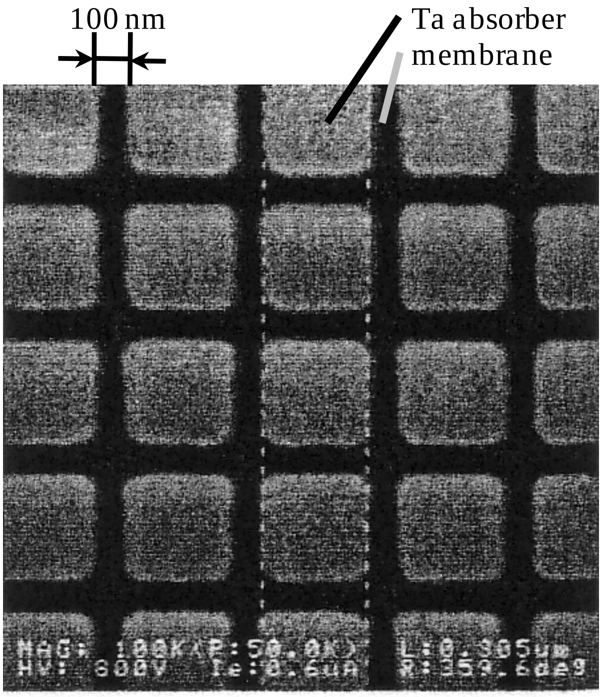

Fig. 9 SEM photograph of mask pattern for the sub-wavelength structures

Fig. 10 and Fig. 11 are the results of lithography with the gap of 20 µm and 60 µm respectively which are corresponding to the results of the simulation properly.

The lithography result at the proximity gap of 20 µm is expressed below. The purpose of this exposure is for obtain high contrast of processing depth as much as possible.

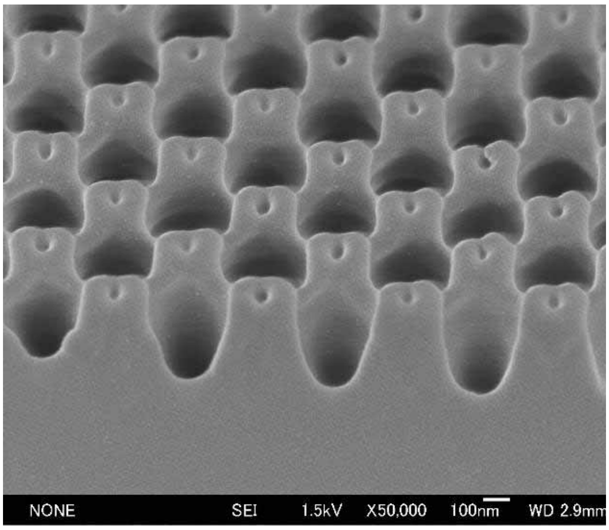

Fig.10 SEM photograph of the fabricated structure with conventional lithography process at the proximity gap of 20 µm

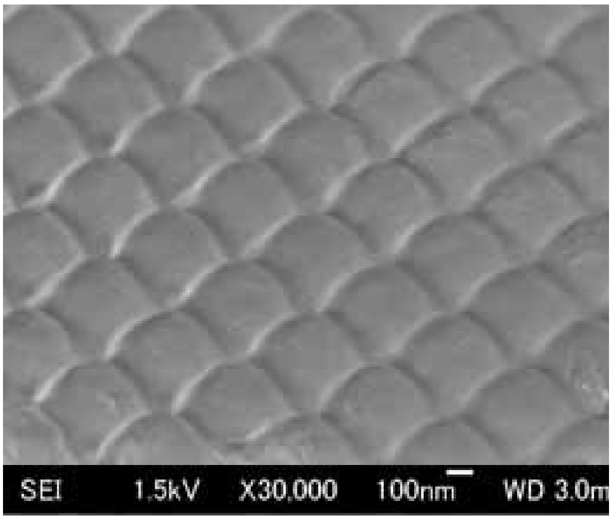

Fig. 11 SEM photograph of the fabricated structure with conventional lithography process at the proximity gap of 60 µm

The processing depth of the structure made by this experiment was about 500 nm. Although the inclination is attached to the lower part of structure, the upper part of structure is a rectangle. It is characteristic that a hole is in each top of the structure. It is thought that this phenomenon happened as a result of complicated distribution of diffraction by the 2-dimensional array mask pattern.
The lithography result at the proximity gap of 60 µm was shown in Fig. 11. This exposure was performed in order to obtain an inclination.

Exposure contrast was decreasing by influence of Fraunhofer diffraction at this gap. Therefore, the shape became round as shown in Fig. 11.

3. FABRICATION OF SUB-WAVELENGTH STRUCTURE

The variable proximity exposure was performed with 1st exposure of 20 µm-gap and 2nd exposure of 40 µm-gap for fabricating SWS.

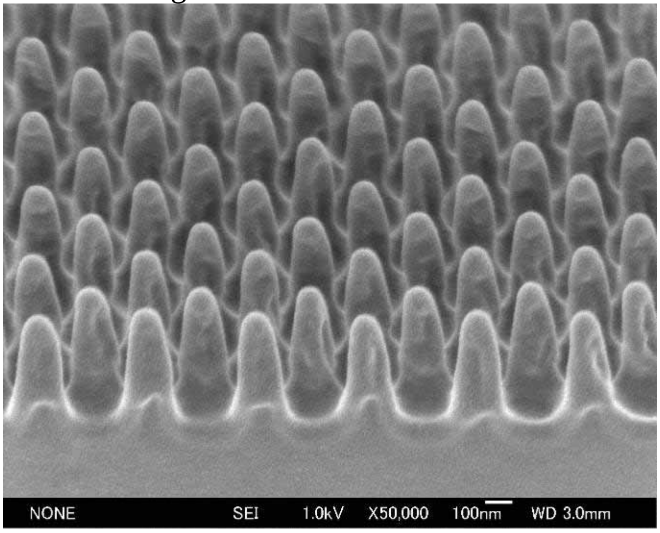

Fig.12 SEM photograph of the fabricated structure with double exposed structure, 1st exposure was 20 µm-gap and 2nd exposure was 40 µm-gap.

Fabricated structure has the height of 400 nm and the width of 250 nm at the bottom of structure. Therefore, the aspect ratio of this structure is 1.6. This structure has a cone shape with 8° inclination, even if the mask shape was rectangular.

4. CONCLUSION

We have investigated the printing characteristics of structure sidewall inclination by means of aerial intensity simulations and lithography experiments, and compared the results with simulations for SR lithography. We also have investigated multiple exposures for fabricating three-dimensional micro/nano structures.

The variable proximity exposure was performed with 1st exposure of 20 µm-gap and 2nd exposure of 40 µm-gap, and fabricated structure has the height of 400 nm and the width of 250 nm at the bottom of structure. It is necessary to inquire about the optical characteristic of this SWS. And it is necessary to also perform improvement for acquiring the more efficient optical characteristic.

SWGs can applicable many optical devices, such as antireflection device. Though, SWGs can acquire high effective devices by using with combining other optical elements. Therefore, it is necessary to investigate the method of manufacturing SWS on other optical devices.

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