Simulation and Fabrication of Submicron 3D Structure by PCT (Plane-pattern to the Cross-section Transfer) Technique

Fumiki Kato*, Shinya Fujinawa, Makoto Tsudo, and Susumu Sugiyama

Abstract

In this paper, influences of Fresnel diffraction for the advance accuracy in sub-micron resolution of the PCT (Plane-pattern to Cross-section Transfer) technique are discussed. Some analytical simulations were performed for a prediction of X-ray intensity distribution. The X-ray mask pattern employed in this work was a set of right triangles placed in double rows facing each other which was designed by the fact that when mask slit becomes narrower while approaching the corner, the influence of the diffraction gradually becomes more significant. In X-ray lithography, especially for optical applications, it has been realized that the Fresnel diffraction is most effective factor for designing the shape of slits in submicron. The group of triangle mask patterns has 1.48 µm-pitch and 20 µm-height with 0.5 µm-thick Ta absorber. The submicron structure was successfully fabricated by PCT with a proximity gap of 300 µm. The fabricated structure exposed by 1.84kJ/cm^3 X-ray dose has 190 nm in height. The analysis was summarized by comparing the PCT simulations and the data from experimental results.

Keywords: PCT, Synchrotron Radiation Lithography, Submicron 3D-structure, Fresnel Diffraction

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1. INTRODUCTION

The study on a deformation occurred during the fabrication of 3D structures with a high-aspect-ratio has become necessary, especially for the fabrication of, not only tall but also wide pitch such as micro needles. The X-ray lithography with additional technique so called PCT enhances the variation of designs to be fabricated. However, the factors influencing the shape-deformation of those structures have been available only for micro-scale [1]. The factor influencing sub-micron structure has also been reported for the fabrication of conventional X-ray lithography [2]. Therefore, in this paper, we have tried to investigate the problems occurred during the PCT fabrication and discussed. The reason that we chose to study on the Synchrotron radiation (SR) lithography is, it is one of the most effective and well-known method for fabrications of high-aspect-ratio micro- and nano-structures with a high-resolution. Particularly in the applications of optical devices, structures fabricated by Deep X-Ray Lithography (DXRL) have been possible to approach a submicron precision and consequents a higher resolution [3]. Although a short-wavelength light as X-ray was used, it is, in fact, not negligible that the resolution of the pattern decreases because of the Fresnel diffraction during the fabrication of a submicron structure [4, 5]. The influence of the diffraction that cannot be avoided is investigated here, for improving the fabrication of a submicron structure by PCT. Generally, the influence of the diffraction is known as a factor causing of lower resolution in DXRL [6]. Consequently, various research consortiums have been investigating on the influence of the diffraction to the mask slit [7].

In fact, a high-resolution X-ray lithography can be approached by two factors; a proper mask design and an efficient exposure system. There is an effect causing the featuring structures on the exposed resist become smaller than the required dimension as designed in the mask. Due to this problem, the proximity gap between X-ray mask and the substrate was taken into the account. We therefore, have chosen the studies on a set of triangular mask-patterns and PCT technique [8] to meet the above mentioned factors respectively and summarize in this paper about the optimized proximity gap for a high-resolution.

PCT is a technique developed by our research group for an extension of the conventional X-ray lithography in order to realize a complete 3-Dimensional structure. The main merit of PCT is a possibility to form a structure with certain cross-section while the structure-length can be controlled. Thus there is no requirement of making a mask with the certain length. The mask pattern with the similar cross-section of the desired pattern is only a must. However, the structure can only be transferred into an area that is wider than the size of the X-ray mask. Structures with a smaller dimension than that of a revolved mask pattern are not taking any advantage from this technique.

PCT has begun to draw the attention of researches on the construction of arbitrary micro-nano- structures. However, it is difficult to control the gap to be as small as possible while using PCT in the fabrication of the submicron structures. A number of reports on the effects of the Fresnel Diffraction have been available so far in case of the conventional X-ray lithography [10] while a useful study of the diffraction effect for PCT users is not yet reported.

2. NUMERICAL MODEL

In principle, a formation of optical configurations in proximity lithography is described by diffraction. Moreover in x-ray lithography, the influence of a photoelectron blur is considered as an additional important factor. The result from x-ray lithography is consequence of these factors [11, 12]. The relation between the minimum size or resolution R_d, wavelength λ, and distance G from the mask to the resist or proximity gap, where the shadow of the mask pattern may form, can be formulated in terms of the number of Fresnel (half-wavelength) zones. Reliable imaging requires at least two Fresnel zones, and in general, the resolution limit is shown by the following expression.

$$R_d = 1.5\sqrt{\lambda \times G / 2} \tag{1}$$

Where the resolution limit value (R_d) is same as available minimum slit-width. The above equation apparently shows that the resolution relatively decreases with the proximity gap. However, the gap between the mask and the resist is not possible to be too narrow in PCT process since the resist is moved independently from the X-ray mask. A narrow gap may cause the damage on the X-ray mask during the exposure. However, it is necessary to satisfy the following expressions (2a), and to reduce the proximity gap to be as small as possible.

$$Z - 100\frac{S}{\lambda} \begin{cases} < 0 & \text{(2a)} \\ > 0 & \text{(2b)} \end{cases}$$

In this expression, Z refers to the distance between the mask the image plane, S refers to dimensions of the mask slit, and λ shows the wavelength of light source. The expression (2a) represent the image plane is in the near-field area and the intensity distribution shows the characteristic of the Fresnel diffraction. And, the expression (2b) shows the image point is in far-field area, and the strength pattern shows characteristic of the Fraunhorfar diffraction. The Fresnel diffraction is described by the following expression;

$$I / I_0 = \frac{1}{2}\{[C(p_2) - C(p_1)]^2 + [S(p_2) - S(p_1)]^2\} \tag{3}$$

Where, I/I_0 refer to absorb correction term which is the ratio of I, integrated diffracted intensity and I_0, incident X-ray beam intensity. C and S represent the Fresnel cosine integral and the Fresnel sine integral respectively, and p_n is the position at a focusing point [13]. Therefore, the study on optimization of the proximity gap when using PCT technique in X-ray lithography was performed. If the slit has high length-width ratio aperture, the effect of Fresnel diffraction appears strongly in the wider direction at the aperture, and it is assumed that there will be not much influence in the narrower direction. Thus, without the diffraction influence in the vertical direction, only that of horizontal direction was considered in the simulation.

3. EXPERIMENTAL

3.1 Exposure System and Fabrication

The experiments were carried out with the SR of the AURORA storage ring at the SR center, Ritsumeikan University, Japan. The condition of the storage ring is as following, the applied electron energy at the maximum current was 300 mA at 575 MeV and the wavelength of X-ray exposing on the resist ranged from 0.07 to 0.85 nm where the peak wavelength was 0.34 nm at the resist surface [15]. The spectrum of the SR beam line is shown in Fig.1.

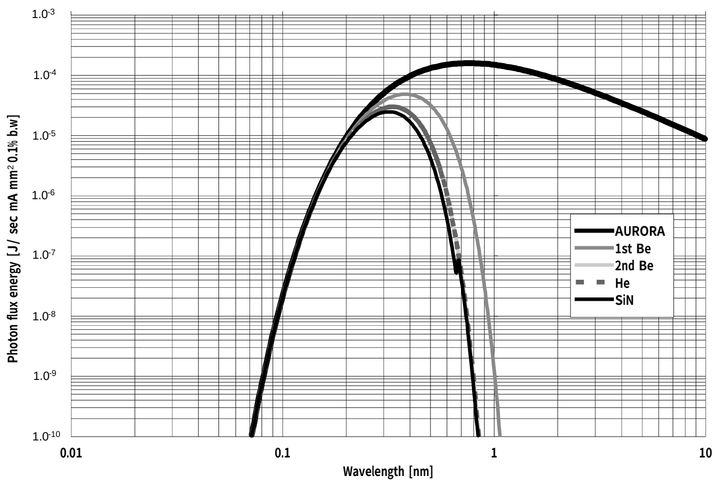


Fig.1 Spectrum of the SR beam line #13 of the AURORA

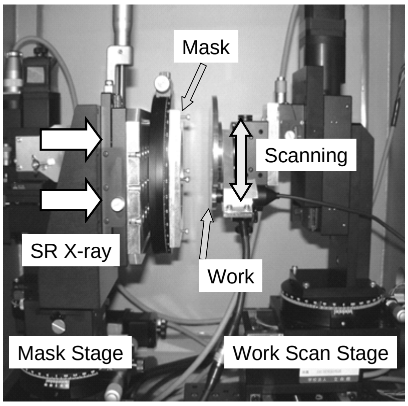


Fig. 2 The motorized stages in the exposure chamber for PCT process

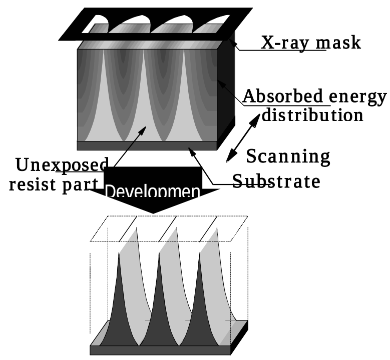


Fig. 3 The schematic of the PCT process.

The exposure chamber is illustrated in Fig.2. Two movable resist stages have been placed in the chamber. A stage was used to hold the mask where the other was used for the resist. The two stages moved independently and controlled by a remote which is digitally connected to a PC. The PC was run by software used particularly at LIGA beam lines of the AURORA. Therefore during the exposure in the closed chamber, moving stage is still able to be controlled. The mechanism is, when X-rays transmitted through the mask membrane and absorber, if the X-ray resists moves, the 2-D pattern on the mask will be exposed repeatedly and deposited dosage on the profiled area will form the 3-D structure on the resist with the similar cross section to the mask pattern. The schematic of PCT process is shown in Fig. The exposed resist, PMMA (Polymethyl-methacrylate) was developed by GG developer [15].

3.2 X-Ray Mask and Influences of Fresnel Diffraction

The X-ray mask was made of Ta absorber with a thickness of 0.5 µm. The submicron mask patterns were formed on a 2.2 µm-thick silicon nitride (SiN) membrane as a set of triangles placed in a double row facing each other as shown Fig.4. where the light-gray area is Ta absorber, and the dark-gray area is SiN membrane.

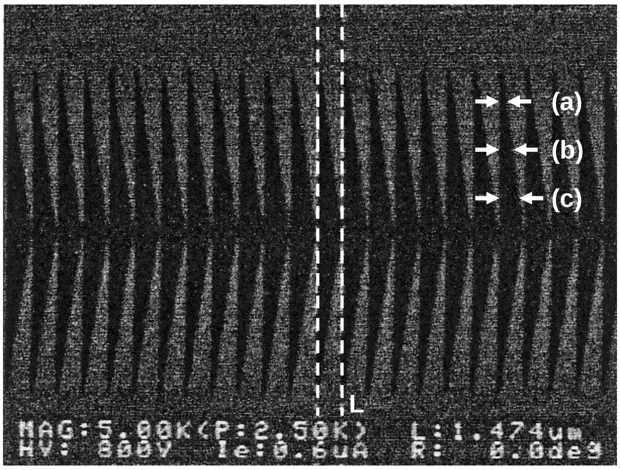


Fig.4 The triangular X-Ray mask-patterns.

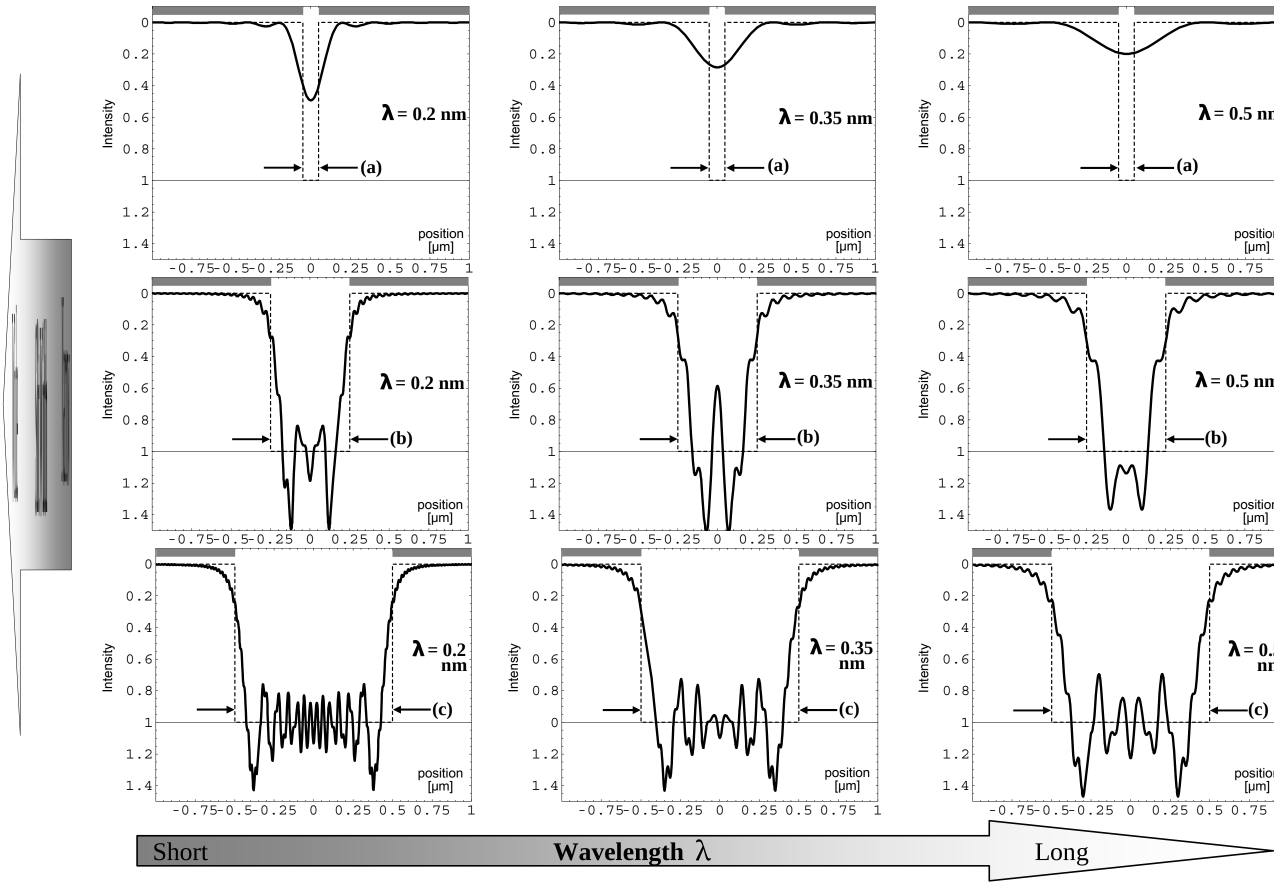


Fig.5 Simulated intensity distributions for three selected plane crossing a slit with the width of (a) 0.1 μm (b) 0.5 μm and (c) 1 μm.

The X-ray transmitted through both materials. According to the materials optical properties, Ta absorbs X-rays more efficiently than SiN, consequently, it is used as the X-ray mask-membrane. The mask contrast with the AURORA was 3.5 for a direct exposure, and reduced to 1.5 for exposure by PCT technique at the beamline-13. The 100 μm aperture with the 20 μm-height of mask pattern was exposed. Figure 4 shows a SEM image of the mask pattern. The simulation was done by using a proximity gap of 100 μm. The equation (3) was used for a calculation of the x-ray intensity at the cross-section of the structure. The intensity distribution was calculated with the slit-width of 0.1 μm, 0.5 μm, 1 μm, and the wavelength of 0.2 nm, 0.35 nm, 0.5 nm. When the light passes through a narrow slit, the influence of the diffraction is greater, the intensity decreases as shown in (a) in Fig. 5. Moreover the intensity distribution was greater for the longer wavelength. Deformations of the structure by the diffraction, especially side-wall slope, decreases as the width gets broadened (shown in (b) and (c) orderly).

4. RESULTS AND DISCUSSION

4.1 SIMULATION RESULT

The result from computing the equation (2) by analytical software, Mathematica® 5.1 shown in Fig. 6. The figure illustrates the intensity distribution in the upper half of the mask pattern. As a result of the simulation, the intensity distribution profile is shown in Fig.6 by a two-dimensional graphic. The figure confirms that the stronger x-ray intensity is at the corner of the triangular mask pattern (see the enlarge image). Fig. 7 shows a 3D-plot of the image in Fig. 6. The configurations resulted from x-ray lithography are consequence of multi-slit-width and multi-wavelength. These images are used in a static exposure.

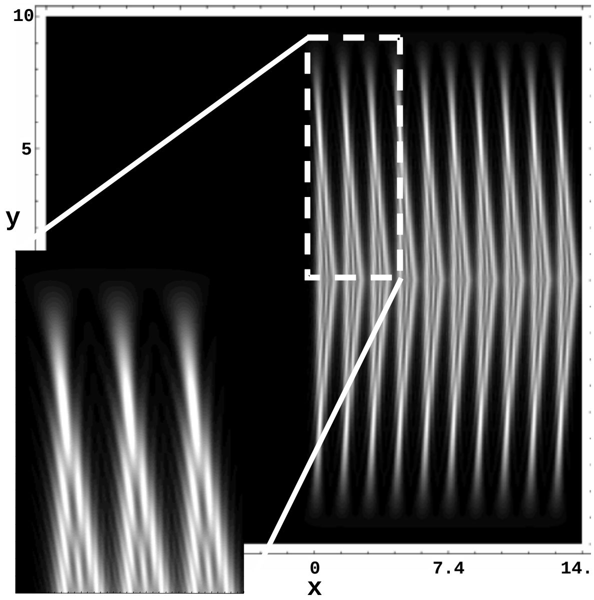


Fig.6 Top view of a simulated intensity distribution during a direct (static) exposure to the mask patterns

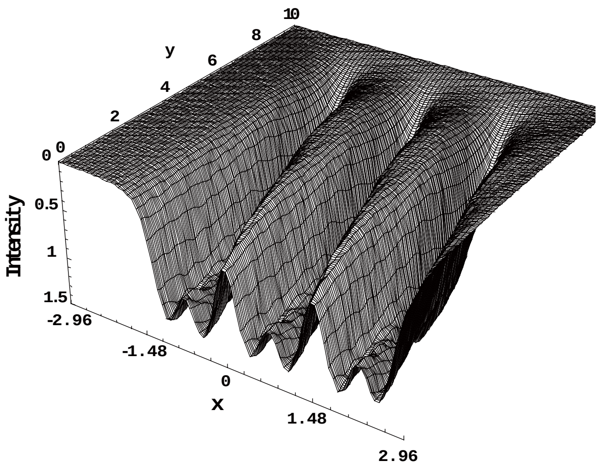


Fig.7 3D-view of the plane pattern intensity distribution from Fig. 6. PCT scanning direction is along y-axis.

Furthermore, the intensity distribution of the PCT technique was simulated. The simulated intensity distribution with proximity gap of 300 μm for PCT is shown in Fig.8. The condition of simulation was arranged from 0.2 nm to 0.7 nm for a dynamic exposure. The result confirms that the intensity was weakened at triangle peak and uplifted at the valley which implies that the exposure contrast has been decreased. In addition, the intensity distribution curve looks like a sine wave which is dissimilar to the ideal line (broken line in Fig.8). The vertical side of the triangles was deformed as a slope.

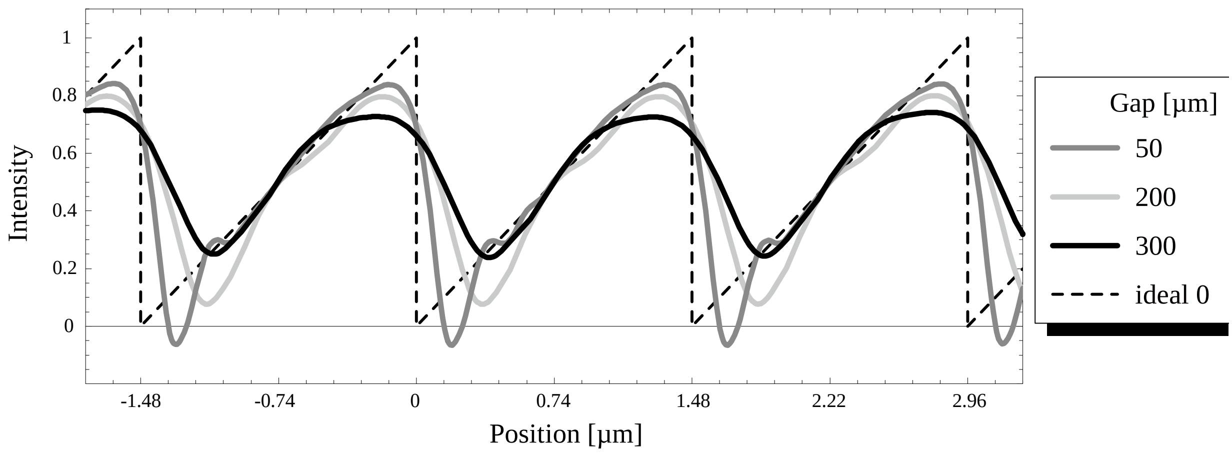


Fig.8 Calculation of X-ray intensity distribution in the resist from multi-wavelength. Data plotted from simulations for structure fabricated by the gaps; 50µm, 100µm, 200µm, 300µm. The broken line is the actual profile of replicated patterns.

4.2EXPERIMENTAL RESULT

With the designed mask, a set of right triangles placed in a double facing row, the experimental result after an exposure by PCT technique is shown as the image taken by a digital microscope in Fig. 9. The black square frame shows the measured area of the pattern height resulted in Fig. 7. The exposed resist can be divided into 2 areas depending on the exposure procedure, direct (static) or PCT (dynamic) exposure. At the turning position where the terminating point of moving stage was approached, the stage was stopped once and changed the movement to the vertically opposite direction, at this point, the mask was directly exposed and the resulting structure was apparently same as the shape of mask-pattern. The position other than ended points of the moving stage was exposed by PCT. The exposed structure looks like a ploughed field as shown in Fig.9 at the area above the direct-exposed area. The cross-sectional profile of the area (a) and (b) are shown in Fig. 10 and Fig. 11, respectively. Moreover, the 3D-view of the (b) area is shown Fig.12.

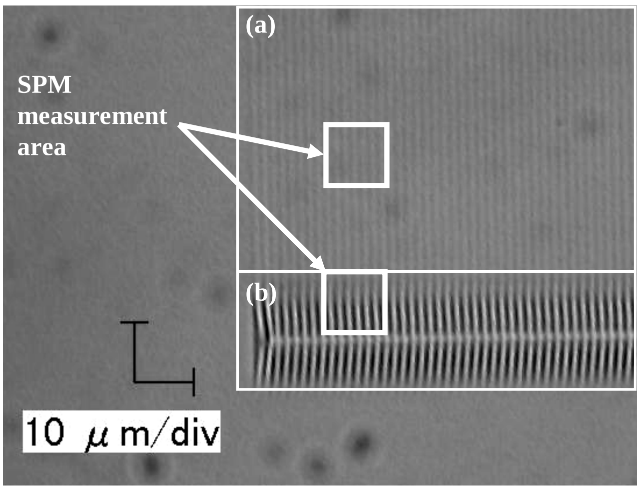


Fig.9 A top-view image of exposed structure, after developed at (a) turning position at the end of moving stage and (b) typical PCT exposed area.

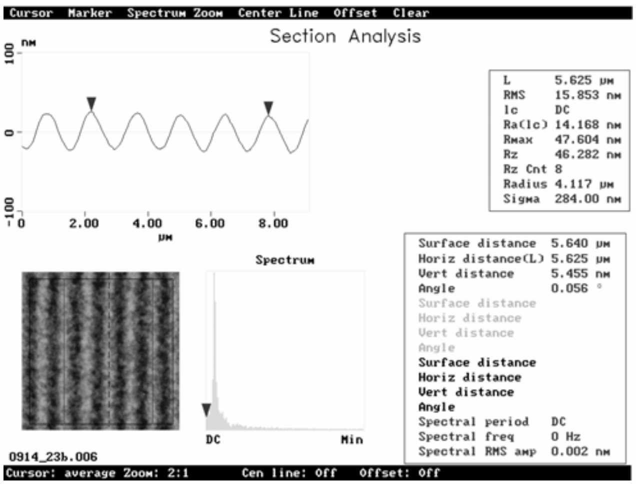
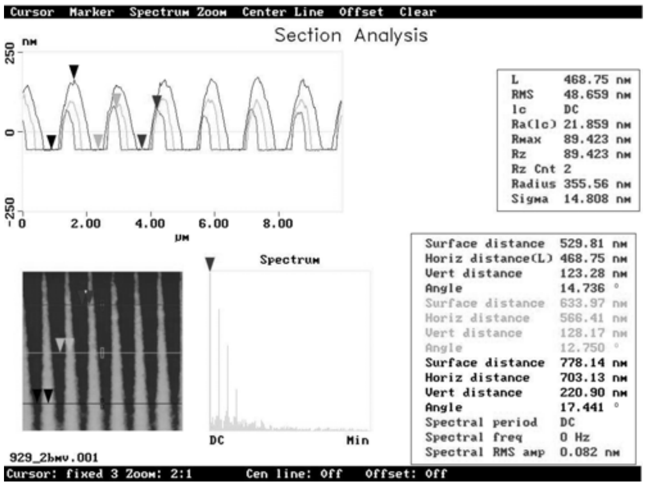


Fig.10 Cross sectional mapping measured by SPM at area (a) in Fig. 9. The height of the structure was 190 nm with dose energy in 0.184 kJ/cm^3.



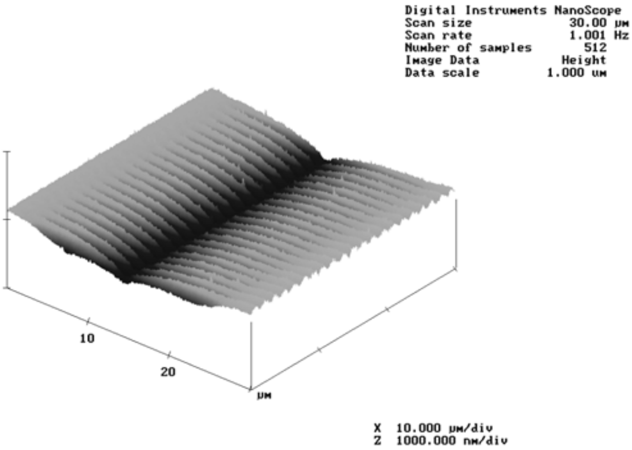


Fig.11 Cross section mapping measured by SPM at (b) area.

Fig.12 3D view measured by SPM at (b) area.

The height of resulting structure exposed by PCT was measured by SPM (Scanning Probe Microscope). The measured height of structure was 84 nm at dosage of 0.118 kJ/cm^3, 112 nm at 0.151 kJ/cm^3, 190 nm at 0.184 kJ/cm^3, by R_z from the measured distance of 5.84 μm. The selected distance for SPM measurement covered 4 triangular patterns. Although the height of patterns is relatively low, the fabricated shape was resulted as expected.
Contrary to the simulation resulted in Fig. 8, the result of PCT (dynamic) exposure, is shown in Fig.12. The intensity distribution at the cross-sectional area in the resist was calculated by integrating intensity distributions as in Fig.8 in the scanning direction (y axis). The fabricated structure has 1.48μm-pitch as similar to that measured on the mask pattern.

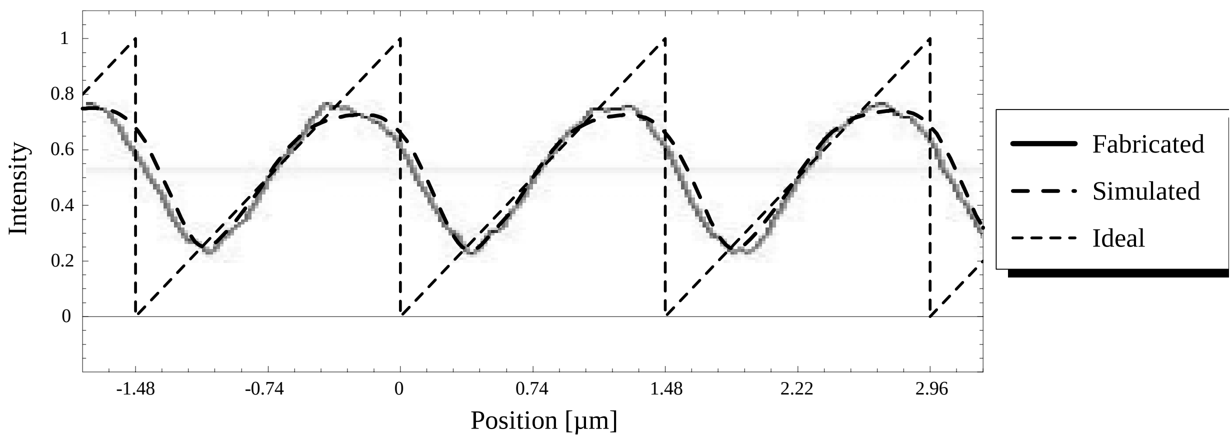


Fig.13 Calculation of the X-ray intensity distribution in the resist compared with the fabrication result.

5. CONCLUSION

In this paper, a set of right-triangular mask-pattern was designed to be exposed and simulated in order to prove that PCT can be employed to fabricate nanosturctures. A simulation of the influence of the Fresnel diffraction in PCT structural was performed. Since PCT has become a useful technique for micro nano-fabrication especially for LIGA users, the study on suitable proximity gap and resolution limit are required. It is necessary to keep a narrow distance between the mask and resist in order protecting the mask surface from scratching by the moving resist. However, a wide proximity gap reduces the contrast of the light and causes the strange form of the structures by the shadows from the edge of each mask pattern. The system installed at the exposure chamber 13 of AURORA at Ritsumeikan University was designed to hold a gap between mask and resist which is not zero. We therefore simulated the system based on a proximity gap as small as possible. The study mainly provides the comprehension of a dynamic exposure (or PCT) with diffraction effect as the novel study where so far, only the static exposure (no movable part included, e.g. motorized stages) has already been studied by many institutions widely. The submicron structure was able to be fabricated by PCT with the optimized proximity gap of 300 µm. Exposure by PCT technique was performed and structure was fabricated, that structure has 190 nm in height by exposing 1.84kJ/cm^3 dose energy. The comparison between the experimental result and simulation confirms that the submicron structure fabricated by PCT is possible with the defined proximity gap. However, it is confirmed that the cross-sectional shape of fabricated structure was a little different from the plane shape on the mask. Evidently, it is because of the Fresnel diffraction effect.

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