EUV Interference Lithography for 22 nm Node and Below

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Extreme ultraviolet interference lithographic exposure tool was installed at the long undulator beamline in NewSUBARU for the resist evaluation in 25 nm node and below. It was confirmed that the spatial coherence length is 1.1 mm using a 10-μm-wide slit in the Young’s double slit experiment. The transmission grating was the key component to decide the resist pattern size and contrast for EUVIL. To obtain the high contrast of the interference fringes of the two window transmission grating on the wafer, the transmission grating was designed. The window size of the transmission grating optimized to be 300×30 μm² in size to avoid Fresnel diffraction which reduces the contrast of the interference fringes on the wafer. In addition, to obtain highest diffraction efficiency, TaN employed as the absorber material, and the thickness of the absorber was optimized to be 70 nm. Furthermore “Center stop” layer was design to reduce the transmitted light from the region between two diffraction grating windows to obtain high contrast of the interference fringes on the wafer. A 25-nm half pitch (hp) resist pattern was successfully replicated by extreme ultraviolet interference lithography (EUV-IL) utilizing a two-window transmission grating pattern of a 50-nm line and space (L/S). As results, the transmission grating design can be applied for the resist patterning of 25 nm and below in EUV-IL.

Keywords: resist, EUV, interference, transmission grating, Fresnel diffraction

1. Introduction

Extreme ultraviolet lithography (EUVL) is the most promising technology for a 32-nm half-pitch (hp) around 2013. According to the ITRS roadmap, EUVL is strongly predicted to be expanded to the 20-nm node by the year 2017 and to the 11-nm node by the year 2022. For the 20-nm node and the 11-nm node, the requirements of line width roughness (LWR) are 1.3 nm (3σ) and 0.8 nm (3σ), respectively. Because the required size of LWR is smaller than the molecular size of a resist, satisfying the LWR criterion is not easy. Thus, because the development of resist material should be started earlier than the development of the EUV exposure alpha tool, extreme ultraviolet interference lithography (EUV-IL) should be recognized as an important part in the evaluation of resist materials at 25-nm and smaller.

The EUVL interference exposure tool was installed at the BL-9 long undulator beamline in the NewSUBARU synchrotron radiation facility.

The transmission grating is a key component to produce the interference fringes to replicate the resist pattern on a wafer in extreme ultraviolet interference lithography (EUV-IL). In addition, since long spatial coherence length is required in EUV-IL, to achieve a practical distance between the transmission grating and the wafer, the coherence length measurement is reported in this paper. Furthermore, considering the influence of Fresnel diffraction arising from the diffraction window area of the transmission grating, the window size of the transmission grating was optimized by a calculation of the influence of Fresnel diffraction. Furthermore, to obtain the high diffraction efficiency, the material, the grating absorber thickness, and the pattern...
width of the absorber of the transmission grating were optimized by calculating the diffraction efficiency.

This paper focused on the coherence length measurement, the design of the transmission grating, and the exposure experiment in EUV-IL.

2. Beamline Setup for EUV-IL in NewSUBARU

EUV-IL was constructed at the BL9 long undulator (LU) beamline in NewSUBARU. An LU source spectrum with the peak at a specific wavelength can be obtained by tuning the gap between the magnets of the undulator. Figure 1 shows the light spectrum used in this experiment. Because the long undulator in NewSUBARU has a total length of 10.8 m and has 200 periods for high-brilliance radiation, the brilliance of EUV light with the undulator as a source is approximately 50,000 times higher than that with a bending magnet as a source. To achieve a 20-nm line and space (L/S) pattern and smaller on a wafer by EUV-IL, the spatial coherence length can increase by enlarging the distance between the pinhole and the transmission grating. Thus, a long spatial coherence length and a low exposure time can be realized simultaneously by increasing the light intensity employing the long undulator.

![Figure 1. Spectrum of long undulator at the BL9 beamline used for EUV-IL.](image)

As described in §4, a spatial coherence length of more than 1 mm can be achieved. The EUV light was focused on a pinhole using an optical component. At the pinhole position, the beam is focused to a size of 10 μm. Because the distance from the pinhole to the resist is maintained at approximately 3.3 m and the high wavelength range beyond 20 nm is removed by a 0.2-μm-thick zirconium (Zr) filter, the light is monochromated with a wavelength of 13.4 nm on the resist sample.

3. Principle of EUV

Figure 2 shows the principle of EUV-IL. In the dual beam interference system, double periodic interference fringes are created at a cross position of two rays which consists of the +1st order ray diffracted from one diffraction window and -1st order ray diffracted from another window of the transmission grating. The diffraction condition of the grating can be expressed as

\[ m\lambda = d(\sin \theta_f - \sin \theta_i) \]

where \( m, d, \theta_f, \) and \( \theta_i \) are the number of the diffraction order, the pitch size of the diffraction grating absorber pattern, the angle of the diffracted light, and the angle of the incident light, respectively. The optical path difference \( \Delta \) is expressed as

\[ \Delta = p\sin \theta_f \]

where \( p \) is the pitch of the replicated resist pattern which is a same size between the constructive interference position and the next constructive interference position of the interferences fringes on the wafer. In addition, since the phase direction of the travelling wave of +1st and -1st order rays are opposite, the phase difference between the constructive interference position and the next constructive interference position is \( \lambda / 2 (= \Delta) \). Thus the pitch size of interference fringes \( p \) can be expressed as

\[ p = \lambda / (2\sin \theta_f) \]

Considering normal incident light, the incident light angle may be expressed as \( \theta_i = 0 \). Then the pitch size of interference fringes \( p \) can be expressed as \( p = d / 2 \). Thus the half-size of the grating pattern pitch size can be replicated on a wafer. In EUV-IL the distance between the two windows should be smaller than the coherence length. In addition, if the grating pitch pattern \( d \) becomes smaller, the diffraction angle \( \theta_f \) of the +1st and -1st diffraction orders becomes larger. If the distance between two windows of a transmission grating is constant, the distance
between the grating and the wafer becomes smaller. Thus, the long coherence length may relax the distance between the grating and the wafer.

Contrast = \( \exp\left(-d_s^2 / 2R_s^2\right) \), where \( R_s (= 2 \times l_c) \), \( l_c \), and \( d_s \) are the coherence radius, the spatial coherence length at the double slit position, and the double slit separation, respectively. The spatial coherence length is defined for the condition where contrast = 0.88. Furthermore, the measured value of contrast is expressed as\( \frac{(I_{\text{max}} - I_{\text{min}})}{(I_{\text{max}} + I_{\text{min}})} \), where \( I_{\text{min}} \) and \( I_{\text{max}} \) are the minimum photodiode current and the maximum photodiode current, respectively. When the distance between the single slit and the double slit and the distance between the double slit and the photodiode are taken into account, the spatial coherence length \( (L_c) \) at the grating position is expressed as \( L_c = 2.4 \times l_c / 0.9 \).

Figure 4 shows the results of the spatial coherence length measurement. The vertical axis is normalized contrast, and the horizontal axis is the double slit separation. Using 25-µm and 10-µm single slits, the spatial coherence lengths \( (l_c) \) at the double slit position were 204 and 440 µm, respectively. Thus, it was confirmed that spatial coherence length \( (L_c) \) using a 25-µm slit and a 10-µm slit was 544 and 1173 µm at the transmission grating position, respectively. As a result, a large spatial coherence length was achieved for replicating a 20-nm L/S pattern and smaller.

4. Spatial Coherence Measurement

The spatial coherence of the light source can be determined by Young’s double slit experiment. Figure 3 shows the experimental setup for the spatial coherence length measurement. The distance between the single slit and the double slit was 0.9 m, and the distance between the double slit and the photodiode installed in the exposure chamber was 2.4 m. The light intensity was measured by changing the photodiode position in the vertical direction. Two single slits of 3 mm (horizontal) × 25 µm (vertical) in size and 3 mm (h) × 10 µm (v) in size were prepared. The size of each slit in the double slit was 3 mm (h) × 25 µm (v). Four double slits with separations of 40, 160, 320, and 640 µm were prepared for Young’s double slit experiment.

The spatial coherence length was calculated by the following method. The contrast of the spatial coherence length is expressed as

![Figure 2. The principle of EUVIL](image)

![Figure 3. Experimental setup for the spatial coherence length measurement](image)

![Figure 4. Results of spatial coherence length measurement](image)

5. The Design of the Transmission Grating

The configuration of the transmission grating
shows in Fig. 5. The transmission grating is the key component for the EUVIL. Since it is impossible to replicate the resist if the contrast of the interference fringes on the wafer is low, it is necessary to design a transmission grating to produce high contrast of the interference fringes. There are two factors to decrease the resist pattern contrast. One is Fresnel diffraction from the window of the transmission grating, and another is the optimization of the absorber materials to obtain high diffraction efficiency.

Fresnel diffraction was determined by the size of the window and the distance between the transmission grating and the wafer. The intensity distribution of Fresnel diffraction was calculated by the in-house software developed using software-development code Maxima. In this calculation the distance between the transmission grating and the wafer was set to 1.0 mm which is a suitable distance to be realized in the EUV-IL exposure tool. The suitable condition of the diffraction grating window size to reduce Fresnel diffraction was calculated.

In addition, it is necessary to improve the diffraction efficiency of the absorption pattern for the improvement of the contrast of the resist pattern. The absorber material and its thickness were optimized to obtain the high diffraction efficiency. Furthermore, to avoid the transmitted light between two diffraction grating windows of the transmission grating, the resist film should employed as a “Center stop” and the resist thickness was optimized by the transmission calculation.

5-1. Optimization of the diffraction window size of the transmission grating

Since Fresnel diffraction reduces the contrast of the interference fringes on a wafer, Fresnel diffraction should be avoided.

The Fresnel diffraction intensity could be calculated by the following equation such as,

\[
I(x, y) = \frac{I_0}{4} \left[ \left| C(u_2) - C(u_1) \right|^2 + \left| S(u_2) - S(u_1) \right|^2 \right] \\
\times \left[ \left| C(v_2) - C(v_1) \right|^2 + \left| S(v_2) - S(v_1) \right|^2 \right],
\]

where \( C(w) \) and \( S(w) = \int_0^w \sin(\pi w'^2 / 2)dw' \) are the Fresnel integral, which are expressed as,

\[
C(w) = \int_0^w \cos(\pi w'^2 / 2)dw' \quad (2)
\]

and

\[
S(w) = \int_0^w \sin(\pi w'^2 / 2)dw' \quad (3)
\]

In horizontal direction on the transmission grating, the integral regions from \( u_1 \) to \( u_2 \) could be expressed as,

\[
u_1 = -\sqrt{2} \times \left( \sqrt{N_x + \frac{x}{\sqrt{\lambda D}}} \right), \quad (4)
\]

\[
u_2 = \sqrt{2} \times \left( \sqrt{N_x - \frac{x}{\sqrt{\lambda D}}} \right), \quad (5)
\]

and

\[
N_x = \frac{m}{4\lambda D}, \quad (6)
\]

where \( \lambda \), \( m \), \( D \), \( N_x \) are a exposure wavelength, the diffraction window width in horizontal direction of the transmission grating, the distance between the transmission grating and the wafer, and the Fresnel number in horizontal direction, respectively.

In horizontal direction on the transmission
grating, the integral regions from \( v_1 \) to \( v_2 \) could be expressed as,

\[
v_1 = - \sqrt{2} \times \left( \sqrt{N_y} + \frac{y}{\sqrt{\lambda D}} \right), \quad (7)
\]

\[
v_2 = \sqrt{2} \times \left( \sqrt{N_y} - \frac{y}{\sqrt{\lambda D}} \right), \quad (8)
\]

and

\[
N_y = \frac{n}{4\lambda D}, \quad (9)
\]

where \( \lambda \), \( n \), \( D \), \( N_y \) are a exposure wavelength, the diffraction window length in vertical direction of the transmission grating, the distance between the transmission grating and the wafer, and the Fresnel number in vertical direction, respectively.

Since Fresnel diffraction reduced the contrast of the interference fringes on a wafer, the resist pattern could not replicated on the wafer. Thus Fresnel diffraction should be avoid by optimizing the window size. For example, as shown in Fig. 6, since Fresnel diffraction was remarkably appeared and it has a good agreement with the calculated Fresnel diffraction intensity distribution when the diffraction window size of 30 \( \mu \)m and the distance between the transmission grating and the wafer was 1.0 mm, resist pattern could not replicated by the affect of Fresnel diffraction.

The diffraction intensity \( I(x, y) \) was calculated with changing variables of the width \( m \) and the length \( n \) of the each direction of the transmission grating window, and the distance \( D \), in the case of the wavelength \( \lambda \) of 13.5 nm. Figure 7 shows Fresnel diffraction calculated for the diffraction window grating widow size of 30 \( \times \) 30 \( \mu \)m\(^2\) for the three cases of the distance \( D \). It was confirmed that the intensity distribution of the diffraction was improved by shortening the distance \( D \). However, the affect of Fresnel diffraction could not reduce even if the distance \( D \) is 0.1 mm.

Figure 6. The SEM image of the exposure area and the intensity distribution of Fresnel diffraction

Figure 8 shows the calculation result of the Fresnel diffraction intensity by changing the diffraction window length \( n \) of the transmission grating window. It was confirmed that the intensity distribution of Fresnel diffraction was improved when the diffraction window length of the transmission grating is enlarged. And to avoid the affect of Fresnel diffraction, and it was considered that the diffraction window length \( n \) of the transmission grating should require more than 300 \( \mu \)m when the distance \( D \) is set to 1.0 mm.

Figure 7. The calculation result of the diffraction intensity by changing the distance \( D \) of the transmission grating and the wafer in the case of the diffraction
5-2. Transmission and diffraction efficiency

The optical contrast of the interference fringes is decided in the light intensity of $I_1$ and $I_2$ as shown in Fig. 5. optical contrast was also calculated. The optical contrast was expressed as,

$$\text{Contrast} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{(\sqrt{I_1} + \sqrt{I_2})^2}{2I_1 + (\sqrt{I_2} + I_2)^2}$$

where $I_1$ and $I_2$ were the transmission intensity between two diffraction grating windows and the intensities of the 1st and -1st order diffraction lights, respectively.

The optical contrast decreases when the light intensity $I_1$ transmitted between two diffraction grating windows is high, or the intensities $I_2$ of the $+1$st and $-1$st diffracted order lights are low. Thus the transmission and the diffraction efficiency of some absorber materials at the wavelength of 13.5 nm were calculated for the absorber material selection and to optimize the absorber thickness.

Figure 9 shows the transmittance curve with varied thickness for the materials such as TaN, Cr, Si, Si$_3$N$_4$, Au, Mo, and Ru, which are the absorber material candidates. Since the intensity $I_1$ should be small value to achieve a high contrast in eq. (10), the Mo, Ru, Si$_3$N$_4$, and Si materials are unsuitable to employ as the absorber.

Figure 10 shows the diffraction efficiency curve with varied thickness for the absorber materials such as TaN, Cr, and Au at the wave length of 13.5 nm. There is little difference in the diffraction efficiency of Au, Cr, and TaN. It is thought that TaN is suitable absorber material, when considering the workability of the dry etching, the stress controllability of these materials, and the small grain size. As shown in Fig. 10, the highest diffraction efficiency can be achieved when the thickness of TaN is 70 nm.

Figure 11 shows the light contrast with varied thickness calculated by eq. (10). It is confirmed that the contrast becomes higher as the TaN thickness becomes thicker. However, it is thought that thick absorber like 150 nm is unsuitable, considering the fabrication process of the transmission grating such as workability of the dry etching process.

Furthermore, to reduce the transmitted intensity $I_1$ when employing a 70-nm-thick TaN as a absorber, the absorber area between the two diffraction windows should be covered with the resist which has a thickness of 1 $\mu$m, so called “Center stop”. When considering the design of the “Center stop”, a 70-nm-thick TaN can be employed as an absorber for the transmission grating which can achieve the high diffraction efficiency and the high contrast between $I_1$ and $I_2$.

Figure 9. The transmittance curve with changing thickness of each absorption pattern materials
Figure 10. The diffraction efficiency curve with changing thickness of each absorption pattern materials

Figure 11. The contrast curve with changing thickness of TaN

6. Resist Patterning by EUV-IL

A 25-nm hp resist pattern was replicated by EUV-IL using the 100-nm-pitch transmission grating. A wafer stage and a grating stage were installed in the EUV-IL exposure chamber. The wafer stage consists of x-, y-, and z-stages and a tilt stage. The grating stage consists of x- and y-stages and a tilt stage. Using these stages, the light axis was adjusted. A nonchemically amplified resist ZEP520A was spin-coated on a 4-in. wafer. The resist thickness was 50 nm, and the prebake was carried out at 180 °C for 180 s. The exposure conditions were as follows: using a 25-µm (vertical) slit, the distance between the wafer and the transmission grating was 250 µm, the current was 560 nA after the transmission grating, and the exposure time was 12 s. Development was carried out at 23 °C for 90 s with o-xylene, and the wafer was rinsed at 23 °C for 30 s with isopropyl alcohol.

Figure 12 shows a photograph of a replicated ZEP520A resist pattern of a 34-nm line and a 16-nm space (25-nm hp) pattern observed using a critical dimension scanning microscope (CD-SEM; Hitachi S8840). In the near future, various types of chemically amplified resist will be evaluated. In addition, in future studies, we will approach replicating 20-nm hp resist patterns and smaller.

Figure 12. SEM image of replicated ZEP520A resist pattern of a 25-nm hp

7. Conclusions

Extreme ultraviolet interference lithographic exposure tool was installed at the long undulator beamline in NewSUBARU for the resist evaluation in 25 nm node and below. It was confirmed that the spatial coherence length is 1.1 mm using a 10-µm-wide slit in the Young’s double slit experiment. The transmission grating was the key component to decide the resist pattern size and contrast for EUVIL. To obtain the high contrast of the interference fringes of the two window transmission grating on the wafer, the transmission grating was designed. The window size of the transmission grating optimized to be 300 × 300 µm² in size to avoid Fresnel diffraction which reduces the contrast of the interference fringes on the wafer. In addition to obtain highest diffraction efficiency, TaN employed as the absorber material, and the thickness of the absorber was optimized to be 70 nm. Furthermore “Center stop” layer was design to reduce the transmitted light from the region between two diffraction grating windows to obtain high contrast of the interference fringes on the wafer. A 25-nm half pitch (hp) resist pattern was
successfully replicated by extreme ultraviolet interference lithography (EUV-IL) utilizing a two-window transmission grating pattern of a 50-nm line and space (L/S). As results, the transmission grating design can be applied for the resist patterning of 25 nm and below in EUV-IL. In future studies, we will approach replicating 20-nm hp resist patterns and smaller.

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References

2) ITRS Roadmap [http://www.itrs.net/].
20) http://www-cxro.lbl.gov/