1. Introduction

Extreme ultraviolet lithography (EUVL) was started to use for the production of 7-nm node-logic-semiconductor devices in 2019. And it was adapted to use for high volume manufacturing (HVM) of 5-nm logic devices in 2020. EUVL is required to be extended to use in 1.5-nm-node-device fabrications. However, it still has many technical issues. Especially, for EUV resists, simultaneous achievement of high sensitivity and low line edge width are required. To solve the EUV resist issue, the fundamental work using synchrotron in soft X-ray region is necessary. The fundamental evaluation study of EUV resist at NewSUBARU synchrotron light facility is described in this paper.

1.1 EUV Resist

EUV resist development is significant, since the wavelength of EUV light and EUV photon energy is 13.5 nm and 91.8 eV, respectively, secondary electron ionization reaction occurs by the high energy electron region. To clarify the reaction by low energy region, it is necessary to use the fundamental evaluation using synchrotron radiation in soft X-ray region.

1.2 Line Edge Roughness (LWR)

To achieve the low LWR resist, the fundamental study of the origin of LWR is necessary. In this study, it is also necessary to use the fundamental evaluation using synchrotron radiation in soft X-ray region as describe later.
BL10 of NewSUBARU as shown in Fig. 1. We have the EUV flood exposure tool for the resist sensitivity evaluation by the actual EUV light spectrum, interference lithographic exposure tool for the patterning 10 nm and below, outgassing and contamination growth evaluation tools by ellipsometry, and chemical reaction analysis by the soft X-ray spectroscopy (XAS). In addition, recently it is prepared additional tools for the fundamental studies of EUV resists. This paper focuses that 1) resist-film layer analysis by the resonant soft X-ray reflectivity method in soft-X-ray energy region, 2) stochastic origin analysis in EUV resist by resonant soft X-ray scattering to achieve low LWR, 3) out of band systematic analysis, and 4) preparation of the photo-electron emission microscopy for the chemical content spatial distribution analysis.

2. Layer Analysis by the Resonant Soft X-ray Reflectivity Method in soft-X-ray Energy Region

For the layer analysis [3, 4] of the single layer resist material which has a thickness of 20 – 50 nm, the resonant soft X-ray reflectivity (RSoXRP) method in soft-X-ray energy region is a powerful method for the chemical layer analysis of the resist film [5]. This method is the hybrid method using soft X-ray absorption spectroscopy [6, 7] and soft X-ray reflectance measurement. By the soft X-ray absorption spectroscopy, the incident energy of the photon is selected for the soft X-ray reflectance measurement to evaluate refractive index of \( n \) and \( k \) values, and thickness of a resist film coated on a wafer. The examples of the measured reflective fringe and fitting results are shown in Fig. 2. The reflectivity fringe spectrum can be fit by \( n \) and \( k \) values, and thickness of the layers.

The commercial chemical amplified (CA) resist was employed for the layer analysis. The resist was spin-coated on a 4 inches silicon wafer to have 26-nm thick. Then the layer analysis was carried out. As a result, the fitting result is shown in Table 1. Even if the CA resist for a single layer process, the thin resist film consists of three layers. The bottom, main body, and top layers have the thickness of 4.5 nm, 14.1 nm, and 7.4 nm, respectively. And these layers have the complex refractive index of \( k \) value of 0.0007, 0.0003, and 0.0004, respectively. The bottom layer between the main body layer might be a pattern collapse region.

![Fig. 1. EUVL R&D at NewSUBARU.](image)

![Fig. 2. Fitting result of the reflectance fringe.](image)

### Table 1. Result of fitting

| Layer names | Thickness (nm) | \( n \)   | \( k \)   | Roughness (nm) |
|------------|---------------|----------|----------|---------------|
| Top        | 7.4           | 0.9996   | 0.0004   | 0.22          |
| Main body  | 14.1          | 0.9996   | 0.0003   | 3.51          |
| Bottom     | 4.5           | 0.9999   | 0.0007   | 4.83          |
| SiO2       | 0.8           | 0.9946   | 0.0018   | 0.1           |
| Si wafer   | --            | 0.9951   | 0.0028   | --            |

3. Stochastic Origin Analysis in EUV Resist by Resonant Soft X-ray Scattering

The low LWR is necessary to maintain the electronic characteristics of semiconductor device, such as logic and memory devices.

The origin of the LWR might be 1) spatial distribution of functional material in resist functional groups, photosensitizers (acid generators), additives such as amines, and so on, 2) spatial distribution of free volume caused by the solvent distribution in prebake process, 3) EUV
photon shot noise, 4) secondary electron blur, 5) solvent effect in PEB process acid diffusion, 6) spatial distribution of developer penetration and development process yield caused by developer and rinse effects, and 7) out of band (OoB) light effect.

In order to reduce LWR of the resist pattern, the controls of the above stochastics are significant. In the above list, in order to control the chemical reaction fluctuation within the nanometer dimensions, the special distribution control of the chemical contents is very significant. However, up to now the measurement of the chemical-contents distribution has not been carried out. Thus, the method of resonant soft X-ray scattering (RSoXS) is used for the measurement. This method is the hybrid method using soft X-ray absorption spectroscopy [6, 7] and soft X-ray scattering as shown in Fig. 3. The scattering vector is defined by the following equation.

\[ q = |\vec{q}| = \frac{4\pi}{\lambda} \sin \frac{\theta}{2} \]  

(1)

By the soft X-ray absorption spectroscopy, the incident energy of the photon is selected for the soft X-ray scattering to obtain the selected chemical-bonding diffraction image. The RSoXS system at BL-10 beamline of NewSUBARU was used for this experiment [8, 9]. This beamline provides monochromatized energy of the soft X-ray region from 80 to 1000 eV [10].

The scattering vector profiles of PMMA and CA resist are shown in Fig. 4 (a) and 4(b). The Scattering vectors of 0.05 and 0.1 correspond to the structure size of 120 nm and 60 nm, respectively. As the results, the spatial distributions between the \( \pi^* \) bonding and acrylate group are very similar in PMMA. However, these are quite different in CA resist. Generally, since the LWR of PMMA is smaller than that of CA resist, the results of the scattering vector profiles are consistent to the LWR tendency [11].

4. Out of Band Systematic Analysis

If the resist exposed by the light which includes the out of band (OoB) light containing the deep UV wavelength region, the OoB lights affects to the LWR of the resist pattern. Thus, reflectance measurement of the mask materials such as Mo/Si multilayer, absorber, and black border (mask substrate surface). Figure 5 shows the beamline setup of the exposure tool and reflectometer by the EUV and OoB lights at BL03A beamline of NewSUBARU. The monochromator setups to enable the EUV at the wavelength of 10 - 80 nm and OoB light at the wavelength of 100 – 200 nm are shown in Fig. 6(a). and Fig. 6(b), respectively. And LiF filter with a thickness of 1 mm were used to cut
the high order lights which is shorter than the wavelength of 100 nm. The reflectance measurement results of the mask materials such as Mo/Si multilayer, absorber, and black border (mask substrate surface) are shown in Fig. 7. The reflectance spectrum of the Mo/Si multilayer was measured completely in the EUV region including high order lights. In the OoB region, the reflectance of Mo/Si multilayer, TaN absorber, and mask substrate as a black border has approximately 30% in maximum. Even if the black border, it has the reflectance of 30%, and the reflectance reduction method should be required.

As described in section 3 of RSoXS is one of the methods to observe the chemical-content distribution. However, since the scattering method is used, the averaged distribution is obtained. Instead of this method, we introduce the photo-electron emission microscopy (PEEM) to observe the real chemical content distribution not an averaged one of resist film.

The PEEM system is going to installed at the BL09A beamline of NewSUBARU. The 3D design and the photography are shown in Fig.s 8 and 9, respectively. The PEEM system consists of load lock chamber to exchange a sample, sample processing chamber adapted the ion beam cluster and sample heating device, and the sample observation chamber adapted the PEEM device. In order to prevent from the vibration and to achieve high spatial resolution in PEEM, the special mechanism is employed.

NewSUBARU is a middle size synchrotron light facility and soft X-ray synchrotron radiation is generated from the 1.0 GeV electron beam storage ring. The soft X-ray absorption spectroscopy in the soft X-ray region is suitable for the chemical analysis of the light atomic elements such as carbon, nitrogen, oxygen, and fluorine etc. Thus, the PEEM in soft X-ray region can observe the chemical imaging of these atomic elements. Since the penetration depth of the soft X-ray is small enough to observe the surface chemical imaging of the resist film, the cluster ion beam tool is employed for the no damage-surface etching of the resist film and enable the chemical imaging in 3D of the resist film.
uniformity of resist material structure, which can highlight the issues to design the low LWR performance.

The out of band systematic analysis tool was prepared at BL03 beamline. In the OoB region, the reflectance of Mo/Si multilayer, TaN absorber, and mask substrate as a black border has approximately 30% in maximum. Even if the black border, it has the reflectance of 30%. And the reflectance reduction method of the OoB lights should be required for the low LWR achievement of the resist patterning.

In order to achieve low LWR, construction of the photo-electron emission microscopy to analyze the chemical content spatial distribution analysis is in progress.

Construction of new injector for NewSUBARU is in progress toward the NewSUBARU phase II operation to start from April 20, 2021.

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6. New Injector for NewSUBARU

The SPring-8 linear accelerator which had been used as an injection of the electron beam both to SPring-8 and NewSUBARU electron beam storage rings in cooperation of the SPring-8 accelerator team. This linear accelerator was shut down on July 29, 2020. From April to December, the new linear accelerator for NewSUBARU was installed at the beam transportation tunnel. This length of the new linear accelerator has a length of approximately 50-m-long and it is a half-length of the previous one. The new one employed the microwave frequency of approximately 6 GHz (C-band microwave) and it is double frequency of the previous one (S-band microwave) to shortening the length.

The commissioning of NewSUBARU phase II will start from April 20, 2021. After the beamline tuning, user time will be operated at electron beam current of 350 mA in electron energy of 1.0 GeV top-up mode. In addition, 1.5 GeV operation will be started at the same time.

7. Conclusions

The RSoXR method is introduced to evaluate the chemical-layer separation of the CAR, and it is sensitive enough to it. In the single layer resist, the preventing from the pattern collapse at the boundary between the bottom and main body layer might be significant for the fine patterning.

The RSoXS method is introduced to evaluate uniformity of resist material distribution, which can modulate absorption contrast of functional group by changing the incident photon energy around carbon absorption edge. The RSoXS results are clarified the