Development of a high-power EUV irradiation tool in a hydrogen atmosphere

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Extreme ultraviolet (EUV) lithography has recently been utilized as a high-volume manufacturing technology for advanced semiconductors. An EUV mirror can be easily contaminated in the existence of a residual hydrocarbon vapor gas inside an exposure chamber in a vacuum environment, which reduces the reflectance of the Mo/Si multilayer coating. To reduce this carbon contamination, hydrogen gas is introduced at a pressure of a few pascals in the EUV scanner. However, during this process, the multilayer may be damaged by hydrogen. In addition, the multilayer surface can become oxidized by residual water vapor in the vacuum chamber. Therefore, an EUV irradiation tool in hydrogen and water vapor atmospheres was developed and installed at BL-09 of the NewSUBARU synchrotron light facility to evaluate the cleaning effect and irradiation durability of the Mo/Si multilayer. The EUV irradiation intensity increased up to 6 W cm−2, and the hydrogen pressure reached 70 Pa.

1. Introduction

Since 2019, extreme ultraviolet (EUV) lithography has been used in high-volume manufacturing of advanced semiconductors.1,2 The working wavelength of EUV lithography is 13.5 nm, which is near the soft X-ray region.3 As absorption of the material is extremely high in the EUV region, a refractive lens cannot be employed for optics in EUV lithography. Thus, EUV optics are composed of reflective mirrors coated with Mo/Si multilayer. However, the reflectance of a single-layer coating at a normal angle of incidence is very low. For examples, the reflectance of a single-layer mirror of Pt and Ni at a normal angle of incidence is 0.4% and 0.2%, respectively. These metals are typically used as reflective coatings for grazing incidence X-ray optics. On the other hand, the Mo/Si multilayer has a reflectance of over 60% in the EUV region due to constructive interference of each layer.7–11

Residual hydrocarbon gas in a vacuum environment is origin of carbon contamination on the mask and optics, which causes the reflectance drop.12–14 To reduce this contamination, several pascals of hydrogen gas are introduced into the EUV scanner. Dolgov et al. reported the cleaning of carbon contamination by EUV-induced plasma.15,16 In a hydrogen atmosphere, high-power EUV generates EUV-induced hydrogen plasma. However, hydrogen plasma would cause reflectance decrease of the Mo/Si multilayer. Because hydrogen gas has a smallest atomic number, it easily diffuses into the Mo/Si interface in the Mo/Si multilayer film, which causes bubbles to form at the interface. This hydrogen damage is called a “blister”.17 Researchers have just begun analyzing the hydrogen plasma generation mechanism;18,19 the mechanism of contamination cleaning using hydrogen gas and the blistering condition has not been clarified yet. Furthermore, the surface of the Mo/Si multilayer can be oxidized by residual water vapor in a vacuum chamber.20 These reductions in the reflectance will worsen the throughput of the scanner.

Therefore, an EUV irradiation tool with a hydrogen and water vapor atmosphere is required to evaluate the blister and oxidation damage of the multilayer. Currently, the power of the EUV source is 250 W at the intermediate focus position, and the expected EUV power on the mask is 5 W cm−2.17 Thus, we developed a high-power EUV irradiation tool to evaluate the damage of the Mo/Si multilayer in a hydrogen and water vapor atmosphere at the BL-09 long-undulator beamline11 of the NewSUBARU synchrotron light facility.

2. Experimental methods

Figure 1 shows a schematic drawing of the BL-09C end station, which is located downstream of the M8 mirror. A high-power-EUV irradiation tool was developed in an atmosphere of hydrogen gas and water vapor and was called “H2-exp tool.” The H2-exp tool was installed 1050-mm upstream of the resist-outgas measurement chamber.22–28 The EUV light in the horizontal and vertical directions was focused on the sample position of the H2-exp tool using spherical concave beamline mirrors, which were positioned upstream of M8 mirror. The M8 mirror shown in Fig. 1 is a flat mirror that changes the position of the beam focusing on the sample. The focused beam size was 2.4 mm and 0.5 mm in the horizontal and vertical directions, respectively. A 10.8 m long-undulator, which can provide a highly brilliant soft X-ray beam, was employed as the light source. This beamline is also used as an EUV interference lithographic tool,20,29 as an interferometer of EUV optics,30 for soft X-ray emission spectroscopy,31 and as a resist-outgassing evaluation tool.22–28 Figure 2 shows the spectrum generated from the 10.8 m long-undulator measured by a soft X-ray photodiode (AXUV100G, Optodiode Inc.). The undulator gap condition was set to 35 mm. This spectrum indicates the 1st-harmonic-order of the light of the undulator. To obtain strong EUV power, we used the 0th-diffraction-order condition of the monochromator. This un-monochromatized specular light had a full width at half maximum (FWHM) bandwidth of 0.6 nm, which is mostly matched with the reflection bandwidth of the Mo/Si multilayer of 0.5 nm (FWHM). Two orifices were installed upstream of the H2-exp tool to allow for the differential exhaust of hydrogen gas as shown in

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The vacuum pressure of the M8 mirror chamber should be maintained at \(10^{-5}\) Pa. By contrast, the hydrogen pressure of the H2-exp tool was several pascals. The orifices were chosen to be 3 mm in diameter to achieve low conductance. Thus, the maximum hydrogen pressure was 5 Pa, which was limited by the vacuum pressure of the M8 mirror chamber. In this study, the orifice condition was used for the irradiation experiments. Recently, we installed an additional orifice and pumping system, which improved the maximum pressure to 70 Pa. This additional orifice is not shown in Fig. 1.

Figures 3 and 4 show the top and side views of the H2-exp tool. Hydrogen gas was introduced using a variable leak valve (59024-GE01, VAT Inc.). Water vapor was also introduced by a variable leak valve (951-7172, ANELVA). This leak valve was attached to the same position of the H2 leak valve, which was not shown in Figs. 3 and 4. Deionized water was filled in a glass tube, which was connected to this leak valve. A capacitor manometer (CMR374, Pfeiffer Inc.) was installed to measure the absolute pressure up to 100 Pa. A quadruple mass spectrometer (M-200QA, Canon Anelva Inc.) was installed to measure the residual gas partial pressure, which can measure the mass number from 1 to 200. Figure 5 shows the results of the quadruple mass spectrometer of the residual gas in the H2-exp tool chamber. The acceleration voltage was set to 1400 V. The chamber vacuum pressure before hydrogen or water vapor introduction was \(6 \times 10^{-6}\) Pa. The majority of residual gas was water.

The EUV photodiode \(PD_{\text{Si/Zr}}\) coated with Si and Zr layers (SXUV-100 Si/Zr, Optodiode Inc.) was used upstream of the orifice to measure the EUV light intensity. A thick coating of Si and Zr was employed to eliminate the visible light component, which has a low EUV transmittance of less than 3%. Because a general CsI scintillator for X-rays is easily degraded by high-power EUV light exposure, a hexagonal boron nitride (hBN) sintered plate was employed as an EUV scintillator. hBN exhibited high durability to EUV light. A visible light camera was used to observe the EUV light. A visible light camera was used to observe the EUV light.
beam shapes on the scintillator. A mechanical shutter (F77-4, Suruga Seiki) was installed to control the irradiation time.

The in situ reflectance of the sample during EUV irradiation was measured using two photodiodes, PD_{DB} and PD_{R}.

The PD_{DB}, which was attached to a beam shutter cylinder, as shown in Fig. 3, can measure the direct-beam (DB) power. The PD_{R} was attached to a rotary arm to measure the reflected (R) beam power. Both PD_{DB} and PD_{R} photodiodes are used for monitoring the EUV power. The EUV scintillator and samples are placed inside the main chamber, which is connected to a load-lock chamber and a transfer rod for sample handling.
are SXUV-100 photodiodes (Optodiode Inc.), which is a standard EUV photodiode with high durability and high quantum efficiency. The photodiode surface was not coated with a thin film. The sample can be loaded into the irradiation chamber from the load-lock chamber using a transfer rod with linear and rotary motions. As this transfer rod is a magnet coupling type, the precision of the linear positions is not sufficiently high. The sample position can be monitored using a visible camera to accurately control the irradiation position, and the sample rotation angle can be adjusted to maximize the reflected-beam power. The maximum sample size was approximately 90 mm in diameter, which was limited by the gate valve size of GV1. Moreover, transmission samples such as EUV pellicles can be measured, where the in situ transmittance can be monitored by two photodiodes. In this study, the sample holder could hold six wafer samples and an hBN scintillator. Each wafer was 7.5 mm × 7.5 mm. The sample holder covered the sample edge area, and the covered area was not irradiated by EUV light.

In Fig. 4, the dashed line indicates the beam shutter cylinder, which has a diameter of 186 mm and a height of 82 mm. The direct-beam photodiode was attached to this cylinder, which had a trimmed entrance aperture (20 mm × 2 mm). The vertical position of the cylinder was controlled using a linear motion manipulator. Figure 6 shows three sites on the cylinder, which indicate the positions for (a) the reflected-beam measurement, (b) the EUV irradiation of the sample, and (c) the direct-beam measurement. At position (a), the reflected light intensity can be measured using the PD_R. At position (b), the incident EUV light can irradiate the sample through the trimmed aperture of the cylinder. Otherwise, as the reflected light is blocked by the sidewall of the cylinder, the reflected light does not irradiate the PD_R. If the reflected light irradiates the PD_R, EUV irradiation can cause contamination and damage the PD_R because of its high EUV power. At position (c), the PD_DB measures the EUV light intensity directly. The three positions were located at (a) 0 mm, (b) 20 mm, and (c) 37 mm of the linear manipulator. All manipulator motions were driven from the outside of the chamber.
vacuum chamber, and no vacuum motors or stages were used inside the vacuum chamber.

The EUV irradiation intensity can be calculated using Eq. (1)

$$I_{\text{EUV}} = \frac{I_{\text{photodiode}}}{p} \times \frac{1}{\alpha \times b} \times \frac{1}{\tau},$$

where $I_{\text{photodiode}}$ is the photodiode current of PDDB; the sensitivity of the photodiode ($p$) is 0.19 A W$^{-1}$ at a wavelength of 13.5 nm; $\alpha$ and $b$ are the beam dimensions in the vertical and horizontal directions, respectively; and $\tau$ is the transmittance of the Si filter utilized for beam attenuation. The measured photodiode current was over 2 mA at the PDDB and PD$_R$ without the silicon attenuation filter. In this region, the photodiode current was not linear to the incident beam intensity. The measured relationship between the photodiode currents of PDDB and PDSiZr is shown in Fig. 7. The current of PDDB is not linear to that of the PDSiZr over the 1.5 mA region of the PDDB. Thus, a Si filter with a transmittance ($\tau$) of approximately 5% was installed to attenuate the beam intensity for photodiode measurements. Using this filter, the PDDB output current can be attenuated to be 0.7 mA, which exhibits a linear relationship with the incident EUV light intensity. The beam size was 0.5 mm (V) $\times$ 2.4 mm (H) on the sample position. Thus, the EUV light intensity on the sample was $\sim$6 W cm$^{-2}$, which depended on the beam condition.

3. Results and discussion

3.1. Irradiation sample and conditions

The irradiation sample was a Mo/Si multilayer coated on a silicon wafer, which had a silicon top layer and no metal capping layer. The sample was cut to a square of 7.5 mm $\times$ 7.5 mm. The period thickness was 6.9 nm. The Mo layer thickness ratio during this period was 0.4. The designed angle of incidence was 6°. Four samples were irradiated with a high-power EUV. The undulator gap was tuned to maximize the reflected EUV power because the irradiation wavelength should match the multilayer reflection wavelength.

Table I shows the experimental conditions of the hydrogen gas and water vapor atmosphere, vacuum pressure, irradiation time, and EUV intensity. Samples #1 and #2 were irradiated in a hydrogen atmosphere of 5 Pa to evaluate the hydrogen damage. Sample #3 was irradiated as the reference condition in vacuum. Sample #4 was irradiated in a water vapor atmosphere of $1 \times 10^{-4}$ Pa.

The in situ reflectance was measured using the H$_2$-exp tool every 30–60 min of irradiation. In this measurement, the EUV intensities were measured using PDDB and PD$_R$ photodiodes with an attenuation Si filter. After the EUV irradiation, the EUV reflectance distribution was measured around the irradiated area using an EUV reflectometer installed at the BL-10 beamline at NewSUBARU. The angle of incidence was 6°, and the measured wavelength was tuned to the peak wavelength of each sample at approximately 13.5 nm. To estimate the carbon contamination and oxidation, the X-ray absorption spectra at the carbon K-edge and oxygen K-edge regions were measured at both the EUV-irradiated and unirradiated positions using the same reflectometer.

3.2. EUV reflectance result

Figure 8(a) shows the in situ reflectance results of the hydrogen atmosphere and the reference conditions for samples #1 to #3. The horizontal and vertical axes show the EUV irradiation dose and the normalized reflectance, respectively. The in situ reflectance was measured using an

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Fig. 7. (Color online) Relationship of photodiode current between PD$_{Si/Zr}$ and PD$_{DB}$. The photodiode signal is not linear to the EUV irradiation intensity over 1.5 mA.
In situ reflectance indicates the averaged reflectance in the irradiation area. The EUV irradiation dose was calculated based on the irradiation time and the EUV intensity [Eq. (1)]. For example, sample #3 was irradiated up to a dose of 130 kJ cm$^{-2}$ for 9 h and 3.1 W cm$^{-2}$. The in situ reflectance of samples #1 and #2 increased by several percentage points. Because the sample was stored in an air atmosphere, the surface was contaminated. This reflectance rise might have been caused by cleaning with high-power EUV irradiation. The in situ reflectance behavior of samples #1 and #3 appeared to be the same, which dropped by 0.5% after an irradiation dose of 40 kJ cm$^{-2}$.

Figure 9(a) shows the reflectance distribution measurement results of samples #1–#3, measured by the EUV reflectometer. The reflectance distributions were measured after the EUV irradiation experiment of Fig. 8. The total irradiation doses of samples #1, #2, and #3 were 80, 40, and 130 kJ cm$^{-2}$, respectively. The horizontal and vertical axes show the vertical position of the sample and the reflectance, respectively. The beam size of the EUV reflectometer was 0.1 mm ($V$) × 0.8 mm ($H$) in FWHM. The sample reflectance measurement direction in the reflectometer was the same as the vertical direction of the sample stage in the H$2$-exp tool. The

| Sample # | Gas    | Pressure (Pa) | Total irradiation time (h) | EUV power (W cm$^{-2}$) |
|----------|--------|---------------|----------------------------|-------------------------|
| 1        | H$_2$  | 5             | 9                          | 2.8                     |
| 2        | H$_2$  | 5             | 3                          | 4.3                     |
| 3        | —      | $8 \times 10^{-6}$ | 9                          | 3.1                     |
| 4        | H$_2$O | $1 \times 10^{-4}$ | 8                          | 3.5                     |

Figure 8. (Color online) In situ reflectance measurement result of (a) the hydrogen, the vacuum and (b) the water vapor conditions.
EUV irradiation center is indicated by an arrow in Fig. 9. The outside position of >2 mm from the center was the un-irradiated position, which was covered by the sample holder. The irradiation centers of samples #1 and #3 had 0.7% and 0.2% lower reflectance than the un-irradiated positions, respectively. In samples #1, #2, and #3, reflectance drops (0.7%) were observed at the edge positions of the EUV irradiation area. However, these centers had almost the same reflectance. There were no differences with and without hydrogen gas.

Figure 8(b) shows the in situ reflectance during the EUV irradiation of samples #3 and #4. Sample #4 was irradiated in a water vapor atmosphere. The in situ reflectance of #4 constantly decreased immediately after irradiation started. The reflectance was 8% lower than the initial value at an irradiation dose of 80 kJ cm$^{-2}$. Figure 9(b) shows the reflectance distribution of samples #3 and #4. The reflectance of the EUV irradiation center of sample #4 was 54%, which was caused by the oxidization of the multilayer. Two (Color online) EUV reflectance distribution measurement results of sample #1–#4. The edge of the EUV irradiation area of sample #1 reduced the reflectance by ∼0.7%.

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**Fig. 9.** (Color online) EUV reflectance distribution measurement results of sample #1–#4. The edge of the EUV irradiation area of sample #1 reduced the reflectance by ∼0.7%.
reflectance drops occurred at the edges of the EUV irradiation area, similar to the other samples. The reflectance at the 1.1–2.2 mm position (58.5%) was also lower than that of the un-irradiated position (3.0 mm, 60%), which indicated that there was weak EUV scattering around the center. This scattering occurred at the orifice. The weak scattering also caused oxidization of the Si layer.

3.3. X-ray absorption spectroscopy (XAS) results

Figure 10(a) shows the XAS results of sample #1 at the carbon K absorption edge of 275–310 eV. The horizontal axis represents the photon energy. The vertical axis represents sample absorption. These spectra were measured using the total electron yield method. A large absorption amount indicates significant carbon existence. The spectra were measured at the EUV-center-irradiated (0 mm), reflectance drop (0.5 mm), and non-irradiated positions (−2.0 mm). The measured positions were determined using the EUV reflectance distribution shown in Fig. 9. Figure 10(b) shows the absorption at 295 eV for the four samples. There was no difference in the contamination among the vacuum and water environments.
hydrogen conditions of samples #1, #2, and #3. The carbon absorption of the un-irradiated position was low, and that of the center and edge positions were high. Notably, the edge position exhibited significant carbon absorption. Thus, the EUV reflectance drop at these positions was due to carbon contamination and not hydrogen damage under 80 kJ cm\(^{-2}\) EUV irradiation. The carbon contamination of sample #4 on the EUV irradiation position was cleaned by oxidization with a water vapor pressure of 1 \(\times\) 10\(^{-4}\) Pa. The residual water vapor pressure of the chamber was approximately 1 \(\times\) 10\(^{-5}\) Pa, as shown in Fig. 5.

Figure 11 shows the XAS results for sample #4 around the oxygen K-edge absorption edge. Absorption at the center position was higher than that at the non-irradiated position. Thus, the EUV irradiation center was oxidized by water, which decreased the EUV reflectance.

4. Conclusions

A EUV irradiation tool in a hydrogen and water vapor atmosphere was developed and installed at the BL-09 long-undulator beamline of the NewSUBARU synchrotron light facility. The EUV intensity increased up to 6 W cm\(^{-2}\), and the hydrogen pressure reached 70 Pa. The EUV irradiation durability of the Mo/Si multilayer under hydrogen gas and water vapor atmospheres was evaluated.

We found that the Mo/Si multilayer without the capping layer was not damaged in a hydrogen atmosphere (5 Pa) up to 80 kJ cm\(^{-2}\) EUV dose. However, carbon contamination was observed on the multilayer surfaces. Thus, no cleaning effect of the hydrogen plasma was observed, and no evidence of hydrogen damage was found in this experiment. The reflectance of the multilayer in the water vapor atmosphere (1 \(\times\) 10\(^{-4}\) Pa) was significantly reduced by oxidation of the Si surface. The Mo/Si multilayer without a capping layer was easily oxidized. Therefore, a capping layer is required to prevent surface oxidation.
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