Homogenized ion milling over the whole area of EUV spherical multilayer mirrors for reflection phase error correction

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Abstract. For accurate reflection phase manipulation of spherical multilayer mirrors used in extreme ultraviolet (EUV) imaging, a wide-area ion beam with a homogenized radial distribution was produced for period-by-period ion milling. Measured variations of the milling depth with incident angle showed that Si and Mo have the same angular dependence within the effective aperture used in our imaging optics. By using the designed homogenizer mask, the ion-milling depth was successfully homogenized to within an error of ±1.9% over a 50-mm-wide concave mirror. Furthermore, a versatile homogenizer mask with adjustable opening angle plates was developed. With this mask, an ion-milling depth-profile homogeneity of ±1.7% was realized. Although a slight decrease in the peak EUV reflectance was measured as the incident angle decreased, the effectiveness and practicality of our correction method has been demonstrated.

1. Introduction
In the extreme ultraviolet (EUV) wavelength region, reflection phase-corrected multilayer mirrors are required for high-definition imaging and nanofocusing. Although various techniques have been developed for the final finishing of substrates [1, 2], a reduction of the figure error to a 0.1-nm level remains difficult to achieve. A possible and practical technique to achieve a precise wavefront based on a physical optics principle has been proposed and consists of a phase-correction method with an accuracy of 0.1 nm achieved by period-by-period milling of the multilayer surface [3]. For the final reflection-wavefront error correction of multilayer mirrors, we developed an ion milling system [4], which affords a stable ion beam over a 100-mm-wide multilayer and can be used for area-selected milling [5, 6].

To demonstrate the reflection phase manipulation of a Mo/Si multilayer, 10 periods of a 40-period Mo/Si multilayer were partially removed, and a partially milled Mo/Si multilayer with a contact double slit was successfully fabricated for interference fringe observations, carried out using a Young’s EUV interferometer in a reflection configuration at BL-12A at the Photon Factory, KEK. The fringe pattern measured at a wavelength of 14.15 nm revealed clearly that the reflection phase change with the removal of 10 periods was smaller than 1 wavelength, as predicted [6]. The EUV interferometry results showed that our proposed method for sub-nanometer digital wavefront error correction in the case of multilayer mirror optics is effective for achieving diffraction-limited imaging.
In this study, the angular dependence of the ion-milling depth using a wide-area ion beam is described for the reflection phase manipulation of spherical mirrors. We also present developments of a homogenizer mask to obtain a uniform ion-milling depth profile over the whole 50-mm-wide area of concave mirrors. Profiles of the homogenized ion-milling depth obtained with the designed mask are then shown. Finally, the EUV reflectance is used to evaluate the Mo/Si multilayer milled at oblique incidence angles of the Ar ion beam.

2. Homogenized milling depth over the whole surface of spherical mirror

2.1. Angular dependences of the ion-milling depth of Si and Mo

For an accurate reflection phase error correction method based a physical optics approach, a period-by-period ion-milling system with an electron cyclotron resonance-type ion gun is used. A large-diameter Ar ion beam is accelerated at 500 V and irradiates the sample through a photoresist contact mask with several apertures that correspond to the correction area. A homogenized milling rate over the whole mirror area rotating at 200 rpm is achieved by a homogenizer mask designed for a uniform radial distribution of the ion dose within the exposure time. The mask is set 18 mm away from the mirror. For accurate 0.1-nm digital correction of the wavefront error, we set a milling-depth homogeneity target of ±2%.

We first attempted to homogenize an originally quadratic profile to achieve a constant milling rate. Using the designed homogenizer mask, the ion-milling depth distribution over a 100-mm-wide area on a Si wafer was successfully homogenized to within an error of ±1.7% [5]. This uniformity can realize the process of 0.1 nm/period correction repeated by 10-times to cover a residual wavefront error of 1 nm. Since the refractive index of Si is much closer to 1 in the EUV wavelength region, the phase shift mainly originates from the Mo layer milling. Using the homogenized ion beam allows the milling process to be finished with a Si layer on the surface over the whole Mo/Si multilayer plane mirror.

In general, the ion-milling rate is dependent on the incident angle of the ion beam [7, 8]. To evaluate the variation in the milling depth, a tilt series was taken using Si pieces and a Mo monolayer on Si pieces. Figure 1 shows the angular dependences of the normalized milling depth of Si and Mo. As the incident angle increases, the Si and Mo milling rates gradually increase and pass through a maximum at an incident angle of around 45°. The rates then fall towards zero as the angle approaches 90°. These measured variations are in good agreement with previous studies [7, 8], and since the angular dependences shown in figure 1 are consistent within the effective aperture of the concave mirror used in our imaging optics, a homogenizer mask of the same shape can be used for both Si and Mo milling.

![Figure 1. Angular dependences of the normalized milling depth of Si (open marks) and Mo (solid marks).](image1)

![Figure 2. Normalized milling depth with plane Si-piece assemblies (solid marks). For reference, the normalized milling depth of a plane Si wafer is indicated by the open marks.](image2)
To realize a constant milling rate on a spherical mirror, the milling rate on a concave substrate with a diameter of 50 mm and a radius of curvature of 65.9 mm was measured using plane Si-piece assemblies. The assemblies were configured with a tangent plane at 6, 9, 12, 15, 18, 21, 24, and 25 mm and form a pseudo-concave shape. Although the optical configuration for the milling depth measurement by X-ray diffractometry is limited by the radius of curvature of the concave substrate, we can measure the milling depth of the assemblies without a concave substrate. Figure 2 shows the normalized milling depth at oblique incident angles with the plane Si-piece assemblies. The original quadratic profile of the normalized milling depth on a Si wafer is shown for reference. A homogeneity of ±5.8% is obtained; however, this is insufficient as ±2% is required for precise wavefront correction.

2.2. Development of homogenizer masks for concave mirrors

Referring to the results in figure 2, a homogenizer mask was designed to control the ion-milling rate by changing the opening angle of the mask $\theta$ according to the distance from the center of the sample and is calculated as follows:

$$f(r) \cdot \theta(r) = \text{constant} \quad (1)$$

where $f$ and $r$ are the profile of ion-milling depth shown in figure 2 and the radius, respectively. The masked area $(x, y)$ can be described by the closing angle $\phi(r) = 2\pi - \theta(r)$ as

$$x = r \cos[\phi(r)/2], \quad (2)$$
$$y = \pm r \sin[\phi(r)/2]. \quad (3)$$

With the one-plate homogenizer mask, a uniform radial distribution was controlled to within an error of ±1.9% as shown in figure 3 (solid marks), meeting our target homogeneity of ±2%. The ion-milling depth profile was measured using plane Si-piece assemblies, and the average milling rate was 9.2 nm/min.

To homogenize the milling depth profile on other materials composed of EUV multilayer mirrors other than Si and Mo with various radii of curvature, a versatile homogenizer mask was developed. The mask is divided into several arc-shaped segments, and $\theta$ can be set by adjusting the fixed points of each segment on the baseplate. A schematic drawing of the general homogenizer mask is shown in figure 4. With the adjustable opening angle plates set to angles between 250.1° and 270.0°, an ion-milling homogeneity of ±1.7% was successfully realized as shown in figure 3. Although the maximum opening angle is limited by the baseplate, the uniform milling rate of 6.2 nm/min for Si is practical enough for repeating the process of 0.1 nm/period period-by-period correction.

![Figure 3](image1.png)

**Figure 3.** Normalized milling depth with a one-plate mask and adjustable opening angle mask (drawn in figure 4).

![Figure 4](image2.png)

**Figure 4.** Schematic drawing of the homogenizer mask with adjustable opening angle segments.
3. EUV reflectance measurements after ion milling at oblique incidence angles
To evaluate the effects of oblique incident-angle ion milling with an Ar ion beam, the EUV reflectance of the milled Mo/Si multilayers were measured at BL-11D at the Photon Factory, KEK. Mo/Si plane multilayers of 70 periods were milled for 20 periods using the homogenizer mask. A theoretical calculation of the reflectance concludes that 50 periods is sufficient to saturate the peak reflectance. The period thickness of the Mo/Si multilayer, measured by X-ray reflectometry, was 6.98 nm. The multilayers were mounted on tilt stages to obtain incident angles of 0°, 5°, 10°, 15°, and 20°.

Figure 5 shows the EUV reflectance of non-milled and milled Mo/Si multilayers for different incident angles. As an incident angle decreases, a gradual decrease in the peak reflectance is also seen; the 10% decrease in the peak reflectance of the milled multilayer set at normal incidence is consistent with our previous experimental results [5]. This decrease can be attributed to the embedding and/or formation of a compound layer with a top layer and sputtered material. Embedding and/or compound layer formation decreases with increases in the sputtering yield shown in figure 1. There was some variation in the peak reflectance of the milled multilayers; however, removal of 20 periods maintained a periodic structure, evidenced by the clear peaks and side band structure produced by constructive interference as shown in figure 5. Although the cause of the decrease in reflectance affects the reflection wavefront, our interferometric observation [6] shows that the influence is negligible due to the small difference in the refractive index in the EUV wavelength region.

Figure 5. EUV reflectance of 50-period Mo/Si multilayer mirrors after removal of 20 periods by oblique ion-beam irradiation.

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