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Development of a period-by-period EUV multilayer milling system for the final nm figure error correction by 0.1 nm per period

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Abstract. A period-by-period ion milling system has been developed for final reflection wavefront error correction of an imaging EUV multilayer mirror by a stepwise 0.1 nm-per-period correction of the residual nm figure errors. For effective, gentle and uniform milling of the surface areas selected by a template, the system is designed with a rotating substrate holder exposed to a 150 mm-wide ion beam with a dose homogenizer mask plate. For demonstration of the wavefront correction principle, local milling of a dielectric multilayer mirror for visible light was carried out by the system. The wavefront as measured by a phase shifting interferometer showed that the reflection phase was “advanced” by the milling, which formed a geometrical depression at the multilayer mirror surface. This confirmed the physical optics principle of our method and proved the procedure of the method being promising and practical for the accurate reflection phase correction of an EUV multilayer mirror.

1. Introduction
In the extreme ultraviolet (EUV) wavelength region, multilayer mirrors are successfully utilized for various normal incidence imaging optics. For diffraction-limit EUV imaging expected by the multilayer mirror optics, the figure error should be smaller than $\lambda/28$, which is in a sub-nm level for the short EUV wavelength $\lambda$ of a few tens nm. Although ion beam figuring (IBF) techniques are recently developed for finishing the substrates [1-3], the figure error of a 0.1 nm level is still difficult to correct. As a possible solution, we proposed a phase correction method by period-by-period milling of the multilayer mirror surface [4] based on a physical optics principle. Theoretical calculation shows that 1-period removal should compensate a reflection phase error of $6^\circ$, which corresponds to the substrate figure error of 0.1 nm.

In this manuscript, a new ion milling system developed for the physical optics phase correction of EUV multilayer mirrors is described briefly. Then, we present an experimental proof of the phase correction principle at a visible wavelength of 633 nm with a dielectric multilayer mirror sample.

2. The period-by-period ion milling system for physical optics phase error correction
For accurate reflection phase error correction based on a physical optics principle, we have developed a period-by-period milling system with an electron cyclotron resonance (ECR) type ion gun enabling...
effective, gentle and uniform milling of EUV multilayer mirrors [5]. Photograph of the ion milling
system and a cut-off view of the milling process chamber are shown in Fig. 1.

An Ar ion beam of a 150 mm in diameter accelerated at a low 500 V for minimal surface
roughening is irradiated through a template having openings for the area of milling. The templates are
prepared with the opening patterns for every 0.1 nm contour mapping of the figure errors as measured
by our EUV interferometer with a laser produced plasma light source [6]. A multilayer mirror up to
φ100 mm, together with the template, is mounted on a rotating holder facing to the ion beam.

A constant milling rate over the whole area of a mirror rotating at 200 rpm is realized by a
homogenizer mask plate designed for uniform radial distribution of the ion dose within the exposure
time. The original profile of the Ar ion current density without the homogenizer mask plate has a
quadratic distribution within φ100 mm with an ion current density of 0.1 mA/cm² at the center (r=0
mm) and of 40% less 0.06 mA/cm² at the peripheral (r=50 mm). With the homogenizer mask plate
designed, ion dose has been successfully controlled for uniform radial distribution. Uniform milling
rates of 2.5 nm/min for Mo and 4.3 nm/min for Si can be realized with the homogenizer mask plate.
The rate of 1-period removal within 2 min is practical enough for repeating the process of 0.1
nm/period correction by 10 times to cover 1 nm figure error in total.

Since contamination of multilayer mirrors by sputtered material of the acceleration grid, the
correction mask and the template would be difficult to avoid, these elements are made of Mo or Si for
transparency at the EUV wavelength of 13.5 nm. For the milling period detection, sensing systems of
visible emission and/or reflection spectrum, total light intensity and the drain current are equipped to
distinguish milling materials during ion beam irradiation. Further details of the system will be
described in a separate publication.

Figure 1. (a) The multilayer ion milling system. (b) Cut off view of the work chamber.

3. Experimental proof of the correction principle at a visible wavelength

For the proof of the reflection phase correction principle specific to a multilayer mirror, local areal
milling of a 10 periods Ta₂O₅/SiO₂ multilayer mirror for the wavelength of 633 nm was carried out by
our ion milling system.

Figure 2. Theoretical reflection phase by surface milling of 10 period Ta₂O₅ (solid curve) /SiO₂
(broken curve) multilayer mirror for visible light and of a bare BK7 glass substrate (dotted line).
Reflectance variation of the multilayer mirror is also shown. For calculation, the refractive indices n
and the layer thickness d of 2.196 and 72.0 nm for Ta₂O₅ layers, 1.468 and 107.8 nm for SiO₂ layers
and 1.515 for a BK7 glass substrate were assumed, respectively.
Fig. 2 shows theoretical expectation of reflection phase and reflectance calculated as a function of milling thickness from the surface. Normal incidence and a wavelength of 633 nm are assumed in the calculation. Calculation method of multilayer milling is described in Ref. [4] in detail. Since the refractive indices of layer materials are larger than 1 in the visible region, the reflection phase at the milling area, specifically of a multilayer mirror, shifts to “positive” direction, whereas the phase of a bare substrate shifts naturally to “negative” direction by the delay as shown in Fig. 2. The “positive” phase shift is caused by the removal of the layer material as in the case of a Schmidt phase correction plate. The surface layers thus behave as a phase correction layer since the multilayer reflection by the constructive interference is a volume effect of the layers underneath.

After the ion milling at a template opening of \( \phi \) 5 mm for 30 min by the Ar ion accelerated at 500V, the reflection phases of the dielectric multilayer mirror and BK7 glass plate were measured by a phase-shifting interferometer (Zygo mark II) at the wavelength of 633 nm. The measured optical pass differences (OPD) of the glass plate and the multilayer are shown in Figs. 3 (a) and (b), respectively.

![Figure 3](image)

**Figure 3.** Measured optical pass differences (OPD) maps of (a) BK7 glass and (b) 10 period Ta$_2$O$_5$/SiO$_2$ multilayer mirror by the phase-shifting interferometer (Zygo mark II) after local millings for 30 min in the area of \( \phi \) 5 mm by the ion milling system we developed. Line profiles of OPD at dotted lines are also shown.

In referring to the reflection phase at the untreated top-surface of the multilayer, the phase at the milling area “proceeds” as seen in Fig. 3 (b). The multilayer surface locally removed by the milling shows wavefront protrusion as predicted in Fig. 2. This is in good contrast to the substrate case Fig. 3 (a) showing depression by the milling. These results confirmed that our physical optics method of phase correction, specifically for the multilayer mirror, is promising and practical for the reflection phase correction with 0.1 nm accuracy at the EUV. The correction factor of \((1-n)\) being equal to 1/70 should result such a high accuracy by the Mo/Si multilayer milling for the final reflection phase correction at the EUV.

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