LOW-ORDER ABERRATIONS CORRECTION OF EXTREME ULTRAVIOLET IMAGING OBJECTIVE WITH DEFORMABLE MULTILAYER MIRRORS*

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Abstract

To realize high spatial resolution of an extreme ultraviolet (EUV) microscope, the key technical challenge would be reducing wave aberrations of an imaging objective. Astigmatism arising from figure error of a mirror substrate is the primary aberration which spoils spatial resolution. In this study, we develop a deformable multilayer mirror which is capable of correcting astigmatism on the Schwarzschild objective for EUV microscopy. The deformable mirror is consisting of a concave mirror with a Mo/Si multilayer coating, and a mirror holder with a three-points holding mechanism. This novel device acts as a stigmator, since radii of curvature in mutually orthogonal directions on the concave mirror can be precisely controlled by applying bending forces on the holding points. We report detail of optical and mechanical design of the deformable mirror, which can correct relatively large astigmatism with amplitude of 4 nm rms.

INTRODUCTION

When we apply extreme ultraviolet (EUV) with a wavelength between 3 to 30 nm to optical microscopy, high spatial resolution of a few tens of nanometers can be expected in diffraction-limited imaging. Recently, we have proposed the three-multilayer mirror objective for a full-field EUV microscope [1, 2]. The primary advantage of this novel design would be large numerical aperture (NA). The objective can provide large NA of 0.25, which is at least ten times larger than that for conventional zoneplate optics in EUV and soft X-ray region. The large NA design yields good Rayleigh resolution as well as high image illuminance, which is proportional to the square of NA.

Besides, the objective can bring high magnification, which is essential for fast video observation with an EUV CCD camera with moderate pixel size. To realize a high magnification of 1500, we employ a two-stage imaging configuration by combining the Schwarzschild mirror as primary objective (magnification: x30) and an additional magnifier with a single concave mirror (magnification: x50). To confirm an imaging performance of the objective, we have developed the full-field microscope for at-wavelength observation of an EUV lithography mask [3], and we successfully demonstrated that the microscope can resolve fine line and space patterns with half pitch of 30 nm, at an operating wavelength of 13.5 nm [4].

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To provide diffraction-limited resolution on the novel objective, the key engineering challenge would be reduction of wave aberrations, where we should eliminate aberrations below 1/14 of an operating wavelength, so as to satisfy the Maréchal criterion [5]. In case of the EUV microscope, allowable aberrations fall within an extremely small value, i.e., 1 nm rms. Wave aberrations does not only originate from an intrinsic effect of optical design, but also from misalignments and figure errors of multilayer mirrors. Especially, astigmatism resulting from figure error of mirror substrates would be a common issue to spoil resolution of the high magnification objective. We often observe astigmatism on the objective, since a small holding forces or gravity applied to mirrors yield considerable figure error, even if we apply well-polished substrates. This fact motivates us to develop a stigmator which can modify surface figure to reduce astigmatism in real time. In this paper, we report detail of a deformable multilayer mirror which can act as a stigmator for stable operation of the EUV microscope.

MECHANICAL DESIGN OF DEFORMABLE MULTILAYER MIRROR

As shown in Fig. 1, the Schwarzschild objective, which is employed as a primary optics for the EUV microscope, is consisting of the two concave (M1) and convex (M2) mirrors.

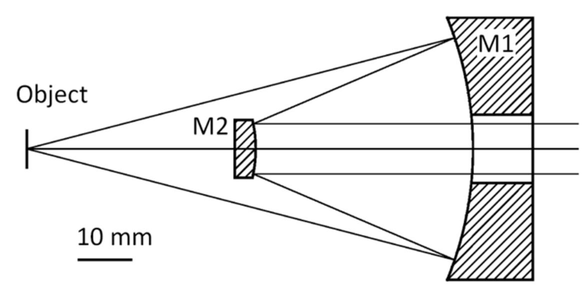

Figure 1: Schematics for the Schwarzschild objective configuration see Table 1.

Table 1: Optical Configuration for the Objective

Magnification	30
Numerical aperture	0.25
Radius of curvature r_1 (mm)	65.935
r_2 (mm)	24.286
Mirror separation d (mm)	41.65
Effective diameter ϕ_1(mm)	42.8
ϕ_2(mm)	9.6

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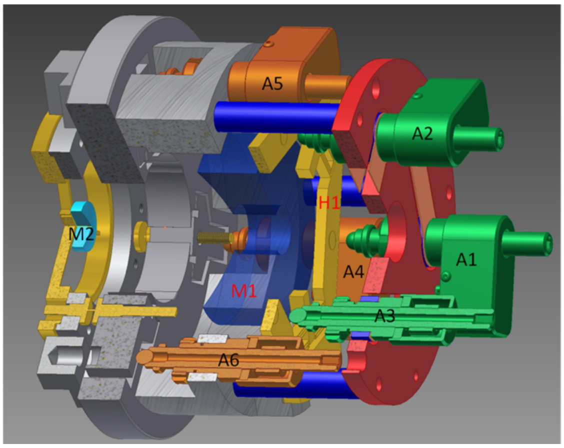

Figure 2: Mechanical drawing of a mirror holder with the substrate bending mechanism.

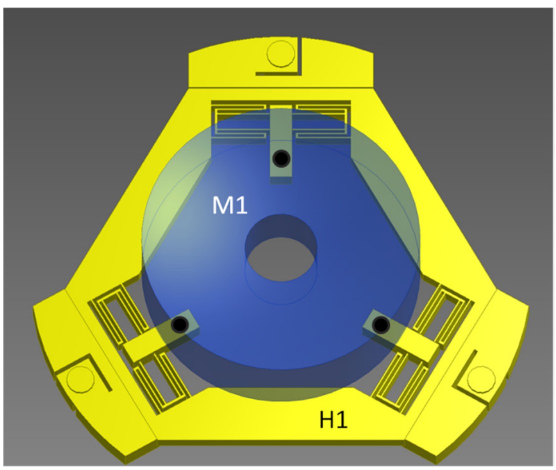

Figure 3: Schematics for the mirror holding plate (H1). The concave mirror (M1) is glued to edge of the holding arm (black circle).

The system in a concentric configuration is capable of correcting first three Seidel aberrations, i.e., spherical aberration, coma, and astigmatism, and thus it can provide blur-free imaging over a large field of view. Optical design has been detailed in Ref. [2]. Figure 2 represents a mechanical drawing for the objective. To realize the concentric configuration, the convex mirror, M2, can be precisely aligned by using the three-axis flexure stage with the piezoelectric motors, A4 to A6.

The both mirror substrates were glued to the holding plates shown in yellow. As shown in Fig. 3, the plate has three holding arms with a flexure spring, and the bottom of the mirror substrate was glued to the edge of the arm. The flexure spring was employed so as to absorb difference of thermal expansion between the mirror substrate and holding plate, which are made of different materials, i.e., fused silica and duralumin, respectively. Basic concept for a stigmator is shown in Fig. 3. Radii of curvature in mutually orthogonal directions of the mirror can be controlled by applying two torsional moments in the opposite direction to the holding arms, which are shown

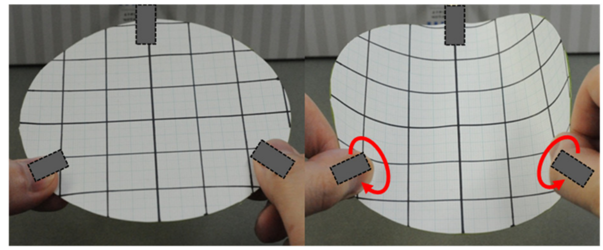

Figure 3: Basic concept of a stigmator.

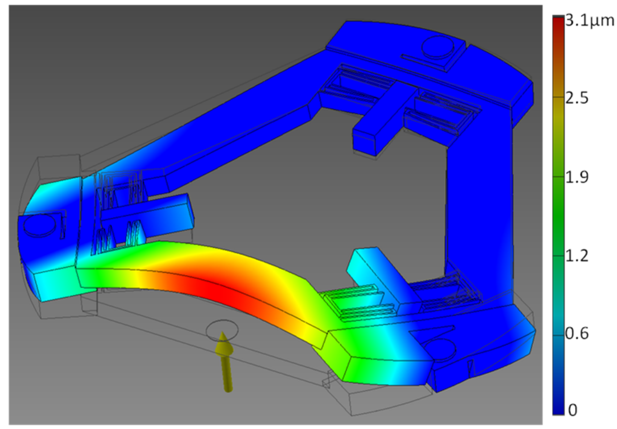

Figure 4: Torsional moments generation on the holding plate. Force along the optical axis (yellow allow: 10 N) is loaded on the plate. The mirror substrate was excluded in the calculation. Color bar shows deformation along the optical axis.

with the red allows. To correct astigmatism with sub-nm accuracy, the torsional moments were precisely controlled by loading forces along an optical axis on the holding plate. The piezoelectric motors, i.e., A1 to A3 in Fig. 2, and flexure springs were equipped to press the middle points between the holding arms with the maximum load of 20 N. Figure 4 illustrates torsional moment generation on the holding plate, which was given with numerical calculation based on a finite element method (FEM). For the numerical analysis, we applied the two software, i.e., Inventor (Autodesk Inc., CA, USA) for 3d modeling, and ANSYS Multiphysics (ANSYS, Inc., PA, USA) for FEM calculation. As shown in Fig. 4, the two holding arms next to the load point are rotated in the opposite direction, when we apply the force on the holding plate. We also see that the edges of the two arms move along the optical axis. This result indicates that applied force should bring a small tilt of the concave mirror.

Wave aberrations generated on the stigmator was numerically analyzed. For quantitative analysis, firstly, surface figure of the concave mirror was calculated with a FEM. Figure 5 shows a FEM result in which we apply 10 N load on the middle point. Then, the surface figure was represented by using annular Zernike polynomials [6]. Amplitudes for the polynomials with obstruction ratio of 0.26 were computed with Mathematica software (Wolfram, IL, USA). Table 2 summarize the amplitudes for the low-order terms, i.e., z_1 to z_6, when we apply a 10-N load

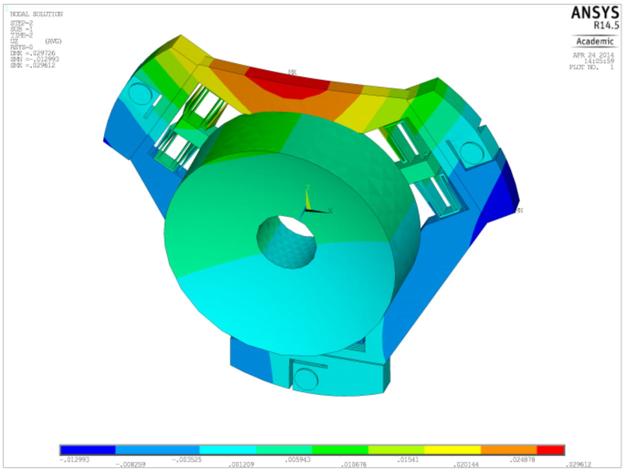

Figure 5: FEM result in which we apply 10-N load on the middle point. Color bar shows deformation along the optical axis.

Table 2: Low-Order Aberration Arising from Figure Deformation of Concave Mirror

Piston z_1 (µm)	7.82
Tilt x z_2 (µm)	-1.52
Tilt y z_3 (µm)	3.91
Power z_4 (nm)	0.09
Astigmatism x z_5 (nm)	-3.96
Astigmatism y z_6 (nm)	-0.69

on the middle point. The data clearly show that astigmatism with an amplitude of 4 nm was generated by the figure deformation, which is large enough value for the stigmator on an EUV imaging system. We also see that the terms representing the piston and tilts i.e., z_1 to z_3, are also raised. These effects yield misalignments of the mirror, where the sphere center moves 4 µm along the optical axis, and 12 µm in the vertical direction to the axis. These misalignments can be easily corrected with the three-axis stage on the convex mirror to be the concentric configuration. Higher-order effects were also estimated. Figure 3 represents amplitudes for the higher-order terms, i.e., z_7 to z_{32}. According to the computation, we confirmed that the amplitudes were below 0.15 nm rms., which indicates the higher-order terms are negligibly small for diffraction-limited imaging in a 13-nm wavelength region.

CONCLUSION

Astigmatism arising from figure error of a mirror substrate is the primary effect which spoils spatial resolution on an EUV microscope. To realize diffraction-limited resolution, the novel stigmator correcting astigmatism on the Schwarzschild objective for EUV microscopy is proposed. The stigmator is consisting of a concave mirror with a Mo/Si multilayer coating, and a mirror holder with a surface bending mechanism. We successfully demonstrate via FEM calculations that the stigmator can correct relatively large astigmatism with an amplitude of 4 nm rms., without introducing higher-order aberrations. In the next step, we experimentally confirm validness of the stigmator proposed by applying an interferometer to measure a wavefront of the EUV imaging objective.

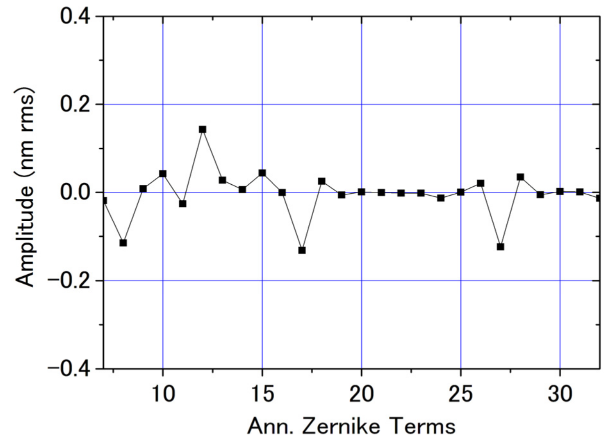

Figure 6: Amplitude for higher-order terms (z_7 to z_{32}). In the calculation, the diameter of unit circle and obstruction ratio was 50 mm and 0.26, respectively.

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