Advanced Technologies for Optical Surface Fabrication at Nikon

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The required accuracy of optical surfaces used in lithography systems has increased as the wavelength of the light used for exposure has becomes shorter owing to the miniaturization of design rules, which has resulted in the remarkable development of optical surface fabrication technologies at Nikon. In the present paper, we describe advanced processing technologies applicable to fabricate mirror surfaces for extreme ultraviolet at a wavelength of 13.5 nm, and the current status of optical surface fabrication at Nikon is reported.

1. Introduction

Optical technologies are used in various major large industrial fields such as electronic device and semiconductor production, and the wavelength of light used in optical systems has tended to become shorter with the miniaturization and increased integration of objects to be observed, probed and fabricated. For instance, in the field of electronic devices, by utilizing a blue laser instead of a red laser, high-density recording can be realized. Moreover, in the field of semiconductor devices, the light wavelength has changed from 436 nm (g-ray) to 193 nm (ArF excimer) in the last 30 years, enabling the rapid miniaturization of design rules from 1 μm to sub-100 nm. In addition, new lithography technology using extreme ultraviolet (EUV) at a wavelength of 13.5 nm is currently being developed to achieve design rules smaller than 32 nm.

The required accuracy of optical surfaces has increased as the light wavelength has become shorter, and optical surface fabrication technologies have also been developed to satisfy the required surface accuracy. Since 1978, Nikon has been engaged in the production of semiconductor exposure apparatus and has developed optical surface fabrication technologies in response to changes in the light wavelength. In this report, advanced fabrication technologies at Nikon which have adequate ability to apply to EUV optical surfaces and the current status are described.

2. Extreme ultraviolet lithography system

EUV lithography is a promising fabrication technology suitable for printing features with design rules of less than 32 nm. In an EUV lithography system, light at a wavelength of 13.5 nm is used, which is much shorter than the wavelengths used previously. Figure 1 shows a schematic of the EUV lithography system used for mass production.

To focus light at such a short wavelength into the required image, the optical devices used in the system cannot be transmissive optics, as used in conventional lithography systems, but must be reflective optics. When the reflective optics is illuminated by the EUV light, at least 30% of the light illuminating the optical surface is not reflected and is converted to heat because EUV light is easily absorbed by matter. Therefore, the number of optical devices used in the EUV system must be minimized to minimize the decrease in the exposure energy due to absorption. Thus, the precision required for each optical device increases.

In evaluating the surface accuracy of an EUV mirror, the shape error and surface roughness, which are composed of various periodic components, are divided into three ranges as follows: low spatial frequency roughness (LSFR), mid spatial frequency roughness (MSFR), and high spatial frequency roughness (HSFR), where spatial wavelength ranges correspond to over 1 mm, 1 mm–1 μm and under 1 μm, respectively. The required surface accuracy is less than 0.1 nm root-mean-square (rms) in all wavelength ranges, which is much higher than that of optical surfaces used in conventional lithography systems.

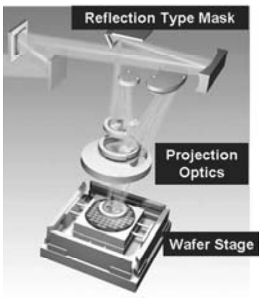


Fig. 1 Schematic of EUV lithography system.

3. Surface fabrication technologies

To achieve the strict requirements discussed above, ultra-precision fabrication techniques are required. In this section, processing technologies used at Nikon, which have adequate ability to satisfy these requirements, are introduced.

(a) Abrasive polishing

The abrasive polishing techniques used at Nikon were remarkably developed by engaging in the development of high-numerical-aperture EUV exposure tool (HiNA) from 2000 to 2004 [1]. The HiNA system is constructed using two different aspherical mirrors with convex and concave surfaces (M1, M2) as shown in Fig. 2. The surface accuracy achieved by numerically controlled polishing is shown in Table 1. LSFR, which causes optical aberrations, was reduced to 0.25 nm rms. MSFR and HSFR, which respectively strongly affect the flare and scattering of optics, were markedly reduced to less than 0.2 nm rms.

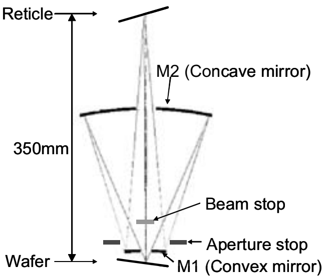


Fig. 2 Projection optics design of high-numerical-aperture EUV exposure tool (HiNA).

Table 1 Surface figure error data of mirrors used in HiNA system.

	LSFR	MSFR	HSFR
M1	0.25 nm rms	0.17 nm rms	0.10 nm rms
M2	0.25 nm rms	0.20 nm rms	—

(b) Plasma chemical vaporization machining (PCVM)

PCVM is an ultraprecision chemical machining method using rf plasma generated in the proximity of an electrode in an atmospheric environment. The principle of PCVM was proposed by Mori et al. of Osaka University. On the basis of the principle, we developed a fabrication system with a pipe electrode for optical surfaces. Using this system, we successfully processed spherical mirrors used in an EUV optical system [2] as well as aspherical surfaces with high accuracy and high smoothness. Figure 3 shows a photograph of the process of a large optics by use of the plasma generated at a 4 mm pipe electrode.

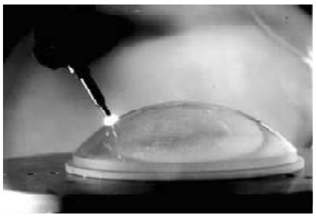
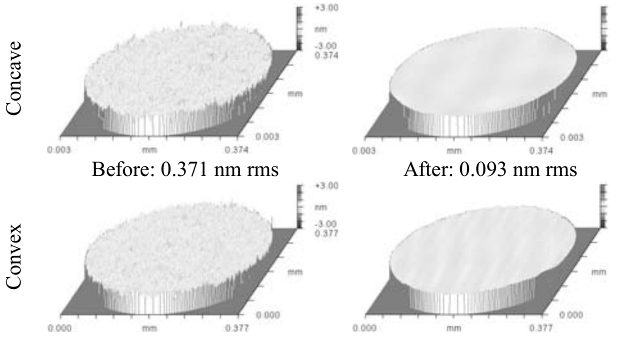


Fig.3 Photo of computer-controlled PCVM using a pipe electrode.

(c) Elastic emission machining (EEM)

EEM is a processing technology which enables the fabrication of an ultra-smooth optical surface, the principle of which was developed by Mori et al. at Osaka University. On the basis of the principle, Nikon developed a machining system applicable to curved optical surfaces. When this system is used for the fabrication of concave and convex surfaces with a radius of 500 mm, high smoothing performance can be successfully achieved, as shown in Fig. 4 [3].



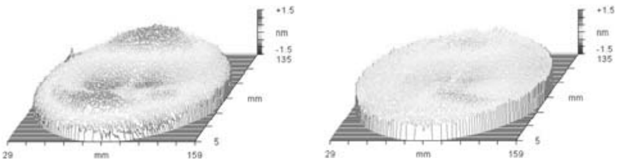
Before: 0.371 nm rms After: 0.093 nm rms

Before: 0.334 nm rms After: 0.091 nm rms

Fig. 4 Fabrication of curved surface using EEM.

(d) Ion beam figuring (IBF)

IBF is carried out by the physical removal using the sputtering of atoms of the workpiece surface by ion beam, which enables surface fabrication at an atomic level. Figure 5 shows the result of fabricating an aspherical surface using a machining system equipped with a 5-degree-of-freedom stage developed by Nikon [4].



Before: 0.40 nm rms After: 0.18 nm rms

Fig. 5 Figure error before and after IBF aspherical fabrication.

4. Recent achievement

The fabrication process for aspherical mirrors used in EUV projection optics has been optimized by combining our processing technologies. LSFR, which causes aberration, MSFR, which causes flare, and HSFR, which causes reflection loss can be simultaneously reduced. Figure 6 shows the current best data for a fabricated aspherical mirror used in EUV projection optics. The plotted line in Fig. 6 shows the PSD of the mirror surface. LSFR of 27 pm rms, MSFR of 70 pm rms and HSFR of 66 pm rms were achieved [5].

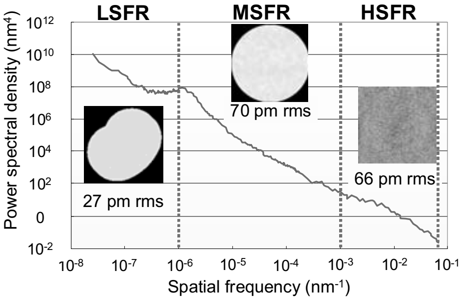


Fig. 6 LSFR, MSFR, HSFR and PSD of fabricated aspherical mirror for EUV projection optics.

5. Conclusions

- Advanced fabrication technologies at Nikon which have adequate ability to apply to EUV optical surfaces were introduced.
- With a combination of our processing technologies, EUV mirror surfaces were fabricated.
- We recently achieved an LSFR of 27 pm rms, MSFR of 70 pm rms and HSFR of 66 pm rms for a mirror surface.

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EEM, IBF

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References

[1] T. Oshino et al., Proc. SPIE, 5533, 10 (2004).
[2] H. Takino et al., Proc. 10th ICPE, 67-71 (2002).
[3] M. Kanaoka et al., Proc. 10th Int. Conf. euspen, 2, 14 (2010).
[4] H. Takino and A. Numata, Ultra Precision, 37-44 (2005) (in Japanese).
[5] K. Murakami et al., Proc. SPIE, 7271, 72711Z (2009).