Ultraprecision Machining of Optical Surfaces

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Abstract – We review the features, applications, and machining of optics that have recently been receiving attention in the optical industry. One topic discussed in this paper is optics having more complex surfaces than conventional aspheres, such as microstructured surfaces and freeform surfaces, which are attracting attention owing to their optical performance. We also discuss aspheric optics with a surface accuracy of better than 100 pm rms, which are required in reduction-projection exposure systems used in the extreme ultraviolet lithography process for integrated circuits. We give a brief overview of an extreme ultraviolet lithography system using accurate aspheric mirrors, and report the results of exposure using the system to demonstrate the quality of the processed mirrors. We describe the recent progress in some ultraprecision machining techniques, such as ion beam figuring and elastic emission machining, which enable the production of highly accurate aspheres.

***Key Words*:** Optical fabrication, DOE, Feeform, EUV, Elastic emission machining, Ion beam, Interferometer

1. Introduction

Since the 1980s, aspheric optics have been mass–produced owing to the progress of precision machining, profile measurement, and molding technologies. In the early stages of mass production using molding, for example, pick-up lenses for compact disc players as small aspheric optics and projection television lenses as large aspheric optics were produced. Nowadays, aspheric lenses are commonly used in single-lens reflex cameras. Such optics are manufactured by a process of glass molding or by a hybrid process involving the application of ultraviolet (UV)-curable resin on glass optics. These optics are simple in shape as they have axial symmetry.

Recently, optics with more complex surfaces than conventional aspheres, such as microstructured surfaces and freeform surfaces, have been attracting attention owing to their optical performance. Moreover, aspheres with a surface accuracy of sub-nanometer level are required for industrial applications although their surfaces are not complex. In this paper, we review the features of optics that have been recently receiving attention in the optical industry, their applications, and their fabrication technologies.

2. Complex-shaped optics

Optics with subwavelength structured (SWS) surfaces, which have microstructures smaller than wavelengths on the surface, have been proposed. SWS surfaces provide optical functions such as antireflection, polarization splitting, and phase control [1]. Such surfaces are mainly produced through lithography. Recently, a replication technique for fabricating SWS surfaces based on glass molding has been developed to realize their mass production [2].

Optics with microstructures larger than the size of wavelengths have also been proposed, which are referred to as diffractive optical elements (DOEs). DOEs change the light path through diffraction, whereas a conventional lens changes it through refraction. Phase Fresnel (PF) lenses, which have blazed gratings, are one type of DOE, the use of which in optical systems has been investigated for a long time. However, DOEs are difficult to use in the imaging optical system of a camera. This is because the light entering the imaging optical system has various wavelengths, leading to the difficulty of achieving high optical imaging performance over a wide range of wavelength.

To resolve this issue, various solutions have been proposed. One solution is to use blazed grating surfaces facing each other while maintaining air gap between both surfaces [3]. Another solution is to use two types of blazed grating made from different optical materials that are joined to each other as shown in Fig. 1, which is referred to as a dual-contact PF lens [4,5]. Recently, another type of dual-contact PF lens have been proposed as shown in Fig. 2: two types of resin having blazed gratings are placed between plastic lenses [6]. These PF lens are practically used in commercial products such as camera lenses and head-mounted displays. Dual-contact PF lenses are produced by the combination of various precision fabrication techniques such as the ultraprecision cutting of molds, glass molding, or the application of UV-curable resin on grating surfaces.

Freeform optics are actively used in commercial products such as optical communication systems, head-mounted displays, and liquid crystal projectors [7-9]. Recently, a digital camera having a liquid crystal projector has been commercialized, with freeform optics [8],

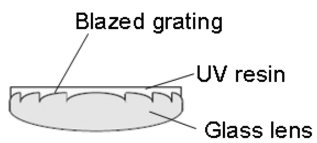

Fig. 1. Schematic of dual-contact phase Fresnel lens.

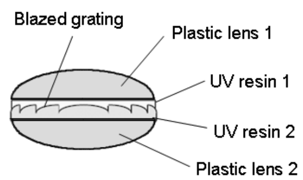

Fig. 2. Schematic of dual-contact phase Fresnel lens.

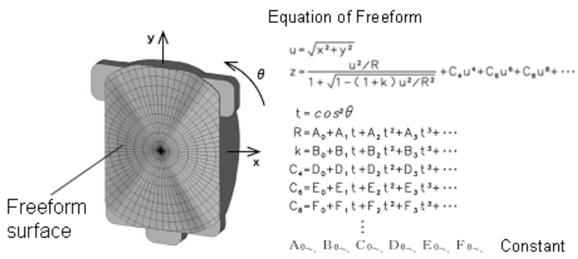

Fig. 3. Schematic of freeform optics used in a projector installed in a digital compact camera.

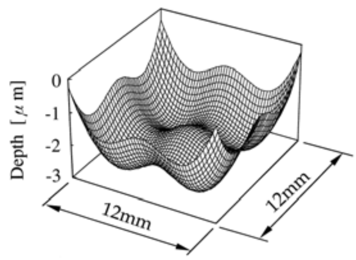

Fig. 4. Surface profile of freeform mirror used for the transformation of laser beam intensity distributions.

one of which is shown in Fig. 3. These optics allow the downsizing of the optical system and the enhancement of illumination efficiency.

Freeform surfaces also enable the transformation of laser beam intensity distributions. It was demonstrated that the circular Gaussian profile of laser beams can be converted into a rectangular flat profile by using the freeform mirror shown in Fig. 4. The mirror was made of fused silica glass, and was processed to have smooth and highly accurate surfaces by plasma-based ultraprecision machining, referred to as plasma chemical vaporization machining (CVM) [10, 11].

3. Highly accurate aspheric surfaces; aspheric mirrors in an extreme ultraviolet lithography system

In the manufacturing process of semiconductor integrated circuits, lithography is an essential process. In the lithography process, a reduction-projection exposure system is used to project circuit patterns onto a silicon wafer. To precisely reduce the scale of circuit patterns on wafers, highly accurate optics must be used in the exposure system. The use of a shorter exposure wavelength in the system results in higher resolution of the circuit patterns on the wafer. In recent years, an exposure wavelength of 193 nm has been used in an immersion method, allowing a linewidth resolution of 32 nm. The use of a shorter exposure wavelength requires optics with higher surface accuracy and smoothness in the exposure system.

To further reduce the linewidth of circuit patterns, an extreme ultraviolet lithography (EUVL) system, in which exposure is carried out at an extreme ultraviolet (EUV) wavelength of 13.5 nm, has attracted attention and is being investigated globally. The EUVL system requires extremely high quality mirrors in its optical system.

The surface characteristics of optics used in the EUVL system, which are referred to as EUV optics, are evaluated by dividing the surface profile into three sections: low spatial frequency roughness (LSFR), mid spatial frequency roughness (MSFR), and high spatial

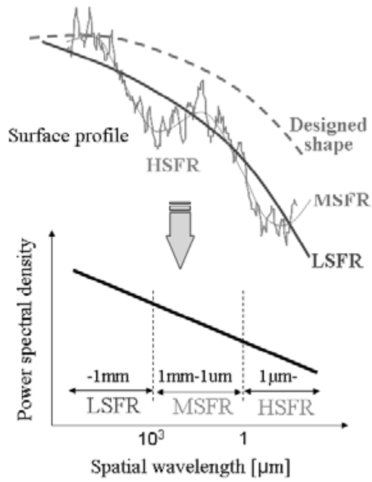

Fig. 5. Schematic of surface profile of EUV optics and power spectral density distribution curve calculated from the surface profile.

frequency roughness (HSRF), as shown in Fig.5. In general, the spatial frequency analysis of the surface profile is conducted to obtain power spectral density (PSD) distributions for the spatial wavelengths in each section. EUV optics require a surface accuracy of better than 100 pm rms for each roughness section. This means that the surface must have atomic level accuracy and smoothness.

In the EUVL system, few optics are used so as to reduce the loss of exposure light. To achieve high optical performance even using few optics, most of the optics must be aspheric. Moreover, low-expansion glass is used as a material to prevent deformation by the heat load generated by exposure. The realization of EUV optics requires ultraprecision machining techniques enabling surface removal that can be controlled to atomic-level accuracy.

4. Fabrication of highly accurate aspheres

Various fabrication techniques for finishing aspheric surfaces have been proposed and discussed from the viewpoints of industrial applications and academic interest [10-18]. We have also been investigating ultraprecision machining and profile measurement technologies to fabricate aspheric optics with high accuracy and smoothness that are applicable to EUV optics.

In this section, we review some our efforts to fabricate EUV optics, demonstrating examples from our studies on ion beam figuring (IBF) [16], elastic emission machining (EEM) [17, 18], and high-repeatability interferometry [19]. These studies were conducted in the management of the Extreme Ultraviolet Lithography System Development Association (EUVA) in Japan.

4.1 Ion beam figuring

4.1.1 Removal principle and ion beam figuring machine

The bombardment of a workpiece with an ion beam results in the removal of its surface through sputtering, as shown in Fig. 6. An ion beam focused to a size small relative to the workpiece is generated by an ion gun. A targeted area on the workpiece surface can be processed by positioning the ion gun to make ions bombard the area. The targeted area is removed at a depth of atomic order through sputtering,

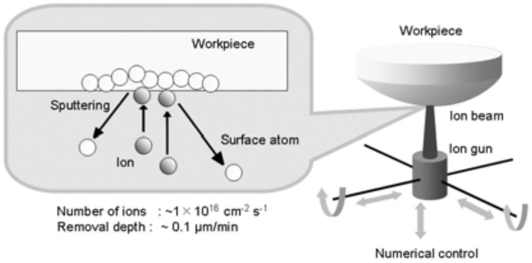

Fig. 6. Principle of ion beam figuring.

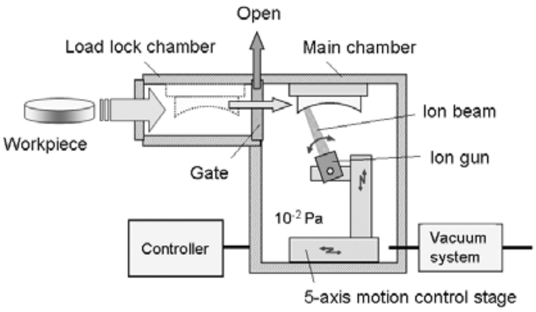

Fig. 7. Ion beam figuring machine for optical finishing.

indicating that IBF enables the machining of surfaces with the high accuracy required for EUV optics. IBF enables the removal of various materials because the removal is based on physical mechanism.

We have developed an IBF machine and investigated its removal characteristics and figuring techniques using the machine. In the IBF of an optical surface, the surface is first measured with a three-dimensional surface profiler such as an interferometer to obtain an error map of the surface. Then, in accordance with the error map, numerically controlled data are calculated for use when scanning the ion beam. Since the removal depth increases with increasing processing time, the processing is conducted such that the ion beam dwells over an area for a specific amount of time depending on the error height. The ion gun is scanned while maintaining a specific working distance between the ion gun and the workpiece surface. Figure 7 shows a schematic construction of the IBF machine, in which an ion gun is set on a five-axis stage and a workpiece is placed above the ion gun. This arrangement allows us to bombard ion beams normal to any point on the workpiece surface while maintaining a constant working distance.

4.1.2 Experiments

Here we discuss examples of figuring experiments using the

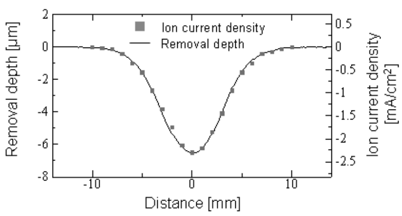

Fig. 8. Removal profile after ion beam bombardment for 30 min.

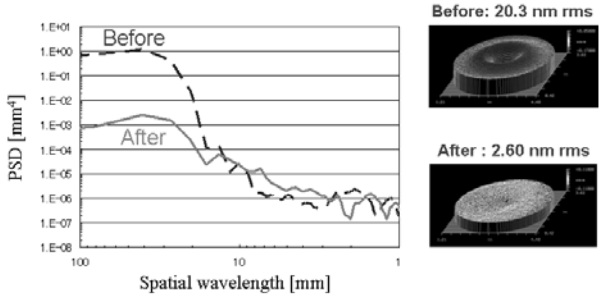

Fig. 9. Improvement of surface accuracy by use of IBF.

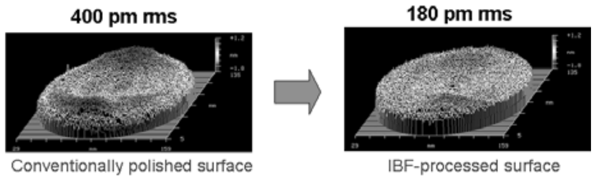

Fig. 10. Improvement of sub-nanometer surface accuracy of large asphere by use of IBF.

machine shown in Fig. 7. The figuring was conducted to improve the accuracy, which corresponds to the LSFR, of a surface processed by conventional polishing.

Fused silica concave spheres with a diameter of 80 mm were processed. Figure 8 shows a removal profile after Ar ion beam bombardment for 30 min with an acceleration voltage of 800 eV when the workpiece and ion gun were stationary relative to each other, with its ion current density measured by a Faraday cup. The figuring process was performed by scanning the beam over the surface with the ion current density shown in Fig. 8. Figure 9 shows the surface topographies and PSD distributions before and after the process, which demonstrate that surface errors corresponding to LSFR are successfully improved, and in particular, errors with spatial wavelengths of above 10 mm are reduced.

Figuring experiments on a surface with sub-nanometer accuracy were performed to validate the effectiveness of the IBF process for EUV optics. In the experiment, large aspheres with a diameter of 130 mm made of low-expansion glass were used in consideration of the actual fabrication of EUV optics. The conditions of ion beam generation were the same as those used for fused silica concave spheres. Figure 10 shows the experimental results. The surface accuracy was improved to 180 pm rms, approaching the required accuracy of EUV optics, demonstrating the usefulness of this technique for the processing of EUV optics. In addition, we have also investigated the process characteristics for MSFR and HSFR, although here we only give those of LSFR.

4.2 Elastic emission machining

4.2.1 Removal principle and elastic emission machining system

EEM was proposed as a polishing method by Prof. Mori of Osaka University about 40 years ago. Since then, fundamental investigations on EEM and its applications have been continued to be performed by many researchers. We are interested in the smoothing capability of

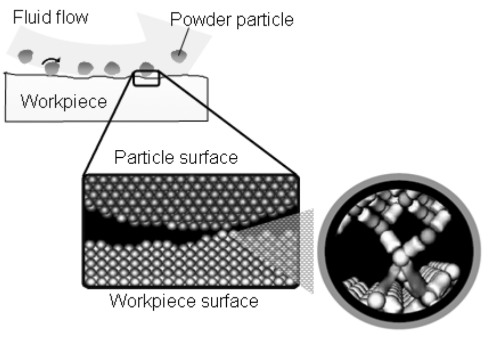

Fig. 11. Principle of elastic emission machining.

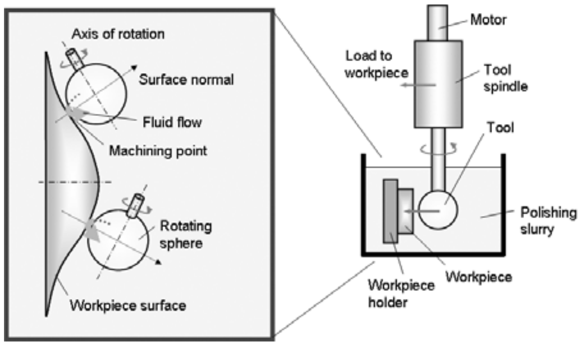

Fig. 12. Fabrication of aspheric surface by EEM.

EEM and have investigated its application to the fabrication process of EUV optics.

EEM processing is conducted in a machining slurry in which powder particles are suspended in pure water. The slurry is continuously supplied to a machining point by a tool, which leads to the powder particles attacking the surface, as shown in Fig. 11. The powder particles chemically react with the surface, thus removing the surface.

A rotating sphere is used as a tool in EEM. The rotation of the sphere close to the workpiece surface produces the flow of slurry with dynamic pressure at the gap. This enables the powder particles to attack the surface while maintaining the noncontact state between both surfaces. Although EEM is a polishing method, it differs from conventional polishing in that the EEM tool is not in contact with the workpiece surface during the process.

We developed an EEM system for processing aspheric surfaces with a five-axis motion control device for the tool and a workpiece to process any desired point on the surface. In this system, five-axis motion control is conducted so that the equator of the rotating sphere tool is positioned over the machining point, as shown in Fig. 12. We performed experiments and numerical analysis to clarify the tribological conditions of the gap between the tool and workpiece, which revealed the generation of elastohydrodynamic lubrication under typical process conditions. This means that polishing using our EEM system is carried out under the noncontact state of the tool with the workpiece surface in accordance with the principle of EEM.

4.2.2 Experiments

We have investigated the removal characteristics of our EEM system, such as removal rate and surface roughness. By optimizing the process conditions of the EEM system, the maximum removal rate of 100×10^{-4} mm^3/h was achieved. This rate is approximately 100 times larger than that of previous EEM systems. Thus, we successfully resolved the issue of the low removal rate in EEM, enabling the application of this system to the processing of large EUV optics.

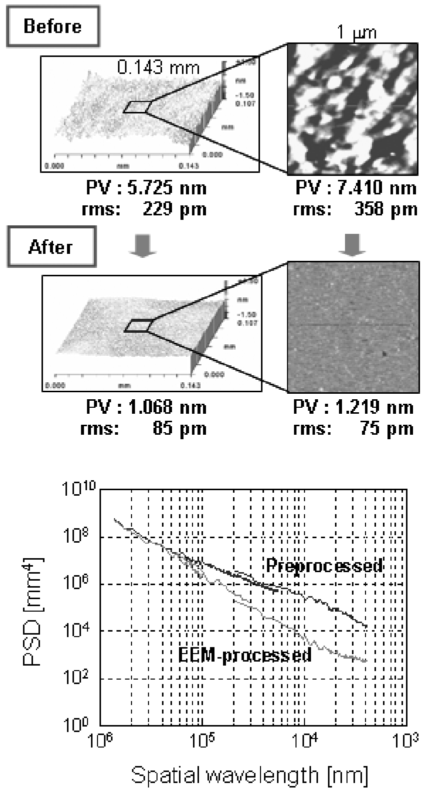

Fig. 13. Surface topographies before and after processing by EEM.

We processed conventionally polished surfaces to examine the surface roughness of MSFR and HSFR. Figure 13 shows examples of surface topographies of fused silica plates before and after EEM processing, observed by an optical profiler and an atomic force microscope. Examples of PSD curves are also shown in the Fig. 13. The surfaces shown in Fig. 13 were obtained under the conditions for which the maximum removal rate is achieved. The figure shows that roughness with a spatial wavelength of below 100 μm is reduced, thus reducing the rms roughness to below 100 pm rms. These findings demonstrate the usefulness of EEM for the smoothing of EUV optics. In addition, we have investigated the process characteristics of curved surfaces made of various materials, some of which have been already reported.

4.3 High-repeatability interferometer

To produce highly accurate aspheric surfaces, a high-repeatability interferometer was developed. The principle of the interferometer is shown in Fig. 14; the interferometer is categorized as a Fizeau laser interferometer. In this interferometer, optics generating an aspheric wavefront are set between a light source and a test surface. A reference surface is placed in proximity to the test surface to minimize the effects of air currents during measurement. In addition, various efforts, such as temperature control and vibration control, are made to

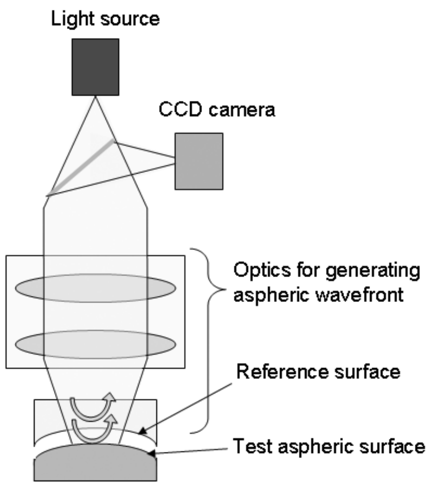

Fig. 14. Schematic of high-repeatability interferometer.

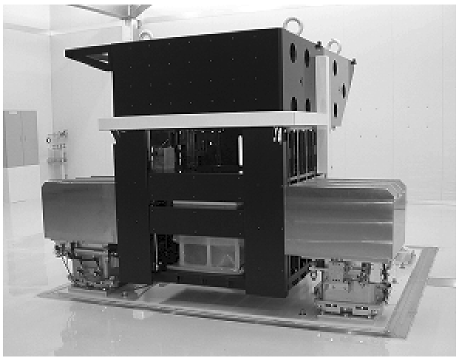

Fig. 15. Photograph of high-repeatability interferometer.

eliminate environmental disturbances.

Figure 15 shows a photograph of the interferometer constructed on the basis of the above concept. Its performance was examined by measuring aspheres, which revealed a repeatability of 6 pm rms and a reproducibility of 17 pm rms, demonstrating that the interferometer has sufficient capability to measure EUV optics. The aspheric surface shown in Fig. 10 was measured by this interferometer.

5. EUVL system

Figure 16 shows a schematic of an EUVL system. In this system, an arc field of a mask on which electric circuit patterns exist is illuminated uniformly through an illumination optical unit, and the patterns are reduced in size and imaged on a silicon wafer through a projection optical unit. We processed the optics in the optical units of the EUVL system using various ultraprecision machining methods and measurement methods, some of which are described above.

Figure 17 shows an example of the surface topographies and PSD curve of a mirror used in the projection optical unit of the EUVL system [20]. The surface roughnesses over entire spatial wavelengths were found to be successfully reduced. Figure 18 shows the evaluation of the illumination optical unit, showing the illumination intensity distribution on the mask. The results demonstrate that the unit enables uniform illumination on the desired arc field with an illumination intensity distribution of ± 0.5% [21].

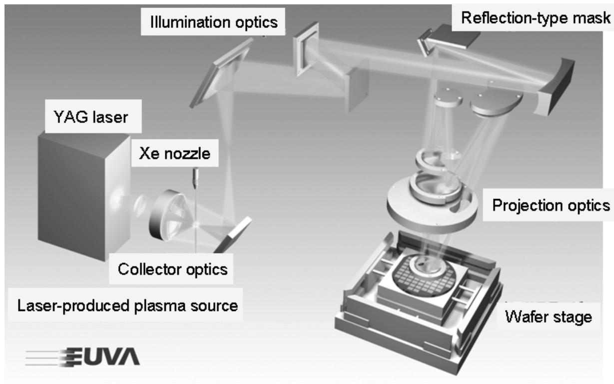

Fig. 16. Schematic of EUVL system.

Lithography processes were conducted using an EUVL system in which the above optical units were installed. Figure 19 shows the resulting patterns, demonstrating the successful generation of patterns of 24 nm half pitch [20]. Thus, the processed optics are sufficiently accurate and smooth for use as EUV optics.

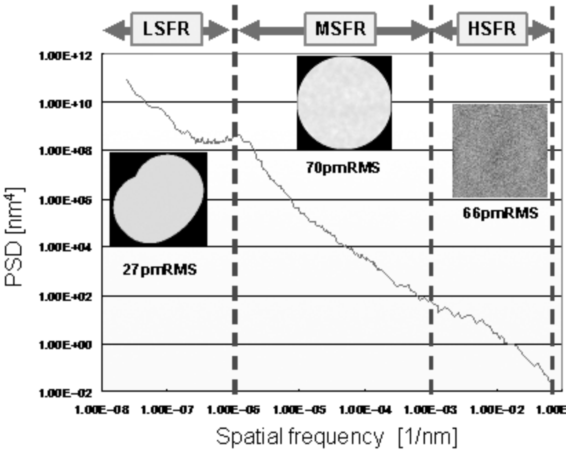

Fig. 17. Evaluation of mirror surface in projection optical unit showing the surface topographies in each roughness section and the PSD curve.

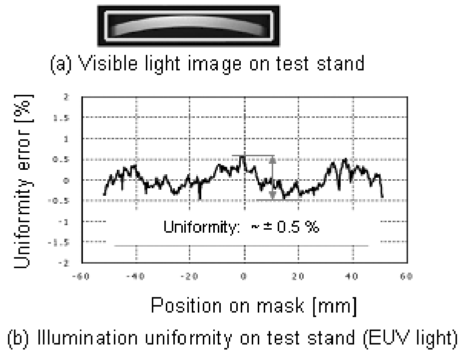

Fig. 18. Evaluation of illumination optical unit.

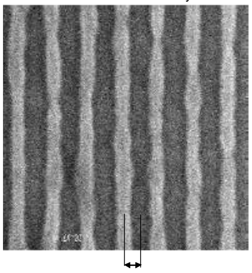

Fig. 19. Resolution evaluation of EUVL system at Selete.

6. Conclusions

We have reviewed the features of optics recently receiving attention, their applications, and their fabrication technologies. Complex-shaped optics, such as microstructured optics and freeform optics, tend to be widely used in optical instruments owing to their optical performance. Moreover, optics with a surface accuracy of better than 100 pm rms are required for industrial optical instruments. These high-quality optics are now being successfully produced by the combination of various ultraprecision machining methods and accurate measurement. In the fields of optical science and industry, various novel optics are being proposed. Thus, innovative ultraprecision machining technologies are desired to realize such novel optics.

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