SOFT X-RAY REDUCTION OPTICAL SYSTEM DESIGN FOR 0.1 μ m LITHOGRAPHY

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A two-mirror telecentric optics has been designed for soft X-ray reduction lithography with high throughput. A resolution of 0.1 μ m is achieved at a wavelength of 130 Å with a 20 x 20mm field using a ring-field scanning method. In the design, aberrations including distortion are reduced using aspherical concave and convex mirrors at a numerical aperture of 0.07. The designed optics achieves a square wave modulation transfer function (MTF) value of over 50% at a spatial frequency of 5000 lines/mm and is capable of resolving 0.1- μ m lines and spaces. The depth of focus is $\pm 1\mu$ m. The distortion is less than 0.01 μ m in the 12.5-mm-radius ring image field. Furthermore, uniform ring shaped illumination for the ring field is achieved by using focusing toroidal mirrors.

1. Introduction

Soft X-ray optics with high resolution has been studied for application to X-ray reduction lithography[1,2,3,4]. Multilayer mirrors, which consist of alternating layer of heavy and light elements, are used in reduction optics. The development of normal incident multilayer mirror with high reflectivity opened the way to various applications of X-ray optics[3,4]. Schwarzschild optics has been widely used in experiments involving X-ray reduction lithography[2,3,4] and X-ray microscopy[5]. This optics has a high resolution capability down to 0.1 μ m, but has small field size.

For lithography applications, high throughput is required and the image field size must be quite large. Furthermore, it must be telecentric at the image plane, that is, the projected chief rays must have normal incidence at the image plane in order to avoid an image shift due to defocus.

A number of designs for a large-field telecentric optics for lithography have been reported using three or four mirror configurations[6,7]. However, two-mirror telecentric optics offers a range of advantages including high total reflectivity, wavelength matching in multilayer mirrors, larger tolerances of mirror figuring and alignment errors. In our work, therefore, we sought to realize a low aberration two-mirror telecentric configuration with a large image field.

In this paper, we present the design of a two-mirror telecentric optics for practical soft X-ray reduction lithography using synchrotron radiation. In the design, our objective is to realize a resolution of 0.1 μm in a 20-mm ring field. The design concept and optical properties of the designed optics are described.

2. System design goals and conditions

Objectives and conditions we sought to achieve with the optical system design are summarized in Table 1. For the reduction optics, we sought a resolution capability of 0.1 μm using synchrotron radiation. The exposure field is required to be a 20-mm square for LSI lithography. Here, a ring-field scanning method was employed for the two-mirror optics to minimize the aberration. This method makes it easier to obtain uniform illumination and large field compared with large square field step-and-scan method.

Table 1. Design Goals and Conditions

Resolution	0.1 μm
Field size	20x20 mm ² (>10 mm radius ring scan)
Distortion	< 0.01 μm
Depth of focus	$\pm 1\mu\text{m}$
Numerical aperture	0.07 ($\lambda=130 \text{ \AA}$)
Aberration	$\leq 0.05 \mu\text{m}$
Telecentricity	< 0.6° at $\pm 1\mu\text{m}$ defocus
Magnification	1/5 (Mask size: 100 x 100 mm ²)

We aimed to reduce the number of mirrors in order to maintain high throughput, and therefore settled on a two-mirror optics for this purpose. Two-mirror optics represents the minimum mirror optics in which aberrations can be corrected. Throughput was estimated for the two-mirror optics with a reflection mask using synchrotron radiation. Conditions for throughput estimation are listed in Table 2. Fig.1 shows the throughput as a parameter of number of mirrors.

Table 2. Conditions for Throughput Estimation

Reflectivity	50%
Band width per mirror	5.5 Å at $\lambda = 130$ Å
Storage beam current	400 mA
Orbital radius	8.66 m
Horizontal beam angle	51 mrad
Resist sensitivity	20 mJ/cm ²
Registration time	0.5 sec/chip
Sample exchange time	10 sec

Fig.1 Throughput Estimations.

Total spectral band width becomes narrower as the number of mirrors increases; for example, the band width is 4 Å for two mirrors and 3.1 Å for four mirrors. Thus, the integrated intensity is also reduced as the number of mirrors increases. The throughput for a two-mirror system is about 26 wafers/h for 6 inch wafers(72 chips), as opposed to less than 7 wafers/h for a four-mirror system.

The fabrication error budget per mirror become severe as the number of mirrors increases. Therefore, another advantage of two-mirror optics is that the mirrors are easier to fabricate and align in achieving a wavefront error of less than $\lambda/8$, the Rayleigh limit. Furthermore, the spectral band width becomes larger with fewer mirrors as shown in Fig.1, thus making it easier to match peak wavelengths among multilayer mirrors.

Exposure wavelength and numerical aperture are important factors in optical system design. Fig.2 shows the relation between numerical aperture NA and wavelength. Resolution d is expressed as $d = 0.5\lambda/NA$. At a wavelength of 130 Å, a numerical aperture of over 0.07 is required to obtain a resolution of 0.1µm. In order to obtain 0.1µm resolution and $\pm 1\mu\text{m}$ depth of focus, a wavelength range of 50-200Å is suitable considering multilayer reflectivity and fabrication limits and optical design possibility of larger NA.

The wavelength for exposure was chosen to be 130Å in the present design. At this wavelength, high reflectivity can be obtained by using Mo/Si multilayer coated mirrors. The measured reflectivity of Mo/Si multilayers fabricated by RF magnetron sputtering[8] is shown in Fig.3. It can be seen that a reflectivity of over 50% was obtained. The measured resist exposure characteristics for various wavelength are shown in Fig.4. Exposure depth becomes shallow for longer wavelengths due to the absorption of carbon in the resist. At 130 Å, an exposure depth of about 0.15µm was obtained at a dose corresponding to 1/e attenuation X-ray absorption depth. In order to realize high-aspect

patterns, Fig.5 demonstrates an example of resist patterns obtained using a multilayer resist(PMMA/Si/OFPR) at a wavelength of 130Å. A linewidth of 0.15µm was obtained with a thickness of 0.5µm. Multilayer resist[3,9] or surface imaging resist such as DESIRE[10] would be required for high-aspect patterning due to the shallow exposure depth. A sensitivity of 12mJ/cm² has been obtained for FBM-G, and 80mJ/cm² for PMMA with a thickness of 0.2 µm at 130Å. Even shorter wavelengths of around 50 - 75 Å are desirable for resist processes, but these give lower reflectivity at present. Continued study should result in further reflectivity enhancement.

Fig.2 Relation of Resolution and Wavelength.

Fig.3 Measured Reflectivity of Mo/Si Multilayer Mirror.

Fig.4 Exposure Characteristics of PMMA for 50-200 Å.

Fig.5 Resist Pattern Obtained by Multilayer Resist.

3. Illumination optics

A schematic of the illumination optics for a ring-field system is shown in Fig.6. Grazing incidence mirrors are used as the focusing mirrors so the reflectivity will not be lowered. For telecentricity in the image plane, synchrotron radiation is focused at the front focus of the reduction optics. The entrance pupil of the reduction optics is situated at the front focal plane. In this configuration, the chief rays are normal to the image plane of the reduction optics.

The synchrotron radiation source has a small angle of beam divergence in the vertical direction, but beam shape is quite wide in the horizontal direction. This fan shape beam property is suitable for illuminating a ring shaped field, although it is exceedingly difficult to obtain uniform illumination of a large square-shaped field system[7]. The ring-shaped field is effective to obtain a uniform illumination.

The designed illumination optics consists of two toroidal mirrors. Using these mirrors, a ring-shaped beam is obtained on the reflection mask by optimizing the curvature of the toroidal mirror as shown in Fig.6. The radius of the ring-shaped beam is controlled to be equal to the radius of the ring field. Beam loss is effectively reduced by this new illumination optics.

Fig.6 Schematic of Illumination Optics for Telecentric Imaging.

4. Two-mirror optical system

In the design of the two-mirror optics, the ring-shaped field system and aspherical mirrors were used to reduce the aberration of the telecentric optics. The mirror dimensions were optimized to reduce aberration of the ring field using a ray-tracing method. The aspherical surfaces of the two mirrors were chosen to be conics to make the aspherical mirrors easier to fabricate by excluding higher order aspheric departure. The curvatures of the two mirrors were chosen to make them nearly equal to obtain a flat image plane. The reflection mask surface is plane. Curved reflection mask[2] for aberration correction was not employed considering our concern for practical reflection mask

fabrication. In addition, incident angles in the mirrors and mask were controlled to approximate normal incidence to ease wavelength matching using the same period multilayers.

Fig.7 Designed Two-Mirror Telecentric Optics.

A schematic of the designed two-mirror optics[11] is shown in Fig.7. The primary mirror is convex, and the secondary mirror is concave. The ring-field radius is 62.5 mm in the object plane, and 12.5 mm in the image plane. An effective ring-field size of 20 mm is obtained by the illumination optics described above. The curvatures are about 980 mm in radius, and the mirror separation is about 820 mm. In the designed optics, it is found that oblate spheroid concave and convex mirrors realize low aberration. The maximum departure from the spherical surface is $0.6\mu\text{m}$ in the convex mirror, and $0.4\mu\text{m}$ in the concave mirror. Diameters of the mirrors are about 50 mm for the convex mirror, and 150 mm for the concave mirror. This small aspheric departure makes it possible to fabricate a mirror surface with high accuracy. The distance from the mask to the wafer is about 1.3 m.

The angles of incidence of the two mirrors and reflection mask are successfully kept below 3° , and thus come close to normal incidence. The layer periods of the multilayers are almost equal under this condition. The two mirrors and the reflection mask can thus be coated with multilayers in a single deposition run to obtain uniform layer period multilayers. This makes it possible to achieve extremely precise wavelength matching between the mirrors and the reflection mask.

Fig. 8 shows the aberration and spot diagram of the designed optics. The maximum aberration is $0.04\mu\text{m}$ in the x direction, and $0.05\mu\text{m}$ in the y direction. The square wave modulation transfer function (MTF) at a wavelength of $130\text{ \AA}$ is shown in Fig.9. An MTF value of 54% is obtained at a spatial frequency of 5000 lines/mm, which corresponds to $0.1\text{-}\mu\text{m}$ lines and spaces. The depth of focus is $\pm 1\mu\text{m}$ to maintain $0.1\text{-}\mu\text{m}$ resolution with over 45% MTF. Sagittal and tangential MTFs are almost equal. Figure 10 shows the distortion at an image height of 12.5 mm. Distortion can be reduced by using a ring field. For a ring field with a radius of 12.5 mm, distortion change in the ring field is below $0.01\mu\text{m}$ within 0.4 mm in the radial direction.

Fig.8 Aberration and Spot Diagram of the Designed Optics.

Fig.10 Distortion of Designed Optics.

Fig.9 Square Wave MTF Curve of Designed Optics for Incoherent Illumination.

Fig.11 Effect of mirror figuring error on the resolution.

We have fabricated and assembled a two-mirror optical system. Up to now, we have used this system to replicate $0.3\text{ }\mu\text{m}$ patterns. The resolution seems to be limited by mirror figuring error and alignment error. Fig.11 shows the resolution as a parameter of the deviation from the designed figure. Further improvement in mirror fabrication and alignment accuracy should allow us to achieve $0.1\text{ }\mu\text{m}$ resolution.

For further study of higher resolution of two-mirror optics, we are designing more compact optics with larger NA. At present, a half size optics with $\text{NA} = 0.1$ has been designed. A square wave MTF of over 70% at 5000 lines/mm was obtained with a depth of focus $\pm 0.5\text{ }\mu\text{m}$. The ring

field radius is the same as the optics shown in Fig.8. We intend to pursue this line of development to achieve resolution below 0.1 μ m for future lithography.

5. Conclusion

A 0.1- μ m resolution two-mirror telecentric optics has been designed for soft X-ray reduction lithography. A two-mirror optical system has advantages of high throughput, high accurate wavelength matching, and mirror alignment. Aberrations, including distortion, are reduced by aspherical concave and convex mirrors with oblate spheroid surfaces in a ring field. Since the mirrors are near normal incidence, wavelength matching has been easy to achieve using the same period multilayers. Telecentric and uniform ring field illumination were realized by two toroidal illumination optics. The optics was designed with a resolution of 0.1 μ m at a wavelength of 130 Å. The designed optics yields an MTF value of over 50% at a spatial frequency of 5000 lines/mm (0.1 μ m L&S). The depth of focus is $\pm 1\mu$ m, and the distortion is less than 0.01 μ m. An exposure field of 20x20 mm is obtained by scanning a ring field with a radius of 12.5 mm.

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