All-reflective optical system design for extreme ultraviolet lithography

Jun Chang (常 军)[1*], Meifang Zou (邹美芳)[1], Ruirui Wang (王蕊瑞)[1], Shulong Feng (冯树龙)[2], and M. M. Talha[3]

[1]*Laboratory of Optoelectronics Technology and Information System, School of Optoelectronics, Beijing Institute of Technology, Beijing 100081, China*

[2]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 343100, China*

[3]*IICS, P. O. Box No. 1384, Islamaabad, Pakistan*

**E-mail: bitchang@bit.edu.cn*

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All-reflective optical systems, due to their material absorption and low refractive index, are used to create the most suitable devices in extreme ultraviolet lithography (EUVL). In this letter, we present a design for an all-reflective lithographic projection lens. We also discuss its design idea and structural system. After analysis of the four-mirror optical system, the initial structural parameters are determined, the optical system is optimized, and the tolerances of the system are analyzed. We also show the implementation of optimal layout and desired imaging performance.

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Semiconductor technology based on very large scale integration (VLSI) manufacturing has been the main pillar of high-tech industries since the 1960s. Lithography is a critical technology in VLSI manufacturing. It is also very important in research areas such as optical technology, precision machinery, and automatic control technology. Lithography is a fundamental tool in the technological aspect of integrated circuit (IC) manufacturing, and it is considered as the decisive factor in further developments in the semiconductor industry. Thus, demand for lithography is increasing[1].

Extreme ultraviolet lithography (EUVL), one of the next generation lithography (NGL) technologies, has its own comparable advantages. The disadvantages of other lithography systems, such as immaturity, incompatibility, and high cost, among other, will make it difficult for these techniques to enter the VLSI in the near future. The EUVL wavelength is between 11 and 14 nm. The optical system of EUVL must be an all-reflective type, due to material absorption and low refractive index[2]. Improvements in optical manufacturing technology and alignment have made designing such type of all-reflective optical system possible. At present, the reflective objective for EUVL has become a topic of high interest to researchers around the world[3−9].

In this letter, the four-mirror optical system is divided into four types depending on the formation and the position of its intermediate image. After analysis of the different configurations, we deduce the aberration formulas of the four-mirror system and provide a method to find its initial structural parameters. A design example is also presented. Finally, we analyze the tolerances on parameters.

The layout of the four-mirror optical system is shown in Fig. 1. Assume that the object is away from its primary mirror (M_1) with the distance of l_1. The conic coefficients of its primary (M_1), secondary (M_2), tertiary (M_3), and quaternary (M_4) mirrors are e_1^2, e_2^2, e_3^2, and e_4^2, respectively. Meanwhile, h_1, h_2, h_3, and h_4 are the height values of edge ray from the on-axis field at the primary, secondary, tertiary, and quaternary mirrors, respectively.

The configuration parameters of the system are as follows: the obscuration ratios of mirrors α_1, α_2, and α_3 are $\alpha_1 = l_2/l_1' \approx h_2/h_1, \alpha_2 = l_3/l_2' \approx h_3/h_2$, and $\alpha_3 = l_4/l_3' \approx h_4/h_3$, respectively; the magnifications of the mirrors β_1, β_2, β_3, and β_4 are

$$\begin{aligned} \beta_1 &= (n_1 l_1')/(n_1' l_1) = -l_1'/l_1, \\ \beta_2 &= (n_2 l_2')/(n_2' l_2) = -l_2'/l_2, \\ \beta_3 &= (n_3 l_3')/(n_3' l_3) = -l_3'/l_3, \\ \text{and} \quad \beta_4 &= (n_4 l_4')/(n_4' l_4) = -l_4'/l_4, \end{aligned}$$

respectively. When objects are placed at l_1, the aperture angle is $u_1 = \frac{h_1}{l_1}$. Assuming that the stop is on the primary mirror, the coordinates of the chief ray through the stop are $x_1 = y_1 = 0$. Let $f' = 1$, then we can get the various aberration expressions.

The conic coefficient of the primary mirror e_1^2 only

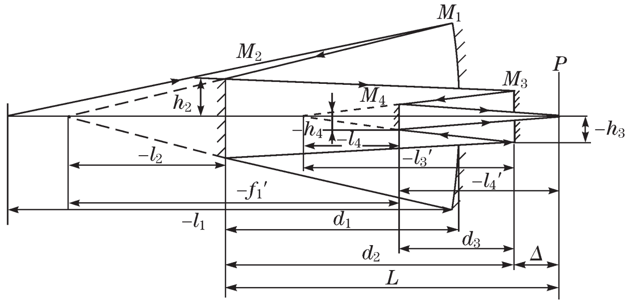

Fig. 1. Layout of the four-mirror optical system.

affects the spherical aberration S_I. Coma S_{II} and astigmatism S_{III} can be controlled by the conic coefficients of the secondary, tertiary, and quaternary mirrors, e_2^2, e_3^2, and e_4^2, respectively. Distortion will be controlled during the optimization because it has no effect on system resolution. In this case, all primary aberrations can be corrected, and there is sufficient freedom to meet the structural requirements of the system and balance the higher-order aberrations of the system.

The above analysis shows that the conic coefficient can be ignored in aberration expressions during the process when the initial structural parameters are determined.

In accordance with the geometric relationship (Fig. 1), several basic conditions are necessary in order to find solutions. The different structures of the four-mirror optical system can be deduced according to different conditions.

Eight system structures with concave and convex primary mirrors but without intermediate image can be achieved[10].

The four structures with a concave primary mirror are

$$\beta_1 < 0, \quad 0 < \alpha_1 < 1, \quad 0 < \alpha_2 < 1, \quad \beta_2 > 0,$$
$$0 < \alpha_3 < 1, \quad \beta_3 > 0, \quad \beta_4 > 0; \tag{1}$$

$$\beta_1 < 0, \quad 0 < \alpha_1 <, \quad 0 < \alpha_2 < 1, \quad \beta_2 > 0,$$
$$\alpha_3 > 1, \quad \beta_3 < 0, \quad \beta_4 < 0; \tag{2}$$

$$\beta_1 < 0, \quad 0 < \alpha_1 < 1, \quad \alpha_2 > 1, \quad \beta_2 < 0,$$
$$\alpha_3 > 1, \quad \beta_3 > 0, \quad \beta_4 < 0; \tag{3}$$

$$\beta_1 < 0, \quad 0 < \alpha_1 < 1, \quad \alpha_2 > 1, \quad \beta_2 < 0,$$
$$0 < \alpha_3 < 1, \quad \beta_3 < 0, \quad \beta_4 > 0. \tag{4}$$

The four structures with a convex primary are

$$\beta_1 > 0, \quad \alpha_1 > 1, \quad \alpha_2 > 1, \quad \beta_2 > 0,$$
$$0 < \alpha_3 < 1, \quad \beta_3 < 0, \quad \beta_4 > 0; \tag{5}$$

$$\beta_1 > 0, \quad \alpha_1 > 1, \quad \alpha_2 > 1, \quad \beta_2 > 0,$$
$$\alpha_3 > 1, \quad \beta_3 > 0, \quad \beta_4 < 0; \tag{6}$$

$$\beta_1 > 0, \quad \alpha_1 > 1, \quad 0 < \alpha_2 < 1, \quad \beta_2 < 0,$$
$$0 < \alpha_3 < 1, \quad \beta_3 > 0, \quad \beta_4 > 0; \tag{7}$$

$$\beta_1 > 0, \quad \alpha_1 > 1, \quad 0 < \alpha_2 < 1, \quad \beta_2 < 0,$$
$$\alpha_3 > 1, \quad \beta_3 < 0, \quad \beta_4 < 0. \tag{8}$$

Structures can be chosen according to their practical applications. After the selection, calculating the required initial structural parameters of the corresponding structure will be very easy.

Based on the above analysis, a structure is selected optionally as a design example as shown in inequality (8). Initial values are α_1=2.86, α_2=0.34, β_1=0.4, and β_3=−0.25. Assuming that the primary and tertiary mirrors are aspheric, with the assistance of Matlab, α_3, β_2, and β_4 can be calculated from the aberration equations.

Initial structural parameters of the system are shown in Table 1.

The layout of the initial structure indicates that the obscuration of the system is serious. In the optimization process, it is necessary to pay more attention in order to remove the obscuration. The layout of the system after optimization is shown in Fig. 2. The modulation transfer function (MTF) curves of the optimized system are shown in Fig. 3. The MTF value can reach up to 0.43 at 10000l p/mm, which is close to the diffraction limit. Distortion of the system is shown in Fig. 4. The distortion value is less than 0.25% at the maximal field of view.

The projection lithography system can achieve a scan ring width of 5 mm and high image of 50 mm with 1/2.3 magnification. The numerical aperture (NA) equals 0.13 in the imagery space. The system performance is listed in Table 2.

The optical system tolerance is analyzed by CODE V software. The floating of the MTF value is used to indicate changes in tolerance sensitivity. The compensation parameter is $D5$ (image plane displacement), with a

Table 1. Optical Parameters of the Four-Mirror System with No Intermediate Image

Mirror	Radius (mm)	Conic Constant (K) and Coefficients (A, B, C, D)	Thickness (mm)
M_1	1380.20	K=−3.058 A=−3.24×10^{-10}	−357.12
M_2	798.00	K=−6.47 C=−3.17×10^{-18} D=8.45×10^{-22}	260.34
M_3	264.00	C=−1.90×10^{-19} D=−3.82×10^{-24} K=3.12	−117.32
M_4	322.02	A=−2.46×10^{-10} B=−7.88×10^{-16} C=−3.84×10^{-20} D=8.07×10^{-25}	

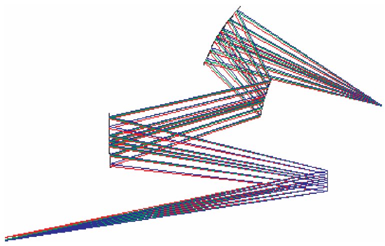

Fig. 2. Layout of the system.

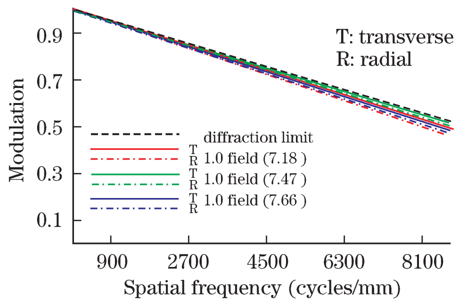

Fig. 3. MTF curves of the system.

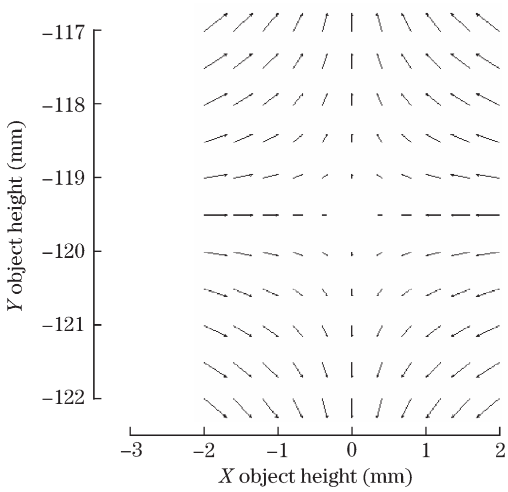

Fig. 4. Field map of designed optical system without intermediate image.

Table 2. Performance of the System without an Intermediate Image

Performance	Value
Magnification	1/2.3
NA	0.13
Field of View (mm)	50
Scan Ring Width (mm)	5
Object Distance (mm)	580
Object Height (mm)	120

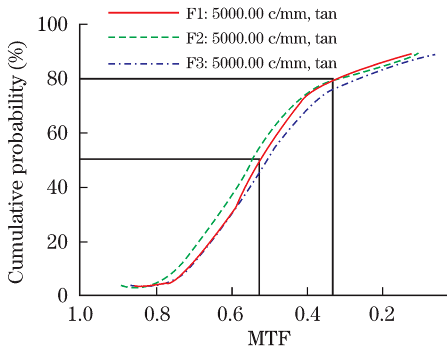

Fig. 5. Probability distribution curves of MTF.

maximum compensation amount of 0.5 mm. The system is not sensitive to radius thickness, tilt, and offset of the primary mirror. The sensitive tolerance is the 45° cylindrical irregularity and the beta surface tilt about Y axis of the tertiary and quaternary mirrors. For the aspheric coefficients, the coefficients of the primary mirror are particularly sensitive. The sensitivities of the tolerance parameters after adjustment are shown in Table 3.

The probability distribution curves of MTF after the tolerance is adjusted are shown in Fig. 5.

Results show that the MTF values of 80% and 50% lenses can be respectively higher than 0.35 and 0.55 at 5000 lp/mm. The image quality also meets the requirement of the actual application. This proves that the tolerance of the system is feasible. If better performance is required, then these sensitive tolerances have to be more stringent.

Table 3. Value of Tolerance Parameters

Name	Value
Radius (mm) (M_1−M_3)	0.02
X Group Displacement (mm) (M_3)	0.01
0° Cylindrical Irregularity (Ring) (M_3, M_4)	0.5 (for 550 nm)
Alpha Surface Tilt about X Axis (deg.)	0.0003
Thickness (mm) (M_1, M_3)	0.01
Y Group Displacement (mm) 45°	0.01
Cylindrical Irregularity (Ring) (M_3, M_4)	0.1
Beta Surface Tilt about Y Axis (deg.)	0.0001

In conclusion, the theory and design requirements of EUV projection lithography system is discussed in detail, and a design method through the solution of the aberration equations of the ultraviolet lithography lens is presented. After analysis of the optical system design, a four-mirror lithography system with a 1/2.3 magnification and a working wavelength from 11 to 13 nm is achieved. The ring width is from 5 to 10 mm. The distortion of the four-mirror lithography system is less than 0.25% in its full-field view. These parameter values show that the four-mirror system has superior performance. Tolerance analysis proves the realization of the four-mirror optical system in lithography technology. Design results can be applied to advanced ultraviolet lithography equipment.

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