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Jiahua Jiang
Qiuli Mei
Yanqiu Li
Yan Liu

SPIE.

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Illumination system with freeform fly's eye to generate pixelated pupil prescribed by source-mask optimization in extreme ultraviolet lithography

Jiahua Jiang, Qiuli Mei, Yanqiu Li,* and Yan Liu

Beijing Institute of Technology, Key Laboratory of Photoelectron Imaging Technology and System of Ministry of Education, School of Optoelectronics, Beijing, China

Abstract. Source-mask optimization (SMO) has emerged as a key technique for 7-nm node and beyond in extreme ultraviolet (EUV) lithography. The pupil required by SMO is usually pixelated, with a free choice of intensity per pixel. However, due to the discrete nature of the EUV illumination system, pupil intensity in current EUV SMO must also be discretized. An illumination system with a freeform fly's eye that is able to generate the pixelated pupil is proposed. Clear apertures of the field facets in the fly's eye are different from each other so that the intensity of each pixel on the pupil can meet the requirements of SMO. Each of the field facets is constructed with a freeform surface to get the required arc-shaped illuminated area on the reticle. A method integrated with a numerical method and an optimization process is used to design the freeform surface of the field facets. The simulation result of the design for a prescribed freeform pixelated pupil shows that the uniformity on the reticle is 96.4%, and the pupil intensity error is approximated to be 0.035. The results indicate that the system is effective in generating the required freeform pixelated pupil and reducing the restrictions imposed on the SMO process in EUV lithography. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.56.6.065101](https://doi.org/10.1117/1.OE.56.6.065101)]

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1 Introduction

Source-mask optimization (SMO) has been a key enabler for 7-nm node and beyond in the extreme ultraviolet (EUV) lithography.^{1,2} The pupil predicted by SMO is usually pixelated, with a free choice of intensity per pixel.³⁻⁵ Figure 1 shows examples of the freeform pixelated pupil for different illumination modes.

The fly's eye configuration including the field facet mirror and pupil facet mirror is usually utilized to realize the different illumination modes in EUV illumination system.^{6,7} Each of the two facet mirrors in a fly's eye comprises many identical reflective facets arranged close to each other. By adopting the field facets with different tilt angles, the system can achieve the illuminated area in the required shape on the pupil. However, it is unable to realize the specific intensity prescribed by SMO for each pixel, restricting the freedom in EUV SMO. To be compliant with the illumination system, the pupil prescribed by EUV SMO must be discretized with discrete intensity within the pupil, as shown in Fig. 2.¹ In recent years, the diffractive optical element and mirror array have been used to realize the freeform pixelated pupil in deep ultraviolet lithography.^{8,9} For EUV lithography, however, adding additional elements to the illumination system is not advisable since it would greatly reduce the light energy efficiency of the system. Until now, there has been no illumination system for EUV lithography capable of generating the freeform pixelated pupil with different intensities per pixels.

In this paper, an illumination system that is able to generate a freeform pixelated pupil required by SMO is proposed. The system is constructed with a freeform fly's eye and two conic relay mirrors. Clear apertures of the field facets are rectangular and different from each other to get the required intensity for each pixel on the pupil. The freeform surface is introduced to configure each field facet to realize an arc-shaped irradiance on the reticle. At the same time, the curvatures of the pupil facets differ from each other so that the arc-shaped illuminated area on the reticle formed by each field facet with different clear apertures are the same. Finally, two conic relay mirrors are deposited downstream to realize the conjugate relationships in Köhler illumination and ensure that the light source and reticle are on different sides of the illumination system. A method integrated with a numerical method and an optimization process is utilized to design the freeform facets. With such a configuration, the system enables the implementation of a freeform pixelated pupil prescribed by SMO and, consequently, increases the resolution further.

2 Illumination System to Generate Pixelated Pupil

Figure 3 shows the typical sketch of an EUV exposure system. As one of the key components, the illumination system should meet two main requirements. The first one is to achieve a uniform illumination across the arc-shaped field on the reticle shown in Fig. 4. The other is that the exit pupil of the illumination system should coincide with the entrance pupil of the objective and provide different illumination modes for the exposure tool. Since the requirement for the irradiance uniformity on the reticle is very high, the illumination system always employs a Köhler configuration.

*Address all correspondence to: Yanqiu Li, E-mail: liyanqiu@bit.edu.cn

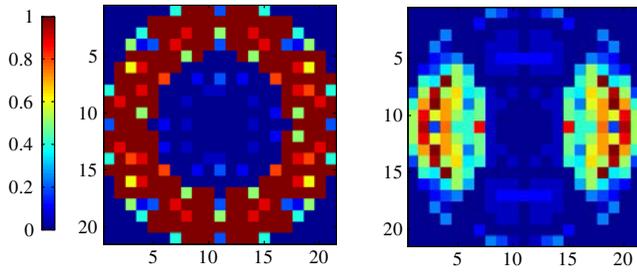


Fig. 1 The intensity distribution of the freeform pixelated pupil required by SMO.



Fig. 2 The discretization process of a freeform pupil with continuous intensity distribution. The optimal freeform pupil is discretized and optimized into a discrete final pupil, degrading the imaging performance more or less.

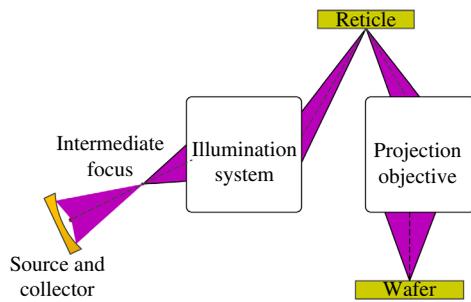


Fig. 3 The typical sketch of an EUV exposure system.

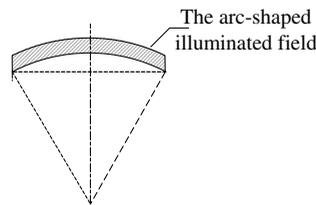


Fig. 4 The arc-shaped field on the reticle.

Figure 5 shows the illumination system that is able to generate the freeform pixelated pupil. For clarification, we set up an XYZ coordinate system based on the right-hand rule for the system shown in Fig. 5. The Y-axis runs upward, and the Z-axis runs to the right. The illumination system consists of the fly's eye configuration and two conic relay mirrors. The beam emitted from the intermediate focus (IF) strikes the field facet mirror. Hundreds of field facets split the beam into light channels with different intensities and image IF to the corresponding pupil facet. Then, the images of the field facets will be formed by the relative pupil facets and overlap each other on a virtual plane. Two conic relay mirrors are employed as relay system to make the light source and reticle locate on different sides of the illumination system. The conjugate relationship between the pupil facets and entrance

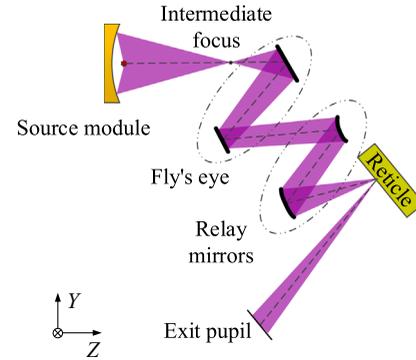


Fig. 5 The illumination system able to generate pixelated pupil.

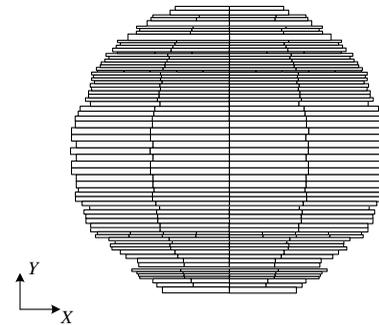


Fig. 6 The arrangement of field facets.

pupil of the objective is realized by the conic relay mirrors. At the same time, the superimposed image of the field facets is imaged to the reticle plane.

Clear aperture of each field facet is rectangular. By utilizing the field facets with different clear aperture sizes, the system is able to achieve the required intensity for each pixel on the exit pupil. Figure 6 shows the arrangements of the field facets. The number of the facets is equal to that of the pixels with nonzero intensity on the exit pupil. Light reflected by each field facet impinges on the relative pixel through the assigned pupil facet and the relay mirrors. Meanwhile, to achieve an arc-shaped illuminated area on the reticle, a freeform surface is used to configure each of the field facets. Tailored by the freeform facet, the beam within each light channel can generate an arc-shaped irradiance distribution on the reticle.

Since the field facets differ in size from each other, the dimensions of the arc-shaped illuminated field formed by each field facet on the reticle are quite different, resulting in deteriorative illumination uniformity and, consequently, influencing the intensity distribution on the exit pupil. To deal with this problem, the system utilizes pupil facets with different curvatures. Such configuration ensures that each arc-shaped field is of the same dimension. When the design of the fly's eye is finished, the two relay mirrors are deposited to realize the conjugate relationships.

3 Method to Design the Freeform Field Facet

The coordinate and surface parameters of the relay system in the illumination system are computed with the reverse ray-trace method.¹⁰ When the arrangement of the field facets is determined, the curvature of each pupil facet is achieved by

geometrical optics. In this section, we will focus on the design of the freeform field facets. Since each pair of the fly's eye functions in a similar way, we just introduce the design of one field facet.

A few design algorithms to calculate freeform surfaces that generate prescribed irradiance distributions have been proposed.¹¹⁻¹⁸ Luo et al. presented an iterative feedback modification method based on variable separation mapping for LED illumination.¹⁵ By iteratively modifying the target illumination and redesigning the freeform surface, a smooth freeform surface is obtained. Due to the Monte-Carlo ray tracing of several millions of rays in each iteration, the method is very time-consuming. Michaelis et al. proposed a Cartesian oval-based method.¹⁶ The illumination problem is discretized and a lot of Cartesian ovals are used to solve the discretized problem. A continuous freeform surface realizing the prescribed illumination is obtained by repeatedly adjusting tens of thousands Cartesian ovals. Obviously, the method is fairly complicated and inefficient. Designing a smooth optical freeform lens to generate an asymmetric irradiance distribution is still very difficult.^{17,18}

A design method integrated with a numerical method and an optimization process to achieve a smooth freeform facet was proposed by us in Ref. 19. The numerical method calculates the freeform surface profile by solving a set of differential equations and interpolating the acquired discrete points with a smooth spline surface. The optimization process aims to improve the shape of the illumination area and enhance irradiance uniformity. The basic steps of this method relating to the field facets design are summarized in the following.

A set of partial differential equations is established based on the Snell's law of reflection.¹⁴ Figure 7 shows the ray path between the field facet mirror and the target plane that coincides with the pupil facet mirror, where \vec{I} is the unit incident vector, $\vec{O} = \vec{PT}/|PT|$ is the unit reflective vector, and \vec{N} is the surface normal. According to Snell's law of reflection,

$$\vec{O} - \vec{I} = \sqrt{2 - 2(\vec{O} \cdot \vec{I})}\vec{N}. \tag{1}$$

A set of partial differential equations is established as follows:

$$\begin{cases} z_x = f_1(x, y, z, t_x, t_y) \\ z_y = f_2(x, y, z, t_x, t_y) \end{cases}, \tag{2}$$

where (x, y, z) is the coordinate of point P on the freeform field facet, z_x and z_y are first-order partial derivatives of z

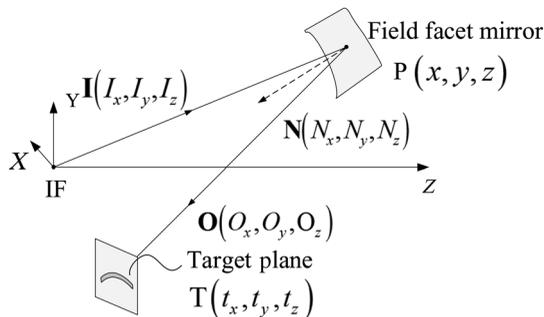


Fig. 7 The ray path between field facet mirror and the target plane.

along the X and Y directions, respectively, and (t_x, t_y) is the coordinate of point T on the target plane.

To solve Eq. (2), specific coordinate relationships between point P and its corresponding point T should be established. The coordinate relationship is obtained by energy mapping method, which has been presented in Ref. 19 in detail. Using the coordinate mapping relationship to solve Eq. (2) with an appropriate numerical equation solving algorithm, a set of discrete data points are obtained. The starting design is generated by interpolating these data points with a smooth spline surface.

After the process to get the starting design, the freeform surface needs to be optimized to get a qualified system performance. The optimization process using the LightTools software (Synopsys, Inc.) depicted in Ref. 19 is used in this paper. Taking into account both the search efficiency and the performance of the freeform surface, we choose 35×7 optimization variables in $X \times Y$ direction in the following design example. Then, the ray-based merit function constructed with the position deviation on the target plane embedded in LightTools is chosen to optimize the freeform surface.

4 Design of the Illumination System

An illumination system for a given projection objective²⁰ was designed with the configuration described above. Parameters of the objective are listed in Table 1. NA is the numerical aperture of the objective in image space. $r_{out_reticle}$ is the radius of the outer circle of the arc on the reticle, and $r_{in_reticle}$ is the radius of the inner circle of the arc.

Based on the dimension of the Sn fragment and the collector for laser produced plasma (LPP) light source, we use a 600- μm -diameter spherical source at the IF for the following simulation.²¹⁻²³ Figure 8 shows the structure of the illumination system in LightTools. The track length of the system is about 2351.49 mm. A freeform pixelated pupil shown in Fig. 9 is chosen as the target pupil that needs to be realized by the illumination system. The number of the pixels is $21 \times 21 = 441$. There are 246 field facets in the illumination system. The arrangement of the field facets is given in Fig. 6. All of the field facets are deposited within a circle. Figure 10

Table 1 Parameters of the objective.

Item	Exposure field (mm)	Reduction ratio	NA	Entrance pupil distance (mm)
Objective	104×6 $r_{in_reticle} = 136$ $r_{out_reticle} = 142$	4	0.33	1322.50

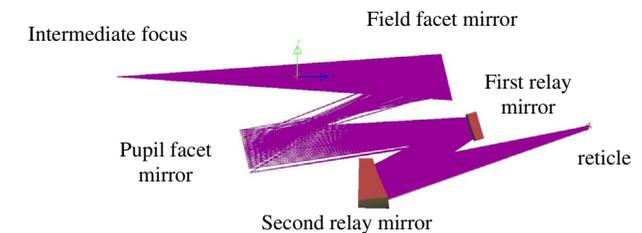


Fig. 8 Structure of the illumination system generating pixelated pupil.

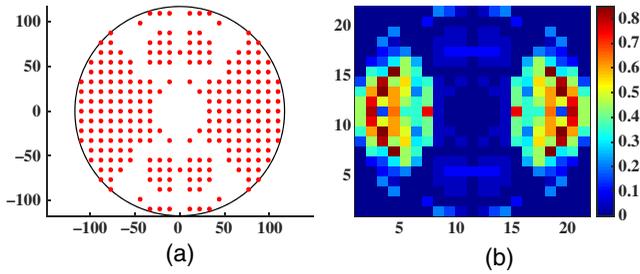


Fig. 9 The pixelated pupil that needs to be realized by the illumination system. (a) The target discrete source point distribution and (b) the light intensity distribution of discrete source points.

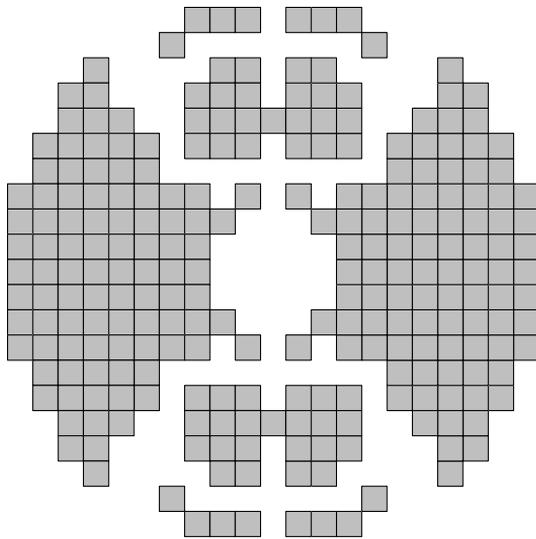


Fig. 10 The arrangement of pupil facets realizing freeform pixelated pupil.

shows the arrangements of the pupil facets. Only the ones depicted dark are illuminated.

When the system is set to realize a different pixelated pupil, the new freeform surface fly's eye is achieved based on the target pixelated pupil and the design method described above. A standard pupil can also be realized by this system with a spherical surface fly's eye configuration, which has been realized by our previous work.¹⁰ In the following, the performance of the illumination system realizing the target pupil shown in Fig. 9 will be evaluated in terms of uniformity on the reticle plane and the pupil intensity error.

4.1 Irradiance Uniformity of the System

The irradiance uniformity of the illumination system is calculated within the arc-shaped ring on the reticle

$$U = \left(1 - \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \right) \times 100\%, \quad (3)$$

where E_{\max} and E_{\min} present the maximum and minimum light intensity line integrals in scanning direction over the irradiance distribution, respectively. With the LightTools ray-tracing program, 200,000,000 rays are created at the IF and then traced nonsequentially. Figure 11 shows the irradiance distribution on the reticle. The uniformity is ~96.4%.

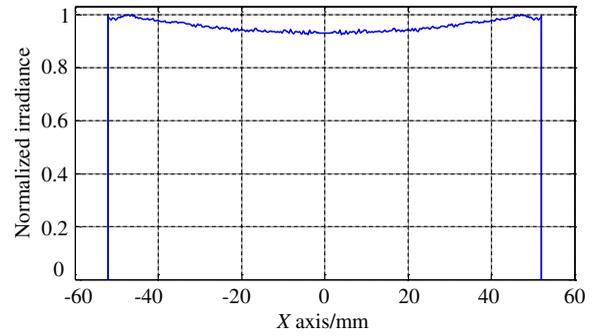


Fig. 11 The normalized irradiance distribution on the reticle.

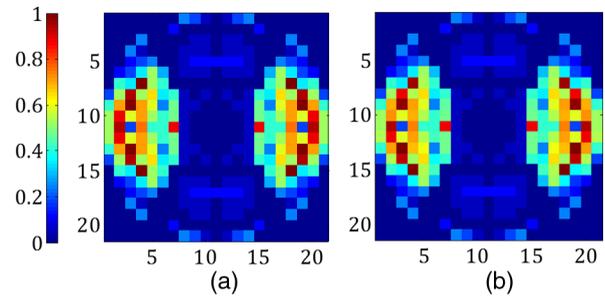


Fig. 12 The normalized intensity distribution on the exit pupil: (a) the prescribed distribution and (b) the actual distribution.

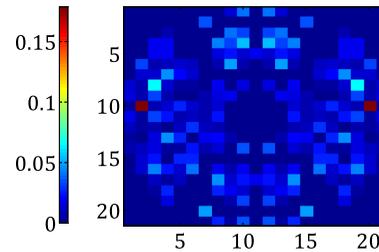


Fig. 13 The error distribution for each pixel.

4.2 Pupil Intensity Error of the System

The normalized intensity distribution on the exit pupil is shown in Fig. 12.

To evaluate the pupil intensity distribution, we define the pupil intensity error as follows:

$$\text{Intensity error} = \sqrt{\frac{\sum_{i=1}^{21} \sum_{j=1}^{21} [I(i, j) - I_0(i, j)]^2}{21 \times 21}}, \quad (4)$$

where i and j represent the row and column of the pixel and $I(i, j)$ and $I_0(i, j)$ represent the actual normalized intensity and prescribed normalized intensity received by the pixel, respectively. Figure 13 shows the distribution of the error for each pixel. With the LightTools ray-tracing program, the pupil intensity error is approximated to be 0.035.

5 Conclusion

In this paper, we propose an illumination system that is able to realize the freeform pixelated pupil required by SMO for EUV lithography. A freeform fly's eye is introduced

to ensure a qualified irradiance distribution along with the freeform pixelated pupil. The method to achieve the freeform surface is described. The design result of the illumination system for a given freeform pixelated pupil is illustrated. The results show that an irradiance uniformity of about 96.4% is achieved. Based on the actual intensity distribution on the exit pupil, the pupil intensity error of the system is approximated to be 0.035. This demonstrates that the proposed illumination system can realize the required freeform pixelated pupil and, further, can add more freedom to the SMO in EUV lithography in the future.

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Jiahua Jiang received his BS degree in optical information science and technology from Beijing Institute of Technology in 2015. Currently, he is a master's candidate directed by Prof. Yanqiu Li in the School of Optoelectronics at Beijing Institute of Technology. His current interests include illumination system design for EUVL.

Qiuli Mei received her BS degree in optical information science and technology from Wuhan University of Technology in 2010, and her PhD in optical engineering from Beijing Institute of Technology in 2016. Her current interests include illumination system design for EUVL.

Yanqiu Li received her MS degree and PhD in optics from Harbin Institute of Technology of China. She worked as a director of the micro- and nanofabrication division at IEECAS as an associate professor at Harbin Institute of Technology of China, a senior engineer at Nikon, an invited professor of Tohoku University of Japan, and a frontier researcher at RIKEN of Japan. Currently, she is a professor in the School of Optoelectronics at Beijing Institute of Technology, Beijing, China. She has published numerous articles on lithographic science.

Yan Liu received his BS degree in optoelectronic information engineering from Changchun University of Science and Technology in 2010. Currently, he is a PhD candidate directed by Prof. Yanqiu Li in the School of Optoelectronics at Beijing Institute of Technology. His current interests include freeform surface optical system design.