Optical design for EUV lithography source collector

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Wolter I collector is the best collector for extreme ultraviolet (EUV) lithography, which has a series of nested mirrors. It has high collection efficiency and can obtain more uniform intensity distribution at the intermediate focus (IF). A new design with the calculation sequence from the outer mirror to the inner one on the premise of satisfying the requirements of the collector is introduced. Based on this concept, a computer program is established and the optical parameters of the collector using the program is calculated. The design results indicate that the collector satisfies all the requirements.

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Nowadays, modern life has become increasingly related to integrated circuit technology whose development depends on lithography. Extreme ultraviolet (EUV) lithography used for super large-scale integration is one of the techniques that may replace 193-nm lithography at present[1−3]. It uses EUV wave (mainly at 13.5 nm) to expose the wafer, and has the advantages of high resolution and less pollution, to name a few[4−6]. In order to collect more energy of the EUV source and match the numerical aperture (NA) of illuminating system behind the EUV source, there must be a collector between them to link the EUV source and the illuminating system. The collector is used for collecting the radiation emitted by the EUV source and making the radiation converge to a spot with high luminance and good uniformity of intensity distribution.

One of the most promising collectors for EUV lithography is Wolter I collector, which has high collection efficiency and good uniformity of intensity distribution[7]. Wolter I collector consists of a series nested mirrors. Each mirror is made up of two surfaces, hyperboloid and ellipsoid, which are in rotational symmetry around the major axis. The two surfaces have one common focus. The EUV source is placed at the other focus of the hyperboloid, and the image point (the intermediate focus (IF) of EUV lithography system) is at the other focus of the ellipsoid (Fig. 1). The Wolter I collector employs the grazing incident mode to reflect EUV ray, so it can ensure the high reflectivity and improve the transmission efficiency of EUV waveband of the entire collector.

The design of the Wolter I collector is different from general optical systems due to its grazing incident mode and nested structure. The main requirements of EUV collector are collection efficiency, size, and distribution of image spot at point IF and the NA at image space. By analyzing the structure of the Wolter I collector, it finds that most requirements are relative to the outermost mirror shell. Thus, our idea in designing Wolter I collector is to find out the family of the combinations of hyperboloid and ellipsoid of the outermost mirror that satisfy the requirements. We optimize these combinations to select the one with best performance. Finally, we use this combination to calculate the other inner mirrors.

The collection efficiency, which is defined as the ratio between the in-band power at the intermediate focus and the in-band power emitted from the source in 2π sr[8] is one of the most important requirements of EUV collector, because the collector must ensure the energy of the EUV wave for exposure of the wafer for mass production. The intensity distribution of the image spot is decided by the mask, and this performance of Wolter I collector is better than that of the collector, which only consists of nested ellipsoid mirrors[7]. The NA is decided by the illuminating system behind the collector.

According to the collection efficiency we can calculate the values of the initial parameters[7], such as collected angle (including the number of mirrors) and the maximal grazing incident angle, after which we choose the kind of coat on the mirror[9]. The NA in image space, the distance of source to the image, the size of collector, and the distance of source to mirrors edge (as decided by the foil trap system) can be fixed depending on the whole EUV lithography system. Table 1 shows the requirements that we choose to design a Wolter I collector.

Next, the main purpose is to find out the satisfying combinations of hyperboloid and ellipsoid of the outmost mirror. Given that the hyperboloid and ellipsoid are in rotational symmetry around the major axis, there

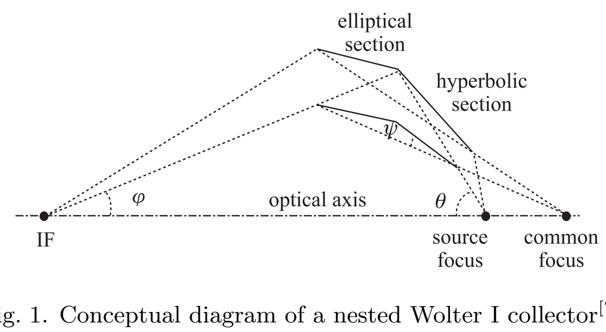

Fig. 1. Conceptual diagram of a nested Wolter I collector[7].

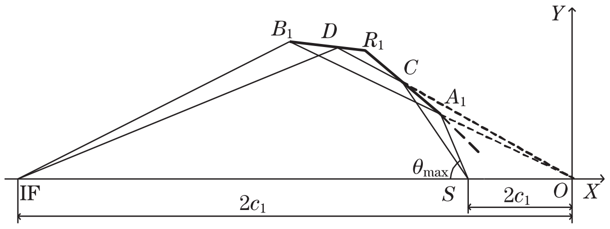

Fig. 2. Reflection case of the EUV ray on the outermost mirror.

is a need to find out the corresponding hyperbola and ellipse of the two surfaces in the cross-section, including the major axis. If we take the common focus of the two surfaces as the origin of coordinate, the major axis as the X axis, and point IF is at the negative direction of the X axis (Fig. 2), then the equations of hyperbola and ellipse can be written as

$$\begin{aligned} &\text{hyperbola}: \frac{(x-c_1)^2}{a_1^2}+\frac{y^2}{b_1^2}=1, \\ &\text{ellipse}: \frac{(x-c_2)^2}{a_2^2}-\frac{y^2}{b_2^2}=1, \end{aligned} \quad (1)$$

where a_1 is the major semi-axis of ellipse, b_1 is the minor semi-axis of ellipse, c_1 is the focal length of ellipse, a_2 is the major semi-axis of hyperbola, b_2 is the minor semi-axis of hyperbola, and c_2 is the focal length of hyperbola.

By analyzing Eq. (1) and the requirements, we choose c_1 and c_2 as the initial parameters whose values must be assumed. The method to choose the values for c_1 and c_2 shall be discussed in the next paragraph. As for ellipse and hyperbola, there are determinate relationships as expressed by

$$\begin{aligned} &a_1^2-b_1^2=c_1^2, \\ &a_2^2+b_2^2=c_2^2. \end{aligned} \quad (2)$$

Now, there is a need to figure out one point on each curve to solve the equations of the curves. The processes to calculate the outermost mirror can be listed in three steps.

Step 1: Choosing the values of the initial parameters c_1 and c_2

From Fig. 2, we know that $2c_1$–$2c_2$ is the distance of source to image (IF). By calculation, it finds the maximal grazing incident angle on the hyperboloid is obtained at point A_1. Meanwhile, the following relationship exists between the grazing incident angles at points A_1 and c_2:

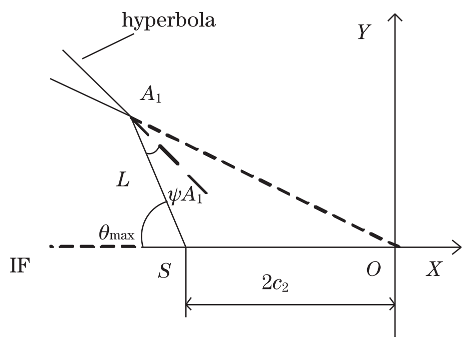

Fig. 3. Local enlarged view of Fig. 2.

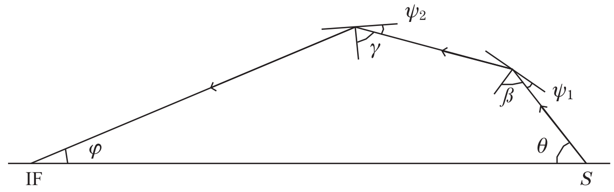

Fig. 4. Angles on the outermost mirror.

$$\psi_{A_1}=\frac{\theta_{\max}-\arctan(\frac{L\sin\theta_{\max}}{2c_2+L\cos\theta_{\max}})}{2}, \quad (3)$$

where $\theta_{\max}$ is the maximal collected angle and L is the distance of source to mirror's edge (Fig. 3).

For the Wolter I collector, a ray is reflected twice on the mirror. The grazing incident angles on these two reflected points are relative to the NA angle and the collected angle expressed as (see Fig. 4)

$$\psi_1+\psi_2=(\theta+\varphi)/2 \quad , \quad (4)$$

where θ is the collected angle, φ is the numerical aperture angle, and ψ_1 and ψ_2 are the grazing incident angles. The corresponding reflected point of A_1 is B_1. As such, when deciding the grazing incidence angle on point A_1 by c_2, we must also satisfy the requirements. For example, assuming that the NA is 0.2 and the NA angle is about 11.5°, thus, the sum of the two points' grazing incident angles is given by $\psi_{A_1}+\psi_{B_1}$=$(\theta+\varphi)/2$=(60 + 11.5)=35.75°.

If ψ_{A_1} is smaller than 15.75 °, ψ_{B_1} will be larger than 20°. Thus, the value of c_2 must be limited in an interval that can ensure that ψ_{A_1} is neither too large nor small. Since $2c_1$–$2c_2$ is the distance of source to point IF, c_1 can also be fixed.

Step 2: Finding out one point on the each curve respectively

After assuming the values of c_1 and c_2, we just need to ascertain the coordinates of the two points on each surface. By the parameters listed in Table 1 and c_1 and c_2, we can calculate the coordinates of points S, IF, and A_1. Then, we can also calculate the coordinates of B_1 with the NA in image space. Substituting c_1 and c_2 and the coordinates of A_1 and B_1 into Eqs. (1) and (2), we can calculate other parameters of ellipse and hyperbola, i.e., a_1, b_1, a_2, and b_2. Using this process, we can identify the structure of the outermost mirror decided by the initial values c_1 and c_2.

Table 1. Main Technical Specification for the EUV Collector

Parameter	Value
Source to the IF Distance (mm)	2100
Source to the Outermost Mirror Edge Distance (mm)	200
Number of Mirrors	10
The Maximal Collected Angle	60°
The Grazing Incidence Angle	< 20°
NA at Intermediate Focus	0.1∼0.25
Mirror Shell Diameters (mm)	< 800
Mirror Shell Length (mm)	< 500

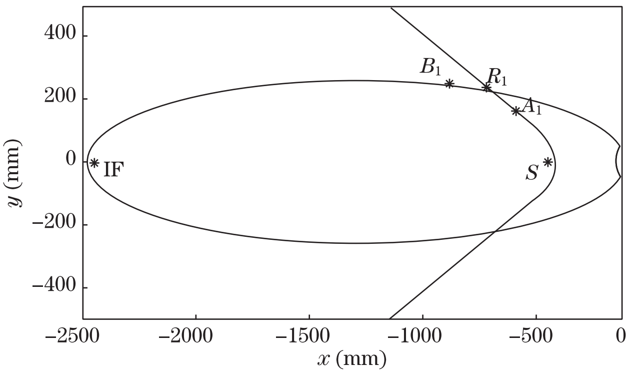

Fig. 5. Hyperbola and ellipse of the outermost mirror.

Step 3: Checking the result derived by c_1,c_2

Next, there is a need to validate whether or not the structure of the mirror satisfies the requirements. If it meets the requirements, this structure can be saved as a model in order to be optimized in the next step. If not, it has to modify the values of c_1 and c_2, calculate the structure parameters (a_1, b_1, a_2, and b_2), the coordinates of A_1 and B_1, and then validate this structure according to the former processes one more time. In the process of modifying c_1 and c_2, the rule of the changes of mirror's structure with the changes of c_1 and c_2 in order to more quickly identify the most proper structure are summarized.

The best way to achieve the processes presented in the former parts is by writing a computer program to perform the calculation. The optimization of the structure can also be achieved by the program written by the authors. The optimizing process runs based mainly on two foundations. First, our computer program can estimate the collection efficiency of each mirror and the whole collector. Second, in practice, when we optimize the structure of the collector to achieve the higher collection efficiency, the only variable in the input parameters is c_2 once the lower limit of collection efficiency is fixed by other input parameters. Thus, it is easy to find out a more appropriate c_2 to achieve the satisfied collection efficiency. The computer program is presented in the appendix. Figure 5 shows the appropriate curves of the outermost mirror as calculated by the program.

After ascertaining the structure of the outermost mirror, we can calculate the structure parameters of the ellipse and hyperbola of the inner mirrors depending on the geometry relationship (Fig. 6). In the design of the inner mirrors, the vignetting resulted from adjacent mirrors must be taken into account. There is a need to pay attention to the relationships of the boundary points on each mirror and the order of calculating their coordinates to ensure that the brim of each mirror does not block

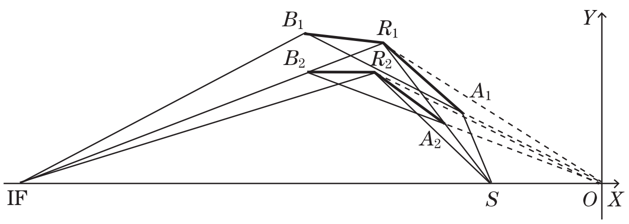

Fig. 6. Conceptual diagram of the two nested mirrors.

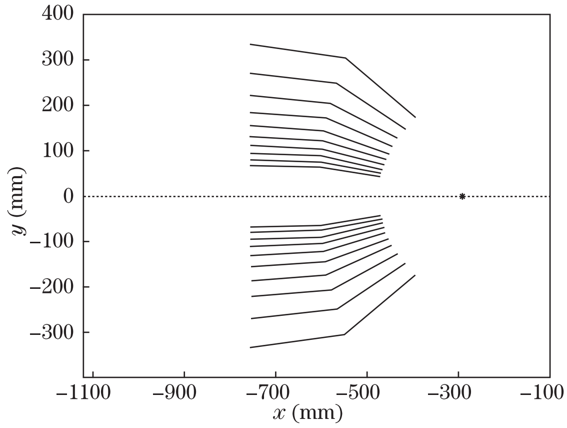

Fig. 7. Structure of the Wolter I collector. The point is the position of the EUV source.

the rays reflected by the adjacent mirrors. The order of calculation is from the image space to the object space (from IF to S).

The processes of calculating the structure of the inner mirrors and the coordinates of edge points (A_2, $A_3, \cdots$, B_2, and $B_3, \cdots$) are similar as those of the outermost mirror. We have also programmed the computer to do this work. Once the parameters of the whole collector were calculated, we used the program that we wrote to optimize the structure to achieve the best uniformity of the intensity distribution. Figure 7 shows the structure

Table 2. Comparison between the Design Results and the Initial Requirements

Parameter	Initial Requirements	Design Results
Source to IF Distance (mm)	2100	2100
Source to Outermost Mirror Edge Distance (mm)	200	200
Number of Mirrors	10	10
The Maximal Collected Angle	60°	60°
The Grazing Incidence Angle	< 20°	19.3°(max)
Numerical Aperture at Intermediate Focus	0.1∼0.25	0.2
Mirror Shell Diameters (mm)	< 800	668.2
Mirror Shell Length (mm)	< 500	363.2

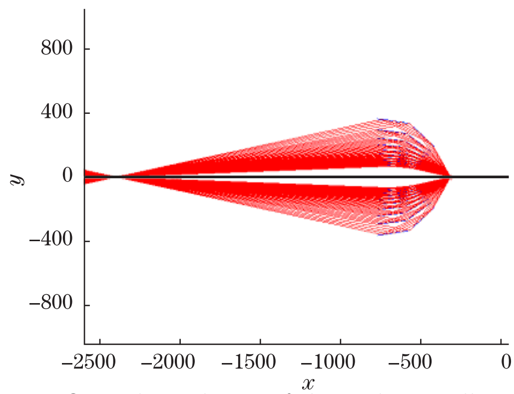

Fig. 8. Optical simulation of the Wolter I collector.

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function [ a ] = EUV_Collector (Lsif, c2, L, thet amax1, thet amax2, n)
%EUV_Collector is the program for design, optimize a EUV collector.%
%Author : Dongyuan Zhu (Harbin Institute of Technology)%
%Completion time : May, 2010%
%Introduction :
% Input parameters :  1  " Lsif " : the distance between source and IF point.
%                     2  " c2 " : the focal lenth of hyperbolas.
%                     3  " L " : the distance btween source and the edge of the mirr
%                     4  " thet amax1 " : the maximal collected angle (units : rad).
%                     5  " thetamax2 " : the numerical aperture angle in image space (un
%                     6  " n " : the number of rays on every mirror in ray trace pro
% Output parameters : 1  " c1 " : the focal lenth of ellipses.
%                     2  " (xa, ya) " : the coordinates of points Ai of each mirror.
%                     3  " (xa, ya) " : the coordinates of points Bi of each mirror.
```

Fig. 9. Introduction of our EUV design program, the "EUV_Collector".

```
%Calculation mudole, from row 28 to row 129.%
c1 = 0.5* (Lsif + 2 * c2)
xs = −2 * c2
ys=0
xa1 = −2 * c2−L * cos (thetamax1);
ya1 = L * sin (thetamax1);
xb1 = (2 * c1 * tan (thetamax2))/(ya1/xa1−tan(thetamax2));
yb1 = tan (thetamax2) * (xb1+2 * c1);
```

Fig. 10. Calculation module of the "EUV_Collector".

of the whole collector as we have designed. Figure 8 is the optical simulation of the collector. Two parts of the program written by us for designing the EUV collector are shown in Figs. 9 and 10. The design results are listed in Table 2 with the comparison of the initial requirements listed in Table 1.

In conclusion, the designed collector satisfies all the initial specifications, and the collection efficiency is about 0.35, which is a high value for an EUV collector[10]. The new method presented in this letter is fit for designing a Wolter I collector for EUV lithography through a series of tests. The advantages of this method are its convenience, accessibility, and potential to be improved when used in related fields and applications.

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