Catadioptric lens development for DUV and VUV projection optics

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ABSTRACT

According to the International Technology Roadmap for Semiconductors (ITRS), the 65nm technology node is forecast to appear in 2007. In this paper, we propose two specifications for the projection optics at 65nm nodes. The one is over 1.0 numerical aperture (NA) at 193nm lithography by liquid immersion$^{1)}$. The other is 0.85 NA at 157nm lithography$^{2), 3)}$. Since it is almost impossible for traditional dioptric optics to realize these specifications, catadioptric is supposedly the leading optics for an extreme optical lithography, like 65nm node. Described in the paper are feasibility study for catadioptric optics, and our assembly strategy. Emphasis is placed on our selection methodology among a variety of catadioptric configurations.

Keywords: 193nm, 157nm, projection optics, catadioptric, dioptric, liquid immersion, assembly strategy

1. INTRODUCTION

The resolution required to projection optics for exposure tools has been rapidly increased. This can be represented in Rayleigh's equation, such that;

$$R = k_1 \frac{\lambda}{NA} \qquad (1)$$

where R is the resolution, λ is wavelength of exposure light, and k_1 is process constant determined by resist performance, mask and illumination condition. In order for the optics to improve the resolution, it has been an orthodox approach to shorten the wavelength of exposure light and to increase the NA of projection optics. However, if the wavelength of the exposure light is shortened, the number of types of available glass materials is limited to a few due to the absorption of light. In fact, usable materials for 193nm are only fused silica and calcium fluoride, and the only one for 157nm is calcium fluoride. Moreover, if the NA is increased, many lens elements with large diameter are required. Because the situation is like mentioned above, it has become all the more important to select proper optics type and study minutely for its assembly strategy for the upcoming lithography optics.

2. CATADIOPTRIC VS. DIOPTRIC

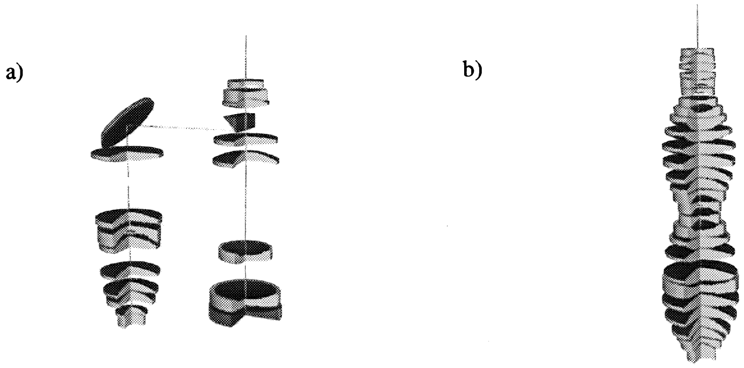

Fig. 1: Sample designs of "Catadioptric" and "Dioptric" optics

The catadioptric optics, which is constructed with refractive elements and mirrors, has been utilized in a camera objective and an astronomical telescope for a long time. For the projection optics for microlithography, it has already been studied for 20 years[4)], an example of which is given in Fig. 1a. However, it has not become the leading optics for the lithography thus far. The dioptric optics (See Fig. 1b) is constructed with only refractive elements. The optics, all the elements of which are rotational symmetric and aligned along one optical axis, can be assembled within one lens barrel. So, it can be concluded that the dioptric has an advantage in terms of lens producibility. The assembling procedure that we have established through many experiences makes the conclusion firm. This superiority is a main reason why the dioptric has been used in actual exposure equipment. Nevertheless, the catadioptric is advantageous in terms of the volume of glass material and correcting chromatic aberrations. The following section deals with the reason briefly.

2.1 Satisfaction of Petzval condition

The projection optics as a whole can be regarded as a positive lens. From very simple considerations, it is clear that a positive lens has an inward-curving field. The effects can readily be understood by examining Fig. 2.

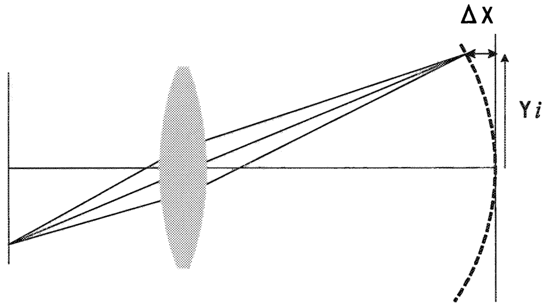

Fig. 2: Field curvature.

The reticle and the wafer have a flat surface, so a flat field is required for the projection optics. When the optics is free of astigmatic image, a field curvature (See Fig. 2) is given by

$$\Delta X = \frac{Yi^2}{2}\sum_{j=1}^{m} P_j \qquad (2)$$

where Pj is refractive power of each lens element, which is given by inverse focal length of the m thin lenses forming the system, ΔX is the displacement of an image point at height Yi from the paraxial image plane. To have a flat field, the lens system needs to satisfy the following expression.

$$\sum_{j=1}^{m} P_j = 0 \qquad (3)$$

This is the so-called “Petzval condition”.

For the dioptric, many lens elements with large diameter are needed to satisfy the Petzval condition. Fig.3 shows an example of power arrangement for dioptric system.

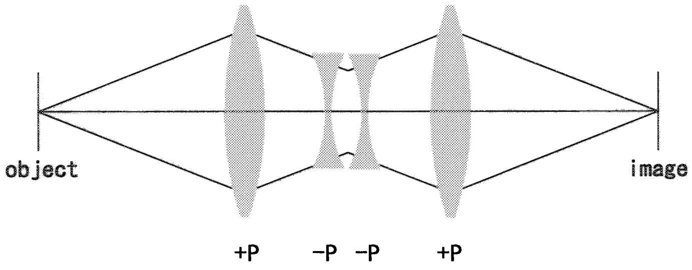

Fig. 3: Example of power arrangement for dioptric system

For easy understanding, in Fig. 3, the system has 1X magnification and very simple configuration. Assume the refractive power of each element is P. Then, the sum of each absolute refractive power is 4P, while the sum of the power is 0 to satisfy the Petzval condition. By contrast, the concave mirror has positive refractive power like a positive lens elements but it works for a negative Petzval sum. This leads an optical system to consist of low refractive power. Fig. 4 shows an example of power arrangement for catadioptric system.

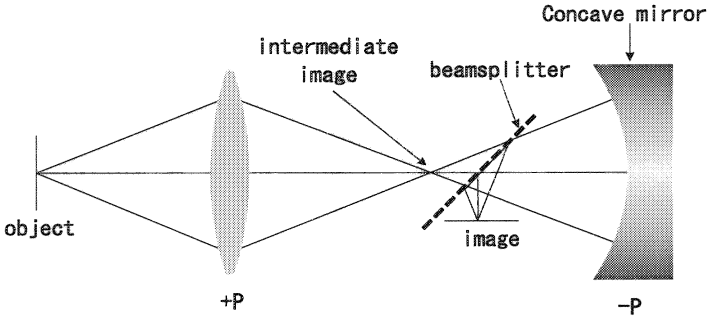

Fig. 4: Example of power arrangement for catadioptric system

The sum of each absolute refractive power is 2P in this conceptual configuration. From the intuition of lens designer, the total refractive power would be proportional to difficulty of correcting aberrations. Therefore, it is possible for the catadioptric to be scaled down, or to reduce all the linear constructional dimensions. For example, when the whole system of Fig. 4 is scaled down by half, the total refractive power becomes 4P, that is same as total of the dioptric system in Fig. 3. That is why the catadioptric has an advantage about glass material volume.

2.2 Correcting chromatic aberrations

The refractive index of glass changes with wavelength. Normally, the refractive power is larger at shorter wavelengths. This effect can readily be understood by examining Fig. 5. For a positive lens, the focal point for red light is farther from the lens than that for blue light. Therefore at least two kinds of material that have different dispersive powers are needed for dioptric, otherwise, ultra-line-narrowed laser which has a narrow spectral bandwidth would be required.

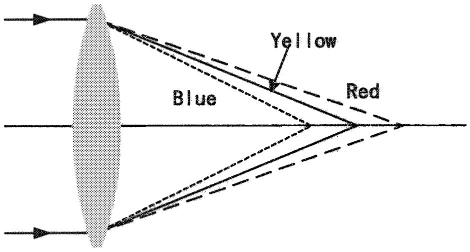

Fig. 5: Axial chromatic aberration for positive lens

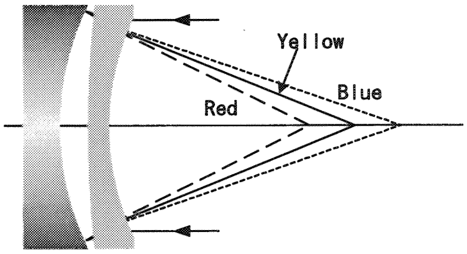

Fig. 6: Axial chromatic aberration for a combination of a Concave mirror and a negative lens

Nevertheless, the combination of a concave mirror and a negative lens (See Fig. 6) also has positive refractive power, but the mirror and the negative lens work oppositely for correcting chromatic aberrations. The negative lens is the so-called "Schupmann achromat.[5), 6)]" For the catadioptric system, chromatic aberrations can be corrected with single material as these are combined. That is why the catadioptric has an advantage about correcting chromatic aberrations.

2.3 Motivation for 193nm microlithographic lens

Designing projection optics with higher NA will require larger diameter for lens elements. Fig. 7 shows a graph of the relation between NA and lens diameter at 193nm projection optics. All spherical lenses had constituted the projection optics under 0.7NA. If it went over 0.7, the larger lens diameter required for the optics would increase rapidly, and exceed a practical limit. At that time "Aspheres" brought about the breakthrough7). They can work for the reduction of lens diameter and the realization of over 0.8NA optics. When NA goes over 1.0, we should choose liquid immersion optics, of course. However, as long as we persist in the dioptric, its lens diameter will go over a practical limit immediately. I would say, " The next breakthrough will be brought by Catadioptric". It will make possible to realize over 1.2NA optics.

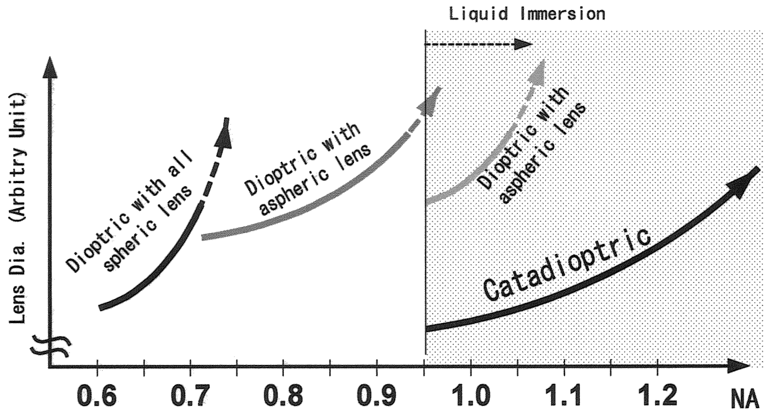

Fig. 7: Lens Dia. vs NA

2.4 Motivation for 157nm microlithographic lens

In case of 157nm projection optics, the motivation for the catadioptric system is obvious. We know that development of the second material, or line narrowed laser and sufficient supply of glass material are necessary conditions for the dioptric. However, for the 157nm optics, usable material is only calcium fluoride, and it is difficult to make achromatized dioptric optics with a single lens material. Ultra-line-narrowed F2 laser with the spectrum bandwidth of 0.15pm FWHM or less makes it possible to realize an achromatized imaging by dioptric optics with only one kind of the material, but around 1.0pm FWHM is current bandwidth of practical F2 lasers with adequate output power and stability. What is worse, supply of calcium fluoride lens is not enough. So, we would take a pessimistic view of all these items. Then our decision is made on catadioptric optics for 157nm projection optics3).

3. CATADIOPTRIC OPTICS TYPE

As I have mentioned, the concave mirror and the Schupmann achromat are very important elements for the catadioptric system. They work to compensate chromatic aberrations and the Petzval sum. However, incident and reflected rays interfere with each other above the mirror, and the imaging ray or the reflected ray must be separated from the incident ray to make the system practical. The catadioptric optics can be classified into three types according to the method how to separate these rays changing the propagation direction.

The first one is the beamsplitter type called type-A, hereafter.8), 9), 10), 11), 12) Fig. 8 shows a conceptual configuration of type-A, which has Quarter Wave Plate (QWP) and Polarized Beam Splitter (PBS) prism close to the concave mirror and the Shupmann achromat. They work to separate beam of returning from the concave reflecting mirror and beam of going to the concave mirror without the loss of energy. The location of prism has a little more allowance than other catadioptric optics. So it allows non-intermediate image in optical system can consist of only the elements with low refractive power. Nevertheless, PBS-coating, large calcium fluoride prism, and large QWP could be difficulty in realizing the optics.

The second one is the central obscuration type called type-B, hereafter (See Fig. 9)13), 14), 15), 16), which can be considered the Schwarzschild objective17) plus refracting relay. This type-B produces not passing area in the pupil of optics to separate the reflected ray from the incident ray. Each of two mirrors has a central hole, and they are arranged close to image plane to keep the obscuration small. The type-B is uni-axial system like dioptric optics, and has an advantage of lens producibility. Nonetheless, we have to remember that the type-B lacks the capability of resolving some kinds of mask patterns. For example, semi-dense–pattern can't be resolved with this type, because some 1st-order diffracted ray from the pattern might be stopped at the obscuration.

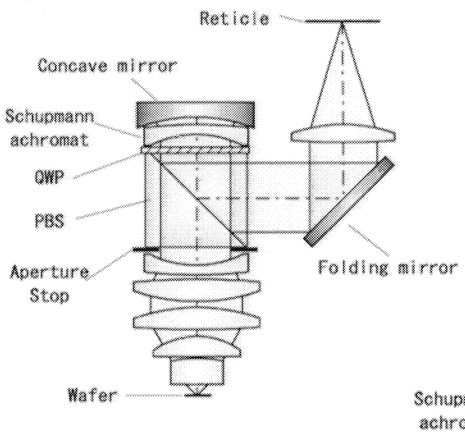

Fig. 8: Beamsplitter type (Type-A)

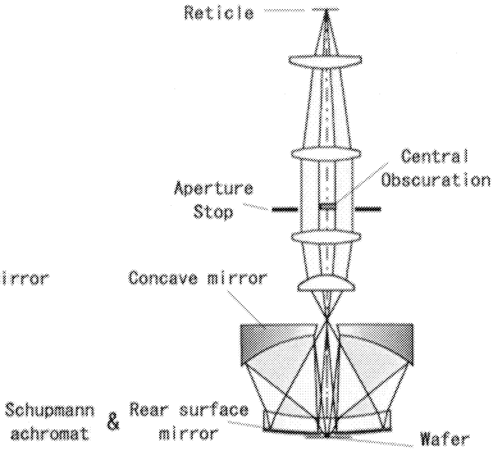

Fig. 9: Central obscuration type (Type-B)

The third one is off-axis type. This type can be further classified into two sub-types by the number of lens barrel: uni-barrel off-axis type called type-C, hereafter (See Fig. 10)[18) 19) 20)] and multi-barrel off-axis type called type-D, hereafter. (See Fig. 11) [6) 21) 22) 23) 24) 25)]

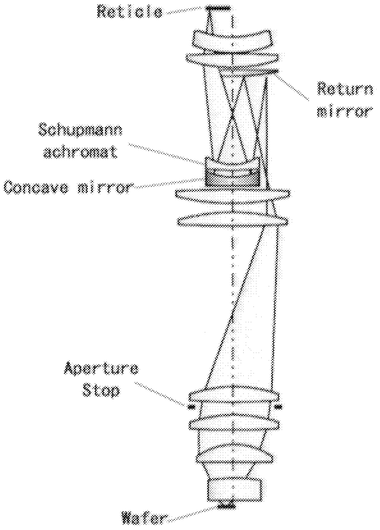

Fig. 10: Uni-barrel off-axis type (Type-C)

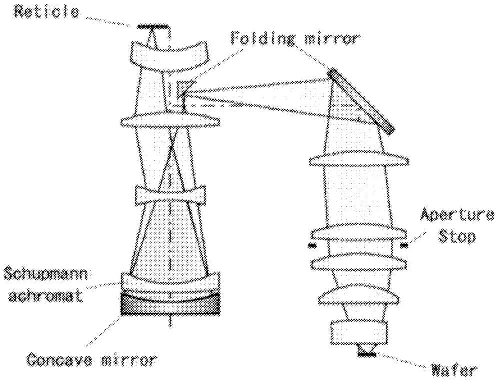

Fig. 11: Multi-barrel off-axis type (Type-D)

The type-C is constituted with the Schupmann achromat and a concave mirror, plus refracting relay. This type has off-axis object and image fields, and an intermediate image close to the concave mirror to avoid the problem of mirror obscuration. The type-C is a kind of attempts to maintain uni-axis system, whose advantage is lens producibility. However, as can be seen in Fig. 10, the Schupmann achromat and the concave mirror have to be kept small enough to avoid mechanical interference. They are, as a result, quite ineffective to correct chromatic aberrations in a spectral bandwidth around 1.0pm.

The type-D, comprising off-axis object and image fields, has some intermediate image close to the folding mirror to avoid the problem of mirror obscuration. Some other forms of design can be considered with the number of intermediate images and variety of the folding mirror position. The chromatic aberration can be corrected by allowing

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