

DESCRIPTION

PROJECTION OPTICAL SYSTEM, EXPOSURE APPARATUS, AND EXPOSURE METHOD

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TECHNICAL FIELD

The present invention relates to a projection optical system, an exposure apparatus, and an exposure method, and more particularly, to a projection optical system optimal for an exposure apparatus used to manufacture microdevices, such as semiconductor devices and liquid crystal display devices, through a photolithography process.

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BACKGROUND ART

An exposure apparatus projects and exposes an image of a pattern of a mask (or a reticle) on a photosensitive substrate (e.g., wafer or a glass plate coated by a photoresist). More specifically, the exposure apparatus uses a projection optical system to project and expose the image in a photolithography process, in which semiconductor devices or the like are manufactured. The projection optical system is required to have a higher resolution due to the increasing level of integration of semiconductor devices or the like manufactured with the exposure apparatus.

To improve the resolution of the projection optical system, the projection optical system needs to shorten the wavelength λ of its illumination light (exposure light) and increase the numerical aperture NA at its image side. The resolution of the projection optical system is written as $k \cdot \lambda/NA$ (where k is a process coefficient). The image-side

numerical aperture NA is written as $n * \sin\theta$, where n is the refractive index of a medium (usually gas, such as air) that arranged between the projection optical system and the photosensitive substrate, and θ is the maximum incident angle at which light enters the photosensitive substrate.

When the maximum angle θ is set larger in an effort to increase the image-side numerical aperture, the angle at which light is emitted from the projection optical system and the angle at which the light enters the photosensitive substrate increase. This increases reflection loss occurring at an optical surface. As a result, the projection optical system cannot obtain a large effective numerical aperture at its image side. One conventional technique for increasing the image-side numerical aperture is an immersion technique (refer to, for example, Patent Document 1), with which an optical path formed between a projection optical system and a photosensitive substrate is filled with a medium such as a liquid having a high refractive index.

Patent Document 1: International Patent Publication No. WO2004/019128

DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

However, when setting an image-side numerical aperture of an immersion projection optical system to be greater than 1.2, a light entering surface of an interface lens (interface optical element), of which light entering side contacts gas and light emitting side contacts liquid, must have a convex surface shape having a large curvature and

projected toward the light entering side to avoid reflection of the incident light. In this case, a holding tab for holding the interface lens is inevitably located near the liquid, and the liquid is apt to easily leaking into the
5 projection optical system. Leakage of liquid into the projection optical system results in deterioration of an anti-reflection film on the optical surface, which, in turn, may increase the risk of the imaging capability (generally, the optical capability) of the projection optical system
10 being lowered.

Accordingly, it is an object of the present invention to prevent leakage of liquid (immersion liquid) into the optical system in order to maintain a satisfactory imaging
15 capability. A further object of the present invention is to provide an exposure apparatus and an exposure method for projecting and exposing a micropattern highly accurately and stably using a high resolution immersion projection optical system that prevents leakage of liquid (immersion liquid)
20 into the optical system in order to maintain a satisfactory imaging capability.

MEANS OF SOLVING THE PROBLEMS

25 To achieve the above object, a first aspect of the present invention provides a projection optical system for projecting an image of a first plane onto a second plane through a liquid. The projection optical system includes an interface optical element including a side towards the first
30 plane that contacts a gas and a side towards the second plane that contacts the liquid. The interface optical element includes a light entering surface, which has a convex shape facing towards the first plane, and a groove,

which is formed to surround an effective region in a light emitting surface of the interface optical element.

5 A second aspect of the present invention provides a projection optical system for projecting an image of a first plane onto a second plane through a liquid. The projection optical system includes an interface optical element including a side towards the first plane that contacts a gas and a side towards the second plane that contacts the
10 liquid. The interface optical element includes a light entering surface, which has a convex shape facing towards the first plane, and a holding tab, which is arranged on a holding plane orthogonal to an optical axis, with the holding tab and the optical axis forming a space
15 therebetween.

A third aspect of the present invention provides a exposure apparatus including an illumination system for illuminating a pattern set on the first plane, and the
20 projection optical system of the first aspect or the second aspect for projecting an image of the pattern onto a photosensitive substrate set on the second plane.

A fourth aspect of the present invention provides a
25 exposure method including an illuminating step of illuminating a pattern set on the first plane, and an exposure step of projecting and exposing an image of the pattern onto a photosensitive substrate set on the second plane with the projection optical system of the first aspect
30 of the second aspect.

A fifth aspect of the present invention provides a device manufacturing method including an exposure step of

projecting and exposing an image of a pattern set on the first plane onto a photosensitive substrate set on the second plane with the projection optical system according to the first aspect or the second aspect, and a development
5 step of developing the photosensitive substrate that has undergone the exposure step.

10 A sixth aspect of the present invention provides an optical element for use in an immersion objective optical system and having one optical surface that contacts liquid. The optical element includes another optical surface of the optical element having a convex shape, and a groove formed to surround an effective region in the one optical surface.

15 A seventh aspect of the present invention provides an optical element for use in an immersion objective optical system and having one optical surface that contacts liquid and another optical surface having a convex shape. The optical element includes a holding tab for holding the
20 optical element, wherein the holding tab is arranged on a holding plane orthogonal to an optical axis of the optical element, wherein a space is formed between the holding tab and the optical axis.

25 An eighth aspect of the present invention provides an immersion objective optical system including the optical element of the sixth aspect or the seventh aspect. The optical element is arranged nearest to a liquid side.

30 EFFECT OF THE INVENTION

In an immersion projection optical system according to a typical aspect of the present invention, a holding tab for

an interface optical element (interface lens) is located near liquid at the light emitting surface side. However, a groove is formed so as to surround an effective region of a light emitting surface of the interface optical element.

5 Thus, the groove functions to resist leakage of liquid into the space between the holding tab and the lens cell thus making it difficult for liquid to leak into the projection optical system.

10 In other words, in the projection optical system of the present invention, leakage of liquid (immersion liquid) into the optical system is prevented, and satisfactory imaging capability is maintained. In the exposure apparatus and exposure method of the present invention, a high
15 resolution immersion projection optical system that prevents leakage of liquid into the optical system and maintains satisfactory imaging capability is used. Thus, fine patterns are stably projected and exposed with high accuracy, and satisfactory microdevices are stably manufactured with high
20 accuracy.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram showing the structure of
25 an exposure apparatus according to a present embodiment of the present invention;

Fig. 2 shows the positional relationship between a rectangular stationary exposure region formed on a wafer and a reference optical axis in the present embodiment of the
30 present embodiment;

Fig. 3 is a schematic diagram showing the structure of an interface lens and a wafer in examples of the present embodiment;

Fig. 4 shows a lens structure of a projection optical system in a first example of the present embodiment;

Fig. 5 shows lateral aberration occurring in the projection optical system in the first example of the present embodiment;

Fig. 6 shows a lens structure of a projection optical system in a second example of the present embodiment;

Fig. 7 shows lateral aberration occurring in the projection optical system in the second example of the present embodiment;

Fig. 8 is a diagram illustrating a problem that occurs when setting a large image-side numerical aperture for an immersion projection optical system;

Fig. 9 is a schematic diagram showing the main features of the projection optical system of the present embodiment;

Fig. 10 is a flowchart showing a method for forming a microdevice, which serves as a semiconductor device; and

Fig. 11 is a flowchart showing a method for forming a microdevice, which serves as a liquid crystal display device.

DESCRIPTION OF REFERENCE NUMERALS

25	R	reticle
	RST	reticle stage
	PL	projection optical system
	Lp	interface lens
	Lp	immersed plane parallel plate
30	Lm1, Lm2	pure water (liquid)
	W	wafer
	1	illumination optical system
	9	Z-stage

- 10 XY-stage
- 12 movable mirror
- 13 wafer laser interferometer
- 14 main control system
- 5 15 wafer stage drive system
- 21 first supply and discharge mechanism
- 22 second supply and discharge mechanism

BEST MODE FOR CARRYING OUT THE INVENTION

10

An embodiment of the present invention will now be described with reference to the drawings. Fig. 1 is a schematic diagram showing the structure of an exposure apparatus of the present embodiment of the present invention. In Fig. 1, X-axis and Y-axis are directions parallel to a wafer W, whereas Z-axis is a direction perpendicular to the wafer W. More specifically, the XY surface is parallel to the horizontal surface, and +Z-axis is oriented upward in the vertical direction.

20

The exposure apparatus of the present embodiment includes an ArF excimer laser light source, which functions for example as an exposure light source, and an illumination optical system 1 as shown in Fig. 1. The illumination optical system 1 includes an optical integrator (homogenizer), a field stop, and a condenser lens. Exposure light (an exposure beam) IL, which is ultraviolet pulsed light having a wavelength of 193 nm, is emitted from the light source, passes through the illumination optical system 1, and illuminates a reticle (mask) R. The reticle R has a pattern that is to be transferred. The entire pattern region on the reticle R includes a rectangular (slit) pattern region of which long sides extend in X-axis direction and of

which short sides extend in the Y-axis direction. The exposure beam IL illuminates the rectangular pattern region on the reticle R.

5 Light that has passed through the reticle R enters an immersion projection optical system PL. The projection optical system PL projects the reticle pattern with a predetermined reduction ratio onto the wafer (photosensitive substrate) W that is coated with a photoresist. The
10 projection optical system PL forms an image of the reticle pattern on the wafer W. More specifically, the projection optical system PL forms the pattern image on a rectangular stationary exposure region (effective exposure region) of which long sides extend in the X-axis direction and of which
15 short sides extend in the Y-axis direction on the wafer W, which optically corresponds to the rectangular illumination region formed on the reticle R.

Fig. 2 shows the positional relationship between the
20 rectangular stationary exposure region (effective exposure region) that is formed on the wafer and a reference optical axis in the present embodiment. In the present embodiment, as shown in Fig. 2, the rectangular effective exposure region ER having a predetermined size is defined at a
25 position distant from the reference optical axis AX in the Y-axis direction by an off-axis amount A within a circular region (image circle) IF. The center of the image circle IF coincides with the reference optical axis AX. The image circle IF has a radius B.

30

The effective exposure region ER has a length LX in the X-axis direction and a length LY in the Y-axis direction. Although not shown in the drawing, the

rectangular illumination region (effective illumination region) corresponding to the rectangular effective exposure region ER is formed on the reticle R. More specifically, a rectangular illumination region having a size and shape
5 corresponding to the effective exposure region ER is formed on the reticle R at a position distant from the reference optical axis AX in the Y-axis direction by the off-axis amount A.

10 A reticle stage RST supports the reticle R in such a manner that the reticle R is parallel to the XY surface. The reticle stage RST incorporates a mechanism for slightly moving the reticle R in the X-axis direction, the Y-axis direction, and a rotation direction. The positions of the
15 reticle stage RST in the X-axis direction, the Y-axis direction, and the rotation direction are measured and controlled in real time by a reticle laser interferometer (not shown). A wafer holder (not shown) fixes the wafer W to a Z-stage 9 in a manner that the wafer W is parallel to the
20 XY surface.

The Z-stage 9 is fixed to an XY-stage 10. The XY-stage 10 moves along the XY surface, which is substantially parallel to an image surface of the projection optical
25 system PL. The Z-stage 9 controls the focus position (Z-axis position) and the tilt angle of the wafer W. The positions of the Z-stage 9 in the X-axis direction, the Y-axis direction, and the rotation direction are measured and controlled in real time by a wafer laser interferometer 13.
30 The wafer laser interferometer 13 uses a movable mirror 12, which is arranged on the Z-stage 9.

The XY-stage 10 is mounted on a base 11. The XY-stage

10 controls the positions of the wafer W in the X-axis direction, the Y-axis direction, and the rotation direction. A main control system 14, which is mounted on the exposure apparatus of the present embodiment, adjusts the positions
5 of the reticle R in the X-axis direction, the Y-axis direction, and the rotation direction based on the values measured by the reticle laser interferometer. More specifically, the main control system 14 transmits a control signal to mechanisms incorporated in the reticle stage RST,
10 and positions the reticle R by slightly moving the reticle stage RST.

The main control system 14 adjusts the focus position (Z-axis position) and the tilt angle of the wafer W to align
15 the surface of the wafer W to the image surface of the projection optical system PL through autofocus and automatic leveling. More specifically, the main control system 14 transmits a control signal to a wafer stage drive system 15 and drives the Z-stage 9 using the wafer stage
20 drive system 15 to adjust the focus position and the tilt angle of the wafer W.

The main control system 14 further adjusts the positions of the wafer W in the X-axis direction, the Y-axis
25 direction, and the rotation direction based on the values measured by the wafer laser interferometer 13. More specifically, the main control system 14 transmits a control signal to the wafer stage drive system 15, and adjusts the positions of the wafer W in the X-axis direction, the Y-axis
30 direction, and the rotation direction by driving the XY stage 10 using the wafer stage drive system 15.

During exposure, the main control system 14 transmits

a control signal to mechanisms incorporated in the reticle stage RST and also transmits a control signal to the wafer stage drive system 15. This drives the reticle stage RST and the XY-stage 10 at a speed ratio determined by the
5 projection magnitude of the projection optical system PL, while the pattern image of the reticle R is projected and exposed within a predetermined shot region formed on the wafer W. Afterwards, the main control system 14 transmits a control signal to the wafer stage drive system 15, and
10 drives the XY-stage 10 using the wafer stage drive system 15 to cause a step movement of the exposure position to another shot region formed on the wafer W.

The pattern image of the reticle R is repeatedly
15 scanned and exposed on the wafer W with the step-and-scan method as described above. More specifically, the reticle stage RST and the XY-stage 10 and consequently the reticle R and the wafer W are moved (scanned) in synchronization in the short-side direction of the rectangular stationary
20 exposure region and the stationary illumination region, or the Y-axis direction, while the positions of the reticle R and the wafer W are adjusted using the wafer stage drive system 15 and the wafer laser interferometer 13 or the like. Through this operation, the reticle pattern is scanned and
25 exposed in the region on the wafer W that has the same length as the length of the long side LX of the stationary exposure region and has the same width as the width corresponding to the scanning amount (moving amount) of the wafer W.

30

Fig. 3 is a schematic diagram showing the structure of an interface lens and a wafer in examples of the present embodiment. As shown in Fig. 3, an immersed plane parallel

plate Lp is arranged nearest to the wafer W in the projection optical system PL in each example of the present embodiment. One surface of the immersed plane parallel plate Lp nearer to the reticle R (object side surface) is in
5 contact with a second liquid Lm2, and another surface of the immersed plane parallel plate Lp nearer to the wafer W (image side surface) is in contact with a first liquid Lm1. An interface lens Lb is arranged adjacent to the immersed plane parallel plate Lp. One surface of the interface lens
10 Lb nearer to the reticle R (reticle side surface) is in contact with gas, and another surface of the interface lens Lb nearer to the wafer W (wafer side surface) is in contact with the second liquid Lm2.

15 The projection optical system PL of each example of the present invention uses pure water (deionized water) as the first liquid Lm1 and the second liquid Lm2, which have a reflective index greater than 1.1. Pure water is easily obtained in large amounts at, for example, a semiconductor
20 manufacturing factory. The projection optical system PL of each example uses, as the interface lens Lb, a positive lens that has a convex surface at the reticle side and a planar surface as the wafer side. The interface lens Lb and the immersed plane parallel plate Lp are both made of silica.
25 Silica is selected as the material for the interface lens Lb and the immersed plane parallel plate Lp because the projection optical system PL may fail to maintain stable imaging performance when, for example, the interface lens Lb and/or the immersed plane parallel plate Lp are made of
30 fluorite, which is soluble in water.

Further, the internal refractive index distribution of fluorite is known to contain a high-frequency element. The

uneven refractive indexes of fluorite including the high-frequency element may cause flares. This may easily lower the imaging performance of the projection optical system. Moreover, fluorite is known to have natural birefringence.

5 The natural birefringence effect of fluorite needs to be corrected to achieve high imaging performance of the projection optical system. The solubility, high-frequency element in the refractive index distribution, and natural birefringence make fluorite unsuitable for the material for
10 the interface lens Lb and the immersed plane parallel plate Lp. It is preferable that the interface lens Lb and the immersed plane parallel plate Lp be made of silica.

The exposure apparatus that performs scanning and
15 exposure while moving the wafer W relative to the projection optical system PL with the step-and-scan method needs to continuously fill the optical path between the interface lens Lb and the wafer W of the projection optical system PL with the liquid (Lm1 and Lm2) from the start to the end of
20 the scanning and exposure process. To enable this, the exposure apparatus may use a technique described for example in International Patent Publication No. WO99/49504 or a technique described for example in Japanese Laid-Open Patent Publication No. 10-303114.

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According to the technique described in International Patent Publication No. WO99/49504, a liquid supply apparatus supplies liquid, which has been adjusted to a predetermined temperature, to fill the optical path between the interface
30 lens Lb and the wafer W through a supply pipe and an ejection nozzle, and then recovers the liquid on the wafer W through a recovery pipe and a suction nozzle. According to the technique described in Japanese Laid-Open Patent

Publication No. 10-303114, a wafer holder table functions as a container for accommodating liquid. The wafer W is positioned and supported at the center of an inner bottom surface of the wafer holder table (immersed in the liquid) by vacuum contact. A distal end of a barrel of the projection optical system PL is immersed in the liquid. A wafer-side optical surface of the interface lens Lb is immersed in the liquid.

As shown in Fig. 1, the projection optical system PL of the present embodiment uses a first supply and discharge mechanism 21 to circulate pure water, which functions as the first liquid Lm1, in the optical path between the immersed plane parallel plate Lp and the wafer W. The projection optical system PL also uses a second supply and discharge mechanism 22 to circulate pure water, which functions as the second liquid Lm2, in the optical path between the interface lens Lb and the immersed plane parallel plate Lp. In this manner, the projection optical system PL circulates a small amount of pure water as the immersion liquid to prevent corrosion or fungal deterioration of the liquid.

In the examples of the present invention, an aspherical surface can be written as expression (a) shown below. In expression (a), y represents the height in the direction vertical to the optical axis, z represents the distance (sag amount) between a tangent plane at the vertex of the aspherical surface and the position at the height y on the aspherical surface, r represents the curvature radius of the vertex, k represents the coefficient of the cone, and C_n represents the n -th degree aspherical coefficient. In tables 1 and 2, which are shown below, the surface number of each aspherical lens surface is marked with *.

Expression (a)

$$z = (y^2/r)/[1+\{1-(1+k)*y^2/r^2\}^{1/2}] + C_4*y^4 + C_6*y^6 + C_8*y^8 + C_{10}*y^{10} + C_{12}*y^{12} + C_{14}*y^{14} + \dots$$

5

The projection optical system PL of each example of the present embodiment includes a first imaging optical system G1, a second imaging optical system G2, and a third imaging optical system G3. The first imaging optical system G1 forms a first intermediate image of a pattern of the reticle R, which is arranged on an object plane (first plane) of the projection optical system PL. The second imaging optical system G2 forms a second intermediate image (which is an image of the first intermediate image as well as a secondary image of the reticle pattern) of the reticle pattern based on the light from the first intermediate image. The third imaging optical system G3 forms a final image (which is a reduced image of the reticle pattern) on the wafer W, which is arranged on an image plane (second plane) of the projection optical system PL, based on light from the second intermediate image. The first imaging optical system G1 and the third imaging optical system G3 are both refractive optical systems. The second imaging optical system G2 is a catadioptric optical system that includes a concave reflective mirror CM.

A first planar reflective mirror (first folding mirror) M1 is arranged in an optical path formed between the first imaging optical system G1 and the second imaging optical system G2. A second planar reflective mirror (second folding mirror) M2 is arranged in an optical path formed between the second imaging optical system G2 and the third imaging optical system G3. In the projection optical system

PL of each example of the present invention, light from the reticle R passes through the first imaging optical system G1 and forms a first intermediate image of the reticle pattern in the vicinity of the first planar reflective mirror M1.

5 Light from the first intermediate image then passes through the second imaging optical system G2 and forms a second intermediate image of the reticle pattern in the vicinity of the second planar reflective mirror M2. Finally, light from the second intermediate image passes through the third
10 imaging optical system G3, and forms a final image of the reticle pattern on the wafer W.

In the projection optical system PL of each example of the present invention, the first imaging optical system G1
15 has an optical axis AX1 and the third imaging optical system G3 has an optical axis AX3. The optical axes AX1 and AX3 extend linearly in the vertical direction. The optical axes AX1 and AX3 coincide with the reference optical axis AX. The second imaging optical system G2 has an optical axis AX2
20 that extends linearly along the horizontal direction (vertical to the reference optical axis AX). The reticle R, the wafer W, all the optical members forming the first imaging optical system G1, and all the optical members forming the third imaging optical system G3 are arranged
25 parallel to one another along planes perpendicular to the direction of gravitational force, that is, along horizontal planes. Further, the first planar reflective mirror M1 and the second planar reflective mirror M2 have reflective surfaces that each form an angle of 45 degrees with the
30 reticle surface. The first planar reflective mirror M1 and the second planar reflective mirror M2 are formed integrally as a single optical member. Further, the projection optical system PL of each example of the present invention is formed

to be substantially telecentric at both of the object side and the image side.

[First Example]

5 Fig. 4 shows a lens structure of a projection optical system according to a first example of the present embodiment. As shown in Fig. 4, the first imaging optical system G1 included in the projection optical system PL of the first example includes a plane parallel plate P1, a
10 biconvex lens L11, a positive meniscus lens L12 having a convex surface at its reticle side, an biconvex lens L13, a biconcave lens L14 having a aspherical concave surface at its reticle side, a positive meniscus lens L15 having a convex surface at its reticle side, a positive meniscus lens
15 L16 having a concave surface at its reticle side, a negative meniscus lens L17 having a concave surface at its reticle side, a positive meniscus lens L18 having an aspherical concave surface at its reticle side, a positive meniscus lens L19 having a concave surface at its reticle side, a
20 biconvex lens L110, and a positive meniscus lens L111 having an aspherical concave surface at its wafer side, which are arranged sequentially in this order from the reticle side.

 The second imaging optical system G2 includes a
25 negative meniscus lens L21 having a concave surface at its reticle side, a negative meniscus lens L22 having a concave surface at its reticle side, and a concave reflective mirror CM having a concave surface at its reticle side, which are arranged sequentially in this order along the traveling path
30 of the incoming light from the reticle side (light entering side) of the projection optical system PL. The third imaging optical system G3 includes a positive meniscus lens L31 having a concave surface at its reticle side, a biconvex

lens L32, a positive meniscus lens L33 having a convex surface at its reticle side, a positive meniscus lens L34 having a spherical concave surface at its wafer side, a biconcave lens L35, a biconcave lens L36 having an
5 aspherical concave surface at its wafer side, a positive meniscus lens L37 having an aspherical concave surface at its reticle side, a positive meniscus lens L38 having an aspherical concave surface at its wafer side, a negative meniscus lens L39 having a aspherical concave surface at its
10 wafer side, a positive meniscus lens L310 having an aspherical concave surface at its reticle side, a biconvex lens L311, an aperture stop AS, a plano-convex lens L312 having a planar surface at its wafer side, a positive meniscus lens L313 having an aspherical concave surface at
15 its wafer side, a positive meniscus lens S314 having an aspherical concave surface at its wafer side, a plano-convex lens L315 (interface lens Lb) having a planar surface at its wafer side, and a plane parallel plate Lp, which are arranged sequentially in this order from the reticle side
20 (light entering side).

In the projection optical system PL of the first example, an optical path between the interface lens Lb and the plane parallel plate (immersed plane parallel plate) Lp
25 and an optical path between the plane parallel plate Lp and the wafer W are filled with pure water (Lm1 and Lm2) having a refractive index of 1.435876 for an ArF excimer laser beam (having a central wavelength λ of 193.306 nm), which is the used light (exposure beam). All the light transmitting
30 members including the interface lens Lb and the plane parallel plate Lp are made of silica (SiO_2), which has a refractive index of 1.5603261 relative to the central wavelength of the used light.

Table 1 below shows the specifications of the projection optical system PL in the first example. In Table 1, λ represents the central wavelength of the exposure beam, β represents the projection magnification (imaging ratio of the entire system), NA represents the numerical aperture at the image side (wafer side) of the system, B represents the radius of the image circle IF on the wafer W, A represents the off-axis amount of the effective exposure region ER, LX represents the size of the effective exposure region ER in the X-axis direction (the long-side dimension of the effective exposure region ER), and LY represents the dimension of the effective exposure region ER in the Y-axis direction (the short-side dimension of the effective exposure region ER).

In the table, the surface number represents the order of each surface on the path of the light traveling from the reticle surface, which is the object surface (first plane), to the wafer surface, which is the image surface (second plane), r represents the curvature radius of each surface (the curvature radius (mm) of the vertex in the case of an aspherical surface), d represents the axial interval of each surface or the surface interval (mm), and n represents the refractive index about the central wavelength of the exposure beam. The sign of the surface interval d is inverted whenever the light is reflected. Accordingly, the surface interval d has a negative sign for the optical path from the reflective surface of the first planar reflective mirror M1 to the concave reflective mirror CM and for the optical path from the second planar reflective mirror M2 to the image surface, whereas the surface interval d has a positive sign for other optical paths.

In the first imaging optical system G1, the curvature radius is positive for convex surfaces facing toward the reticle side, and the curvature radius is negative for concave surfaces facing toward the reticle side. In the second imaging optical system G2, the curvature radius is positive for concave surfaces facing toward the light entering side (reticle side) of the incoming light, and the curvature radius is negative for convex surfaces facing toward the light entering side. The notations used in Table 1 are used in Table 2, which will be described later.

Table 1

(Main Specifications)

$\lambda = 193.306 \text{ nm}$

$\beta = 1/4$

$\text{NA} = 1.32$

$B = 15.3 \text{ mm}$

$A = 2.8 \text{ mm}$

$\text{LX} = 26 \text{ mm}$

$\text{LY} = 5 \text{ mm}$

(Specifications of Optical Members)

25

Surface No.	r	d	n	Optical Member
	(Reticle Surface)	113.7542		
1	∞	8.0000	1.5603261	(P1)
2	∞	6.0000		
3	961.49971	52.0000	1.5603261	(L11)
4	-260.97642	1.0000		
5	165.65618	35.7731	1.5603261	(L12)

6	329.41285	15.7479		
7	144.73700	56.4880	1.5603261	(L13)
8	-651.17229	4.1450		
9*	-678.61021	18.2979	1.5603261	(L14)
10	173.73534	1.0000		
11	82.85141	28.4319	1.5603261	(L15)
12	122.17403	24.6508		
13	-632.23083	15.8135	1.5603261	(L16)
14	-283.76586	22.9854		
15	-95.83749	44.8780	1.5603261	(L17)
16	-480.25701	49.9532		
17*	-327.24655	37.6724	1.5603261	(L18)
18	-152.74838	1.0000		
19	-645.51205	47.0083	1.5603261	(L19)
20	-172.70890	1.0000		
21	1482.42136	32.7478	1.5603261	(L110)
22	-361.68453	1.0000		
23	185.06735	36.2895	1.5603261	(L111)
24*	1499.92500	72.0000		
25	∞	-204.3065		(M1)
26	115.50235	-15.0000	1.5603261	(L21)
27	181.35110	-28.1819		
28	107.57500	-18.0000	1.5603261	(L22)
29	327.79447	-34.9832		
30	165.18700	34.9832		(CM)
31	327.79446	18.0000	1.5603261	(L22)
32	107.57500	28.1819		
33	181.35110	15.0000	1.5603261	(L21)
34	115.50235	204.3065		
35	∞	-72.0000		(M2)
36	552.89298	-24.4934	1.5603261	(L31)
37	211.40931	-1.0000		
38	-964.15750	-27.5799	1.5603261	(L32)

39	451.41200	-1.0000		
40	-239.74429	-35.7714	1.5603261	(L33)
41	-171769.23040	-1.0000		
42	-206.94777	-50.0000	1.5603261	(L34)
43*	-698.47035	-43.1987		
44	560.33453	-10.0000	1.5603261	(L35)
45	-116.92245	-46.5360		
46	209.32811	-10.0000	1.5603261	(L36)
47*	-189.99848	-23.6644		
48*	1878.63986	-31.5066	1.5603261	(L37)
49	211.85278	-1.0000		
50	-322.20466	-33.1856	1.5603261	(L38)
51*	-1160.22740	-10.0172		
52	-2715.10365	-22.0000	1.5603261	(L39)
53*	-959.87714	-42.0799		
54*	727.37853	-62.0255	1.5603261	(L310)
55	240.59248	-1.0000		
56	-16276.86134	-62.1328	1.5603261	(L311)
57	333.64919	-1.0000		
58	∞	-1.0000		(AS)
59	-303.09919	-68.2244	1.5603261	(L312)
60	∞	-1.0000		
61	-182.25869	-77.6122	1.5603261	(L313)
62*	-472.72383	-1.0000		
63	-131.14200	-49.9999	1.5603261	(L314)
64*	-414.78286	-1.0000		
65	-75.90800	-43.3351	1.5603261	(L315: Lb)
66	∞	-1.0000	1.435876	(Lm2)
67	∞	-13.0000	1.5603261	(Lp)
68	∞	-2.9999	1.435876	(Lm1)

(Wafer Surface)

(Aspherical Surface Data)

9th surface

$$\kappa = 0$$

	$C_4 = -7.9031 \times 10^{-8}$	$C_6 = 8.6709 \times 10^{-12}$
5	$C_8 = -6.5472 \times 10^{-16}$	$C_{10} = 1.5504 \times 10^{-20}$
	$C_{12} = 2.6800 \times 10^{-24}$	$C_{14} = -2.6032 \times 10^{-28}$
	$C_{16} = 7.3308 \times 10^{-33}$	$C_{18} = 0$

17th surface

10 $\kappa = 0$

	$C_4 = 4.7672 \times 10^{-9}$	$C_6 = -8.7145 \times 10^{-13}$
	$C_8 = -2.8591 \times 10^{-17}$	$C_{10} = 3.9981 \times 10^{-21}$
	$C_{12} = -1.9927 \times 10^{-25}$	$C_{14} = 2.8410 \times 10^{-30}$
	$C_{16} = 6.5538 \times 10^{-35}$	$C_{18} = 0$

15

24th surface

$$\kappa = 0$$

	$C_4 = 2.7118 \times 10^{-8}$	$C_6 = -4.0362 \times 10^{-13}$
	$C_8 = 8.5346 \times 10^{-18}$	$C_{10} = -1.7653 \times 10^{-22}$
20	$C_{12} = -1.1856 \times 10^{-27}$	$C_{14} = 5.2597 \times 10^{-31}$
	$C_{16} = -2.0897 \times 10^{-35}$	$C_{18} = 0$

43th surface

$$\kappa = 0$$

25	$C_4 = -1.8839 \times 10^{-8}$	$C_6 = 5.6009 \times 10^{-13}$
	$C_8 = -1.8306 \times 10^{-17}$	$C_{10} = 2.2177 \times 10^{-21}$
	$C_{12} = -2.3512 \times 10^{-25}$	$C_{14} = 1.7766 \times 10^{-29}$
	$C_{16} = -6.5390 \times 10^{-34}$	$C_{18} = 0$

30 47th surface

$$\kappa = 0$$

	$C_4 = 9.0773 \times 10^{-8}$	$C_6 = -5.4651 \times 10^{-12}$
	$C_8 = 4.4000 \times 10^{-16}$	$C_{10} = -2.7426 \times 10^{-20}$

$$C_{12} = 3.2149 \cdot 10^{-25}$$

$$C_{14} = 2.3641 \cdot 10^{-28}$$

$$C_{16} = -1.3953 \cdot 10^{-32}$$

$$C_{18} = 0$$

48th surface

$$5 \quad \kappa = 0$$

$$C_4 = 3.0443 \cdot 10^{-8}$$

$$C_6 = -1.6528 \cdot 10^{-12}$$

$$C_8 = 2.3949 \cdot 10^{-17}$$

$$C_{10} = -4.4953 \cdot 10^{-21}$$

$$C_{12} = 3.0165 \cdot 10^{-25}$$

$$C_{14} = -1.2463 \cdot 10^{-28}$$

$$C_{16} = 1.0783 \cdot 10^{-32}$$

$$C_{18} = 0$$

10

51th surface

$$\kappa = 0$$

$$C_4 = 1.8357 \cdot 10^{-8}$$

$$C_6 = -4.3103 \cdot 10^{-13}$$

$$C_8 = -9.4499 \cdot 10^{-17}$$

$$C_{10} = 4.3247 \cdot 10^{-21}$$

$$15 \quad C_{12} = -1.6979 \cdot 10^{-25}$$

$$C_{14} = 8.6892 \cdot 10^{-30}$$

$$C_{16} = -1.5935 \cdot 10^{-34}$$

$$C_{18} = 0$$

53th surface

$$\kappa = 0$$

$$20 \quad C_4 = -3.9000 \cdot 10^{-8}$$

$$C_6 = -7.2737 \cdot 10^{-13}$$

$$C_8 = 1.1921 \cdot 10^{-16}$$

$$C_{10} = -2.6393 \cdot 10^{-21}$$

$$C_{12} = -3.1544 \cdot 10^{-26}$$

$$C_{14} = 1.8774 \cdot 10^{-30}$$

$$C_{16} = -2.3545 \cdot 10^{-35}$$

$$C_{18} = 0$$

25 54th surface

$$\kappa = 0$$

$$C_4 = 1.9116 \cdot 10^{-8}$$

$$C_6 = -6.7783 \cdot 10^{-13}$$

$$C_8 = 1.5688 \cdot 10^{-17}$$

$$C_{10} = -6.0850 \cdot 10^{-22}$$

$$C_{12} = 1.8575 \cdot 10^{-26}$$

$$C_{14} = -4.2147 \cdot 10^{-31}$$

$$30 \quad C_{16} = 7.3240 \cdot 10^{-36}$$

$$C_{18} = 0$$

62th surface

$$\kappa = 0$$

$$\begin{array}{ll}
C_4 = 3.0649 \cdot 10^{-8} & C_6 = -2.3613 \cdot 10^{-12} \\
C_8 = 1.5604 \cdot 10^{-16} & C_{10} = -7.3591 \cdot 10^{-21} \\
C_{12} = 2.1593 \cdot 10^{-25} & C_{14} = -3.5918 \cdot 10^{-30} \\
C_{16} = 2.5879 \cdot 10^{-35} & C_{18} = 0
\end{array}$$

5

64th surface

$$\kappa = 0$$

$$\begin{array}{ll}
C_4 = -6.0849 \cdot 10^{-8} & C_6 = -8.7021 \cdot 10^{-13} \\
C_8 = -1.5623 \cdot 10^{-16} & C_{10} = 1.5681 \cdot 10^{-20} \\
C_{12} = -1.6989 \cdot 10^{-24} & C_{14} = 7.9711 \cdot 10^{-29} \\
C_{16} = -2.7075 \cdot 10^{-33} & C_{18} = 0
\end{array}$$

10

Fig. 5 shows lateral aberrations in the projection optical system PL of the first example. In the aberration charts, Y represents the image height, the solid line represents lateral aberration occurring when the exposure beam has a central wavelength of 193.3060 nm, the broken line represents lateral aberration occurring when the exposure beam has a central wavelength of 193.306 nm + 0.2 pm = 193.3062 nm, the single-dash line represents lateral aberration occurring when the exposure beam has a central wavelength of 193.306 nm - 0.2 pm = 193.3058 nm. The notations used in Fig. 5 are used in Fig. 7, which will be described later. As apparent from Fig. 5, the aberration is corrected in a satisfactory manner for the exposure beams with a wavelength width of 193.306 nm $\pm$ 0.2 pm although the projection optical system PL has an extremely large image-side numerical aperture (NA = 1.32) and a relatively large effective exposure region ER (26 mm by 5 mm).

30

[Second Example]

Fig. 6 shows a lens structure for a projection optical system according to a second example of the present

embodiment. As shown in Fig. 6, the first imaging optical system G1 in the projection optical system PL of the second example includes a plane parallel plate P1, a biconvex lens L11, a positive meniscus lens L12 having a convex surface at its reticle side, a positive meniscus lens L13 having a convex surface at its reticle side, a biconcave lens L14 having an aspherical concave surface at its reticle side, a positive meniscus lens L15 having a convex surface at its reticle side, a positive meniscus lens L16 having a concave surface at its reticle side, a negative meniscus lens L17 having a concave surface at its reticle side, a positive meniscus lens L18 having an aspherical concave surface at its reticle side, a positive meniscus lens L19 having a concave surface at its reticle side, a biconcave lens L110, and a positive meniscus lens L111 having an aspherical concave surface at its wafer side, which are arranged sequentially in this order from the reticle side.

The second imaging optical system G2 includes a negative meniscus lens L21 having a concave surface at its reticle side, a negative meniscus lens L22 having a concave surface at its reticle side, and a concave reflective mirror CM having a concave surface at its reticle side, which are arranged sequentially in this order along a traveling path of the incoming light from the reticle side (light entering side) of the projection optical system PL. A third imaging optical system G3 includes a positive meniscus lens L31 having a concave surface at its reticle side, a biconvex lens L32, a positive meniscus lens L33 having a convex surface at its reticle side, a positive meniscus lens L34 having an aspherical concave surface at its wafer side, a biconcave lens L35, a biconcave lens L36 having an aspherical concave surface at its wafer side, a positive

meniscus lens L37 having an aspherical concave surface at its reticle side, a positive meniscus lens L38 having an aspherical concave surface at its wafer side, a plano-concave lens L39 having an aspherical concave surface at its wafer side, a positive meniscus lens L310 having an aspherical concave surface at its reticle side, a positive meniscus lens L311 having a concave surface at its reticle side, an aperture stop AS, a plano-convex lens L312 having a planar surface at its wafer side, a positive meniscus lens L313 having an aspherical concave surface at its wafer side, a positive meniscus lens S314 having an aspherical concave surface at its wafer side, a plano-convex lens L315 (interface lens Lb) having a planar surface at its wafer side, and a plane parallel plate Lp, which are arranged sequentially in this order from the reticle side (light entering side).

In the same manner as in the first example, in the second example, an optical path between the interface lens Lb and the plane parallel plate (immersed plane parallel plate) Lp and an optical path between the plane parallel plate Lp and the wafer W are filled with pure water (Lm1 and Lm2) having a refractive index of 1.435876 relative to an ArF excimer laser beam (having a central wavelength λ of 193.306 nm), which is the used laser beam (exposure beam). All the light transmitting members including the interface lens Lb and the plane parallel plate Lp are made of silica (SiO_2), which has a refractive index of 1.5603261 relative to the central wavelength of the used light. Table 2 below shows the specifications of the projection optical system PL according to the second example.

Table 2

(Main Specifications)

$\lambda = 193.306 \text{ nm}$

$\beta = 1/4$

5 NA = 1.3

B = 15.4 mm

A = 3 mm

LX = 26 mm

LY = 5 mm

10

(Specifications of Optical Members)

Surface No.	r	d	n	Optical Member
	(Reticle Surface)	128.0298		
1	∞	8.0000	1.5603261	(P1)
2	∞	3.0000		
3	708.58305	50.0000	1.5603261	(L11)
4	-240.96139	1.0000		
5	159.28256	55.0000	1.5603261	(L12)
6	1030.42583	15.3309		
7	175.91680	33.4262	1.5603261	(L13)
8	1901.42936	13.4484		
9*	-313.76486	11.8818	1.5603261	(L14)
10	235.56199	1.0000		
11	90.40801	53.3442	1.5603261	(L15)
12	109.36394	12.8872		
13	-1337.13410	20.2385	1.5603261	(L16)
14	-314.47144	10.2263		
15	-106.13528	42.5002	1.5603261	(L17)
16	-334.97792	56.0608		
17*	-1619.43320	46.3634	1.5603261	(L18)
18	-167.00000	1.0000		

19	-568.04127	48.4966	1.5603261	(L19)
20	-172.67366	1.0000		
21	637.03167	27.8478	1.5603261	(L110)
22	-838.93167	1.0000		
23	264.56403	30.7549	1.5603261	(L111)
24*	3443.52617	72.0000		
25	∞	-237.1956		(M1)
26	134.07939	-15.0000	1.5603261	(L21)
27	218.66017	-33.2263		
28	111.51192	-18.0000	1.5603261	(L22)
29	334.92606	-28.5215		
30	170.92067	28.5215		(CM)
31	334.92606	18.0000	1.5603261	(L22)
32	111.51192	33.2263		
33	218.66017	15.0000	1.5603261	(L21)
34	134.07939	237.1956		
35	∞	-72.0000		(M2)
36	1133.17643	-25.2553	1.5603261	(L31)
37	247.47802	-1.0000		
38	-480.60890	-29.6988	1.5603261	(L32)
39	626.43077	-1.0000		
40	-208.29831	-36.2604	1.5603261	(L33)
41	-2556.24930	-1.0000		
42	-173.46230	-50.0000	1.5603261	(L34)
43*	-294.18687	-26.4318		
44	699.54032	-11.5000	1.5603261	(L35)
45	-106.38847	-47.9520		
46	158.19938	-11.5000	1.5603261	(L36)
47*	-189.99848	-27.6024		
48*	487.32943	-34.3282	1.5603261	(L37)
49	153.21216	-1.0000		
50	-280.33475	-39.4036	1.5603261	(L38)
51*	-1666.66667	-17.3862		

52	∞	-22.0000	1.5603261	(L39)
53*	-1511.71580	-40.3150		
54*	655.86673	-62.2198	1.5603261	(L310)
55	242.88510	-1.0000		
56	843.73059	-49.2538	1.5603261	(L311)
57	280.00000	-1.0000		
58	∞	-1.0000		(AS)
59	-291.92686	-61.1038	1.5603261	(L312)
60	∞	-1.0000		
61	-179.32463	-67.4474	1.5603261	(L313)
62*	-438.34656	-1.0000		
63	-128.42402	-52.4156	1.5603261	(L314)
64*	-401.88080	-1.0000		
65	-75.86112	-41.5893	1.5603261	(L315: Lb)
66	∞	-1.0000	1.435876	(Lm2)
67	∞	-16.5000	1.5603261	(Lp)
68	∞	-3.0000	1.435876	(Lm1)

(Wafer Surface)

(Aspherical Surface Data)

9th surface

$\kappa = 0$

$$\begin{array}{ll}
 5 \quad C_4 = -3.1753 \times 10^{-8} & C_6 = 9.0461 \times 10^{-12} \\
 C_8 = -1.0355 \times 10^{-15} & C_{10} = 1.2398 \times 10^{-19} \\
 C_{12} = -1.1221 \times 10^{-23} & C_{14} = 5.7476 \times 10^{-28} \\
 C_{16} = -1.1800 \times 10^{-32} & C_{18} = 0
 \end{array}$$

10 17th surface

$\kappa = 0$

$$\begin{array}{ll}
 C_4 = -2.8399 \times 10^{-8} & C_6 = -3.0401 \times 10^{-13} \\
 C_8 = 1.1462 \times 10^{-17} & C_{10} = 4.0639 \times 10^{-22} \\
 C_{12} = -8.6125 \times 10^{-26} & C_{14} = 4.4202 \times 10^{-30} \\
 15 \quad C_{16} = -9.9158 \times 10^{-35} & C_{18} = 0
 \end{array}$$

24th surface

$$\kappa = 0$$

$$C_4 = 2.1499 \cdot 10^{-8}$$

$$C_6 = -3.8861 \cdot 10^{-13}$$

$$5 \quad C_8 = 5.4812 \cdot 10^{-18}$$

$$C_{10} = -2.1623 \cdot 10^{-23}$$

$$C_{12} = -2.5636 \cdot 10^{-26}$$

$$C_{14} = 2.1879 \cdot 10^{-30}$$

$$C_{16} = -6.5039 \cdot 10^{-35}$$

$$C_{18} = 0$$

43th surface

$$10 \quad \kappa = 0$$

$$C_4 = -2.0533 \cdot 10^{-8}$$

$$C_6 = 7.8051 \cdot 10^{-13}$$

$$C_8 = 9.4002 \cdot 10^{-18}$$

$$C_{10} = -2.1043 \cdot 10^{-21}$$

$$C_{12} = 7.8182 \cdot 10^{-25}$$

$$C_{14} = -9.2007 \cdot 10^{-29}$$

$$C_{16} = 3.6742 \cdot 10^{-33}$$

$$C_{18} = 0$$

15

47th surface

$$\kappa = 0$$

$$C_4 = 9.8639 \cdot 10^{-8}$$

$$C_6 = -6.7359 \cdot 10^{-12}$$

$$C_8 = 6.8579 \cdot 10^{-16}$$

$$C_{10} = -6.1604 \cdot 10^{-20}$$

$$20 \quad C_{12} = 5.1722 \cdot 10^{-24}$$

$$C_{14} = -2.9412 \cdot 10^{-28}$$

$$C_{16} = 8.6688 \cdot 10^{-33}$$

$$C_{18} = 0$$

48th surface

$$\kappa = 0$$

$$25 \quad C_4 = 4.3101 \cdot 10^{-8}$$

$$C_6 = -3.2805 \cdot 10^{-12}$$

$$C_8 = 5.6432 \cdot 10^{-17}$$

$$C_{10} = -9.2345 \cdot 10^{-22}$$

$$C_{12} = 1.0713 \cdot 10^{-25}$$

$$C_{14} = -9.9944 \cdot 10^{-30}$$

$$C_{16} = 1.8148 \cdot 10^{-33}$$

$$C_{18} = 0$$

30 51th surface

$$\kappa = 0$$

$$C_4 = 2.5839 \cdot 10^{-8}$$

$$C_6 = -1.8848 \cdot 10^{-12}$$

$$C_8 = -4.9271 \cdot 10^{-17}$$

$$C_{10} = 4.4946 \cdot 10^{-21}$$

$$\begin{array}{ll} C_{12} = -7.2550 \cdot 10^{-26} & C_{14} = 4.9237 \cdot 10^{-31} \\ C_{16} = -2.4260 \cdot 10^{-35} & C_{18} = 6.2565 \cdot 10^{-40} \end{array}$$

53th surface

$$5 \quad \kappa = 0$$

$$\begin{array}{ll} C_4 = -4.7449 \cdot 10^{-8} & C_6 = -2.3075 \cdot 10^{-13} \\ C_8 = 1.0475 \cdot 10^{-16} & C_{10} = -2.1805 \cdot 10^{-21} \\ C_{12} = -9.0530 \cdot 10^{-26} & C_{14} = 4.6274 \cdot 10^{-30} \\ C_{16} = -6.4961 \cdot 10^{-35} & C_{18} = 3.4402 \cdot 10^{-41} \end{array}$$

10

54th surface

$$\kappa = 0$$

$$\begin{array}{ll} C_4 = 2.0328 \cdot 10^{-8} & C_6 = -7.7439 \cdot 10^{-13} \\ C_8 = 1.6217 \cdot 10^{-17} & C_{10} = -3.5531 \cdot 10^{-22} \\ 15 \quad C_{12} = 8.2634 \cdot 10^{-27} & C_{14} = 2.6232 \cdot 10^{-31} \\ C_{16} = -2.0989 \cdot 10^{-35} & C_{18} = 4.0888 \cdot 10^{-40} \end{array}$$

62th surface

$$\kappa = 0$$

$$\begin{array}{ll} 20 \quad C_4 = 2.5121 \cdot 10^{-8} & C_6 = -2.0342 \cdot 10^{-12} \\ C_8 = 1.2906 \cdot 10^{-16} & C_{10} = -5.4455 \cdot 10^{-21} \\ C_{12} = 1.2885 \cdot 10^{-25} & C_{14} = -1.4600 \cdot 10^{-30} \\ C_{16} = 3.2850 \cdot 10^{-36} & C_{18} = 0 \end{array}$$

25 64th surface

$$k = 0$$

$$\begin{array}{ll} C_4 = -2.8098 \cdot 10^{-8} & C_6 = -3.9565 \cdot 10^{-12} \\ C_8 = 3.1966 \cdot 10^{-16} & C_{10} = -2.7246 \cdot 10^{-20} \\ C_{12} = 1.8266 \cdot 10^{-24} & C_{14} = -8.6244 \cdot 10^{-29} \\ 30 \quad C_{16} = 2.1570 \cdot 10^{-33} & C_{18} = 0 \end{array}$$

Fig. 7 shows lateral aberrations occurring in the projection optical system PL of the second example. As

apparent from Fig. 7, the aberration is corrected in an satisfactory manner for the exposure beams having a wavelength width of $193.306 \text{ nm} \pm 0.2 \text{ pm}$ even though the projection optical system PL of the second example has an
5 extremely large image-side numerical aperture ($\text{NA} = 1.3$) and a relatively large effective exposure region ER (26 mm by 5 mm) in the same manner as in the projection optical system PL of the first example.

10 In this manner, the optical path formed between the interface lens Lb and the wafer W is filled with pure water (Lm1 and Lm2) having a large refractive index in the projection optical system PL of the present embodiment. This enables the projection optical system PL to have a
15 relatively large effective imaging region while achieving a large effective image-side numerical aperture. The projection optical system PL of each example of the present invention has a rectangular effective exposure region (stationary exposure region) ER having the dimensions of 26
20 mm by 5 mm while achieving a high image-side numerical aperture of about 1.3 for an ArF excimer laser beam having a central wavelength of 193.306 nm. This enables the projection optical system PL of each example to scan and expose a circuit pattern within a rectangular exposure
25 region of, for example, 26 mm by 33 mm with a high accuracy.

When the image-side numerical aperture of the immersion projection optical system is, for example, less than 1.2, as shown in Fig. 8(a), reflection of incident
30 light at a light entering surface Lba can be avoided even if the curvature of convex light receiving surface Lba of the interface lens Lb is not that large. As a result, a holding tab Lbb for holding the interface lens Lb may sufficiently

be spaced from liquid (immersion liquid, not shown) at the side of a light emitting surface Lbc. This lowers the risk of liquid entering the space between the holding tab Lbb and a hold Hd in the lens cell and liquid leaking into the
5 projection optical system.

However, when setting the image-side numerical aperture of the immersion projection optical system to be greater than, for example, 1.2, as shown in Fig. 8(b), to
10 avoid reflection of incident light to the light entering surface Lba of the interface lens Lb, the light entering surface Lba must have a convex shape with a significantly large curvature. In this case, the holding tab Lbb for the interface lens Lb is inevitably located near the liquid at
15 the side of the light emitting surface Lbc, and liquid is apt to easily leaking into the space between the holding tab Lbb and the hold Hd and further into the projection optical system.

20 When liquid leaks into the space between the holding tab Lbb and the hold Hd, the leaking liquid acts to produce a force that attracts the holding tab Lbb and the hold Hd toward each other. This may move or deform the interface lens Lb and increase the risk of the imaging capability of
25 the projection optical system being lowered. Further, when liquid passes through the holding lens Lbb and the hold Hd and leaks into the projection optical system, the anti-reflection film formed on the optical surface of a light transmission member, which includes the interface lens Lb,
30 may be deteriorated thereby increasing the risk of the imaging capability of the projection optical system being lowered.

Fig. 9 is a schematic diagram showing the main feature of the projection optical system in the present embodiment. Referring to Fig. 9(a), in the projection optical system PL of the present embodiment, a groove Gr (that is, a space) is formed so as to surround an effective region (region through which effective light beam passes) of the light emitting surface Lbc of the interface lens (interface optical element) Lb. The groove Gr is, for example, continuously formed so as to entirely surround the effective region of the light emitting surface Lbc and includes an inclined surface Gra that is in accordance with the effective circumferential surface Lbd (for example, substantially parallel to an effective circumferential surface Lbd) connecting the circumference of the effective region of the light entering surface Lba to the effective region of the light emitting surface Lbc.

In the projection optical system PL, the image-side numerical aperture of the immersion projection optical system is to be substantially greater than, for example, 1.2 (1.32 or 1.3). Thus, the light entering surface Lba of the interface lens Lb has a large curvature, and the holding tab Lbb is located near liquid Lm2 (not shown) at the side of the light emitting surface Lbc. However, the groove Gr extends deeper than the holding tab Lbb to be closer to the light entering surface Lba. In other words, the holding tab Lbb is arranged on a holding plane Lbbs (hypothetical plane shown by double-dashed line in the drawing), which is orthogonal to the optical axis AX. Space, or the interior of the groove Gr, is formed between the holding tab Lbb and the optical axis AX. In this specification, "groove" is a broad concept including a recess and gouged out portions. For example, a step may be formed between the level of the inner

surface of the groove Gr (light emitting surface Lbc) and the level of an outer surface Lbe.

In the projection optical system PL of the present embodiment, a liquid holding mechanism LH for holding the liquid Lm2 is arranged between the effective region of the light emitting surface Lbc of the interface lens Lb and the immersed plane parallel plate Lp. The liquid holding mechanism LH is formed from, for example, titanium or stainless steel, and partially projects into the interior (i.e., space) of the groove Gr. More specifically, the liquid holding mechanism LH has an opposed surface LHa, which is spaced from and opposed toward the inclined surface Gra of the groove Gr. A water repellant treatment is performed on at least either one of the inclined surface Gra and the opposed surface LHa. Alternatively, a water repellant film is formed on at least either one of the inclined surface Gra and the opposed surface LHa.

As described above, in the projection optical system PL of the preferred embodiment, the light entering surface Lba of the interface lens Lb has a large curvature. Thus, the holding tab Lbb is located near the liquid Lm2 at the side of the light emitting surface Lbc. However, the groove Gr is formed so as to surround the effective region of the light emitting surface Lbc. Therefore, even when the liquid holding mechanism LH is not used, the groove Gr functions to resist leakage of the liquid Lm2 into the space between the holding tab Lbb and the hold Hd of the lens cell and further into the projection optical system PL.

That is, in the projection optical system PL of the present embodiment, the leakage of liquid (immersion liquid)

into the optical system is prevented and a satisfactory imaging capability is maintained. Further, the exposure apparatus of the present embodiment uses the high resolution immersion projection optical system PL, which prevents
5 liquid from entering into the optical system and maintains satisfactory capability. Thus, micropatterns may stably be projected and exposed with high accuracy.

A plurality of unconnected grooves Gr may be formed so
10 as to surround, for example, the effective region of the light emitting surface Lbc of the interface lens Lb. However, to effectively prevent the liquid Lm2 from reaching the holding tab Lbb, as described above, it is preferred that the groove Gr be formed continuously so as to surround
15 the entire effective region of the light emitting surface Lbc and that the groove Gr be formed to extend deeper than the holding tab Lbb to the side of the light entering surface Lba.

20 In the projection optical system PL of the present embodiment, the plane parallel plate (generally an optical member has substantially no refractive power) Lp is arranged in the optical path between the interface lens Lb and the wafer W. Thus, even when pure water, which serves as the
25 immersion liquid, is contaminated by out gas or the like due to the photoresist applied to the wafer W, the plane parallel plate Lp arranged between the interface lens Lb and the wafer W functions to effectively prevent the image side optical surface of the interface lens Lb from being
30 contaminated by the contaminated pure wafer. Further, the refractive rate difference between the liquid (pure wafer: Lm1 and Lm2) is small. This significantly moderates the orientation and positional accuracy required for the plane

parallel plate Lp. Thus, even when the plane parallel plate Lp is contaminated, the optical capability may be recovered by replacing parts whenever necessary. Further, the plane parallel plate Lp functions to reduce pressure fluctuations of the liquid Lm2, which contacts the interface lens Lb, during scanning and exposure or during a step movement. Thus, liquid may be held in a relatively small space.

In the projection optical system PL of the present embodiment, the liquid holding mechanism LH partially projects into the groove Gr so as to avoid contact with the interface lens Lb, that is, so as to prevent external force from acting on the interface lens Lb. This ensures that the liquid Lm2 is held in the optical path between the effective region of the light emitting surface Lbc of the interface lens Lb and the plane parallel plate Lp. However, when a pressure fluctuation that is greater than predicted occurs in the liquid Lm2, which contacts the interface lens Lb, the liquid Lm2 may be transmitted to the holding tab Lbb through the space between the inclined surface Gra of the groove Gr and the opposed surface LHa of the liquid holding mechanism LH.

Accordingly, it is preferable that a water repellent treatment be performed on at least either one of the hydrophilic inclined surface Gra and the opposed surface LHa or that a water repellent film be applied to at least either one of the inclined surface Gra and the opposed surface LHa so that the liquid Lm2 is not transmitted to the holding tab Lbb through the space between the inclined surface Gra and the opposed surface LHa even when a pressure fluctuation that is greater than predicted occurs in the liquid Lm2, which is in contact with the interface lens Lb. It is

preferred that the groove Gr have the inclined surface Gra that is in accordance with the effective circumferential surface Lbd (has an inclination corresponding to the effective circumferential surface Lbd) connecting the circumference of the effective region of the light entering surface Lba to the effective region of the light emitting surface Lbc in order to ensure space for the arrangement of the liquid holding mechanism LH.

10 In the projection optical system PL of the present embodiment, the effective range in the light emitting surface Lbc of the interface lens Lbc is planar. Thus, the layer of the liquid Lm2 between the interface lens Lb and the plane parallel plate Lp has a uniform thickness. This prevents luminance differences in the exposure region on the wafer W even when the transmissivity of the liquid Lm2 with respect to exposure light is insufficient.

20 In the above embodiment, the plane parallel plate Lp is arranged in the optical path between the interface lens Lb and the wafer W. However, the present invention is not limited in such a manner and, as shown in the modification of Fig. 9(b), the plane parallel plate Lp may be eliminated. The same advantages as the present embodiment may be obtained with the modification of Fig. 9(b) by forming the groove Gr (that is, a space) so as to surround the effective region in the light emitting surface Lbc of the interface lens Lb.

30 In the above embodiment, the pure water (Lm1 and Lm2) is filled in the optical path between the interface lens Lb and the wafer W. A liquid having a refractive index higher than the pure water (e.g., a liquid having a refractive

index of 1.6 or more) may be used instead. Examples of such high-refractive index liquids include glycenol ($\text{CH}_2[\text{OH}]\text{CH}[\text{OH}]\text{CH}_2[\text{OH}]$) and heptane (C_7H_{16}). Further, water containing H^+ , Cs^- , K^+ , Cl^- , SO_4^{2-} , or PO_4^{2-} , water containing
5 particles of oxide of aluminum, isopropanol, hexane, and decane may also be used.

When such a high-refractive index liquid is used, it is preferable that some of the lenses in the projection
10 optical system PL, in particular, lenses near the image surface (to the wafer W), be formed from a material having a high refractive index. It is preferable that calcium oxide, magnesium oxide, barium fluoride, strontium oxide, barium
oxide, or a mixed crystal mainly composed of these materials
15 be used as the high-refractive index material.

This realizes a high numerical aperture with a feasible size. When, for example, an ArF excimer laser (having a wavelength of 193 nm) is used, the projection
20 optical system PL achieves a high numerical aperture of about 1.5 or more. When an F_2 laser having a wavelength of 157 nm is used as the exposure beam IL, it is preferable to use a liquid enabling transmission of an F_2 laser beam, specifically, a fluorinated fluid, such as
25 perfluoropolyalkyether (PFPE), or fluorinated oil as the liquid.

The exposure apparatus of the above embodiment illuminates the reticle (mask) using an illumination
30 apparatus (an illumination process) and exposes a transfer pattern in the mask onto the photosensitive substrate using the projection optical system (an exposure process). Through the illumination and exposure processes, the exposure

apparatus manufactures microdevices (semiconductor devices, imaging devices, liquid crystal display devices, or thin-film magnetic heads). A method for manufacturing a microdevice or specifically a semiconductor device through formation of a predetermined circuit pattern on a wafer or the like as a photosensitive substrate using the exposure apparatus of the present embodiment will now be described with reference to a flowchart shown in Fig. 10.

10 In step S301 in Fig. 10, a metal film is first formed on wafers of a single lot through vapor deposition. In step S302, photoresist is applied to a metal film formed on each wafer of the single lot. In step S303, the exposure apparatus of the present invention is used to sequentially expose and transfer an image of a pattern in a mask onto shot-regions of each wafer in the single lot with the projection optical system. Then, in step S304, the photoresist formed on each wafer of the single lot is developed. In step S305, each wafer of the single lot is etched using the resist pattern formed on the wafer as a mask. This forms a circuit pattern corresponding to the mask pattern in the shot-regions of each wafer.

 Afterwards, circuit patterns corresponding to upper layers are formed to complete the semiconductor device or the like. With the semiconductor device manufacturing method described above, a semiconductor device with an extremely fine circuit pattern is produced with high throughput. In steps S301 to S305, metal is deposited on the wafer through vapor deposition, resist is coated on the metal film, and then processes in which the resist is exposed, developed, and etched are performed. Prior to these processes, a silicon oxide film may first be formed on the wafer, and the

resist may be coated on the silicon oxide film. Then, the processes in which the resist is exposed, developed, and etched may be performed.

5 The exposure apparatus of the present embodiment may also be used to produce a liquid crystal display device serving as a microdevice by forming a predetermined pattern (a circuit pattern or an electrode pattern) on a plate (glass substrate). One example method for manufacturing a
10 liquid crystal display device will now be described with reference to a flowchart shown in Fig. 11. In Fig. 11, a pattern formation process is performed in step S401. In step S401, a mask pattern is transferred and exposed onto a
15 photosensitive substrate (e.g., a glass substrate coated with resist) using the exposure apparatus of the present embodiment. In other words, a photolithography process is performed. Through the photolithography process, a predetermined pattern including, for example, a large number of electrodes is formed on the photosensitive substrate.
20 Afterwards, a predetermined pattern is formed on the substrate through processes including a developing process, an etching process, and a resist removing process. Then, a color filter formation process is performed in step S402.

25 In step S402, a color filter is formed by, for example, arranging plural sets of R (red), G (green), and B (blue) dots in a matrix, or arranging plural of sets of filters formed by R, G, and B stripes in horizontal scanning line directions. After the color filter formation process is
30 performed in step S402, a cell assembly process is performed in step S403. In step S403, the substrate having a predetermined pattern obtained through the pattern formation process performed in step S401 and the color filter or the

like obtained through the color filter formation process performed in step S402 are assembled together to form the liquid crystal panel (liquid crystal cell).

5 In S403, for example, a liquid crystal is injected between the substrate having the predetermined pattern obtained through the pattern formation process performed in S401 and the color filter obtained through the color filter formation process performed in S402 to form the liquid
10 crystal panel (liquid crystal cell). In a module assembly process performed subsequently in step S404, an electric circuit for enabling the assembled liquid crystal panel (liquid crystal cell) to perform a display operation and other components including a backlight are mounted. This
15 completes the liquid crystal display device. The liquid crystal display device manufacturing method described above enables a liquid crystal device having an extremely fine circuit pattern to be produced with high throughput.

20 Although the ArF excimer laser light source is used in the above embodiment, other appropriate light sources, such as an F₂ laser light source, may be used. When an F₂ laser beam is used as the exposure beam, a fluorinated liquid enabling transmission of an F₂ laser beam, such as
25 fluorinated oil or perfluoropolyalkyether (PFPE), is used as the liquid that fills the image space portion.

 The present invention is applied to an immersion projection optical system that is mounted on the exposure
30 apparatus in the above embodiment. However, the application of the present invention is not limited to such an optical system. The present invention is also applicable to other typical immersion projection optical systems. Further, in

the above embodiment, the present invention is applied to an off-axis catadioptric optical system of which effective field of view does not include the optical axis. However, the application of the present invention is not limited to such an optical system. The present invention is also applicable to other typical projection optical systems. Additionally, in the above embodiment, the present invention is applied to an immersion projection optical system. However, the application of the present invention is not limited to such an optical system. The present invention is also applicable to an immersion objective optical system.

In the above embodiment, the interface lens Lb and the immersed plane parallel plate Lp are formed from silica, which is an amorphous material. However, the material forming the interface lens Lb and the immersed plane parallel plate Lp is not limited to silica. For example, a crystalline material, such as magnesium oxide, calcium oxide, strontium oxide, barium oxide, barium fluoride, barium lithium fluoride (BaLiF_3), lutetium aluminum garnet (LuAG), or crystalline magnesium aluminum spinel (MgAl_2O_4) may be used.

Although pure water is used as the first liquid and the second liquid in the above embodiment, the first and second liquids are not limited to pure water. For example, water containing H^+ , Cs^+ , K^+ , Cl^- , SO_4^{2-} , or PO_4^{2-} , isopropanol, glycerol, hexane, heptane, decane, Delphi (cyclic hydrocarbon compound) manufactured by Mitusi Chemicals, Inc., HIF-001 manufactured by JSR Corporation, and IF131, IF132, and IF175 manufactured by E. I. du Pont de Nemours and Company may be used as the first and second liquids.

CLAIMS

1. A projection optical system for projecting an image of a first plane onto a second plane through a liquid,
5 the projection optical system being characterized by:

an interface optical element including a side towards the first plane that contacts a gas and a side towards the second plane that contacts the liquid;

wherein the interface optical element includes a light
10 entering surface, which has a convex shape facing towards the first plane, and a groove, which is formed to surround an effective region in a light emitting surface of the interface optical element.

15 2. The projection optical system according to claim 1, being characterized in that the groove is formed continuously to entirely surround the effective region.

3. The projection optical system according to claim
20 1 or 2, being characterized in that the groove includes an inclined surface that is in accordance with an effective circumferential surface connecting the circumference of an effective region in the light entering surface and the circumference of the effective region in the light emitting
25 surface.

4. The projection optical system according to any one of claim 1 to 3, being characterized in that the groove extends closer to the light entering surface than a holding
30 tab for holding the interface optical element.

5. The projection optical system according to any one of claims 1 to 4, further being characterized by:

an optical member having substantially no refractive power and being arranged in an optical path between the interface optical element and the second plane.

5 6. The projection optical system according to claim 5, further being characterized by:

 a liquid holding mechanism for holding the liquid in an optical path between the effective region in the light emitting surface of the interface optical element and the
10 optical member having substantially no refractive power, wherein the liquid holding mechanism partially projects into the groove.

 7. The projection optical system according to any
15 one of claims 1 to 4, further being characterized by:

 a liquid holding mechanism for holding the liquid in an optical path between the effective region in the light emitting surface of the interface optical element and the second plane, wherein the liquid holding mechanism partially
20 projects into the groove.

 8. The projection optical system according to claim 6 or 7, being characterized in that the liquid holding mechanism includes an opposed surface spaced from and
25 opposed to the inclined surface of the groove, with a water repellent treatment being performed on at least either one of the inclined surface and the opposed surface.

 9. The projection optical system according to claim
30 6 or 7, being characterized in that the liquid holding mechanism includes an opposed surface spaced from and opposed to the inclined surface of the groove, with a water repellent film being formed on at least either one of the

inclined surface and the opposed surface.

10. A projection optical system for projecting an image of a first plane onto a second plane through a liquid,
5 the projection optical system being characterized by:

an interface optical element including a side towards the first plane that contacts a gas and a side towards the second plane that contacts the liquid;

wherein the interface optical element includes a light
10 entering surface, which has a convex shape facing towards the first plane, and a holding tab, which is arranged on a holding plane orthogonal to an optical axis; and

wherein a space is formed between the holding tab and the optical axis.

15

11. The projection optical system according to claim 10, being characterized in that the space is formed continuously to entirely surround a light emitting surface of the interface optical element.

20

12. The projection optical system according to claim 10 or 11, being characterized in that the space includes an inclined surface that is in accordance with an effective circumferential surface connecting the circumference of an effective region in the light entering surface and the
25 circumference of an effective region in a light emitting surface.

13. The projection optical system according to any
30 one of claim 10 to 12, further being characterized by:

an optical member having substantially no refractive power and being arranged in an optical path between the interface optical element and the second plane.

14. The projection optical system according to claim 13, further being characterized by:

5 a liquid holding mechanism for holding the liquid in an optical path between the light emitting surface of the interface optical element and the optical member having substantially no refractive power, wherein the liquid holding mechanism partially projects into the space.

10 15. The projection optical system according to any one of claims 11 to 13, further being characterized by:

15 a liquid holding mechanism for holding the liquid in an optical path between the light emitting surface of the interface optical element and the second plane, wherein the liquid holding mechanism partially projects into the space.

16. The projection optical system according to claim 14 or 15, being characterized in that:

20 the space includes an inclined surface that is in accordance with an effective circumferential surface connecting the circumference of an effective region in the light entering surface and the circumference of an effective region in the light emitting surface;

25 the liquid holding mechanism includes an opposed surface spaced from and opposed to the inclined surface of the space, with a water repellent treatment being performed on at least either one of the inclined surface and the opposed surface.

30 17. The projection optical system according to claim 14 or 15, being characterized in that:

the space includes an inclined surface that is in accordance with an effective circumferential surface

connecting the circumference of an effective region in the light entering surface and the circumference of an effective region in the light emitting surface;

the liquid holding mechanism includes an opposed surface spaced from and opposed to the inclined surface of the space, with a water repellent film being formed on at least either one of the inclined surface and the opposed surface.

10 18. The projection optical system according to any one of claims 1 to 17, being characterized in that the effective region in the light emitting surface of the interface element is formed to be planar.

15 19. The projection optical system according to any one of claims 1 to 18, being characterized in that a reduced image of the first plane is formed on the second plane based on light from the first plane.

20 20. The projection optical system according to claim 19, further being characterized by:

a refractive first imaging optical system for forming a first intermediate image based on light from the first plane;

25 a second imaging optical system including at least one concave reflective mirror for forming a second intermediate image based on light from the first intermediate image;

a refractive third imaging optical system for forming the reduced image on the second plane based on light from the second intermediate image;

30 a first folding mirror arranged in an optical path between the first imaging optical system and the second imaging optical system; and

a second folding mirror arranged in an optical path between the second imaging optical system and the third imaging optical system.

5 21. The projection optical system according to any one of claims 1 to 20, further being characterized in that the interface optical element is formed from a crystalline material.

10 22. The projection optical system according to any one of claims 1 to 20, further being characterized in that the interface optical element is formed from an amorphous material.

15 23. An exposure apparatus being characterized by:
 an illumination system for illuminating a pattern set on the first plane; and
 the projection optical system according to any one of claims 1 to 22 for projecting an image of the pattern onto a
20 photosensitive substrate set on the second plane.

 24. An exposure method being characterized by:
 an illuminating step of illuminating a pattern set on the first plane; and
25 an exposure step of projecting and exposing an image of the pattern onto a photosensitive substrate set on the second plane using the projection optical system according to any one of claims 1 to 22.

30 25. A device manufacturing method being characterized by:
 an exposure step of projecting and exposing an image of a pattern set on the first plane onto a photosensitive

substrate set on the second plane using the projection optical system according to any one of claims 1 to 22; and a development step of developing the photosensitive substrate that has undergone the exposure step.

5

26. An optical element for use in an immersion objective optical system and having one optical surface that contacts liquid, the optical element being characterized by: another optical surface of the optical element having a convex shape; and a groove formed to surround an effective region in the one optical surface.

10

27. The optical element according to claim 26, being characterized in that the groove is formed continuously to entirely surround the effective region of the one optical surface.

15

28. The optical element according to claim 26 or 27, being characterized in that the groove includes an inclined surface that is in accordance with an effective circumferential surface connecting the circumference of an effective region in the another optical surface of the optical element and the circumference of the effective region in the one optical surface of the optical element.

20

25

29. The optical element according to any one of claims 26 to 28, being characterized in that the groove extends closer to the another optical surface of the optical element than a holding tab for holding the optical element.

30

30. An optical element for use in an immersion objective optical system and having one optical surface that

contacts liquid and another optical surface having a convex shape, the optical element being characterized by:

a holding tab for holding the optical element, wherein the holding tab is arranged on a holding plane orthogonal to
5 an optical axis of the optical element, wherein a space is formed between the holding tab and the optical axis.

31. The optical element according to claim 30, being characterized in that the space is formed continuously to
10 entirely surround the one optical surface of the optical element.

32. The optical element according to claim 30 or 31, being characterized in that the space includes an inclined
15 surface that is in accordance with an effective circumferential surface connecting the circumference of an effective region in the another optical surface of the optical element and the circumference of the effective region in the one optical surface of the optical element.

20

33. The optical element according to any one of claims 26 to 32, being characterized in that the optical element is formed from a crystalline material.

25 34. The optical element according to any one of claims 26 to 32, being characterized in that the optical element is formed from an amorphous material.

35. An immersion objective optical system including
30 the optical element according to any one of claims 26 to 34, being characterized in that the optical element is arranged nearest to a liquid side.

36. The immersion objective optical system according to claim 35, being characterized in that the immersion objective optical system forms an image of an object through the liquid.