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Sato et al.

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(54) **MASK AND PATTERN FORMING METHOD**

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(51) **Int. Cl.**

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G03F 1/28	(2012.01)
G03F 1/50	(2012.01)
H01L 21/308	(2006.01)

(52) **U.S. Cl.**
CPC ***H01L 21/308*** (2013.01); ***G03F 1/50*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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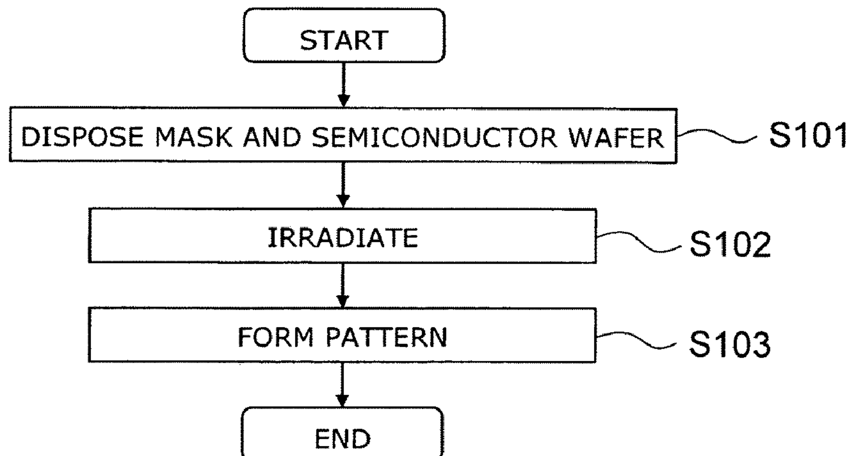
(57) **ABSTRACT**

According to one embodiment, a mask includes a substrate, first and second pattern portions. The substrate includes a first surface, and the substrate is light transmissive. The first pattern portion includes first optical members. The first optical members are provided on the first surface. A light transmittance of the first optical members is lower than a light transmittance of the substrate. A distance between the adjacent two first optical members is a first distance. The second pattern portion includes second optical members. The second optical members are provided on the first surface. A light transmittance of the second optical members is lower than the light transmittance of the substrate. A distance between the adjacent two second optical members is a second distance. A first phase of a light penetrating the first pattern portion is different from a second phase of a light penetrating the second pattern portion.

20 Claims, 7 Drawing Sheets



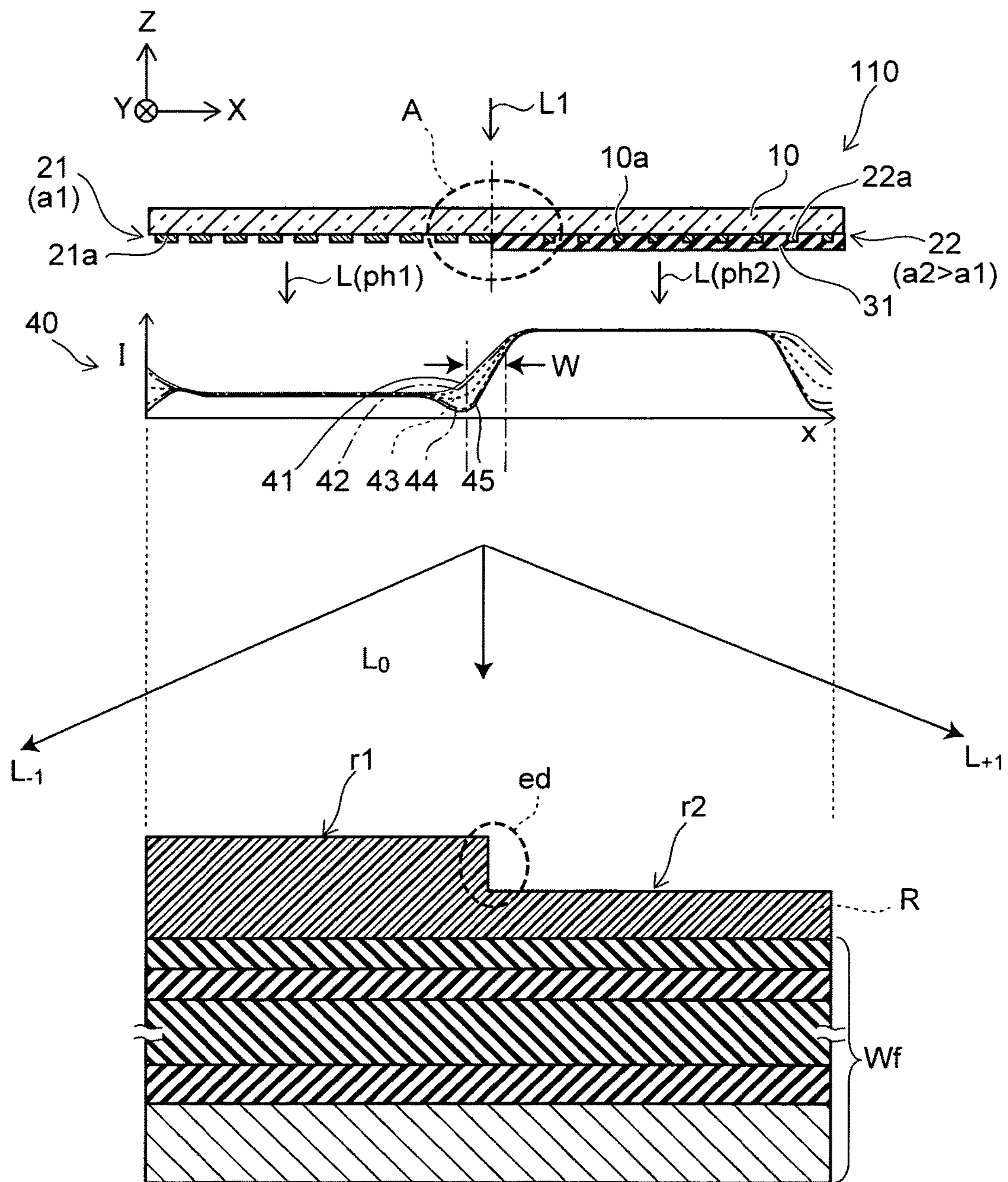


FIG. 1

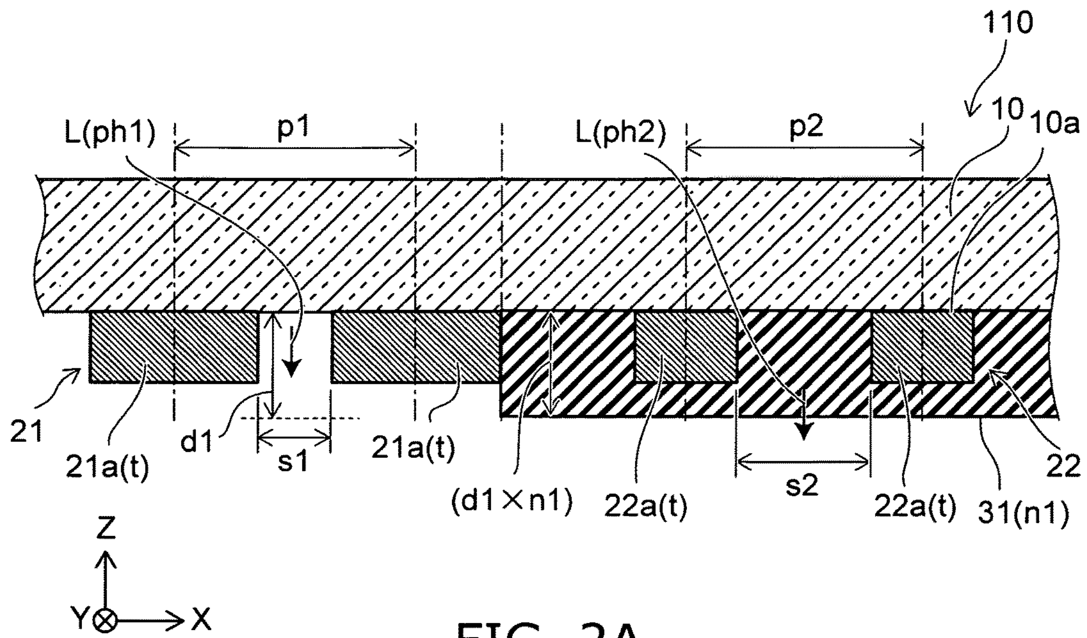


FIG. 2A

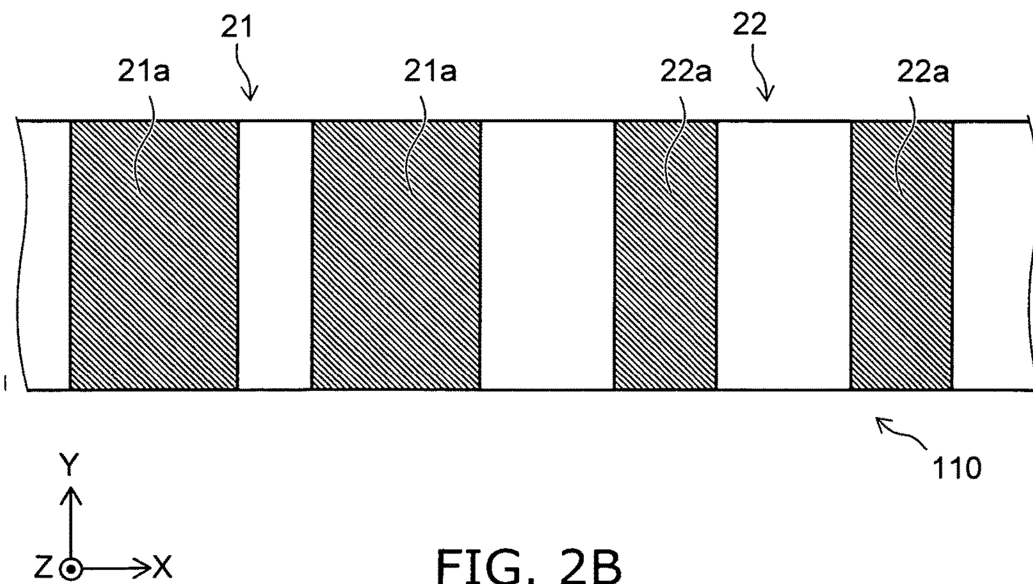


FIG. 2B

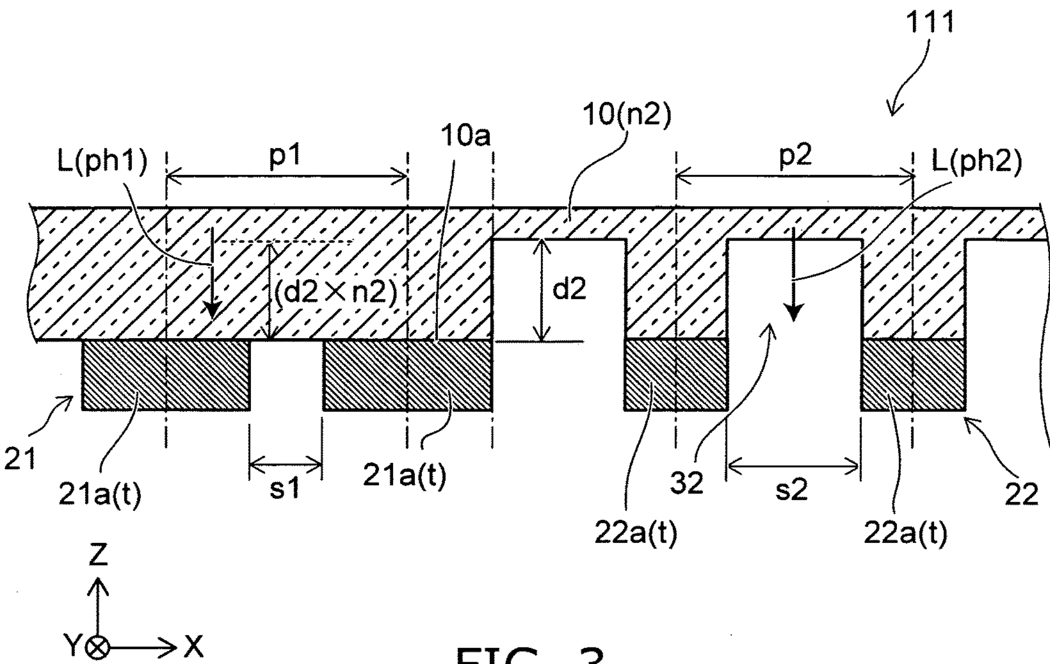


FIG. 3

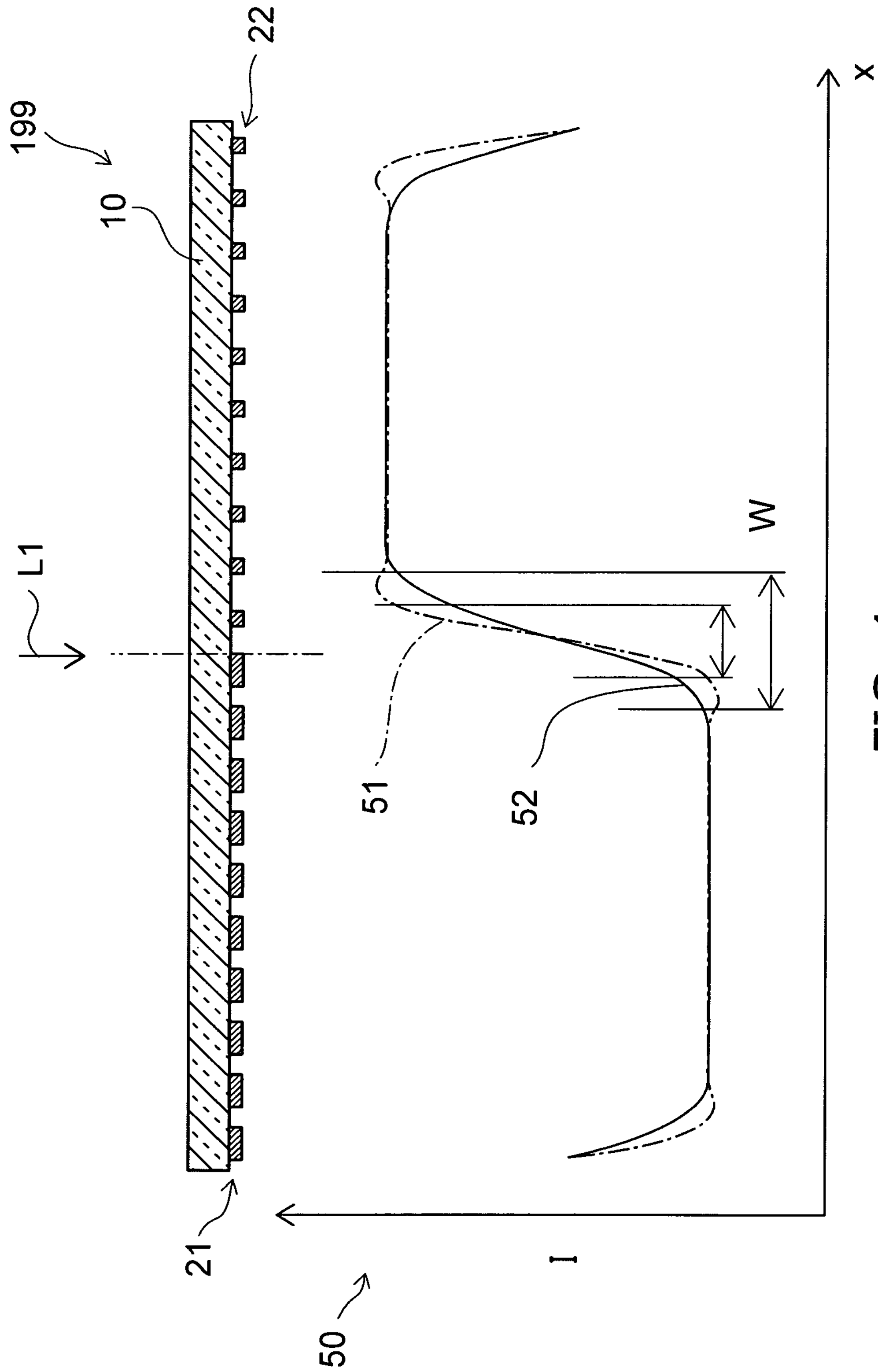


FIG. 4

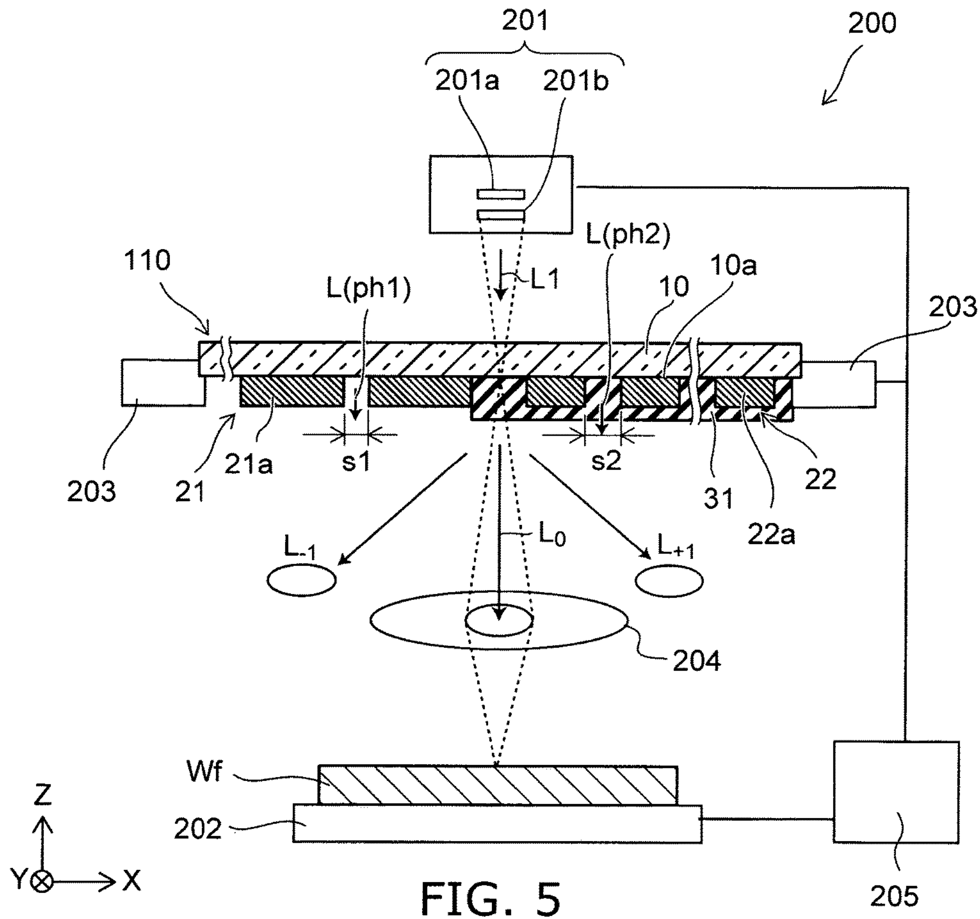


FIG. 5

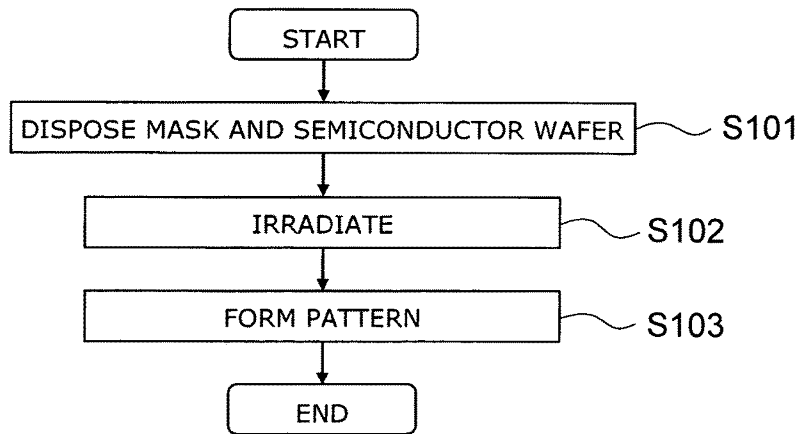


FIG. 6

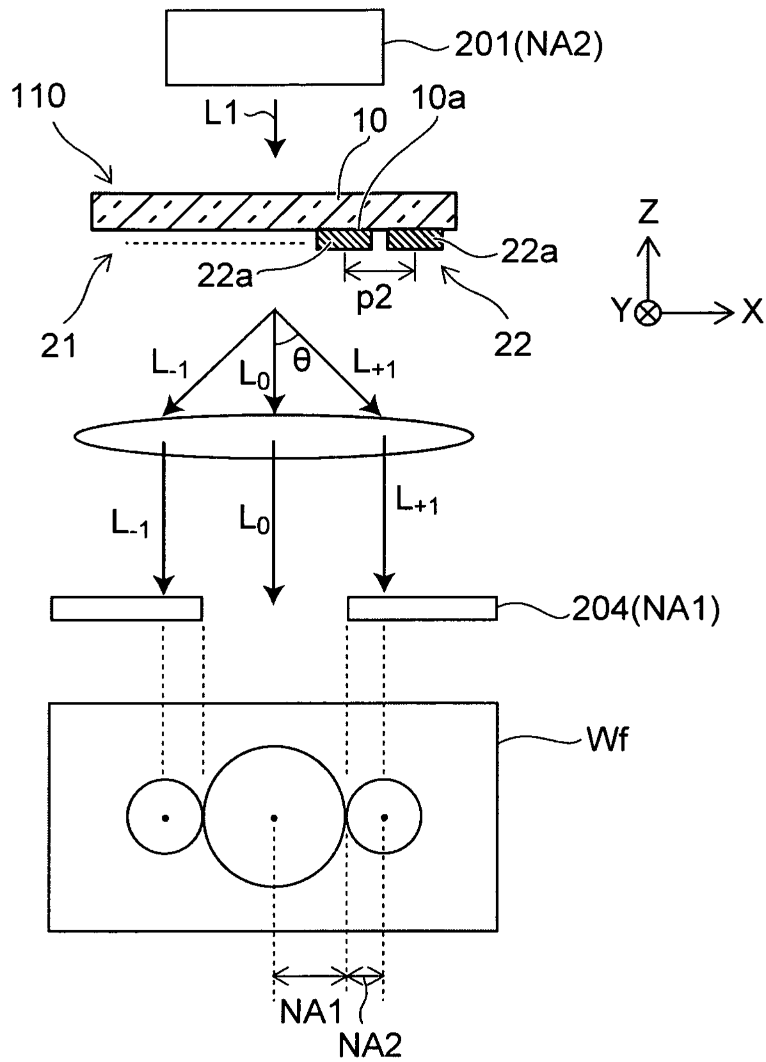


FIG. 7

FIG. 8

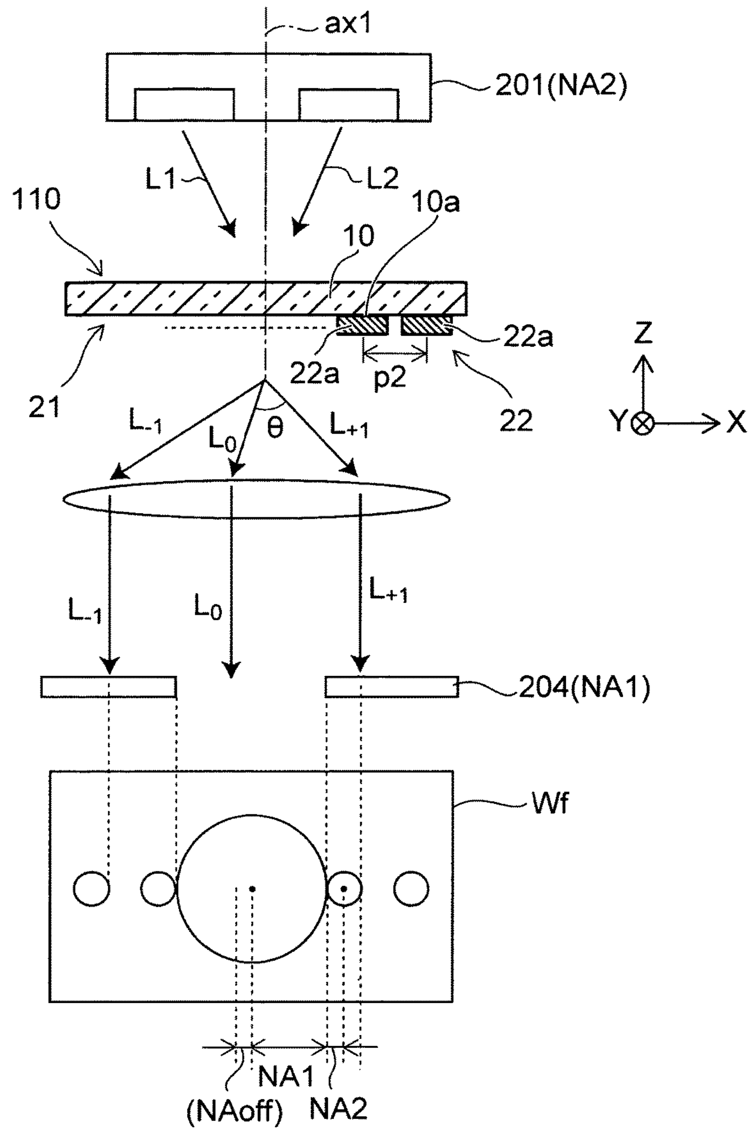
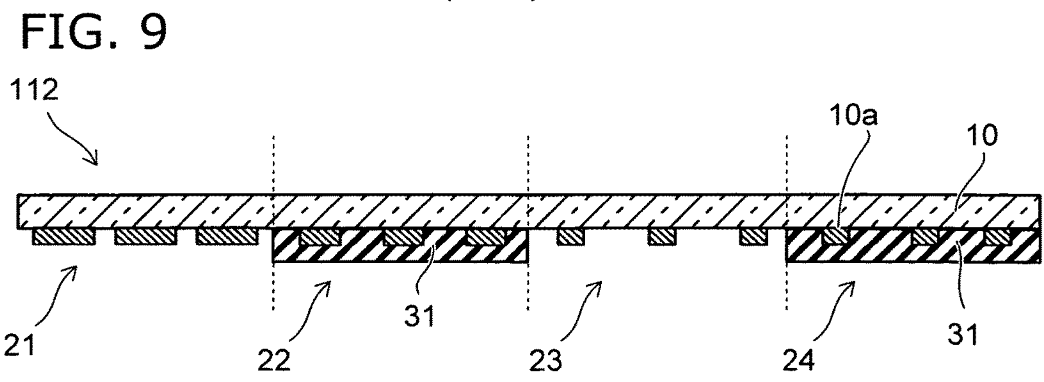


FIG. 9



MASK AND PATTERN FORMING METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2015-180100, filed on Sep. 11, 2015; the entire contents of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to a mask and a pattern forming method.

BACKGROUND

A mask having a repeated pattern is irradiated with light, and thereby a substrate to be transferred is exposed by light intensity according to an opening ratio and a gray level exposure region (gray region) can be formed on the substrate to be transferred. For the mask used for forming such a gray region, a high accuracy pattern is desired to be formed easily.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic view illustrating a mask and a semiconductor wafer according to a first embodiment;

FIG. **2**A and FIG. **2**B are schematic views illustrating the mask according to the first embodiment;

FIG. **3** is a schematic partial cross-sectional view illustrating a mask according to a second embodiment;

FIG. **4** is a schematic cross-sectional view illustrating a mask according to a reference example;

FIG. **5** is a schematic view illustrating an exposure device according to a third embodiment;

FIG. **6** is a flow chart illustrating a pattern forming method according to the third embodiment;

FIG. **7** is a schematic view illustrating an illumination optical system and a projection optical system according to the third embodiment;

FIG. **8** is a schematic view illustrating an illumination optical system and a projection optical system according to a fourth embodiment; and

FIG. **9** is a schematic cross-sectional view illustrating a mask according to a fifth embodiment.

DETAILED DESCRIPTION

According to one embodiment, a mask includes a substrate, a first pattern portion and a second pattern portion. The substrate includes a first surface, and the substrate is light transmissive. The first pattern portion includes a plurality of first optical members. The first optical members are provided on the first surface and arranged in a first direction along the first surface. A light transmittance of the first optical members is lower than a light transmittance of the substrate. A distance between the adjacent two first optical members is a first distance. The second pattern portion includes a plurality of second optical members. The second optical members are provided on the first surface and arranged in the first direction. A light transmittance of the second optical members is lower than the light transmittance of the substrate. A distance between the adjacent two second optical members is a second distance different from the first distance. A first phase of a light penetrating the first pattern

portion after a first light being incident on the first pattern portion is different from a second phase of a light penetrating the second pattern portion after the first light being incident on the second pattern portion.

According to another embodiment, a pattern forming method is disclosed. The method is based on a mask. The mask includes a substrate, a first pattern portion and a second pattern portion. The substrate includes a first surface, and the substrate is light transmissive. The first pattern portion includes a plurality of first optical members. The first optical members are provided on the first surface and arranged in a first direction along the first surface. A light transmittance of the first optical members is lower than a light transmittance of the substrate. A distance between the adjacent two first optical members is a first distance. The second pattern portion includes a plurality of second optical members. The second optical members are provided on the first surface and arranged in the first direction. A light transmittance of the second optical members is lower than the light transmittance of the substrate. A distance between the adjacent two second optical members is a second distance different from the first distance. The method can dispose the mask and a semiconductor wafer. The method can cause a first light from an illumination optical system to enter the first pattern portion and the second pattern portion. The method can cause a first phase of a light penetrating the first pattern portion to be different from a second phase of a light penetrating the second portion by the mask, and to emit a 0-order diffraction light, a +1-order diffraction light and a −1-order diffraction light of respective optical images of the light of the first phase and the light of the second phase to a projection optical system. The method can cause the 0-order diffraction light to penetrate by the projection optical system and finally form a pattern on the semiconductor wafer by the semiconductor wafer being irradiated with the 0-order diffraction light.

Various embodiments will be described hereinafter with reference to the accompanying drawings.

The drawings are schematic and conceptual; and the relationships between the thickness and width of portions, the proportions of sizes among portions, etc., are not necessarily the same as the actual values thereof. Further, the dimensions and proportions may be illustrated differently among drawings, even for identical portions.

In the specification and drawings, components similar to those described or illustrated in a drawing thereinabove are marked with like reference numerals, and a detailed description is omitted as appropriate.

First Embodiment

FIG. **1**, FIG. **2**A and FIG. **2**B are schematic views illustrating a mask and a semiconductor wafer according to a first embodiment.

FIG. **1** is a schematic cross-sectional view illustrating a mask and a semiconductor wafer.

FIG. **2**A is a schematic partial cross-sectional view of an enlarged portion A in FIG. **1**.

FIG. **2**B is a schematic partial plan view of an enlarged portion A in FIG. **1**.

A mask **110** according to the embodiment includes a substrate **10**, a first pattern portion **21**, a second pattern portion **22**, and a first member **31**.

The substrate **10** includes a first surface **10**a. The substrate is light transmissive. The substrate **10** includes, for example, quartz or synthetic quartz or the like.

The first pattern portion **21** is provided on the first surface **10***a*. The first pattern portion **21** includes a plurality of first optical members **21***a*. The plurality of first optical members **21** are arranged separately in a first direction along the first surface **10***a* and are light shielding. The first optical members **21***a* include, for example, chromium (Cr) or the like. A light transmittance of the first optical members **21***a* is lower than a light transmittance of the substrate **10**. The first optical members **21***a* shield first light L**1** with which the mask **110** is irradiated in lithography. The first light L**1** is light with which the mask **110** is irradiated. The first light L**1** is incident light to the mask **110**. A distance between the adjacent two first optical members **21***a* is a first distance s**1**. The first light L**1** enters respective portions between the plurality of first optical members **21***a*.

The second pattern portion **22** is provided on the first surface **10***a*. The second pattern portion **22** is located next to the first pattern portion **21**. The second pattern portion **22** includes a plurality of second optical members **22***a*. The plurality of second optical members **22** are arranged separately in the first direction and are light shielding. The second optical members **22***a* include, for example, chromium (Cr) or the like. A light transmittance of the second optical members **22***a* is lower than the light transmittance of the substrate **10**. The second optical members **22***a* shield the first light L1 with which the mask **110** is irradiated in lithography. A distance between the adjacent two second optical members **22***a* is a second distance s**2**. The second distance s**2** is different from the first distance s**1**. In this example, the second distance s**2** is longer than the first distance s**1**.

Here, a direction orthogonal to the first surface **10***a* is taken as an X-axis direction. One direction crossing the Z-axis direction is taken as an X-axis direction. One direction crossing the Z-axis direction and the X-axis direction is taken as a Y-axis direction. The first direction is, for example, the X-axis direction.

The mask **110** functions as, for example, a grating mask forming a stair shaped gray region on the semiconductor wafer Wf.

A resist R is provided on the semiconductor wafer Wf. The semiconductor wafer Wf is, for example, for a 3-dimensional stacked semiconductor memory element. In the 3-dimensional stacked semiconductor memory element, an end portion of the semiconductor wafer Wf is made to be a stair structure and wiring is performed. At this time, the resist R is made to be a stair shaped and the semiconductor wafer Wf is etched at a time. The stair shape of the resist R is formed depending on the mask pattern of the mask **110**.

When the first light L1 enters, the mask **110** emits light L according to the mask pattern. The light L is transmitted light that penetrates the mask **110**. The light L includes 0-order diffraction light L_0, +1-order diffraction light L_{+1}, and −1-order diffraction light L_1. The mask **110** is patterned so that only 0-order light L_0 arrives at the semiconductor wafer Wf. Thereby, a first gray region **r1** and a second gray region **r2** are formed in the resist R depending on the opening ratio of the mask pattern. That is, the first gray region **r1** has a thickness according to the light intensity of the 0-order diffraction light L_0 penetrating the first pattern potion **21**. The second gray region **r2** has a thickness according to the light intensity of the 0-order diffraction light L_0 penetrating the second pattern potion **22**. The thickness of the gray region decreases with increasing light intensity.

Here, as shown in FIG. **2**A, a distance between centers in the X-axis direction of the adjacent two first optical members **21***a* is taken as a first pattern pitch p**1**. A distance between centers in the X-axis direction of the adjacent two second optical members **22***a* is taken as a second pattern pitch p**2**. In this example, the first pattern pitch p**1** is equal to the second pattern pitch p**2**. Both of the light transmittance of the first optical members **21***a* and the light transmittance of the second optical members **22***a* are taken as t. A first normalized pattern interval a**1** of the first pattern portion **21** is taken as s**1**/p**1**. A second normalized pattern interval a**2** of the second pattern portion **22** is taken as s**2**/p**2**.

The light intensity I_{01} of the 0-order diffraction light L_0 emitted from the first pattern portion **21** can be expressed by the following formula 1.

$$I_{01}=|A_{01}|^2$$

$$A_{01}=a1(1+t)-t \tag{1}$$

The light intensity I_{02} of the 0-order diffraction light L_0 emitted from the second pattern portion **22** can be expressed by the following formula 2.

$$I_{02}=|A_{02}|^2$$

$$A_{02}=a2(1+t)-t \tag{2}$$

Here, the respective light intensities $I_{1\pm1}$ of the +1-order diffraction light L_{+1} and the −1-order diffraction light L_{-1} emitted from the first pattern portion **21** are expressed by the following formula 3.

$$I_{1\pm1}=|A_{1\pm1}|^2$$

$$A_{1\pm1}=(1+t)\sin(a1n)/n \tag{3}$$

The respective light intensities $I_{2\pm1}$ of the +1-order diffraction light L_{+1} and the −1-order diffraction light L_{-1} emitted from the second pattern portion **22** are expressed by the following formula 4.

$$I_{12\pm1}=|A_{1\pm1}|^2$$

$$A_{2\pm1}=(1+t)\sin(a2n)/n \tag{4}$$

From the formula 1, the light intensity I_n of the 0-order diffraction light L_0 emitted from the first pattern portion **21** is determined by the first normalized pattern interval a**1**, namely, the first distance s**1**. From the formula 2, the light intensity I_{02} of the 0-order diffraction light L_0 emitted from the second pattern portion **22** is determined by the second normalized pattern interval a**2**, namely, the second distance s**2**. The second distance s**2** is longer than the first distance s**1**. That is, the light intensity I_{02} is larger than the light intensity I_n. Therefore, the thickness of the second gray region **r2** results in being thinner than the thickness of the first gray region **r1**.

In this way, the distances (s**1**, s**2**) between the normalized pattern intervals (a**1**, a**2**), namely, the distances s**1**, s**2**) between the adjacent two optical members (**21***a*, **22***a*) are changed, and thus the stair shaped gray regions (r**1**, r**2**) can be possible to be formed on the semiconductor wafer Wf.

In the embodiment, a first phase ph**1** of the light L penetrating the first pattern portion **21** when the first light L**1** enters the first pattern portion **21** is different from a second phase ph**2** of the light L penetrating the second pattern portion **22** when the first light L**1** enters the second pattern portion **22**. The first phase ph**1** is a phase of the transmitted light (light L) of the first pattern portion **21**. The second phase ph**2** is a phase of the transmitted light (light L) of the second pattern portion **22**.

The second pattern portion **22** includes a first member **31**. The first member **31** is light transmissive. At least a portion of the first member **31** is provided between the plurality of

second optical members **22***a*. At least the portion of the first member **31** is provided between the two adjacent second optical members **22***a*. The first member **31** includes, for example, a silicon oxide such as SiO_2. In this example the first member **31** covers the plurality of second optical members **22***a*. The first member **31** may not cover the plurality of second optical members **22***a*. The first phase ph**1** is caused to be different from the second phase ph**2** by providing the first member **31**.

A thickness d**1** of the first member **31** can be determined based on a phase difference between the first phase ph**1** and the second phase ph**2**. This phase difference is desirable, for example, to be not less than 45 degrees and not more than 180 degrees. The reason will be described based on a graph **40** in FIG. **1**.

The graph **40** represents the relationship between a position on the wafer surface and the light intensity when the semiconductor wafer Wf is exposed by using the mask **110**. The vertical axis represents the light intensity I and the horizontal axis represents the position x on the wafer surface of the semiconductor wafer Wf.

The mask **110** forms the first gray region r**1** and the second gray region r**2** on the semiconductor wafer Wf. At this time, at a boundary portion ed of a boundary line between the first gray region r**1** and the second gray region r**2**, unsharpness amount W shown in the graph **40** exists. The unsharpness amount can be approximated by λ/NA. λ represents a wavelength (nanometer: nm) of the first light L**1**, and NA (Numerical Aperture) represents a numerical aperture of the projection optical system.

When the unsharpness amount is large, the boundary portion ed varies gradually. For this reason, the boundary between the first gray region r**1** and the second gray region r**2** is unclear. The end portion of the semiconductor wafer Wf does not form the stair shape having clear unevenness of a level difference. For this reason, regions may not be differentiated at the end portion of the semiconductor wafer Wf. Therefore, the unsharpness amount is desired to be small.

The inventors have found that the phase difference of the transmitted light of the mask pattern is effectively given to decrease the unsharpness amount.

The graph **40** shows the simulation results of change of the unsharpness amount when changing the phase difference between the first phase ph**1** and the second phase ph**2** of the mask **110**. The first light L**1** is incident on the mask **110** along the Z-axis direction with reduced illumination. The phase difference characteristic **41** shows the case of the phase difference of 0 degree. The phase difference characteristic **42** shows the case of the phase difference of 45 degrees. The phase difference characteristic **43** shows the case of the phase difference of 90 degrees. The phase difference characteristic **44** shows the case of the phase difference of 135 degrees. The phase difference characteristic **45** shows the case of the phase difference of 180 degrees.

In this manner, with increasing phase difference between the first phase ph**1** and the second phase ph**2**, the unsharpness amount becomes small. That is, if the phase difference is not less than 45 degrees and not more than 180 degrees, the unsharpness amount can be small.

Here, the wavelength of the first light L**1** is taken as λ (nm), a refractive index of the first member **31** is taken as n**1**, and the phase difference between the first phase ph**1** and the second phase ph**2** is taken as ph (degree). In the second pattern portion **22**, an optical length (optical path length) of the first light L**1** traveling through the first member **31** of the thickness d**1** (nm) is d**1**×n**1**. Assuming a refractive index of vacuum being 1, in the first pattern portion **21**, a distance of the first light L**1** traveling between the two adjacent first optical members **21***a* is d**1**. Therefore, the thickness d**1** of the first member **31** can be determined from the following formula 5.

$$d1=ph\cdot\lambda/\{360(n1-1)\} \quad (5)$$

In the formula 5, when the phase difference is intended to be 180 degrees, ph=180 may be set. When the phase difference is intended to be 135 degrees, ph=135 may be set. When the phase difference is intended to be 90 degrees, ph=90 may be set. When the phase difference is intended to be 45 degrees, ph=45 may be set. In this manner, the thickness d**1** of the first member **31** can be determined depending on the desired phase difference. The thickness d**1** of the first member **31** is desired, for example, to be not less than 0.8 times and not more than 1.2 times of the value determined by the formula 5.

As described above, according to the embodiment, the unsharoness amount can be decreased and the boundary portion ed between the first gray region r**1** and the second gray region r**2** can be set to be the stair structure having clear unevenness of the level difference. Thereby, a high accuracy pattern can be formed easily.

Second Embodiment

FIG. **3** is a schematic partial cross-sectional view illustrating a mask according to a second embodiment.

A mask **111** according to the embodiment is provided with a groove portion in place of the first member **31**.

The second pattern portion **22** includes the groove portion **32** provided on the substrate **10**. A position of the groove portion **32** in the X-axis direction is between the adjacent two second optical members **22***a*. The position of the groove portion **32** in the X-axis direction is between positions of the respective two of the plurality of second optical members **22***a* in the X-axis direction. The groove **32** is formed by recessing the substrate **10** through etching.

A depth d**2** of the groove **32** can be determined based on the phase difference between the first phase ph**1** and the second phase ph**2**. This phase difference is, for example, desired to be not less than 45 degrees and not less than 18-degrees as well as the first embodiment.

Here, the wavelength of the first light L**1** is taken as A (nm), a refractive index of the substrate **10** is taken as n**2**, and the phase difference between the first phase ph**1** and the second phase ph**2** is taken as ph (degree). In the first pattern portion **21**, an optical length (optical path length) of the first light L**1** traveling through the substrate **10** of the thickness d**2** (nm) is d**2**×n**2**. Assuming a refractive index of vacuum being 1, in the second pattern portion **22**, a distance of the first light L**1** traveling the groove portion **32** of the depth d**2** (nm) is d**2**. Therefore, the depth d**2** of the groove portion **32** can be determined from the following formula 6.

$$d2=ph\cdot\lambda/\{360(n2-1)\} \quad (6)$$

In the formula 6, when the phase difference is intended to be 180 degrees, ph=180 may be set. When the phase difference is intended to be 135 degrees, ph=135 may be set. When the phase difference is intended to be 90 degrees, ph=90 may be set. When the phase difference is intended to be 45 degrees, ph=45 may be set. In this manner, the depth d**2** of the groove portion **32** can be determined depending on the desired phase difference. The depth d**2** of the groove portion **32** is desired, for example, to be not less than 0.8 times and not more than 1.2 times of the value determined by the formula 6.

As described above, according to the embodiment, the unsharoness amount can be decreased and the boundary portion ed between the first gray region **r1** and the second gray region r**2** can be set to be the stair structure having clear unevenness of the level difference. Thereby, a high accuracy pattern can e formed easily.

FIG. **4** is a schematic cross-sectional view illustrating a mask according to a reference example.

A mask **199** according to the reference example includes the substrate **10**, the first pattern portion **21**, and the second pattern portion **22**.

The mask **199** is not provided with the first member **31** and the groove portion **32**. That is, the first phase ph**1** of the transmitted light of the first pattern portion **21** is in the same phase as the second phase ph**2** of the transmitted light of the first pattern portion **22**.

The graph **50** represents the relationship between a position on the wafer surface and the light intensity when the semiconductor wafer is exposed by using the mask **199**. The vertical axis represents the light intensity I and the horizontal axis represents the position x on the wafer surface of the semiconductor wafer.

The mask **199** forms the first gray region **r1** and the second gray region r**2** on the semiconductor wafer. At this time, at a boundary portion ed of a boundary line between the first gray region **r1** and the second gray region r**2**, unsharpness amount W shown in the graph **50** exists. The unsharpness amount can be approximated by λ/NA. λ represents a wavelength (nanometer: nm) of the first light L**1**, and NA represents a numerical aperture of the projection optical system.

The graph **50** shows the simulation results of change of the unsharpness amount when changing the numerical aperture NA of the projection optical system. The first light L**1** is incident on the mask **199** along the Z-axis direction with reduced illumination. The numerical aperture characteristic **51** shows the case of the numerical aperture NA of 0.630. The numerical aperture characteristic **52** shows the case of the numerical aperture NA of 0.315. The unsharpness amount W of the numerical aperture characteristic **51** is smaller than the unsharpness amount W of the numerical aperture characteristic **52**. That is, it is efficient to make the numerical aperture NA of the projection optical system large in order to make the unsharpness amount W small.

However, the numerical aperture of the projection optical system is determined by specification of the exposure device. Because of this, if the specification of the exposure device is once determined, its change is difficult and pattern cannot be easily formed.

On the other hand, according to the embodiment, it is only necessary to process the mask and give the phase difference corresponding to the respective regions of the semiconductor wafer. Thereby, without depending on the specification of the exposure device, a high accuracy pattern can be formed easily.

Third Embodiment

An exposure device used for a pattern forming method according to a third embodiment will be described.

In a lithography process in manufacturing a semiconductor device, when a high resolution is needed, for example, deep ultra violet (DUV) light using ArF excimer laser of a wavelength of 193 nm as a light source is used for an illumination light source. For forming a fine pattern, a mask (reticle) having a size of four times of the pattern actually formed and the exposure device constituted from the reduction projection optical system are used.

FIG. **5** is a schematic view illustrating the exposure device according to the third embodiment.

As shown in FIG. **5**, an exposure device **200** includes an illumination optical system **201**, a stage **202**, a mask holder **30**, a projection optical system **204**, and a controller **205**.

The semiconductor wafer Wf is placed on the stage **202**. The semiconductor wafer Wf is adsorbed and held on the stage **202**, for example, by vacuum adsorption. The stage **202** is movable along the Z-axis direction and an X-Y plane surface.

The mask holder **203** holds the mask **110**. Thereby, the mask **110** and the semiconductor wafer Wf are displaced separately each other. The mask holder **203** is movable along the Z-axis direction and the X-Y plane surface. Thereby, the relative position relationship between the semiconductor wafer Wf and the mask **110** is adjustable.

The mask **110** includes the substrate **10**, the first pattern portion **21**, and the second pattern portion **22**. The substrate **10** transmits the first light L**1** having a prescribed wavelength. The first pattern portion **21** includes the plurality of first optical members **21***a*. The second pattern portion **22** includes the plurality of second optical members **21***a*.

The substrate includes, for example, quartz and synthetic quartz or the like. The plurality of first optical members **21***a* and the plurality of second optical members **22***a* include, for example, chromium (Cr). The plurality of first optical members **21***a* and the plurality of second optical members **22***a* shield the first light L**1** with which the mask **110** is irradiated in lithography.

A periodic pattern of line and space is formed on each of the plurality of first optical members **21***a* and the plurality of second optical members **22***a*, however the periodic pattern may be island-shaped.

The first distance s**1** between the adjacent two first optical members **21***a* is different from the second distance s**2** between the adjacent two second optical members **21***a*. In this example, the second distance s**2** is longer than the first distance s**1**.

The first phase ph**1** of the light L penetrating respective portions between the plurality of first optical members **21***a* is different from the second phase ph**2** of the light L penetrating respective portion's between the plurality of second optical members **22***a*. The first phase ph**1** is a phase of the transmitted light of the first pattern portion **21**. The second phase ph**2** is a phase of the transmitted light of the second pattern portion **22**.

At least a portion of the first member **31** is provided between the plurality of second optical members **22***a*. The first member **31** includes, for example, a silicon oxide such as SiO_2. In this example the first member **31** covers the plurality of second optical members **22***a*. The first member **31** may not cover the plurality of second optical members **22***a*. The first phase ph**1** is caused to be different from the second phase ph**2** by providing the first member **31**. The groove portion **32** shown in FIG. **3** may be provided in place of the first member **31**.

The illumination optical system **201** includes a light source **201***a* and an optical unit **201***b*. For example, one of ArF excimer laser and KrF excimer laser is used for the light source **201***a*. The wavelength of illumination light emitted from the light source **201***a* is, for example, not less than 190 nm and not less than 250 nm. A high pressure mercury lamp and other laser light sources may be used for the light source **201***a*.

The optical unit **201***b* includes at least one of a lens, a mirror, a diaphragm, a polarizer, an optical diffusion plate, and an optical filter. For example, at least one of fly-eye lens, the optical diffusion plate, and an oscillation mirror can be used for the optical unit **201**.

The fly-eye lens is an optical member having a plurality of lenses arranged in a plain surface.

The optical diffusion plate is an optical member diffusing the incident light in multiple directions. That is, a portion of the incident light to the optical diffusion plate travels in one direction, and another portion of the incident light travels in another direction different from the one direction.

The oscillation mirror is a reflection member capable of switching directions in which the incident light is reflected. That is, the oscillation mirror has a first state in which the incident light is reflected in one direction, and a second state in which the incident light is reflected in another direction different from the one direction. For example, the light source is converted from a point source to a surface light source and luminance unevenness of the light source can be suppressed by using the optical member such as a fly-eye lens, an optical diffusion plate and an oscillation mirror. For example, the numerical aperture of the illumination optical system can be adjusted.

The illumination optical system **201** irradiates the first light L**1** emitted from the light source **201***a* to the mask **110** via the optical unit **201***b*.

The projection optical system **204** is provided between the mask **110** and the semiconductor wafer Wf. The projection optical system **204** includes, for example, a projection lens.

The projection optical system **204** selectively transmits only 0-order diffraction light L_0 out of the 0-order diffraction light L_0, the +1-order diffraction light L_{+1}, and the −1-order diffraction light L_{-1}.

FIG. **6** is a flow chart illustrating a pattern forming method according to the third embodiment.

The pattern forming method according to the embodiment includes a step S**101** to a step S**103**.

In the step S**101**, the mask **110** according to the embodiment and the semiconductor wafer Wf are disposed. In the step S**102**, the semiconductor wafer Wf is irradiated with the light L penetrating the mask **110**.

That is, in the step S**102**, the first light L**1** from the illumination optical system **201** is incident on the first pattern portion **21** and the second pattern portion **22** of the mask **110**.

The first phase ph**1** of the light L penetrating the first pattern portion **21** is differentiated from the second phase ph**2** of the light L penetrating the second pattern portion **22** by the mask **110**, and the 0-order diffraction light L_0, the +1-order diffraction light L_{+1} and the −1-order diffraction light L_{-1} of respective optical images of the light L in the first phase ph**1** and the light L in the second phase ph**2** are emitted to the projection optical system **204**.

The only 0-order diffraction light L_0 is selectively transmitted by the projection optical system **204**.

The semiconductor wafer Wf is irradiated with the 0-order diffraction light L_0 transmitted by the projection optical system **204**.

In the step S**103**, the patter is formed on the semiconductor wafer Wf depending on the region irradiated with the 0-order diffraction light L_0. The pattern forming method according to the embodiment relates to a lithography process like this.

Here, optical conditions for forming the gray region on the semiconductor wafer Wf, namely, conditions to the projection optical system **204** and the illumination optical system **201** so as to cause the +1-order diffraction light L_{+1} and the −1-order diffraction light L_{-1} not to contribute to imaging will be described.

FIG. **7** is a schematic view illustrating the illumination optical system and the projection optical system according to the third embodiment.

FIG. **7** show an example of an angle between the first light L**1** and the first surface **10***a* being 90 degrees. For convenience to see the drawing, the first member **31** (or groove portion **32**) and the first optical member **21***a* of the first pattern portion **21** are not shown.

The conditions to the projection optical system **204** and the illumination optical system **201** so as to cause the +1-order diffraction light L_{+1} and the −1-order diffraction light L_1 not to contribute imaging are that a distance between the centers of the optical axes of the 1-order diffraction light L_{+1}, is larger than a sum of the numerical aperture NA**1** of the projection optical system **201** and the numerical aperture NA**2** of the illumination optical system **201**. That is, the following conditions are satisfied.

$$NA1+NA2<\sin\theta$$

$$\sin\theta=\lambda/p2 \quad (7)$$

In the formula (7), p**2** indicates a second pattern pitch (nm) of the second optical members **22***a*. The second pattern pitch **p2** is a distance between the centers in the X-axis direction of the adjacent two second optical members **22***a*. A indicates a wavelength (nm) of the first light L**1**. NA**1** indicates the numerical aperture of the projection optical system **204**. NA**2** indicates the numerical number of the illumination optical system **201**.

From the formula (7), the following formula (8) is derived.

$$P2<\lambda/[\{1+(NA2/NA1)\}NA1] \quad (8)$$

If a ratio of the numerical aperture NA**2** to the numerical aperture NA**1** is taken as a**1** (namely, NA**2**/NA**1**), the following formula (9) is obtained.

$$P2<\lambda/\{(1+\sigma1)NA1\} \quad (9)$$

The second pattern pitch **p2** of the second optical members **22***a* is determined so as to satisfy the formula (8), the formula (9). Similarly, the first pattern pitch **p1** of the first optical members **21***a* may be determined. The first pattern pitch **p1** is a distance between the centers in the X-axis-direction of the adjacent two first optical members **21***a*. Thereby, the +1-order diffraction light L_{+1} and the −1-order diffraction light L_1 are caused not to be imaged, and the semiconductor wafer Wf can be irradiated with only the 0-order diffraction light L_0. The gray region can be formed on the semiconductor wafer Wf.

In the above embodiment, the case of illuminating perpendicularly to the mask **110** has been illustratively described. However, in the mask **110**, if the phase difference is given to only one side of one of the first pattern portion **21** and the second pattern portion **22**, the pattern position may be shifted laterally depending on the focus position. In order to avoid this, as described below, illumination of the illumination optical system **201** is desired to be, for example, dipole illumination.

Fourth Embodiment

FIG. **8** is a schematic view illustrating an illumination optical system and a projection optical system according to a fourth embodiment.

FIG. **8** shows an example of the first light L**1** being slanted to the first surface **10***a*. Furthermore, FIG. **8** shows the case where the second light L**2** symmetric to the first light L**1** around a first axis ax**1** perpendicular to the first surface **10***a* is incident to the first pattern portion **21** and the second pattern portion **22**. For convenience to see the drawing, the first member **31** (or groove portion **32**) and the first optical member **21***a* of the first pattern portion **21** are not shown.

The illumination optical system **201** lets the first light L**1** slanted to the first axis ax**1** perpendicular to the first surface **10***a* and the second light L**2** symmetric to the first light L**1** around the first axis ax**1** be incident on the mask **110**. The illumination optical system **201** is, for example, the dipole illumination. The first light L**1** and the second light L**2** are incident at a slant on the mask **110**. In this example, incidence is performed in two directions, however a light source shape is made, for example, circular or elliptical and incidence may be performed in multi directions to avoid the center.

Here, in the case of using the dipole illumination, the optical conditions for forming the gray region on the semiconductor wafer Wf, namely, the conditions to the projection optical system **204** and the illumination optical system **201** so as to cause the +1-order diffraction light L_1 and the −1-order diffraction light L_{-1} not to contribute to imaging will be described.

The conditions to the projection optical system **204** and the illumination optical system **201** so as to cause the +1-order diffraction light L_{+1} and the −1-order diffraction light L_1 not to contribute imaging are that a distance between the centers of the optical axes of the 1-order diffraction light L_{+1}, L_{-1} is larger than a sum of the numerical aperture NA**1** of the projection optical system **201**, the numerical aperture NA**2** of the illumination optical system **201** and offset NA_{off} of the numerical aperture of the illumination optical system **201**. The offset NA_{off} is an amount which the shift amount of the center position of the illumination light soured from the optical axis is converted to NA. That is, the following conditions are satisfied.

$$NA1+NA2+NA_{off}<\sin\theta$$

$$\sin\theta=\lambda/p2 \tag{10}$$

In the formula (10), p**2** represents the second patter pitch of the second optical members **22***a*. The second pattern pitch p**2** is the distance between the centers in the X-axis direction of the second optical members **22***a*. λ represents the wavelength (nm) of the first light L**1** and the second light L**2**. NA**1** represents the numerical aperture of the projection optical system **204**. NA**2** represents the numerical aperture of the illumination optical system **201**. NA_{off} represents offset of the numerical aperture of the illumination optical system **201**.

The following formula (11) is derived from the formula (10).

$$p2<\lambda/[\{1+(NA2/NA1)+(NA_{off}/NA1)\}NA1] \tag{11}$$

If a ratio of the numerical aperture NA**2** to the numerical aperture NA**1** is taken as σ**1** (namely, NA**2**/NA**1**), and a ratio of the offset N_{off} to the numerical aperture NA**1** is taken as σ_{off}(N_{off}/NA**1**), the following formula 12 is obtained.

$$p2<\lambda/\{(1+\sigma1+\sigma_{off})NA1\} \tag{12}$$

The second pattern pitch **p2** is determined so as to satisfy the formula (11), the formula (12). Similarly, the first pattern pitch **p1** of the first optical members **21***a* may be determined. The first pattern pitch **p1** is the distance between the centers in the X-axis direction of the adjacent two first optical members **21***a*. Thereby, the +1-order diffraction light L_{+1} and the −1-order diffraction light L_1 are caused not to be imaged, and the semiconductor wafer Wf can be irradiated with only the 0-order diffraction light L_0. The gray region can be formed on the semiconductor wafer Wf.

In this manner, according to the embodiment, if the illumination is the dipole illumination, the right-and-left light intensity can be generally uniform on the imaging surface when the focus position is shifted. Thereby, even if the focus position is shifted, the pattern position can be suppressed from being shifted.

FIG. **9** is a schematic cross-sectional view illustrating a mask according to a fifth embodiment.

A mask **112** includes the substrate **10**, the first pattern portion **21**, the second pattern portion **22**, a third, pattern portion **23**, and a fourth pattern portion. Each of the third pattern portion and the fourth pattern portion is periodically provided with a plurality of optical members being light shielding.

In the first to fourth embodiments, the mask including the first pattern portion **21** and the second pattern portion **22** is illustratively described, however the number of pattern portions may be 3 or more. In this case, the first member **31** or the groove **32** may be provided in every other one of pattern portions. As shown in FIG. **9**, in the case of four pattern portions included, for example, the first member **31** is provided in the second pattern portion **22** located at the second position from the left and the fourth pattern portion **24** located at the fourth position from the left. The groove **32** may be provided in each of the second pattern portion **22** and the fourth pattern portion **24** in place of the first member **31**.

In a portion where light amount is intended to be changed, a width of the pattern changes well without change of the pattern pitch. The pattern pitch is, for example, the distance between the centers of the adjacent two first optical members **21***a* in the X-axis direction. The pattern pitch is, for example, the distance between the centers of the adjacent two second optical members **22***a* in the X-axis direction. The pattern position can be suppressed from being shifted by not changing the pattern pitch.

According to the embodiments, a mask capable of forming a high accuracy pattern easily and a pattern forming method can be provided.

Hereinabove, exemplary embodiments of the invention are described with reference to specific examples. However, the embodiments of the invention are not limited to these specific examples. For example, one skilled in the art may similarly practice the invention by appropriately selecting specific configurations of components such as substrates, first pattern portions, second pattern portions, etc., from known art. Such practice is included in the scope of the invention to the extent that similar effects thereto are obtained.

Further, any two or more components of the specific examples may be combined within the extent of technical feasibility and are included in the scope of the invention to the extent that the purport of the invention is included.

Moreover, all masks and pattern forming methods practicable by an appropriate design modification by one skilled in the art based on the masks and the pattern forming methods described above as embodiments of the invention also are within the scope of the invention to the extent that the spirit of the invention is included.

Various other variations and modifications can be conceived by those skilled in the art within the spirit of the

invention, and it is understood that such variations and modifications are also encompassed within the scope of the invention.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the invention.

What is claimed is:

1. A mask comprising:

a substrate including a first surface, the substrate being light transmissive;

a first pattern portion including a plurality of first optical members provided on the first surface and arranged periodically in a first direction along the first surface, a light transmittance of the first optical members being lower than a light transmittance of the substrate, a distance between the adjacent two first optical members being a first distance; and

a second pattern portion including a plurality of second optical members provided on the first surface and arranged periodically in the first direction, a light transmittance of the second optical members being lower than the light transmittance of the substrate, a distance between the adjacent two second optical members being a second distance different from the first distance, the second pattern portion including a first member, the first member being light transmissive, and at least a portion of the first member being provided between the second optical members.

2. The mask according to claim **1**, wherein

when a thickness of the first member is taken as d**1** (nanometer), a refractive index of the first member is taken as n**1**, a wavelength of the first light is taken as A (nanometer), and a phase difference between a first phase of a light penetrating the first pattern portion after a first light being incident on the first pattern portion and a second phase of a light penetrating the second pattern portion after the first light being incident on the second pattern portion is taken as ph (degree), the d**1** is not less than 0.8 times and not more than 1.2 times of $ph \cdot \lambda/\{360(n1-1)\}$.

3. The mask according to claim **2** wherein

the phase difference is not less than 45 degrees and not more than 180 degrees.

4. The mask according to claim **1** wherein

the first member includes a silicon oxide.

5. The mask according to claim **1** wherein

when an angle between the first light and the first surface is 90 degrees,

a distance between centers of the adjacent two second optical members in the first direction is p**2** (nanometer),

a wavelength of the first light is λ (nanometer),

a numerical number of a projection optical system is NA**1**, and a numerical aperture of an illumination optical system is NA**2**,

the p**2** is smaller than $\lambda/[\{1+(NA2/NA1)\}NA1]$.

6. The mask according to claim **1** wherein

when the first light is slanted to the first surface,

a second light symmetric to the first light around a first axis perpendicular to the first surface is incident to the first pattern portion and the second pattern portion,

a distance between centers of the adjacent two second optical members in the first direction is p**2** (nanometer),

a wavelength of the first light and the second light is λ (nanometer),

a numerical number of a projection optical system is NA**1**, a numerical aperture of an illumination optical system is NA**2**, and an offset of the numerical aperture of the illumination optical system is NA_{off},

the p**2** is smaller than $\lambda/[\{1+(NA2/NA1)+(NA_{off}/NA1)\}NA1]$.

7. The mask according to claim **1** wherein

a first ratio of the first distance to a third distance between centers of the adjacent two first optical members in the first direction is different from a second ratio of the second distance to a fourth distance between centers of the adjacent two second optical members in the first direction.

8. The mask according to claim **7** wherein

the third distance is equal to the fourth distance.

9. A mask comprising:

a substrate including a first surface, the substrate being light transmissive;

a first pattern portion including a plurality of first optical members provided on the first surface and arranged periodically in a first direction along the first surface, a light transmittance of the first optical members being lower than a light transmittance of the substrate, a distance between the adjacent two first optical members being a first distance; and

a second pattern portion including a plurality of second optical members provided on the first surface and arranged periodically in the first direction, a light transmittance of the second optical members being lower than the light transmittance of the substrate, a distance between the adjacent two second optical members being a second distance different from the first distance, the second pattern portion including a groove portion provided on the substrate, and a position of the groove portion in the first direction being between the adjacent two second optical members.

10. The mask according to claim **9**, wherein

when a depth of the groove portion is taken as d**2** (nanometer), a refractive index of the substrate is taken as n**2**, a wavelength of the first light is taken as λ (nanometer), and a phase difference between the first phase and the second phase is taken as ph (degree), the d**2** is not less than 0.8 times and not more than 1.2 times of $ph \sim \lambda/\{360(n2-1)\}$.

11. The mask according to claim **10** wherein

the phase difference is not less than 45 degrees and not more than 180 degrees.

12. The mask according to claim **9** wherein

a first ratio of the first distance to a third distance between centers of the adjacent two first optical members in the first direction is different from a second ratio of the second distance to a fourth distance between centers of the adjacent two second optical members in the first direction.

13. The mask according to claim **12** wherein

the third distance is equal to the fourth distance.

14. A pattern forming method, comprising:

the method being based on a mask including:

a substrate including a first surface, the substrate being light transmissive;

a first pattern portion including a plurality of first optical members provided on the first surface and arranged periodically in a first direction along the first surface, a light transmittance of the first optical members being lower than a light transmittance of the substrate, a distance between the adjacent two first optical members being a first distance; and

a second pattern portion including a plurality of second optical members provided on the first surface and arranged periodically in the first direction, a light transmittance of the second optical members being lower than the light transmittance of the substrate, a distance between the adjacent two second optical members being a second distance different from the first distance,

disposing the mask and a semiconductor wafer;

causing a first light from an illumination optical system to enter the first pattern portion and the second pattern portion;

causing a first phase of a light penetrating the first pattern portion to be different from a second phase of a light penetrating the second portion by the mask, and emitting a 0-order diffraction light, a +1-order diffraction light and a −1-order diffraction light of respective optical images of the light of the first phase and the light of the second phase to a projection optical system;

causing the 0-order diffraction light to penetrate by the projection optical system; and

forming a pattern on the semiconductor wafer by the semiconductor wafer being irradiated with the 0-order diffraction light.

15. The method according to claim **14**, wherein

the second pattern portion includes a first member, the first member being light transmissive, and

at least a portion of the first member being provided between the second optical members.

16. The method according to claim **15**, wherein

when a thickness of the first member is taken as d**1** (nanometer), a refractive index of the first member is taken as n**1**, a wavelength of the first light is taken as λ (nanometer), and a phase difference between the first phase and the second phase is taken as ph (degree), the d**1** is not less than 0.8 times and not more than 1.2 times of $ph \cdot A/\{360(n1-1)\}$.

17. The method according to claim **14**, wherein

the second pattern portion includes a groove portion provided on the substrate, and

a position of the groove portion in the first direction is between the adjacent two second optical members.

18. The method according to claim **17**, wherein

when a depth of the groove portion is taken as d**2** (nanometer), a refractive index of the substrate is taken as n**2**, a wavelength of the first light is taken as λ (nanometer), and a phase difference between the first phase and the second phase is taken as ph (degree), the d**2** is not less than 0.8 times and not more than 1.2 times of $ph \cdot \lambda/\{360(n2-1)\}$.

19. The method according to claim **14**, wherein

when an angle between the first light and the first surface is 90 degrees,

a distance between centers of the adjacent two second optical members in the first direction is p**2** (nanometer),

a wavelength of the first light is λ (nanometer),

a numerical number of a projection optical system is NA**1**, and a numerical aperture of an illumination optical system is NA**2**,

the p**2** is smaller than $\lambda/[\{1+(NA2/NA1)\}NA1]$.

20. The method according to claim **14**, wherein

when the first light is slanted to the first surface,

a second light symmetric to the first light around a first axis perpendicular to the first surface is incident to the first pattern portion and the second pattern portion,

a distance between centers of the adjacent two second optical members in the first direction is p**2** (nanometer),

a wavelength of the first light and the second light is λ (nanometer),

a numerical number of a projection optical system is NA**1**, a numerical aperture of an illumination optical system is NA**2**, and an offset of the numerical aperture of the illumination optical system is NA_{off},

the p**2** is smaller than $\lambda/[\{1+(NA2/NA1)+(NA_{off}/NA1)\}NA1]$.

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