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Wu et al.

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(54) **SURFACE TREATMENT METHOD TO REMOVE CONTAMINATED AND IMPLANTED WAVEGUIDE SURFACE**

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C11D 7/32 (2006.01)

(52) **U.S. Cl.**
CPC ***C11D 7/3281*** (2013.01); *C11D 2111/14* (2024.01); *C11D 2111/44* (2024.01); *C11D 2111/46* (2024.01)

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

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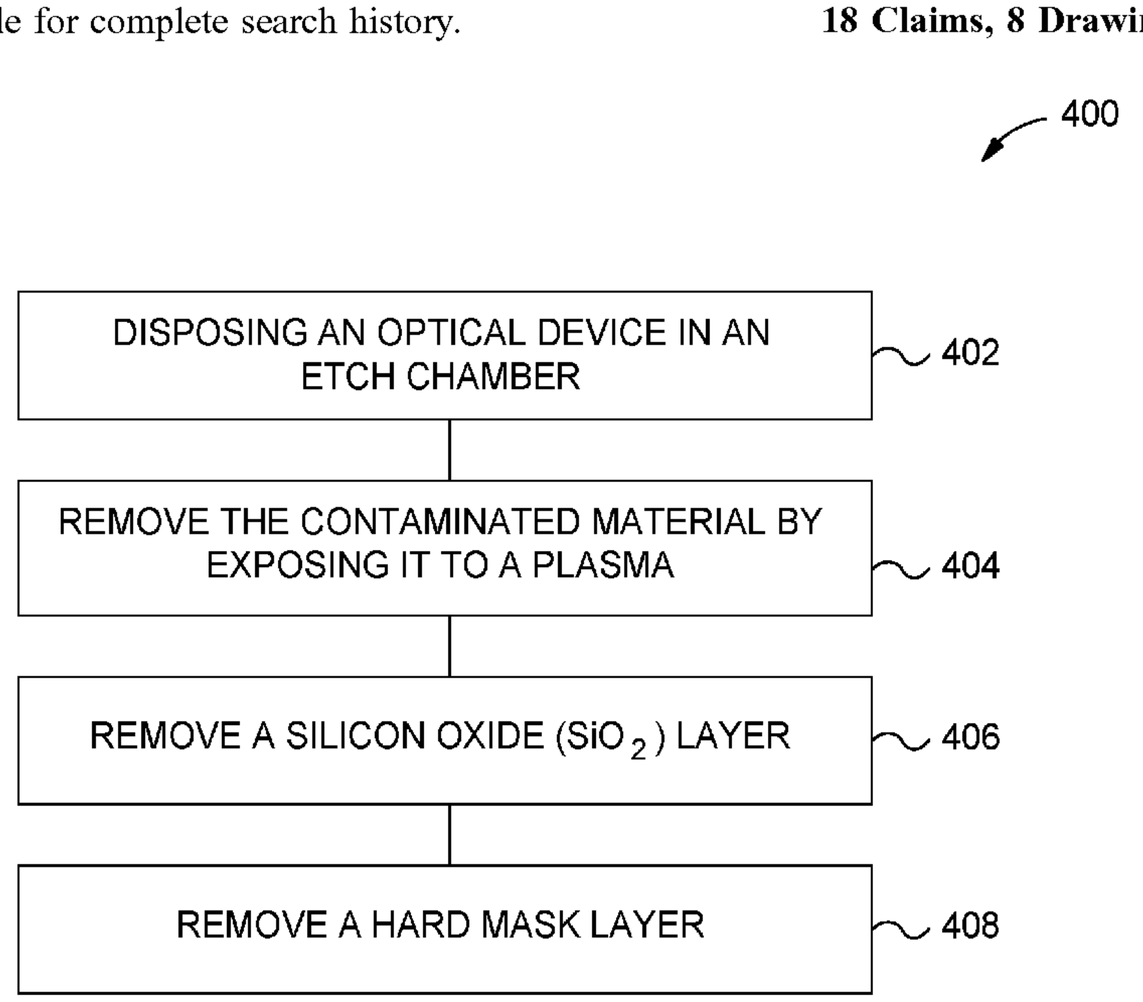
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(57) **ABSTRACT**

Embodiments of the present disclosure herein include a method of removing a contamination material from an optical device. The method may include disposing an optical device in a process chamber, the optical device having optical device structures formed in a substrate, the contamination material is disposed at least on sidewalls of the optical device structures and within trenches between the optical device structures, and exposing the optical device to a plasma generated in the process chamber, the plasma generated from oxygen gas (O_2), chlorine gas (Cl_2), Argon (Ar), or a combination thereof, the exposing the optical device to the plasma removes the contamination material.

18 Claims, 8 Drawing Sheets



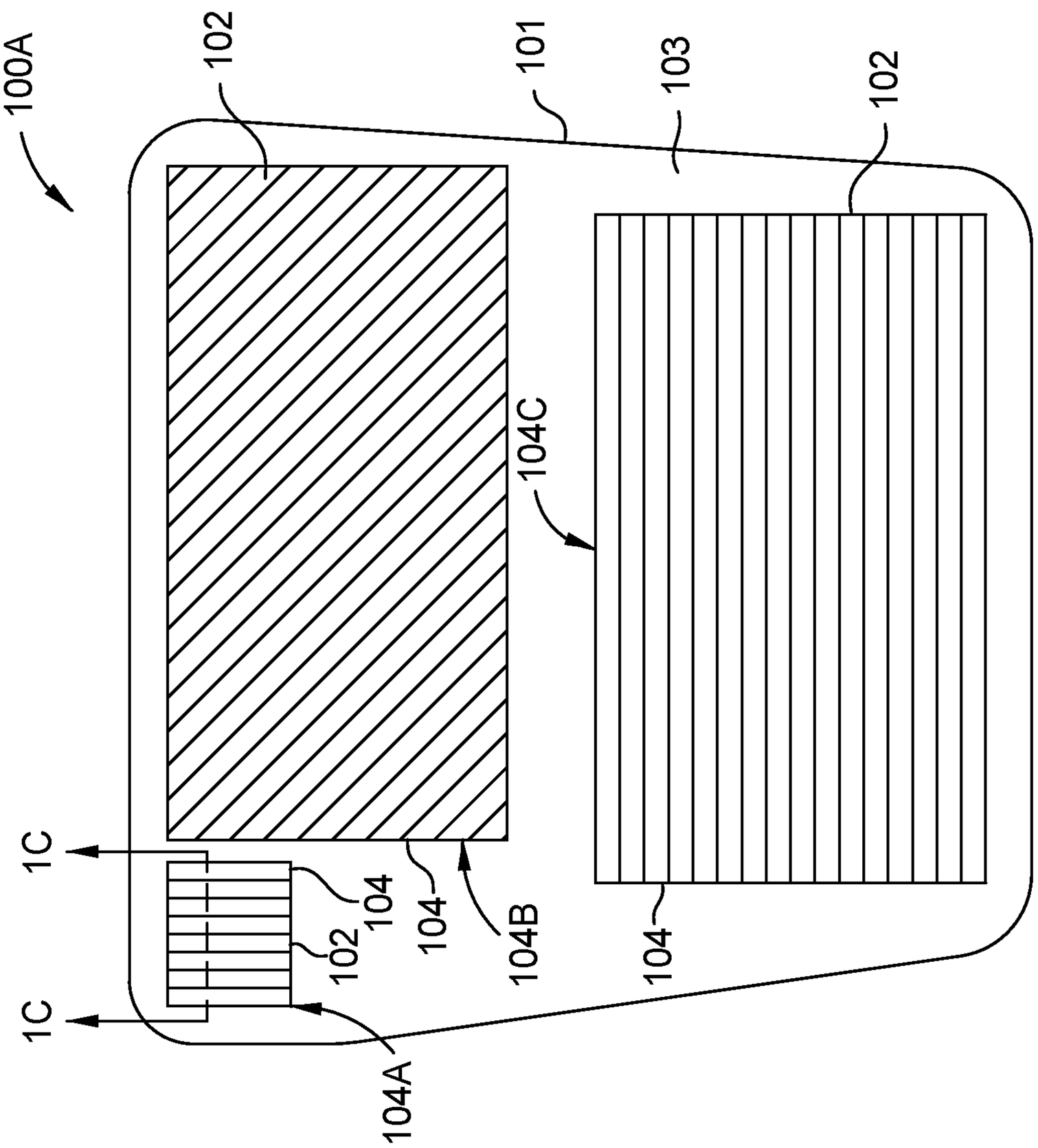


FIG. 1A

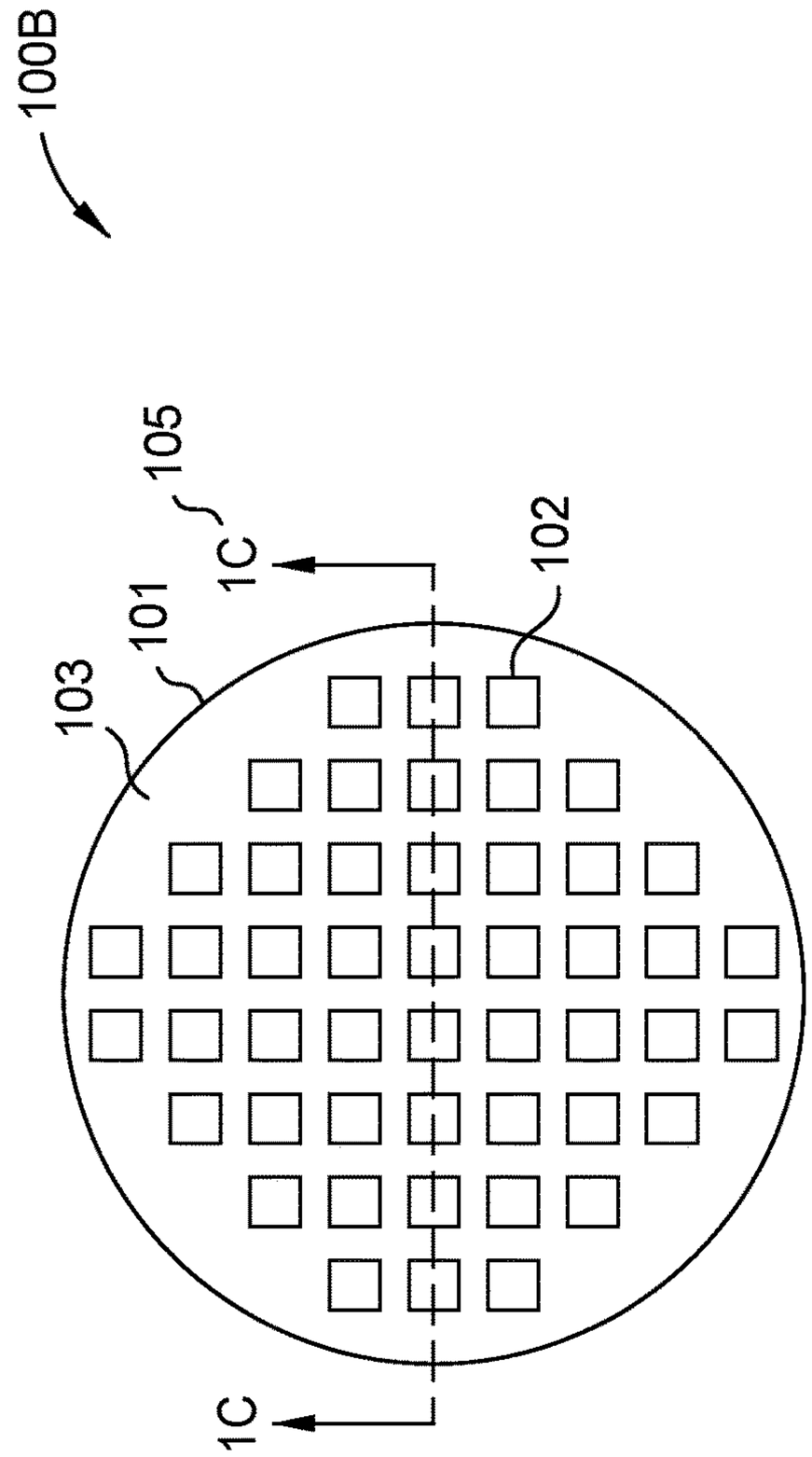

100B
105
1C
101
103
102
1C

FIG. 1B

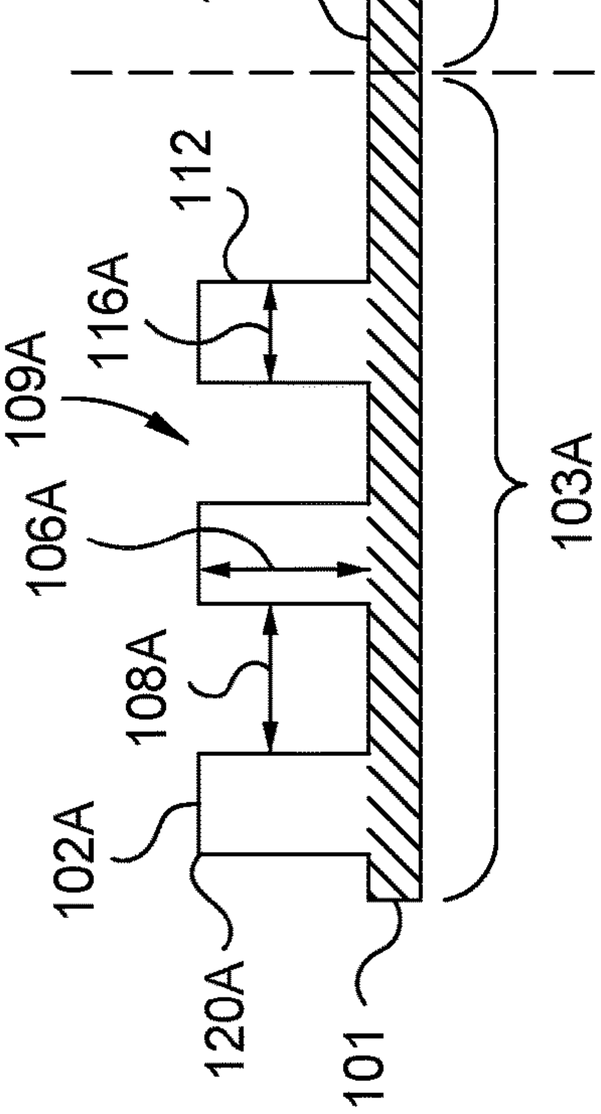

105
102B
120B
109B
106B
118
θ
108B
116B
103
103B
112
116A
109A
106A
103A
108A
102A
120A
101

FIG. 1C

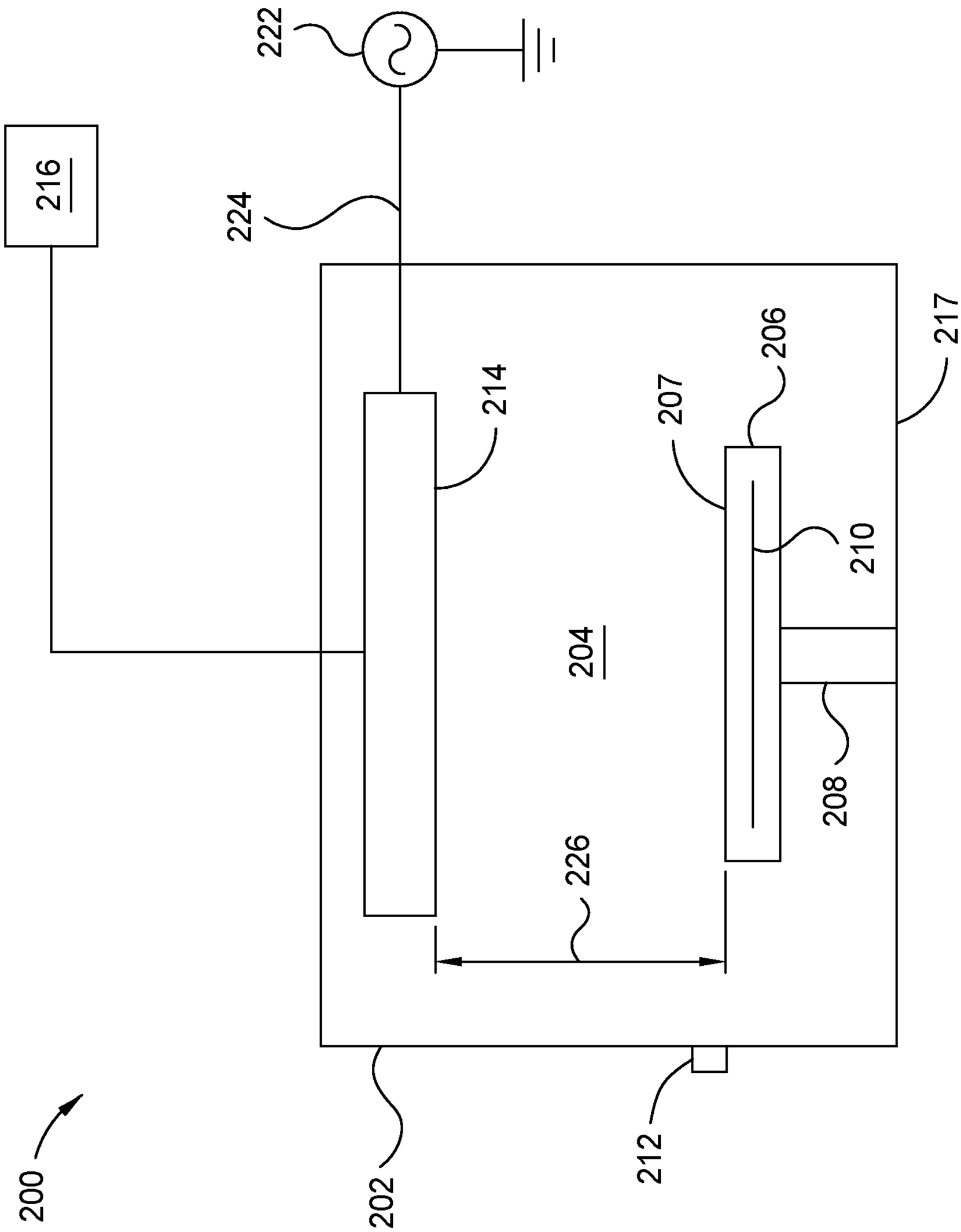


FIG. 2

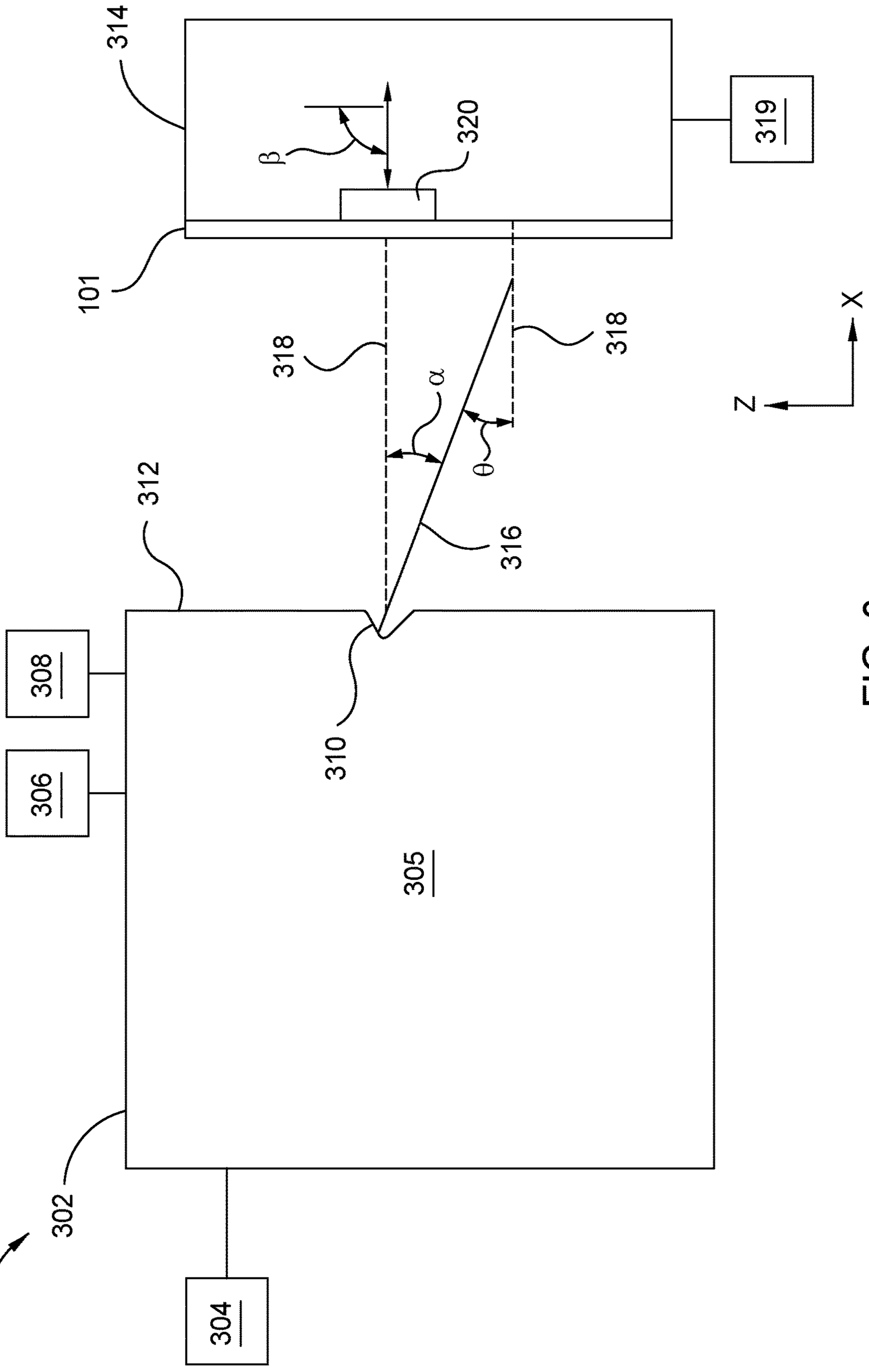

314
319
β
320
101
318
318
α
θ
X
Z
312
316
310
308
306
305
302
300
304

FIG. 3

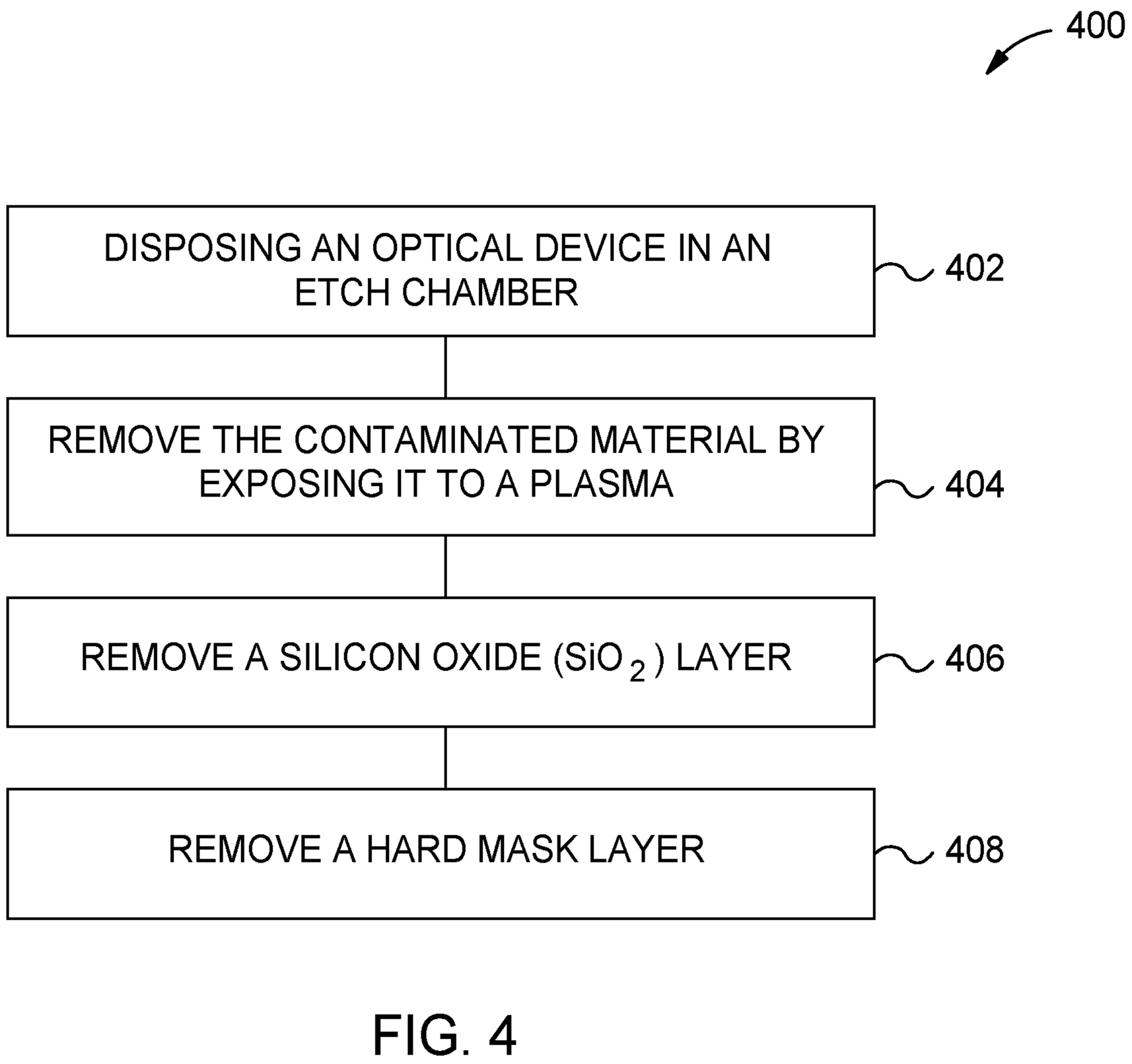

400
DISPOSING AN OPTICAL DEVICE IN AN ETCH CHAMBER
402
REMOVE THE CONTAMINATED MATERIAL BY EXPOSING IT TO A PLASMA
404
REMOVE A SILICON OXIDE (SiO_2) LAYER
406
REMOVE A HARD MASK LAYER
408

FIG. 4

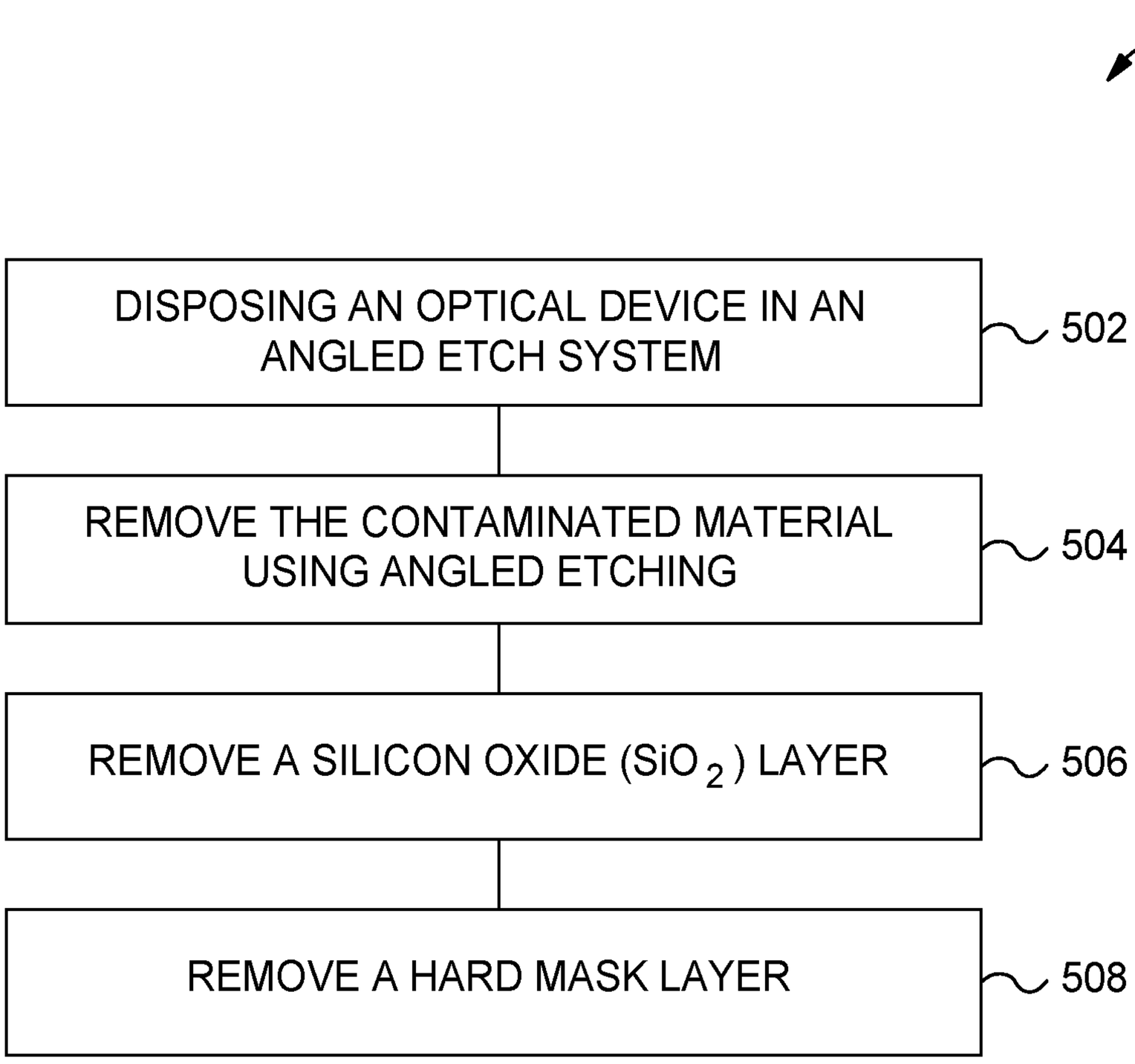

500
DISPOSING AN OPTICAL DEVICE IN AN ANGLED ETCH SYSTEM
502
REMOVE THE CONTAMINATED MATERIAL USING ANGLED ETCHING
504
REMOVE A SILICON OXIDE (SiO_2) LAYER
506
REMOVE A HARD MASK LAYER
508

FIG. 5

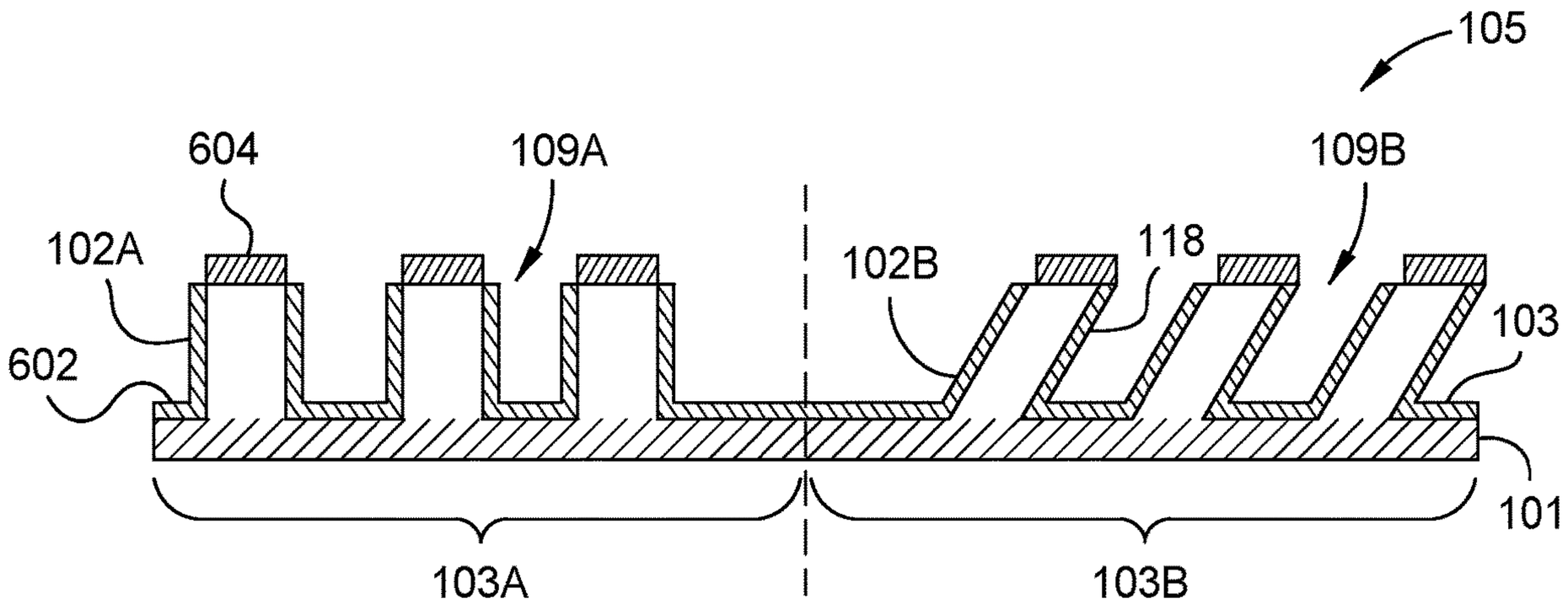


FIG. 6A

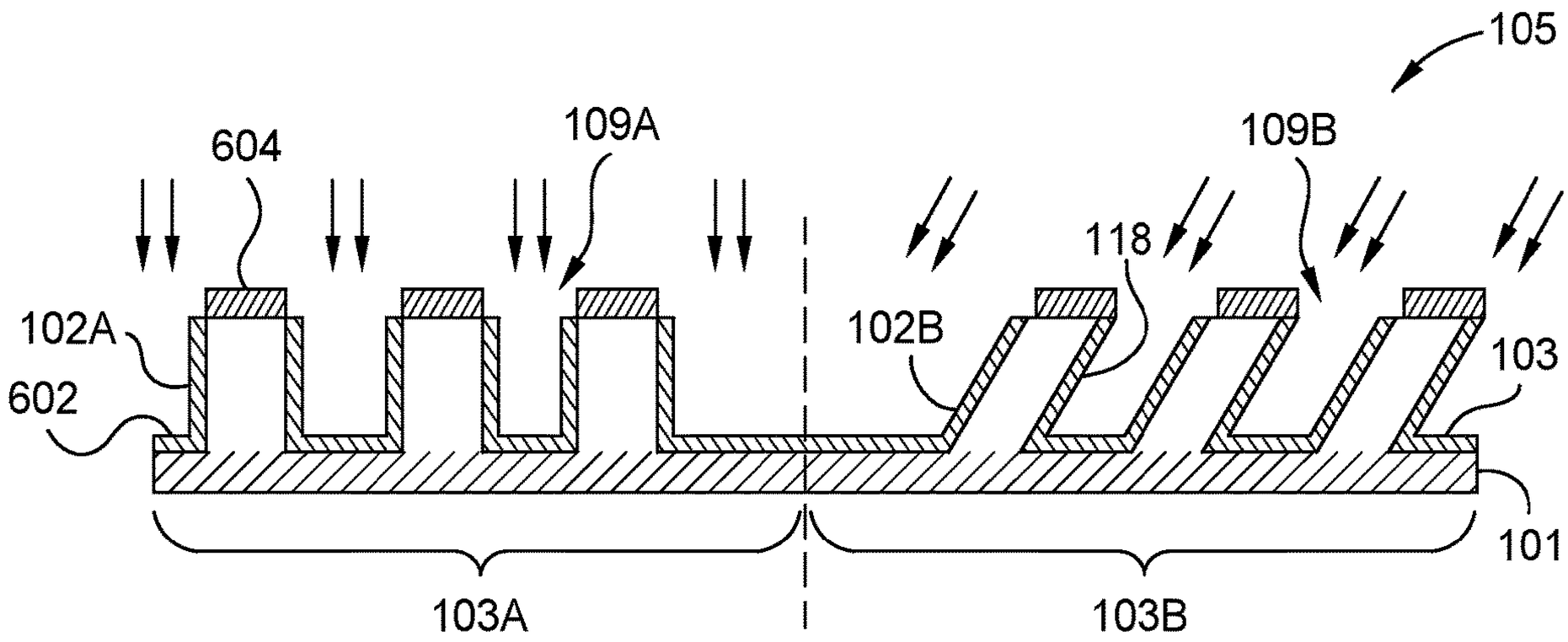


FIG. 6B

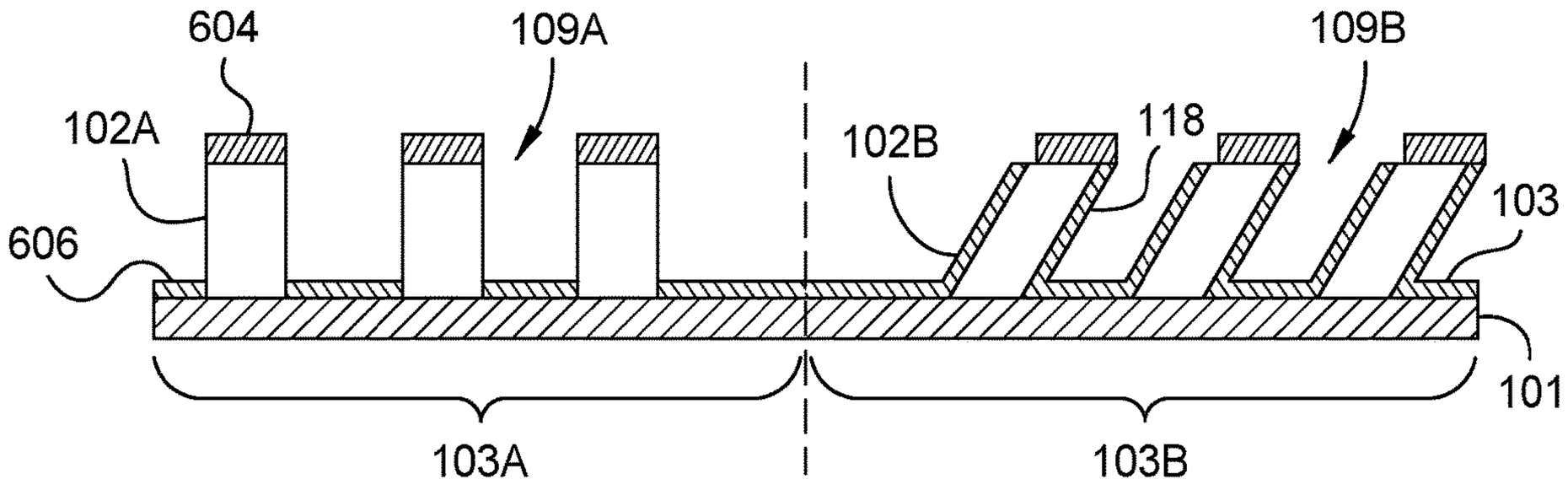


FIG. 6C

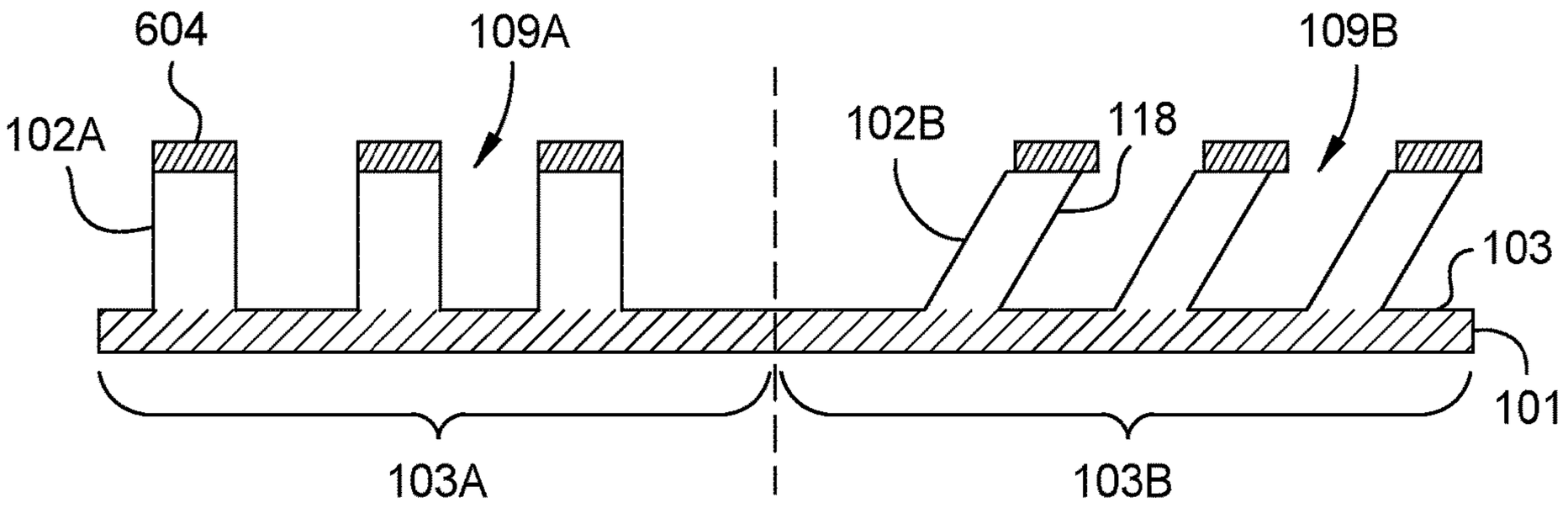

604
109A
109B
102A
102B
118
103
101
103A
103B

FIG. 6D

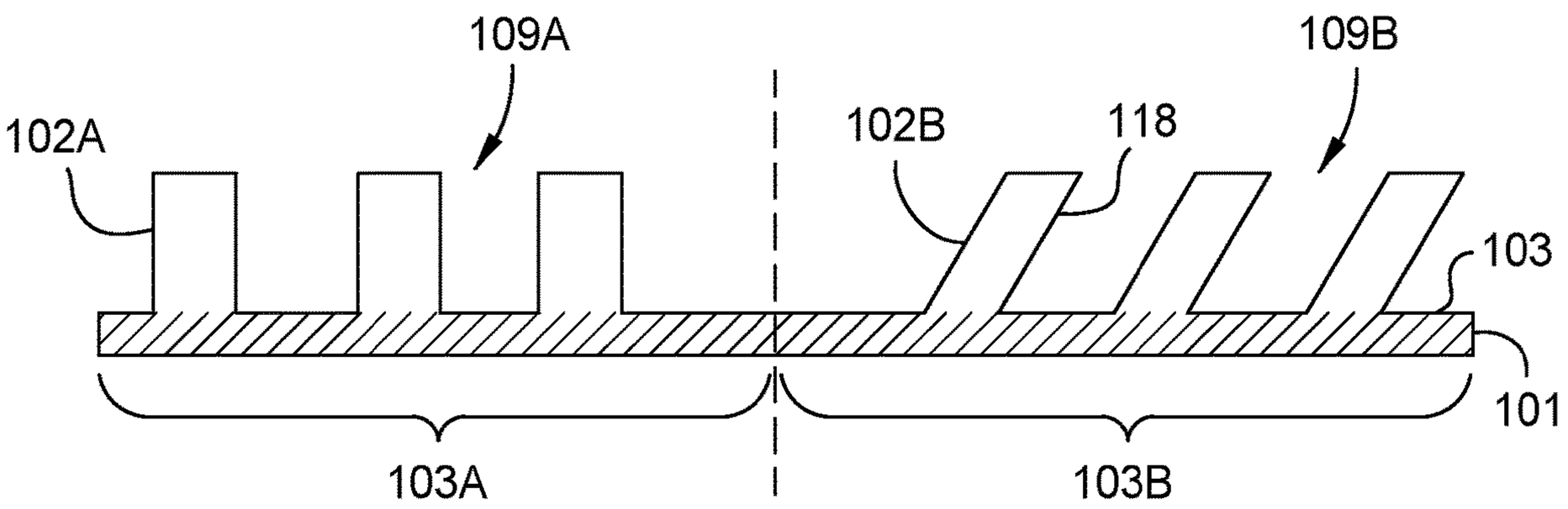

109A
109B
102A
102B
118
103
101
103A
103B

FIG. 6E

SURFACE TREATMENT METHOD TO REMOVE CONTAMINATED AND IMPLANTED WAVEGUIDE SURFACE

CROSS-REFERENCE TO RELATED APPLICATIONS

This Application claims the benefit of U.S. Provisional Application 63/376,721 filed on Sep. 22, 2022.

BACKGROUND

Field

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to methods of removing a contamination material from an optical device.

Description of the Related Art

Virtual reality is generally considered to be a computer generated simulated environment in which a user has an apparent physical presence. A virtual reality experience can be generated in 3D and viewed with a head-mounted display (HMD), such as glasses or other wearable display devices that have near-eye display panels as lenses to display a virtual reality environment that replaces an actual environment.

Augmented reality, however, enables an experience in which a user can still see through the display lenses of the glasses or other HMD device to view the surrounding environment, yet also see images of virtual objects that are generated for display and appear as part of the environment. Augmented reality can include any type of input, such as audio and haptic inputs, as well as virtual images, graphics, and video that enhances or augments the environment that the user experiences. As an emerging technology, there are many challenges and design constraints with augmented reality.

One such challenge is displaying a virtual image overlaid on an ambient environment. Optical devices including waveguide combiners, such as augmented reality waveguide combiners, and flat optical devices, such as metasurfaces, are used to assist in overlaying images. Generated light is propagated through an optical device until the light exits the optical device and is overlaid on the ambient environment. It is desirable for optical devices to be uncontaminated. Accordingly, what is needed in the art methods of removing a contamination material from an optical device.

SUMMARY

The present disclosure generally includes a method of removing a contamination material from an optical device, that includes disposing an optical device in a process chamber, the optical device having optical device structures formed in a substrate, the contamination material is disposed at least on sidewalls of the optical device structures and within trenches between the optical device structures, and exposing the optical device to a plasma generated in the process chamber, the plasma generated from oxygen gas (O_2), chlorine gas (Cl_2), Argon (Ar), or a combination thereof, the exposing the optical device to the plasma removes the contamination material.

Embodiments of the present disclosure may further provide a method of removing a contamination material from an optical device including disposing an optical device in an angled etch chamber, the optical device having optical device structures formed in a substrate, the contamination material is disposed at least on sidewalls of the optical device structures and within trenches between the optical device structures, and removing the contaminated material using angled etching by exposing the substrate to a directional plasma generated from oxygen gas (O_2) and Argon (Ar).

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

FIG. **1**A is a perspective frontal view of an optical device according to embodiments described herein.

FIG. **1**B is schematic top view of an optical device according to embodiments described herein.

FIG. **1**C is a schematic cross-sectional view of a plurality of optical device structures according to embodiments described herein.

FIG. **2** is a schematic cross-sectional view of a etch chamber according to embodiments described herein.

FIG. **3** is a schematic cross-sectional view of an angled etch system according to embodiments described herein.

FIG. **4** is a flow diagram of a method of removing a contamination material from an optical device according to embodiments described herein.

FIG. **5** is a flow diagram of a method of removing a contamination material from an optical device according to embodiments described herein.

FIGS. **6**A-**6**E are schematic cross sectional view of a portion of a substrate during methods of removing a contamination material from an optical device.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to methods of removing a contamination material from optical devices. In one embodiment, a method of removing a contamination material from an optical device using etching is provided. In another embodiment, a method of removing a contamination material from an optical device using angled etching is provided.

FIG. **1**A is a perspective, frontal view of an optical device **100**A. FIG. **1**B is a schematic, top view of an optical device **100**B. It is to be understood that the optical devices **100**A and **100**B described below are exemplary optical devices. In one embodiment, which can be combined with other embodiments described herein, the optical device **100**A is a waveguide combiner, such as an augmented reality waveguide combiner. In another embodiment, which can be combined with other embodiments described herein, the

optical device **100**B is a flat optical device, such as a metasurface. The optical devices **100**A and **100**B include a plurality of optical device structures **102** disposed on a surface **103** of a substrate **101**. The optical device structures **102** may be nanostructures having sub-micron dimensions, e.g., nano-sized dimensions. In one embodiment, which can be combined with other embodiments described herein, regions of the optical device structures **102** correspond to one or more gratings **104**, such as a first grating **104***a*, a second grating **104***b*, and a third grating **104***c*. In another embodiment, which can combined with other embodiments described herein, the optical device **100**A is a waveguide combiner that includes at least the first grating **104***a* corresponding to an input coupling grating and the third grating **104***c* corresponding to an output coupling grating. The waveguide combiner, according to the embodiment, which can be combined with other embodiments described herein, includes the second grating **104***b* corresponding to an intermediate grating.

While FIG. **1**B depicts the optical device structures **102** as having square or rectangular shaped cross-sections, the cross-sections of the optical device structures **102** may have other shapes including, but not limited to, circular, triangular, elliptical, regular polygonal, irregular polygonal, and/or irregular shaped cross-sections. In some embodiments, which can be combined with other embodiments described herein, the cross-sections of the plurality of optical device structures **102** have different shaped cross-sections. In other embodiments, which can be combined with other embodiments described herein, the cross-sections of the optical device structures **102** have cross-sections with substantially the same shape.

FIG. **1**C is a schematic cross-sectional view of a plurality of optical device structures **102**. FIG. **10** is a portion **105** of the optical device **100**A or the optical device **100**B. In some embodiments, the portion **105** of the optical devices **100**A and **100**B include the plurality of optical device structures **102** disposed on a surface **103** of a substrate **101**. The portion **105** may correspond to one or more gratings **104**. The substrate **101** includes at least one of a first portion **103**A or a second portion **103**B. The first portion **103**A includes first optical device structures **102**A. The second portion **103**B includes second optical device structures **102**B.

In some embodiments, the first optical device structures **102**A may be binary structures with a first top surface **120**A parallel to the surface **103** of the substrate **101**. The sidewalls **118** of each of the first optical device structures **102**A are parallel to each other. The sidewalls **118** of each of the first optical device structures **102**A are oriented normal to a major axis of the substrate **101**. Each optical device structure of the first optical device structures **102**A has a first optical device structure width **116**A. In one embodiment, which may be combined with other embodiments described herein, the first optical device structure width **116**A is less than 1 micrometer (μm) and corresponds to the width or the diameter of each first optical device structure **102**A, depending on the cross-section of the first optical device structure **102**A. In one embodiment, which can be combined with other embodiments described herein, at least one first optical device structure width **116**A may be different from another first optical device structure width **116**A. In another embodiment, which can be combined with other embodiments described herein, each first optical device structure width **116**A of the first optical device structures **102**A is substantially equal to each other.

Each first optical device structure **102**A of the plurality of optical device structures **102** has a first height **106**A. The first height **106**A is the distance from the surface **103** of the substrate **101** to a top surface **120**A of each first optical device structure **102**A. In one embodiment, which can be combined with other embodiments described herein, at least one first height **106**A of the first optical device structures **102**A is different than the first height **106**A of the other first optical device structures **102**A. In another embodiment, which can be combined with other embodiments described herein, each first height **106**A of the plurality of first optical device structures **102**A is substantially equal to the adjacent first optical device structures **102**A.

The first optical device structures **102**A include a first critical dimension **108**A, i.e., a linewidth, defined as the distance between adjacent first optical device structures **102**A. As shown in FIG. **1**C, the first critical dimension **108**A of each of the adjacent first optical device structures **102**A is substantially equal to each other. In some embodiments, which can be combined with other embodiments described herein, at least one a first critical dimension **108**A of adjacent first optical device structures **102**A is different from the first critical dimension **108**A of other adjacent first optical device structures **102**A of the portion **105**. A first optical device trench **109**A is defined by each pair of adjacent first optical device structures **102**A of the first optical device structures **102**A and the surface **103** of the substrate **101**. The width of each first optical device trench **109**A corresponds to the first critical dimension **108**A. The height of each first optical device trench **109**A corresponds to the first height **106**A of the adjacent first optical device structures **102**A.

The second optical device structures **102**B may be angled structures with the sidewalls **118** slanted relative to the surface **103** of the substrate **101**. In some embodiments, the second optical device structures **102**B with an angle ϑ between one another. Each optical device structure of the plurality of the second optical device structures **102**B has a second optical device structure width **116**B. In one embodiment, which may be combined with other embodiments described herein, the second optical device structure width **116**B is less than 1 micrometer (μm) and corresponds to the width or the diameter of each second optical device structure **102**B, depending on the cross-section of the second optical device structure **102**B. In one embodiment, which can be combined with other embodiments described herein, at least one second optical device structure width **116**B may be different from another second optical device structure width **116**B. In another embodiment, which can be combined with other embodiments described herein, each second optical device structure width **116**B of the second optical device structures **102**B is substantially equal to each other. The second optical device structure widths **116**B may be the same or different from the first optical device structure widths **116**A.

The second optical device structures **102**B of the plurality of optical device structures **102** has a second height **106**B. The second height **106**B is the distance from the surface **103** of the substrate to a second top surface **120**B of each second optical device structure **102**B. In one embodiment, which can be combined with other embodiments described herein, at least one second height **106**B of the second optical device structures **102**B is different that the second height **106**B of the other second optical device structures **102**B. In another embodiment, which can be combined with other embodiments described herein, each second height **106**B of the plurality of second optical device structures **102**B is sub-

stantially equal to the adjacent second optical device structures **102**B. The second heights **106**B may be the same or different from the first heights **106**A.

The second optical device structures **102**B include a second critical dimension **108**B, i.e., a linewidth, defined as the distance between adjacent second optical device structures **102**B. As shown in FIG. **1**C, the second critical dimension **108**B of each of the adjacent second optical device structures **102**B is substantially equal to each other. In some embodiments, which can be combined with other embodiments described herein, at least one a second critical dimension **108**B of adjacent second optical device structures **102**B is different from the second critical dimension **108**B of other adjacent second optical device structures **102**B of the portion **105**. The second critical dimension **108**B may be the same or different from the first critical dimension **108**A. A second optical device trench **109**B is defined by each pair of adjacent second optical device structures **102**B of the second optical device structures **102**B and the surface **103** of the substrate **101**. The width of each second optical device trench **109**B corresponds to the second critical dimension **108**B. The height of each second optical device trench **109**B corresponds to the second height **106**B of the adjacent second optical device structures **102**B.

The second optical device structures **102**B are formed at a device angle ϑ relative to the substrate **101**. The device angle ϑ is the angle between the surface **103** of the substrate **101** and a sidewall **118** of the second optical device structure **102**B. In one embodiment, which can be combined with other embodiments described herein, each respective device angle ϑ for each second optical device structure **102**B is substantially equal throughout the portion **105**. In another embodiment, which can be combined with other embodiments described herein, at least one respective device angle ϑ of the plurality of second optical device structures **102**B is different than another device angle ϑ of the plurality of second optical device structures **102**B.

The substrate **101** may also be selected to transmit a suitable amount of light of a desired wavelength or wavelength range, such as one or more wavelengths from about 100 to about 3000 nanometers. Without limitation, in some embodiments, the substrate **101** is configured such that the substrate **101** transmits greater than or equal to about 50% to about 100%, of an infrared to ultraviolet region of the light spectrum. The substrate **101** may be formed from any suitable material, provided that the substrate **101** can adequately transmit light in a desired wavelength or wavelength range and can serve as an adequate support for the optical devices **100**A and **100**B described herein. Substrate selection may include substrates of any suitable material, including, but not limited to, amorphous dielectrics, non-amorphous dielectrics, crystalline dielectrics, silicon oxide, polymers, or combinations thereof. In some embodiments, which may be combined with other embodiments described herein, the substrate **101** includes a transparent material. In one embodiment, which may be combined with other embodiments described herein, the substrate **101** is transparent with absorption coefficient smaller than 0.001. Suitable examples may include, but are not limited to, an oxide, sulfide, phosphide, telluride or combinations thereof. In one example, the substrate **101** includes silicon carbide (SiC), silicon (Si), silicon dioxide (SiO_2), germanium (Ge), silicon germanium (SiGe), InP, GaAs, GaN, fused silica, quartz, sapphire, and high-index transparent materials such as glass, or combinations thereof.

FIG. **2** is a schematic cross-sectional view of a etch chamber **200**. It is to be understood that the system described below is an exemplary system and other systems, including systems from other manufacturers, may be used with or modified to accomplish aspects of the present disclosure.

As shown in FIG. **2**, the etch chamber **200** includes the process chamber **217**. The process chamber **217** has a chamber body **202** that includes a processing volume **204** that includes a substrate support **206** disposed therein to support a substrate (not shown). The substrate support **206** includes a heating element **210** and a mechanism (not shown) that retains the substrate on a top surface **207** of the substrate support **206**, such as an electrostatic chuck, a vacuum chuck, a substrate retaining clamp, or the like. The substrate support **206** is coupled to and movably disposed in the processing volume **204** by a stem **208** connected to a lift system (not shown) that moves the substrate support **206** between an elevated processing position and a lowered position.

A processes gas source **216** may be coupled to the showerhead **214**. The process gas source **216** is configured to supply at least one process gas to the showerhead **214**. The process gases include, but is not limited to, one or more of a chlorine containing gas (Cl_2), an oxygen containing gas (O_2), Argon (Ar), or combinations thereof. The showerhead **214** is connected to a RF power source **222** by a RF feed **224** for generating a plasma in the processing volume **204** from the process gasses. In operation, the RF power source **222** provides RF energy to the showerhead **214** to facilitate generation of a plasma between the showerhead **214** and the substrate support **206**. The stem **208** is configured to move the substrate support **206** to an elevated processing position at a process distance **226** between top surface **207** and the showerhead **214**. The vacuum pump **220** is coupled to the chamber body **202** for controlling the pressure within the processing volume **204**.

FIG. **3** is a schematic, side view of an angled etch system **300**. It is to be understood that the angled etch system **300** described below is an exemplary angled etch system and other angled etch systems may be used.

The angled etch system **300** includes an ion beam chamber **302**. A power source **304**, a first gas source **306**, and a second gas source are coupled to the ion beam chamber **302**. In one embodiment, which can be combined with other embodiments described herein, the power source **304** is a radio frequency (RF) power source. The first gas source **306** is in fluid communication with the interior volume **305** of ion beam chamber **302**. The first gas source **306** is an inert gas source which supplies an inert gas to the ion beam chamber **302**, such as Ar. The second gas source **308** is in fluid communication with the interior volume **305** of ion beam chamber **302**. The second gas source **308** is a process gas source which supplies a process gas to the ion beam chamber **302**. The process gases include, but is not limited to, an oxygen containing gas (O_2).

In operation, a plasma is generated in the ion beam chamber **302** by applying RF power via the power source **304** to the inert gas and the process gas provided to the interior volume **305** of ion beam chamber **202** to generate a plasma. Ions of the plasma of the inert gas and the process gas are extracted through an aperture **310** of an extraction plate **312** to generate an ion beam **316**. The aperture **310** of the ion beam chamber **302** is operable to direct the ion beam **316** at an angle α relative to a datum plane **318** oriented normal to the substrate **101**.

The substrate **101** is retained on a platen **314** coupled to a first actuator **319**. The first actuator **319**, which may be a linear actuator, a rotary actuator, a stepper motor, or the like, is configured to move the platen **314** in a scanning motion

along a y-direction and/or a z-direction. In one embodiment, which can be combined with other embodiments described herein, the first actuator **319** is further configured to tilt the platen **314** such that the substrate **101** is positioned at a tilt angle β relative to the x-axis of the ion beam chamber **302**. The angle α and tilt angle β result in a beam angle θ relative to the datum plane **318** normal to the substrate **101**. A second actuator **320** may also be coupled to the platen **314** to rotate the substrate **101** about the x-axis of the platen **314**.

FIG. **4** is a flow diagram of a method **400** for removing a contamination material from an optical device, as shown in FIGS. **6**A-**6**E. In one example, method **400** may be performed using etch chamber **200** of FIG. **2**.

FIGS. **6**A-**6**E are schematic, cross-sectional views of a substrate during operations of removing a contamination material **602** from the optical device **100**A or **100**B. FIGS. **6**A-**6**E are a portion **105** of the optical device **100**A or the optical device **100**B. The portion **105** of the optical devices **100**A and **100**B include the first optical device structures **102**A disposed on a first portion **103**A of the surface **103** of a substrate **101**, and/or the second optical device structures **102**B disposed on a second portion **103**B of the surface **103** of the substrate **101**. In one embodiment, which can be combined with other embodiments described herein, the portion **105** may correspond to a portion or a whole surface of the substrate **101** of a flat optical device such as optical device **100**B illustrated in FIG. **1**B. In another embodiment, which can be combined with other embodiments described herein, the portion **105** may correspond to a portion or a whole surface of the substrate **101** of a waveguide combiner, such as optical device **100**A illustrated in FIG. **1**A. In one embodiment, which can be combined with other embodiments described herein, the portion corresponds to one or more of the first grating **104***a*, the second grating **104***b*, or the third grating **104***c*. In another embodiment, the portion **105** comprises the first optical device structures **102**A in both the first portion **103**A and the second portion and **103**B. In another embodiment, the portion **105** comprises the second optical device structures **102**B in both the first portion **103**A and the second portion and **103**B.

At operation **402**, as shown in FIG. **6**A, an optical device is disposed in an etch chamber, such as etch chamber **200**. Contamination material **602** is disposed on portions of a surface **103** of the substrate **101** disposed between optical device structures **102**. The contamination material **602** is formed at least on sidewalls **118** of the first optical device structures **102**A and the second optical device structures **102**B, and within the first trenches **109**A and the second trenches **109**B. The contamination material **602** may be deposited during etching of the substrate **101**. The contamination material **602** is formed while etching the substrate **101** to form the optical device structures **102**. The contamination material **602** may be formed of etch by-products and/or hard mask layer **604** material.

For example, during ion beam etching of the substrate **101**, the ion beam may contact the hard mask layer **604** material and redeposit hard mask layer **604** material into the first trenches **109**A and the second trenches **109**B. The hard mask layer **604** material may include, but is not limited to chromium (Cr), ruthenium (Ru), titanium nitride (TiN), Tantalum nitride (TaN), chromium oxide (CrO), or combinations thereof. Additionally, or alternatively, by-products of the process gasses used during ion-beam etching of the substrate **101** may be implanted in the first trenches **109**A and the second trenches **109**B.

The contamination material **602** may include, but is not limited to aluminum (Al), Cr, nitrogen (N), oxygen (O), SiC (silicon carbide), Ru, Fluorine (F), carbon (C), or combinations thereof.

At operation **404**, as shown in FIG. **6**B, the contamination material **602** is removed. In some embodiments, as described in method **400**, the contamination material **602** may be removed using exposing the substrate **101** to a plasma. In one example, the process gasses used to form the plasma include, but are not limited to, O_2, Cl_2, or argon (Ar). The substrate **101** is exposed to the plasma, and the plasma selectively etches the contamination material **602**. As illustrated in FIG. **6**C, a silicon oxide (SiO_2)-containing layer **606** remains in the trenches after removing the contamination material **602**.

At operation **406**, as shown in FIG. **6**D, the SiO_2-containing layer **606** is removed. The SiO_2-containing layer **606** is removed using a wet cleaning process. For example, the wet cleaning process is a wet dihydrofolic acid (dHF) cleaning process.

At operation **408**, as shown in FIG. **6**E, the hard mask layer **604** material may be removed. The hard mask layer **604** material may be removed using either wet or dry cleaning processes.

FIG. **5** is a flow diagram of a method **500** of removing a contamination material **602** from an optical device, as shown in FIGS. **6**A-**6**E, using ion beam etching. In one example the process of FIG. **5** may be performed by the angled etch system **300**.

At operation **502**, as shown in FIG. **6**A, an optical device is disposed in an angled etch system **300**. Contamination material **602** is disposed on portions of a surface **103** of the substrate **101** disposed between optical device structures **102**. The contamination material **602** is formed at least on sidewalls **118** of the first optical device structures **102**A and the second optical device structures **102**B, and within the first trenches **109**A and the second trenches **109**B. The contamination material **602** may be deposited during etching of the substrate **101**. The contamination material **602** is formed while etching the substrate **101** to form the optical device structures **102**. The contamination material **602** may be formed of etch by-products and/or hard mask layer **604** material.

For example, during ion beam etching of the substrate **101**, the ion beam may contact the hard mask layer **604** material and redeposit the hard mask layer **604** material into the first trenches **109**A and the second trenches **109**B. The hard mask layer **604** material may include, but is not limited to Cr, Ru, or combinations thereof. Additionally, or alternatively, by-products of the process gasses used during ion beam etching of the substrate **101** are implanted in the first trenches **109**A and the second trenches **109**B.

The contamination material **602** may include, but is not limited to Al, Cr, N, O, SiC(amorphous), Ru, F, Cl, SiOC, or combinations thereof.

At operation **504**, as shown in FIG. **6**B, the contamination material **602** is removed by using an angled etch, such as an ion beam etch or a reactive ion etch (RIE). In one example, the process gasses are used to form a directional plasma. The processes gasses used in the angled etch system **300** include, but are not limited to, O_2, Ar, or combinations thereof. As illustrated in FIG. **6**B, the plasma is directed in a substantially vertical direction over the first optical device structures **102**A. Additionally, or alternatively, the plasma is directed over the second optical device structures **102**B at an angle. As illustrated in FIG. **6**C, a SiO_2-containing layer **606** remains in the trenches after etching the contamination

material **602**. The plasma may bond to the atoms that make-up the contamination material **602**, convert the atoms into volatile compounds, resulting in the removal of the contamination material **602**.

At operation **506**, as shown in FIG. **6**D, the SiO_2-containing layer **606** is removed. The SiO_2-containing layer **606** is removed using a wet cleaning process such a wet dHF cleaning process.

At operation **508**, as shown in FIG. **6**E, the hard mask layer **604** material is removed. The hard mask layer **604** material may be removed using a dry or a wet chemistry.

In summation, improved methods and materials to form optical devices without contamination. To achieve desirable optical properties, a contamination material **602** is removed using plasma after forming optical device structures **102**. The contamination material **602** may absorb a percentage of light in a single interaction. In a waveguide, light may bounce ten to hundreds of times inside a substrate causing significant light loss. Therefore, removing the contamination material **602** significantly increases waveguide efficiency.

While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method of removing a contamination material from a waveguide, comprising:

disposing the waveguide in a process chamber, the waveguide comprising an input coupler comprising first optical device structures and an output coupler comprising second optical device structures, and the contamination material is disposed at least on sidewalls of the first optical device structures and the second optical device structures, and within trenches disposed between adjacent first optical device structures and adjacent second optical device structures; and

exposing the waveguide to a plasma generated in the process chamber, the plasma generated from oxygen gas (O_2), chlorine gas (Cl_2), Argon (Ar), or a combination thereof, the exposing the waveguide to the plasma removing the contamination material.

2. The method of claim **1**, wherein the first optical device structures and the second optical device structures are binary optical device structures or angled optical device structures.

3. The method of claim **1**, wherein the contaminated material comprises a hard mask material or a residual material from an etching process.

4. The method of claim **1**, wherein the contamination material comprises silicon carbide (SiC), chromium (Cr), aluminum (Al), ruthenium (Ru), nitrogen (N), oxygen (O), or a combination thereof.

5. The method of claim **1**, wherein the waveguide further comprises a substrate made from silicon carbide (SiC).

6. The method of claim **1**, wherein the exposing the waveguide to the plasma forms a silicon oxide (SiO_2)-containing layer on the sidewalls of the first optical device structures and the second optical device structures and a surface of a substrate disposed between the adjacent first and the adjacent second optical device structures.

7. The method of claim **6**, wherein the SiO_2-containing layer is removed via a wet cleaning process.

8. The method of claim **1**, wherein a hardmask is disposed on a top surface of the first optical device structures and the second optical device structures.

9. The method of claim **8**, wherein the hardmask is removed after a wet cleaning process.

10. A method of removing a contamination material from a waveguide, comprising:

disposing the waveguide in an angled etch chamber, the waveguide having an input coupler comprising first optical device structures and an output coupler comprising second optical device structures, and the contamination material is disposed at least on sidewalls of the first optical device structures and the second optical device structures, and within trenches disposed between adjacent first optical device structures and adjacent second optical device structures; and

removing the contaminated material using angled etching by exposing the waveguide to a directional plasma generated from oxygen gas (O_2) and Argon (Ar).

11. The method of claim **10**, wherein the first optical device structures and the second optical device structures are binary optical device structures or angled optical device structures.

12. The method of claim **10**, wherein the contamination material comprises a hard mask material or a residual material from an etching process.

13. The method of claim **10**, wherein the contamination material is made of silicon carbide (SiC), chromium (Cr), aluminum (Al), ruthenium (Ru), nitrogen (N), oxygen (O), or a combination thereof.

14. The method of claim **10**, wherein the waveguide further comprises a substrate made of silicon carbide (SiC).

15. The method of claim **10**, wherein the exposing the waveguide to the directional plasma forms a silicon oxide (SiO_2)-containing layer on the sidewalls of the first optical device structures and the second optical device structures and a surface of a substrate disposed between the adjacent first optical device structures and the adjacent second optical device structures.

16. The method of claim **15**, wherein the SiO_2-containing layer is removed via a wet cleaning process.

17. The method of claim **10**, wherein a hardmask is disposed on a top surface of the first optical device structures and the second optical device structures.

18. The method of claim **17**, wherein the hardmask is removed after a wet cleaning process.

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