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(54) **OPTICAL DEVICE IMPROVEMENT**

(71) Applicant: **Applied Materials, Inc.**, Santa Clara, CA (US)

(72) Inventors: **Yue Chen**, Sunnyvale, CA (US); **Jinyu Lu**, Santa Clara, CA (US); **Yongmei Chen**, San Jose, CA (US); **Jinxin Fu**, Fremont, CA (US); **Zihao Yang**, Santa Clara, CA (US); **Mingwei Zhu**, San Jose, CA (US); **Takashi Kuratomi**, San Jose, CA (US); **Rami Hourani**, Santa Clara, CA (US); **Ludovic Godet**, Sunnyvale, CA (US); **Qun Jing**, Santa Clara, CA (US); **Jingyi Yang**, Santa Clara, CA (US); **David Masayuki Ishikawa**, Mountain View, CA (US)

(73) Assignee: **Applied Materials, Inc.**, Santa Clara, CA (US)

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H01J 7/02 (2006.01)

(52) **U.S. Cl.**
CPC ..... ***H01J 37/32449*** (2013.01); ***H01J 7/02*** (2013.01); ***H01J 37/32458*** (2013.01); (Continued)

(58) **Field of Classification Search**
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(Continued)

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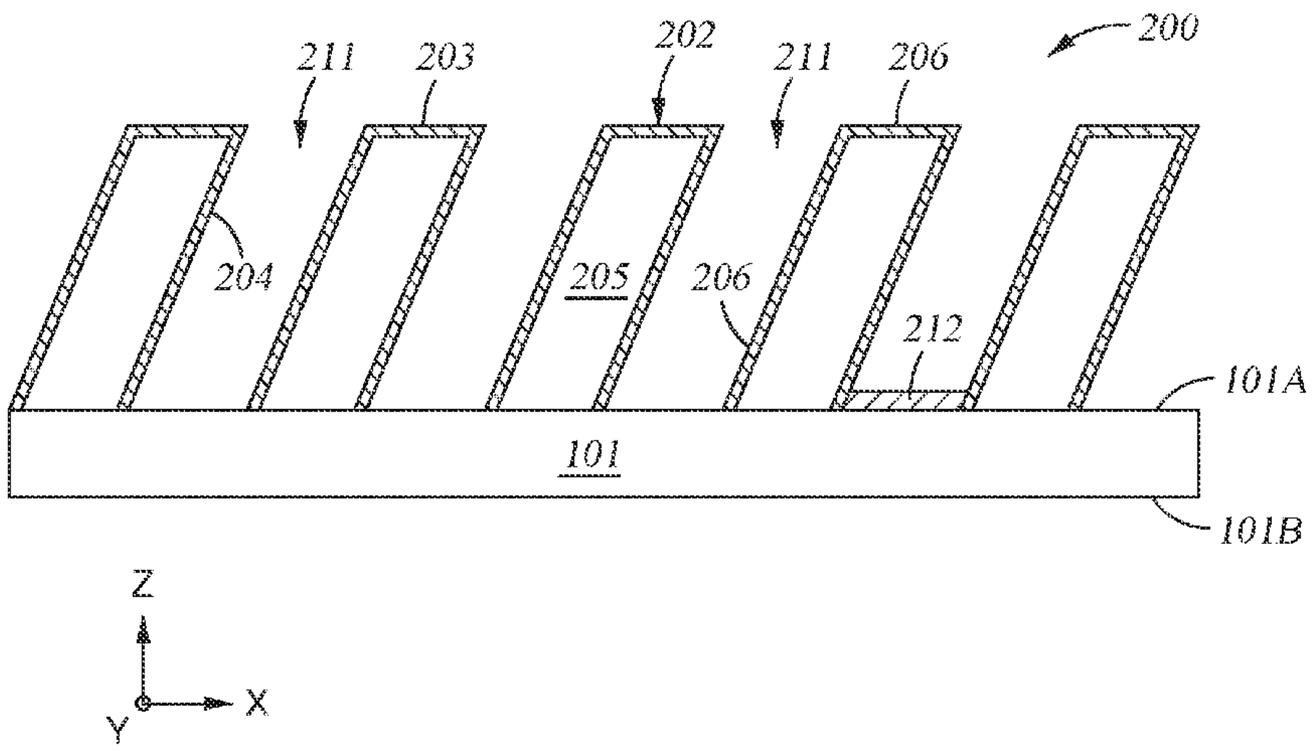
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Primary Examiner — Abdullah A Riyami
Assistant Examiner — Syed M Kaiser
(74) *Attorney, Agent, or Firm* — Patterson + Sheridan, LLP

(57) **ABSTRACT**

A method of processing an optical device is provided, including: positioning an optical device on a substrate support in an interior volume of a process chamber, the optical device including an optical device substrate and a plurality of optical device structures formed over the optical device substrate, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide. The method further includes providing one or more process gases to the interior volume of the process chamber, and generating a plasma of the one or more process gases in the interior volume for a first time period when the optical device is on the substrate support, and stopping the plasma after the first time period. A carbon content of the one or more surface
(Continued)



regions of each optical device structure is reduced by at least 50% by the plasma.

20 Claims, 5 Drawing Sheets

Related U.S. Application Data

filed on Apr. 28, 2022, provisional application No. 63/362,935, filed on Apr. 13, 2022.

(52) **U.S. Cl.**
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(58) **Field of Classification Search**
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See application file for complete search history.

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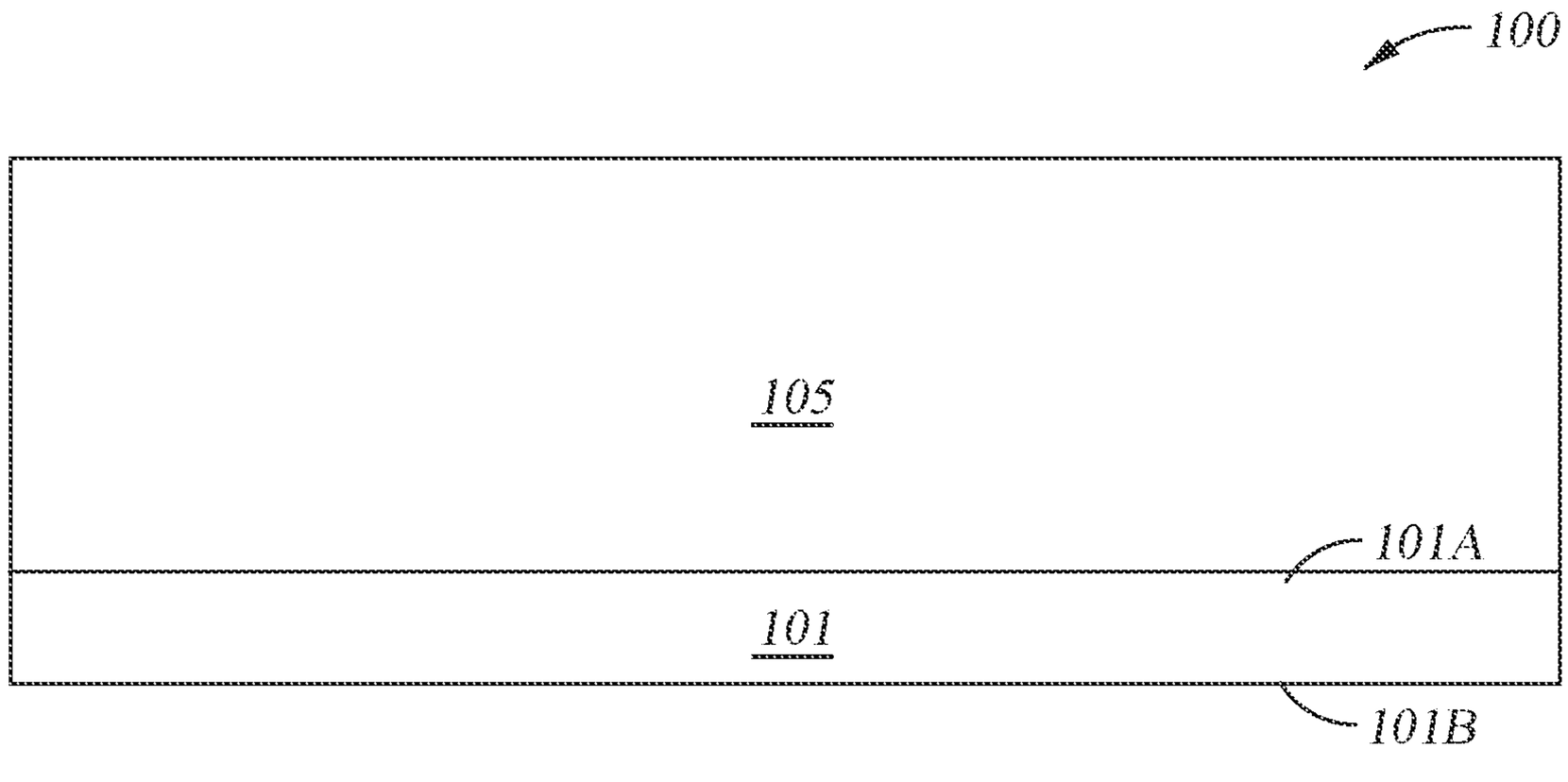

100
105
101A
101
101B
Z
X
Y

Fig. 1

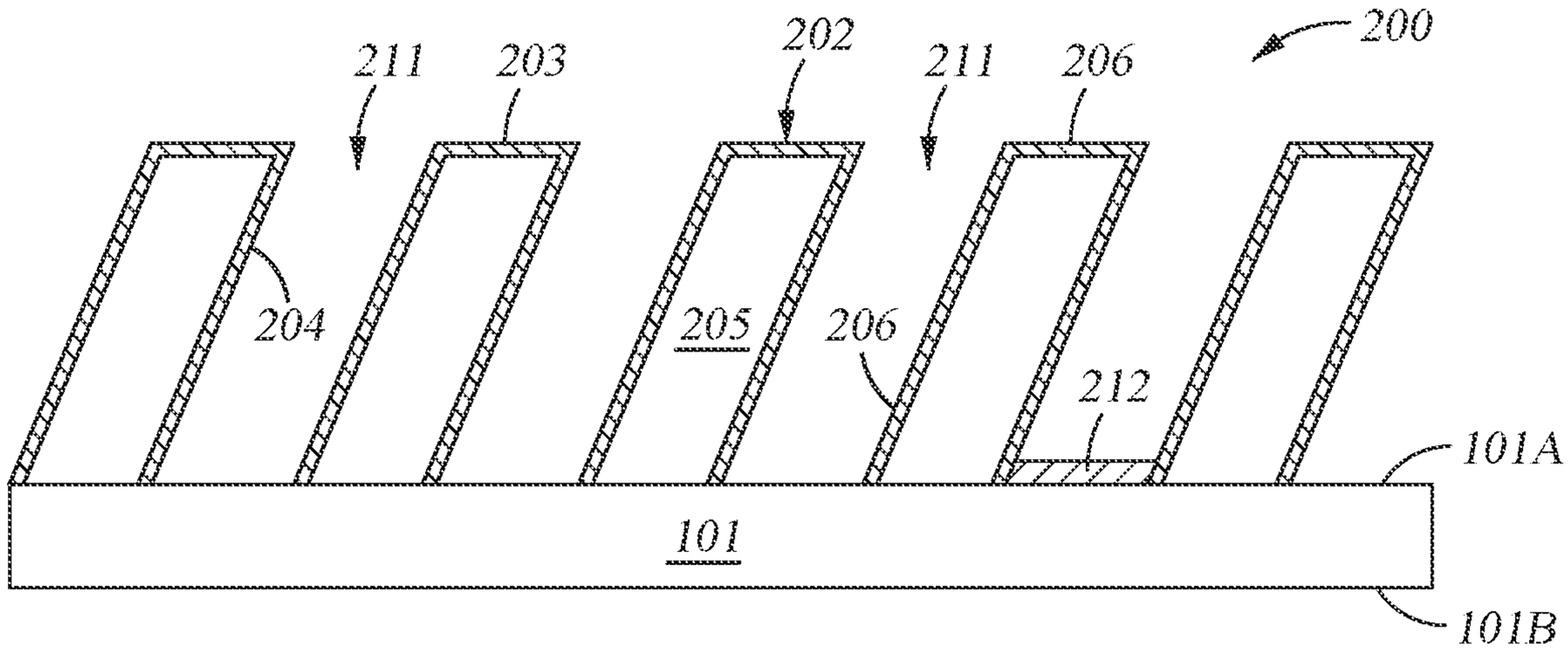

200
211
203
202
211
206
204
205
206
212
101A
101
101B
Z
X
Y

Fig. 2

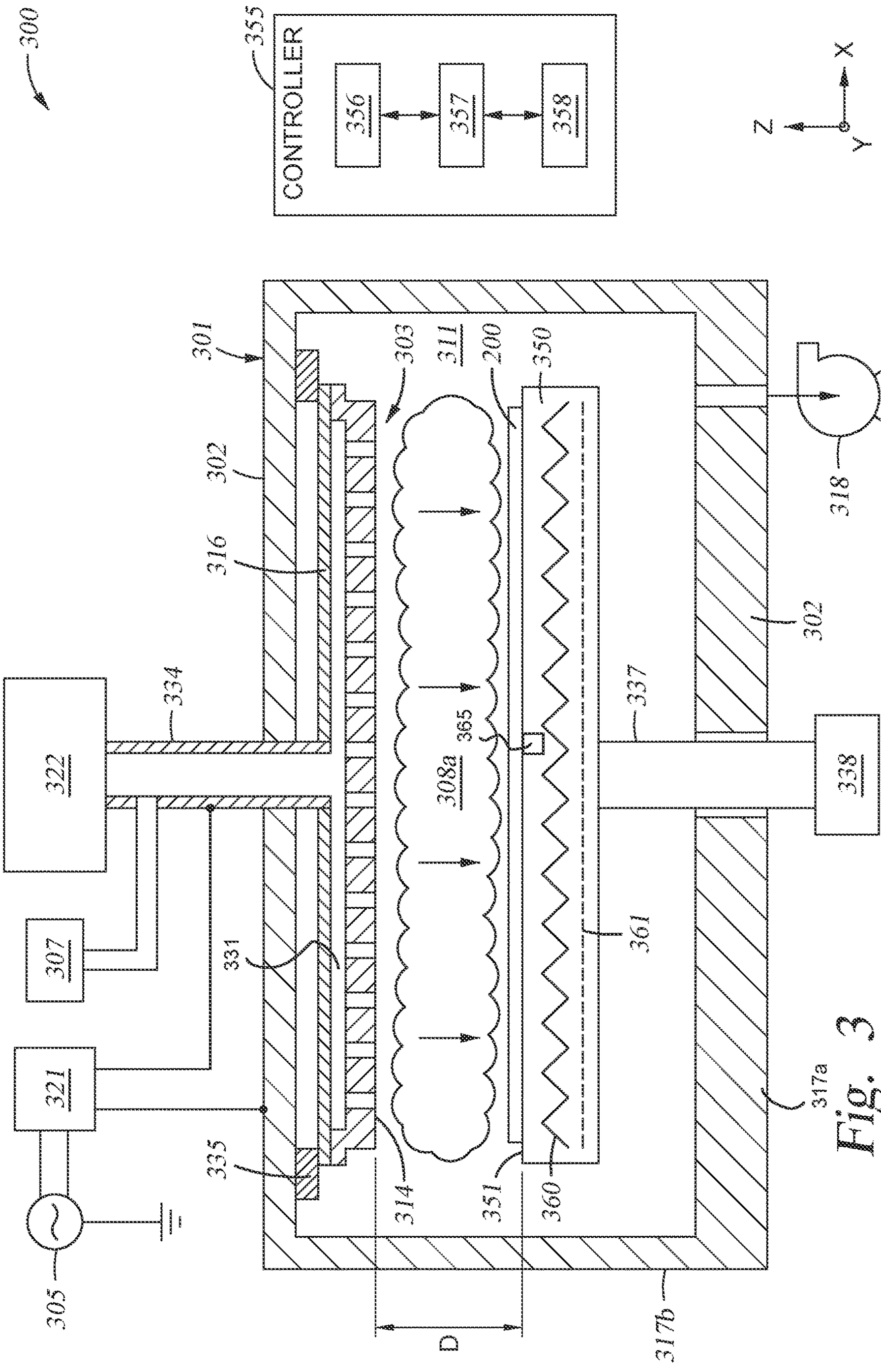

300
355
CONTROLLER
356
357
358
Z
X
Y
301
303
311
200
350
302
316
318
334
322
308a
365
337
338
307
321
331
361
335
314
351
360
305
D
317b
317a

Fig. 3

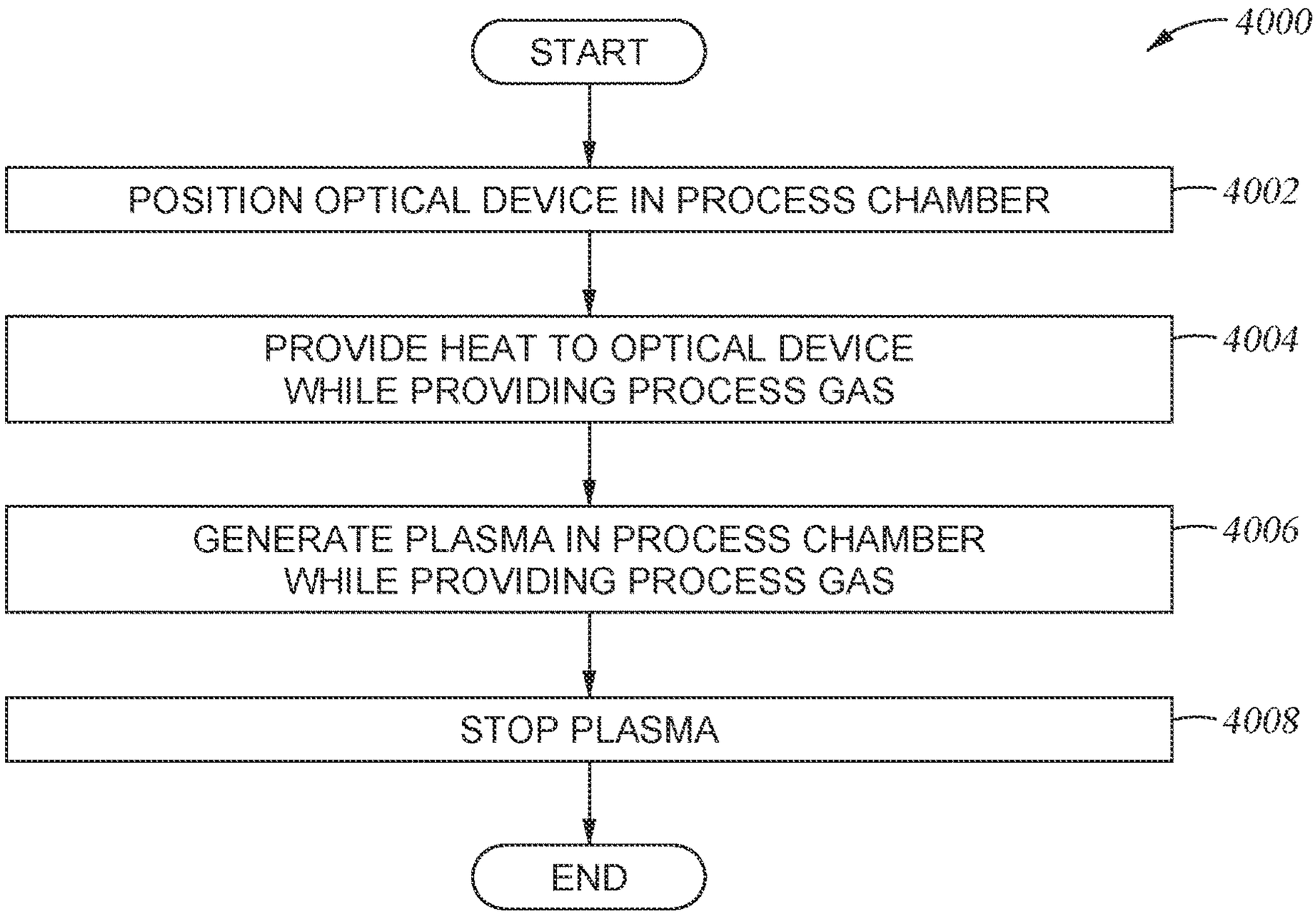

4000
START
POSITION OPTICAL DEVICE IN PROCESS CHAMBER
4002
PROVIDE HEAT TO OPTICAL DEVICE WHILE PROVIDING PROCESS GAS
4004
GENERATE PLASMA IN PROCESS CHAMBER WHILE PROVIDING PROCESS GAS
4006
STOP PLASMA
4008
END

Fig. 4

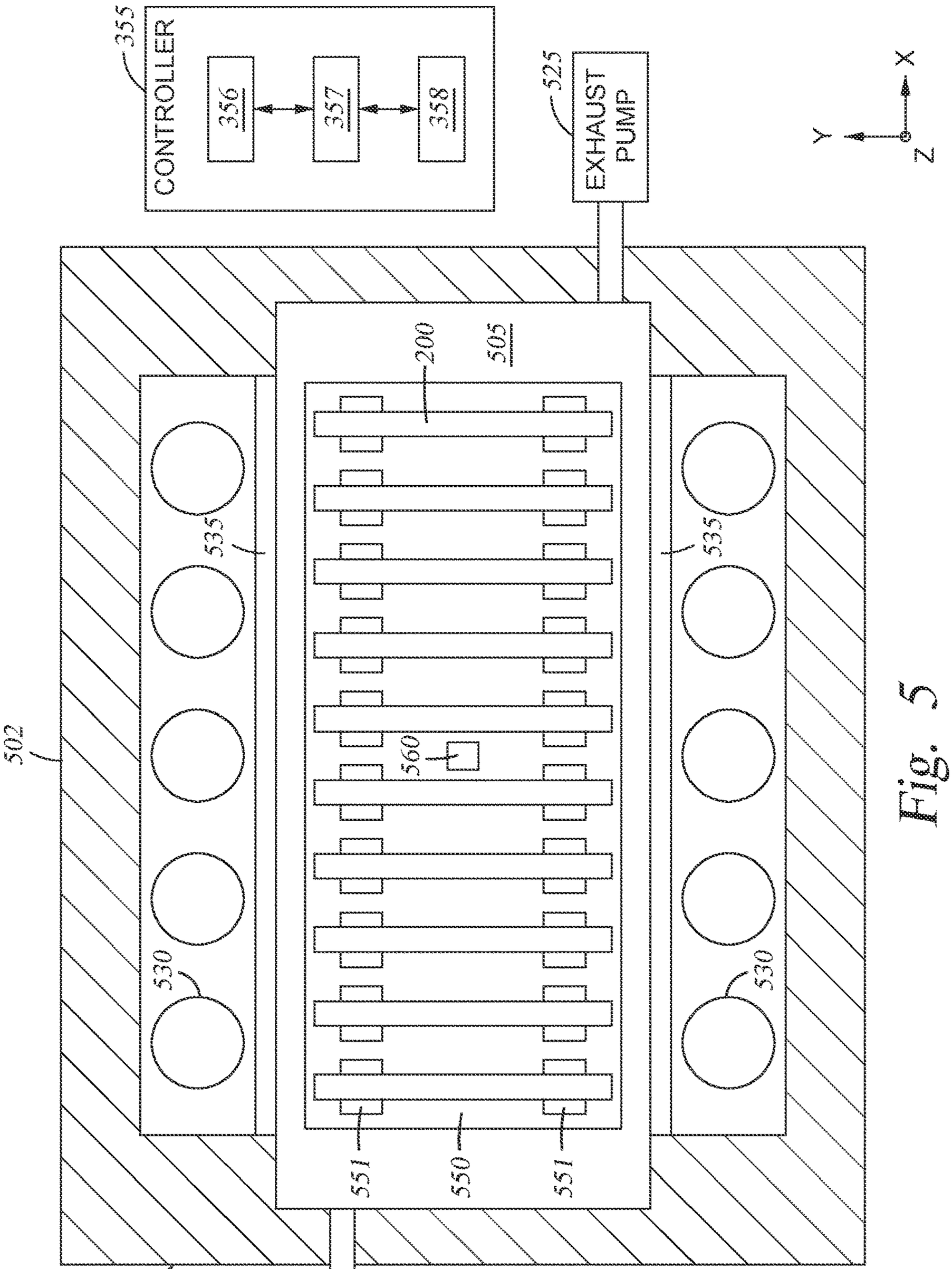

355
CONTROLLER
356
357
358
525
EXHAUST PUMP
Y
X
Z
502
200
505
535
560
530
551
550
551
500
501
520
GAS SOURCES

Fig. 5

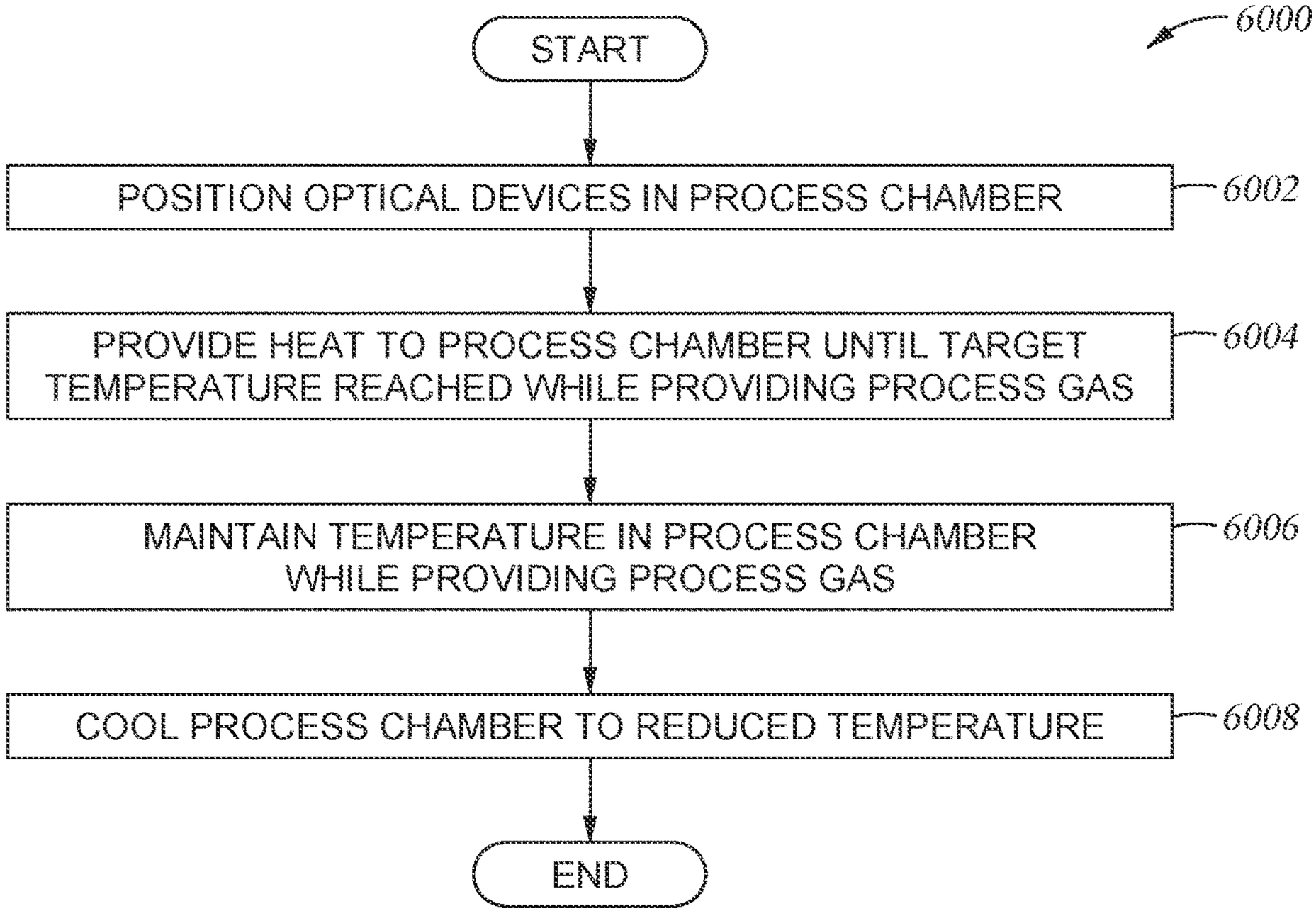

6000
START
POSITION OPTICAL DEVICES IN PROCESS CHAMBER
6002
PROVIDE HEAT TO PROCESS CHAMBER UNTIL TARGET TEMPERATURE REACHED WHILE PROVIDING PROCESS GAS
6004
MAINTAIN TEMPERATURE IN PROCESS CHAMBER WHILE PROVIDING PROCESS GAS
6006
COOL PROCESS CHAMBER TO REDUCED TEMPERATURE
6008
END

Fig. 6

OPTICAL DEVICE IMPROVEMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to: (1) U.S. Provisional Patent Application Ser. No. 63/362,935, filed on Apr. 13, 2022; (2) U.S. Provisional Patent Application Ser. No. 63/363,773, filed on Apr. 28, 2022; and (3) U.S. Provisional Patent Application Ser. No. 63/352,854, filed on Jun. 16, 2022, which are each incorporated by reference in their entirety.

BACKGROUND

Embodiments of the present disclosure generally relate to optical devices. More specifically, embodiments described herein relate to improved optical devices and methods of improving the optical properties of one or more surface regions of optical devices.

DESCRIPTION OF THE RELATED ART

Optical devices, such as augmented reality waveguide combiners, are used for overlaying images for users. Generated light is propagated through the optical device until the light exits the optical device and is overlaid on the ambient environment for the user. Absorption of light inside the optical device can reduce the efficiency of the optical device as well diminish the user's experience due to reduced intensity of images output by the optical device. Although efforts have been made to reduce the absorption of light inside optical devices, absorption of light remains a problem.

Accordingly, what is needed in the art are optical devices and methods of forming optical devices that further reduce the absorption of light inside optical devices.

SUMMARY

In one embodiment, a method of processing an optical device is provided, comprising: positioning an optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide; providing one or more process gases to the interior volume of the process chamber; generating a plasma of the one or more process gases in the interior volume of the process chamber for a first time period when the optical device is on the substrate support; and stopping the plasma after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 50% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

In another embodiment, a method of processing an optical device is provided, comprising: positioning an optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide; providing one or more process gases to the interior volume of the process chamber; heating the interior volume of the process chamber to a temperature of at least 600° C. for a first time period when the optical device is on the substrate support; and stopping the heat after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 50% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

In another embodiment, a method of processing an optical device is provided, comprising: positioning an optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide, wherein the optical device substrate is formed of silicon carbide and the plurality of optical device structures are gratings configured for use in a waveguide combiner; providing one or more process gases including hydrogen to the interior volume of the process chamber; exposing the optical device to a plasma generated from the one or more process gases for a first time period when the optical device is on the substrate support; and stopping the plasma after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 80% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

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 of the present disclosure and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

FIG. **1** is a cross-sectional view of an optical device, according to one embodiment.

FIG. **2** is a cross-sectional view of an optical device, according to one embodiment.

FIG. **3** is a side cross-sectional view of a plasma processing system, according to one embodiment.

FIG. **4** is a process flow diagram of a method of performing a plasma process on the optical device shown in FIG. **2**, according to one embodiment.

FIG. **5** is a top cross-sectional view of a batch processing system, according to one embodiment.

FIG. **6** is a process flow diagram of a method of performing a batch annealing process on a plurality of the optical devices shown in FIG. **2**, according to one embodiment.

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 relate to improved optical devices and methods of improving the optical prop-

erties of one or more surface regions of optical devices. Optical device structures (e.g., optical gratings for a waveguide combiner) are often formed of silicon carbide due to the refractive index and other optical properties of silicon carbide. These silicon carbide optical device structures are often formed on substrates formed of silicon carbide. Forming the optical device structures on silicon carbide substrates using methods, such as ion-beam etching (IBE), can result in regions near the surface of the optical device structures and substrate being formed of silicon oxycarbide due to gases (e.g., oxides) used in the process. These silicon oxycarbide regions can cause high levels of optical loss and diminish the optical performance of the optical device.

Disclosed herein are methods and related process equipment that can substantially reduce the carbon content of these silicon oxycarbide regions (e.g., >50% reduction) formed over the optical device structures and the substrate, so that the optical loss caused by the silicon oxycarbide regions is substantially reduced. In one embodiment, a plasma treatment process is performed to substantially reduce the carbon content in the surface regions of the optical device structures and substrate. In another embodiment, an annealing process is performed with one or more process gases to substantially reduce the carbon content in the surface regions of the optical device structures and substrate. These methods can be used to improve the optical performance of the optical device and restore the optical loss to levels substantially the same as optical loss levels of the material (e.g., silicon carbide) before the process (e.g., IBE) used to form the optical device structures is performed. In some embodiments, these methods can improve the optical device efficiency for red light, green light, and blue light by at least 50%, such as by at least 70%. In some embodiments, these methods can improve the optical device efficiency for green light by at least 100%, such as by at least 149%. In some embodiments, these methods can improve the optical device efficiency for green light by at least 100%, such as by at least 260%.

FIG. **1** is a cross-sectional view of an optical device **100**, according to one embodiment. The optical device **100** includes an optical device substrate **101** and an optical device film **105**. The optical device substrate **101** includes a first surface **101**A and an opposing second surface **101**B. The optical device film **105** is disposed over the first surface **101**A of the optical device substrate **101**. In some embodiments, the optical device film **105** is disposed directly on the first surface **101**A of the substrate **101**.

In some embodiments, which can be combined with other embodiments described herein, the optical device substrate **101** can be formed of an optically transparent material. In some embodiments, the optical device substrate **101** can be formed of silicon carbide.

The optical device film **105** can also be formed of silicon carbide. In some embodiments, the optical device film **105** can be formed of another optically transparent material, for example another optically transparent material including silicon and/or carbon. In some embodiments, the optical device film **105** can be formed over the optical device substrate **101** using chemical vapor deposition (CVD), plasma-enhanced CVD, or physical vapor deposition among other techniques. In other embodiments, there is not a separate film **105** and the optical device structures described below can be formed by etching a silicon carbide substrate.

FIG. **2** is a cross-sectional view of an optical device **200**, according to one embodiment. The optical device **200** is formed by modifying the optical device film **105** from the optical device **100** of FIG. **1**. In one embodiment, which can be combined with other embodiments described herein, the optical device **200** 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 **200** is a flat optical device, such as a metasurface. Other optical devices that can be formed from the optical device film **105** include optical filters and dielectric mirrors.

The optical device **200** includes a plurality of optical device structures **202** disposed over (e.g., directly on) the first surface **101**A of the substrate **101**. The optical device structures **202** can be spaced apart from each other in the X-direction by trenches **211**. In some embodiments, the trenches **211** extend down to the first surface **101**A of the optical device substrate **101**. The optical device structures **202** can each include a top surface **203** and side surfaces **204**. The optical device structures **202** can each further include a bulk region **205** and surface regions **206**. The optical device structures **202** are formed from the optical device film **105** from FIG. **1**, and thus the bulk regions **205** of the optical device structures **202** are formed of silicon carbide. In some embodiments, the optical device structures **202** can be formed of another optically transparent material, for example another optically transparent material including silicon and/or carbon. In one embodiment, the optical device structures **202** are gratings for a waveguide combiner configured for use in an augmented reality device.

The surface regions **206** are formed of silicon oxycarbide. The surface regions **206** can extend along the top surface **203** and the side surfaces **204** of each optical device structure **202**. Although the surface regions **206** are shown having a uniform thickness, the thickness of the surface regions **206** can vary along the top surface **203** and the side surfaces **204**. The thickness of the surface regions **206** can be from about 0.1 nm to about 50 nm, such as from about 1 nm to about 10 nm, such as about 3 nm. Furthermore, the carbon content can vary within the surface regions **206** along any dimension. The accumulation of carbon in the surface regions **206** can reduce the optical performance of the optical device **200** compared to the same optical device **200** that does not include the accumulated carbon in the surface regions **206**.

In some embodiments, surface regions **212** are formed over the first surface **101**A of the optical device substrate **101** at the bottom of the trenches **211** as a result of the process used to form the optical device structures **202** (e.g., an IBE process). Although only one example of the surface regions **212** is shown, in some embodiments, the surface regions **212** are formed at the bottom of each trench **211**. In one embodiment, the surface regions **212** can have a similar composition (e.g., formed of silicon oxycarbide) and dimensions as the surface regions **206** described above.

The plurality of optical device structures **202** can be spaced apart from each other in a direction (e.g., the X-direction) parallel to the first surface **101**A of the substrate **101**. The optical device structures **202** include sub-micron critical dimensions, e.g., nanosized dimensions, corresponding to the widths of the optical device structures **202** in the X-direction. In some embodiments, the optical device structures **202** may be binary structures (not shown) with side surfaces **204** perpendicular to the first surface **101**A of the substrate **101**. In other embodiments, the optical device structures **202** may be angled structures with at least one of the side surfaces **204** angled relative to the first surface **101**A of the substrate **101**. The optical device structures **202** can be formed from the optical device film **105** via one or more lithography and/or etch processes, such as an ion beam etching process on the optical device film **105**.

FIG. **3** is a side cross-sectional view of a plasma processing system **300**, according to one embodiment. The plasma processing system **300** includes a process chamber **301**, a radio frequency power source **305**, an optional remote plasma source **307**, and a controller **355** for controlling processes performed by the processing system **300**. The plasma processing system **300** can be used to generate a plasma in the process chamber **301** or supply a plasma to the process chamber **301**. The optical device **200** from FIG. **2** can be exposed to the plasma to remove the carbon or substantially reduce the carbon content of the surface regions **206**, **212** of the optical device **200**.

The process chamber **301** includes a chamber body **302** having a bottom **317***a* and one or more sidewalls **317***b* that are disposed around a processing volume **311** (also referred to as interior volume). The process chamber **301** includes a substrate support **350** disposed in the processing volume **311**. The substrate support **350** is adapted to support the optical device **200** on a top surface **351** of the substrate support **350** during processing.

The process chamber **301** further includes an actuator **338** and a shaft **337**. The substrate support **350** is coupled to the actuator **338** by the shaft **337**. The actuator **338** is configured to move the substrate support **350** at least vertically to (1) facilitate transfer of the optical device **200** into and out of the chamber body **302** and/or (2) adjust a distance D between the optical device **200** and a showerhead assembly **303**.

The process chamber **301** can include a heater **360** in the substrate support **350** configured to provide heat to the optical device **200** during processing. In some embodiments, the heater **360** is a resistive heater embedded in the substrate support **350**. In some embodiments, the process chamber **301** includes a temperature sensor **365**, such as a thermocouple, configured to measure a temperature of the substrate supporting surface **351** of the substrate support **350**. The controller **355** can use measurements from the temperature sensor **365** to adjust the power provided to the heater **360** to control the temperature of the top surface **351** of the substrate support **350**. In some embodiments, the process chamber **301** can include an electrode **361** embedded in the substrate support **350**. In some of these embodiments, the electrode **361** can be connected to an electrical ground to provide a return path for RF energy provided to the showerhead for generating the plasma in the process chamber **301** as described in further detail below.

The process chamber **301** includes a showerhead assembly **303** that is configured to supply gases to the processing volume **311** from a plurality of gas sources **322**. The plasma processing system **300** also includes an exhaust system **318** configured to apply vacuum pressure to the processing volume **311**. The showerhead assembly **303** is generally disposed opposing the substrate support **350**, for example directly above the substrate support **350**, in a substantially parallel relationship.

The showerhead assembly **303** includes a gas distribution plate **314** and a backing plate **316**. The backing plate **316** may function as a blocker plate to enable formation of a gas volume **331** between the gas distribution plate **314** and the backing plate **316**. The gas sources **322** are connected to the gas distribution plate **314** by a conduit **334**. In one embodiment, an optional remote plasma source **307** is coupled to the conduit **334** for supplying a plasma through the gas distribution plate **314** to the processing volume **311**.

The gas distribution plate **314**, the backing plate **316**, and the conduit **334** are generally formed from electrically conductive materials and are in electrical communication with one another. The chamber body **302** is also formed from an electrically conductive material. The chamber body **302** is electrically insulated from the showerhead assembly **303**. In one embodiment, the showerhead assembly **303** can be suspended below a top of the chamber body **302** by attaching the showerhead assembly **303** to an insulator **335** that electrically separates the showerhead assembly **303** from the chamber body **302**.

In one embodiment, the substrate support **350** is also electrically conductive. The electrically conductive substrate support **350** and the showerhead assembly **303** can be configured as opposing electrodes for generating a plasma **308***a* between the substrate support **350** and the showerhead assembly **303** during plasma processes. In one embodiment, the electrode **361** in the substrate support **350** can be connected to electrical ground of the RF power source described below.

The plasma processing system **300** can include the radio frequency (RF) power source **305** that can be used to generate the plasma **308***a* between the showerhead assembly **303** and the substrate support **350** during processing. The RF power source **305** may also be used to maintain energized species or further excite gases supplied from the remote plasma source **307**. The plasma generated by the RF power source **305** or provided from the remote plasma source **307** can help remove carbon from the surface regions **206**, **212** of the optical device **200** (see FIG. **2**), which can improve the optical performance of the optical device **200**.

The RF power source **305** can be coupled to the showerhead assembly **303** to supply RF power for generating the plasma. The RF power source **305** can also be connected to the chamber body **302** and the electrode **361** embedded in the substrate support **350** to allow for a return path for the RF circuit. The RF power source **305** can make these corresponding connections to the showerhead assembly **303**, the chamber body **302**, and the electrode **361** through an impedance matching circuit **321**.

The controller **355** can be any type of controller used in an industrial setting, such as a programmable logic controller (PLC). The controller **355** includes a processor **357**, a memory **356**, and input/output (I/O) circuits **358**. The controller **355** can further include one or more of the following components (not shown), such as one or more power supplies, clocks, communication components (e.g., network interface card), and user interfaces typically found in controllers for semiconductor equipment.

The memory **356** can include non-transitory memory. The non-transitory memory can be used to store the programs and settings described below. The memory **356** can include one or more readily available types of memory, such as read only memory (ROM) (e.g., electrically erasable programmable read-only memory (EEPROM), flash memory, floppy disk, hard disk, or random access memory (RAM) (e.g., non-volatile random access memory (NVRAM).

The processor **357** is configured to execute various programs stored in the memory **356**, such as a programs configured to execute the methods **4000**, **6000** described below in reference to corresponding FIGS. **4** and **6**. During execution of these programs, the controller **355** can communicate to I/O devices through the I/O circuits **358**. For example, during execution of these programs and communication through the I/O circuits **358**, the controller **355** can control outputs (e.g., pumps and valves) and monitor inputs (e.g., sensors). The memory **356** can further include various operational settings used to control the processing system **300** (FIG. **3**) and the processing system **500** (FIG. **5**). For example, the settings can include settings for controlling the operating conditions (e.g., temperature, pressure, and gas

concentrations) inside the process chamber **301** (FIG. **3**) and process chamber **501** (FIG. **5**).

FIG. **4** is a process flow diagram of a method **4000** of performing a plasma process on the optical device **200** shown in FIG. **2**, according to one embodiment. The method **4000** can be performed on the optical device **200** using the processing system **300** described above in reference to FIG. **3**.

The method **4000** begins at block **4002**. At block **4002**, the optical device **200** is positioned on the substrate support **350** in the processing volume **311** of the process chamber **301**.

At block **4004**, heat is provided by the heater **360** to heat the substrate support **350** and the optical device **200** on the substrate support **350**. The heater **360** can be used to heat the substrate supporting surface **351** to a temperature setpoint (e.g., 200° C. to 500° C.) as measured by the temperature sensor **365**. Also, at block **6004** one or more process gases are provided to the process volume **311** from the gas sources **322**. In some embodiments, the process gases can include one or more of hydrogen, steam, nitrogen, and oxygen. In some of these embodiments, an inert gas, such as argon, can also be provided from the gas sources **322**. The controller **355** can be used to adjust power provided to the heater **360** during block **4004** to maintain the top surface **351** of the substrate support **350** at the temperature setpoint. Block **4004** can be performed for a duration extending from about five seconds to about five minutes, such as for about one minute.

At block **4006**, the gases provided to the processing volume **311** during block **4004** continue to be provided to the processing volume **311** and a plasma is generated from the gases provided to the processing volume **311** from the gas sources **322**. In one embodiment, RF power can be provided from the RF power source **305** to the showerhead assembly **303** to generate the plasma **308***a* between the showerhead assembly **303** and the substrate support **350**. In one embodiment, the electrode **361** in the substrate support **350** is connected to electrical ground for the RF power source **305**, so that the capacitively coupled plasma **308***a* can be generated in the processing volume **311** by the RF power provided to the showerhead assembly **303** from the RF power source **305**. In some embodiments, the RF power provided by the RF power source **305** has a frequency of about 13.56 MHz and a power level from about 100 Watts to about 1000 Watts.

The plasma and heat provided to the interior volume **311** of the process chamber **301** during blocks **4004**, **4006** can substantially reduce the carbon content in the surface regions **206**, **212** of the optical device **200** (FIG. **2**) by at least 50%, such as by at least 80% (e.g., 5⁄6 of the carbon being removed), such as by at least 90%, such as by at least 99%. By reducing the carbon content in the surface regions **206** by a substantial amount, the surface regions **206** of the optical device structures **202** obtain optical properties significantly more similar to silicon oxide. These substantially lower levels of carbon in the regions **206**, **212** improve the optical performance of the optical device **200** and cause substantially lower levels of optical loss when compared to the optical device **200** including the silicon oxycarbide regions **206**, **212** with higher levels of carbon.

In some embodiments, the plasma **308***a* can alternatively be generated in the remote plasma source **307** and provided to the processing volume **311** to expose the optical device **200** to the plasma **308***a* instead of being generated in the processing volume **311** by the RF power provided by the RF power source **305**.

At block **4008**, the plasma generation and the heat provided by the heater **360** is stopped, and the processing volume **311** of the process chamber **301** is cooled to a reduced temperature. In some embodiments, the process gas and/or the inert gas can be provided during the execution of block **6008**.

FIG. **5** is a top cross-sectional view of a batch processing system **500**, according to one embodiment. The batch processing system **500** includes a batch processing chamber **501**, a plurality of gas sources **520**, an exhaust pump **525**, and the controller **355** described above in reference to FIG. **3**.

The batch processing chamber **501** includes a chamber body **502** enclosing an interior volume **505**. The batch processing chamber **501** includes a support **550** and a plurality of stands **551** on the support **550**. The optical devices **200** can each be positioned between the stands **551** to enable the optical devices **200** to each be oriented in a vertical direction, for example with the surfaces **101**A, **101**B of the optical device substrate **101** (see FIG. **2**) facing in the plus and minus X-directions.

The batch processing chamber **501** further includes a plurality of heating coils **530** on opposing sides of the support **550**. In some embodiments, the coils **530** can each be positioned behind an infrared-transparent window **535**, such as a quartz window. Power can be provided to the coils **530** during processing to heat the optical devices **200** to temperatures from about 600° C. to about 2000° C. during processing. The batch processing chamber **501** can further include a temperature sensor **560**, such as a thermocouple, positioned on the support **550** near the optical devices **200** to monitor and control the temperature of the interior volume **505** during processing. The controller **355** can be configured to receive measurements from the temperature sensor **560** and modulate power provided to the coils **530** to control the temperature of the interior volume **505** during processing. In some embodiments, the batch processing chamber **501** can include two or more temperature sensors, such as five temperature sensors or ten temperature sensors (e.g., one temperature sensor for each coil **530**, so that the temperature measured by each sensor can be controlled by one coil **530**).

FIG. **6** is a process flow diagram of a method **6000** of performing a batch annealing process on a plurality of the optical devices **200** shown in FIG. **2**, according to one embodiment. The method **6000** can be performed on the optical devices **200** using the batch processing system **500** described above in reference to FIG. **5**.

The method **6000** begins at block **6002**. At block **6002**, a plurality of the optical devices **200** (e.g., ten optical devices **200** as shown in FIG. **5**) are positioned on the support **550** in the interior volume **505** of the batch process chamber **501**. The optical devices **200** can be positioned and vertically oriented within the stands **551**. The optical devices **200** can be spaced apart from each other, for example in the X-direction of FIG. **5**, so that the optical device structures **202** (FIG. **2**) can be exposed to the gases provided to the interior volume **505**.

At block **6004**, heat is provided from the coils **530** to increase the interior volume **505** of the process chamber **501** to a temperature setpoint. In some embodiments, the temperature of the interior volume **505** is heated to a temperature from about 600° C. to about 2000° C., such as from about 900° C. to about 1400° C.

One or more process gases (e.g., hydrogen, steam, oxygen, and nitrogen) can be provided to the interior volume **505** of the process chamber **501** from the gas sources **520** during block **6004**. In some embodiments, an inert gas (e.g.,

argon) can be used as a carrier gas to assist in flowing the one or more process gases over surfaces of the optical devices **200**.

At block **6006**, the controller **355** can use measurements from the temperature sensor **560** to control the power provided to the coils **530**, so that the temperature measured by the temperature sensor **560** can be maintained within a specified threshold (0.5 degrees ° C.) of the temperature setpoint during processing.

The duration of block **6006** can be from about one minute to about three hours, such as from about five minutes to about one hour, such as about ten minutes. The one or more process gases and the optional inert gas from the gas sources **520** can be provided to the interior volume **505** of the process chamber **501** during block **6006**.

In some embodiments, the process gas can be hydrogen (H_2). In some of these embodiments, the flowrate (e.g., sccm) of H_2 can be from about 0.1% to about 10%, such as from about 1% to about 5% (e.g., 2.8%) of the total gas flowrate (e.g., sccm) provided to the interior volume **505** of the process chamber **501** during blocks **6004** and **6006**. In some of these embodiments, the remainder of the gas flowrate is provided by an inert gas, such as argon. In other of these embodiments, the remainder of the gas flowrate is provided by nitrogen.

During blocks **6004** and **6006**, the pressure in the interior volume **505** of the process chamber **501** can be maintained at a pressure from about 250 Torr to about 1000 Torr, such as from about 300 Torr to about 760 Torr, such as about 400 Torr to about 500 Torr.

The heat and process gases provided to the interior volume **505** of the process chamber **501** during blocks **6004**, **6006** can substantially reduce the carbon content in the surface regions **206**, **212** of the optical device **200** (FIG. **2**) by at least 50%, such as by at least 80% (e.g., 5% of the carbon being removed), such as by at least 90%, such as by at least 99%. By reducing the carbon content in the surface regions **206** by a substantial amount, the surface regions **206**, **212** of the optical device **200** obtain optical properties significantly more similar silicon oxide. which improves the optical performance of the optical device **200**. These substantially lower levels of carbon in the regions **206**, **212** improve the optical performance of the optical device **200** and cause substantially lower levels of optical loss when compared to the optical device **200** including the silicon oxycarbide regions **206**, **212** with higher levels of carbon.

At block **6008**, the interior volume **505** of the process chamber **501** is cooled to a reduced temperature. In some embodiments, the process gas and/or the inert gas can be provided during some or all of the cooling down period at block **6008**.

While the foregoing is directed to examples of the present disclosure, other and further examples 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 processing an optical device comprising:

positioning the optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide;

providing one or more process gases to the interior volume of the process chamber;

generating a plasma of the one or more process gases in the interior volume of the process chamber for a first time period when the optical device is on the substrate support; and

stopping the plasma after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 50% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

2. The method of claim **1**, wherein the optical device substrate is formed of silicon carbide.

3. The method of claim **1**, wherein the one or more process gases include one or more of hydrogen, oxygen, and nitrogen.

4. The method of claim **1**, wherein the one or more process gases includes hydrogen.

5. The method of claim **1**, wherein the carbon content of the one or more surface regions of each optical device structure is reduced by at least 80% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

6. The method of claim **1**, further comprising heating the optical device with a heater in the substrate support to a temperature between 200° C. and 500° C. before the plasma is generated.

7. The method of claim **6**, further comprising continuing to heat the optical device with the heater during the plasma generation.

8. The method of claim **1**, further comprising forming the optical device structures by etching a silicon carbide layer formed over the optical device substrate, wherein the optical device substrate is formed of silicon carbide.

9. The method of claim **8**, wherein the etching is performed using ion beam etching.

10. A method of processing an optical device comprising:

positioning the optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide;

providing one or more process gases to the interior volume of the process chamber;

heating the interior volume of the process chamber to a temperature of at least 600° C. for a first time period when the optical device is on the substrate support; and

stopping the heat after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 50% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

11. The method of claim **10**, wherein the optical device substrate is formed of silicon carbide.

12. The method of claim **10**, wherein the one or more process gases include one or more of hydrogen, steam, oxygen, and nitrogen.

13. The method of claim **10**, wherein the one or more process gases includes hydrogen.

14. The method of claim **10**, wherein the carbon content of the one or more surface regions of each optical device structure is reduced by at least 80% compared to the carbon

content of the one or more surface regions of each optical device structure before the first time period.

15. The method of claim **10**, wherein the interior volume of the process chamber is heated to a temperature from about 900° C. to about 1400° C. during the first time period.

16. The method of claim **10**, further comprising forming the optical device structures by etching a silicon carbide layer formed over the optical device substrate, wherein the optical device substrate is formed of silicon carbide.

17. The method of claim **16**, wherein the etching is performed using ion beam etching.

18. A method of processing an optical device comprising:

positioning the optical device on a substrate support in an interior volume of a process chamber, the optical device comprising an optical device substrate and a plurality of optical device structures formed over the optical device substrate and spaced apart from each other, each optical device structure including a bulk region formed of silicon carbide and one or more surface regions formed of silicon oxycarbide, wherein the optical device substrate is formed of silicon carbide and the plurality of optical device structures are gratings configured for use in a waveguide combiner;

providing one or more process gases including hydrogen to the interior volume of the process chamber;

exposing the optical device to a plasma generated from the one or more process gases for a first time period when the optical device is on the substrate support; and

stopping the plasma after the first time period, wherein a carbon content of the one or more surface regions of each optical device structure is reduced by at least 80% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

19. The method of claim **18**, wherein the carbon content of the one or more surface regions of each optical device structure is reduced by at least 90% compared to the carbon content of the one or more surface regions of each optical device structure before the first time period.

20. The method of claim **18**, further comprising heating the optical device to a temperature between 200° C. and 500° C. before the plasma is generated.

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