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**Liu et al.**

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(54) **EXTENSION OF PVD CHAMBER WITH MULTIPLE REACTION GASES, HIGH BIAS POWER, AND HIGH POWER IMPULSE SOURCE FOR DEPOSITION, IMPLANTATION, AND TREATMENT**

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***H01L 21/265*** (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ..... ***C23C 14/3485*** (2013.01); ***C23C 14/35*** (2013.01); ***C23C 14/48*** (2013.01);
(Continued)

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CPC ..... C23C 14/3485; C23C 14/35; C23C 14/48
See application file for complete search history.

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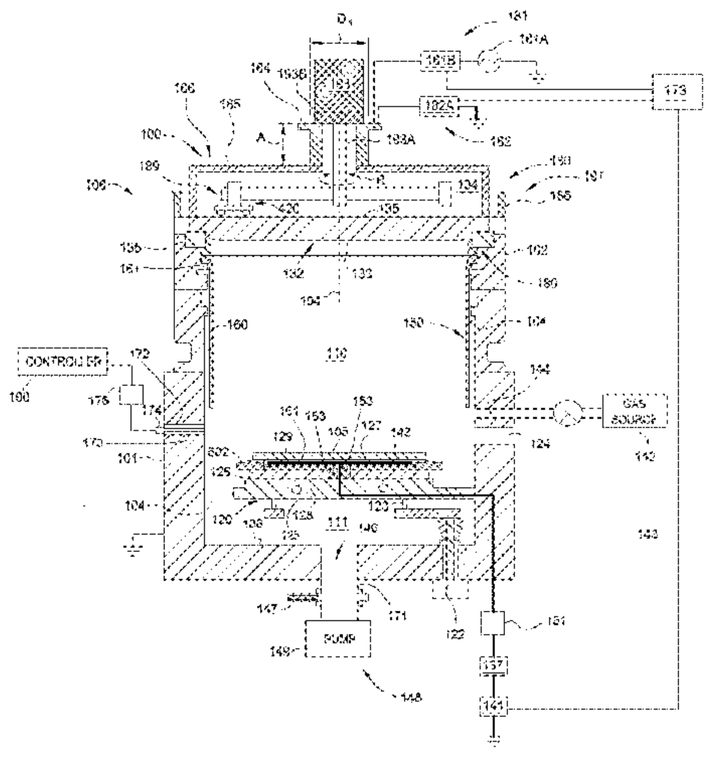
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(57) **ABSTRACT**

Embodiments of the present disclosure provide a sputtering chamber with in-situ ion implantation capability. In one embodiment, the sputtering chamber comprises a target, an RF and a DC power supplies coupled to the target, a support body comprising a flat substrate receiving surface, a bias power source coupled to the support body, a pulse controller coupled to the bias power source, wherein the pulse controller applies a pulse control signal to the bias power source such that the bias power is delivered either in a regular pulsed mode having a pulse duration of about 100-200 microseconds and a pulse repetition frequency of about 1-200 Hz, or a high frequency pulsed mode having a pulse duration of about 100-300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, and an
(Continued)



exhaust assembly having a concentric pumping port formed through a bottom of the processing chamber.

**17 Claims, 6 Drawing Sheets**

(51) **Int. Cl.**

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|---|---|
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| ***C23C 14/50*** | (2006.01) |
| ***C23C 14/35*** | (2006.01) |
| ***C23C 14/48*** | (2006.01) |
| ***H01J 37/32*** | (2006.01) |
| ***H01L 21/223*** | (2006.01) |

(52) **U.S. Cl.**

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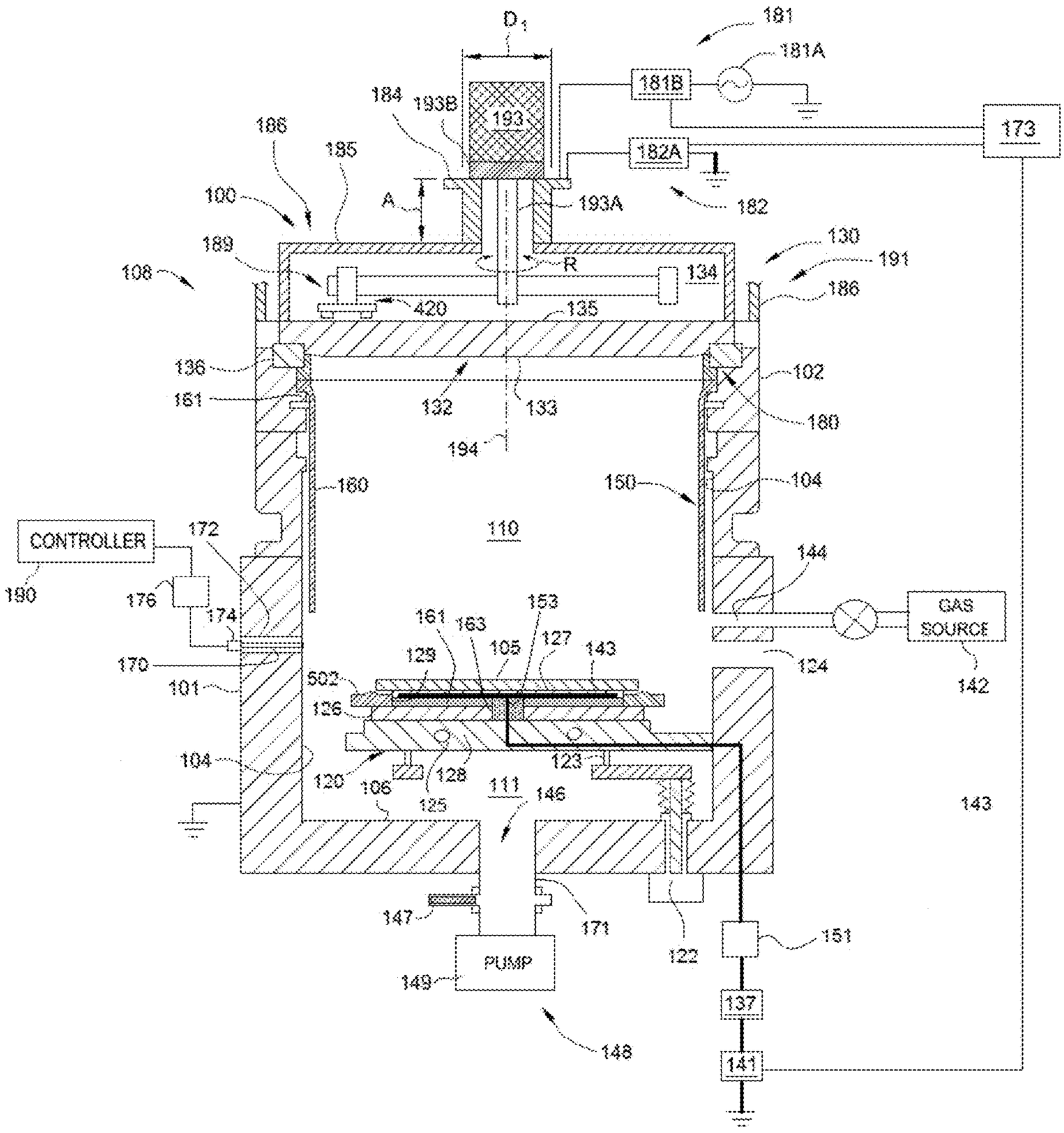

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181A
181B
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182A
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193B
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FIG. 1

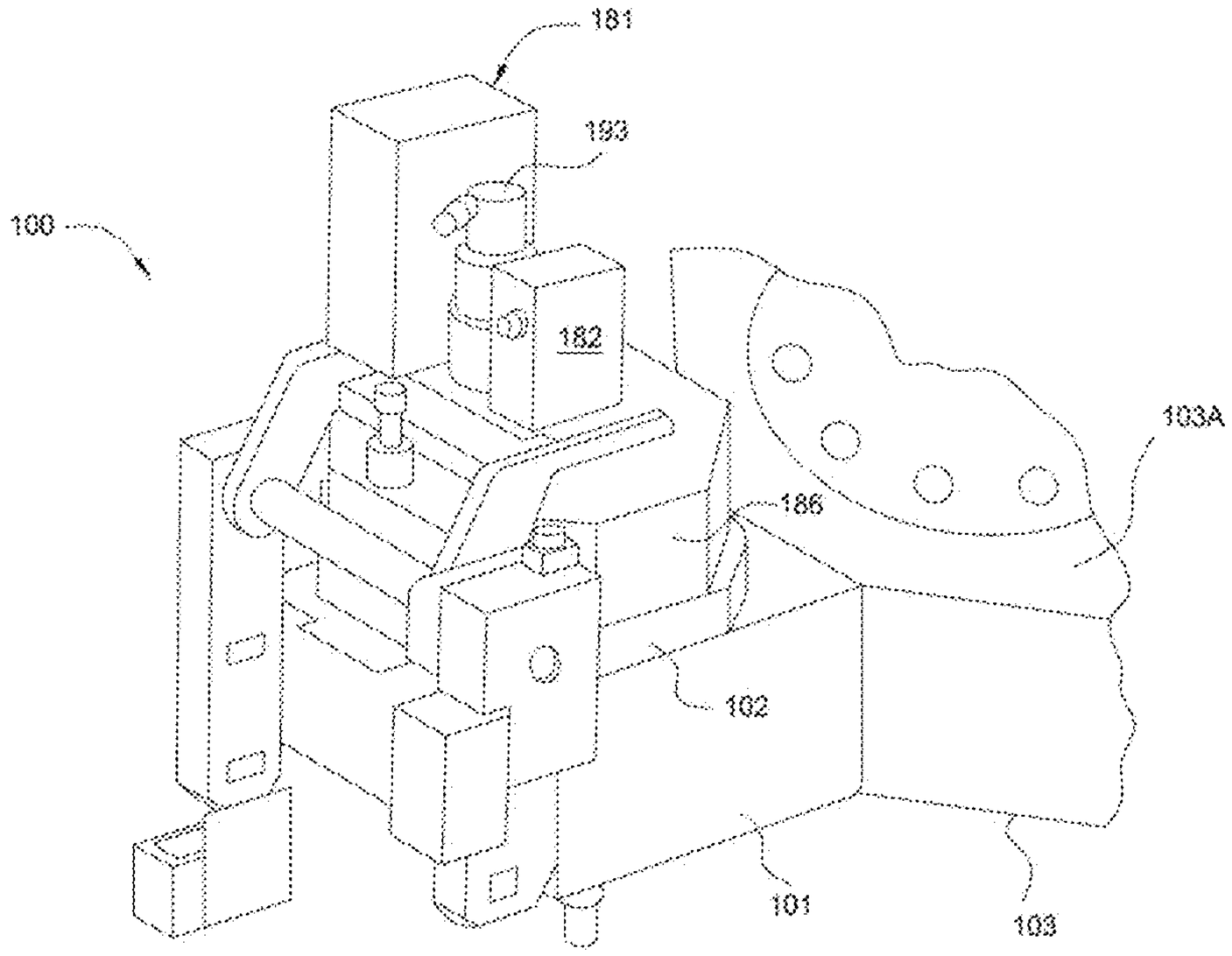

181
193
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182
103A
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FIG. 2

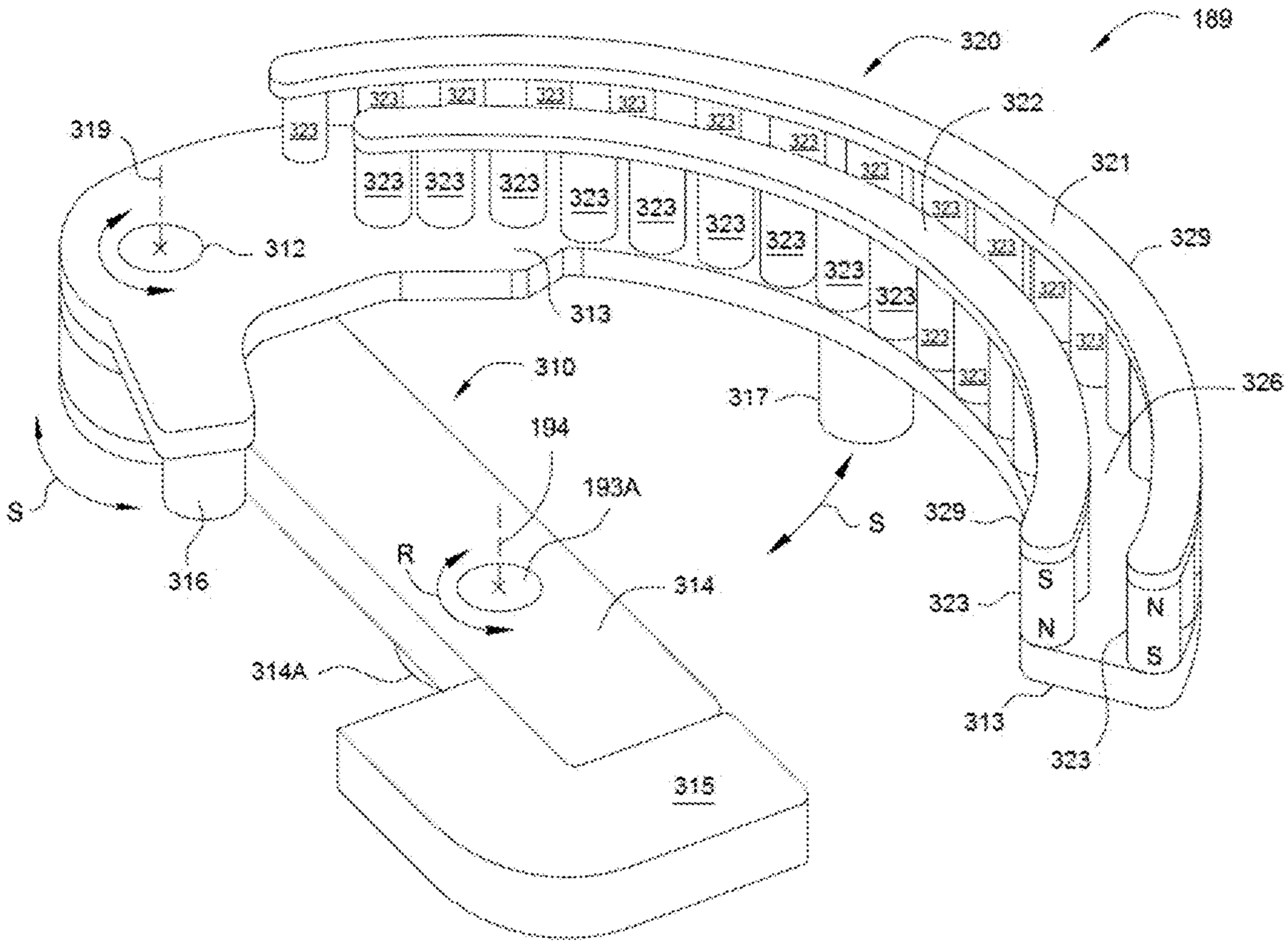

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FIG. 3A

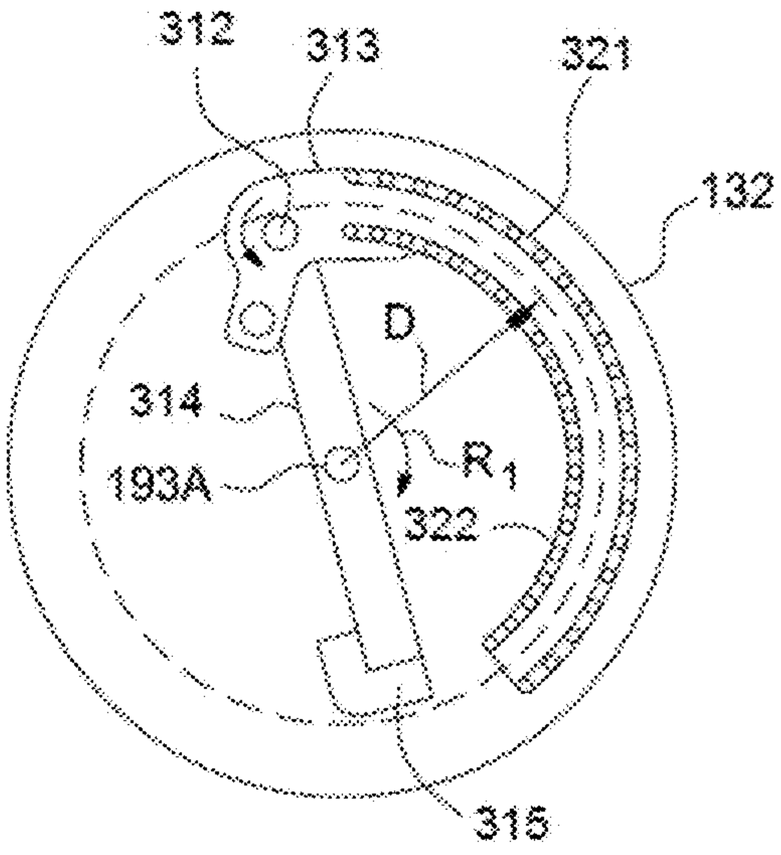



FIG. 3B

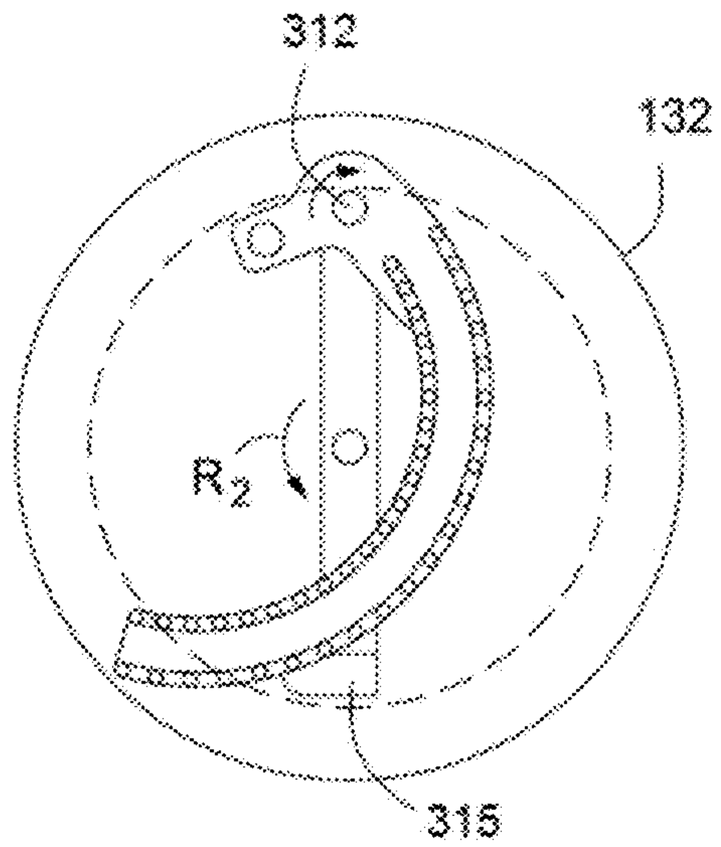



FIG. 3C

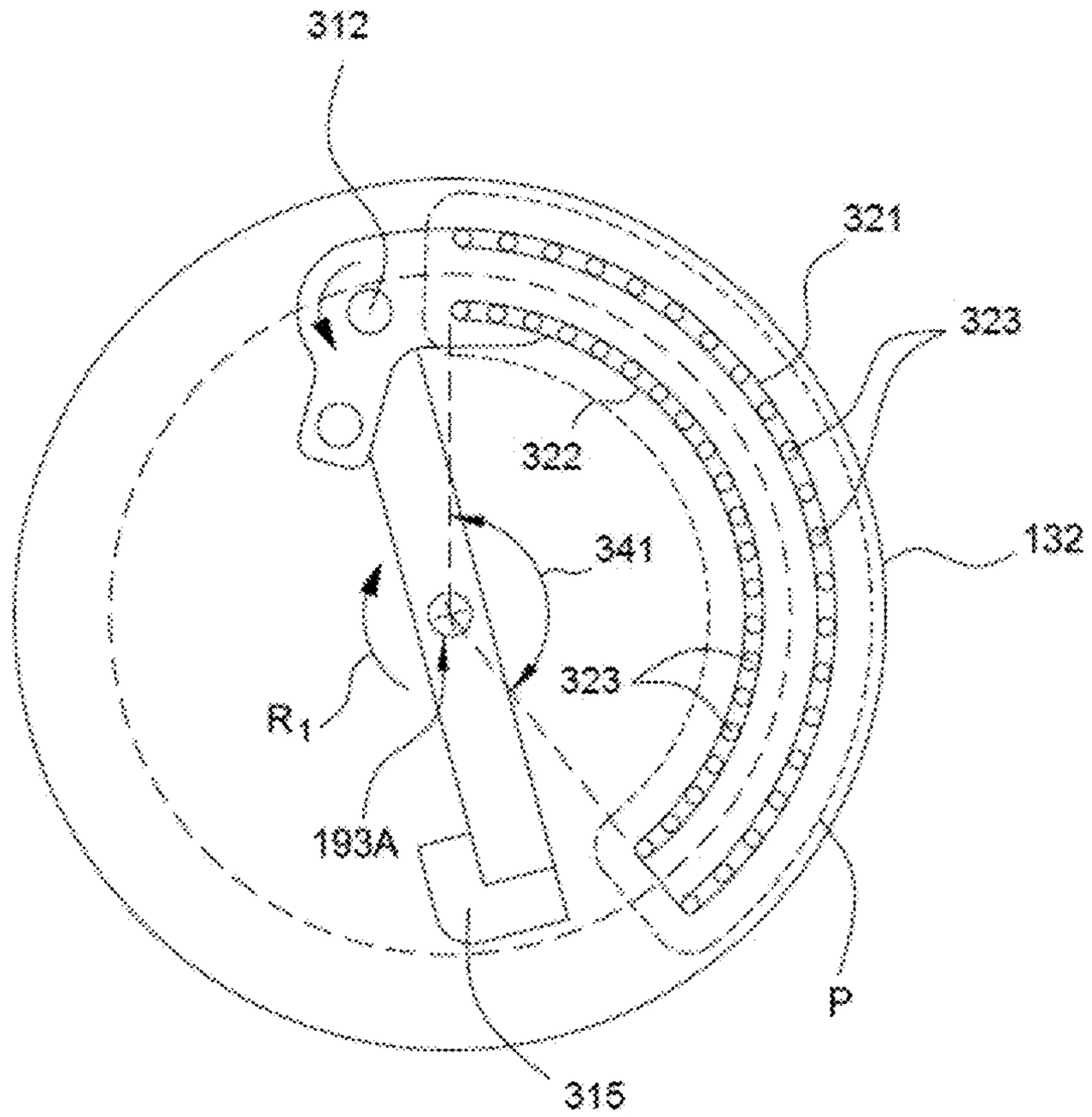



FIG. 3D

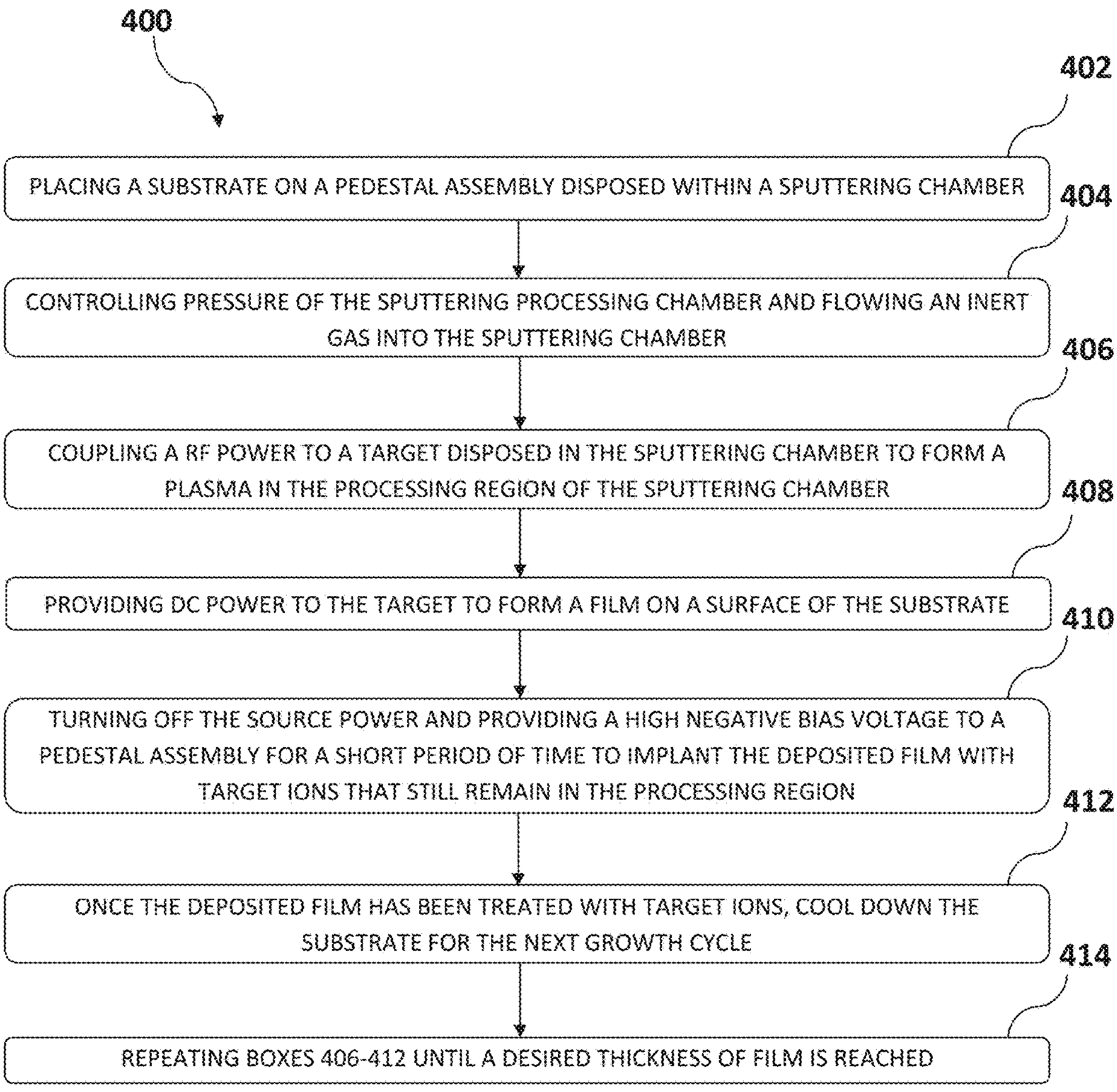

400
402
PLACING A SUBSTRATE ON A PEDESTAL ASSEMBLY DISPOSED WITHIN A SPUTTERING CHAMBER
404
CONTROLLING PRESSURE OF THE SPUTTERING PROCESSING CHAMBER AND FLOWING AN INERT GAS INTO THE SPUTTERING CHAMBER
406
COUPLING A RF POWER TO A TARGET DISPOSED IN THE SPUTTERING CHAMBER TO FORM A PLASMA IN THE PROCESSING REGION OF THE SPUTTERING CHAMBER
408
PROVIDING DC POWER TO THE TARGET TO FORM A FILM ON A SURFACE OF THE SUBSTRATE
410
TURNING OFF THE SOURCE POWER AND PROVIDING A HIGH NEGATIVE BIAS VOLTAGE TO A PEDESTAL ASSEMBLY FOR A SHORT PERIOD OF TIME TO IMPLANT THE DEPOSITED FILM WITH TARGET IONS THAT STILL REMAIN IN THE PROCESSING REGION
412
ONCE THE DEPOSITED FILM HAS BEEN TREATED WITH TARGET IONS, COOL DOWN THE SUBSTRATE FOR THE NEXT GROWTH CYCLE
414
REPEATING BOXES 406-412 UNTIL A DESIRED THICKNESS OF FILM IS REACHED

FIG. 4

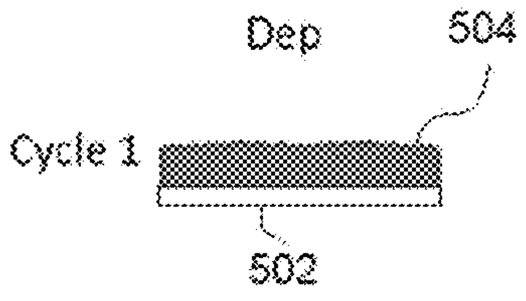



FIG. 5A

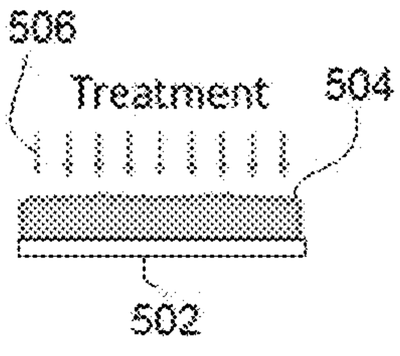



FIG. 5B

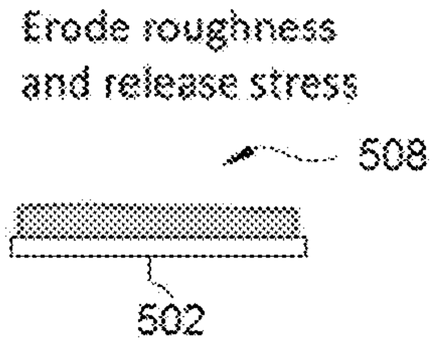



FIG. 5C

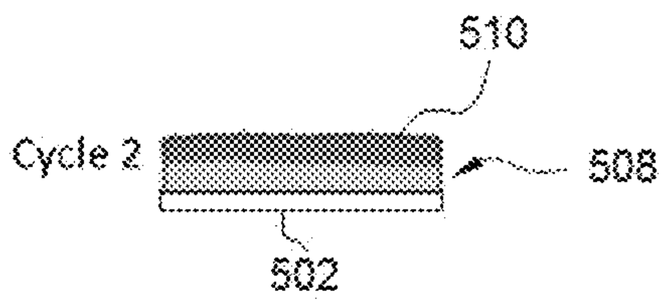



FIG. 5D

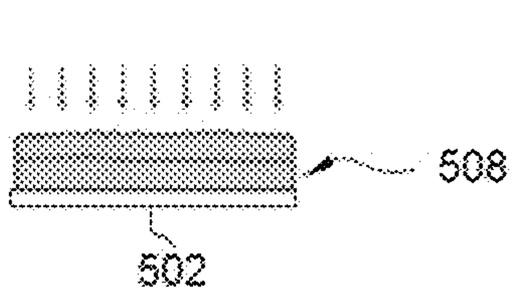



FIG. 5E

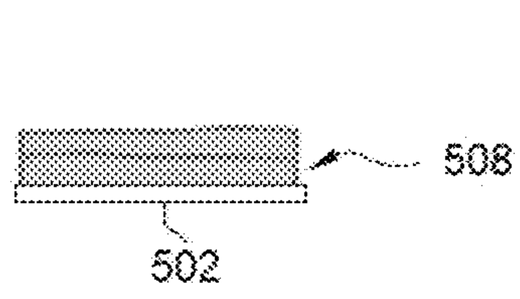



FIG. 5F

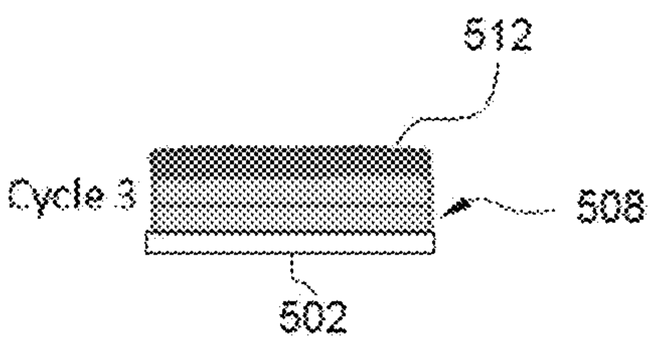



FIG. 5G

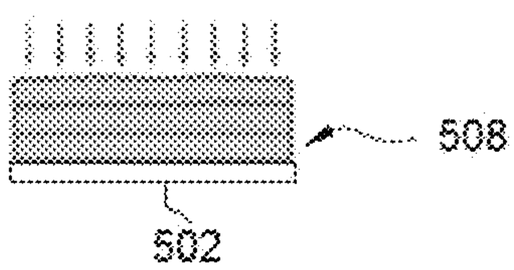



FIG. 5H

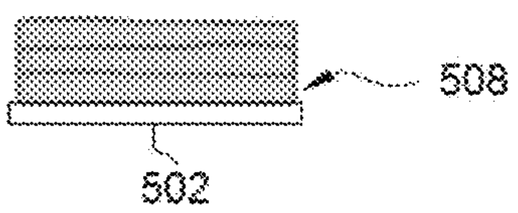



FIG. 5I




FIG. 6A




FIG. 6B

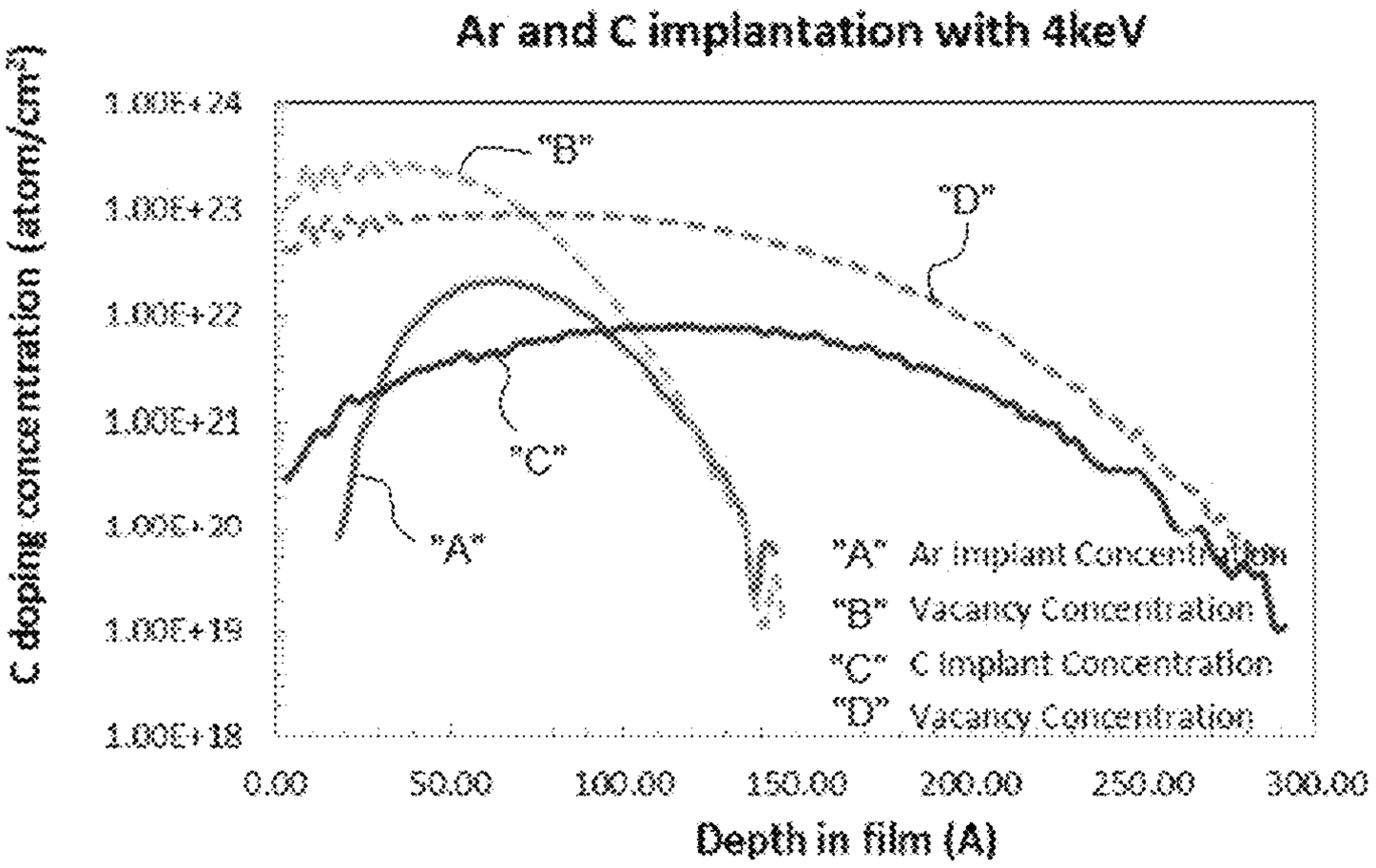



FIG. 6C

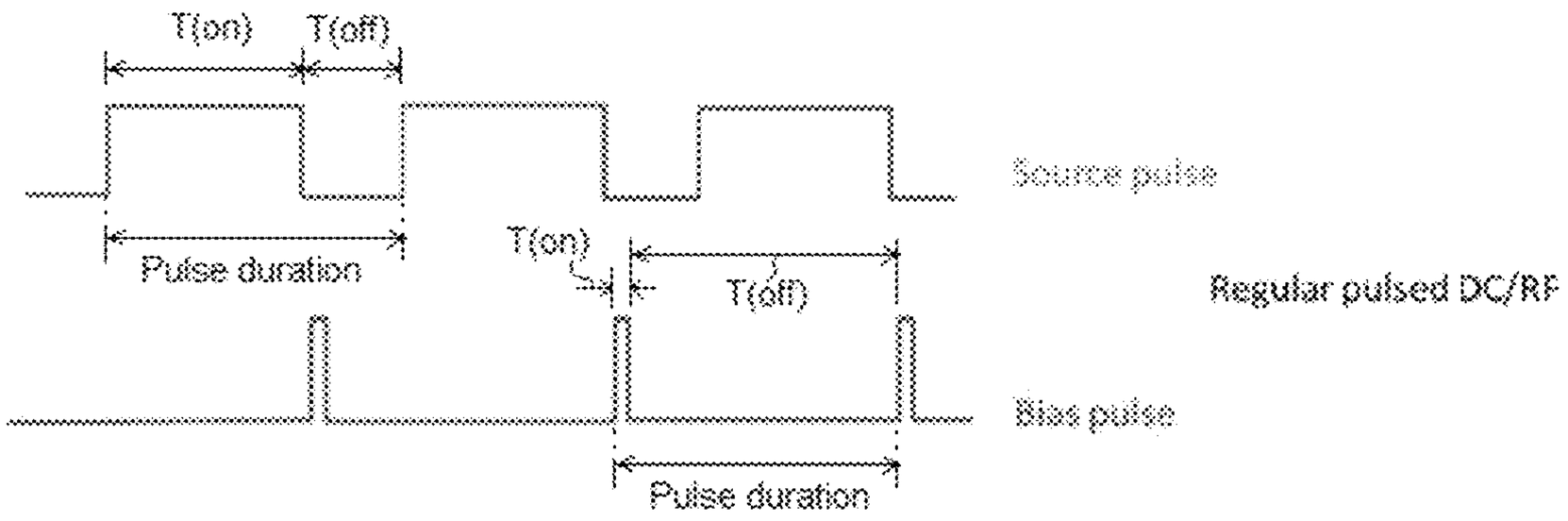



FIG. 7A

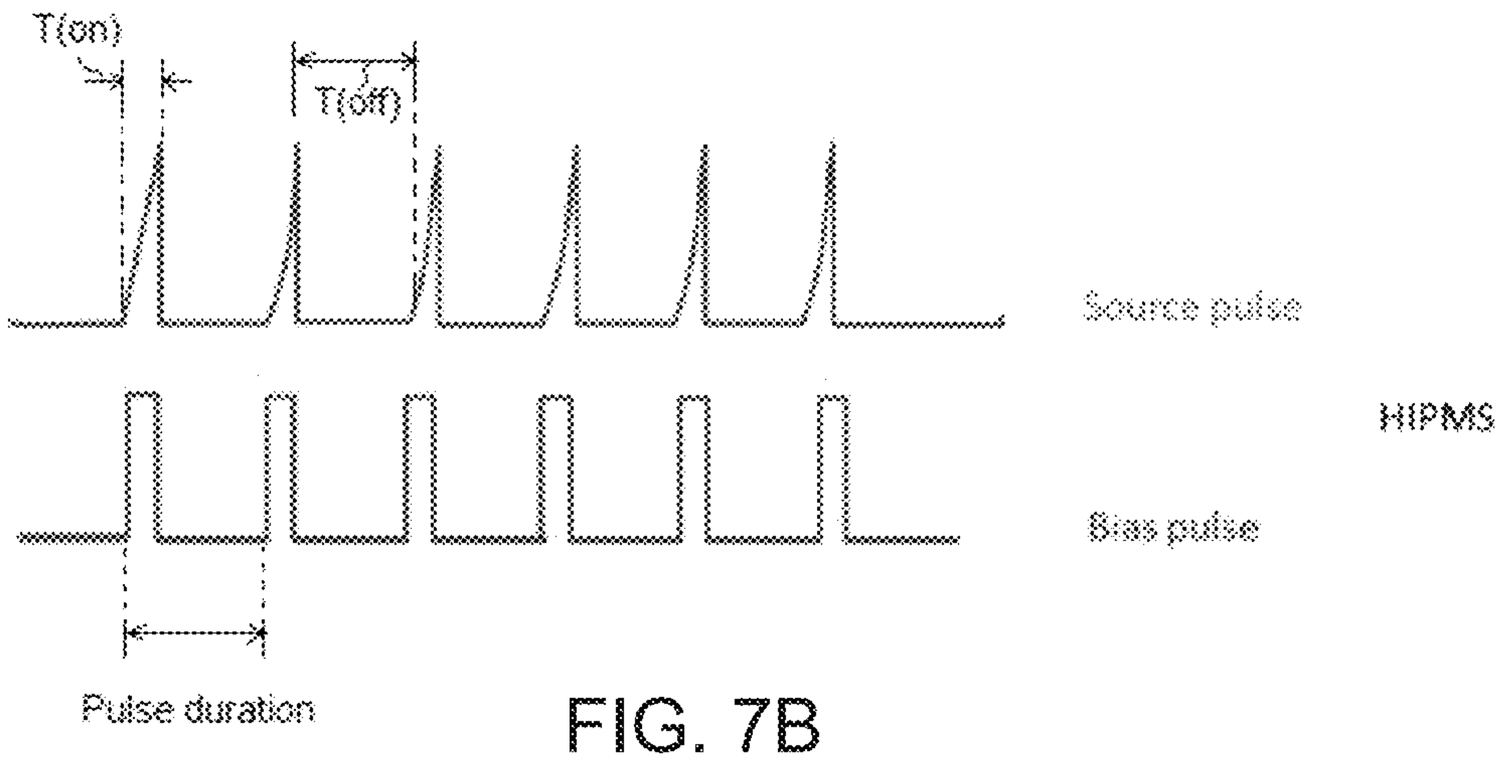



FIG. 7B

# EXTENSION OF PVD CHAMBER WITH MULTIPLE REACTION GASES, HIGH BIAS POWER, AND HIGH POWER IMPULSE SOURCE FOR DEPOSITION, IMPLANTATION, AND TREATMENT

## CROSS-REFERENCE TO RELATED PATENT APPLICATION

This application claims benefit of U.S. Provisional Patent Application Ser. No. 62/450,318, filed Jan. 25, 2017, which is hereby incorporated herein by reference.

## FIELD

Embodiments of the present disclosure generally relate to apparatuses and methods of forming and ion implanting of metal and dielectric layers.

## BACKGROUND

The fabrication of semiconductor devices involves, in part, the introduction of doping elements into the semiconductor substrate to form doped regions. The doping elements are selected to bond with the semiconductor material so as to create electrical carriers, thus altering the electrical conductivity of the semiconductor material. The electrical carriers can either be electrons (generated by N-type dopants) or holes (generated by P-type dopants). The concentration of dopant elements so introduced determines the electrical conductivity of the resultant region. Many such N-type and P-type doping regions are created to form transistor structures, isolation structures and other electronic structures, which function collectively as a semiconductor device. Some other applications may include implantation of metals to gate metal materials for surface function modification.

One method of introducing dopants into a semiconductor substrate is by ion implantation. Ion implantation is a process by which a desired dopant material is ionized in an ion source and the ions are accelerated in an electrical field to form an ion beam. The ion beam is directed at the substrate to implant ions into the substrate in a controllable doping profile by controlling the energy of the ion beam. The implantation dose that can be delivered to a substrate over any given period of time is largely a function of the current density and power of the ion beam. One problem encountered with ion implantation processes is the ion beam may become unwieldy and either thermal damage or erratic implantation profiles ensue when the implantation current rises above a certain threshold (e.g., about 75 milliamps). The limit on the ion beam power is undesirable since certain dopant materials, such as rare earth metals, require higher ion beam power to ionize due to their high melting point.

Therefore, there exists a need for an improved plasma doping system for ion implantation of various types of materials.

## SUMMARY

Embodiments of the present disclosure generally provide an improved sputtering chamber with in-situ ion implantation capability for various materials from metal to dielectric with high film quality. In one embodiment, the sputtering chamber comprises a target having a first surface disposed in a processing region of the processing chamber and a second surface that is opposite the first surface, an RF and a DC power supply coupled to the target, a support body comprising a flat substrate receiving surface across the entire diameter of the substrate support, a bias power source coupled to the support body, a pulse controller coupled to the bias power source, wherein the pulse controller applies a pulse control signal to the bias power source such that the bias power is delivered either in a regular pulsed mode having a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, or a high frequency pulsed mode having a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, and an exhaust assembly having a concentric pumping port formed through a bottom of the processing chamber.

In another embodiment, the sputtering chamber comprises a sputtering target, a rotating magnetron disposed adjacent to a surface of the sputtering target, an RF power supply coupled to the sputtering target, a DC power supply coupled to the sputtering target, a support body comprising a substrate receiving surface, wherein at least a portion immediately below the substrate receiving surface has a uniform thickness across the diameter of the substrate receiving surface, a bias power source coupled to the support body, a pulse controller coupled to the bias power source, the pulse controller applying a pulse control signal to the bias power source such that the bias power is delivered either in a regular pulsed mode having a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, or a high frequency pulsed mode having a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, a gas conduit disposed at a sidewall of the processing chamber, a shield coupled to the sidewall of the processing chamber, wherein the shield extends downwardly to at least partially confine a portion of a processing region, and an exhaust assembly having a pumping port formed through a bottom of the processing chamber, wherein the pumping port is disposed symmetrically about a central axis passing through the center of the processing chamber.

In yet another embodiment, a method for processing a substrate is provided. The method comprises providing a substrate on a substrate support disposed in a processing region of a processing chamber, wherein the processing chamber has an RF power supply and a DC power supply coupled to a target disposed in the processing chamber, pumping the processing region to mTorr range, providing an RF power to the target to form a plasma in the processing region, providing a DC power to the target to form a film layer on a surface of the substrate, and after a predetermined thickness of the film layer is formed, turning off the RF power supply and the DC power supply, and providing a bias power of about 1 kW to about 30 kW to the substrate support for a short period of time to implant ions remaining in the processing region into the surface of the substrate.



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

FIG. **1** illustrates an exemplary processing chamber according to embodiments of the present disclosure.

FIG. **2** is an isometric view of the processing chamber that is coupled to a processing position of a cluster tool.

FIG. **3**A is an isometric view of a magnetron viewed from the target side according to one embodiment of the disclosure.

FIG. **3**B is a bottom view of a portion of the magnetron according to one embodiment of the disclosure.

FIG. **3**C is a bottom view of a portion of the magnetron according to one embodiment of the disclosure.

FIG. **3**D is a bottom view of a portion of the magnetron according to one embodiment of the disclosure.

FIG. **4** is an exemplary process flow diagram for forming a carbon-based film according to embodiments of the present disclosure.

FIGS. **5**A-**5**I are schematic cross-section views of a carbon-based film formed using the process flow diagram of FIG. **4**.

FIG. **6**A is a graph of DC voltage and dosage as a function of the bias power according to embodiments of the present disclosure.

FIG. **6**B is a graph of sputter rate as a function of bias power according to embodiments of the present disclosure.

FIG. **6**C is a graph of simulation data of ion species implantation profile according to embodiments of the present disclosure.

FIGS. **7**A and **7**B are schematics of duty cycle and pulse variation for regular pulsed mode and high frequency pulsed mode, respectively, according to embodiments of the present disclosure.

## DETAILED DESCRIPTION

FIG. **1** illustrates an exemplary processing chamber **100** according to embodiments of the present disclosure. The processing chamber **100** generally includes an upper process assembly **108**, a process kit **150** and a pedestal assembly **120**, which are all configured to process a substrate **105** disposed in a processing region **110**. In the embodiment shown, the processing chamber **100** is a sputtering chamber, such as a physical vapor deposition (PVD) chamber, capable of depositing a single or multi-compositional material from a target **132** onto a substrate **105**. While a PVD chamber is discussed and shown, it is contemplated that embodiments of the present disclosure are equally applicable to other process chambers, such as a plasma etch chamber, a plasma enhanced chemical vapor deposition chamber, a plasma treatment chamber, an ion implantation chamber, or other suitable vacuum processing chamber. It is contemplated that other processing chambers including those from other manufacturers may be adapted to benefit from one or more of the embodiments of the disclosure described herein.

The processing chamber **100** includes a chamber body **101** having sidewalls **104**, a bottom wall **106**, and an upper process assembly **108** that enclose a processing region **110** or plasma zone. The chamber body **101** is typically fabricated from welded plates of stainless steel or a unitary block of aluminum, either anodized or non-anodized. In one embodiment, the sidewalls comprise aluminum and the bottom wall comprises a stainless steel plate. The sidewalls **104** contains a slit valve **124** to provide for entry and egress of a substrate **105** to and from the processing chamber **100**.

The process kit **150** may comprise various components that can be easily removed from the chamber **100**, for example, to clean sputtering deposits off the component surfaces, replace or repair eroded components, or to adapt



the chamber **100** for other processes. In one embodiment, the process kit **150** comprises a shield **160** and an isolator ring assembly **180**. The shield **160** is fastened to and supported by a ledge **161** of an adaptor **102**. The adaptor **102** is coupled to the sidewalls **104**, and is configured to help with the removal of the upper process assembly **108** and isolator ring assembly **180**. The shield **160** extends downwardly and may have a generally tubular shape with a constant diameter. In one embodiment, the shield **160** is extended along the sidewalls **104** downwardly to a point adjacent to the gas conduits **144**. In one embodiment, the shield **160** is electrically coupled to a ground. The shield **160** at least partially encloses a portion of the processing region **110** above the substrate receiving surface. Components in the upper process assembly **108** of the processing chamber **100** in cooperation with the shield **160** and the pedestal assembly **120** reduce particle generation and stray plasma outside the processing region **110**. Particularly, the tubular shape of the shield **160** confines the plasma formed in the processing region **110** to the interior processing region above the substrate **105**, thereby increasing the plasma interaction with the surface of the substrate **105** while reducing undesirable deposition of sputtered material onto the chamber components, such as the sidewalls **104**.

FIG. **2** is an isometric view of the processing chamber **100** that is coupled to a processing position of a cluster tool **103**. The cluster tool **103** may also contain other processing chambers (not shown) that are adapted to perform one or more processing steps on a substrate prior to or after performing the deposition process in the processing chamber **100**. An exemplary cluster tool **103** may include a Centura™ or an Endura™ system available from Applied Materials, Santa Clara, Calif. The cluster tool **103** may include one or more load-lock chambers (not shown), one or more process chambers, and a cool-down chamber (not shown), all of which are attached to a central transfer chamber **103**A. In one example, the cluster tool **103** may have processing chambers that are configured to perform a number of substrate processing operations such as cyclical layer deposition, chemical vapor deposition (CVD), physical vapor deposition (PVD), atomic layer deposition (ALD), etch, pre-clean, degas, anneal, orientation and other substrate processes. A transfer tool, for example, a robot (not shown) disposed in the transfer chamber **103**A, may be used to transfer substrates to and from one or more chambers attached to the cluster tool **103**.

### Pedestal Assembly

The pedestal assembly **120** generally includes a support **126** coupled to a platform **128**. The platform **128** is typically fabricated from a metallic material such as stainless steel or aluminum. The support **126** may be comprised of aluminum or ceramic. A cooling channel **125** is disposed within the platform **128** to regulate the temperature of the support **126** by circulating a heat transfer medium from a medium source (not shown). Alternatively, a cooling plate may be used. In such a case, the cooling plate may be disposed against a bottom surface of the support **126**. The cooling plate may be fabricated from a material having good thermal conductivity to promote uniform heat transfer between the cooling plate and the support **126**. For example, the cooling plate may be fabricated from copper, stainless steel, tungsten, or molybdenum etc. The cooling plate should have a low linear thermal expansion coefficient or have a thermal expansion

coefficient matching the platform **128** and/or the support **126**. In one example, the cooling plate is fabricated of tungsten or molybdenum.

The pedestal assembly **120** may be supported from the bottom **106** or cantilever mounted on the sidewalls **104** of the chamber **100**. In the embodiment shown, the pedestal assembly **120** is supported by the sidewalls **104** of the chamber **100** through the platform **128**. A portion of the chamber wall, such as the sidewall **104**, is grounded. Additionally or alternatively, the platform **128** may be grounded through the chamber wall. While the pedestal assembly **120** is shown as a fixed-type configuration to reduce circuit wiring complexities, it is contemplated that the pedestal assembly **120** may be configured to move vertically between different processing positions by lift pins **123** of a lift mechanism **122**.

The support **126** has a substrate receiving surface **127** that receives and supports the substrate **105** during processing, the substrate receiving surface **127** being substantially parallel to a sputtering surface **133** of the target **132**. The support **126** also has a peripheral edge **129** that may terminate before an overhanging edge of the substrate **105**. The support **126** may be an electrostatic chuck, a ceramic body, a heater, a chiller, or any combination thereof. In one embodiment, the support **126** is a ceramic body having one or more electrodes (such as the bias electrode **143**) disposed therein. In another embodiment, the support **126** is an electrostatic chuck that includes a dielectric body having one or more electrodes (such as the bias electrode **143**) disposed therein. The dielectric body is typically fabricated from a high thermal conductivity dielectric material such as pyrolytic boron nitride, aluminum nitride, silicon nitride, alumina or an equivalent material.

The pedestal assembly **120** supports a deposition ring **502** along with the substrate **105**. The deposition ring **502** is generally formed in an annular shape, or annular band, surrounding the support **126**. The deposition ring **502** is configured to reduce formation of sputter deposits on the peripheral edges **129** of the support **126** during processing. In the embodiment shown, the deposition ring **502** may also include a bump or projection extending upwardly from the top surface of the deposition ring **502** to impede or prevent ingress of plasma species from contacting the backside of the substrate **105** around the peripheral edge. The deposition ring **502** may be fabricated from a material that can resist erosion by the sputtering plasma, for example, a metallic material such as stainless steel, titanium or aluminum, or a ceramic material, such as aluminum oxide. In one embodiment, the deposition ring **502** is formed from a stainless steel material.

A lift mechanism **122** is configured to move lift pins **123** to position a substrate a distance from the pedestal assembly **120** to facilitate the exchange of the substrate with a substrate transfer mechanism (not shown, disposed exterior to the processing chamber **100**) passing through the slit valve **124**.

In one embodiment, a bias power source **141** is provided and connected to a bias electrode **143** embedded in the support **126** through a matching network **137**. The bias electrode **143** may be a single electrode plate extending across the diameter of the support **126** as shown. Alternatively, the bias electrode **143** may be comprised of discrete bias electrodes **143** in any desired arrangement, such as a concentric circular pattern, a spiral-like pattern, or a radial spoke pattern, etc. The bias power source **141** applies a high negative bias voltage to the support **126**, and thus to the substrate **105** placed on the substrate receiving surface **127**. In various examples, the bias power source **141** may be configured to provide a bias power of about 0.1 kW to about 50 kW, such as between about 0.5 kW and about 30 kW, for example about 1 kW to about 25 kW. In one embodiment, the bias power source **141** is configured to provide a bias power of about 10 kW to about 16 kW, for example about 14 kW.

The bias electrode **143** may be directly or indirectly supported within the support **126** by at least an electrical bias insulator **161** and/or an inner seal ring **163** disposed in the support **126**. The electrical bias insulator **161** and the inner seal ring **163** may include dielectric materials such as quartz, and other insulators. The inner seal ring **163** may extend through the electrical bias insulator **161** to allow wiring of the bias power source **141** to the bias electrode **143** as shown. The electrical bias insulator **161** and the inner seal ring **163** may be sized to provide a low capacitance between the support **126** and the bias electrode **143**. In some embodiments, the electrical bias insulator **161** is sized to electrically isolate an upper portion of the support **126** (e.g., a portion directly beneath or adjacent to the substrate receiving surface **127**) from the pedestal assembly **120**, thereby preventing arcing within the processing chamber **100** when a high bias voltage (e.g., 1 kW or greater) is supplied to the bias electrode **143**. In the embodiment shown, the electrical bias insulator **161** is extended radially across the entire diameter of the support **126**. The bias power source **141** may use a bipolar DC supply or an RF supply.

Unlike conventional pedestal designs, which provide gas conduits or grooves in the upper surface of the pedestal assembly **120** to facilitate heat transfer of a cooling gas (e.g., helium) between the substrate and the pedestal assembly in a low pressure or vacuum environment, the pedestal assembly **120** of the present disclosure uses a flat substrate receiving surface **127** without gas conduits or grooves. A common problem with conventional pedestal design is that it would easily cause arcing at the upper surface of the pedestal when the pedestal is subjected to high bias voltage (e.g., 400 W or above) and high density plasma immediately above the substrate. One reason for this arcing to occur is that the gas conduits or grooves in the smooth, upper surface of the pedestal form air gaps and introduces discontinuity in the pedestal surface that distorts the electric field in the vicinity of the discontinuity, making arcing more probable. The gas conduits or grooves also decrease the efficiency of heat transfer between the substrate and the pedestal by reducing the solid to solid contact area across the diameter of the substrate receiving surface.

To reduce arcing and improve heat transfer efficiency between the cooling channel **125** and the substrate **105**, the support **126** of the pedestal assembly **120** of the present disclosure uses a ceramic body having a flat substrate receiving surface **127** across the entire diameter of the support **126**. The "flat" substrate receiving surface as described herein can be defined as a completely level surface without any cavities, holes or grooves formed therein. In the embodiment shown, at least the portion of the support **126** immediately below the substrate receiving surface **127**, or the portion of the support **126** to be in physical contact with the substrate **105**, has a uniform thickness across the diameter of the substrate receiving surface **127**. Having the support **126** fabricated from bulk ceramic prevents the support **126** from being easily destroyed by high bias voltage used during the process. Since the flat substrate receiving surface **127** eliminates the air gaps between the pedestal assembly and the substrate, as would otherwise be seen in the conventional pedestal design using gas conduits

or grooves for backside cooling, arcing is greatly minimized or eliminated even when a high bias voltage is supplied to the bias electrode **143**. The heat transfer efficiency is also improved since the substrate **105** is in full solid to solid contact with the substrate receiving surface **127**. The pedestal assembly **120** therefore has the ability of handling much higher bias power (i.e., above 1 kW), which enables a sputtering chamber to perform in-situ ion implantation process that has never been possible in the past with a conventional PVD chamber.

A pulse controller **173** may connect to and apply pulse control signals to the bias power source **141**. Alternatively, high negative bias voltage can be provided in a constant manner. The pulse controller **173** is programmable to produce the desired pulse mode and/or duty cycle for the bias power source **141**. For example, the bias power source **141** may be operated in a regular pulsed mode or a high frequency pulsed mode. In the regular pulsed mode, the high negative bias voltage may have a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, for example about 50 Hz to about 100 Hz. The high negative bias voltage may be provided at a duty cycle of 1% to 10%. In the high frequency pulsed mode, the high negative bias voltage may have a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, for example about 300 Hz to about 600 Hz. The high negative bias voltage may be provided at a duty cycle of 1% to 20%. The pulse duration or repetition frequency may be tuned to achieve designated film thickness and growth rate.

As will be discussed in more detail below, the bias power source **141** may be turned on at the end of each cycle of sputtering deposition for a short period of time for ion implantation of the deposited film, which releases film stress and smoothes film roughness. The bias power source **141** provides high negative bias voltage to the bias electrode **143** to attract the positive sputtered ions left from the sputtering deposition process. Particularly, high negative bias voltage increases the directionality of the sputtered ions toward the substrate **105** by producing an electrical potential gradient in the plasma sheath in front of the support **126**, which in turn provides the force to accelerate the positively ionized sputtered dopant materials toward and onto the substrate surface. Since the bias voltage is high, the kinetic energy of the ions collided to the substrate will be greater. As a result, a greater doping profile is achieved.

In some embodiments, a probe **151** may be positioned on a feedpoint **153** between the matching network **137** and the embedded bias electrode **143** to simultaneously or nearly simultaneously measure and/or monitor implantation DC voltage, DC current (or RF voltage/current if an RF supply is used), and an instantaneous dosage. The measured current is used to estimate ion dose rate and/or dose profile, which may be used to control dosage or determine an endpoint. The probe **151** may be a voltage/current probe. Alternatively, the probe **151** may be replaced by individual instruments, such as a voltage sensor and a current sensor.

In order to monitor plasma species for accurate dosing control, a mass distribution sensor, such as an optical emission spectrometer (OES) **170**, may be provided in the processing chamber **100** to quantitatively measure optical emissions from excited species in the plasma generated inside the processing chamber **100**. In one embodiment shown, the optical emission spectrometer **170** is disposed adjacent a quartz window **172** formed on the chamber body **101**. The optical emission spectrometer **170** may comprise a lens **174** disposed next to the quartz window **172**. The lens **174**, connected to the spectrometer **176**, may be configured to collimate radiation of the plasma or excited species pass through the quartz window **172**. The spectrometer **176** then spectrally separates the radiation based on wavelength and generates detection signals for one or more spatially separated wavelengths. Excited species, such as ionized sputtered dopant materials, may decay back from the excited energy level to the lower energy level by emitting light. Since the transition is between distinct atomic energy levels, wavelength of the emitted light can be used to identify the excited species. In addition, intensity of the emitted lights can also reflect concentration or distribution of different species in a plasma. Therefore, the use of an optical emission spectrometer **170** can monitor plasma species for accurate dosing control by detecting a portion of these emissions. A data acquisition device in a controller **190** may be used to collect data representing separated wavelength, hence properties of the ion species in the plasma, at a periodic sampling rate. The collected data may be processed and analyzed for generating control singles to the bias power source **141** or any other controllable components of the processing chamber **100** to adjust the process parameters, such as the bias voltage on the substrate, to control the degree of bombardment on the substrate surface during processing.

## Centered Exhaust Assembly

Vacuum is maintained in the processing region **110** by an exhaust assembly **148**, which removes spent processing gases, contaminants and byproducts from the processing chamber **100** through the evacuation region **111**. The exhaust assembly **148** includes a vacuum pump **149** disposed adjacent to the bottom of the processing chamber **100**. The vacuum pump **149** is in fluid communication with the evacuation region **111** via an exhaust conduit **171**. The exhaust conduit **171** connects to a pumping port **146** formed through the bottom of the processing chamber **100**. A throttle valve **147** is provided in the exhaust conduit **171** to permit isolation of the vacuum pump **149** when not in use. The vacuum pump **149** may be any suitable pump such as a turbomolecular pump. The throttle valve **147** is used in conjunction with the vacuum pump **149** to allow accurate pressure control in mTorr range within the processing region **110** by symmetrically drawing exhaust gases from the processing region **110** to the evacuation region **111**, and out of the processing chamber **100** through a pumping port **146**.

In various embodiments, the pumping port **146** is disposed directly beneath the pedestal assembly **120**. In one embodiment, the pumping port **146** may be substantially concentric with the processing chamber **100**. For example, the pumping port **146** may be disposed symmetrically about a central axis **194** passing vertically through the center of the processing chamber **100**. The symmetrical positioning of the pumping port **146** about the central axis **194** provides improved gas flow symmetry within the processing chamber **100** to allow more uniform gas flow over the substrate surface about the entire circumference thereof and radially downwardly and outwardly from the processing chamber **100**. Thus, the centrally located pumping port promotes uniform plasma formation and allows greater control of the plasma species and gas flow in the processing region **110**, as compared to the conventional plasma systems having the difficulty in providing uniform plasma density due to asymmetry of the pumping port in the chamber.

## Lid Assembly

The upper process assembly **108** may comprise an RF source **181**, a direct current (DC) source **182**, an adaptor

102, a motor 193, and a lid assembly 130. The lid assembly 130 generally comprises a target 132, a magnetron system 189 and a lid enclosure 191. The upper process assembly 108 is supported by the sidewalls 104 when in a closed position, as shown in FIG. 1. A ceramic target isolator 136 is disposed between the isolator ring assembly 180, the target 132 and adaptor 102 of the lid assembly 130 to prevent vacuum leakage therebetween. As discussed above, the adaptor 102 is coupled to the sidewalls 104 and configured to help with the removal of the upper process assembly 108 and isolator ring assembly 180.

When in the processing position, the target 132 is disposed adjacent to the adaptor 102, and is exposed to the processing region 110 of the processing chamber 100. The target 132 contains material that is to be implanted or deposited on the substrate 105 during a sputtering or an ion implantation process. The isolator ring assembly 180 is disposed between the target 132 and the shield 160 and chamber body 101 to electrically isolate the target 132 from the shield 160 and chamber body 101.

During sputtering processing, the target 132 is biased relative to a grounded region of the processing chamber (e.g., chamber body 101 and adaptor 102) by a source power disposed in the RF source 181 and the direct current (DC) source 182 under high pressure. The combination of RF and DC power sources allows for a lower overall RF power to be used during processing versus a RF only source, which can help to decrease plasma related damage of the substrate and increase device yield. In addition, delivering RF power to a DC powered target may decrease the target voltage and provide a corresponding sheath surrounding and dominating the DC power induced sheath. While an RF-DC powered target has a thicker plasma sheath formed below the target, and an overall higher voltage drop between the target and the plasma, the conductivity of the plasma will be increased due to the increased ion concentration in the plasma, which will make the target voltage drop at low to moderate RF powers. Thus, an argon ion (Ar+) is accelerated even more with a thicker sheath, providing a higher sputtering ion energy. The thicker plasma sheath will also increase the scattering yield. The addition of RF power also increases the ionization of the plasma which helps improve the affects of substrate bias on the depositing ions, and thus help improve step coverage of the film.

In one embodiment, the RF source 181 comprises an RF power source 181A and an RF match 181B that are configured to efficiently deliver RF power to the target 132. In most examples, the RF power source 181A is capable of generating RF currents at a frequency of between about 1 MHz and about 128 MHz, such as about 2 MHz to about 13.56 MHz, at powers between about 0 and about 20 kWatts, such as about 2 kW to about 10 kW. In one example, the RF power source 181A is configured to provide RF current at a frequency of 13.56 MHz at a power of 5 kW. The DC power supply 182A in the DC source 182 is capable of delivering between about 0 and about 10 kWatts of DC power, for example about 4 kW. Regardless of whether a regular pulsed mode or a high frequency pulsed mode is adapted during process, the RF power source 181A may be configured to generate an RF power density of between about 0 and about 33 kWatts/$m^2$ at the target and the DC source 182 may be configured to deliver a power density of between about 0 and about 66 kWatts/$m^2$.

The pulse controller 173 may connect to and apply pulse control signals to each of the RF power source 181A and the DC source 182. Alternatively, the source power can be provided in a constant manner. The pulse controller 173 is programmable to produce the desired pulse mode and/or duty cycle relationship for the RF power source 181A and the DC source 182. Similarly, the RF power and the DC power may be operated in a regular pulsed mode or a high frequency pulsed mode. In the regular pulsed mode, the RF power and the DC power may have a pulse duration of about 300 microseconds to about 800 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, for example about 50 Hz to about 100 Hz. The RF power and the DC power may be provided at a duty cycle of 50% to 90%. In the high frequency pulsed mode, the RF power and the DC power may have a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, for example about 300 Hz to about 600 Hz. The RF power and the DC power may be provided at a duty cycle of 1% to 10%. In either mode, the RF source 181 and the DC source 182 may be pulsed synchronously or asynchronously. The pulse duration or repetition frequency may be tuned to achieve designated film thickness and growth rate. High-pulse high-frequency power source helps to breakdown target chemical bonds and create plasma with large fraction of target material ion species.

During sputtering deposition process, a gas, such as argon, is supplied to the processing region 110 from a gas source 142 via gas conduits 144 (only one is shown) disposed at sidewalls 104 of the chamber body 101. The gas source 142 may comprise a non-reactive gas such as argon, krypton, helium or xenon, which is capable of energetically impinging upon and sputtering material from the target 132. The gas source 142 may also include any desired reactive gas, such as one or more of an oxygen-containing gas or a nitrogen-containing gas, which is capable of reacting with the sputtering material to form a layer on a substrate. Multiple gases sources and gas conduits may be provided to enable other doping species. A plasma is formed between the substrate 105 and the target 132 from the gas. Ions within the plasma are accelerated toward the target 132 and cause material to become dislodged from the target 132. The dislodged target material is then deposited on the substrate, or implanted into the substrate upon application of high bias power to the pedestal assembly 120.

Spent process gas and byproducts are exhausted from the chamber 100 through pumping port 146 that receives spent process gas and direct the spent process gas to an exhaust conduit 171 having an adjustable position throttle valve 147 to control the pressure in the processing region 110 in the processing chamber 100. The exhaust conduit 171 is connected to one or more vacuum pump 149. Typically, the pressure of the sputtering gas in the chamber 100 during processing is set to sub-atmospheric levels, such as a vacuum environment, for example, a pressure of about 0.6 mTorr to about 400 mTorr. In one embodiment, the processing pressure is set to about 5 mTorr to about 100 mTorr. While only one gas conduit 144 is shown, it is contemplated that multiple gas conduits may be disposed at the sidewalls 104 to enable flowing of other doping species through the side of the processing chamber, and allow doping species to diffuse at the chamber operating pressure.

The lid enclosure 191 generally comprises a conductive wall 185, a center feed 184 and a shielding 186. In one configuration as shown, the conductive wall 185, the center feed 184, the target 132 and a portion of the motor 193 enclose and form a back region 134. The back region 134 is a sealed region disposed on the back side of the target 132 and is generally filled with a flowing liquid during processing to remove the heat generated at the target 132 during

processing. The shielding **186** may comprise one or more dielectric materials that are positioned to enclose and prevent the RF energy delivered to the target **132** from interfering with and affecting other processing chambers disposed in the cluster tool **103** (FIG. **2**). In one embodiment, the conductive wall **185** and center feed **184** are configured to support the motor **193** and magnetron system **189**, so that the motor **193** can rotate the magnetron system **189** during processing. The motor **193** may be electrically isolated from the RF or DC power delivered from the power supplies by use of a dielectric layer **193**B.

Magnetron Assembly

To provide efficient sputtering, a magnetron system **189** is positioned in back of the target **132** in the upper process assembly **108** to create a magnetic field in the processing region **110** adjacent the sputtering surface **133** of the target **132**. The magnetic field is created to trap electrons and ions to thereby increase the plasma density and to thereby also increase the sputtering rate. According to one embodiment of the present disclosure, the magnetron system **189** includes a source magnetron assembly **320** that comprises a rotation plate **313**, an outer pole **321** and an inner pole **322**. The rotation plate **313** allows the positioning of the magnetic field generating components in the source magnetron assembly **320** to be moved relative to the central axis **194** of the processing chamber **100**.

FIGS. **3**A, **3**B and **3**D, illustrate a source magnetron assembly **320** that is positioned at a first radial position relative to the central axis **194**, as viewed from the sputtering surface **133** side of the target **132**. FIG. **3**C illustrates the source magnetron assembly **320** when it is positioned at a second radial position relative to the central axis **194**, which is different from the first radial position, and as discussed below is created by adjusting the rotation direction and speed. The rotation plate **313** is generally adapted to support and magnetically couple the outer pole **321** of a first magnetic polarity in the vertical direction and the inner pole **322** having a second magnetic polarity opposite to that of the first magnetic polarity. The inner pole **322** is separated from the outer pole **321** by a gap **326**, and each of the poles generally comprises one or more magnets and a pole piece **329**. The magnetic field extending between the two poles **321**, **322** creates a plasma region "P" (FIG. **3**D) adjacent a first portion of the sputtering face of the target **132**. The plasma region "P" forms a high density plasma region that generally follows the shape of the gap **326**.

In one embodiment, as shown in FIGS. **3**A-**3**D, the magnetron system **189** is a non-closed loop design (e.g., open loop design) to reduce the intensity of the plasma formed in the plasma region "P" to compensate for the use of the improved ionization potential created by the delivery of the RF power, from the RF source **181**, to the target **132**. One will note that RF-powered plasmas are more effective in increasing the ionization of atoms (e.g., gas atoms and sputtered atoms) in the plasma than a DC-powered plasma, due to the more efficient coupling of the applied energy to the electrons in the plasma and other electron-plasma interaction phenomena that increase the energy of the electrons and enhance the ionization levels in the plasma.

In general, a "closed loop" magnetron configuration is formed such that the outer pole of the magnetron surrounds the inner pole of the magnetron forming a gap between the poles that is a continuous loop. In the closed loop configuration, the magnetic fields that emerge and reenter through a surface of the target form a "closed loop" pattern can be used to confine electrons near the surface of the target in a closed pattern, which is often called a "racetrack" type pattern. A closed loop, as opposed to the open-loop, magnetron configuration is able to confine electrons and generate a high density plasma near the sputtering surface **133** of the target **132** to increase the sputtering yield.

In an open loop magnetron configuration, the electrons trapped between the inner and outer poles will migrate, leak out and escape from the B-fields created at open ends of the magnetron, thus only holding the electrons for a short period of time during the sputtering process due to the reduced confinement of the electrons. However, surprisingly it has been found that the use of an open loop magnetron configuration, as described herein, provides improved material composition uniformity across the substrate surface, when used in conjunction with the RF and DC sputtering of target described herein.

In one embodiment of the magnetron system **189**, a rotary shaft **193**A powered by the motor **193** extends along a central axis **194** and supports a radial shifting mechanism **310**, which comprises the rotation plate **313**, counterweight **315** and the source magnetron assembly **320**. Thereby, the radial shifting mechanism **310** moves the source magnetron assembly **320** in complementary radial directions, such as radially towards or away from the central axis **194** (i.e., reference numerals "S" in FIG. **3**A) as the motor **193** is rotated in clockwise direction $R_1$ and counter-clockwise direction $R_2$ (FIGS. **3**B, **3**C).

FIG. **3**A, which is an isometric view of one embodiment of the magnetron system **189**, generally includes a cross arm **314** fixed at its center to the rotary shaft **193**A by a clamp **314**A. One end of the cross arm **314** supports a counterweight **315**. The other end of the cross arm **314**, which is across the rotation axis **194** from the counterweight **315**, supports a pivot **312**, or rotation bearing, that is used to rotatably support the source magnetron assembly **320** for rotation about an offset vertical pivot axis **319**. In one configuration, the pivot axis **319** is substantially parallel to the rotation axis **194**. In this configuration the magnetron **320** on the cross arm **314** allows it to swing in different and complementary radial directions with respect to the rotation center **194**. The complementary motion arises due to the center of mass of the source magnetron assembly **320** being a distance from the pivot axis **319**. Thus, as the cross arm **314** and source magnetron assembly **320** are rotated by the motor **193**, the centripetal acceleration acting on the source magnetron assembly **320** cause it to pivot about pivot axis **319** in one direction or the other depending on the direction that the motor **193** is turning. The center of mass of the source magnetron assembly **320** may be defined as the center of gravity of the source magnetron assembly **320**, which may be in-board of the inner pole **322**, or closer to the rotation axis **194**, for the configuration illustrated in FIGS. **3**A-**3**D.

The switching between the two positions is effected by reversing the direction of rotation of the rotary shaft **193**A about the rotation axis **194** and hence of the entire magnetron system **189** about the rotation axis **194**. As illustrated in the top plan view of FIG. **3**D, when the rotary shaft **193**A rotates the cross arm **314** in the counter clockwise direction $R_1$ about the rotation axis **194**, the inertia and impeding forces cause the source magnetron assembly **320** to rotate in the counter-clockwise direction about the pivot axis **319** until the bumper **316** fixed to the source magnetron assembly **320** engages one side of the cross arm **314**. In this processing configuration, or magnetron processing position, the source magnetron assembly **320** is disposed at its radi-

ally outward position close to the edge of the target **132**, so that the source magnetron assembly **320** can support a plasma for sputter deposition or sputter implantation of the substrate **105**. This position may be referred to as a magnetron "out" position or first processing position.

Alternately, as illustrated in the top plan view of FIG. **3**C, when the rotary shaft **193**A rotates the cross arm **314** in the counter-clockwise direction $R_2$ about the rotation axis **194**, the inertia and impeding forces cause the source magnetron assembly **320** to rotate in a clockwise direction about the pivot axis **319** until the bumper **317** (FIG. **3**A), which is fixed to the source magnetron assembly **320** engages the other side of the cross arm **314**. In this configuration, the source magnetron assembly **320** is disposed at its inward location away from the edge of the target **132** and closer to the rotation axis **194** so that the source magnetron assembly **320** can support a plasma near the center of the target to clean this region. This position may be referred to as a magnetron "in" position or second processing position.

In one embodiment, as noted above and illustrated in FIGS. **3**A and **3**D, the source magnetron assembly **320** is formed in a non-closed loop design to reduce the intensity of the plasma formed in the plasma region "P". In this configuration, the non-closed loop design is formed in an arc shape that has a radius D (FIGS. **3**B and **3**D), which extends from the arc center to the center of the gap **326**. The arc may be sized and positioned so that the center of the radius D of the arc is coextensive with the center of the rotation axis **194** when it is disposed in the magnetron in a first processing position. In one embodiment, the formed arc has a radius D between about 7.3 inches (185 mm) and 8.3 inches (210 mm) and the target **132** has a diameter of about 17.8 inches (454 mm). In one embodiment, the arc is circular in shape and subtends an angle **341** (FIG. **3**D) between about 70 and about 180 degrees, such as about 130 degrees. In one embodiment, the distance from the rotation axis **194** to the pivot axis **319** is equal to about the radius D of the arc.

In various embodiments, the outer pole **321** and inner pole **322** each comprise a plurality of magnets **323** that are positioned in an array pattern on either side of the gap **326** and are capped by a pole piece **329** (FIG. **3**A). In one configuration, the north (N) poles of the magnets **323** in the outer pole **321** are positioned away from the rotation plate **313** and south (S) poles of the magnets **323** in the inner pole **322** are positioned away from the rotation plate **313**. In some configurations, a magnetic yoke (not shown) is disposed between the magnets of the inner and outer poles and the rotation plate **313**. In one example, the source magnetron assembly **320** comprises an outer pole **321** that has 18 magnets contained therein and an inner pole **322** that has 17 magnets contained therein. In one embodiment, the magnets **323** are each configured to create a magnetic field having a strength, at or near their tip, of between about 1.1 kGauss and about 2.3 kGauss.

## Exemplary Process

The improved sputtering chamber as outlined above has been proved to be able to offer low temperature deposition of various metals and dielectrics with high film quality as compared to CVD and ALD systems. One exemplary process that can benefit from the improved sputtering chamber is carbon-based hardmask films used in 3D NAND flash memory applications. Carbon-based materials, such as amorphous hydrogenated carbon films (a-C:H), have been used as an etch hardmask for metals, dielectric materials, or poly-Si due to its chemical inertness, optical transparency, and good mechanical properties. However, carbon films with high concentration of hydrogen often show poor film structure and intrinsic film stress that may result in patterned line bending or line breakage during the subsequent etching process. Amorphous carbon films substantially consists only of carbon has shown great film hardness and excellent etching selectivity since the film contains a large proportion of diamond bonds ($sp^3$ bonds). A hydrogen-free amorphous carbon film can be formed using a PVD method. However, PVD deposited amorphous carbon films also suffer from large surface roughness and high compressive stress. It has been found that implantation of the hydrogen-free film with carbon ions using the improved sputtering chamber proposed above can significantly release film stress and erode surface roughness. The final film post implantation shows relaxed stress, smooth surface, and etch selectivity that is 3 time higher than current state of the art carbon-based hardmasks. An exemplary process will be discussed below using the processing chamber discussed above with respect to FIGS. **1**A-**1**B to **3**A-**3**D.

FIG. **4** is an exemplary process flow diagram for forming a carbon-based film according to embodiments of the present disclosure. FIGS. **5**A-**5**C illustrate schematic cross-section views of a carbon-based film formed using the process flow diagram of FIG. **4**. The process begins at box **402** by placing a substrate on a pedestal assembly **120** disposed within the processing chamber **100** depicted in FIG. **1**. The substrate **502**, as shown in FIG. **5**A, may have a substantially planar surface. Alternatively, the substrate **502** may have patterned structures, a surface having trenches, holes, or vias formed therein. While the substrate **502** is illustrated as a single body, it is understood that the substrate **502** may comprise one or more metal layers, one or more dielectric materials, semiconductor material, and combinations thereof, depending upon application.

At box **404**, the pressure of the processing chamber **100** is set to a sub-atmospheric level between about 0.6 mTorr to about 400 mTorr, for example about 5 mTorr to about 30 mTorr, using the vacuum pump **149** shown in FIG. **1**. An inert gas, such as argon, is introduced into the processing region **110** via gas conduits **144** of the processing chamber. The flow rate of the inert gas varies as a function of the chamber size, ranging from about 30-300 sccm for a processing chamber with a processing region **110** that is 200 mm in diameter to 800-2000 sccm for a processing chamber with a processing region **110** that is 1300 mm×1500 mm in area. One skilled in the art can readily determine an appropriate flow rate and related process parameters discussed herein, depending on the size of the processing chamber.

At box **406**, a plasma is formed in the processing region **110** of the processing chamber **100** by coupling a RF power (from the RF source **181**) to the target **132** disposed in the processing chamber **100**. In cases where a carbon film is desired, a carbon target or a carbon-containing target is used. The RF power may be supplied to the target **132** in a range of about 0 kW to about 10 kW, for example about 1 kW to about 5 kW, at a frequency of about 2 MHz to about 13.56 MHz.

At box **408**, while the target **132** is electrically biased by the RF power, the DC source **182** is turned on to provide DC power to the target **132**. DC power coupled to the target provides a higher sputtering ion energy to the argon ions in the processing region **110**, resulting in strong bombardment of the carbon target surface to dislodge carbon atoms from the target **132**. The sputtered carbon atoms travel toward and land on the surface of the substrate **502** to form a first layer of carbon film **504** thereon, as shown in FIG. **5**A. During the

sputtering process, the target **132** may be supplied with RF power in a range of about 0 kW to about 20 kW, for example about 1 kW to about 10 kW, at a frequency of 13.56 MHz, and DC power in a range of about 0 kW to about 10 kW, for example about 1 kW to about 5 kW. In one embodiment, an RF power density of about 1 kW/$m^2$ and a DC power density of about 5 kW/$m^2$ are coupled to the target. The sputtering process may be performed for a period of time, for example about 0.1 seconds to about 120 seconds, which may vary depending on the desired thickness of the carbon film.

The source power, i.e., the RF power and the DC power, may be provided in a constant or pulsed manner. In some embodiments, the RF power may be provided in a constant manner while the DC power may be provided in a pulsed manner, or vice versa. In some embodiments, the RF power and the DC power are operated in a pulsed manner (pulsed RF-DC operation). The pulsed RF-DC operation, as discussed previously, may include a regular pulsed mode and a high frequency pulsed mode controlled by the pulse controller **173** shown in FIG. **1**. If the regular pulsed mode is desired, each RF/DC pulse provided to the target **132** may have a pulse duration of about 300 microseconds to about 800 microseconds, for example about 350 microseconds to about 650 microseconds. Each RF/DC pulse provided to the target **132** can have a pulse repetition frequency ranging from about 1 Hz to about 200 Hz, such as about 5 Hz to about 100 Hz. The RF power and the DC power may be provided at a duty cycle of 50% to 90%. If the high frequency pulsed mode is desired, each RF/DC pulse provided to the target **132** may have a duration of about 100 microseconds to about 300 microseconds, for example about 150 microseconds to about 250 microseconds. Each RF/DC pulse provided to the target **132** can have a pulse repetition frequency ranging from about 200 Hz to about 20 KHz, for example about 300 Hz to about 600 Hz. The RF power and the DC power may be provided at a duty cycle of 1% to 10%. The pulse duration or repetition frequency may be tuned to achieve designated film thickness and growth rate. In either mode, the RF source **181** and the DC source **182** may be pulsed synchronously or asynchronously. It is believed that high frequency pulsed mode helps to breakdown target chemical bonds and creates plasma with large fraction of target material ion species.

During sputtering process, the magnetron system **189** shown in FIG. **1** may be translated relative to the target **132** so that the magnetron system **189** is positioned in a first processing position, such as depicted in FIG. **3**D. Alternatively, the magnetron system **189** may be translated by rotating the magnetron system **189** about the center point of the target to any desired processing position illustrated in FIGS. **3**B-**3**C. The magnetron system includes an outer pole **321** comprising a plurality of magnets **323** and an inner pole **322** comprising a plurality of magnets **323**, wherein the outer and inner poles form an open-loop magnetron assembly. As discussed previously, the use of an open loop magnetron configuration provides improved material composition uniformity across the substrate surface, when used in conjunction with high pressure, RF and DC sputtering of the target. Alternatively, in some embodiments the outer and inner poles may form a close loop magnetron configuration.

At box **410**, once the first layer of carbon film has deposited on the surface of the substrate **502**, both RF source **181** and DC source **182** are turned off. A high negative bias voltage is then provided (by the bias power source **141**) to the pedestal assembly **120** of FIG. **1** for a short period of time to implant the deposited carbon film with carbon ions **506** that still remain in the processing region **110**, as shown in FIG. **5**B. The negative bias voltage may be between about 1 kW and about 30 kW, for example about 5 kW to about 10 kW. The kinetic energy of the carbon ions collided to the substrate will be greater with such high negative bias voltage, and the treated carbon film will have low density due to an amorphous and coarse texture. In addition, when high bias voltage is used, the substrate temperature rises due to high-energy carbon ion irradiation. As a result, the residual stress in the deposited carbon film is moderated. FIG. **5**C shows the treated carbon film with relaxed film stress and smooth surface roughness.

The high negative bias voltage may be applied to the pedestal assembly **120** in a constant manner. In some embodiments, the high negative bias voltage is applied to the pedestal assembly **120** in a regular pulsed mode or a high frequency pulsed mode as discussed previously. If the regular pulsed mode is desired, the high negative bias voltage may have a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, for example about 50 Hz to about 100 Hz. The high negative bias voltage may be provided at a duty cycle of 1% to 10%. If the high frequency pulsed mode is desired, the high negative bias voltage may have a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, for example about 300 Hz to about 600 Hz. The high negative bias voltage may be provided at a duty cycle of 1% to 20%. The pulse duration or repetition frequency may be tuned to achieve designated film thickness and growth rate. In one embodiment where a high frequency pulsed mode is adapted, the bias voltage and the source power are synchronized such that high density of target ion species exited by high frequency pulse source are deposited and implanted on the substrate surface. As a result, a higher deposition rate is achieved.

FIGS. **6**A and **6**B show the relationship between the bias voltage and implantation characteristics using the processing chamber of FIG. **1**. Specifically, FIG. **6**A illustrates a graph of DC voltage and dosage as a function of the bias power according to embodiments of the present disclosure. FIG. **6**B illustrates a graph of sputter rate as a function of bias power according to embodiments of the present disclosure. As can be seen, the implantation dosage and sputtering rate both increase when the bias power is raised. This is because the high negative bias power affects the energy of the ions that strike the substrate surface as well as the doping level. FIG. **6**C shows a graph of simulation data of ion species implantation profile according to embodiments of the present disclosure. Particularly, FIG. **6**C illustrates characterization of doped argon and carbon ions trace in a targeting film by simulation and secondary ion mass spectrometry (SIMS) analysis. With all these information, a skilled artisan in the art can tailor or control designated implantation energy based on DC bias voltage monitoring, and control, calculate total dosage, and modulate sputter rate by controlling bias, source power, pressure and pulse duration as discussed in this disclosure to perform deposition-implantation cycle.

FIGS. **7**A and **7**B are schematics of duty cycle and pulse variation for regular pulsed mode and high frequency pulsed mode, respectively, that may be applied to various embodiments of the present disclosure. As can be seen in FIG. **7**A, the pulsing and duty cycle of the source power (i.e., the RF power and the DC power) and the bias voltage may be controlled for cyclic deposition and treatment process, where the bias voltage is turned on "T(on)" during source power off "T(off)" cycle and using the radicals left from the

source plasma for implantation of ions. FIG. **7**B shows that the bias voltage and the source power are synchronized in order to increase the deposition rate.

At box **412**, once the deposited carbon film has been treated with carbon ions, the substrate **502** is cool down for the next growth cycle.

At box **414**, the process described at boxes **406-412** is repeated until a desired thickness of carbon film is reached. FIGS. **5**D-**5**I schematically show another two growth cycles in which a second layer of carbon film **510** and a third layer of carbon film **512** are sequentially formed over the first layer of carbon film **504** and treated with carbon ions. Although three layers of carbon film are illustrated, embodiments of the present disclosure are not limited to a particular number of layers.

While the description above primarily discusses the processes of carbon film formation, the concept is not intended to be limiting as to the scope of the disclosure described herein. Embodiments of the present disclosure provide the ability to deposit metals, which may include, but are not limited to scandium (Sc), yttrium (Y), zirconium (Zr), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Th), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), and hafnium (Hf). Other materials such as aluminum, copper, nickel, platinum, silver, chrome, gold, molybdenum, silicon, ruthenium, tantalum, tantalum nitride, tantalum carbide, titanium nitride, tungsten, tungsten nitride, alumina, lanthanum oxides, nickel platinum alloys, and titanium, and or combination thereof, may also benefit from the present disclosure.

In summary, embodiments of the present disclosure enable a sputtering chamber to provide in-situ ion implantation capability by coupling a high bias voltage (e.g., 1 kW or above) to a pedestal assembly. The pedestal assembly has a flat substrate receiving surface and is fabricated by a bulk ceramic without having gas conduits or grooves formed in the substrate receiving surface that would easily cause arcing at high power. The sputtering chamber utilizes RF-DC power sources coupling to a target to provide strong bombardment of the target with minimized plasma related damage of the substrate. The addition of RF power to the target also increases the ionization of the plasma which helps improve the affects of substrate bias on the depositing ions. An optical emission spectrometer is disposed inside the sputtering chamber to work with a probe equipped in the pedestal assembly to simultaneously or nearly simultaneously measure and/or control implantation bias voltage and dosage for accurate dosing control. The sputtering chamber also provides side gas injection and an exhaust assembly having a pumping port disposed concentric with the sputtering chamber. The symmetrical positioning of the pumping port provides improved gas flow symmetry within the sputtering chamber to allow more uniform gas flow over the substrate surface and promote uniform plasma formation. These unique chamber designs in combination allow low temperature deposition of multiple materials from metal to dielectric with high film quality as compared to conventional PVD, CVD or ALD systems.

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.

The invention claimed is:

**1**. A processing chamber for processing a substrate, comprising:

a target having a first surface disposed in a processing region of the processing chamber and a second surface that is opposite the first surface;

an RF power supply configured to generate a plasma, the RF power supply coupled to the target;

a DC power supply coupled to the target;

a substrate support comprising a support body, the support body having an electrode embedded therein, and a substrate receiving surface across an entire diameter of the substrate support, the DC power supply configured to energize ions from the target for forming a film layer on a surface of the substrate;

a bias power source coupled to the substrate support;

a pulse controller coupled to the bias power source, the pulse controller configured to apply a pulse control signal to the bias power source such that bias power is delivered either in a regular pulsed mode having a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, and a high frequency pulsed mode having a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, wherein the bias power source is configured to implant ions into the substrate;

a probe coupled to the electrode and bias power source, the probe configured collect data for estimating an ion dose rate, the bias power source electrically coupled between the probe and the pulse controller; and

an exhaust assembly having a concentric pumping port formed through a bottom of the processing chamber.

**2**. The processing chamber of claim **1**, further comprising:

a rotatable magnetron disposed adjacent to the second surface of the target.

**3**. The processing chamber of claim **1**, wherein the RF power supply and the DC power supply are configured to operate at a pulse duration of about 300 microseconds to about 800 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz.

**4**. The processing chamber of claim **3**, wherein the RF power supply and the DC power supply are configured to operate at a duty cycle of 50% to 90%.

**5**. The processing chamber of claim **1**, wherein the RF power supply and the DC power supply are configured to operate at a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz.

**6**. The processing chamber of claim **5**, wherein the RF power supply and the DC power supply are configured to operate at a duty cycle of 1% to 10%.

**7**. The processing chamber of claim **1**, wherein the bias power source is configured to provide a negative bias voltage of about 1 kW to about 25 kW.

**8**. The processing chamber of claim **7**, wherein the bias power source is configured to operate in a regular pulsed mode running at a duty cycle of 1% to 10%.

**9**. The processing chamber of claim **7**, wherein the bias power source is configured to operate in a high frequency pulsed mode running at a duty cycle of 1% to 20%.

**10**. The processing chamber of claim **1**, wherein the support body is an electrostatic chuck, a ceramic body, a aluminum body, a heater, a chiller, or any combination thereof.

11. The processing chamber of claim 1, wherein the substrate support is mounted cantilevered from a sidewall of the processing chamber.

12. A plasma processing chamber, comprising:

a sputtering target;

a rotating magnetron disposed adjacent to a surface of the sputtering target;

an RF power supply configured to generate a plasma, the RF power supply coupled to the sputtering target;

a DC power supply coupled to the sputtering target;

a support body configured to support a substrate, the support body comprising an electrode embedded therein, and a substrate receiving surface, wherein at least a portion immediately below the substrate receiving surface has a uniform thickness across a diameter of the substrate receiving surface, the DC power supply configured to energize ions from the sputtering target for forming a film layer on a surface of the substrate;

a bias power source coupled to the support body;

a pulse controller coupled to the bias power source, the pulse controller applying a pulse control signal to the bias power source such that bias power is delivered either in a regular pulsed mode having a pulse duration of about 100 microseconds to about 200 microseconds and a pulse repetition frequency of about 1 Hz to about 200 Hz, and a high frequency pulsed mode having a pulse duration of about 100 microseconds to about 300 microseconds and a pulse repetition frequency of about 200 Hz to about 20 KHz, wherein the bias power source is configured to implant ions into the substrate;

a probe coupled to the electrode and bias power source, the probe configured collect data for estimating an ion dose rate, the bias power source electrically coupled between the probe and the pulse controller;

a gas conduit disposed at a sidewall of the plasma processing chamber;

a shield coupled to the sidewall of the plasma processing chamber, wherein the shield extends downwardly to at least partially confine a portion of a processing region; and

an exhaust assembly having a pumping port formed through a bottom of the plasma processing chamber, wherein the pumping port is disposed symmetrically about a central axis passing through the center of the plasma processing chamber.

13. The plasma processing chamber of claim 12, wherein the RF power supply and the DC power supply are configured to operate synchronized with the bias power source.

14. The plasma processing chamber of claim 12, wherein the RF power supply and the DC power supply are configured to operate asynchronously from the bias power source.

15. The plasma processing chamber of claim 12, wherein the RF power supply and the DC power supply are configured to operate at a duty cycle of 50% to 90%.

16. The plasma processing chamber of claim 12, wherein the RF power supply and the DC power supply are configured to operate at a duty cycle of 1% to 10%.

17. The plasma processing chamber of claim 12, wherein the bias power source is configured to provide a negative bias voltage of about 1 kW to about 25 kW.

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