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(54) **ACOUSTIC RESONANCE SENSOR DEVICES FOR RADICAL SPECIES DETECTION WITH ENHANCED FILTERS**

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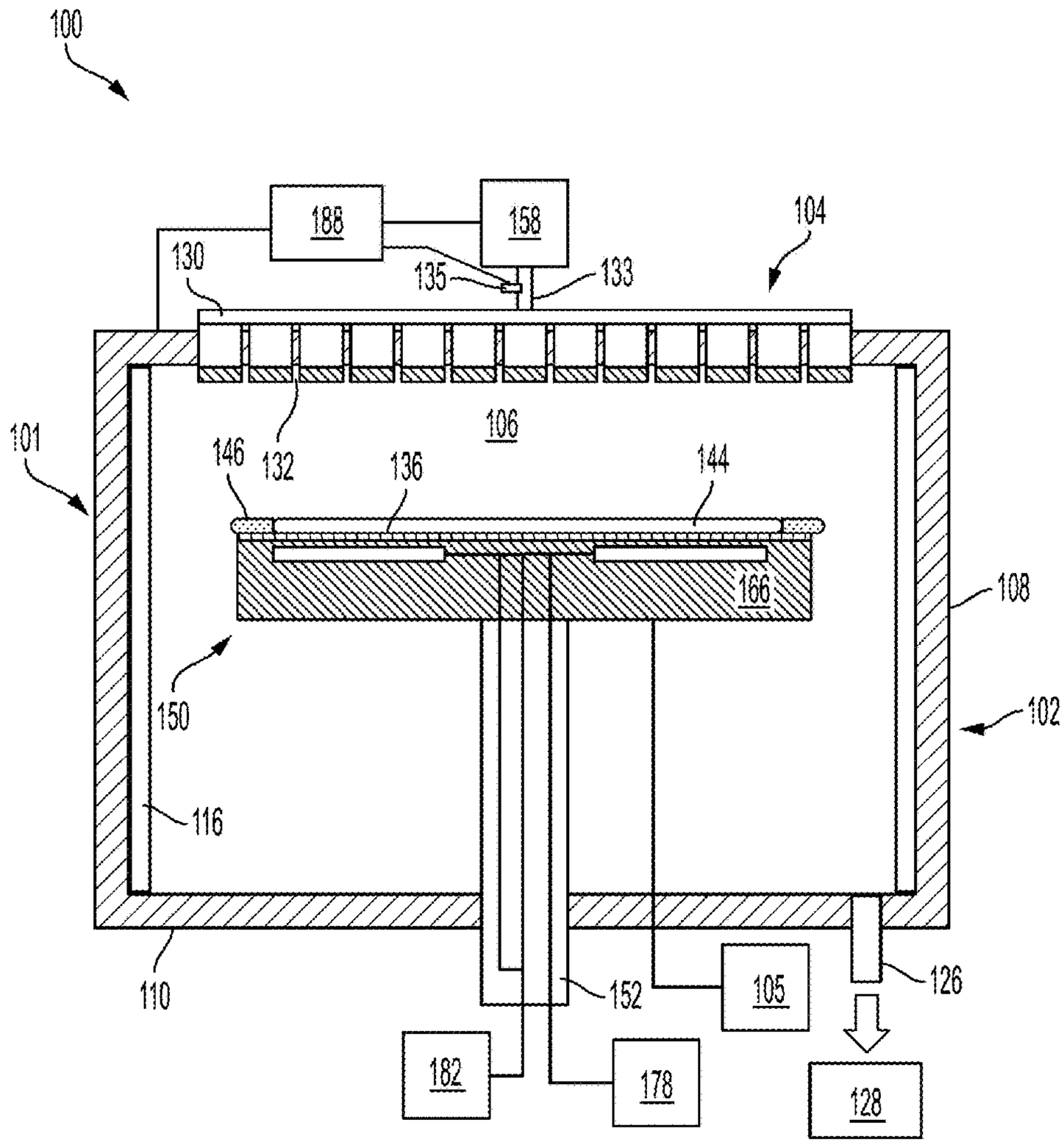
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(57) **ABSTRACT**

A device can include a radical sensor including a piezoelectric resonator. The radical sensor includes a base structure including a piezoelectric material, and a filter formed on the base structure to selectively react with a radical species. A resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter. The filter includes at least one of: a crystalline material, a doped coating, or a coating having a thickness that ranges from about 5 micrometers to about 50 micrometers.



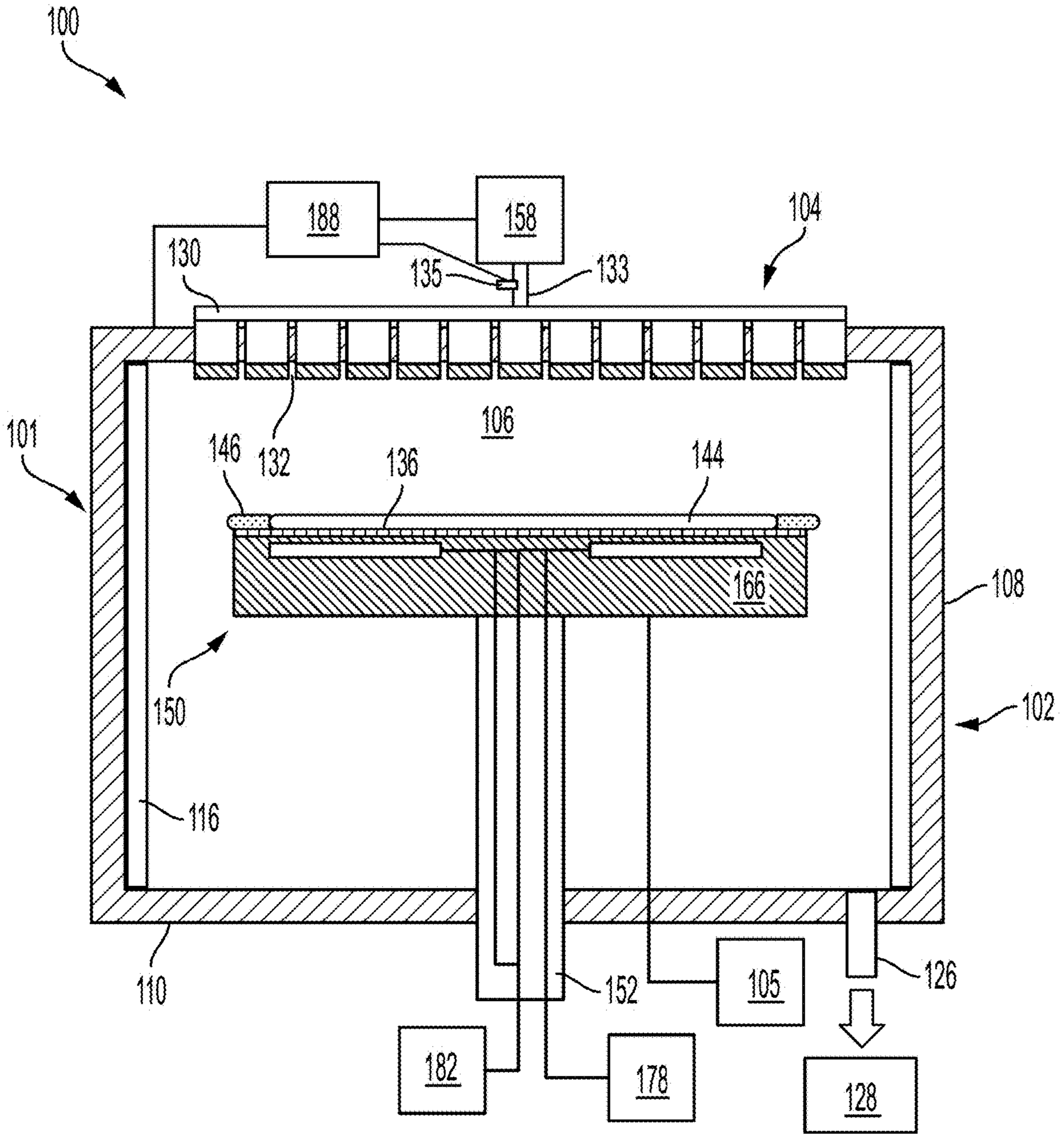

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FIG. 1

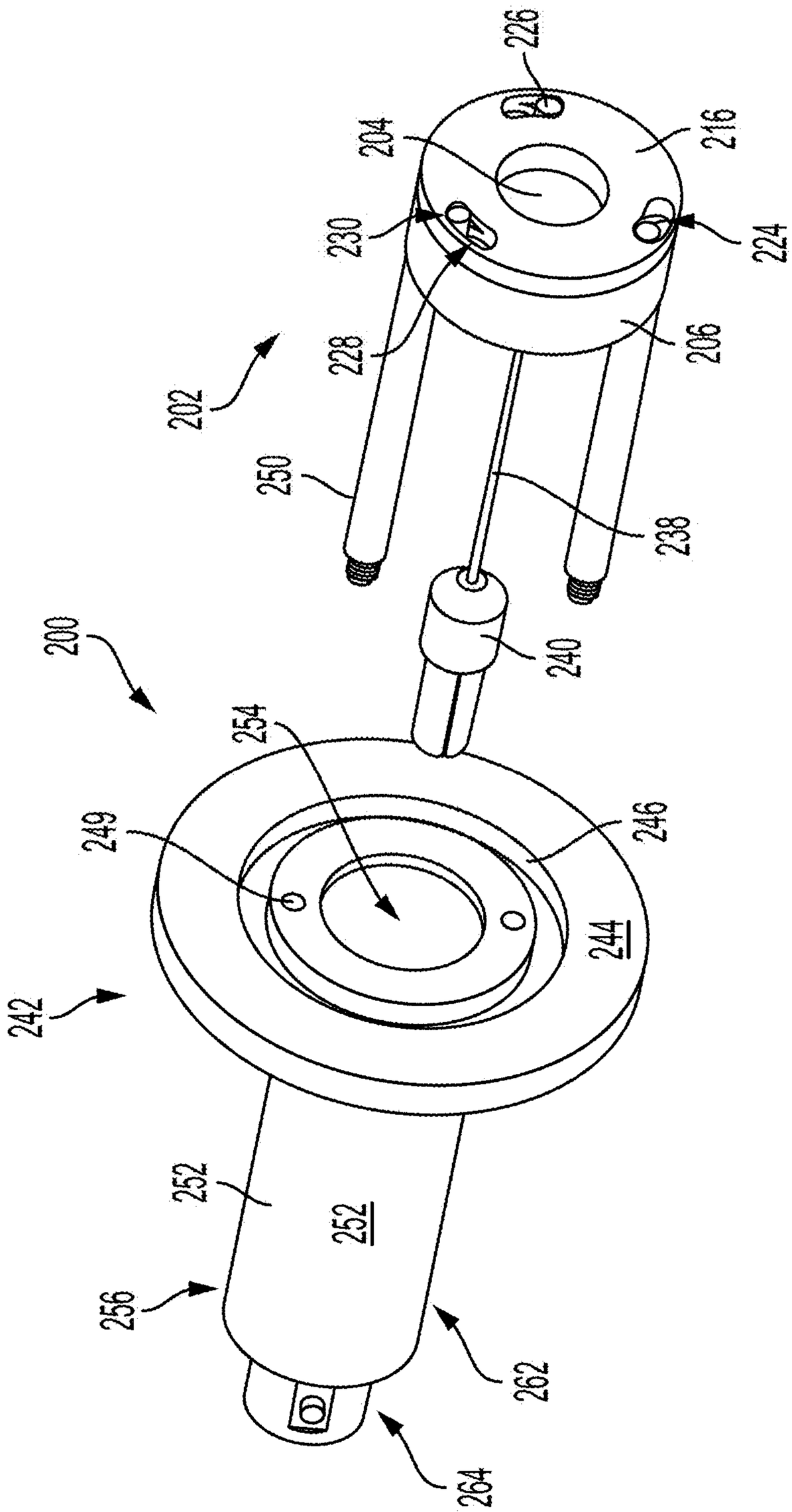

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FIG. 2A

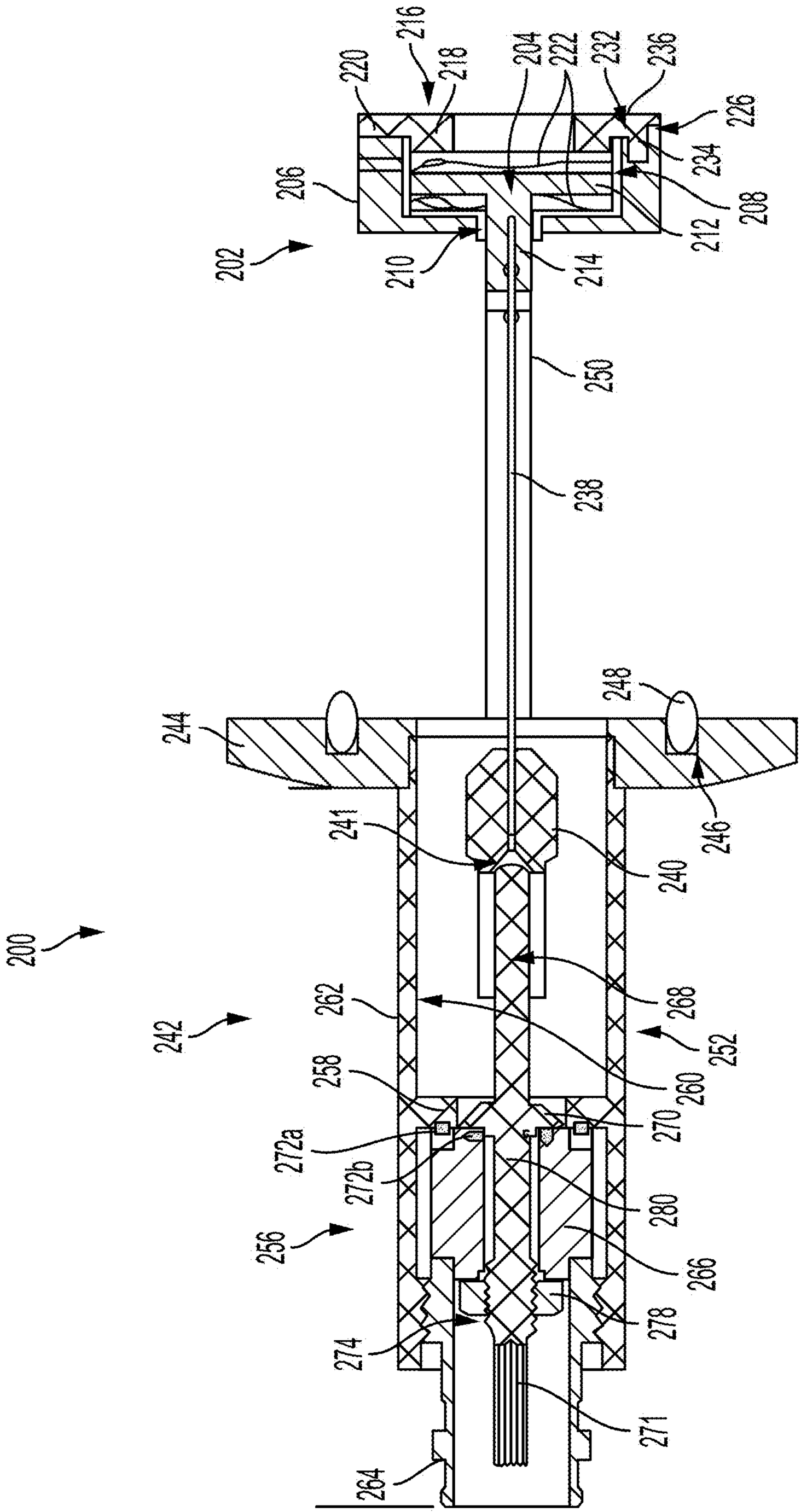

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FIG. 2B

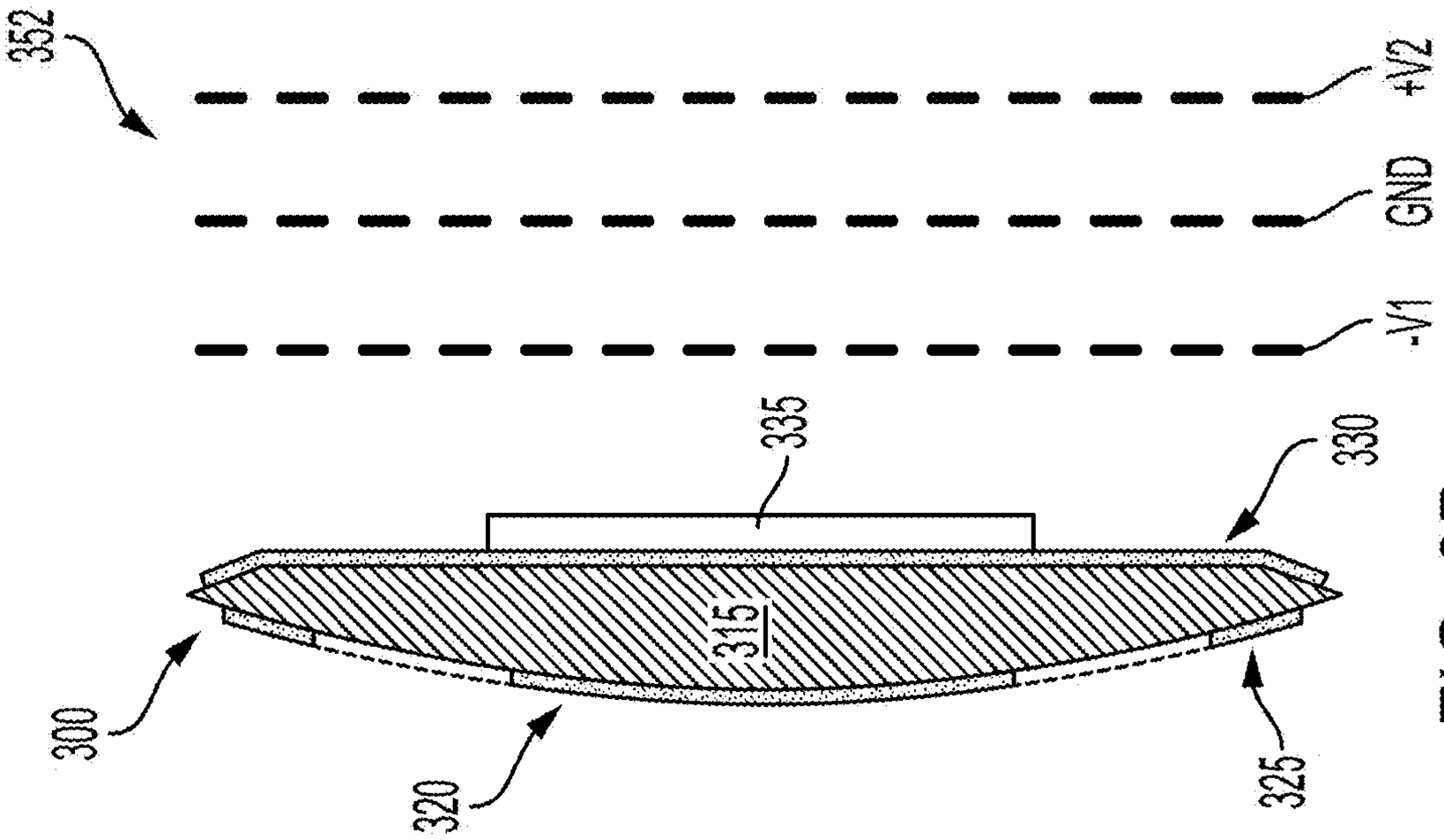


FIG. 3D

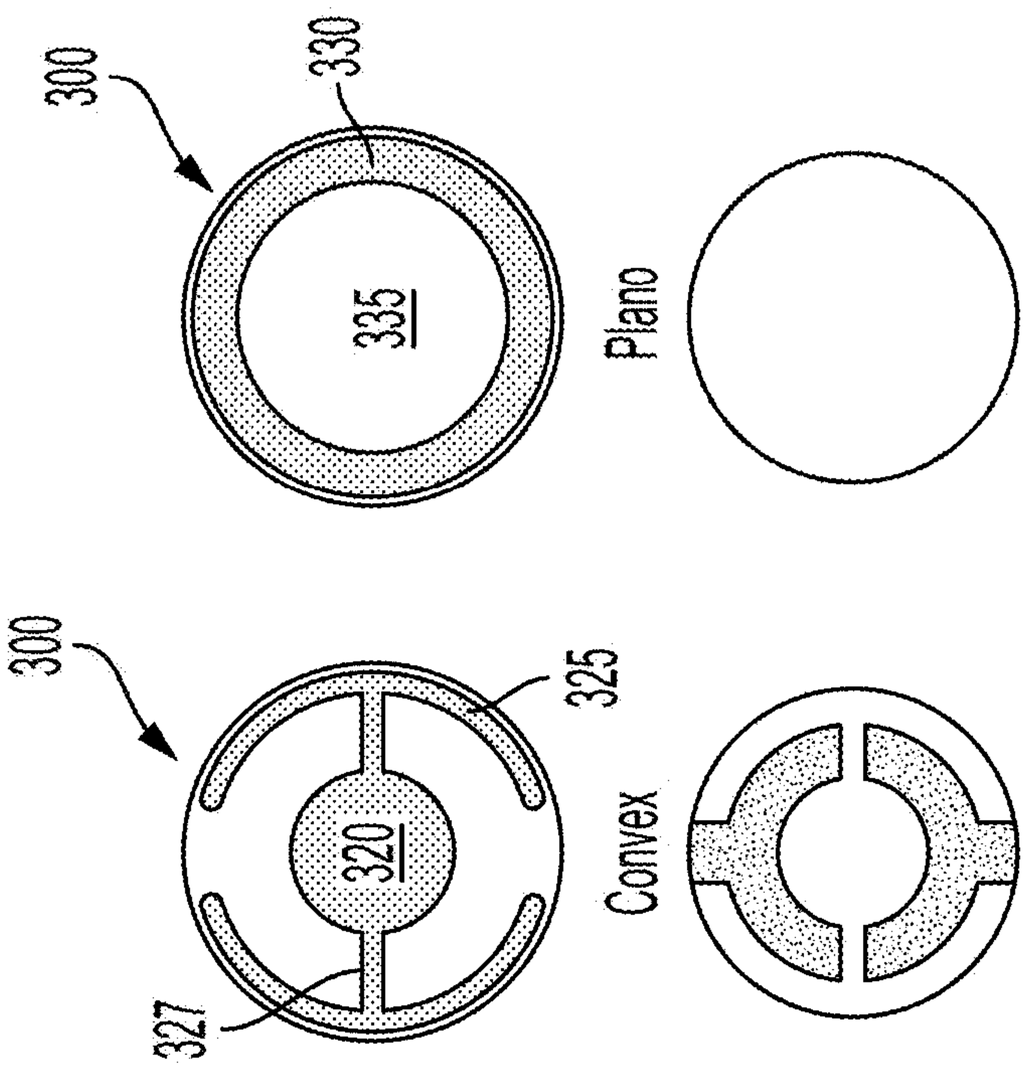


FIG. 3C

FIG. 3B

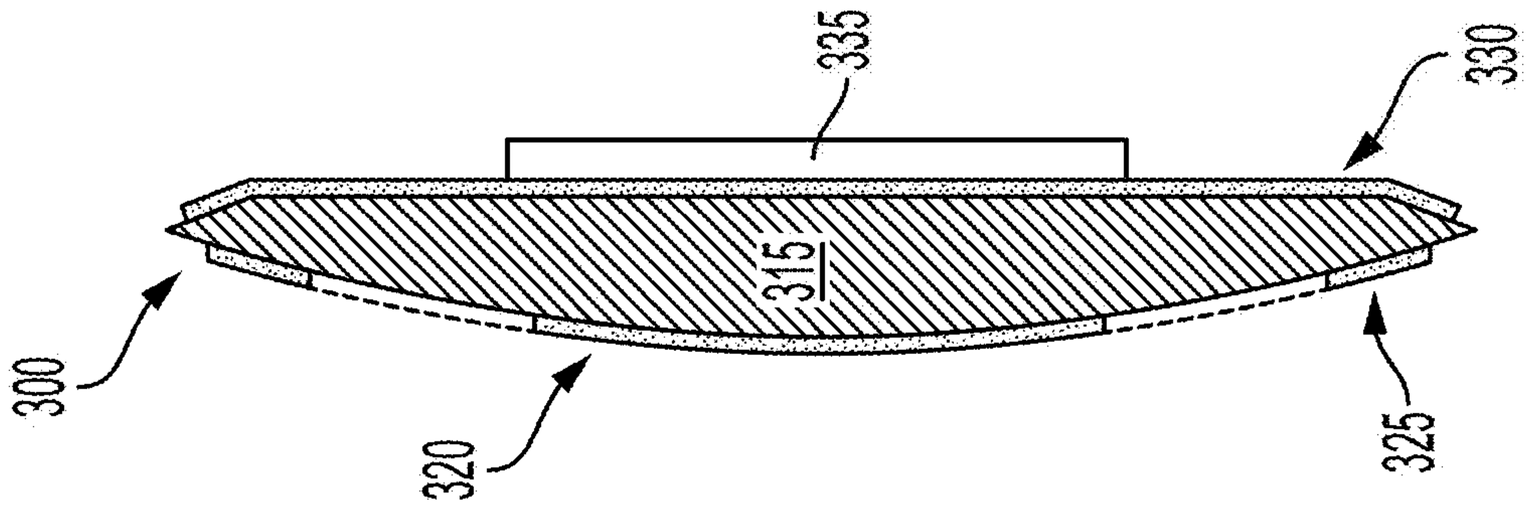


FIG. 3A

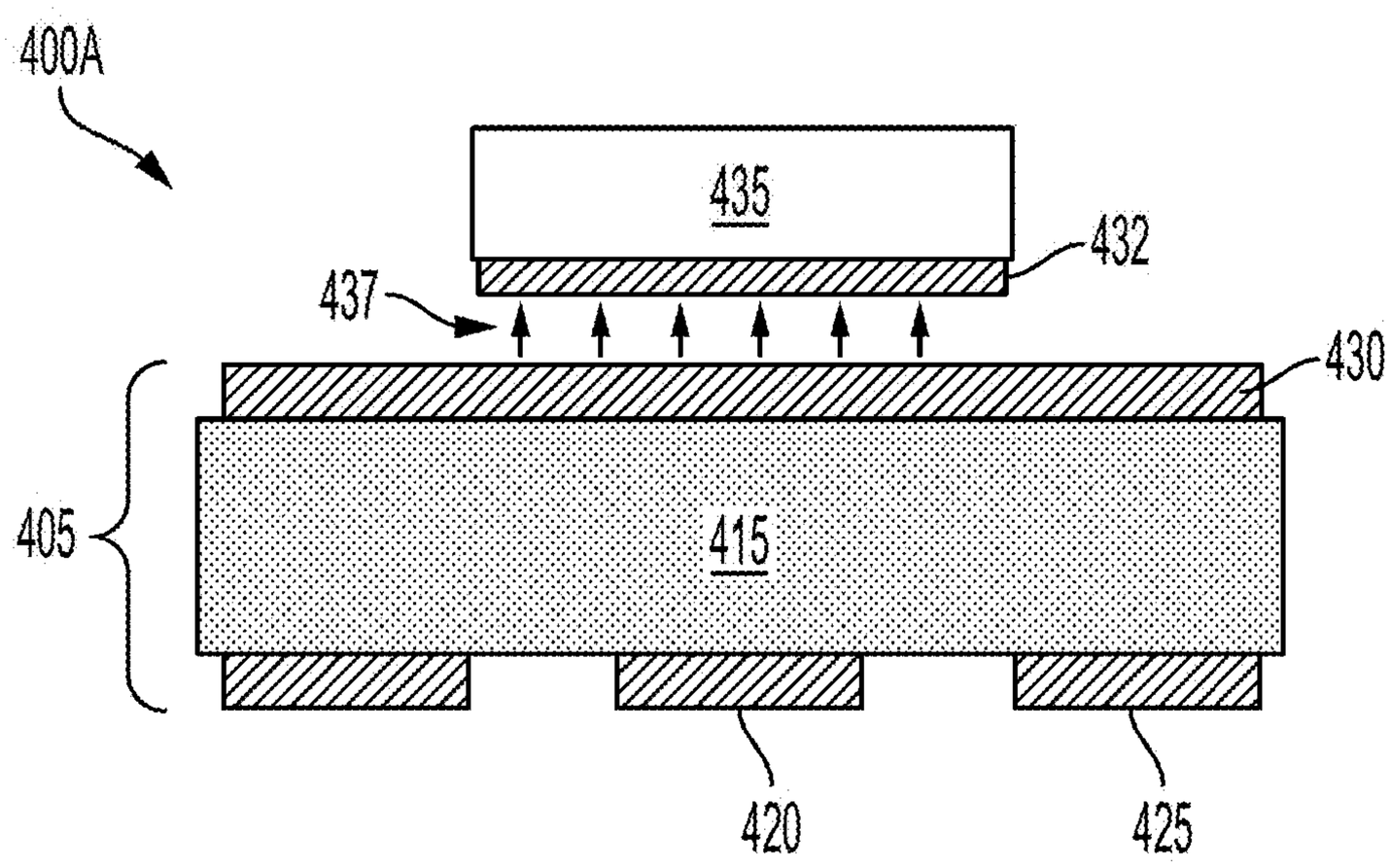

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FIG. 4A

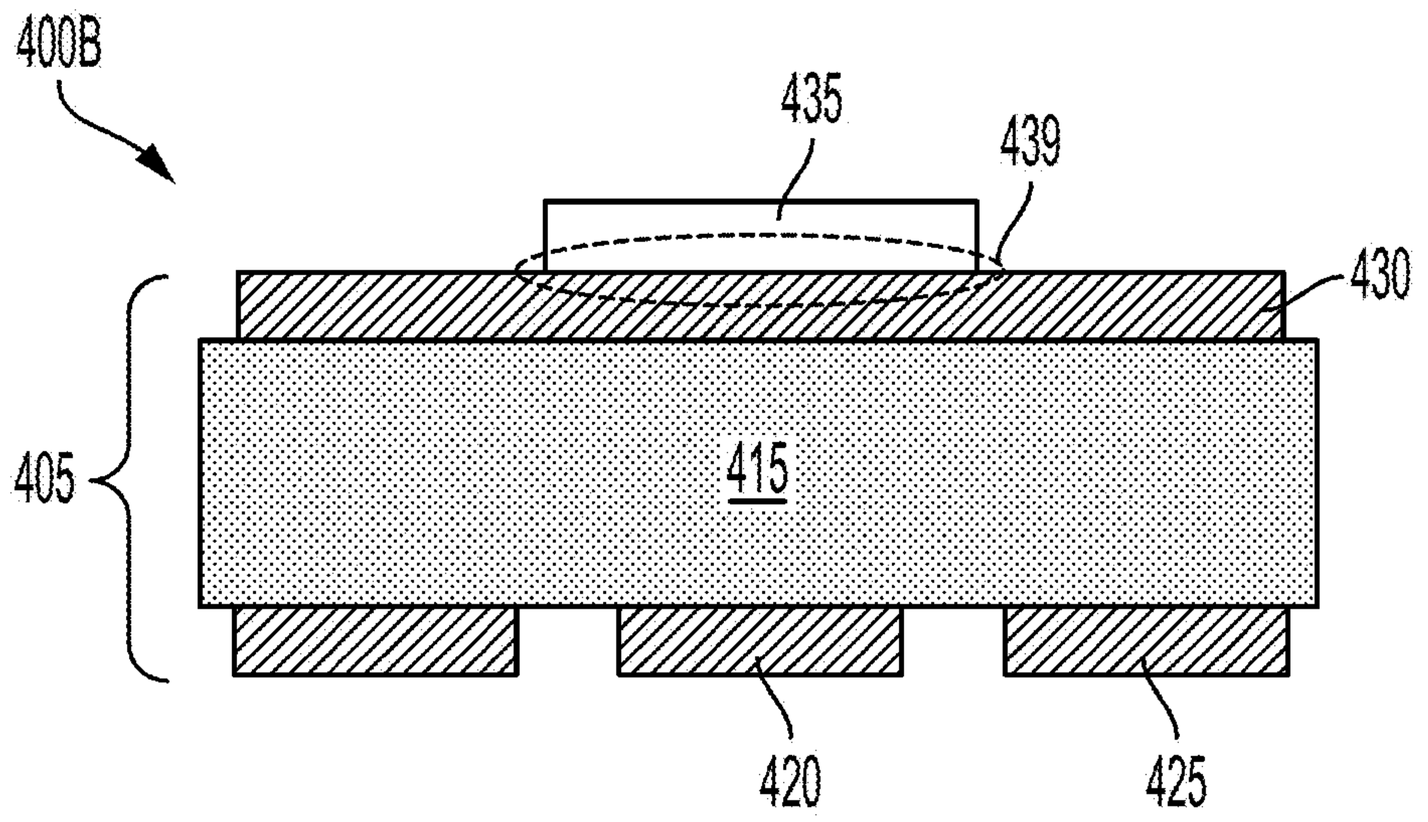

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FIG. 4B

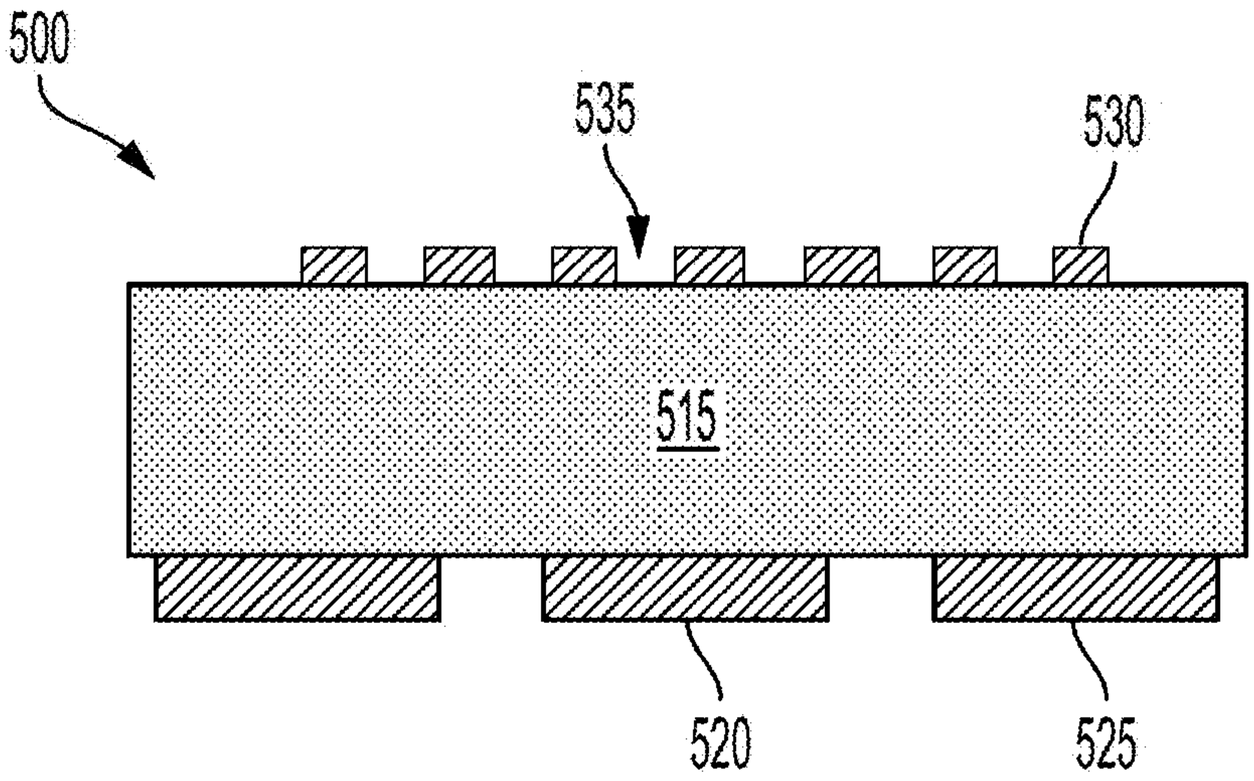


FIG. 5

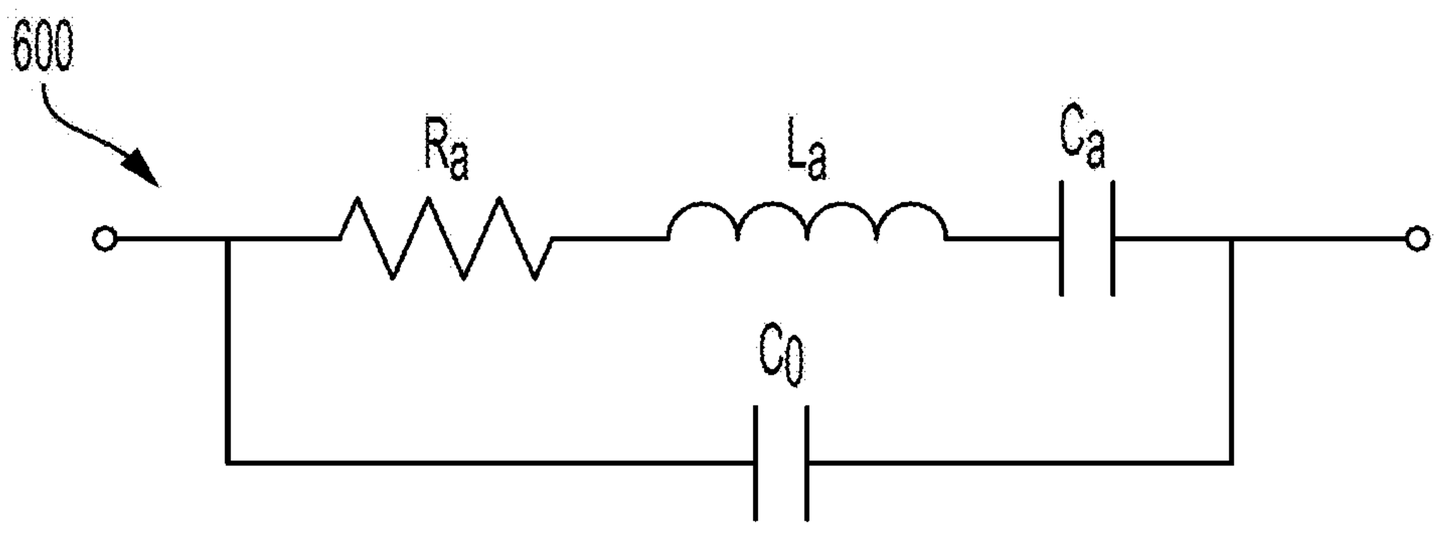


FIG. 6

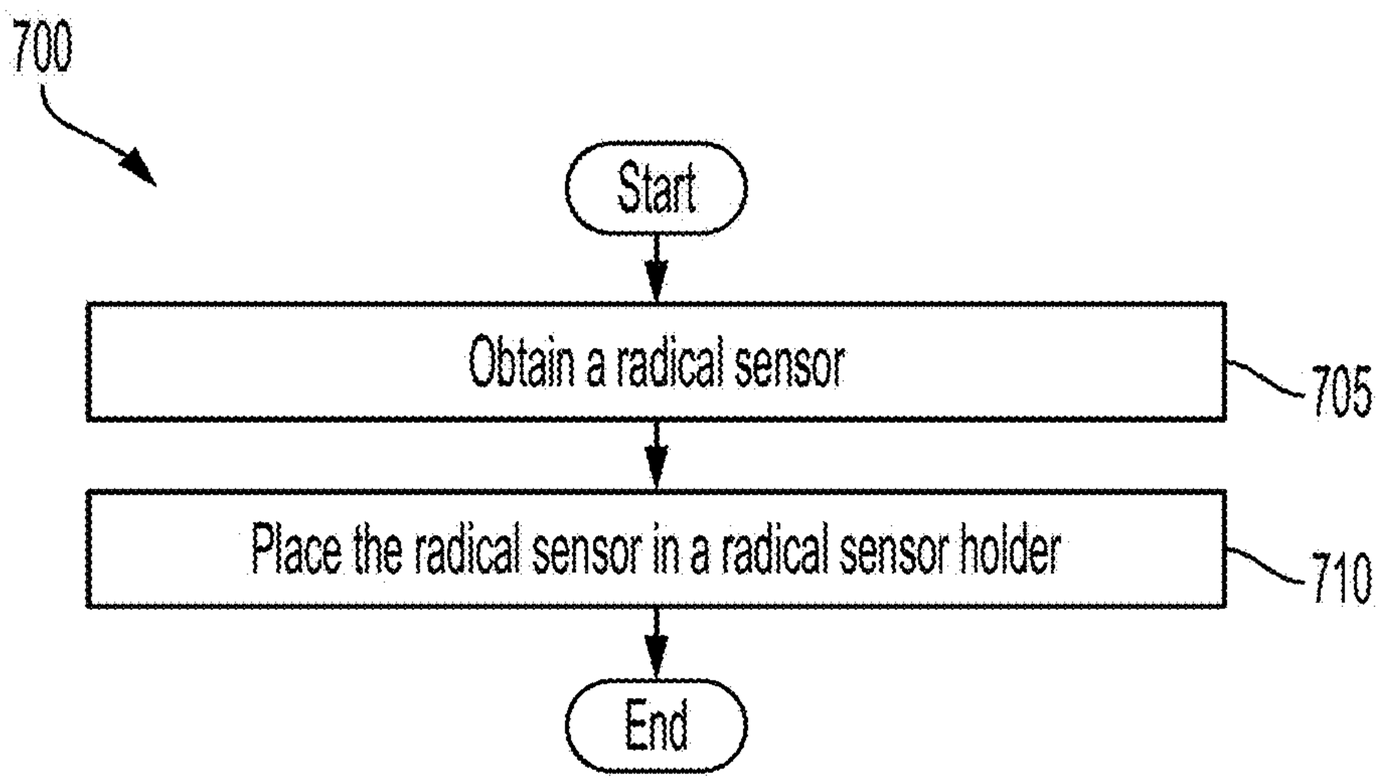


FIG. 7

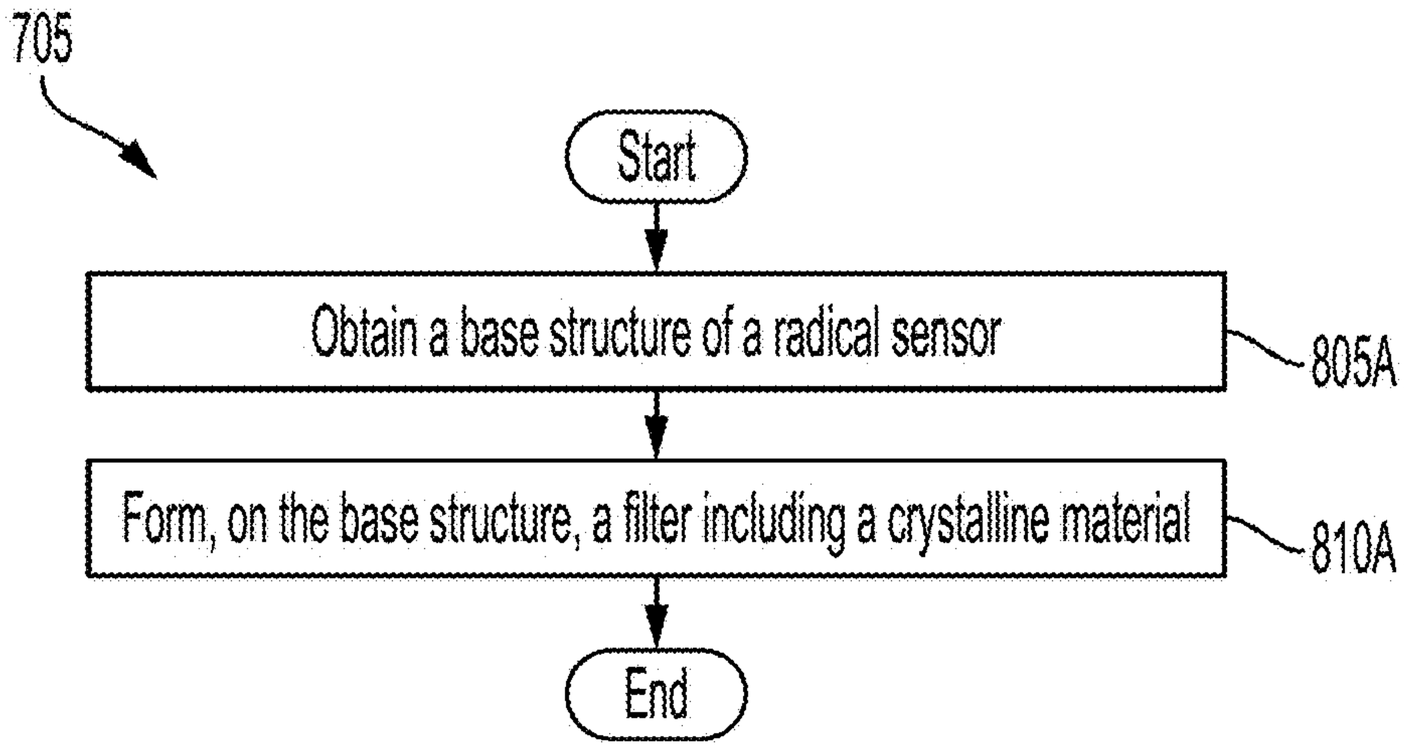


FIG. 8A

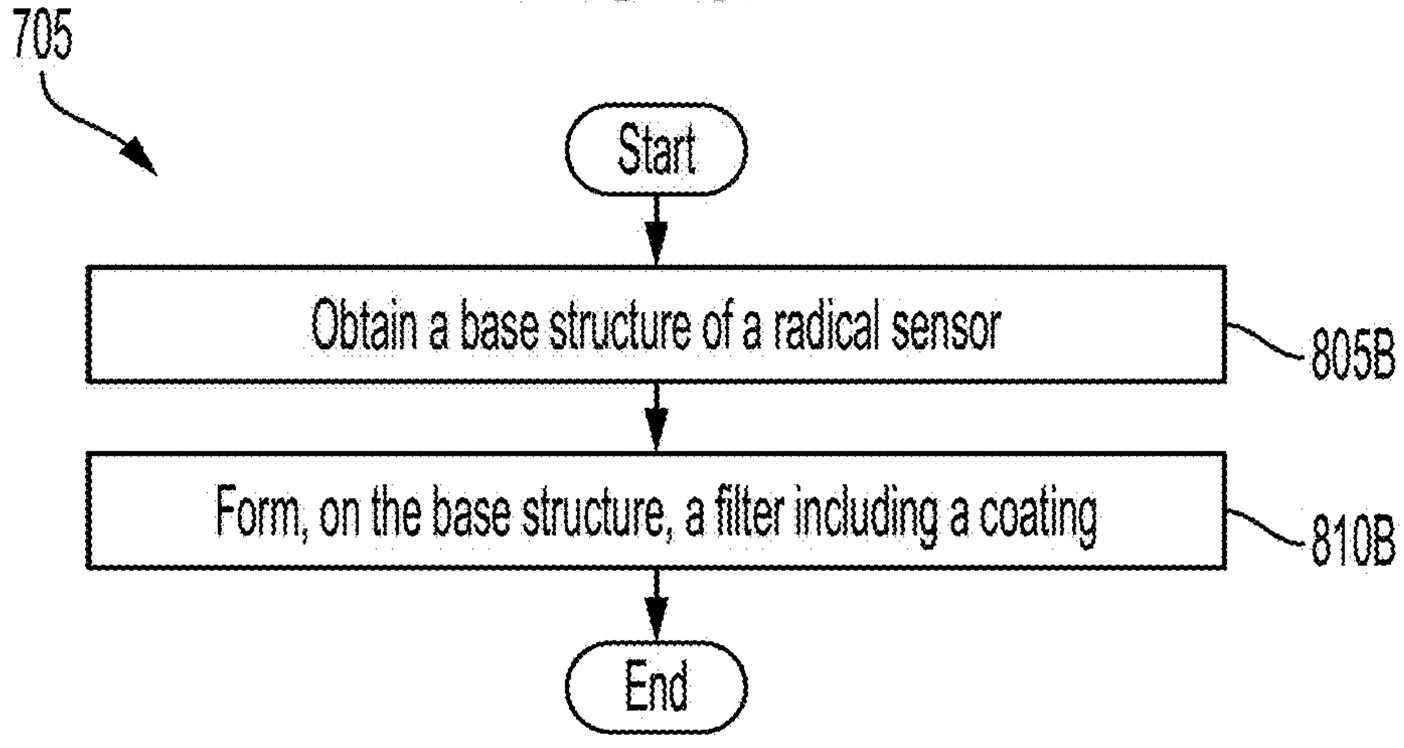


FIG. 8B

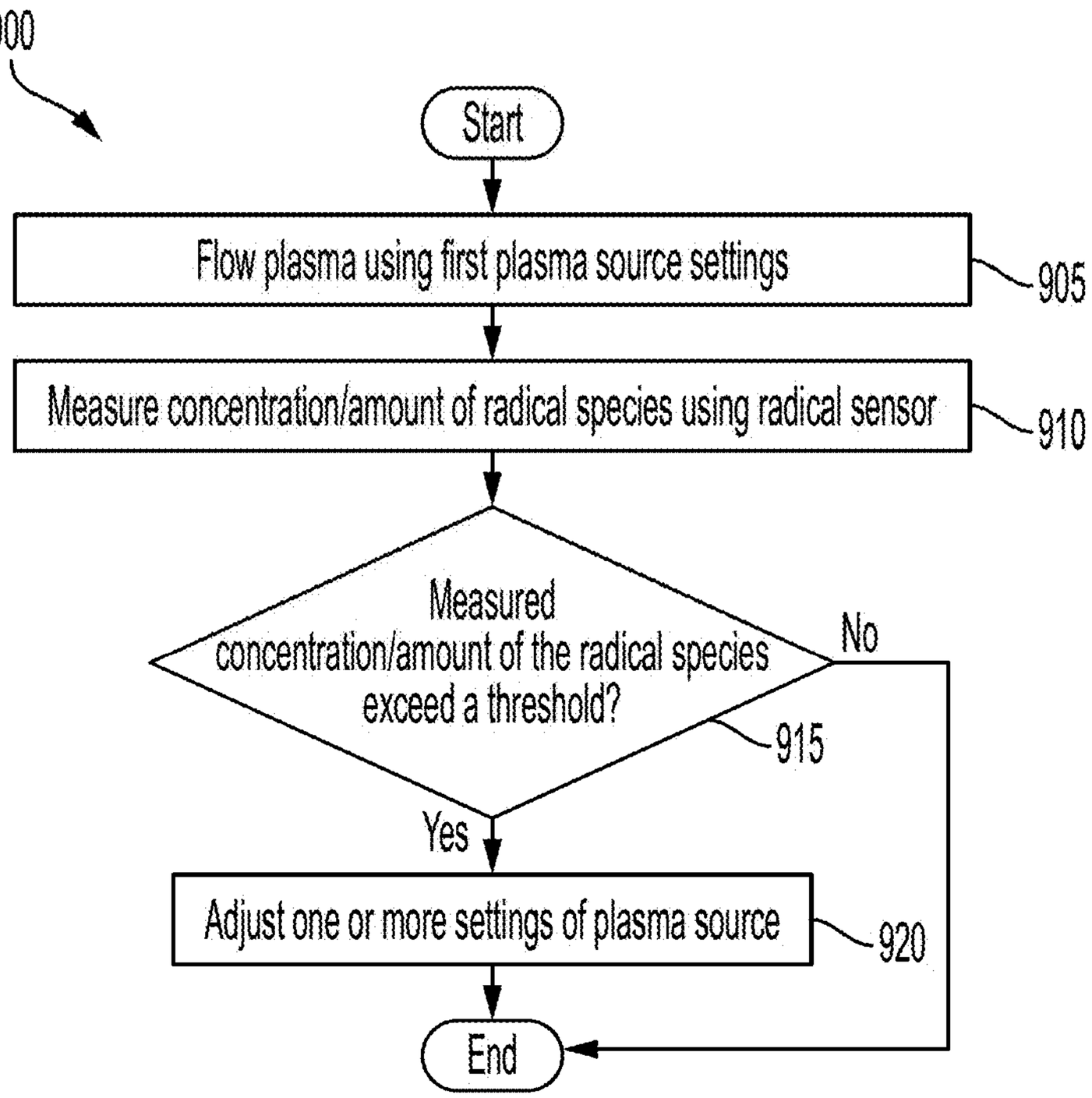

900
Start
Flow plasma using first plasma source settings
905
Measure concentration/amount of radical species using radical sensor
910
Measured concentration/amount of the radical species exceed a threshold?
915
No
Yes
Adjust one or more settings of plasma source
920
End

FIG. 9

ACOUSTIC RESONANCE SENSOR DEVICES FOR RADICAL SPECIES DETECTION WITH ENHANCED FILTERS

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] The present application claims priority to U.S. Provisional Patent Application No. 63/539,183, filed on Sep. 19, 2023 and entitled "ACOUSTIC RESONANCE SENSOR DEVICES FOR RADICAL SPECIES DETECTION WITH ENHANCED FILTERS", the entire contents of which are hereby incorporated by reference herein.

TECHNICAL FIELD

[0002] The instant specification relates to components and apparatuses for semiconductor manufacturing. More specifically, the instant specification relates to acoustic resonance sensor devices for radical species detection with enhanced filters.

BACKGROUND

[0003] Electronic devices, such as integrated circuits, are made possible by processes which produce intricately patterned material layers on substrate surfaces. Forming patterned material layers on a substrate can be performed using controlled methods for forming and removing material. Such methods can use gases to deposit layers, etch layers, clean substrates, and so on. Some processes are plasma-enhanced, during which a plasma can be formed and used during deposition, etching, cleaning, etc. A gas flow sensor, such as a mass flow controller, can be used to detect the amount of gas that is flowed. However, some gas flow sensors can measure a total amount of gases, and cannot measure specific subspecies of a gas, such as the amount of radical species and/or ions in a gas. For example, a mass flow controller can measure a total gas flow, but cannot measure an amount of any specific type of gas or an amount of a specific molecular species of a particular type of gas. Also, some sensors are made from machinable materials that can corrode in the presence of radical species, such as stainless steel.

[0004] In electronic device processing, radical species are often used for various processing operations in a processing chamber ("chamber"). For example, a radical species, such as atomic fluorine, may be used in an etch process or a chamber cleaning process. Radical species can be formed by various processes. One process to generate radical species is to use a plasma. For example, a gas or gas mixture including fluorine (F_2) can be flown into the chamber, and the plasma can break the compound into elemental fluorine (F). Radical species are highly chemically reactive.

[0005] Process control of radical species is difficult. Particularly, it may not be possible to effectively measure radical species concentration in a chamber. This is due, in part, to the highly reactive nature of the radical species. A radical species can react whenever the radical species contacts any surface or other compound. Even if the surface does not react with the radical species, it still may serve as a site for recombination of the radical species with each other thus converting the species to other useless compounds. As such, some mass spectrometry tools may not be able to measure the concentration of radical species. Without the ability to quantitatively measure radical species concentrations, effective process control, such as closed loop control, is not possible in existing electronic device manufacturing tools. Closed loop control refers to the use of measurements as a feedback signal to a controller in order to modify processing conditions in an ongoing process.

SUMMARY

[0006] The following is a simplified summary of the disclosure in order to provide a basic understanding of some aspects of the disclosure. This summary is not an extensive overview of the disclosure. It is intended to neither identify key or critical elements of the disclosure, nor delineate any scope of the particular implementations of the disclosure or any scope of the claims. Its sole purpose is to present some concepts of the disclosure in a simplified form as a prelude to the more detailed description that is presented later.

[0007] In some embodiments, a device is provided. The device includes a radical sensor including a piezoelectric resonator. The radical sensor includes a base structure including a piezoelectric material, and a filter formed on the base structure to selectively react with a radical species. A resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter. The filter includes at least one of: a crystalline material, a doped coating, or a coating having a thickness that ranges from about 5 micrometers to about 50 micrometers.

[0008] In some embodiments, a method is provided. The method includes obtaining a base structure of a radical sensor including a piezoelectric resonator, the base structure including a piezoelectric material, and forming, on the base structure, and a filter including a crystalline material to selectively react with a radical species. A resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter.

[0009] In some embodiments, a method is provided. The method includes obtaining a base structure of a radical sensor including a piezoelectric resonator, the base structure including a piezoelectric material, and forming, on the base structure, a filter including a coating to selectively react with a radical species. A resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter. Forming the filter includes at least one of: doping an initial coating with a dopant to form the coating, using a base material and the dopant to deposit the coating, forming the coating to have a thickness that ranges from about 5 micrometers to about 50 micrometers, or forming the coating using a deposition process performed at a temperature ranging from about 150° C. to about 450° C.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present disclosure is illustrated by way of example, and not by way of limitation in the figures of the accompanying drawings.

[0011] FIG. **1** is a sectional side view of an example manufacturing system including an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0012] FIGS. **2**A-**2**B are views of an example acoustic resonance sensor device for radical species detection, according to some embodiments.

[0013] FIGS. **3**A-**3**D are views of an example radical sensor of an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0014] FIGS. **4**A-**4**B are cross-sectional views of the formation of an example radical sensor of an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0015] FIG. **5** is a cross-sectional view of an example radical sensor of an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0016] FIG. **6** shows an example equivalent circuit for a radical sensor of an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0017] FIGS. **7**-**8**B are flowcharts of example methods for manufacturing an acoustic resonance sensor device for radical species detection, according to some embodiments.

[0018] FIG. **9** is a flowchart of an example method for utilizing an acoustic resonance sensor device for radical species detection, according to some embodiments.

DETAILED DESCRIPTION

[0019] Embodiments of the present disclosure relate to acoustic resonance sensor devices for radical species detection with enhanced filters. Plasma enhanced deposition processes may energize one or more constituent precursors to facilitate the formation of layers of materials (e.g., films) on a substrate. Any layers may be produced to develop semiconductor structures, display structures, and/or other types of structures, including conductive and dielectric films, as well as films to facilitate transfer and removal of materials. For example, hardmask films may be formed to facilitate patterning of a substrate, while protecting the underlying materials to be otherwise maintained. In many processing chambers ("chambers"), a number of precursors may be mixed in a gas panel and delivered to a processing region of a chamber where a substrate may be disposed.

[0020] As device features reduce in size, tolerances across a substrate surface may be reduced, and material property differences across a film may affect device realization and uniformity. Many chambers include a characteristic process signature, which may produce non-uniformity across a substrate. For example, the formation of radical species within the processing region and/or presence of remotely generated radical species present within the processing region may affect deposition times and profiles.

[0021] Some gas sensors (e.g., such as those in mass flow controllers) measure a total amount of gases, and cannot distinguish between specific species of molecules and/or atoms of gases. For example, a mass flow controller can measure a total gas flow, but cannot measure an amount of any specific type of gas or an amount of a specific molecular species of a particular type of gas.

[0022] In some embodiments, a chamber incorporates an acoustic resonance sensor device for radical species detection. An acoustic resonance sensor device can include a radical sensor to detect and/or measure radical species (e.g., plasma radical species) within a processing region of the chamber. For example, the processing region can be a region proximate to a substrate support of the chamber. A radical sensor device described herein may be designed to measure an amount of a radical species, such as fluorine radicals, hydrogen radicals, nitrogen radicals, etc., which other sensor devices may be incapable of detecting without use of expensive optical equipment such as spectroscopy equipment.

[0023] A radical sensor described herein can be used to measure amounts and/or concentrations of a radical species of a target gaseous species. In some embodiments, the radical sensor includes a piezoelectric resonator. The piezoelectric resonator can include a base structure including piezoelectric material that oscillates at a measurable resonant frequency. In some embodiments, the piezoelectric material includes a crystal.

[0024] In some embodiments, the base structure further includes at least one electrode formed on the piezoelectric material. For example, the at least one electrode can include a front electrode formed on a frontside of the piezoelectric material and/or a back electrode formed on a backside of the piezoelectric material. The frontside can correspond to a flat face of the piezoelectric material, and the backside can correspond to a convex face of the piezoelectric material. The at least one electrode can be formed from any suitable metal. Examples of suitable metals include aluminum (Al), gold (Au), etc.

[0025] The piezoelectric resonator can further include a filter (e.g., chemical filter) formed on the piezoelectric material. In some embodiments, the filter is formed on an electrode (e.g., the front electrode). The filter is a specialized filter can be used to filter out all molecules except for the radical species of the target gaseous species. The filter can change mass based on the reaction of the filter to the select molecular gaseous species (e.g., to radical species of a particular molecule). The change in the filter's mass can cause the resonant frequency at which the piezoelectric material oscillates to change. This change in the resonant frequency is measurable, and may be used to determine the quantity of the molecular species that reacted with the filter. Accordingly, a radical sensor described herein can include a filter, formed on a surface of a piezoelectric material, that is reactive to a target radical species of a target gas or molecule, but that is not reactive to stable molecules of the gas or molecule or to radical or stable species of other gases or molecules that are flowed together with the target gas or molecule.

[0026] In some embodiments, the piezoelectric resonator is a quartz crystal microbalance (QCM) resonator that uses a quartz crystal including silicon dioxide (SiO_2) as a piezoelectric material. A QCM resonator can be used to detect changes in the resonance frequency of the quartz crystal, which can be used to measure an amount and/or concentration of radical species.

[0027] A piezoelectric resonator can be designed for a specific application, and the filter of the piezoelectric resonator can include a material reactive to only radicals formed from a select molecular gaseous species used in the specific application. Examples of specific applications include etch operations, plasma assisted deposition processes (e.g., plasma assisted atomic layer deposition), etc. In an example, for a fluorine-based etch process, an etch rate of the chemical filter film or the etch rate of the piezoelectric crystal may strongly correlate to a concentration of fluorine radicals. Without the use of a radical sensor device including a suitable piezoelectric resonator (e.g., QCM resonator), the concentration of fluorine may not be directly detectable, and so engineers would guess at the concentration of fluorine radicals based on other known values such as a known plasma power, a known gas flow rate, and so on. By using a radical sensor including a suitable piezoelectric resonator as described herein (e.g., QCM resonator), the amount of fluorine radicals being flowed may be directly measured, and this measurement may be used to finely control the

amount of radicals being output by a plasma source, such as a remote plasma source (RPS).

[0028] A radical sensor described herein can obtain a measurement of the amount and/or concentration of a radical species, which can enable closed loop control of a processing environment based on the measurement. Closed loop control refers to the use of measurements as a feedback signal to a controller in order to modify processing conditions in an ongoing process. For example, a radical sensor described herein can measure the amount and/or concentration of the radical species to obtain a measured value, and the measured value can be compared to a setpoint value. When the measured value is below the setpoint value, processing parameters may be changed to increase the generation rate and output concentration of radical species. Alternatively, when the measured value is above the setpoint value, processing parameters may be changed to decrease the concentration of radical species. As such, a radical sensor described herein can be used to implement more stable and reproducible processes.

[0029] In some implementations, the filter of the piezoelectric resonator of a radical sensor is formed as coating. For example, the coating can include a film of an amorphous material (e.g., amorphous SiO_2). However, such coatings can degrade relatively quickly over time due to mass reduction caused by radical species (e.g., etching), which may prompt replacement of the piezoelectric resonator. Additionally, the degradation can affect the ability of the radical sensor to perform radical species detection.

[0030] To improve the lifespan and performance of a radical sensor device, embodiments described herein can be used to form an enhanced filter on a base structure of a piezoelectric resonator. In some embodiments, a piezoelectric resonator is a QCM resonator. The base structure can include a piezoelectric material. In some embodiments, the base structure further includes at least one electrode formed on the piezoelectric material. For example, the at least one electrode can include a front electrode and/or a back electrode, as described above. The at least one electrode (e.g., a coating of the at least one electrode) can include any suitable material in accordance with embodiments described herein. Examples of suitable materials include Al, Au, etc. The enhanced filter can have a more stable reaction and/or a lower rate of reaction with a radical species, while still being unreactive to a non-radical species (e.g., a more stable reaction and lower rate of reaction with atomic fluorine (F), while still being unreactive to molecular fluorine (F_2)).

[0031] In some embodiments, the enhanced filter is formed on the front electrode of the piezoelectric resonator. In some embodiments, the base structure does not include a front electrode, and the enhanced filter is formed directly on the piezoelectric material. Various methods for forming an enhanced filter are contemplated.

[0032] In some embodiments, forming an enhanced filter on a base structure of a piezoelectric resonator includes forming a crystalline material on the base structure. For example, the crystalline material can be formed on a front electrode of the base structure. In some embodiments, the crystalline material is a polycrystalline material. In some embodiments, the crystalline material includes SiO_2.

[0033] An interface between the crystalline material and the base structure can be a high-quality interface to enable an acoustic wave to travel through the interface. For example, a high-quality interface can be an interface having a suitable porosity. In some embodiments, a high-quality interface has a porosity of less than or equal to about 20%, a porosity of less than or equal to about 30%, or a porosity of less than or equal to 40%.

[0034] In some embodiments, the crystalline material is cut from a base material. For example, the crystalline material can include a SiO_2 crystal (e.g., polycrystalline SiO_2) cut from a base quartz material. In some embodiments, the crystalline material has a thickness that ranges from about 5 micrometers to about 50 micrometers.

[0035] In some embodiments, forming the crystalline material on the base structure includes attaching or bonding the crystalline material to base structure (e.g., the front electrode). For example, forming the crystalline material on the base structure can include using a bonding layer (e.g., glue) to attach the crystalline material to a surface of the base structure (e.g., a surface of the front electrode). The bonding layer can have suitable properties to enable an acoustic wave to penetrate through an interface. In some embodiments, the bonding layer improves an interface between the crystalline material and the base structure (e.g., reduces a porosity at the interface between the crystalline material and the base structure, such as by flowing to fill pores or voids at the interface).

[0036] In some embodiments, forming the crystalline material on the base structure includes etching the crystalline material of the piezoelectric material. More specifically, the base structure can lack a front electrode, and a mesh can be formed directly on a surface of the piezoelectric material. In some embodiments, forming the mesh includes placing the mesh on the surface of the piezoelectric material. In some embodiments, forming the mesh includes depositing the mesh on the surface of the piezoelectric material. The mesh can include any suitable material in accordance with embodiments described herein. Examples of suitable materials include Al, Au, nickel (Ni), etc. After the mesh is formed, a radical species can then be used to etch the piezoelectric material in a pattern defined by the mesh. In such an embodiment, the front surface of the piezoelectric material of the base structure itself acts as the filter, and so the base structure may be composed of a material that is selectively reactive to a target radical. In some embodiments, the base structure is or includes SiO_2.

[0037] In some embodiments, the filter includes a crystal structure having a number of grains. A grain can refer to a region within which the crystal lattice has a particular orientation. A crystal structure (e.g., polycrystalline material) can include multiple grains each having a respective orientation (e.g., random orientation) within the crystal structure. A pair of grains of a crystal structure can be separated by an interface referred to as a grain boundary. In some embodiments, a grain has a microstructure grain size selected to achieve a target filter lifetime depending on process conditions within which the radical sensor operates. In some embodiments, the microstructure grain size ranges between about 100 nanometers to about 50 micrometers, such as 200 nanometers, 300 nanometer, 400 nanometer, 500 nanometers, 1 micrometer, 5 micrometers, 10 micrometers, 25 micrometers, and so on. Additionally, increasing grain boundary size can increase the activation energy needed to induce a chemical reaction. Therefore, increasing grain boundary size can result in a greater amount or concentration of radical species being accumulated before etching of the material of the filter occurs.

[0038] In some embodiments, forming an enhanced filter on a base structure of a piezoelectric resonator includes forming an enhanced coating on the base structure. For example, the enhanced coating can be formed on a front electrode of the base structure.

[0039] In some embodiments, forming the enhanced coating on the base structure (e.g., on the front electrode) includes forming a coating on the base structure using a high temperature deposition process. In contrast to deposition processes that performs an initial low temperature or "cold" deposition of material, a high temperature deposition process maintains a high temperature throughout the entire process. An enhanced coating formed using a high temperature deposition process can exhibit decreased etch rates when exposed to a radical species as compared to a coating formed using other deposition processes. In some embodiments, the high temperature deposition process is performed at a temperature that ranges from about 150° C. to about 450° C., such as 200° C., 250° C., 300° C., 350° C., or 400° C. Examples of deposition processes that can be used to perform a high temperature deposition process include physical vapor deposition (PVD) (e.g., magnetron sputtering or electron beam evaporation), atomic layer deposition (ALD), chemical vapor deposition (CVD), plasma spray, ion assisted deposition (IAD), etc. In some embodiments, a deposition process is a thin-film deposition process.

[0040] For example, the deposition process can be electron beam evaporation. Electron beam evaporation is a type of PVD process. During electron beam evaporation, a target material (e.g., anode) is bombarded with an electron beam. The electron beam can be generated from a filament (e.g., tungsten filament) and steered by electric and magnetic fields to strike the target material. The electron beam causes atoms from the target material to transform into a gaseous phase. These atoms can then precipitate into solid form, coating surfaces with a layer of the target material. Electron beam evaporation can occur under high vacuum conditions to avoid contamination. In some embodiments, the deposition process is ion-assisted electron beam evaporation. During ion-assisted electron beam evaporation, an ion beam including ions (e.g., argon ions) with various energies can be directed to a target substrate along with the target material. The ion beam can impart energy into the gaseous phase atoms to improve properties of the layer of the target material (e.g., adhesion, density and/or grain structure).

[0041] In some embodiments, forming the enhanced coating on the base structure includes forming a thick coating on the base structure using a deposition process. In some embodiments, the deposition process is a high temperature deposition process, as described above. A thicker coating can increase the lifespan of the piezoelectric resonator. However, too thick of a coating can have a negative impact on performance of the piezoelectric resonator by blocking the transmission of acoustic waves. Thus, the thickness of the coating can be optimized to balance piezoelectric resonator lifespan with piezoelectric resonator performance. In some embodiments, the thick coating has a thickness that ranges between about 5 micrometers to about 50 micrometers, such as 10 micrometers, 15 micrometers, 20 micrometers, 25 micrometers, 30 micrometers, 35 micrometers, 40 micrometers, or 45 micrometers.

[0042] In some embodiments, forming the enhanced coating on the base structure includes forming an initial coating on the base structure using a deposition process (e.g., PVD, ALD or CVD), and doping the initial coating to obtain the enhanced coating. In some embodiments, the deposition process is a high temperature deposition process, as described above. Any suitable doping process can be used to dope the initial coating to obtain the enhanced coating. Examples of doping processes include particle bombardment (e.g., helium (He) bombardment), particle implantation (e.g., ion implantation), etc. Examples of dopants that can be used to dope the initial coating include yttrium (Y), phosphorous (P), boron (B), etc. In some embodiments, the dopant is deposited at the same time as a base material (e.g., base coating).

[0043] In some embodiments, a filter includes a material that increases radical species detection resolution and measurement accuracy in a radical sensor by reducing sensor signal noise. For example, in the context of fluorine radical detection, the material can include a silicon material. Such a material can increase the radical detection rate of the filter to the radical species. The thickness range of the material can vary between 500 nanometers to about 50 micrometers. The diameter of the region coated with the material can range between about 2 millimeters to about 14 millimeters. The deposited material may have reaction rates with the target radical that are several times higher and as such the detection sensitivity is enhanced while the relative lifetime for the same coating thickness is reduced.

[0044] The radical sensor can be used to measure thickness change of the filter formed on the base structure. Thickness change expressed in terms of areal mass density (mass per unit area) may be more appropriate at subatomic sizes. For heavy loading on the base structure, accuracy of the measurement can depend on the knowledge of the shear-mode acoustic impedance value of the deposited material. Larger crystals do not have higher sensitivity. Since a radical sensor is not a weighing device as it does not require a gravitational force, a radical sensor can be used in zero gravity environments such as outer space. In some embodiments, a thickness reading of the filter, t_f, may be derived from the areal mass density value of the filter based on the density of the material, pf (e.g., $t_f \rho_f$). The areal mass density measurement is in absolute value, in some embodiments. In some embodiments, no calibration is needed for a properly designed radical sensor. Temperature variation, stress, gas adsorption and desorption, surface reaction, etc. can all give false signals.

[0045] Embodiments described herein can provide various technical benefits. For example, embodiments described herein can improve the lifespan and/or performance of radical sensors. These and other embodiments, along with many of their advantages and features, are described in more detail in conjunction with the below description and attached figures.

[0046] Although the remaining disclosure will routinely identify specific deposition and/or etch processes utilizing the disclosed technology, it will be readily understood that the systems and methods are equally applicable to other deposition, etch, and cleaning chambers, as well as processes as may occur in the described chambers. Accordingly, the technology should not be considered to be so limited as for use with these specific deposition processes or chambers alone. The disclosure will discuss one possible system and chamber that may include lid stack components according to embodiments of the present technology before additional

variations and adjustments to this system according to embodiments of the present technology are described.

[0047] FIG. **1** is a sectional view of a manufacturing system **100**, according to some embodiments. The manufacturing system **100** may include a processing chamber ("chamber") **101** coupled to a plasma source **158** via one or more gas delivery lines **133**. The chamber **101** may be, for example, a plasma etch reactor, a deposition chamber, etc. The chamber **101** may be suitable for an etching operation, a deposition operation, a chamber cleaning operation, a plasma treatment operation, or any other type of operation typical of a semiconductor manufacturing facility. In some embodiments, one or more substrates (e.g., wafers) **144** may be provided within the chamber **101**. In some embodiments, chamber **101** may be maintained at a pressure suitable for the target operation. In a particular embodiment, the pressure may be between approximately a fraction of a Torr and approximately 200 Torr. The chamber **101** and/or plasma source **158** may be connected to a system controller **188**, which may control processing of the plasma source **158** and/or chamber **101** (e.g., by controlling set points, loading recipes, and so on).

[0048] An acoustic resonance sensor device **135** may be connected to the gas delivery line(s) **133**. The acoustic resonance sensor device **135** can include a radical sensor to detect radical species in a gas or plasma delivered by the plasma source **158**. For example, the radical sensor can measure an amount or concentration of the radical species. In some embodiments, the acoustic resonance sensor device **135** is fluidically coupled to the chamber **101** and/or to the gas delivery line(s) **133**. For example, a valve may be provided along a tube between the chamber **101** and the acoustic resonance sensor device **135**. In some embodiments, the valve is a type of valve that allows for an unobstructed line of sight between the chamber **101** and the radical sensor. For example, the valve may be an isolation gate valve. An isolation gate valve may allow for a binary state of operation. That is, the valve may be open (i.e., **1**) or closed (i.e., **0**). When the valve is open, the line of sight is unobstructed. Alternately, another type of valve such as a needle valve may be used.

[0049] In some embodiments, the radical sensor includes a piezoelectric resonator. For example, the piezoelectric resonator can include a QCM resonator. A piezoelectric resonator can resonate at a resonant frequency by applying an alternating current to a base structure including a piezoelectric material. A filter can be formed on one or more surfaces of the base structure. The filter can be reactive to a narrow range of molecular species. In particular, the filter can be composed of a material that is reactive to a target molecular species of a particular target gas from among gases being used in a process. In some embodiments, the acoustic resonance sensor device **135** includes a radical sensor holder to hold the radical sensor. The acoustic resonance sensor device **135** will be described in greater detail below with reference to the proceeding figures.

[0050] In some embodiments, the plasma source **158** is a remote plasma source (RPS) that generates plasma at a remote location and delivers the externally generated plasma to the chamber **101**. Alternatively, the chamber **101** may include an integrated plasma source (not shown) that can generate plasma within the processing chamber. In either instance, the radical sensor may be disposed within or connected to the chamber **101** rather than in or connected to the gas delivery lines **133** in some embodiments.

[0051] The chamber **101** can include a substrate support assembly **150**. The substrate support assembly **150** can include a puck **166**. The puck **166** may perform chucking operations, e.g., vacuum chucking, electrostatic chucking, etc. The substrate support assembly **150** may further include base plate, cooling plate and/or insulator plate (not shown).

[0052] The chamber **101** can include a chamber body **102** and a lid **104** that enclose an interior volume **106**. The chamber body **102** may be fabricated from aluminum, stainless steel, or other suitable material. The chamber body **102** generally includes sidewalls **108** and a bottom **110**. An outer liner **116** may be disposed adjacent to the sidewalls **108**, e.g., to protect the chamber body **102**. The outer liner **116** may be fabricated and/or coated with a plasma or halogen-containing gas resistant material. The outer liner **116** may be fabricated from or coated with aluminum oxide. The outer liner **116** may be fabricated from or coated with yttria, yttrium alloy, oxides thereof, etc.

[0053] The exhaust port **126** may be defined in the chamber body **102**, and may couple the interior volume **106** to a pump system **128**. The pump system **128** may include one or more pumps, valves, lines, manifolds, tanks, etc., utilized to evacuate and regulate the pressure of the interior volume **106**.

[0054] The lid **104** may be supported on one of the sidewalls **108** of the chamber body **102**. The lid **104** may be openable, allowing access to the interior volume **106**. The lid **104** may provide a seal for the chamber **101** when closed. The plasma source **158** may be coupled to the chamber **101** to provide process, cleaning, backing, flushing, etc., gases and/or plasmas to the interior volume **106** through a gas distribution assembly **130**, which can be integrated with the lid **104**.

[0055] Examples of processing gases that may be used in the manufacturing system **100** include halogen-containing gases, such as F_2, C_2F_6, SF_6, $SiCl_4$, HBr, NF_3, CF_4, CHF_3, CH_2F_3, Cl_2 and SiF_4. Other reactive gases may include O_2 or N_2O. Non-reactive gases may be used for flushing or as carrier gases, such as N_2, He, Ar, etc. The gas distribution assembly **130** (e.g., showerhead) may include multiple apertures **132** on the downstream surface of the gas distribution assembly **130**. The apertures **132** may direct gas flow to the surface of a substrate **144**. In some embodiments, gas distribution assembly may include a nozzle (not pictured) extended through a hold in the lid **104**. A seal may be made between the nozzle and the lid **104**. The gas distribution assembly **130** may be fabricated and/or coated by a ceramic material, such as silicon carbide, yttrium oxide, etc., to provide resistance to processing conditions of the chamber **101**.

[0056] The substrate support assembly **150** is disposed in the interior volume **106** below the gas distribution assembly **130**. The substrate support assembly **150** holds the substrate **144** during processing. An inner liner (not shown) may be coated on the periphery of substrate support assembly **148**. The inner liner **118** may share features (e.g., materials of manufacture, function, etc.) with outer liner **116**.

[0057] The substrate support assembly **150** may include supporting a pedestal **152**, an insulator plate, a base plate, a cooling plate, and a puck **166**. The puck **166** may include electrodes **136** for providing one or more functions. For example, the electrodes **136** may include chucking elec-

trodes (e.g., for securing the substrate **144** to an upper surface of the puck **166**), heating electrodes, RF electrodes for plasma control, etc.

[0058] A protective ring **146** may be disposed over a portion of the puck **166** at an outer perimeter of the puck **166**. The puck **166** may be coated with a protective layer (not shown). The protective layer may be a ceramic such as Y_2O_3 (yttria or yttrium oxide), $Y_4Al_2O_9$(YAM), Al_2O_3 (alumina), $Y_3Al_5O_{12}$ (YAG), $YAlO_3$ (YAP), quartz, SiC (silicon carbide), Si_3N_4 (silicon nitride), Sialon, AlN (aluminum nitride), AlON (aluminum oxynitride), TiO_2 (titania), ZrO_2 (zirconia), TiC (titanium carbide), ZrC (zirconium carbide), TiN (titanium nitride), TiCN (titanium carbon nitride), Y_2O_3 stabilized ZrO_2 (YSZ), and so on. The protective layer may be a ceramic composite such as YAG distributed in an alumina matrix, a yttria-zirconia solid solution, a silicon carbide-silicon nitride solid solution, or the like. The protective layer may be sapphire or MgAlON.

[0059] The puck **166** may further include multiple gas passages such as grooves, mesas, and other features that may be formed in an upper surface of the puck **166**. Gas passages may be fluidly coupled to a gas source **105**. Gas from the gas source **105** may be utilized as a heat transfer or backside gas, may be utilized for control of one or more lift pins of the puck **166**, etc. Multiple gas sources may be utilized (not shown). Gas passages may provide a gas flow path for a backside gas such as He via holes drilled in the puck **166**. Backside gas may be provided at a controlled pressure into gas passages to enhance heat transfer between the puck **166** and the substrate **144**.

[0060] The puck **166** may include one or more clamping electrodes. The clamping electrodes may be controlled by a chucking power source **182**. Clamping electrodes may further couple to one or more RF power sources through a matching circuit for maintaining a plasma formed from process and/or other gases within the chamber **101**. The RF power sources may be capable of producing an RF signal having a frequency from about 50 kilohertz (kHz) to about 3 gigahertz (GHz) and a power of up to about 10,000 Watts. Heating electrodes of the puck **166** may be coupled to heater power source **178**.

[0061] The system controller **188** may control one or more parameters and/or set points of the plasma source **158** and/or the chamber **101**. The system controller **188** can be and/or include a computing device such as a personal computer, a server computer, a programmable logic controller (PLC), a microcontroller, and so on. The system controller **188** can include one or more processing devices, which can be general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processing device can be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, or a processor implementing other instruction sets or processors implementing a combination of instruction sets. The processing device can also be one or more special-purpose processing devices such as an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a digital signal processor (DSP), network processor, or the like. The system controller **188** can include a data storage device (e.g., one or more disk drives and/or solid-state drives), a main memory, a static memory, a network interface, and/or other components. The system controller **188** can execute instructions to perform any one or more of the methodologies and/or embodiments described herein. The instructions can be stored on a computer readable storage medium, which can include the main memory, static memory, secondary storage and/or processing device (during execution of the instructions). In some embodiments, execution of the instructions by the system controller **188** causes the system controller **188** to perform methods, such as the methods described below with reference to FIG. **9**. For example, the system controller **188** may receive measurements from radical sensor indicating a concentration of a particular species of radical species in a received or generated plasma, and may adjust one or more properties or settings (e.g., such as a plasma power) of the plasma source **158** responsive to the measured radical concentration. The system controller **188** can also be configured to permit entry and display of data, operating commands, and the like by a human operator.

[0062] FIGS. **2**A-**2**B illustrate an example acoustic resonance sensor device for radical species detection ("device") **200**, in accordance with some embodiments. The device **200** may can be disposed within a processing region of a deposition chamber, etch chamber, or other type of chamber, such as chamber **101** of manufacturing system **100** of FIG. **1**.

[0063] The device **200** may include a radical sensor holder **202**, which may be sized and shaped to receive a radical sensor **204**. In some embodiments, the radical sensor **204** includes a piezoelectric resonator. For example, the radical sensor **204** can include a QCM resonator.

[0064] For example, the radical sensor holder **202** may include a body **206** that defines a recess **208** and an aperture **210**. The radical sensor **204** may include a disc body **212** and may include a stem **214** extending from the disc body **212**. The disc body **212** may be circular or otherwise round in some embodiments, although other shapes are possible. The disc body **212** may be seated within a recess **208**, while the stem **214** may extend through an aperture **210**.

[0065] In some embodiments, electrically conductive resilient members **222** (such as springs) may be positioned above and/or below the disc body **212** to help maintain electrical contact between the radical sensor **204** and the radical sensor holder **202**, while ensuring that pressure between a lid **216** and the body **206** does not crack or otherwise damage the radical sensor **204**. In some embodiments, the electrically conductive resilient members **222** may be formed from and/or coated with chamber-compatible materials to ensure that the electrically conductive resilient members **222** do not corrode during exposure to process gases and plasma radical species. In some embodiments, the electrically conductive resilient members **222** may be formed from and/or coated with a corrosion-resistant material. For example, the electrically conductive resilient members **222** can be formed from palladium (Pd), although other materials may be used in various embodiments.

[0066] In some embodiments, the body **206** is in-line. In some embodiments, the body **206** is configured to be tilted in accordance with a range of angles relative to the vertical axis. In some embodiments, the body **206** can be tilted between about 0 degrees to about 90 degrees relative to the vertical axis. In some embodiments, the body **206** can be tilted about 45 degrees relative to the vertical axis.

[0067] The lid **216** may be coupled with body **206** to secure the radical sensor **204** within a recess **208**. The lid **216** may include an inner portion **218** that may extend into

a recess **208** and may press against the radical sensor **204** and/or the electrically conductive resilient members **222** that may be disposed between the lid **216** and the radical sensor **204**. The lid **216** may also include a flange **220** that is coupled with the inner portion **218**. The flange **220** may be positioned against an upper surface of the body **206**. The flange **220** may include slots **224** that may receive fasteners **226** that secure the lid **216** to the body **206**. In some embodiments, the fasteners **226** may be screws. However, when the body **206** is formed from aluminum alloys, screws may be undesirable due to the nature of aluminum threads to wear over time. In such embodiments, other fasteners, such as press-fit connections, may be utilized as the fasteners **226**. For example, each slot **224** may be generally arcuate in shape and may be keyed. In the present embodiment, each slot **224** may include a receiving end **228** and a locking end **230**. The receiving end **228** may be wider than the locking end **230**. For example, medial and/or bottom portion of each slot may taper to a narrower width along a length of each slot **224** to form the locking end **230** having a shelf **232**. In some embodiments, an upper portion of each slot **224** may have a constant width. The fasteners **226** may each be a pin having an elongate pin body **234** that couples with a pin head **236** having a greater diameter than the pin body **234**. Each pin body **234** may be secured within the body **206**, such as by being press fit within a recess formed within the body **206**, with each respective pin head **236** extending above and being spaced apart from an upper surface of the body **206**. The lid **216** may be positioned atop the body **206** with each pin head **236** extending through the receiving end **228** of respective slot **224**. The lid **216** may then be rotated relative to the body **206** to slide each pin head **236** toward and into engagement with the locking end **230** of each slot **224** to secure the lid **216** against the body **206**. In such a position, a bottom surface of each pin head **236** may be seated against a shelf **232**, which prevents the lid **216** from being pulled away from the body **206** until rotated in the opposite direction to align each pin head **236** with the receiving end **228** of respective slot **224**. Such a configuration may enable the lid **216** to be repeatedly removed from and resecured to the body **206** to insert and/or remove the radical sensor **204** from the recess **208**.

[0068] The radical sensor **204** may include a crystalline material, such as a polycrystalline material, that may react with radical species (e.g., plasma radical species). The reaction with the radical species may result in the additional or removal of a small amount of mass of the crystalline material and/or filter, such as due to oxide growth/decay and/or a film deposition on the surface of the radical sensor **204**. The mass change may alter the frequency of the radical sensor **204**. The frequency may be measured and correlated to plasma radical concentration values, which may enable the radical sensor **204** to be effectively used to monitor (e.g., detect and/or measure) radical species within a processing region of a chamber. The radical sensor **204** may be formed from various quartz crystals, such as, but not limited to, SiO_x.

[0069] The radical sensor holder **202** may be formed from an electrically conductive and/or chamber compatible material. In some embodiments, an entirety of the radical sensor holder **202** is formed from, or coated with, an electrically conductive chamber compatible material. In some embodiments, the radical sensor holder **202** includes Al. For example, the radical sensor holder **202** can include an Al alloy. In some embodiments, an Al alloy includes magnesium, such as between 5% and 20% by mass of magnesium, which may provide enhanced corrosion resistance (e.g., when fluorinated during processing operations). In some embodiments, aluminum **5083** and/or aluminum **6061** may be used, although other aluminum alloys may be utilized in various embodiments. The use of aluminum may also provide a large surface area of thermally conductive material in contact with the radical sensor **204** and thereby reduce acoustic resonance shifts due to thermal effects.

[0070] The device **200** may include an electrical transmission line **238** that may be electrically coupled with the radical sensor **204**. For example, the stem **214** may define a recess **241** that may receive an end of the electrical transmission line **238**. In some embodiments, the end of the electrical transmission line **238** may be secured within the stem **214** using a set screw, however other securement techniques are possible in various embodiments. An opposite end of the electrical transmission line **238** may be secured within a first end of an adapter **240**, such as by using an additional set screw to secure the opposite end of the electrical transmission line **238** into a recess formed in the first end of the adapter **240**. In some embodiments, the electrical transmission line **238** is formed from aluminum. In some embodiments, the electrical transmission line **238** provides tension release (e.g., slack) between adapter **240** and the stem **214**. For example, the tension release provided by the electrical transmission line **238** can enable proper functionality of the electrically conductive resilient members **222**. As another example, if the electrical transmission line **238** is too rigid, there is a risk of disconnection with respect to the adapter **240**.

[0071] The radical sensor holder **202** and at least a portion of the electrical transmission line **238** may be designed to be exposed to the processing region of a chamber. To help mount holder within the chamber, the device **200** may include an exterior portion **242**, which may be positioned outside of the processing region. For example, the exterior portion **242** may be disposed against an outer wall of a chamber body, liner assembly, and/or other component of the chamber that defines a portion of the processing region. The component may define a small aperture through which the radical sensor holder **202** may be inserted. Exterior portion **242** may include a flange **244** having a greater diameter than the radical sensor holder **202**. The flange **244** may be positioned against an outer surface of the chamber component defining the aperture, and may prevent the remaining parts of the exterior portion **242** from being inserted within the chamber. The flange **244** may have vacuum sealing in circular shape or non-circular shape depending on matching flange on the process chamber or vacuum system. The flange **244** may define an annular recess **246**. An annular sealing member **248** may be seated within the annular recess **246** and may be used to provide a vacuum seal for an interface between the flange **244** and a chamber component that the flange **244** is positioned against. The flange **244** may define connectors **249**, such as threaded connectors. Each of the connectors **249** may receive an end of a respective one of standoffs **250**. The standoffs **250** may extend between and couple the radical sensor holder **202** and the flange **244**. The standoffs **250** may be removably coupled with the flange **244** and/or the radical sensor holder **202**, such as via threaded connections. In some embodiments, ends of each of the standoffs **250** may be

permanently coupled with one of the radical sensor holder **202** or the flange **244**. The connectors **249** and the standoffs **250** may be disposed radially inward of an annular recess **246**, which may ensure that an annular sealing member **248** is able to seal an area radially outward of the connectors **249** and the standoffs **250**.

[0072] The exterior portion **242** may include a connector **256** having a housing **252** that extends from the flange **244** in a direction opposite of the radical sensor holder **202**. The housing **252** and the flange **244** may collectively define a central aperture **254** that extends through an entire length of the exterior portion **242**. The housing **252** may include a housing shoulder **258** that extends radially inward from an inner sidewall **260** of the housing **252**. The housing shoulder **258** may define a portion of a central aperture **256**, with the portion of the central aperture **256** that passes through the housing shoulder **258** having a smaller diameter than the rest of the central aperture **256**. In some embodiments, the housing **252** may include first housing portion **262** and a second housing portion **264** that are coupled together, either permanently or reversibly (e.g., using a threaded connection). For example, the first housing portion **262** may extend from the flange **244** and may define the housing shoulder **258**. The second housing portion **264** may be coupled with a distal end of the first housing portion **262** and may define a coupling mechanism for coupling the device **200** with a coupling mechanism of an electrical port, such as a Bayonet Neill-Concelman (BNC) connection. The first housing portion **262** and the second housing portion **264** may be reversibly coupled with one another to enable interior components, such as an isolator **266**, to be inserted and secured within an interior of the housing **252**.

[0073] The adapter **240** and one end of the electrical transmission line **238** may be disposed within the central aperture **256**. A second end of the adapter **240** may define an additional recess that may receive a first end of the electrical connection **268**. A second end of the electrical connection **268** may include a connection member **271**, such as a BNC bayonet that may be inserted within a corresponding electrical port of a chamber. The electrical connection **268** and the electrical transmission line **238** may be used to electrically couple the radical sensor **204** with the chamber electrical port for transmission of electrical signals between the radical sensor **204** and chamber electronics. In some embodiments, a medial portion of the electrical connection **268** may include a flange **270** that extends radially outward from a body of the electrical connection **268**. The flange **270** may be positioned in alignment or a slight offset with the housing shoulder **258**. The isolator **266** may define an aperture **273** through which a portion of the electrical connection **268** may pass. A first end of the isolator **266** may be seated against a rear surface of the housing shoulder **258** and a rear surface of the flange **270**. In some embodiments, the first end of the isolator **266** may be a single planar surface, such as when rear surfaces of the housing shoulder **258** and the flange **270** are in substantial alignment. In other embodiments, the first end of the isolator **266** may include a stepped interface, such that an outer portion of the first end protrudes beyond an inner portion of the first end. Such a configuration may enable an offset between rear surfaces of the housing shoulder **258** and the flange **270**. Sealing members **272** may be disposed between the first end of the isolator **266** and rear surfaces of each of the housing shoulder **258** and the flange **270**. For example, a first sealing member **272***a* may be disposed between the first end of the isolator **266** and a rear surface of the housing shoulder **258** and a second sealing member **272***b* may be disposed between the first end of the isolator **266** and a rear surface of the flange **270**. In some embodiments, each sealing member **272** may be an O-ring, gasket, or other compressible sealing element. Each sealing member **272** can be formed from an elastomeric polymer and/or chamber-compatible material.

[0074] Compression of the sealing members **272** may provide a vacuum seal within the interior of the central aperture **254** and may enable the radical sensor holder **202** to be positioned within a low pressure/vacuum environment while an exterior portion **242** remains at higher (e.g., atmospheric) pressures. To ensure that the sealing members **272** are sufficiently compressed, the device **200** may include an adjustment mechanism that enables an amount of compressive force applied to the sealing members **272** to be controlled. In the illustrated embodiment, the adjustment mechanism may include threads **274** formed on a shaft **280** of the electrical connection **268**. A nut **278** may be threadingly engaged with the threads **274** such that as the nut **278** is tightened, the nut **278** moves toward and contacts a second end of isolator to force the isolator **266** toward the flange **270**, the housing shoulder **258**, the flange **244**, and the radical sensor holder **202**. Movement of the isolator **266** in this direction causes the sealing members **272** to be compressed to create a vacuum seal between the isolator **266**, the housing **252**, and the electrical connection **268**. In some embodiments, the nut **278** may be secured to the threads **274** and tightened prior to coupling the second housing portion **264** with the first housing portion **262**, which may provide additional clearance for a wrench or other tool to manipulate the nut **278**. Once the nut **278** is tightened, the second housing portion **264** may be secured to the first housing portion **262**, such as by engaging threaded connectors of each housing portion. In some embodiments, a proximal/inner end of the second housing portion **264** may be disposed within the central aperture **254** and may contact the second end of the isolator **266**. In some embodiments, the second end of isolator **266** may be a single planar surface such that when nut **278** and the second housing portion **264** are tightened, the nut **278** and the second housing portion **264** are in substantial alignment. In other embodiments, the second end of the isolator **266** may include a stepped interface, such that an inner portion of the second end protrudes beyond an outer portion of the second end. Such a configuration may accommodate an offset between surfaces of the nut **278** and the second housing portion **264**.

[0075] The isolator **266** may be formed from an electrically insulting material, such as a dielectric or ceramic material (e.g., alumina). Such materials may ensure that the isolator **266** may support the electrical connection **268** within a center of the central aperture **254** while insulating the housing **252** from the electrical connection **268** to ensure that there is no shorting or transmission of electrical signals between the electrical connection **268** and the housing **252**. Other than the isolator **266**, the exterior portion **242** may be formed from and/or coated with a chamber compatible material, such as an aluminum alloy, as portions of the interior of exterior portion that are between the sealing members **272** and the flange **244** may be exposed to process gases, radical species, and/or low pressure environments. In some embodiments, at least a portion of the exterior portion

242 (aside from the isolator **266**) may be formed from and/or coated with a same material as the radical sensor holder **202**, although other materials are possible in various embodiments.

[0076] FIGS. **3**A-**3**D illustrate an example radical sensor **300**, in accordance with embodiments of the present disclosure. In some embodiments, the radical sensor **300** corresponds to the radical sensor **204** of FIGS. **2**A-**2**B. FIG. **3**A is a sectional side view of the radical sensor **300**, according to some embodiments. FIG. **3**B is a back view of the radical sensor **300** of FIG. **3**A, according to some embodiments. FIG. **3**C is a front view of the radical sensor **300** of FIG. **3**A, according to some embodiments.

[0077] In some embodiments, the radical sensor **300** includes a piezoelectric resonator. For example, the radical sensor **300** can include a QCM resonator. As shown, the radical sensor **300** can include a base structure including a radical sensor base **315**. In some embodiments, the radical sensor **300** includes a piezoelectric resonator and the radical sensor base **315** includes a piezoelectric material that can oscillate at certain resonant frequencies. The radical sensor base **315** may include a thin plate of a piezoelectric crystal (e.g., quartz crystal) that oscillates in the thickness-shear mode because the radical sensor base **315** is sensitive to mass change on the crystal. The piezoelectric nature of the crystal allows the crystal to be driven into oscillation and with its resonant frequency measured by simple electrical means. In some embodiments, the crystal is precisely cut at certain angles with respect to its crystallographic axes. By increasing the mass of the vibrating unit, the typical result is the decrease of that solid material's resonant frequencies.

[0078] As shown in FIGS. **3**A-C, the radical sensor base **315** can have a flat face and a convex face. The flat face may be a front face and the convex face may be a back face. As shown, the base structure can further include a back electrode **320** and a front electrode **330**. For example, in this example, the flat face may be covered by the front electrode **330** and the convex face may be covered by the back electrode **320**. In some embodiments, the back electrode **320** includes a back electrode edge **325** connected to a back electrode center **320** via one or more electrode bridges **327**. This configuration enables an alternating current to be applied to and/or read from the electrodes without compromising the ability of the radical sensor base **315** to oscillate freely. A sensing surface of the radical sensor **300** may be a center region of the front face (e.g., a center region of the front electrode **330**).

[0079] In some embodiments, the sensing surface of the radical sensor **300** is coated with a filter **335** that is sensitive to reaction with a particular molecular species of a target gaseous species. The composition of the filter **335** may depend on the application for which the radical sensor **300** will be used. In some embodiments, the filter **335** includes a coating (e.g., film).

[0080] In some embodiments, the filter **335** is composed of a material that reacts with a radical molecular species of a target gas, but that does not react to stable molecular species of the target gas. For example, the material of the filter **335** may react to fluorine radical species, but may not react to stable molecules containing fluorine (e.g., F_2, C_2F_6, SF_6, NF_3, CF_4, CHF_3, CH_2F_3, etc.). The material of the filter **335** may also not react to other molecules that may be included in a gas flow, whether those other molecules are radical species or stable molecular species. For example, the material of the filter **335** may react to fluorine radical species, but may not react to carbon radical species, nitrogen radical species, hydrogen radical species, etc. Alternatively, the material may only react to hydrogen radical species, or may only react to carbon radical species, or may only react to some other radical species.

[0081] In some embodiments in which the radical sensor **300** is tuned to detect fluorine radical species, the filter **335** includes silicon dioxide (SiO_2), tungsten, or a tungsten oxide (e.g., tungsten (III) oxide or W_2O_3) and/or organic materials (such as photoresist). In some embodiments in which the radical sensor is tuned to detect fluorine radical species, the filter **335** includes a transition metal that selectively reacts with fluorine radical species. In some embodiments in which the radical sensor is tuned to detect hydrogen radical species, the filter **335** comprises a polymer of carbon and hydrogen. One example of a polymer that may be used is polymethyl methacrylate (PMMA). In some embodiments in which the radical sensor is tuned to detect nitrogen radical species, the filter **335** includes a fluorinated polymer.

[0082] In some embodiments, the target radical species react with the filter **335** to form a gas, which consumes a portion of the filter **335**. The consumption of the portion of the filter **335** reduces the number of molecules of the filter **335**, and thus reduces an overall mass of the film of the filter **335**. This reduction in mass may be detected by the radical sensor **300** on which the filter **335** has been formed.

[0083] In some embodiments, the reaction of the target radical species with the filter **335** produces a solid byproduct. The solid byproduct can adhere to the filter **335**, which can increase the mass of the filter **335**. This increase in mass may be detected by the radical sensor **300** on which the filter **335** has been formed.

[0084] In some embodiments, the reaction of the target radical species with the filter **335** is an absorption process where the filter **335** absorbs the target radical species. The absorption of the radical species causes the mass of the filter **335** to increase. Once the filter **335** becomes saturated with the target radical species and/or between process runs, a purge or cleaning process may be performed to cause the radical species to desorb from the filter **335**. In an example, a QCM with a coating of PMMA may be used to detect fluorine radical species. The PMMA may absorb fluorine radical species, and the mass change of the film caused by absorption of the fluorine radical species may be detected by a change in resonant frequency of radical sensor **300**. The fluorine radical species may then be desorbed by flowing another gas such as argon across radical sensor **300**.

[0085] In some embodiments, the filter **335** has a thickness of about 1-100 micrometers. In some embodiments, the filter **335** has a thickness of about 30-40 micrometers. Other thicknesses, such as 10, 20, 30, 40, 50, 60, 70, 80 or 90 micrometers may also be used for the filter **335**.

[0086] In some embodiments, the filter **335** is a coating. In some embodiments, forming filter **335** includes forming the coating using a high temperature deposition process. A coating formed using a high temperature deposition process can exhibit decreased etch rates when exposed to a radical species as compared to a coating formed using other deposition processes. In some embodiments, the high temperature deposition process is performed at a temperature that ranges from about 150° C. to about 450° C. Examples of deposition processes that can be used to perform a high

temperature deposition process include PVD (e.g., magnetic sputtering or electron beam evaporation), ALD, CVD, plasma spray, IAD, etc.

[0087] In some embodiments, the filter **335** includes a thick coating formed using a deposition process. In some embodiments, the deposition process is a high temperature deposition process, as described above. A thicker coating can increase the lifespan of the radical sensor **300**. However, too thick of a coating can negative impact performance of the radical sensor **300** by blocking the transmission of acoustic waves. Thus, the thickness of the coating can be optimized to balance lifespan with performance. In some embodiments, the coating of the filter **335** has a thickness that ranges between about 5 micrometers to about 50 micrometers.

[0088] In some embodiments, the filter **335** includes a doped coating. For example, forming the filter **335** can include forming an initial coating on the base structure using a deposition process (e.g., PVD, ALD or CVD), and doping the initial coating with a dopant to obtain the filter **335**. In some embodiments, the deposition process is a high temperature deposition process, as described above. Any suitable doping process can be used to dope the initial coating to obtain the enhanced coating. Examples of doping processes include particle bombardment (e.g., He bombardment), particle implantation (e.g., ion implantation), etc. Examples of dopants that can be used to dope the initial coating include Y, P, B, etc. In some embodiments, a base material (e.g., base coating) and the dopant are deposited at substantially the same time to form the filter **335**.

[0089] In some embodiments, the filter **335** includes a material that increases radical species detection resolution and measurement accuracy of the radical sensor **300** by reducing sensor signal noise. Such a material can increase the radical detection rate of the filter **335** to the radical species. The thickness range of the material can vary between 500 nanometers to about 50 micrometers. The diameter of the material can range between about 2 millimeters to about 14 millimeters. For example, in the context of fluorine radical detection, the material can be a silicon material.

[0090] In some embodiments, the filter **335** includes a crystalline material. For example, the crystalline material can be formed on the front electrode **330**. In some embodiments, the crystalline material is a polycrystalline material. In some embodiments, the crystalline material includes SiO_2.

[0091] An interface between the crystalline material and the base structure can be a high-quality interface to enable an acoustic wave to travel through the interface. For example, a high-quality interface can be an interface having a suitable porosity. In some embodiments, a high-quality interface has a porosity of less than or equal to about 20%, a porosity of less than or equal to about 30%, or a porosity of less than or equal to 40%.

[0092] In some embodiments, the crystalline material is cut from a base material. For example, the crystalline material can include a SiO_2 crystal (e.g., polycrystalline SiO_2) cut from a base quartz material. In some embodiments, the crystalline material has a thickness that ranges from about 5 micrometers to about 50 micrometers.

[0093] In some embodiments, forming the crystalline material on the base structure includes attaching the crystalline material to the base structure (e.g., the front electrode **330**). For example, forming the crystalline material on the base structure can include using a bonding layer to attach the crystalline material to a surface of the base structure (e.g., a surface of the front electrode **330**). The bonding layer can have suitable properties to enable an acoustic wave to penetrate through an interface.

[0094] In some embodiments, the filter **335** includes a crystal structure having a number of grains. In some embodiments, a grain has a microstructure grain size selected to achieve a target filter lifetime depending on process conditions within which the radical sensor **300** operates. In some embodiments, the microstructure grain size ranges between about 100 nanometers to about 50 micrometers. Additionally, increasing grain boundary size can increase the activation energy needed to induce a chemical reaction. Therefore, increasing grain boundary size can result in a greater amount or concentration of radical species being needed before seeing etching of the material of the filter **335**.

[0095] In some embodiments, the radical sensor **300** shown in FIGS. **3**A-**3**C measures radical species without respect to charge. In some embodiments, it may be advantageous to measure only neutral radical species or only radical species having a particular charge.

[0096] FIG. **3**D is a sectional side view of the radical sensor **300** of FIG. **3**A with the addition of a charged grating or grid **352**, according to some embodiments. The charged grating or grid **352** may be disposed in front of the front face of the radical sensor **300** to measure only neutral radical species of a particular molecular species. The charged grating or grid **352** may include a stack of meshes (e.g., wire meshes) that have particular charge. In some embodiments, as shown, a first grating or mesh is positively charged, a second grating or mesh may be grounded, and a third grating or mesh may be negatively charged. The positively charged mesh or grating may repel positively charged molecules or ions and the negatively charged mesh or grating may repel negatively charged molecules or ions. As a result, the only molecules that reach the filter **335** may be neutral molecules. Of the neutral molecules that reach the filter **335**, only the radical species of a particular gaseous species may actually react with the filter **335**.

[0097] In some embodiments, in order to measure an amount of positively and/or negatively charged radical species, a pair of radical sensors may be used. A first radical sensor may include the charged gratings or grids, and a second radical sensor may not include the charged gratings or grids. All radical species of a target gaseous species may be detected by the second radical sensor, and only neutral radical species of the target gaseous species may be detected by the first radical sensor. A difference between the measurements of the two radical sensors may then be computed to determine an amount of the radical species detected by the second radical sensor that were attributable to charged radical species. The grating may be modified to only filter out positively charged molecules/ions or to only filter out negatively charged molecules. Accordingly, by combining two or more radical sensors, each with a different grating configuration (e.g., one not including any grating), an amount of positively charged radical species may be detected, an amount of negatively charged radical species may be detected, and/or an amount of neutral radical species may be detected.

[0098] FIGS. **4**A-**4**B are diagrams **400**A and **400**B illustrating the formation of a radical sensor of a radical sensor

device, in accordance with embodiments of the present disclosure. In some embodiments, the radical sensor corresponds to the radical sensor **204** of FIGS. **2**A-**2**B and/or the radical sensor **300** of FIGS. **3**A-**3**D. In some embodiments, the radical sensor includes a piezoelectric resonator. For example, the radical sensor can include a QCM resonator.

[0099] As shown in FIG. **4**A, a radical sensor can include a base structure **405** including a radical sensor base **415** (e.g., piezoelectric layer), a back electrode **420**, a back electrode edge **425** and a front electrode **430**, similar to the radical sensor base **315** and the electrodes **320**, **325** and **330** as described above with reference to FIGS. **3**A-**3**D. In some embodiments, the front electrode **330** has a thickness that ranges between about 5 micrometers to about 30 micrometers.

[0100] As further shown, the radical sensor can include a filter **435** formed on a layer **432**. The filter **435** can be sensitive to reaction with a particular molecular species of a target gaseous species. The composition of the filter **435** may depend on the application for which the radical sensor will be used. In some embodiments, the filter **435** is composed of a material that reacts with a radical molecular species of a target gas, but that does not react to stable molecular species of the target gas. For example, the material of filter **410**A may react to fluorine radical species, but may not react to stable molecules containing fluorine (e.g., F_2, C_2F_6, SF_6, NF_3, CF_4, CHF_3, CH_2F_3, etc.). The material of the filter **435** may also not react to other molecules that may be included in a gas flow, whether those other molecules are radical species or stable molecular species. For example, the material of the filter **435** may react to fluorine radical species, but may not react to carbon radical species, nitrogen radical species, hydrogen radical species, etc. Alternatively, the material may only react to hydrogen radical species, or may only react to carbon radical species, or may only react to some other radical species.

[0101] In some embodiments, the filter **435** includes a crystalline material. In some embodiments, the crystalline material is a polycrystalline material. In some embodiments, the crystalline material includes SiO_2. In some embodiments, the filter **435** has a thickness that ranges from about 5 micrometers to about 80 micrometers. In some embodiments, the filter **435** has a diameter that ranges from about 4 millimeters to about 12 millimeters. In some embodiments, the layer **432** includes the same material as the front electrode **430** (e.g., Al). In some embodiments, the layer **432** has a thickness that ranges between about 5 micrometers to about 30 micrometers.

[0102] In some embodiments, the crystalline material of the filter **435** is cut from a base material. For example, the crystalline material can include a SiO_2 crystal (e.g., polycrystalline SiO_2) cut from a base quartz material. In some embodiments, the crystalline material has a thickness that ranges from about 5 micrometers to about 50 micrometers.

[0103] In some embodiments, the filter **435** includes a crystal structure having a number of grains. In some embodiments, a grain has a microstructure grain size selected to achieve a target filter lifetime depending on process conditions within which the radical sensor operates. In some embodiments, the microstructure grain size ranges between about 100 nanometers to about 50 micrometers. Additionally, increasing grain boundary size can increase the activation energy needed to induce a chemical reaction. Therefore, increasing grain boundary size can result in a greater amount or concentration of radical species being needed before seeing etching of the material of the filter **435**.

[0104] In some embodiments, and as shown, a process **437** can be performed to attach or bond the layer **432** to the front electrode **430**. For example, the process **437** can include using a bonding layer or adhesive (e.g., glue) to bond the layer **432** to the front electrode **430**. The bonding layer can have suitable properties to enable an acoustic wave to penetrate through an interface. Further details regarding the process **437** are described above with reference to FIGS. **3**A-**3**D and will be described in further detail below with reference to FIGS. **7**-**8**B.

[0105] As shown in FIG. **4**B, the processing of attaching or bonding the base structure **405** to the layer **432** can result in an interface **439** between the filter **435** and the base structure **405**. The interface **439** can be a high-quality interface to enable an acoustic wave to travel through the interface **439**. For example, the interface **439** can have a suitable porosity. In some embodiments, a high-quality interface has a porosity of less than or equal to about 20%, a porosity of less than or equal to about 30%, or a porosity of less than or equal to 40%. Further details regarding the interface **439** are described above with reference to FIGS. **3**A-**3**D and will be described in further detail below with reference to FIGS. **7**-**8**B.

[0106] FIG. **5** illustrates an example radical sensor **500**, in accordance with embodiments of the present disclosure. In some embodiments, the radical sensor **500** corresponds to radical sensor **204** of FIGS. **2**A-**2**B. In some embodiments, the radical sensor **500** includes a piezoelectric resonator. For example, the radical sensor **500** can include a QCM resonator. As shown, the radical sensor **500** can include a base structure including a radical sensor base **515**, a back electrode **520** and a back electrode edge **525**, similar to those described above with reference to FIGS. **3**A-**3**D.

[0107] Additionally, the radical sensor **500** can include a mesh **530** formed on the radical sensor base **515**. In some embodiments, the mesh **530** is formed by placing the mesh **530** on the surface of the radical sensor base **515**. In some embodiments, the mesh **530** is formed by depositing the mesh **530** on the surface of the radical sensor base **515**. The mesh **530** can include any suitable material in accordance with embodiments described herein. Examples of suitable materials include Al, Au, Ni, etc. In some embodiments, the mesh **530** has an approximately 30% opening. In some embodiments, a thickness of the mesh **530** is less than or equal to about 5 millimeters. In some embodiments, a thickness of the mesh **530** is less than or equal to about 3 millimeters. Exposed regions **535** of the radical sensor base **515** can thus react with a radical species. Further details regarding the radical sensor **500** are described above with reference to FIGS. **3**A-**3**D and will be described in further detail below with reference to FIGS. **7**-**8**B.

[0108] A radical sensor including a piezoelectric resonator (e.g., QCM resonator) can be represented by a simple equivalent circuit **600** for electrical analysis, as shown in FIG. **6**. The mechanical behavior of the radical sensor can be represented by an electrical equivalent model as shown. This is the so-called the Butterworth van Dyke (BVD) electrical model. In the motional arm (the upper branch) of the BVD model, it consists of three components that determine the series resonance frequency of the quartz crystal plate. R_a corresponds to the energy dissipation due to mechanical

coupling between the crystal and its holder. For some applications, added mass load on the crystal surface also causes R_a to increase. L_a corresponds to the mass being displaced during oscillation. For some applications, the total mass includes that of the crystal, the electrodes, and the deposited thin film materials. C_a corresponds to the stored energy in the piezoelectric resonator that is related to the elastic properties of quartz, electrodes, and the deposited materials. The parasitic capacitance Co represents the total static capacitances of the crystal electrodes, the radical sensor holder, and the connecting cable.

[0109] FIG. **7** is a flow chart of a method **700** for manufacturing an acoustic resonance sensor device for radical species detection, in accordance with some embodiments. At block **705**, a radical sensor is obtained. At block **710**, the radical sensor is placed in a radical sensor holder.

[0110] For example, obtaining the radical sensor at block **705** can include forming a filter on a base structure of the radical sensor. The base structure can include a piezoelectric material (e.g., quartz material). In some embodiments, the filter is formed directly on the piezoelectric material. In some embodiments, the base structure further includes a front electrode corresponding to a sensing surface of the radical sensor, and forming the filter on the base structure includes forming the filter on front electrode. The filter may be composed of a material that is selectively reactive to radical species of a target gaseous species, but that is not reactive to stable molecules of the particular gaseous species, and that is not reactive to stable molecules or radical species of other gaseous species that will be used together with the target gaseous species. In some embodiments, the filter includes a crystalline material. Further details regarding forming a filter including a crystalline material will be described herein below with reference to FIG. **8**A. In some embodiments, the filter includes a coating. Further details regarding forming a filter including a coating will be described herein below with reference to FIG. **8**B. Further details regarding blocks **705** and **710** are described above with reference to FIGS. **2**A-**6** and will now be described in further detail below with reference to FIGS. **8**A-**8**B.

[0111] FIG. **8**A is a flow chart of a method **705** for obtaining a radical sensor, in accordance with some embodiments. At block **805**A, a base structure of a radical sensor is obtained and, at block **810**A, a filter including a crystalline material is formed on the base structure. In some embodiments, the radical sensor includes a piezoelectric resonator and the base structure includes a piezoelectric material. In some embodiments, the piezoelectric material includes a crystal (e.g., quartz). The filter can selectively react with a radical species and a resonant frequency of the radical sensor can change in response to reaction of the radical species to the filter. In some embodiments, the crystalline material includes SiO_2. For example, the crystalline material can be a polycrystalline material. In some embodiments, the crystalline material includes a grain having a grain size that ranges from about 100 nanometers to about 50 micrometers. The grain size can be selected to achieve a target filter lifetime depending on process conditions within which the radical sensor operates. Additionally, increasing grain boundary size can increase the activation energy needed to induce a chemical reaction. Therefore, increasing grain boundary size can result in a greater amount or concentration of radical species being needed before seeing etching in the coating.

[0112] In some embodiments, forming the filter includes forming the crystalline material directly on the piezoelectric material. For example, forming the crystalline material directly on the piezoelectric material can include etching the piezoelectric material using a mesh formed on the piezoelectric material. In some embodiments, the mesh is deposited on the piezoelectric material. In some embodiments, the mesh is placed on the piezoelectric material. The mesh can include any suitable material in accordance with embodiments described herein. Examples of suitable materials include, Al, Au, Ni, etc.

[0113] In some embodiments, the base structure further includes a front electrode and a back electrode formed on the piezoelectric material. In some embodiments, forming the filter includes attaching or bonding the crystalline material to the front electrode. For example, forming the crystalline material on the base structure can include using a bonding layer (e.g., glue) to attach the crystalline material to a surface of the front electrode. The bonding layer can have suitable properties to enable an acoustic wave to penetrate through an interface. The front electrode and the back electrode can each include any suitable material in accordance with embodiments described herein. Examples of suitable materials include, Al, Au, etc. Further details regarding blocks **705**A and **710**A are described above with reference to FIGS. **2**A-**6**.

[0114] FIG. **8**B is a flow chart of a method **705** for obtaining a radical sensor, in accordance with some embodiments. At block **805**B, a base structure of a radical sensor is obtained and, at block **810**B, a filter including a coating is formed on the base structure. In some embodiments, the radical sensor includes a piezoelectric resonator and the base structure includes a piezoelectric material. The filter can selectively react with a radical species and a resonant frequency of the radical sensor can change in response to reaction of the radical species to the filter. In some embodiments, the coating includes an amorphous material (e.g., SiO_x).

[0115] In some embodiments, forming the filter includes at least one of: doping an initial coating to form the coating, forming the coating to have a thickness that ranges from about 5 micrometers to about 50 micrometers, or forming the coating using a deposition process performed at a temperature ranging from about 150° C. to about 450° C. The coating can be formed using any suitable deposition process (e.g., PVD, ALD or CVD). In some embodiments, a deposition process is a thin-film deposition process. For example, the deposition process can be electron beam evaporation (e.g., ion-assisted electron beam evaporation).

[0116] In some embodiments, the base structure further includes a front electrode and a back electrode formed on the piezoelectric material. In some embodiments, forming the filter includes forming the filter on the front electrode.

[0117] In some embodiments, doping the initial coating includes doping the initial coating with at least one dopant. Any suitable doping process can be used to dope the initial coating. Examples of doping processes include particle bombardment (e.g., He bombardment), particle implantation (e.g., ion implantation), etc. Examples of dopants that can be used to dope the initial coating include Y, P, B, etc.

[0118] Forming the coating can include placing a mask (e.g., hard mask or soft mask) over the base structure. The coating can then be formed over the exposed region of the base structure, and the mask may be removed. Alternatively,

the coating may be formed on an entirety of a surface, and a portion of the coating may then be selectively removed (e.g., by forming a hard or soft mask over the portion of coating that is not to be removed, and then etching the exposed portion of the coating, and finally removing the mask). Further details regarding blocks **805**B and **810**B are described above with reference to FIGS. **2**A-**7**.

[0119] FIG. **9** is a flow chart of a method **900** for utilizing an acoustic resonance sensor device for radical species detection, in accordance with some embodiments.

[0120] At block **905**, a manufacturing system flows a plasma using first plasma source settings. The plasma may be generated by a remote plasma source (e.g., a plasma source external to a processing chamber) or by a local plasma source (e.g., a plasma source internal to a process chamber).

[0121] At block **910**, a radical sensor (e.g., as described hereinabove) is used to measure a concentration or an amount of radical species of a target gaseous species in the plasma. The radical species of a target gaseous species may react with a filter on the radical sensor, causing a mass on a sensing surface of the radical sensor to change. The density and/or mass of the filter may be known, and a change in the mass of the filter may be detected based on a change in the resonant frequency of a piezoelectric material of the radical sensor. This change in mass together with knowledge about the mass of the materials that make up the filter may be used to determine a number of radical species that reacted with the filter, and thus the concentration and/or amount of radical species.

[0122] At block **915**, processing logic determines whether the measured concentration/amount of radical species exceeds a threshold. For example, processing logic can determine whether the measured concentration/amount of radical species varies from a target concentration/amount of the radical species by more than a threshold amount (e.g., if a difference between the target concentration and the detected concentration is more than a difference threshold). If the difference exceeds a difference threshold, the method continues to block **920** and one or more settings of the plasma source are adjusted. For example, the plasma power may be increased in increase an amount of radical species that are included in the plasma or may be decreased to reduce an amount of radical species that are included in the plasma. If the difference is less than the difference threshold, then the method may end.

[0123] Unless specifically stated otherwise, terms such as "first," "second," "third," "fourth," etc. as used herein are meant as labels to distinguish among different elements and may not have an ordinal meaning according to their numerical designation.

[0124] Examples described herein also relate to an apparatus for performing the methods described herein. This apparatus may be specially constructed for performing the methods described herein, or it may include a general purpose system selectively configured to perform methods described herein.

[0125] The terms "over," "under," "between," "formed on," "support," and "on" as used herein refer to a relative position of one material layer or component with respect to other layers or components. For example, one layer formed on, over, or under another layer may be directly in contact with the other layer or may have one or more intervening layers. Moreover, one layer disposed between two layers may be directly in contact with the two layers or may have one or more intervening layers. Similarly, unless explicitly stated otherwise, one feature disposed between two features may be in direct contact with the adjacent features or may have one or more intervening layers.

[0126] The above description is intended to be illustrative, and not restrictive. Although the present disclosure has been described with references to specific illustrative examples and implementations, it will be recognized that the present disclosure is not limited to the examples and implementations described. The scope of the disclosure should be determined with reference to the following claims, along with the full scope of equivalents to which the claims are entitled.

1. A device comprising:

a radical sensor comprising a piezoelectric resonator, the radical sensor comprising:

a base structure comprising a piezoelectric material; and

a filter formed on the base structure to selectively react with a radical species,

wherein a resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter, and wherein the filter comprises at least one of: a crystalline material, a doped coating, or a coating having a thickness that ranges from about 5 micrometers to about 50 micrometers.

2. The device of claim **1**, wherein the piezoelectric material comprises a quartz crystal.

3. The device of claim **1**, wherein the piezoelectric resonator is a quartz crystal microbalance (QCM) resonator.

4. The device of claim **1**, wherein the crystalline material is a polycrystalline material.

5. The device of claim **1**, wherein the crystalline material comprises a grain having a grain size that ranges from about 100 nanometers to about 50 micrometers.

6. The device of claim **1**, wherein the filter is formed directly on the piezoelectric material.

7. The device of claim **1**, wherein the base structure further comprises a front electrode formed on the piezoelectric material, and wherein the filter is formed on the front electrode.

8. The device of claim **1**, wherein the doped coating comprises at least one of SiO_2 or SiC doped with at least one of yttrium, phosphorous, or boron.

9. The device of claim **1**, wherein the base structure further comprises a mesh formed on a first side of the piezoelectric material, and an electrode formed on a second side of the piezoelectric material opposite the first side, and wherein the filter is formed on the first side of the piezoelectric material.

10. A method comprising:

obtaining a base structure of a radical sensor comprising a piezoelectric resonator, the base structure comprising a piezoelectric material; and

forming, on the base structure, a filter comprising a crystalline material to selectively react with a radical species, wherein a resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter.

11. The method of claim **10**, wherein the piezoelectric material comprises a quartz crystal, and wherein the piezoelectric resonator is a quartz crystal microbalance (QCM) resonator.

12. The method of claim **10**, wherein forming the filter further comprises depositing the crystalline material directly on the piezoelectric material.

13. The method of claim **12**, wherein forming the filter further comprises etching the piezoelectric material using a mesh formed on the piezoelectric material.

14. The method of claim **10**, wherein the base structure further comprises a front electrode formed on the piezoelectric material.

15. The method of claim **14**, wherein forming the filter further comprises attaching or bonding the crystalline material to a surface of the front electrode.

16. The method of claim **10**, wherein the crystalline material comprises a grain having a grain size that ranges from about 100 nanometers to about 50 micrometers.

17. A method comprising:

obtaining a base structure of a radical sensor comprising a piezoelectric resonator, the base structure comprising a piezoelectric material; and

forming, on the base structure, a filter comprising a coating to selectively react with a radical species, wherein a resonant frequency of the radical sensor changes in response to reaction of the radical species to the filter, and wherein forming the filter comprises at least one of: doping an initial coating with a dopant to form the coating, using a base material and the dopant to deposit the coating, forming the coating to have a thickness that ranges from about 5 micrometers to about 50 micrometers, or forming the coating using a deposition process performed at a temperature ranging from about 150° C. to about 450° C.

18. The method of claim **17**, wherein the piezoelectric material comprises a quartz crystal, and wherein the piezoelectric resonator is a quartz crystal microbalance (QCM) resonator.

19. The method of claim **17**, wherein the base structure further comprises a front electrode, and wherein the filter is formed on the front electrode.

20. The method of claim **17**, wherein the dopant comprises at least one of: yttrium, phosphorous, or boron.

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