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(54) **APPARATUS TO DETECT AND QUANTIFY RADICAL CONCENTRATION IN SEMICONDUCTOR PROCESSING SYSTEMS**

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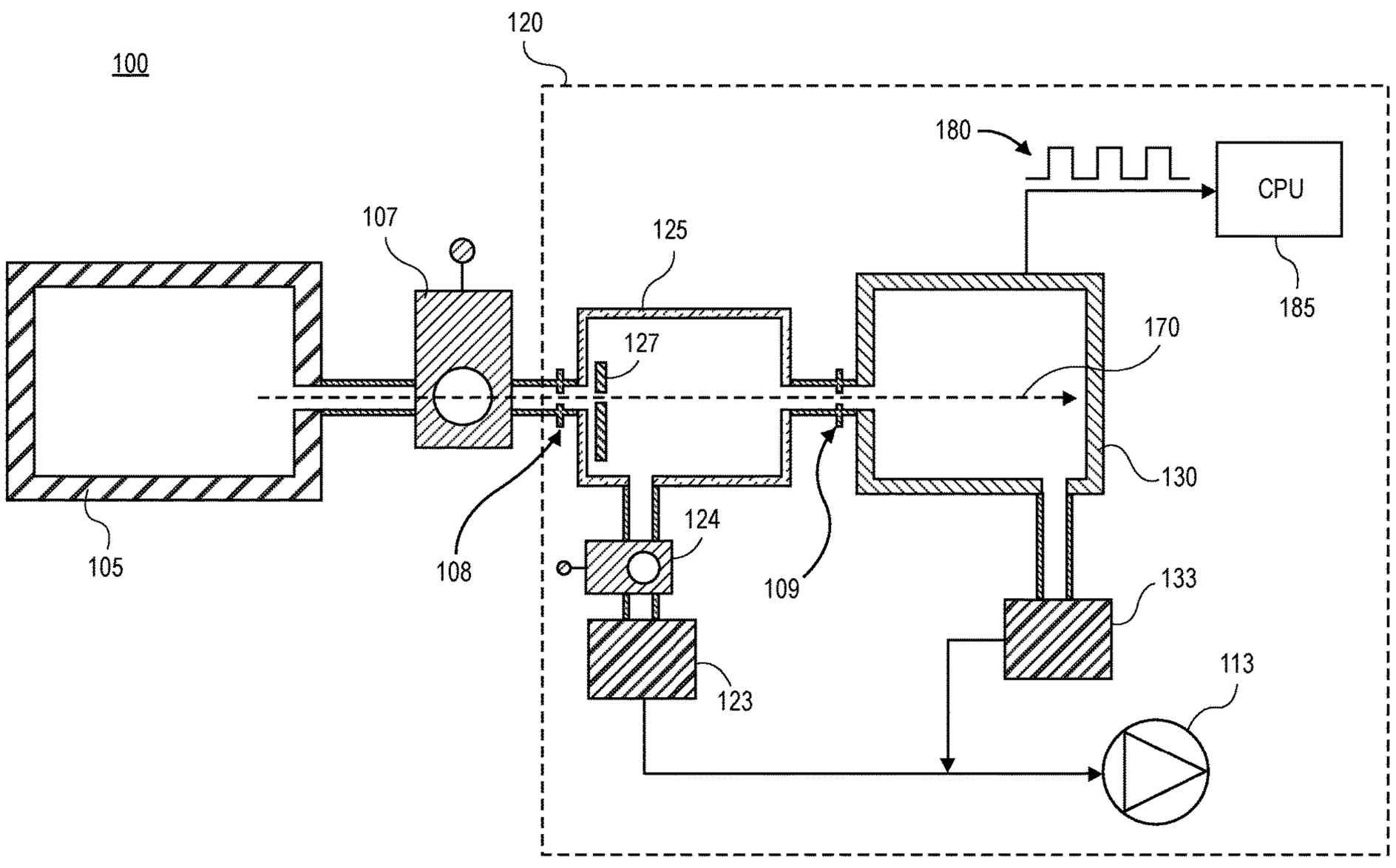
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H01J 37/32	(2006.01)

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(57) **ABSTRACT**

Embodiments disclosed herein include a processing tool for measuring neutral radical concentrations. In an embodiment, the processing tool comprises a processing chamber, and a neutral radical mass spectrometry (NRMS) analyzer fluidically coupled to the processing chamber. In an embodiment, the NRMS analyzer comprises a first chamber fluidically coupled to the processing chamber, where the first chamber comprises a modulator, and a second chamber fluidically coupled to the first chamber, where the second chamber is a residual gas analyzer or a mass spectrometer. In an embodiment, an unobstructed line of sight passes from the processing chamber to the second chamber.



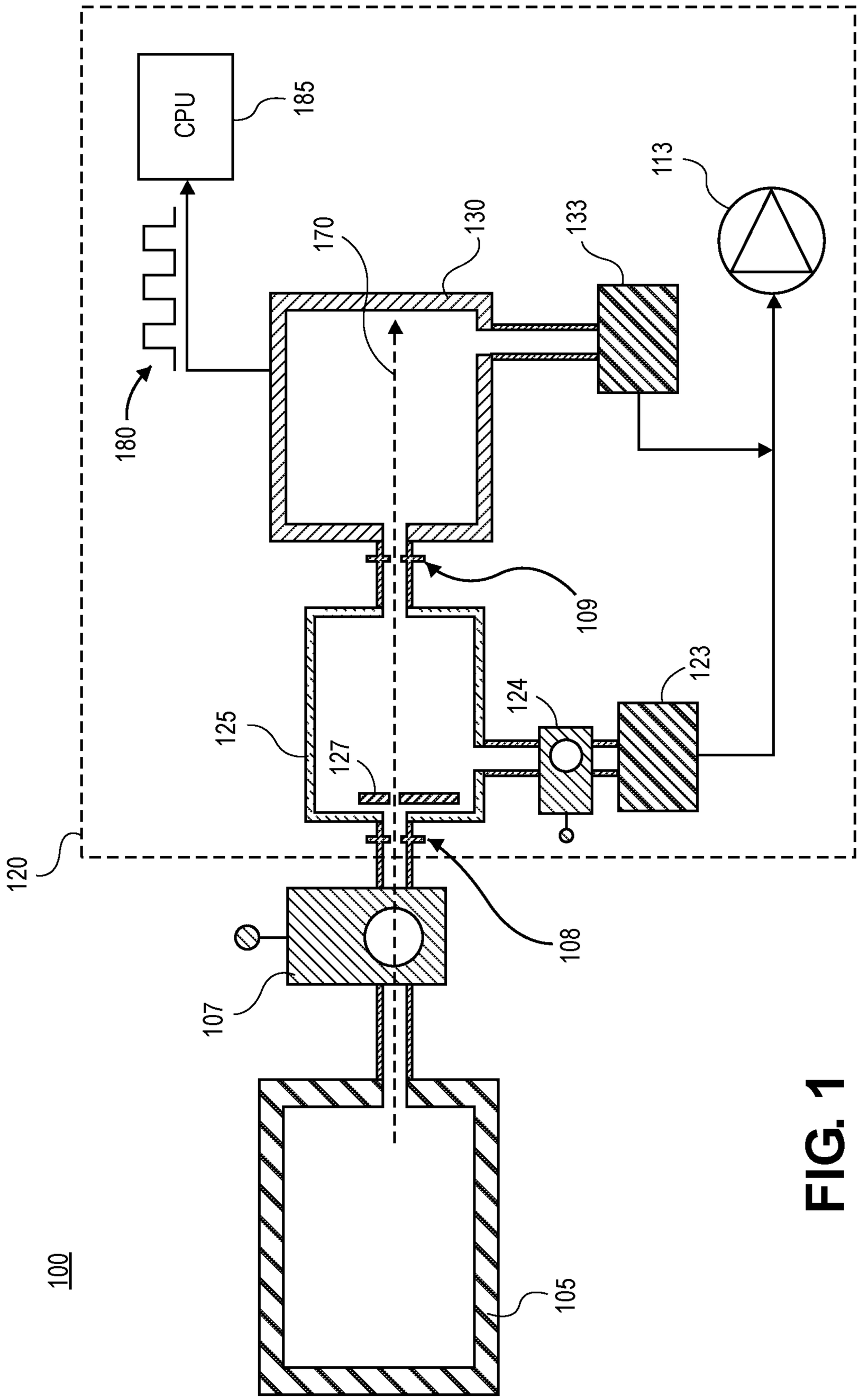

CPU
185
113
170
130
133
180
109
123
124
125
127
120
108
107
105
100

FIG. 1

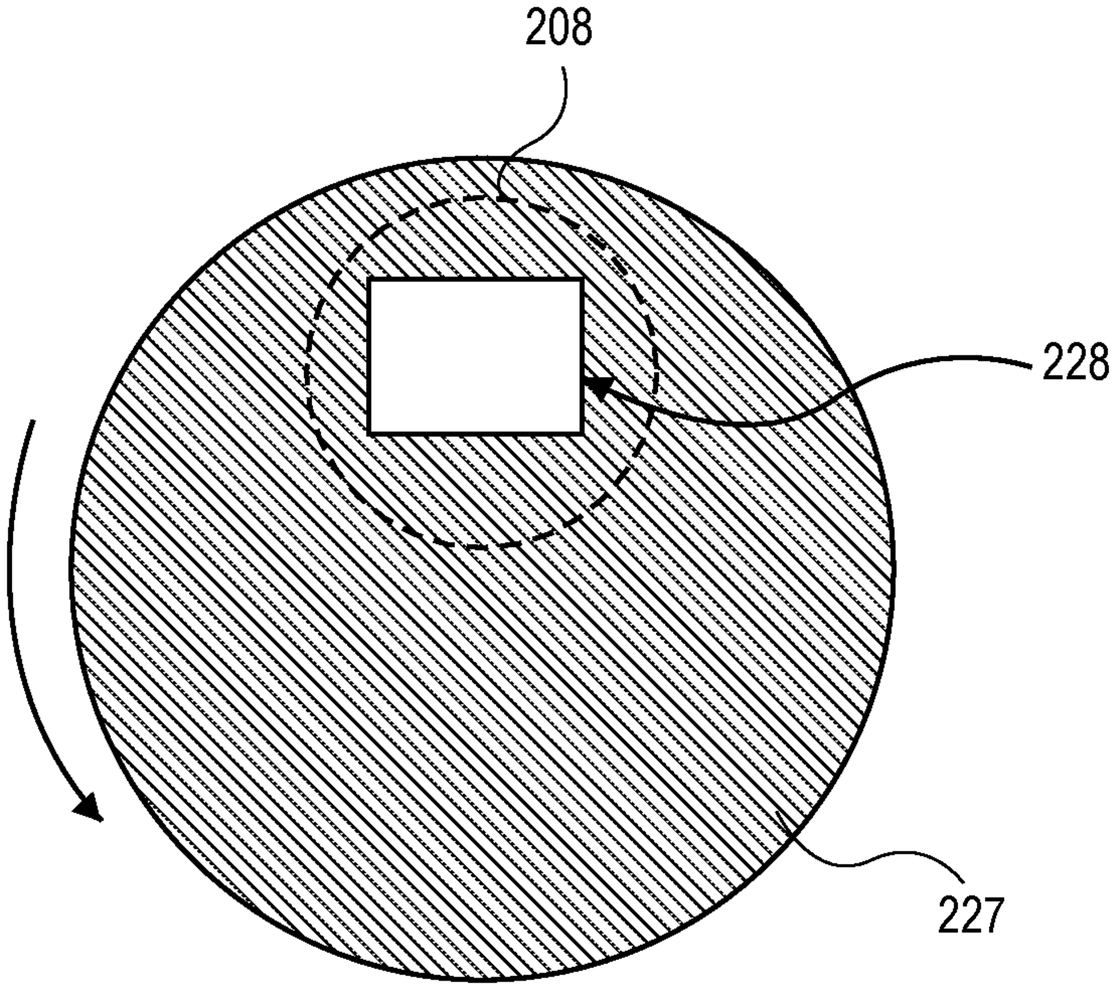

208
228
227

FIG. 2

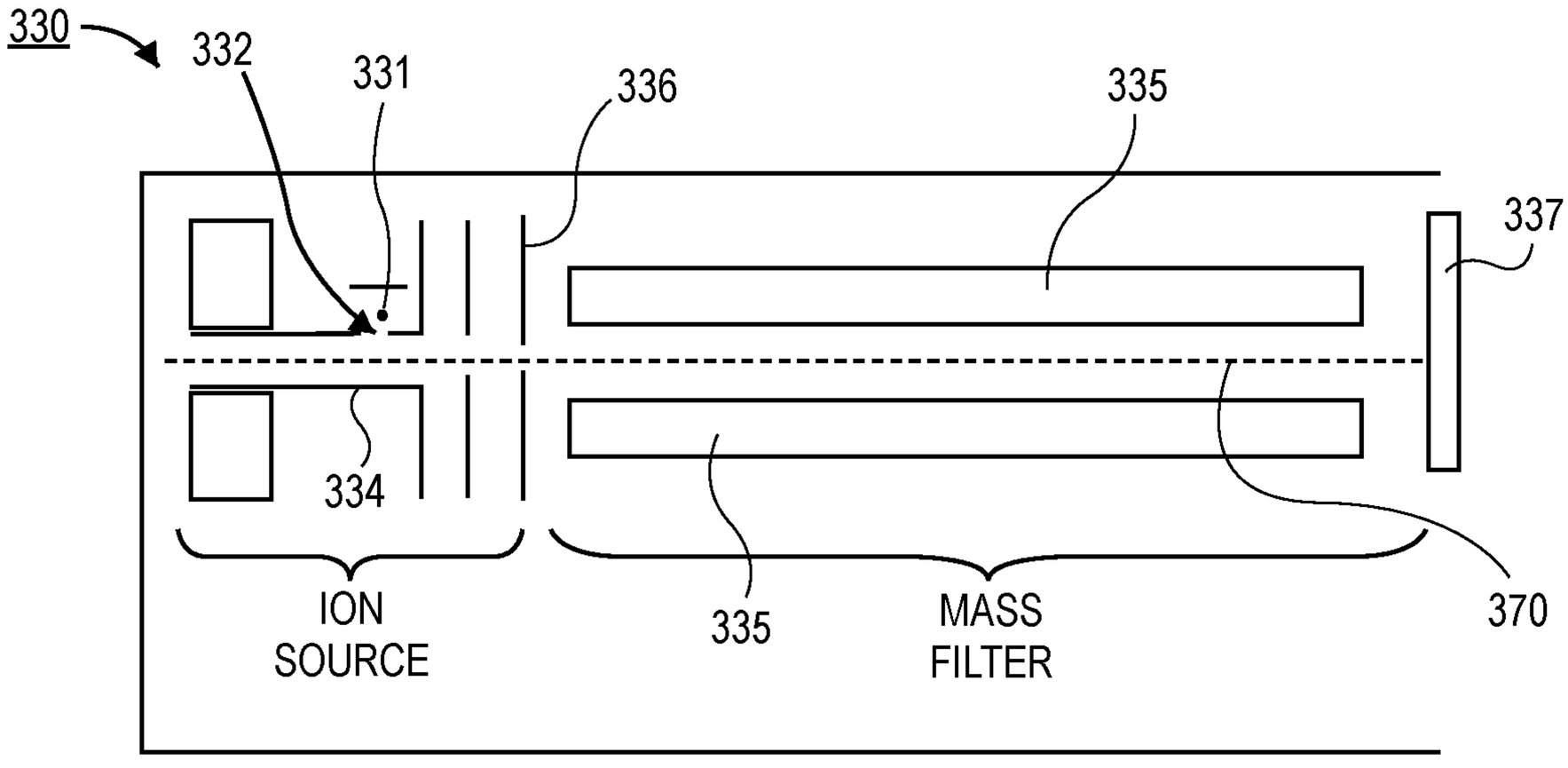

330
332
331
336
335
337
334
ION SOURCE
335
MASS FILTER
370

FIG. 3A

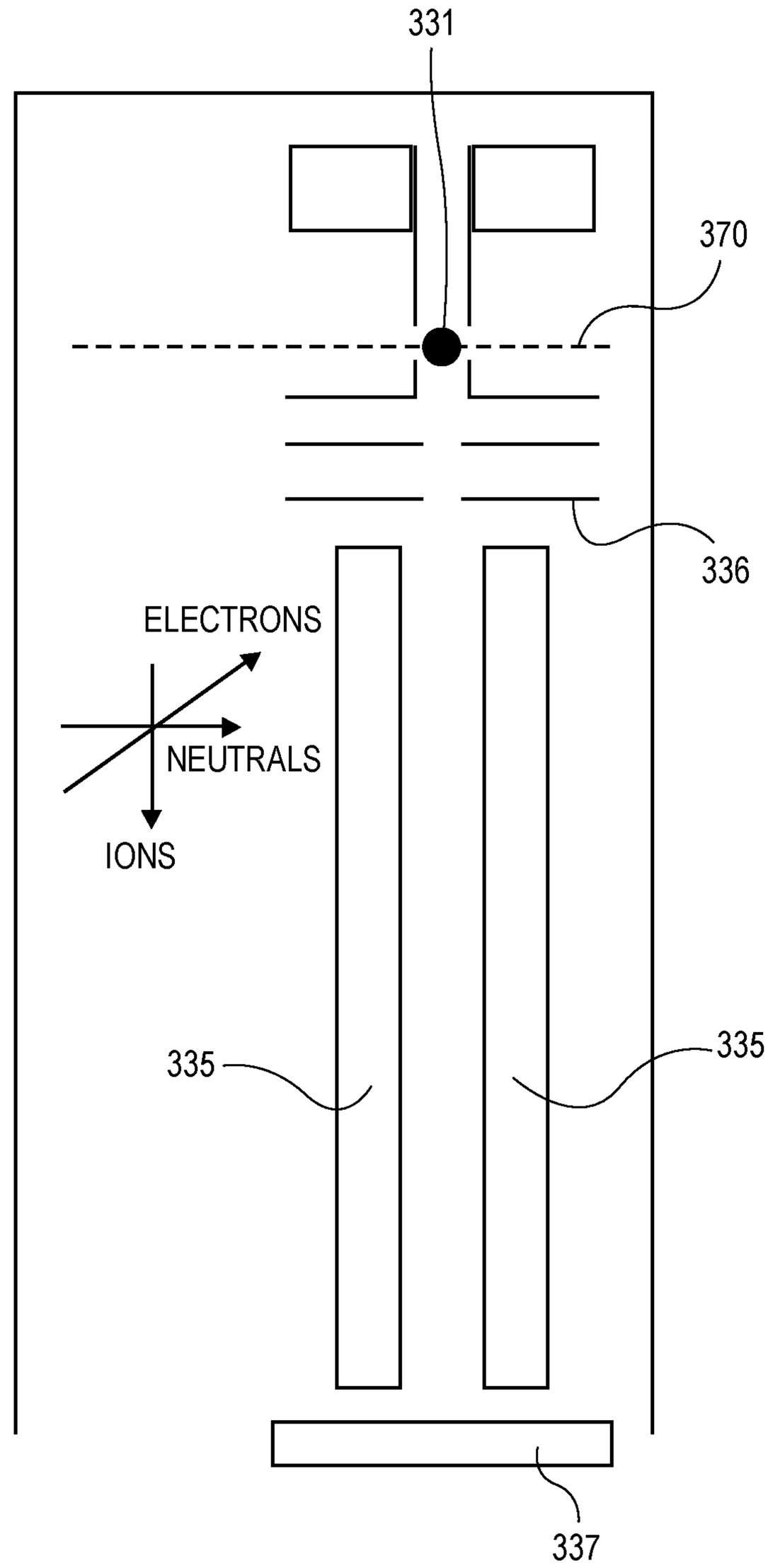


FIG. 3B

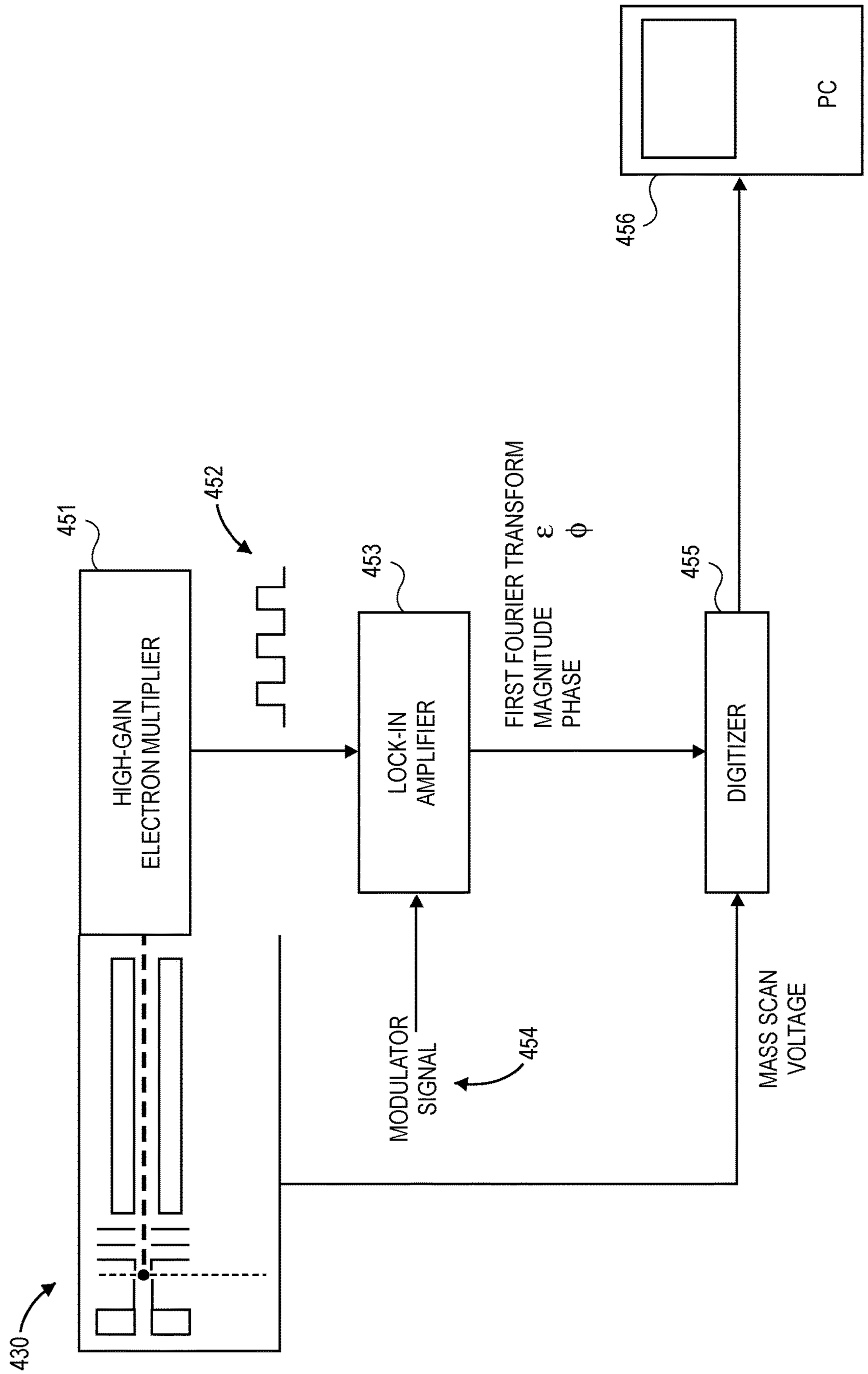

PC
456
451
HIGH-GAIN
ELECTRON MULTIPLIER
452
453
LOCK-IN
AMPLIFIER
FIRST FOURIER TRANSFORM
MAGNITUDE ε
PHASE ϕ
455
DIGITIZER
MODULATOR
SIGNAL
454
MASS SCAN
VOLTAGE
430

FIG. 4

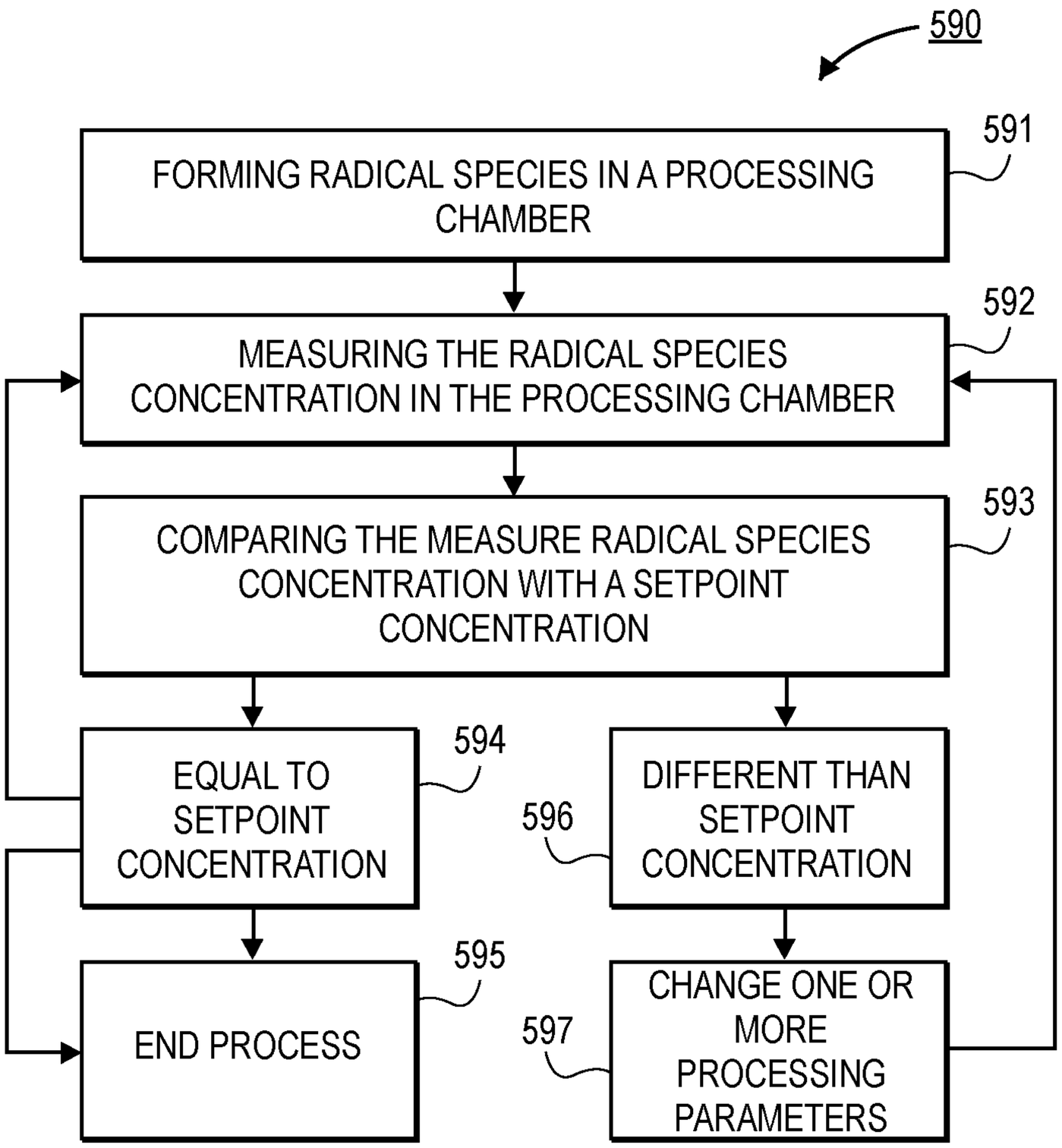

590
591
FORMING RADICAL SPECIES IN A PROCESSING CHAMBER
592
MEASURING THE RADICAL SPECIES CONCENTRATION IN THE PROCESSING CHAMBER
593
COMPARING THE MEASURE RADICAL SPECIES CONCENTRATION WITH A SETPOINT CONCENTRATION
594
EQUAL TO SETPOINT CONCENTRATION
596
DIFFERENT THAN SETPOINT CONCENTRATION
595
END PROCESS
597
CHANGE ONE OR MORE PROCESSING PARAMETERS

FIG. 5

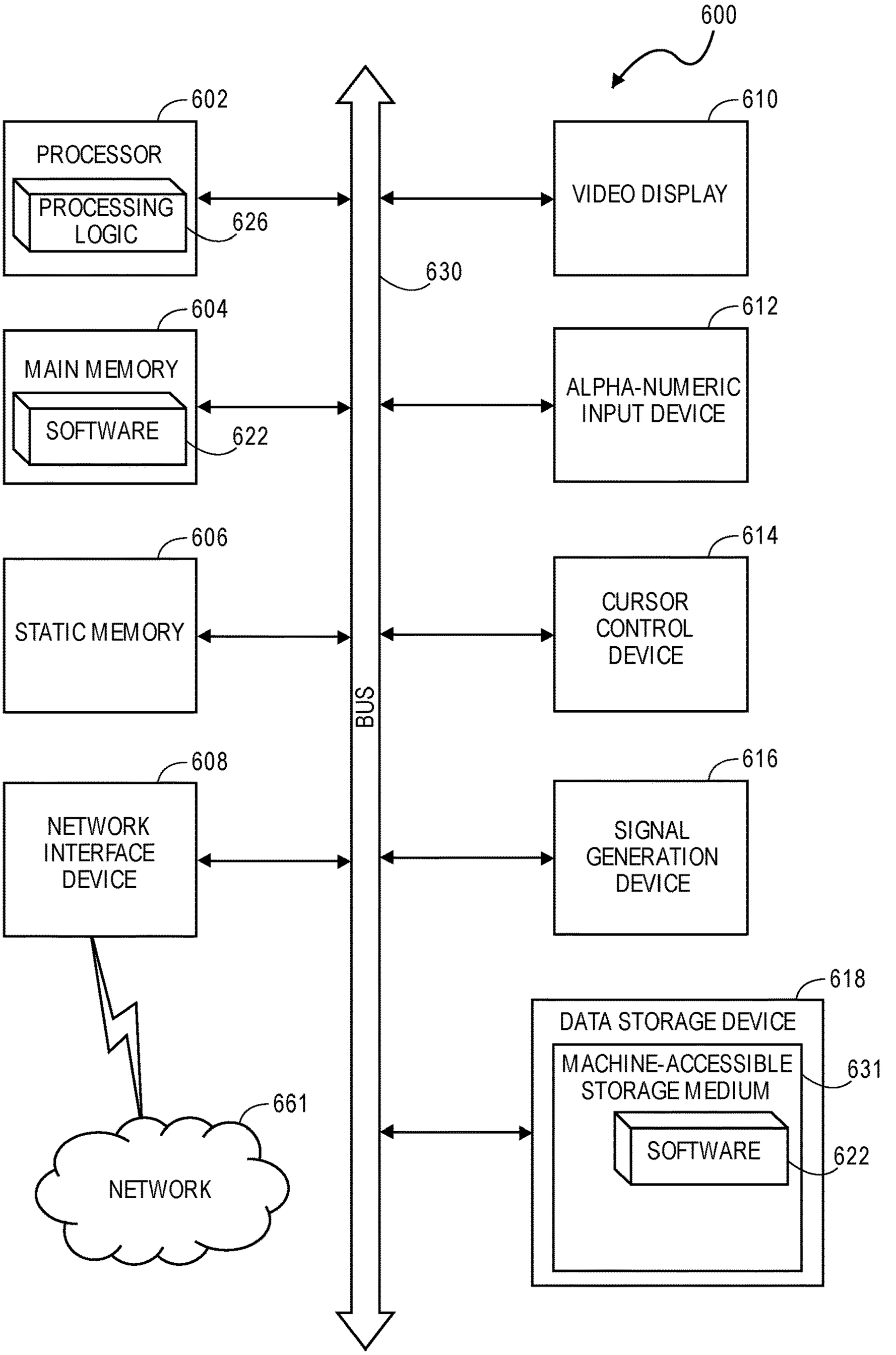

600
602
PROCESSOR
PROCESSING LOGIC
626
604
MAIN MEMORY
SOFTWARE
622
606
STATIC MEMORY
608
NETWORK INTERFACE DEVICE
661
NETWORK
630
BUS
610
VIDEO DISPLAY
612
ALPHA-NUMERIC INPUT DEVICE
614
CURSOR CONTROL DEVICE
616
SIGNAL GENERATION DEVICE
618
DATA STORAGE DEVICE
MACHINE-ACCESSIBLE STORAGE MEDIUM
631
SOFTWARE
622

FIG. 6

APPARATUS TO DETECT AND QUANTIFY RADICAL CONCENTRATION IN SEMICONDUCTOR PROCESSING SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/196,576, filed on Jun. 3, 2021 and U.S. Provisional Application No. 63/242,402, filed on Sep. 9, 2021, the entire contents of which are hereby incorporated by reference herein.

BACKGROUND

1) Field

[0002] Embodiments of the present disclosure pertain to the field of semiconductor processing and, in particular, to a tool to implement neutral radical mass spectrometry (NRMS) and methods of using an NRMS tool.

2) Description of Related Art

[0003] In semiconductor processing, radical species are often used for various processing operations in a chamber. For example, a radical species, such as atomic fluorine, may be used in an etching 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 fluorine containing gas is flown into the chamber, and the plasma breaks the compound into elemental fluorine. Radical species are highly chemically reactive. The chemically active free radicals generated in the plasma can diffuse to the sample surface (e.g., a wafer surface). The free radicals decrease the activation energy in a chemical reaction, resulting in material removal. The volatile chemical reaction byproducts are removed from the sample surface and the process chamber by the vacuum system.

[0004] Process control of radical species is difficult. Particularly, it is currently not possible to effectively measure radical species concentration in a processing chamber. This is due, in part, to the highly reactive nature of the radical species. The radical species 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 radicals with each other thus converting the species to other useless compounds. As such, existing mass spectrometry tools are not able to measure the concentration of radical species. Without the ability to quantitatively measure the radical species concentrations, effective process control, such as closed loop control, is not possible in existing semiconductor-manufacturing tools.

SUMMARY

[0005] Embodiments disclosed herein include a processing tool for measuring neutral radical concentrations. In an embodiment, the processing tool comprises a processing chamber, and a neutral radical mass spectrometry (NRMS) analyzer fluidically coupled to the processing chamber. In an embodiment, the NRMS analyzer comprises a first chamber fluidically coupled to the processing chamber, where the first chamber comprises a modulator, and a second chamber fluidically coupled to the first chamber, where the second chamber is a residual gas analyzer or a mass spectrometer. In an embodiment, an unobstructed line of sight passes from the processing chamber to the second chamber.

[0006] Embodiments disclosed herein may also comprise a method of processing a substrate. In an embodiment, the method comprises initiating a plasma in a processing chamber that comprises a substrate. In an embodiment, the method continues with measuring a concentration of radical species in the plasma with a neutral radical mass spectrometry (NRMS) analyzer that is fluidically coupled to the processing chamber. In an embodiment, the method further comprises comparing a measured concentration of the radical species in the plasma with a setpoint concentration of the radical species, and adjusting one or more plasma parameters with a controller in order to return the measured concentration of the radical species to the setpoint concentration of the radical species.

[0007] An additional embodiment, may include a plasma processing tool. In an embodiment, the processing tool comprises a processing chamber, and a neutral radical mass spectrometry (NRMS) analyzer fluidically coupled to the processing chamber. In an embodiment, the NRMS analyzer comprises a first chamber fluidically coupled to the processing chamber by an isolation gate valve, where the first chamber comprises a modulator, and where a first pump is fluidically coupled to the first chamber. In an embodiment, the NRMS analyzer further comprises a second chamber fluidically coupled to the first chamber, where the second chamber is a residual gas analyzer or a mass spectrometer, where a second pump is fluidically coupled to the second chamber, and where an unobstructed line of sight passes from the processing chamber to the second chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1** is a schematic illustration of a processing chamber that is coupled to a neutral radical mass spectrometry (NRMS) analyzer, in accordance with an embodiment.

[0009] FIG. **2** is an illustration of a modulator for use in the NRMS analyzer, in accordance with an embodiment.

[0010] FIG. **3**A is a schematic of a residual gas analyzer, in accordance with an embodiment.

[0011] FIG. **3**B is a schematic of a residual gas analyzer that is uses cross-beam ionization, in accordance with an embodiment.

[0012] FIG. **4** is a diagram of a process for measuring radical concentrations with low background noise, in accordance with an embodiment.

[0013] FIG. **5** is a process flow diagram of processing a substrate in a processing chamber using closed loop control, in accordance with an embodiment.

[0014] FIG. **6** illustrates a block diagram of an exemplary computer system, in accordance with an embodiment of the present disclosure.

DETAILED DESCRIPTION

[0015] A tool to implement neutral radical mass spectrometry (NRMS) and methods of using an NRMS tool are described herein. In the following description, numerous specific details are set forth in order to provide a thorough understanding of embodiments of the present disclosure. It will be apparent to one skilled in the art that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known aspects, such as integrated circuit fabrication, are not described in detail in

order to not unnecessarily obscure embodiments of the present disclosure. Furthermore, it is to be understood that the various embodiments shown in the Figures are illustrative representations and are not necessarily drawn to scale.

[0016] As noted above, it is currently not possible to measure the concentration of radical species in a processing tool, such as a plasma chamber. Radical species are difficult to measure, in part, due to their high chemical reactivity with other elements. For example, the radical species may react with other gasses in the process, the surface of the workpiece, the surface of the chamber, and the like. Since the radical species are a primary driver of the desired chemical reactions in the process (e.g., radical fluorine is a primary driver in an etching operation) it is highly desirable to obtain quantitative measurements of the radical species concentration in real time.

[0017] Without the ability to have a quantitative measurement of the concentration of radical species, closed loop control of the processing environment is not possible. Closed loop control refers to the use of quantitative measurements as a feedback signal to a controller in order to modify processing conditions in an ongoing process. For example, in the case of the measurement of radical species, a concentration of the radical species can be measured, 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, or when the measured value is above the setpoint value, processing parameters may be changed to decrease the concentration of radical species. As such, more stable and reproducible processes can be implemented.

[0018] Accordingly, embodiments disclosed herein include the use of a neutral reactive (radical) mass spectrometry (NRMS) analyzer. The NRMS analyzer is coupled to a processing chamber, such as a plasma processing chamber. The NRMS analyzer may include a pair of vacuum chambers. A first vacuum chamber includes a modulator, and a second chamber comprises the residual gas analyzer. Differential pumping allows for the first vacuum chamber to be at a pressure lower than the processing chamber, and allows for the second vacuum chamber to be at a pressure lower than the first vacuum chamber. Due to the step downs in pressure, a molecular beam including the radicals will travel from the processing chamber to the residual gas analyzer. Furthermore, a line of sight path is present from the processing chamber to the residual gas analyzer. This ensures that the molecular beam does not contact any surfaces between the plasma source and the residual gas analyzer. As such, an accurate and reproducible measurement of the radical concentration in the process chamber is provided.

[0019] In an embodiment, the NRMS analyzer further includes a modulator to mitigate the presence of noise. The modulator chops the molecular beam and when the beam is detected by RGA it generates a square wave signal that can be processed using a lock-in amplifier. Since the frequency of the square wave signal is known, noise that is at different frequencies can be filtered out, leaving behind a pristine signal with a high signal-to-noise ratio. Accordingly, accurate and sensitive readings can be used to inform a controller that is capable of closed loop control of a processing operation.

[0020] Referring now to FIG. **1**, a schematic illustration of a tool **100** is shown, in accordance with an embodiment. In an embodiment, the tool **100** comprises a processing chamber **105**. The processing chamber **105** may be a plasma chamber or other sub-atmospheric chamber. In an embodiment, the processing tool **105** is 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 an embodiment, one or more substrates (e.g., wafers) (not shown) may be provided within the processing tool **105**. In an embodiment, processing chamber **105** may be maintained at a pressure suitable for the desired operation. In a particular embodiment, the pressure may be between approximately 1 Torr and approximately 200 Torr.

[0021] In an embodiment, the tool **100** may further comprise an NRMS analyzer **120** that is fluidically coupled to the processing chamber **105**. For example, a valve **107** may be provided along a tube between the processing chamber **105** and the NRMS analyzer **120**. In an embodiment, the valve **107** is a type of valve that allows for an unobstructed line of sight **170** between the processing chamber **105** and the NRMS analyzer **120**. For example, the valve **107** may be an isolation gate valve. An isolation gate valve may allow for a binary state of operation. That is, the valve **107** may be open (i.e., 1) or closed (i.e., 0). When the valve **107** is open, the line of sight **170** is unobstructed and a pristine molecular beam from the processing chamber **105** may pass into the NRMS analyzer **120**. The use of such a valve **107** is distinct from typical valves used processing chambers. Typically, a needle valve would be used. However, a needle valve would result in the line of sight **170** being obstructed. As such a pristine molecular beam may not travel out from the processing chamber **105** when a needle valve is used.

[0022] In an embodiment, the NRMS analyzer **120** may comprise a first chamber **125**. The first chamber is fluidically coupled to the valve **107** by a tube. In an embodiment, an orifice **108** may be provided between the valve **107** and the first chamber **125**. The orifice **108** may have a diameter that is approximately 1 mm or smaller. However, it is to be appreciated that the line of sight **170** passes through the orifice **108** unobstructed. In an embodiment, the first chamber **125** may be at a pressure lower than the processing chamber **105**. For example, a turbo pump **123** may provide a desired pressure to the first chamber **125**. In an embodiment, the pressure in the first chamber **125** may be between approximately 1 mTorr and approximately 100 mTorr. In a particular embodiment, the pressure in the first chamber **125** may be approximately 10 mTorr. A valve **124** may be provided between the first chamber **125** and the turbo pump **123**. The turbo pump **123** may be fluidically coupled to a fore pump **113**.

[0023] Despite being fluidically coupled together, a pressure difference between the processing chamber **105** and the first chamber **125** may be maintained. The pressure differential may be maintained by the use of a small orifice **108** and the turbo pump **123**. That is the turbo pump **123** is not the same pump that is used for the processing chamber **105**. Such a setup (i.e., a setup with each chamber having its own pump) may be referred to herein as a differential pumping arrangement. One embodiment may be the use of a multistage pump with different stages connected to the two differentially pumped chambers thus allowing for different pressure in each chamber. Radical species flow from the

processing chamber **150** to the first chamber **125** along the unobstructed line of sight **170** while the lower pressure in subsequent chambers reduces the background of target species thus effectively increasing the signal to noise ratio.

[0024] In an embodiment, the first chamber **125** may be referred to as a modulation chamber. This is because the first chamber **125** may comprise a modulator **127**. The modulator **127** may be a device that allows for the molecular beam to be modulated. For example, the modulator **127** may include a rotating disk with an opening in right location that allows for the molecular beam to pass through a fraction of the time, while the remainder of the time, the modulator **127** blocks the molecular beam. As such, the molecular beam is switched on and off by the modulator **127**.

[0025] Referring now to FIG. **2**, an illustration of a modulator is shown, in accordance with an embodiment. As shown, the modulator **227** comprises an opening **228**. As the modulator **227** is spun (as indicated by the arrow) the opening **228** aligns with the orifice **208**. When the opening **228** is aligned with the orifice **208**, the signal is on, and when the opening is not aligned with the orifice **208**, the signal is off. The speed of rotation can be selected to provide a desired frequency to the signal. For example, the frequency may be chosen to be between approximately 10 Hz and approximately 1000 Hz. In a particular embodiment, the frequency may be approximately 40 Hz. In the illustrated embodiment, a single opening **228** is shown. However, it is to be appreciated that multiple openings **228** may be used to increase the signal frequency without needing to increase the speed of rotation of the modulator **227**.

[0026] Referring back to FIG. **1**, a second chamber **130** is fluidically coupled to the first chamber **125**. The second chamber **130** may be a residual gas analyzer (RGA), a mass spectrometer, or the like. The second chamber **130** is maintained at a pressure that is lower than the pressure of the first chamber **125**. In an embodiment, the second chamber **130** may have a pressure between approximately 0.1 μTorr and approximately 100 μTorr. In a particular embodiment, the pressure in the second chamber **130** may be approximately 1 μTorr. The pressure in the second chamber **130** may be maintained by a turbo pump **133**. As noted above, the use of separate turbo pumps **133** between the first chamber **125** and the second chamber **130** may be referred to as differential pumping.

[0027] In an embodiment, the second chamber **130** is fluidically coupled to the first chamber **125** through an orifice **109** along a tube between the two chambers. The orifice **109** may have a diameter that is approximately 1 mm or smaller. Despite the small diameter, the line of sight **170** continues from the first chamber **125** to the second chamber **130**. That is, the line of sight **170** is unobstructed from the processing chamber **105**, to the first chamber **125**, and into the second chamber **130**. As such, a molecular beam of radical species can pass from the processing chamber **105** to the second chamber **130** (i.e., the mass spectrometer or the RGA) without contacting any surfaces. The pristine nature of the molecular beam results in a concentration reading at the second chamber **125** that is essentially identical to the concentration of radicals within the processing chamber **105**.

[0028] Referring now to FIG. **3**A, a schematic of the second chamber **330** is shown, in accordance with an embodiment. The second chamber **330** may comprise an ion source and a mass filter. The mass filter may be tuned to filter out all ionic species except the ones having a particular atomic or molecular mass to charge ratio. As shown, the line of sight **370** continues through the RGA components of the second chamber. While a specific RGA architecture is shown in FIG. **3**A, it is to be appreciated that any suitable RGA or mass spectrometer arrangement may be used in conjunction with the NRMS analyzer **120**.

[0029] In the particular embodiment shown in FIG. **3**A, a quadrupole mass spectrometer is shown. That is, a pair of the rods **335** are shown in the illustrated cross-section. The third and fourth rods **335** are out of the plane of FIG. **3**A. In an embodiment, a filament **331** is provided at a first end of the RGA device. The filament **331** may be a tungsten filament or any other suitable material for generating electrons. In an embodiment, the filament **331** is held at a potential of approximately −70V. The electrons enter the optical path **370** through an opening **332** through grounded components **334** of the ion source. The electrons hit reactive species along the line of sight **370** and ionize them. Negative potential ion optics and extraction plate **336** focus the ionized reactive species before entering the mass filter portion of the RGA device.

[0030] The mass filter may include a set of four rods **335**. The rods **335** may be supplied an AC voltage. For example, the AC voltage may be approximately 2,000V. In an embodiment, a DC voltage may be supplied over the AC voltage. Control of the DC voltage allows for the selection of the mass that will propagate through the four rods **335** to a sensor **337**. In a particular embodiment, the DC voltage may be between approximately 0V and approximately 100V. The sensor **337** senses the number of radical species that have made it through the RGA device. In an embodiment, the sensor **337** may comprise an electron multiplier in order to increase the sensitivity of the device. In other embodiments, the sensor **337** may comprise a Faraday cup.

[0031] Referring now to FIG. **3**B, a cross-sectional illustration of an RGA device in accordance with an additional embodiment. The RGA in FIG. **3**B utilizes cross-beam ionization. As indicated by the axes, neutrals along the molecular beam **370** travel from left to right. The electrons from the filament **331** propagate into the plane of FIG. **3**B. The ions resulting from the collision of electrons with neutral species are then propagated down towards the mass filter portion and the sensor **337**. That is, the sensor **337** need not be in line with the molecular beam **370** in some embodiments.

[0032] Referring back to FIG. **1**, a signal **180** is provided from the NRMS analyzer **120** to a computer **185**. As shown, the signal **180** is a modulated signal (e.g., a square wave). The modulated signal **180** is provided as a result of the modulator **127**. As will be described in greater detail below, the modulated signal **180** may be used in conjunction with signal processing operations in order to provide a high signal-to-noise ratio. In an embodiment, the computer **185** may be any computational device that is able to receive the modulated signal **180** as an input. In such an embodiment, the computer **185** may analyze the modulated signal **180** in order to determine a concentration of the radical species in the processing chamber **105**. In a particular embodiment, the computer **185** may be a controller. When the radical concentration is away from a desired setpoint, the controller may be configured to change one or more processing parameters of processing chamber **105** (e.g., gas flow rates, voltages, frequencies, or any other controllable parameter)

in order to return the radical concentration to the desired setpoint. In this way, the NRMS analyzer **120** allows for closed loop control of the processing environment.

[0033] Referring now to FIG. **4**, a process flow of a method for processing a signal obtained by the NRMS analyzer **120** is shown, in accordance with an embodiment. As shown, a signal **452** is generated by a high-gain electron multiplier **451** at the end of the second chamber **430** (e.g., the RGA or mass spectrometer). As shown, the signal **452** is a modulated signal (e.g., square wave). Since the modulation frequency of the modulator **127** is known, a modulator signal **454** can be fed to a lock-in amplifier **453**. The lock-in amplifier essentially filters out all of the signals that are not at the modulation frequency, leaving behind a high signal-to-noise ratio signal. A fast Fourier transform (FFT) then provides a magnitude and phase that can be fed to a digitizer **455**. The resulting signal is then provided to a computer **456**. The computer **456** may be used as a controller in order to provide closed loop control of a processing operation in a processing chamber. In one embodiment the square-wave signal from the RGA and control signal from the modulator may be digitized first and then the digital information be processed to numerically obtain the FFT values for magnitude and phase thus replacing the hardware of the lock-in detector with the software employing the Fourier Transform algorithm.

[0034] It is to be appreciated that closed loop control refers to the use of quantitative measurements as a feedback signal to a controller in order to modify processing conditions in an ongoing process. For example, in the case of the measurement of radical species, a concentration of the radical species can be measured, 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, or when the measured value is above the setpoint value, processing parameters may be changed to decrease the concentration of radical species. As such, more stable and reproducible processes can be implemented.

[0035] Referring now to FIG. **5**, a process flow diagram illustrating a process **590** for processing a substrate in a processing chamber using closed loop control is shown, in accordance with an embodiment. In an embodiment, the processing chamber may be used for any process that utilizes radical species. In some embodiments, the process **590** is 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 a particular embodiment, the process **590** is a process that utilizes radical species in order to implement the process. For example, radical fluorine may be used in an etching or a chamber cleaning process.

[0036] In an embodiment, process **590** may begin with operation **591** which comprises forming radical species in a processing chamber. In an embodiment, the radical species may be formed with a plasma process. A controller may be used to control the plasma source, the flow rate of source gasses, pressures, and the like in order to provide a desired radical species concentration. In a particular embodiment, the radical species is atomic fluorine.

[0037] In an embodiment, process **590** may continue with operation **592** which comprises measuring the radical species concentration in the processing chamber. In an embodiment, the radical species concentration may be detected by an NRMS analyzer. For example, the NRMS analyzer may be fluidically coupled to the processing chamber. The NRMS analyzer may be substantially similar to the NRMS analyzer **120** described in greater detail above. For example, the NRMS analyzer may comprise a first chamber for modulation and a second chamber for mass spectrometry (e.g., a quadrupole mass spectrometer). The NRMS analyzer may be coupled to the processing chamber by an isolation gate valve. When operation **591** is implemented, the isolation gate valve is opened. A molecular beam is then able to propagate from the processing chamber to the second chamber in an unobstructed manner. The NRMS analyzer may provide a measure of the radical species concentration to the controller. For example, a process similar to the process shown in FIG. **4** may be used in some embodiments.

[0038] In an embodiment, process **590** may continue with operation **593**, which comprises comparing the measured radical species concentration with a setpoint concentration. When the measured radical species concentration is substantially equal to the setpoint concentration, then the control parameters are maintained and the processing continues, as indicated by branch **594**. Branch **594** may continue by cycling back to operation **592** to make additional measurements or the process may be ended, as indicated by branch **595**. When the measured radical species concentration is substantially above or below a setpoint concentration branch **596** is taken. On branch **596**. the controller may adjust one or more of the processing parameters in order to bring the radical species concentration back towards the setpoint concentration, as indicated by box **597**. The process may then continue by cycling back to operation **592** where additional measurements of the radical species concentration are made and compared to the setpoint at operation **593**.

[0039] In some embodiments, the process **590** may be utilized as part of a machine learning (ML) and/or artificial intelligence (AI) algorithms used in the control of processing of one or more substrates in a processing tool and/or control of processing of substrates in multiple different processing chambers. For example, the controller may use ML or AI processes in order to return radical species concentrations back to the setpoint. Additionally, data collected by the process **590** may be stored for use as learning or training data for ML or AI algorithms.

[0040] FIG. **5** illustrates a diagrammatic representation of a machine in the exemplary form of a computer system **500** within which a set of instructions, for causing the machine to perform any one or more of the methodologies described herein, may be executed. In alternative embodiments, the machine may be connected (e.g., networked) to other machines in a Local Area Network (LAN), an intranet, an extranet, or the Internet. The machine may operate in the capacity of a server or a client machine in a client-server network environment, or as a peer machine in a peer-to-peer (or distributed) network environment. The machine may be a personal computer (PC), a tablet PC, a set-top box (STB), a Personal Digital Assistant (PDA), a cellular telephone, a web appliance, a server, a network router, switch or bridge, or any machine capable of executing a set of instructions (sequential or otherwise) that specify actions to be taken by that machine. Further, while only a single machine is illustrated, the term "machine" shall also be taken to include any collection of machines (e.g., computers) that individually or

jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies described herein.

[0041] The exemplary computer system **500** includes a processor **502**, a main memory **504** (e.g., read-only memory (ROM), flash memory, dynamic random access memory (DRAM) such as synchronous DRAM (SDRAM) or Rambus DRAM (RDRAM), etc.), a static memory **506** (e.g., flash memory, static random access memory (SRAM), MRAM, etc.), and a secondary memory **518** (e.g., a data storage device), which communicate with each other via a bus **530**.

[0042] Processor **502** represents one or more general-purpose processing devices such as a microprocessor, central processing unit, or the like. More particularly, the processor **502** may be a complex instruction set computing (CISC) microprocessor, reduced instruction set computing (RISC) microprocessor, very long instruction word (VLIW) microprocessor, processor implementing other instruction sets, or processors implementing a combination of instruction sets. Processor **502** may 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. Processor **502** is configured to execute the processing logic **526** for performing the operations described herein.

[0043] The computer system **500** may further include a network interface device **508**. The computer system **500** also may include a video display unit **510** (e.g., a liquid crystal display (LCD), a light emitting diode display (LED), or a cathode ray tube (CRT)), an alphanumeric input device **512** (e.g., a keyboard), a cursor control device **514** (e.g., a mouse), and a signal generation device **516** (e.g., a speaker).

[0044] The secondary memory **518** may include a machine-accessible storage medium (or more specifically a computer-readable storage medium) **532** on which is stored one or more sets of instructions (e.g., software **522**) embodying any one or more of the methodologies or functions described herein. The software **522** may also reside, completely or at least partially, within the main memory **504** and/or within the processor **502** during execution thereof by the computer system **500**, the main memory **504** and the processor **502** also constituting machine-readable storage media. The software **522** may further be transmitted or received over a network **520** via the network interface device **508**.

[0045] While the machine-accessible storage medium **532** is shown in an exemplary embodiment to be a single medium, the term "machine-readable storage medium" should be taken to include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) that store the one or more sets of instructions. The term "machine-readable storage medium" shall also be taken to include any medium that is capable of storing or encoding a set of instructions for execution by the machine and that cause the machine to perform any one or more of the methodologies of the present disclosure. The term "machine-readable storage medium" shall accordingly be taken to include, but not be limited to, solid-state memories, and optical and magnetic media.

[0046] In accordance with an embodiment of the present disclosure, a machine-accessible storage medium has instructions stored thereon which cause a data processing system to perform a method of closed loop control of a radical concentration in a processing operation using an NRMS analyzer.

[0047] Thus, methods for measuring gas concentration have been disclosed.

What is claimed is:

1. A processing tool, comprising:

a processing chamber; and

a neutral radical mass spectrometry (NRMS) analyzer fluidically coupled to the processing chamber, wherein the NRMS analyzer comprises:

a first chamber fluidically coupled to the processing chamber, wherein the first chamber comprises a modulator; and

a second chamber fluidically coupled to the first chamber, wherein the second chamber is a residual gas analyzer or a mass spectrometer, and wherein an unobstructed line of sight passes from the processing chamber to the second chamber.

2. The processing tool of claim **1**, wherein the first chamber is configured to be at a first pressure that is lower than a pressure of the processing chamber, and wherein the second chamber is configured to be at a second pressure that is lower than the first pressure.

3. The processing tool of claim **2**, wherein differential pumping is used to provide the first pressure and the second pressure.

4. The processing tool of claim **2**, wherein the first pressure is between approximately 1 mTorr and approximately 100 mTorr, and wherein the second pressure is between approximately 0.1 μTorr and approximately 100 μTorr.

5. The processing tool of claim **1**, further comprising:

a valve between the processing chamber and the first chamber.

6. The processing tool of claim **5**, wherein the valve is an isolation gate valve.

7. The processing tool of claim **1**, wherein the modulator is a disk that comprises one or more openings, and wherein the disk is configured to be rotated to provide a desired modulation frequency.

8. The processing tool of claim **7**, wherein the modulation frequency is between approximately 10 Hz and approximately 1000 Hz.

9. The processing tool of claim **1**, wherein the second chamber is a quadrupole mass spectrometer.

10. The processing tool of claim **9**, wherein the quadrupole mass spectrometer is configured to provide cross-beam ionization.

11. The processing tool of claim **1**, wherein the second chamber further comprises a sensor.

12. The processing tool of claim **11**, wherein the sensor is an electron multiplier or a Faraday cup.

13. A method of processing a substrate, comprising:

initiating a plasma in a processing chamber that comprises a substrate;

measuring a concentration of radical species in the plasma with a neutral radical mass spectrometry (NRMS) analyzer that is fluidically coupled to the processing chamber;

comparing a measured concentration of the radical species in the plasma with a setpoint concentration of the radical species; and

adjusting one or more plasma parameters with a controller in order to return the measured concentration of the radical species to the setpoint concentration of the radical species.

14. The method of claim **13**, wherein the NRMS analyzer comprise a modulator in order to modulate the signal sensed by a sensor of the NRMS analyzer.

15. The method of claim **14**, wherein the modulated signal sensed by the sensors is provided to a lock-in amplifier in order to reduce noise.

16. The method of claim **13**, wherein the NRMS analyzer comprises a quadrupole mass spectrometer.

17. The method of claim **16**, wherein the quadrupole mass spectrometer is configured to use cross-beam ionization.

18. The method of claim **13**, wherein adjusting one or more plasma parameters is implemented using

19. A plasma processing tool, comprising:

a processing chamber; and

a neutral radical mass spectrometry (NRMS) analyzer fluidically coupled to the processing chamber, wherein the NRMS analyzer comprises:

a first chamber fluidically coupled to the processing chamber by an isolation gate valve, wherein the first chamber comprises a modulator, and wherein a first pump is fluidically coupled to the first chamber; and

a second chamber fluidically coupled to the first chamber, wherein the second chamber is a residual gas analyzer or a mass spectrometer, wherein a second pump is fluidically coupled to the second chamber, and wherein an unobstructed line of sight passes from the processing chamber to the second chamber.

20. The plasma processing tool of claim **19**, wherein the NRMS analyzer is configured to provide closed loop control of a radical species concentration in the processing chamber.

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