



(51) International Patent Classification:

H01J 37/32 (2006.01) H01L 21/3065 (2006.01)

(21) International Application Number:

PCT/US2019/019278

(22) International Filing Date:

22 February 2019 (22.02.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/634,725 23 February 2018 (23.02.2018) US

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(81) Designated States (unless otherwise indicated, for every

kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,

DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every

kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— of inventorship (Rule 4.17(iv))

Published:

— with international search report (Art. 21(3))

(54) Title: RF CURRENT MEASUREMENT IN SEMICONDUCTOR PROCESSING TOOL

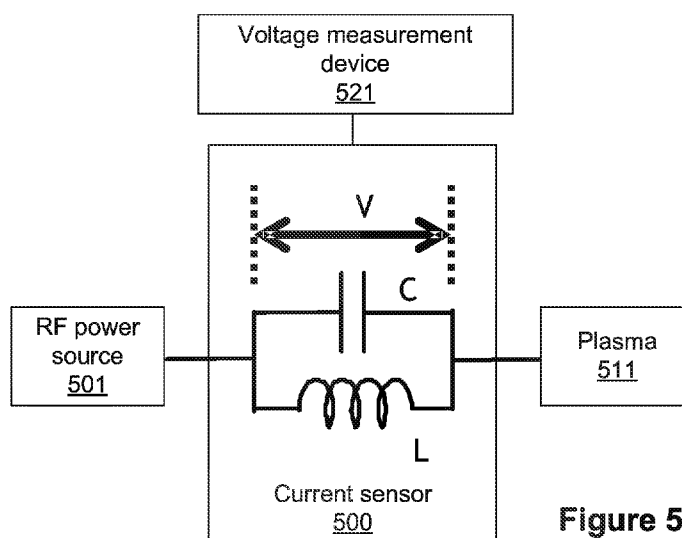


Figure 5

(57) **Abstract:** A method of plasma-assisted semiconductor processing in multiple stations in a process chamber is provided. The method comprises: a) providing substrates at each of the multiple stations; b) distributing RF power to multiple stations to thereby generate a plasma in the station, wherein the RF power is distributed according to a RF power parameter that is adjusted to reduce station to station variations; c) tuning a frequency of the RF power, wherein tuning the frequency includes: i) measuring a current of the plasma; ii) determining, according to the current measured in (i), a change to the frequency of the RF power, and iii) adjusting the frequency of the RF power; and d) performing a semiconductor processing operation on the substrate at each station.



RF CURRENT MEASUREMENT IN SEMICONDUCTOR PROCESSING TOOL

CROSS-REFERENCE TO RELATED APPLICATIONS

5 **[0001]** This application claims priority to and benefit of USSN 62/634,725 filed on February 23, 2018 titled “RF CURRENT MEASUREMENT IN SEMICONDUCTOR PROCESSING TOOL,” which is incorporated herein by reference in its entirety for all purposes.

10 BACKGROUND

[0002] Semiconductor device fabrication involves the processing of semiconductor wafers in a semiconductor processing reactor. Typical processes involve deposition and removal (i.e., etching) of material on the wafer. In commercial scale manufacturing, each wafer contains many copies of a particular semiconductor device being manufactured, and many wafers are required to achieve the required volumes of devices. The commercial viability of a semiconductor processing operation depends in large part upon within-wafer uniformity and wafer-to-wafer repeatability of the process conditions. Accordingly, efforts are made to ensure that each portion of a given wafer and each wafer processed are exposed to the same processing conditions. Variation in the processing conditions can cause variation in deposition and etch rates resulting in unacceptable variation in the overall process and product.

SUMMARY

[0003] A system of one or more computers can be configured to perform particular operations or actions by virtue of having software, firmware, hardware, or a combination of them installed on the system that in operation causes the system to perform the actions. One or more computer programs can be configured to perform particular operations or actions by virtue of including instructions that, when executed by data processing apparatus, cause the apparatus to perform the actions.

30 **[0004]** One general aspect includes a method of plasma-assisted semiconductor processing in multiple stations in a process chamber, the method including: a)

providing substrates at each of the multiple stations; b) distributing RF power to multiple stations to thereby generate a plasma in the stations, where the RF power is distributed according to a RF power parameter that is adjusted to reduce station to station variations; c) tuning a frequency of the RF power, where tuning the frequency includes: i) measuring a current of the plasma, ii) determining, according to the current measured in (I), a change to the frequency of the RF power, and iii) adjusting the frequency of the RF power; and d) performing a semiconductor processing operation on the substrate at each station. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

[0005] Implementations may include one or more of the following features. The method where the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film. The method where i) includes: a) measuring a voltage across an inductive element in a current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and b) converting the measured voltage across the inductive element to the current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the plasma. The method where the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, where the linear proportionality factor is represented by $1 / 2\pi fL$. The method where the capacitive element and inductive element are integrated on a printed circuit board. The method where the capacitive element has a capacitive value of less than or equal to about 0.017 pf. The method where the inductive element has an inductance value of less than or equal to about 610 nh. The method where the linear proportionality factor is determined in part by an impedance z of the inductive element at the RF power frequency of the plasma. The method where the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor. The method where the linear proportionality factor is determined in part by determining an impedance z of the current sensor over a frequency range that includes a resonant frequency ω_{res} . The method where the linear proportionality factor is determined in part by determining an inductance value l of the inductive element and a

capacitance value c of the capacitive element. The method where the RF power frequency is a frequency of about 56 MHz. The method where the RF power frequency is modified to an adjusted RF power frequency, and further where i) is repeated with the current sensor at the adjusted RF power frequency using a second linear proportionality factor. The method where the capacitive element has a capacitance value $c = \epsilon a / d$, where ϵ is a dielectric constant, a is an area of the capacitive element, and d is a distance between electrodes of the capacitive element.

[0006] One general aspect includes an apparatus for plasma-assisted semiconductor depositions, the apparatus including: multiple process stations, where each of the process stations includes at least one wafer support and is configured to receive at least one substrate, and where the multiple process stations are within a chamber; a power source configured to provide RF power to the chamber to generate and maintain a plasma; a current sensor configured to measure plasma current; a RF frequency tuner configured to tune the RF power frequency; one or more RF power adjusters configured to adjust the RF power distributed to the multiple process stations and thereby reduce station to station variations; and one or more controllers, where the one or more controllers, the power source, the current sensor, the RF frequency tuner, and the RF power adjusters are communicatively connected and the controller is configured to: tune the RF power frequency, where tuning the RF power frequency includes: i) determining the plasma current using the current sensor by: a) measuring a voltage across an inductive element in the current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the chamber for generating and maintaining the plasma; b) converting the measured voltage across the inductive element to the plasma current based in part by applying a linear proportionality factor dependent on the RF power frequency of the plasma; ii) determining, according to the current measured in (i), a change to the frequency of the RF power; and iii) adjusting the frequency of the RF power via the RF frequency tuner, and iv) instruct the one or more RF power adjusters to adjust the RF power distributed to each station to reduce station-to-station variations when performing a semiconductor processing operation at each process station. Other embodiments of this aspect include corresponding computer systems, apparatus, and computer programs recorded on one

or more computer storage devices, each configured to perform the actions of the methods.

[0007] Implementations may include one or more of the following features. The apparatus where the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film. The apparatus where the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, where the linear proportionality factor is represented by $1 / 2\pi fL$. The apparatus where the capacitive element and inductive element are integrated on a printed circuit board. The apparatus where the capacitive element has a capacitance value $c = \epsilon a / d$, where ϵ is a dielectric constant, a is an area of the capacitive element, and d is a distance between electrodes of the capacitive element. The apparatus where the capacitive element has a capacitive value of less than or equal to about 0.017 pf. The apparatus where the inductive element has an inductance value of less than or equal to about 610 nh. The apparatus where the linear proportionality factor is determined in part by an impedance z of the current sensor at the RF power frequency of the plasma. The apparatus where the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor. The apparatus where the linear proportionality factor is determined in part by determining an impedance z of the current sensor over a frequency range that includes a resonant frequency ω_{res} . The apparatus where the linear proportionality factor is determined in part by determining an inductance value l of the inductive element and a capacitance value c of the capacitive element.

[0008] One general aspect includes a method of plasma-assisted semiconductor processing in a process chamber, the method including: a) measuring a voltage across an inductive element in a current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and b) converting the measured voltage across the inductive element to the current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the plasma for performing a semiconductor processing operation on a substrate at a station in the process chamber. Other embodiments of this aspect include corresponding computer systems, apparatus,

and computer programs recorded on one or more computer storage devices, each configured to perform the actions of the methods.

[0009] Implementations may include one or more of the following features. The method where the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film. The method where the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, where the linear proportionality factor is represented by $1 / 2\pi fL$. The method where the capacitive element has a capacitive value of less than or equal to about 0.017 pf, and the inductive element has an inductance value of less than or equal to about 610 nh. The method where the capacitive element and inductive element are integrated on a printed circuit board, and further where the capacitive element has a capacitance value $c = \epsilon a / d$, where ϵ is a dielectric constant, a is an area of the capacitive element, and d is a distance between electrodes of the capacitive element. The method where the linear proportionality factor is determined in part by an impedance z of the inductive element at the RF power frequency of the plasma. The method where the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor. The method where the linear proportionality factor is determined in part by determining an impedance z of the current sensor over a frequency range that includes a resonant frequency ω_{res} . The method where the linear proportionality factor is determined in part by determining an inductance value l of the inductive element and a capacitance value c of the capacitive element. The method where the RF power frequency is a frequency of about 13.56 MHz. The method where the RF power frequency is modified to an adjusted RF power frequency, and further where b) is repeated with the current sensor at the adjusted RF power frequency using a second linear proportionality factor.

[0010] One general aspect includes an apparatus for plasma-assisted semiconductor processing in a process chamber, the apparatus including: a process station within the process chamber, the process station having at least one wafer support configured to receive at least one substrate; a power source configured to provide RF power to the process chamber to generate and maintain a plasma; a current sensor configured to measure plasma current; one or more controllers, where the one or more controllers, the power source, and the current sensor are communicatively connected and the controller

is configured to: a) measure a voltage across an inductive element in a current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and b) convert
5 the measured voltage across the inductive element to the current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the plasma for performing a semiconductor processing operation on a substrate at a station in the process chamber.

[0011] Implementations may include one or more of the following features. The
10 apparatus where the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film. The apparatus where the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, where the linear
15 proportionality factor is represented by $1 / 2\pi fL$. The apparatus where the capacitive element has a capacitive value of less than or equal to about 0.017 pF, and the inductive element has an inductance value of less than or equal to about 610 nH. The apparatus where the capacitive element and inductive element are integrated on a printed circuit board, and further where the capacitive element has a capacitance value $c = \epsilon a / d$,
20 where ϵ is a dielectric constant, a is an area of the capacitive element, and d is a distance between electrodes of the capacitive element. The apparatus where the linear proportionality factor is determined in part by an impedance z of the inductive element at the RF power frequency of the plasma. The apparatus where the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor. The apparatus where the linear proportionality factor is determined
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30 power frequency is modified to an adjusted RF power frequency, and further where b) is repeated with the current sensor at the adjusted RF power frequency using a second linear proportionality factor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] Figure 1 shows a substrate processing apparatus for depositing films on semiconductor substrates.

5 [0013] Figure 2 shows an example multi-station substrate processing apparatus that may utilize plasma balancing hardware.

[0014] Figure 3 is a schematic diagram showing various components in an example multi-station plasma reactor with multiple stations sharing a RF power source utilizing RF frequency tuning.

10 [0015] Figure 4A is a process flow diagram of a multi-station deposition process utilizing RF frequency tuning and RF power parameter adjustment.

[0016] Figure 4B is a process flow diagram of a multi-station deposition process utilizing RF frequency tuning.

[0017] Figure 5 shows an example implementation of an in-line current sensor.

15 [0018] Figure 6 shows an example printed circuit board (PCB) implementation of an in-line current sensor.

[0019] Figure 7 shows an example flow diagram for converting a measured voltage to a measured current.

[0020] Figure 8 shows an example linear proportional relationship between measured voltage and measured current for a particular frequency.

20 [0021] Figure 9 shows an example flow diagram for calibrating and operating an in-line current sensor.

[0022] Figure 10 shows an example flow diagram for calibrating and operating an in-line current sensor.

25

DETAILED DESCRIPTION

[0023] In the following detailed description, numerous specific implementations are set forth. However, as will be apparent to those skilled in the art, the techniques and apparatus disclosed herein may be practiced without these specific details or by using alternate elements or processes. In other instances, well-known processes, procedures

and components have not been described in detail so as not to unnecessarily obscure aspects of the present disclosure.

[0024] Measuring RF current accurately is one of the major requirements of metrology for control and troubleshooting configurations of semiconductor fabrication tools.

- 5 Technologies developed for measuring the RF current include but are not limited to, for example, the Pearson probe and Rogowski coil. In such technology, flux, generated from current flow, is used to induce current in a secondary coil. This induced current generates a voltage across the secondary coil which is proportional to current flow in the primary path. The disadvantages of such technologies include, for example, narrow
10 bandwidth.

[0025] Apparatus and methods are provided to control RF power used in multi-cycle deposition operations in a semiconductor tool with multiple processing stations that share an RF power source. The frequency of the RF power and the power applied to individual stations that share an RF power source are controlled.

- 15 **[0026]** Figure 1 shows a substrate processing apparatus for depositing films on semiconductor substrates. The apparatus 100 of Figure 1 has a single processing chamber 102 with a single substrate holder 108 in an interior volume which may be maintained under vacuum by vacuum pump 118. Also fluidically coupled to the chamber for the delivery of (for example) film precursors, carrier and/or purge and/or
20 process gases, secondary reactants, etc. is gas delivery system 101 and showerhead 106. Equipment for generating a plasma within the processing chamber is also shown in Figure 1. The apparatus schematically illustrated in Figure 1 provides the basic equipment for performing film deposition operations such as chemical vapor deposition (CVD) or ALD on semiconductor substrates.

- 25 **[0027]** For simplicity, processing apparatus 100 is depicted as a standalone process station having a process chamber body 102 for maintaining a low-pressure environment. However, it will be appreciated that a plurality of process stations may be included in a common process tool environment—e.g., within a common reaction chamber—as described herein. For example, Figure 2 depicts an implementation of a
30 multi-station processing tool. Further, it will be appreciated that, in some implementations, one or more hardware parameters of processing apparatus 100,

including those discussed in detail above, may be adjusted programmatically by one or more system controllers.

[0028] Process station 100 fluidly communicates with reactant delivery system 101 for delivering process gases to a distribution showerhead 106. Reactant delivery system
5 101 includes a mixing vessel 104 for blending and/or conditioning process gases for delivery to showerhead 106. One or more mixing vessel inlet valves 120 may control introduction of process gases to mixing vessel 104.

[0029] Some reactants may be stored in liquid form prior to vaporization and subsequent delivery to the process chamber 102. The implementation of Figure 1
10 includes a vaporization point 103 for vaporizing liquid reactant to be supplied to mixing vessel 104. In some implementations, vaporization point 103 may be a heated liquid injection module. In some other implementations, vaporization point 103 may be a heated vaporizer. In yet other implementations, vaporization point 103 may be eliminated from the process station.

15 **[0030]** In some implementations, a liquid flow controller (LFC) upstream of vaporization point 103 may be provided for controlling a mass flow of liquid for vaporization and delivery to processing chamber 102.

[0031] Showerhead 106 distributes process gases and/or reactants (e.g., film precursors) toward substrate 112 at the process station, the flow of which is controlled
20 by one or more valves upstream from the showerhead (e.g., valves 120, 120A, 105). In the implementation shown in Fig. 1, substrate 112 is located beneath showerhead 106, and is shown resting on a pedestal 108. Showerhead 106 may have any suitable shape, and may have any suitable number and arrangement of ports for distributing processes gases to substrate 112.

25 **[0032]** A volume 107 is located beneath showerhead 106. In some implementations, pedestal 108 may be raised or lowered to expose substrate 112 to volume 107 and/or to vary a volume of volume 107. Optionally, pedestal 108 may be lowered and/or raised during portions the deposition process to modulate process pressure, reactant concentration, etc. within volume 107.

30 **[0033]** In Figure 1, showerhead 106 and pedestal 108 are electrically connected to RF power supply 114 and matching network 116 for powering a plasma. In some implementations, the plasma energy may be controlled (e.g., via a system controller

having appropriate machine-readable instructions) by controlling one or more of a process station pressure, a gas concentration, an RF source power, an RF source frequency, and a plasma power pulse timing. For example, RF power supply 114 and matching network 116 may be operated at any suitable power to form a plasma having
5 a desired composition of radical species. Likewise, RF power supply 114 may provide RF power of any suitable frequency.

[0034] In some implementations, the plasma may be monitored in-situ by one or more plasma monitors. In one scenario, plasma power may be monitored by one or more capacitance, voltage and/or current sensors (e.g., load sensors such as VI probes).
10 Examples of such sensors include MKS VI-Probe-4100 and 350. Such sensors may measure the capacitance, voltage, current, and phase differences. In certain implementations, the sensors may be electrically connected to the RF power supply and may be located at or near the showerhead. In such implementations, the impedance, as seen by the RF power supply may be representative of the impedance of the plasma. In
15 another scenario, plasma density and/or process gas concentration may be measured by one or more optical emission spectroscopy (OES) sensors. In some implementations, one or more plasma parameters may be programmatically adjusted based on measurements from such in-situ plasma monitors. For example, a load sensor may be used in a feedback loop for providing programmatic control of plasma power. It will be
20 appreciated that, in some implementations, other monitors may be used to monitor the plasma and other process characteristics. Such monitors may include, but are not limited to, infrared (IR) monitors, acoustic monitors, and pressure transducers.

[0035] In some implementations, the plasma may be controlled via input/output control (IOC) sequencing instructions. In one example, the instructions for setting plasma
25 conditions for plasma activation may be included in a corresponding plasma activation recipe of a process recipe. In some cases, process recipes may be sequentially arranged, so that all instructions for a process are executed concurrently with that process. In some implementations, instructions for setting one or more plasma parameters may be included in a recipe preceding a plasma process. For example, a
30 first recipe may include instructions for setting a flow rate of an inert (e.g., helium) and/or a reactant gas, instructions for setting a plasma generator to a power set point, and time delay instructions for the first recipe. A second, subsequent recipe may include instructions for enabling the plasma generator and time delay instructions for

the second recipe. A third recipe may include instructions for disabling the plasma generator and time delay instructions for the third recipe. It will be appreciated that these recipes may be further subdivided and/or iterated in any suitable way within the scope of the present disclosure.

5 **[0036]** In some deposition processes, plasma strikes last on the order of a few seconds or more in duration. In certain implementations described herein, much shorter plasma strikes may be applied during a processing cycle. These may be on the order of less than 50 milliseconds, with 25 milliseconds being a specific example. Such short RF plasma strikes require quick stabilization and tuning of the plasma. To accomplish the
10 quick stabilization and tuning of the plasma, the plasma generator may be configured through a two-step tuning process that includes a coarse tuning component and a fine tuning component. In the coarse tuning component, the impedance match may be preset to a particular impedance. The coarse tuning component may be preset such that a magnitude of the impedance is at a value of, for example, 50 ohms. In certain
15 implementations, the coarse tuning component may be limited to adjustments affecting the magnitude of the impedance. In the fine tuning component, the RF frequency may be allowed to float from a baseline frequency in order to attempt to match the phase to a target value, such as a phase value of zero. Conventionally, high-frequency plasmas are generated at an RF frequency of about 13.56 MHz. In various implementations
20 disclosed herein, the frequency may be allowed to float to a value that is different from this standard value in order to match the phase to the target value. In certain implementations, the fine tuning component may be limited to adjustments affecting the phase of the impedance. By permitting the frequency to float while fixing the impedance match to a predetermined impedance, the plasma can stabilize much more
25 quickly. Very short plasma strikes, such as strikes associated with ALD or atomic layer etching (ALE) cycles, may benefit from quick stabilization of the plasma.

[0037] The first 1-2 milliseconds of a typical deposition cycle involve the ignition of the plasma. After ignition of the plasma, the fine tuning of the RF frequency is then carried out to match the plasma phase to the target value.

30 **[0038]** As described above, one or more process stations may be included in a multi-station substrate processing tool. Figure 2 shows an example multi-station substrate processing apparatus that may utilize plasma balancing hardware. Various efficiencies may be achieved through the use of a multi-station processing apparatus like that

shown in Figure 2 with respect to both equipment cost and operational expenses. For instance, a single vacuum pump may be used to create a single high-vacuum environment for all four process stations by evacuating spent process gases, etc. for all four process stations. Depending on the implementation, each process station may
5 have its own dedicated showerhead for gas delivery, but may share the same gas delivery system. Likewise, certain elements of the plasma generator equipment may be shared amongst process stations (e.g., power supplies), although depending on the implementation, certain aspects may be process station-specific (for example, if showerheads are used to apply plasma-generating electrical potentials). Once again, it
10 is to be understood that such efficiencies may also be achieved to a greater or lesser extent by using more or fewer numbers of process stations per processing chamber such as 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, or 16, or more process stations per reaction chamber.

[0039] The substrate processing apparatus 200 of Figure 2 employs a single substrate
15 processing chamber 214 that contains multiple substrate process stations, each of which may be used to perform processing operations on a substrate held in a wafer holder at that process station. In this particular implementation, the multi-station substrate processing apparatus 200 is shown having four process stations 201, 202, 203, and 204. Other similar multi-station processing apparatuses may have more or fewer processing
20 stations depending on the implementation and, for instance, the desired level of parallel wafer processing, size/space constraints, cost constraints, etc. Also shown in Figure 2 are a substrate handler robot 226 and a controller 250.

[0040] As shown in Figure 2, the multi-station processing tool 200 has a substrate
loading port 220, and a robot 226 configured to move substrates from a cassette loaded
25 through a pod 228 through atmospheric port 220, into the processing chamber 214, and onto one of the four stations 201, 202, 203, or 204.

[0041] The depicted processing chamber 214 shown in Figure 2 provides four process
stations, 201, 202, 203, and 204. The RF power is generated at an RF power system
213 and distributed to each of the stations 201-04. The RF power system may include
30 one or more RF power sources, e.g., a high frequency (HFRF) and a low frequency (LFRF) source, impedance matching modules, and filters. In certain implementation, the power source may be limited to only the high frequency or low frequency source. Unless otherwise stated, assume that the described deposition processes employ only

high frequency power. The distribution system of the RF power system is symmetric about the reactor and has high impedance. This symmetry and impedance result in approximately equal amounts of power being delivered to each station. Small differences in RF power, in the order of 5 to 15%, may arise from tolerances in
5 distribution system components, station alignments, temperature differences, and process conditions.

[0042] Small differences in RF power, due to reasons including but not limited to inaccurate tuning of variable capacitors in an impedance matching module, or inaccurate measurements of current from a RF power source, can cause wafer-to-wafer
10 non-uniformity in a variety of film characteristics, e.g., composition, thickness, density, amount of cross-linking, chemistry, reaction completion, stress, refractive index, dielectric constant, hardness, etch selectivity, stability, hermeticity, etc. The ability to fine-tune plasma power at individual stations and to dynamically respond to changing station conditions may decrease wafer-to-wafer non-uniformity. Note that the present
15 method and apparatus are not limited to a multi-station reactor; the method and apparatus disclosed herein applies to other RF power systems where multiple processing areas share an RF power source.

[0043] Figure 2 also depicts an implementation of a substrate transferring device 290 for transferring substrates between process stations 201, 202, 203, and 204 within
20 processing chamber 214. It will be appreciated that any suitable substrate transferring device may be employed. Non-limiting examples include wafer carousels and wafer handling robots.

[0044] Figure 2 also depicts an implementation of a system controller 250 employed to control process conditions and hardware states of process tool 200 and its process
25 stations. System controller 250 may include one or more memory devices 256, one or more mass storage devices 254, and one or more processors 252. Processor 252 may include one or more CPUs, ASICs, general-purpose computer(s) and/or specific purpose computer(s), one or more analog and/or digital input/output connection(s), one or more stepper motor controller board(s), etc.

30 **[0045]** In some implementations, system controller 250 controls some or all of the operations of process tool 200 including the operations of its individual process stations. System controller 250 may execute machine-readable system control

instructions 258 on processor 252—the system control instructions 258, in some implementations, loaded into memory device 256 from mass storage device 254. System control instructions 258 may include instructions for controlling the timing, mixture of gaseous and liquid reactants, chamber and/or station pressure, chamber and/or station temperature, wafer temperature, target power levels, RF power levels, RF exposure time, substrate pedestal, chuck, and/or susceptor position, and other parameters of a particular process performed by process tool 200. These processes may include various types of processes including, but not limited to, processes related to deposition of film on substrates. System control instructions 258 may be configured in any suitable way. For example, various process tool component subroutines or control objects may be written to control operation of the process tool components. System control instructions 258 may be coded in any suitable computer readable programming language. In some implementations, system control instructions 258 are implemented in software, in other implementations, the instructions may be implemented in hardware—for example, hard-coded as logic in an ASIC (application specific integrated circuit), or, in other implementations, implemented as a combination of software and hardware.

[0046] In some implementations, system control software 258 may include input/output control (IOC) sequencing instructions for controlling the various parameters described above. For example, each step of a deposition process or processes may include one or more instructions for execution by system controller 250. The instructions for setting process conditions for a primary film deposition process, for example, may be included in a corresponding deposition recipe, and likewise for a capping film deposition. In some implementations, the recipes may be sequentially arranged, so that all instructions for a process are executed concurrently with that process.

[0047] Other computer-readable instructions and/or programs stored on mass storage device 254 and/or memory device 256 associated with system controller 250 may be employed in some implementations. Examples of programs or sections of programs include a substrate positioning program, a process gas control program, a pressure control program, a heater control program, and a plasma control program.

[0048] In some implementations, there may be a user interface associated with system controller 250. The user interface may include a display screen, graphical software

displays of the apparatus and/or process conditions, and user input devices such as pointing devices, keyboards, touch screens, microphones, etc.

[0049] In some implementations, parameters adjusted by system controller 250 may relate to process conditions. Non-limiting examples include process gas compositions and flow rates, temperatures, pressures, plasma conditions (such as RF bias power levels, frequencies, and exposure times), etc. These parameters may be provided to the user in the form of a recipe, which may be entered utilizing the user interface.

[0050] Signals for monitoring the processes may be provided by analog and/or digital input connections of system controller 250 from various process tool sensors. The signals for controlling the processes may be output on the analog and/or digital output connections of process tool 200. Non-limiting examples of process tool sensors that may be monitored include mass flow controllers (MFCs), pressure sensors (such as manometers), thermocouples, load sensors, OES sensors, etc. Appropriately programmed feedback and control algorithms may be used with data from these sensors to maintain process conditions.

[0051] System controller 250 may provide machine-readable instructions for implementing deposition processes. The instructions may control a variety of process parameters, such as DC power level, RF bias power level, station-to-station variations such as RF power parameter (voltage, current, capacitance, impedance, phase, load power, etc.) variations, frequency tuning parameters, pressure, temperature, etc. The instructions may control the parameters, such as but not limited to controlling the variable capacitance in an impedance matching module, or controlling a current source based on measuring the current delivered from a RF power source to a plasma, to operate in-situ deposition of film stacks according to various implementations described herein.

[0052] The system controller will typically include one or more memory devices and one or more processors configured to execute machine-readable instructions so that the apparatus will perform operations in accordance with the processes disclosed herein. Machine-readable, non-transitory media containing instructions for controlling operations in accordance with the substrate doping processes disclosed herein may be coupled to the system controller.

[0053] Various other configurations for multi-cycle deposition processes and multi-station semiconductor processing apparatuses are described in U.S. Provisional Patent Application No. 61/994,025, filed May 15, 2014, and are hereby incorporated by reference.

5 [0054] Figure 3 is a schematic diagram showing various components in an example multi-station plasma reactor with multiple stations sharing a RF power source utilizing RF frequency tuning. As shown, a RF power source 301, which may be a high frequency RF power source, is distributed via a distribution network 321 to multiple stations 351. The HFRF may have a frequency of about 2-60 MHz, or about 13.56
10 MHz. In other implementations, a low frequency RF power source may be used in addition to or in place of the high frequency RF power source. The low frequency RF power source may have a frequency of about 100 kHz to about 1 MHz, or about 400 kHz. Certain commercially available RF power sources include the ability to tune the frequency of the RF power. Examples of such RF power sources include Advanced
15 Engineer's Paramount series, MKS's SurePower series, Comdel's CB, CLX, and CDX series, and Huettinger's TruPlasma series.

[0055] The power from the RF power source 301 may be routed through an impedance matching system that may include a fixed match module 303. In certain implementations that contain both the high and the low frequency RF power source, a
20 high pass filter and/or a low pass filter may also be present. Additionally, in certain implementations, the power from the RF power source may be routed through an auto match module. Implementations that include the low frequency RF power source, whether in addition to or in place of the high frequency RF power source, low frequency power may be routed through either a fixed or auto match. In certain
25 implementations, an auto match module may be used to match the RF power frequency to a set impedance of a load of the plasma. In other implementations, a fixed match module, which does not automatically match the RF power frequency to a set impedance of a load of the plasma, may be used.

[0056] In the implementation shown in Figure 3, the RF power source 301 is connected
30 to the distribution network 321. The distribution network 321 may distribute the RF power generated by the RF power source 301 to each of the multiple stations 351. The distribution network 321 is connected to a RF adjuster 323 for each of the multiple stations 351. For each of the multiple stations 351, the RF adjuster 323 is connected to

a power parameter sensor 333 before the showerhead 353. The power parameter sensor 333 may be a sensor of any type previously disclosed, such as a voltage, current, capacitance, impedance, phase, or load power or an OES sensor. The RF power source 301 may obtain instructions from the RF controller 343 and vary the frequency of the RF power distributed to the stations. The instructions may be a frequency adjustment according to the voltage, current, capacitance, impedance, phase, or load power as detected by the one or more power parameter sensors 333. In other implementations, an additional sensor may measure a final phase that is representative of the phase of the plasmas in all of the stations 351. The RF controller 343 may then vary the frequency of the RF power distributed to the station according to the final phase measured by the additional sensor. In certain implementations, the RF controller 343 may include instructions, e.g., code, to vary the frequency of the RF power such that the phase of the impedance is zero or near zero. In the implementation shown in Figure 3, the RF controller 343 may vary the frequency of the RF power from the RF power source 301 upstream of the individual stations.

[0057] The RF adjuster 323 is controlled by RF controller 343. RF controller 343 may change the RF power at individual stations by a determined amount based on the measurement from the sensors 333 at each station 351. In certain implementations, the RF adjusters 323 may be variable capacitors. The RF controller 343 may control a stepper motor (not shown) that can vary the capacitance of a variable capacitor. Other ways to vary a capacitance may be used. For example, the RF adjusters 323 may also be a bank of capacitors with individual switches. The RF power may be controlled by activating (turning on) a number of capacitors having a specified value. For example, capacitors may be selected to add 1 pF, 2 pF, 4 pF, 8 pF, and 16 pF shunt capacitance to the station. In this example, all combinations of active (turned on) and non-active (turned off) capacitors cover the range from 0 pF to 31 pF with 1 pF resolution. By selecting which capacitors to activate, the controller can change the RF power to a station. This digital control can be faster than using a stepper motor to control a variable capacitor, especially when a wide range of capacitance needs to be covered. Depending on the space available and the amount of control required, one skilled in the art would be able to design a RF adjuster using one or more capacitors to change RF power by a certain amount.

[0058] In other implementations, the RF adjusters 323 may be variable coil inductors. The RF controller 343 may control the variable coil inductors to affect RF power delivered to the station. In certain implementations, the RF adjusters are not limited to capacitor and inductors. In certain implementations, other RF adjusters 323 may utilize
5 different mechanisms to change the RF power, such as resonator circuits or resistive circuits.

[0059] The sensors 333 measure at least one RF power parameter. The RF power parameter measured may be voltage, current, capacitance, impedance, phase, or load power. Commercially available probes may be used to measure the RF power
10 parameter and provide the measurement to the RF controller 343. It is also possible to measure a non-RF parameter and use it as source signal for the RF controller 343. For example, optical emission from station plasma or substrate temperature sensors can measure station characteristics and feed them to the adjuster controller 343. An optical emission system may be installed in the vicinity of each station to collect light emitted
15 by station plasma. A substrate temperature sensor may use remote infrared detection system built under a substrate. The sensor 333 may also measure multiple RF power parameters, or multiple sensors may be used in certain implementations to measure multiple RF power parameters.

[0060] In some implementations, the RF adjusters may be set to a fixed value or range
20 of values over multi-step processes such as a multi-cycle ALD process. In such implementations, there is little or no need for real-time sensing of the RF power parameter(s) and adjustment of the station-to-station distribution of RF power.

[0061] In some implementations, the RF adjusters 323 are used for auto-matching the
25 generator impedance of the RF power source 301 and the load impedance of the plasma. For example, the RF adjusters 323 can include two variable capacitors. The first variable capacitor can be a series (Tune) capacitor, and the second variable capacitor can be a shunt (Load) capacitor. The two variable capacitors can be adjusted such that the load impedance of the plasma is matched to a generator impedance of the
30 RF power source 301 (e.g., 50 ohms) to minimize reflections and maximize power transfer.

[0062] In certain implementations, a current flowing through the RF adjusters 323 can indicate whether there is an impedance match. For example, a current measurement

indicating a current maximum or a current minimum represents that the generator impedance and the load impedance are not matched. In various implementations, the RF controller 343 communicates with sensor 333 to obtain measurements of the current flowing through the RF adjusters 323, and the RF controller 343 communicates with
5 the RF adjusters 323 to control, for example, the variable capacitors in the RF adjusters 323 such that current flow is changed from a current maximum or current minimum.

[0063] It should be noted that the current sensor as disclosed herein is not limited to being within the sensor 333 and is also not limited to measuring current for the RF adjusters 323. It should be appreciated that the current sensor as disclosed herein may
10 be used to measure current for a variety of components in the multi-station plasma reactor described herein, and may also be used to measure current in other semiconductor apparatuses.

[0064] In various implementations, the sensor 333 can measure current using a wide variety of techniques. Examples of current measurement techniques include the Pearson
15 probe, Rogowski coil, etc. In such techniques, flux, generated from current flow in a primary path, is used to induce current in a secondary coil. This induced current generates a voltage across the secondary coil which is proportional to current flow in the primary path. In some scenarios, such techniques for current measurement are expensive, narrow band, and exhibit high variability.

[0065] In a class of implementations, the sensor 333 is a broadband current sensor that measures inline current at components in the multi-station plasma reactor. In some
20 implementations, the sensor 333 includes at least an inductor and a capacitor. As nonlimiting examples, the inductor can be a low value and can serve as the main path for current flow, and the capacitor can be a low value capacitor (e.g., $<1\text{pF}$) that can
25 result in a high impedance circuit across which a voltage can be measured.

[0066] An example of a method of operating an implementation of the sensor 333 configured to provide current sensing over a broad frequency bandwidth is shown with reference to an example implementation of sensor 500 on FIG. 5 and the flow diagram of FIG. 7. As illustrated in FIG. 5, a capacitor C is coupled in parallel to an inductor L
30 to form a parallel LC circuit. The illustrated implementation of the sensor 500 can be included inline for measuring the current in components including but not limited to the RF adjusters 323, the RF power source 301, the distribution network 321, the fixed

match module 303, or the plasma. In the example illustration of FIG. 5, the sensor 500 is measuring current flowing from RF power source 501 to plasma 511. When the sensor 500 is inserted inline where current is to be measured, a voltage V is developed across the inductor L that is proportional to the current flow for the sensor 500, and the voltage V is measured (step 705). The voltage across the inductor is linearly proportional to the current flow in the sensor 500 based on a frequency dependent proportionality factor that is determined for the particular frequency of operation (step 710) of, for example, the RF adjusters 323, the RF power source 301, the distribution network 321, the fixed match module 303, or the plasma. By applying the frequency dependent proportionality factor to the measured voltage V , a measured current is obtained (step 715).

[0067] FIG. 8 provides an example of the frequency dependent proportionality factor for converting a measured voltage to a measured current. As an example, a measured voltage of about 5 V can be converted to a measured current of about 6 A, whereas a measured voltage of about 10 V can be converted to a measured current of about 12 A, thereby corresponding to a proportionality factor of about 1.2. It should be appreciated that the sensor 500 can be used to measure current at different frequencies by varying the proportionality factor used to convert a measured voltage across the inductor L to a current value, rather than requiring modification of the hardware in the sensor 500 or replacing the sensor 500.

[0068] The sensor 500 can include an interface for coupling to a voltage measurement device 521 for measuring the voltage at the terminals of the inductor L . The voltage measurement device may be implemented with any one of a variety of architectures as known in the art. In some implementations, the voltage measurement can be performed with an oscilloscope. In various implementations, a voltage divider and/or peak detector circuit is used to facilitate measuring voltage with data acquisition, input/output controller, etc. equipment. The voltage measurement device may be integrated with the sensor 500, or may interface with the sensor 500 through input/output ports.

[0069] An example of a PCB layout of the sensor 333 configured to provide current sensing over a broad frequency bandwidth is shown as sensor 600 on FIG. 6. In some implementations, because the PCB current sense board does not require additional active or passive elements, the sensor 600 can be simple and cost-effective to

manufacture. Sensor 600 includes an inductive element 605. In various implementations, the inductive element 605 provides a very low value inductance and serves as the main path (through line) for current flow. The inductance of the line depends on the size of the line length and width (e.g., PCB board size). Sensor 600 also includes a capacitive element 610. The capacitance of capacitive element 610 can be calculated and/or measured using the formula $C = \epsilon A / d$, where ϵ is the dielectric constant of the board material, A is the area of the patch and d is the thickness of the board. It should be appreciated that the backside of the board (not depicted) has a similar parallel patch that serves as an electrode for the capacitive element 610. In a range of implementations, the capacitive element provides a very low capacitance and creates a very high impedance circuit across which the voltage will be measured. As depicted in the example of FIG. 6, front side plate connection 615 and back side plate connection 620 electrically couple the capacitor plates in capacitive element 610 to the through line having inductive element 605. In certain implementations, sensor 600 includes one or more fine tuning capacitors, as illustrated by the four dotted patches of varying sizes (one of which are identified as fine tuning capacitor 625). For a sample implementation of a 7 cm x 7 cm PCB current sense board, the inventors observed an inductance of approximately 610 nH and a capacitance of approximately 0.017 pF. The sample PCB current sense board provided approximately 18 V at 100 W, increasing to approximately 53 V at 3 kW. It should be appreciated that a smaller board can decrease the inductance, the capacitance, and the measured voltage. It should further be appreciated that the same sensor board can be used for measuring voltage and current, and that if the same node point is used, the phase difference can be accurate.

[0070] In some implementations, the frequency dependent proportionality factor indicating the linear relationship between a measured voltage across the inductor L and a current flow in the sensor 333 can be determined based on calibration measurements. For example, the sensor 333 can be coupled to a current source, the inductor L can be coupled to a voltage meter, and the current source can be configured to perform a current magnitude ramp, such as from zero Amps to 12 Amps, at a particular frequency. The resulting voltage versus current magnitude relationship can be used to derive the proportionality factor for the particular frequency. It should be appreciated that the current magnitude ramp can be performed at different frequencies to obtain the different proportionality factors for the different frequencies.

- [0071] In certain implementations, the sensor 333 can be used to determine a current I using an estimated inductance L value and/or capacitance C value based on theoretical calculations or manufacturing specifications. In various implementations, the sensor 333 can provide high accuracy even without inductance or capacitance value calibration measurements. For example, if the actual capacitor value is higher by 100% from an estimated capacitor value (e.g., from 1pF to 2pF), the error in the measured current will be constrained to $<0.0073\%$, and furthermore, if the actual capacitor value is lower by 50% from an estimated capacitor value (e.g., from 1pF to 0.5pF), the error in measured current will be constrained to $<0.0037\%$.
- [0072] In various implementations, the sensor 333 can be operated using inductance and capacitance values based on calibration measurements, as illustrated in the example flow of FIG. 9. For example, the calibration measurements for the sensor 333 involve a resonant frequency measurement (step 905). For example, one terminal of the parallel LC circuit, which includes the inductor L and the capacitor C , is coupled to a variable frequency generator, and the second terminal of the parallel LC circuit is connected to, for example, electrical ground. The sensor 333 can include an interface for coupling to a resonance meter for detecting the resonance frequency ω_{res} at the terminals of the capacitor C and inductor L . The resonance meter may be integrated with the sensor 333, or may interface with the sensor 333 through input/output ports. The resonance meter may be implemented with any one of a variety of architectures as known in the art. For example, at the resonant frequency, a minimum current flows through the sensor 333, and the resonance meter may include a current meter measuring the current flowing in the sensor 333. Continuing the example, in a frequency scan performed by sweeping the output of the variable frequency generator across a frequency range, a minimum in a current flow vs. frequency plot indicates the resonant frequency ω_{res} of the parallel LC circuit in the sensor 333. The resonant frequency of a parallel LC circuit is a characteristic of the values of L and C , and the relationship is expressed in radian frequency as $\omega_{\text{res}} = 1/\text{sqrt}(LC)$ or hertz frequency as $f_{\text{res}} = 1/(2\pi \text{sqrt}(LC))$. For example, increasing the inductance L or the capacitance C in a parallel LC circuit decreases the resonant frequency.
- [0073] In some implementations, as part of or separate from the frequency sweep for determining the resonant frequency, measurements for an impedance Z versus frequency curve can also be obtained (step 910). In certain implementations, impedance

measurements are derived from voltage and current measurements, where the impedance is the ratio of V/I . The impedance, voltage, and/or current measurement devices may be implemented with any one of a variety of architectures as known in the art. The impedance Z versus frequency relationship can be expressed as $Z = V/I =$

5 $|j\omega L) / (1 - \omega^2 LC)|.$

[0074] In a range of implementations, the calibration measurements that can be used to determine the resonant frequency and the impedance Z versus frequency ω relationship provides two knowns, namely ω_{res} (or f_{res}) and Z , that can be used to derive the value of two unknowns, namely L and C (step 915). Specifically, the expressions $\omega_{\text{res}} =$

10 $1/\sqrt{LC}$ and $Z = V/I = |j\omega L) / (1 - \omega^2 LC)|$ can be rearranged as the frequency ω dependent expressions of $L = (Z / \omega) (1 - (\omega^2 / \omega_{\text{res}}^2))$ and $C = 1 / (\omega_{\text{res}}^2 L)$. The calibration based determinations of L and C and then be used during the operation of the sensor 333 for in-line current sensing for determining a frequency dependent linear proportionality constant, such as by determining the impedance Z at a particular

15 operational frequency $\omega = 2\pi f$ (step 920). As a nonlimiting example, expressions including but not limited to $I = C (dV/dt)$ or $C = I / (dV/dt)$ allow derivation of a current I for a particular capacitance C value, and a measured rate of change in voltage across the capacitor.

[0075] In various implementations, the sensor 333 can be operated as illustrated in the

20 example flow of FIG. 10. Calibration measurements as described earlier can be used to determine the resonant frequency (step 1005). The capacitance of, for example, capacitive element 610 in an implementation of sensor 333, can be calculated and/or measured using the formula $C = \epsilon A / d$, where ϵ is the dielectric constant of the board material, A is the area of the patch and d is the thickness of the PCB board (step 1010).

25 The inductance L can be determined from the known C and known resonant frequency, where $\omega_{\text{res}} = 1/\sqrt{LC}$ or $f_{\text{res}} = 1/(2\pi \sqrt{LC})$ (step 1015). The voltage across the inductive element is measured (step 1020). Since the impedance Z_L of an inductive element L is $Z_L = j\omega L$, the measured voltage V across the inductive element L can be converted to the measured current I (step 1025), where $I = V / 2\pi f L$, with f representing

30 the particular operational frequency, and $\omega = 2\pi f$.

[0076] In some implementations, the parallel LC circuit in the sensor 333 can be characterized based on a Q value. The Q value represents the bandwidth selectivity of the parallel LC circuit, and is proportional to the ratio of C/L . For example, the higher

the inductance L and/or the lower the capacitance C, the lower the Q value, which corresponds to a wider bandwidth for the sensor 333.

[0077] It should be appreciated that in some implementations, the parallel LC circuit in the sensor 333 provides broadband current sensing capabilities for a bandwidth that includes potential noise signals. In certain implementations, the bandwidth characteristics of the sensor 333 can be adjusted to exclude the potential noise signals by techniques including but not limited to varying the Q value or shifting a center frequency. In various implementations, a filter can be coupled to the sensor 333 to filter out the potential noise sources. The filter can be implemented using any one of a variety of architectures as known in the art. It should be appreciated that the term filter as used herein includes a single filter element or an equivalent filter corresponding to a plurality of filter elements. In various implementations, the filter passes frequency signals in the 2-60 MHz range, such as but not limited to 13.56 MHz. In a class of implementations, the filter passes frequency signals in the 100 kHz to about 1 MHz range, such as but not limited to 400 kHz.

[0078] The inductor and the capacitor in the sensor 333 can each be implemented using any one of a variety of architectures as known in the art. It should be appreciated that the term capacitor (or inductor) as used herein includes a single capacitor (or inductor) element or an equivalent capacitor (or inductor) corresponding to a plurality of capacitor (or inductor) elements. In a class of implementations, the capacitor is a variable capacitor, and/or the inductor is a variable inductor. For example, the variable capacitor and/or the variable inductor can be adjusted to vary the frequency characteristics of the sensor 333 as an in-built fine tuning mechanism. As a nonlimiting example, the RF controller 343 may control a stepper motor that can vary the capacitance/inductance of the variable capacitor/inductor, or the RF controller 343 may control a bank of capacitors/inductors with individual switches.

[0079] It should be appreciated that the example implementations of sensor 333 for measuring RF current can be accurate, inexpensive, have wide bandwidth, be easily manufactured (e.g., PCB package, etc.), and involve a simple calibration procedure. In various implementations, the sensor 333 can include an in-built fine tuning mechanism such that the voltage across the capacitor is linearly proportional to the current. As described in further detail above, the proportionality factor changes with frequency and the sensor 333 can be used at any frequency by changing the proportionality factor.

[0080] In certain implementations, the sensor 333 includes an inductor, a capacitor, an interface for in-line coupling to a component in a multistation plasma reactor, an interface for coupling to a voltage measurement device, wherein the inductor and capacitor are arranged in parallel, the value of the inductor is configured such that the inductor is the main path for current flow through the sensor 333, and the value of the capacitor is configured such that the capacitor creates a high impedance across the interface for the voltage measurement device. In various implementations, the sensor 333 is calibrated using a method of determining a resonant frequency, determining an impedance versus frequency relationship, and determining an inductance and capacitance value of a corresponding inductor and capacitor in the sensor 333 based on the resonant frequency and the impedance versus frequency relationship.

[0081] Each station 351 contains a showerhead 353 working in conjunction with a grounded pedestal 357. The power and frequency supplied is sufficient to generate a plasma from the process gas, for example within the range of about 50 – 6,000W per station. Power levels may vary according to the implementation. RF power is connected to the station processing area via the showerhead 353 and generates or sustains a plasma when RF power is applied. The plasma causes material to be deposited onto the substrate by a variety of mechanisms. For example, the plasma can cause process gas to break down and react on the substrate surface. In the implementation shown, the RF current is grounded at the pedestals 357, which are connected to the ground 331. In certain other implementations, the RF current may be grounded at a different location in the chamber such as at the showerheads.

[0082] The semiconductor tools previously described may be used for plasma balancing. Plasma balancing may be especially beneficial in a multi-cycle deposition process with short cycle durations such as ALD and atomic layer etching (ALE). Atomic layer etching methods are further discussed in the following U.S. Patents, each of which is herein incorporated by reference in its entirety: U.S. Patent No. 7,416,989, titled “ADSORPTION BASED MATERIAL REMOVAL PROCESS”; U.S. Patent No. 7,977,249, titled “METHODS OF REMOVING SILICON NITRIDE AND OTHER MATERIALS DURING FABRICATION OF CONTACTS”; U.S. Patent No. 8,187,486, titled “MODULATING ETCH SELECTIVITY AND ETCH RATE OF SILICON NITRIDE THIN FILMS”; U.S. Patent No. 7,981,763, titled “ATOMIC LAYER REMOVAL FOR HIGH ASPECT RATIO GAPFILL”; and U.S. Patent No.

8,058,179, titled "ATOMIC LAYER REMOVAL PROCESS WITH HIGHER ETCH AMOUNT."

[0083] The plasma activation step of multi-step deposition processes with short cycle durations may be brief. The duration of the plasma activation step may be about 150
5 milliseconds or less (e.g., about 50 milliseconds). Due to the short durations, control of plasma consistency has an effect on process uniformity. Plasma balancing may be used to control plasma consistency.

[0084] Figure 4A is a process flow diagram of a multi-station deposition process utilizing RF frequency tuning and RF power parameter adjustment. The process
10 described in Figure 4A may be applicable to a variety of steps in deposition processes, such as step 3 of the ALD cycle which was previously described. Although the process is discussed in the context of a deposition procedure, elements of the process may be applied to any plasma-assisted semiconductor process.

[0085] In operation 401, a substrate is provided. Substrates may be provided to one or
15 more stations of a multi-station tool. Substrates may be provided through the loading of a station with a substrate or the substrate may already be in the station due to a previous operation, such as from a previous cycle.

[0086] After a substrate is provided, gas flow is established in operation 403 and pressure is stabilized at a set point. Operation 405 starts the generation of RF power.
20 The RF power may be HFRF, LFRF, or both HFRF and LFRF. Before operation 405, the impedance between the electrode, typically the showerhead, and the substrate may be very high, similar to the impedance of an open circuit. In operation 405, the RF power may be generated and applied to ignite the plasma. The RF power may be applied such that the magnitude of the impedance is fixed at a certain resistance, such
25 as a resistance of 50 ohms. The RF power may be applied at a fixed frequency. The fixed frequency may be a pre-determined frequency of RF power. In certain other implementations, the frequency of the RF power generated in operation 405 may not be according to a fixed frequency. In such implementations, the frequency in operation 405 may be varied in a variety of ways, such as through algorithms, user input,
30 feedback from previous operations of the deposition process, etc. In certain implementations, operation 405 may last for a limited duration, such as a period of less than 5 milliseconds.

[0087] After the plasma has been ignited properly, the process may continue to operation 407. Full power may be delivered from operation 407 onward. Operations 407-19 are repeated for the remaining duration of the step of the deposition process. Hence, if the process of Figure 4A is used in step 3 of the ALD cycle, operations 407-19 are repeated until the end of step 3. In operation 407, the impedance of the plasma may be measured. During the process described in Figure 4A, chemical reactions and changes in the environmental conditions within the processing station may lead to changes in the impedance of the plasma. Impedance may be measured by any sensor typically used to measure impedance of plasmas. The impedance measured may be impedance as seen by a source of the RF power. The impedance as seen by the source of the RF power may be measured by the sensors described elsewhere in this disclosure herein. For example, a load sensor conductively connected to the source of the RF power may measure the impedance as seen by the source of the RF power.

[0088] In operation 408, the frequency of the RF power may be tuned according to the impedance measured in step 407. Certain implementations of the semiconductor processing tool may include a controller and associated instructions for matching RF power frequencies to detected impedances. The instructions may be based on plots, may be according to formulas, or other methods of calculating the required RF power frequency. For example, the RF power frequency may be tuned such that the phase of the impedance is as close to a zero value as possible. As the impedance changes during semiconductor processing, the RF power frequency may be adjusted accordingly in operation 408. In certain implementations, the impedance may be measured as an average of the impedance at each station. Other implementations may include the ability to measure the impedance at each individual station. As previously mentioned, operations 407 and 408 are continuously performed until the end of the deposition process step due to the potential for changes in the impedance.

[0089] In operation 409, a RF power parameter may be measured at each station to determine variations among the stations. The RF power parameter may be measured after plasma is generated in the station and reflects the dynamic impedances in each station. This parameter may be a voltage, current, capacitance, impedance, phase, load power, power delivered to the station, or any combination of the previous.

[0090] The RF power parameter measurements may be compared with a set point for each station in operation 411. In certain implementations of RF power balancing, the

set points may be the same for every cycle of the deposition process. In other implementations, the set points may vary between cycles of the deposition process. For example, the set points may be an average of the measured power delivered to each station. In yet other implementations, the set points may be different at each station.

- 5 This comparison may be performed at a local controller, a central controller for RF adjusters, or at a system control for the entire tool.

[0091] The total RF power delivered to the all stations that share a common RF source depends on the power set point at the RF generator, the impedance of the plasma load and the impedance of RF network. The RF adjusters affect primarily station-to-station
10 power distribution. Adjuster effects on total power are usually secondary. In certain cases, depending on the type of RF adjuster used, a reduction in RF power of one station may increase RF power in other stations. In those cases the controller may determine an adjustment taking station-station RF power interactions into account or simply repeat the adjustment many times until the measurements are within a threshold
15 margin to the set point.

[0092] In certain cases an absolute RF power level is desired. In this case, RF power can be measured at each station and then two adjustments executed. For example, first, total power at the generator output is changed to match the sum of station set points. Second, the station RF adjusters are tuned to split power according to the set points.
20 The order of adjustments (total power vs. split) may be reversed. The procedure is repeated until power split is within a threshold margin to the set points.

[0093] In operation 413, the measured RF power parameter distribution may be compared with the set point(s). If the difference is higher than a threshold, then an adjuster change at each station may be determined at operation 415. The adjuster
25 change needed may vary station by station. Certain stations may require no adjuster change at all while other stations may require an adjuster change. This adjuster change may be determined by the RF controller or another controller. Note that the parameter or RF characteristic to be adjusted may be different from the RF power parameter measured. In one example, RF power may be measured and capacitance or impedance
30 adjusted.

[0094] The needed adjuster change may be applied to adjust a station RF characteristic at operation 417. In certain implementations, the station impedance may be adjusted by

the adjuster change amount in operation 417. The impedance and station RF power parameter may then be measured again starting from operation 407 and the adjustment cycles of the RF power frequency and the power parameter may continue until the deposition process has finished.

- 5 **[0095]** If the power parameter measured in operation 411 and compared in operation 413 is within an acceptable range, the semiconductor processing continues in operation 419. The process may then continue starting from operation 407 until the deposition process has finished. While the description of certain example implementations in this disclosure are in the context of a deposition process, it should be appreciated that other
- 10 semiconductor processing operations in addition to or instead of deposition, including but not limited to etching, stripping, or cleaning a thin film from a substrate, are contemplated for the disclosed current measurement techniques. It should further be appreciated that the disclosed current measurement techniques facilitate providing uniform and/or repeatable process conditions (e.g., RF power, etc.) at multiple
- 15 semiconductor processing stations for semiconductor processing operations (e.g., deposition, etch, strip, clean, etc.), thereby improving the yield of semiconductor fabrication.

- [0096]** In various implementations, the sequence of operations 407-19 may be arranged in different orders. For example, operation 409 (and possibly operations 409-19) may
- 20 be performed before operation 407. In other implementations, operations 407-08 may be performed concurrently with operations 409-19. In yet other implementations, the measurement operations 407 and 409 may be performed before the tuning and adjustment operations 408 and 411-19.

- [0097]** In the power balancing context, continuous RF power control during processing
- 25 may be needed for at least two reasons. One possibility is following an intentional RF power curve. The set points may vary over time during a processing sequence. The RF adjusters may be used to maintain specific power distribution as set points vary. In another possibility, the station RF power may have tendency to drift during processing and needs to be adjusted based on dynamic feedback.

- 30 **[0098]** In certain implementations, a semiconductor processing operation may include multiple different deposition processes in a single multistation reactor. The multiple different deposition processes may deposit different materials, particularly layers of

material such as a barrier layer or a nucleation layer in contact with an underlying substrate, a bulk layer on top of the nucleation layer, a capping layer on top of the bulk layer, etc. These individual layers may have relatively similar (or different) compositions. In some cases, the different deposition processes may use different process gases. When a semiconductor processing operation has multiple different deposition processes, different recipes are typically used for the different deposition processes. In such cases, different RF power parameter set points for individual stations may be used for the different recipes. In certain implementations, the differences in the set points would result in variations between the initial adjuster setting for the different recipes. Such initial adjuster settings may be contained in or a part of the recipes for the deposition processes. The different recipes of the different deposition processes may reflect the variations in the initial adjuster settings of the different processes. In such cases, the initial adjuster settings for the separate processes may be determined through prior simulation or testing results. In certain implementations, the RF power frequency that is first generated and distributed to the stations may be at different per-station power settings for the individual recipes. In such implementations, the RF adjusters may be further tuned during the deposition process according to the techniques described herein. In certain embodiments, the initial adjuster position may be an adjuster position that is calculated to result in the least amount of RF adjuster tuning when the deposition process is performed over multiple cycles.

[0099] Figure 4B is a process flow diagram of a multi-station deposition process utilizing RF frequency tuning. Figure 4B is similar to Figure 4A, however while Figure 4A describes a process utilizing both RF frequency tuning and RF power parameter adjustment during the deposition process, Figure 4B describes a process utilizing only RF frequency tuning during the deposition process.

[0100] Process flow diagram of Figure 4B may be a process utilized for a deposition process utilizing RF frequency tuning. Certain implementations may use the process illustrated in Process 4B for an individual deposition process of a semiconductor processing operation that includes multiple different deposition processes. The multiple different deposition processes may deposit different materials as described herein. In other embodiments, only a single deposition process is used. Either way, the station-to-station RF power adjustment is fixed and may be set prior to the deposition process.

Typically, the process does not employ feedback of an RF power parameter to determine appropriate RF power adjustment during deposition.

5 [0101] In process flow diagram 420 of Figure 4B, operations 421 and 423 are similar to operations 401 and 403 of Figure 4A, respectively. In operation 425 of Figure 4B, RF adjustments for the multiple stations are determined. The RF adjustments for the multiple stations are determined prior to generation of RF power and the processing of the substrates. The RF adjustments may be determined via historical data, calculations, or trial and error.

10 [0102] After the RF adjustment has been performed in operation 425, the process may proceed to operation 427. Operations 427, 429, and 431 are similar to operations 405, 407, and 408 of Figure 4A, respectively. In operation 433, the current cycle is processed for each station and the process is then repeated for the desired number of cycles. During each of the desired number of cycles, operations 427, 429 and 431 are repeated so that the RF power frequency is continuously tuned according to the requirements of the impedance measured. The RF power frequency may be tuned according to the techniques described elsewhere in this disclosure herein.

20 [0103] It should be appreciated that in some implementations, capacitance and/or current are measured instead of or in addition to measuring impedance as referred to in FIG. 4A and 4B, using, such as, the example implementations of sensor 333 described in this specification. It should further be appreciated that in some implementations, the frequency of the RF power is tuned based on the capacitance and/or current that is measured, instead of or in addition to the measured impedance as referred to in FIG. 4A and 4B, using, such as, the example implementations of sensor 333 in this specification.

25 [0104] Various other configurations and apparatus for power balancing for multi-station semiconductor processing apparatuses are described in U.S. Patent No. 8,282,983, issued October 9, 2012, which is incorporated herein by reference in its entirety.

CLAIMS

What is claimed is:

1. A method of plasma-assisted semiconductor processing in multiple stations in a
5 process chamber, the method comprising:
 - a) providing substrates at each of the multiple stations;
 - b) distributing RF power to multiple stations to thereby generate a plasma in the stations, wherein the RF power is distributed according to a RF power parameter that is adjusted to reduce station to station variations;
 - 10 c) tuning a frequency of the RF power, wherein tuning the frequency includes:
 - i) measuring a current of the plasma,
 - ii) determining, according to the current measured in (i), a change to the frequency of the RF power, and
 - iii) adjusting the frequency of the RF power; and
 - 15 d) performing a semiconductor processing operation on the substrate at each station.
2. The method of claim 1, wherein the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film.
- 20 3. The method of claim 2, wherein i) comprises:
 - a) measuring a voltage across an inductive element in a current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically
25 inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and
 - b) converting the measured voltage across the inductive element to the current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the
30 plasma.

4. The method of claim 3, wherein the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, wherein the linear proportionality factor is represented by $1 / 2\pi fL$.
5. The method of claim 4, wherein the capacitive element and inductive element are integrated on a printed circuit board.
6. The method of claim 3, wherein the capacitive element has a capacitive value of less than or equal to about 0.017 pF.
7. The method of claim 3, wherein the inductive element has an inductance value of less than or equal to about 610 nH.
8. The method of claim 5, wherein the capacitive element has a capacitance value $C = \epsilon A / d$, where ϵ is a dielectric constant, A is an area of the capacitive element, and d is a distance between electrodes of the capacitive element.
9. The method of claim 3, wherein the linear proportionality factor is determined in part by an impedance Z of the inductive element at the RF power frequency of the plasma.
10. The method of claims 3 or 9, wherein the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor.
11. The method of claim 10, wherein the linear proportionality factor is determined in part by determining an impedance Z of the current sensor over a frequency range that includes a resonant frequency ω_{res} .
12. The method of claim 11, wherein the linear proportionality factor is determined in part by determining an inductance value L of the inductive element and a capacitance value C of the capacitive element.

13. The method of claim 12, wherein the RF power frequency is a frequency of about 13.56 MHz.

14. The method of claim 13, wherein the RF power frequency is modified to an
5 adjusted RF power frequency, and further wherein i) is repeated with the current sensor at the adjusted RF power frequency using a second linear proportionality factor.

15. An apparatus for plasma-assisted semiconductor depositions, the apparatus comprising:

10 multiple process stations, wherein each of the process stations includes at least one wafer support and is configured to receive at least one substrate, and wherein the multiple process stations are within a chamber;

a power source configured to provide RF power to the chamber to generate and maintain a plasma;

15 a current sensor configured to measure plasma current;

a RF frequency tuner configured to tune the RF power frequency;

one or more RF power adjusters configured to adjust the RF power distributed to the multiple process stations and thereby reduce station to station variations; and

20 one or more controllers, wherein the one or more controllers, the power source, the current sensor, the RF frequency tuner, and the RF power adjusters are communicatively connected and the controller is configured to:

tune the RF power frequency, wherein tuning the RF power frequency includes:

i) determining the plasma current using the current sensor by:

25 a) measuring a voltage across an inductive element in the current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the chamber for generating and maintaining the plasma;

30 b) converting the measured voltage across the inductive element to the plasma current based in part by applying a linear proportionality factor dependent on the RF power frequency of the plasma;

ii) determining, according to the current measured in (i), a change to the frequency of the RF power; and

iii) adjusting the frequency of the RF power via the RF frequency tuner, and

5 iv) instruct the one or more RF power adjusters to adjust the RF power distributed to each station to reduce station-to-station variations when performing a semiconductor processing operation at each process station.

16. The apparatus of claim 15, wherein the semiconductor processing operation is
10 one of: depositing, etching, stripping, or cleaning a thin film.

17. The apparatus of claim 16, wherein the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I) of the plasma based in part on $I = V / 2\pi fL$, wherein the linear
15 proportionality factor is represented by $1 / 2\pi fL$.

18. The apparatus of claim 17, wherein the capacitive element and inductive element are integrated on a printed circuit board.

20 19. The apparatus of claim 15, wherein the capacitive element has a capacitive value of less than or equal to about 0.017 pF.

20. The apparatus of claim 15, wherein the inductive element has an inductance value of less than or equal to about 610 nH.

25

21. The apparatus of claim 18, wherein the capacitive element has a capacitance value $C = \epsilon A / d$, where ϵ is a dielectric constant, A is an area of the capacitive element, and d is a distance between electrodes of the capacitive element.

30 22. The apparatus of claim 15, wherein the linear proportionality factor is determined in part by an impedance Z of the current sensor at the RF power frequency of the plasma.

23. The apparatus of claims 15 or 22, wherein the linear proportionality factor is determined in part by determining a resonant frequency ω_{res} of the current sensor.
24. The apparatus of claim 23, wherein the linear proportionality factor is
5 determined in part by determining an impedance Z of the current sensor over a frequency range that includes a resonant frequency ω_{res} .
25. The apparatus of claim 24, wherein the linear proportionality factor is determined in part by determining an inductance value L of the inductive element and a
10 capacitance value C of the capacitive element.
26. A method of plasma-assisted semiconductor processing in a process chamber, the method comprising:
- a) measuring a voltage across an inductive element in a current sensor,
15 the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and
- b) converting the measured voltage across the inductive element to the
20 current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the plasma for performing a semiconductor processing operation on a substrate at a station in the process chamber.
27. The method of claim 26, wherein the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film.
28. The method of claim 27, wherein the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the current (I)
30 of the plasma based in part on $I = V / 2\pi fL$, wherein the linear proportionality factor is represented by $1 / 2\pi fL$.

29. The method of claim 28, wherein the capacitive element has a capacitive value of less than or equal to about 0.017 pF, and the inductive element has an inductance value of less than or equal to about 610 nH.
- 5 30. The method of claim 29, wherein the capacitive element and inductive element are integrated on a printed circuit board, and further wherein the capacitive element has a capacitance value $C = \epsilon A / d$, where ϵ is a dielectric constant, A is an area of the capacitive element, and d is a distance between electrodes of the capacitive element.
- 10 31. The method of claim 28, wherein the linear proportionality factor is determined in part by an impedance Z of the inductive element at the RF power frequency of the plasma.
32. The method of claims 28 or 31, wherein the linear proportionality factor is
15 determined in part by determining a resonant frequency ω_{res} of the current sensor.
33. The method of claim 32, wherein the linear proportionality factor is determined in part by determining an impedance Z of the current sensor over a frequency range that includes a resonant frequency ω_{res} .
20
34. The method of claim 33, wherein the linear proportionality factor is determined in part by determining an inductance value L of the inductive element and a capacitance value C of the capacitive element.
- 25 35. The method of claim 34, wherein the RF power frequency is a frequency of about 13.56 MHz.
36. The method of claim 35, wherein the RF power frequency is modified to an adjusted RF power frequency, and further wherein b) is repeated with the current sensor
30 at the adjusted RF power frequency using a second linear proportionality factor.
37. An apparatus for plasma-assisted semiconductor processing in a process chamber, the apparatus comprising:

a process station within the process chamber, the process station having at least one wafer support configured to receive at least one substrate;

a power source configured to provide RF power to the process chamber to generate and maintain a plasma;

5 a current sensor configured to measure plasma current;

one or more controllers, wherein the one or more controllers, the power source, and the current sensor are communicatively connected and the controller is configured to:

10 a) measure a voltage across an inductive element in a current sensor, the inductive element being electrically parallel to a capacitive element in the current sensor, the inductive element being electrically inline relative to plasma current flow towards the process chamber for generating and maintaining the plasma; and

15 b) convert the measured voltage across the inductive element to the current of the plasma based in part by applying a linear proportionality factor dependent on a RF power frequency of the plasma for performing a semiconductor processing operation on a substrate at a station in the process chamber.

20 38. The apparatus of claim 37, wherein the semiconductor processing operation is one of: depositing, etching, stripping, or cleaning a thin film.

39. The apparatus of claim 38, wherein the measured voltage (V) across the inductive element (L) at the RF power frequency of the plasma (f) is converted to the
25 current (I) of the plasma based in part on $I = V / 2\pi fL$, wherein the linear proportionality factor is represented by $1 / 2\pi fL$.

40. The apparatus of claim 39, wherein the capacitive element has a capacitive value of less than or equal to about 0.017 pF, and the inductive element has an
30 inductance value of less than or equal to about 610 nH.

41. The apparatus of claim 40, wherein the capacitive element and inductive element are integrated on a printed circuit board, and further wherein the capacitive element has a capacitance value $C = \epsilon A / d$, where ϵ is a dielectric constant, A is an

area of the capacitive element, and d is a distance between electrodes of the capacitive element.

42. The apparatus of claim 39, wherein the linear proportionality factor is
5 determined in part by an impedance Z of the inductive element at the RF power frequency of the plasma.

43. The apparatus of claims 39 or 42, wherein the linear proportionality factor is
10 determined in part by determining a resonant frequency ω_{res} of the current sensor.

44. The apparatus of claim 43, wherein the linear proportionality factor is
determined in part by determining an impedance Z of the current sensor over a
frequency range that includes a resonant frequency ω_{res} .

15 45. The apparatus of claim 44, wherein the linear proportionality factor is
determined in part by determining an inductance value L of the inductive element and a
capacitance value C of the capacitive element.

46. The apparatus of claim 45, wherein the RF power frequency is a frequency of
20 about 13.56 MHz.

47. The apparatus of claim 46, wherein the RF power frequency is modified to an
adjusted RF power frequency, and further wherein b) is repeated with the current sensor
at the adjusted RF power frequency using a second linear proportionality factor.
25

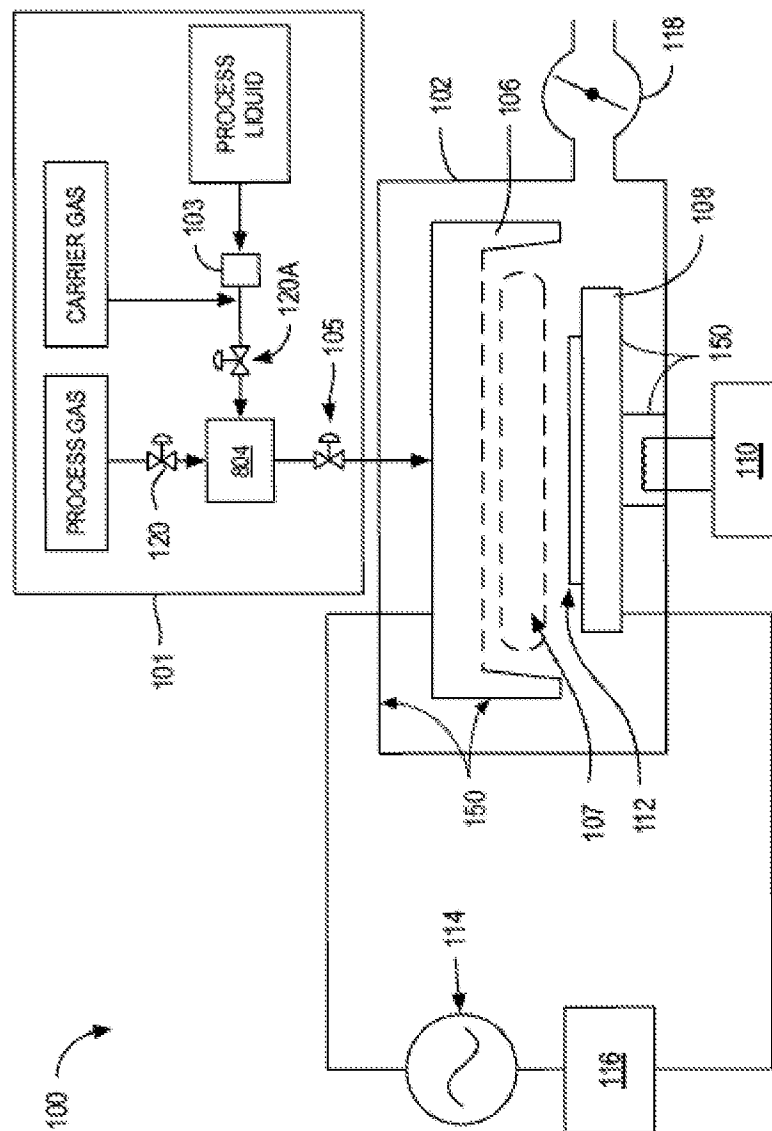


Figure 1

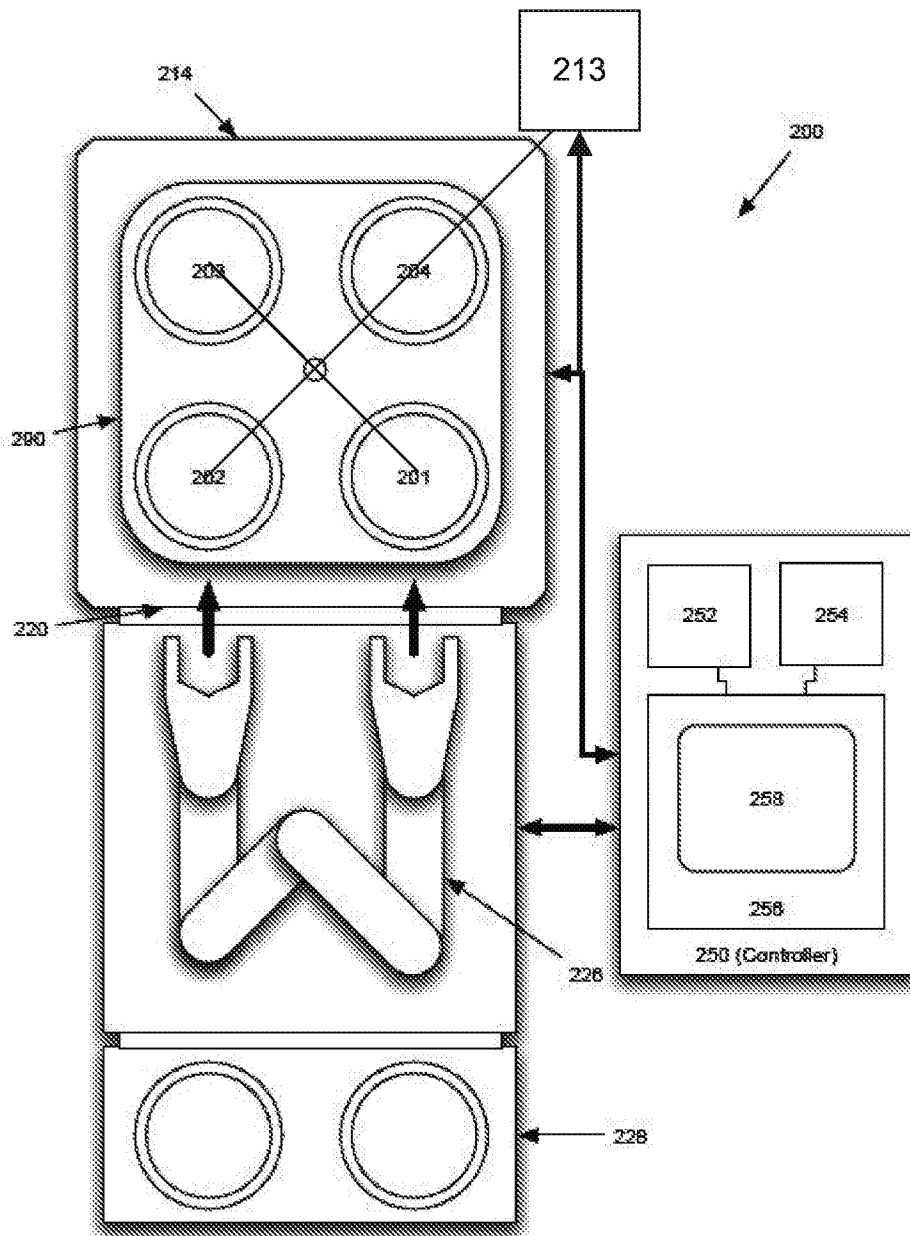
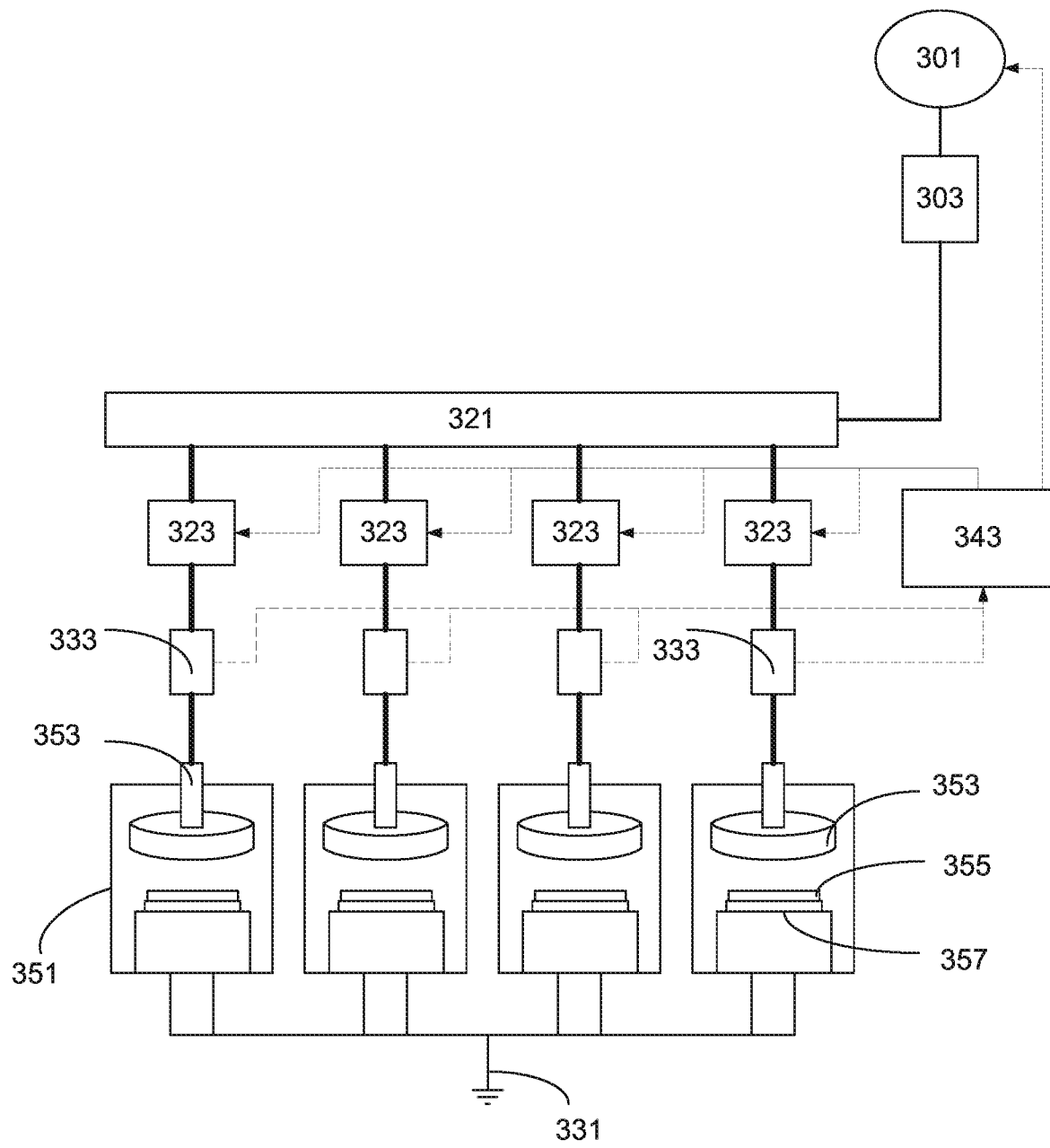


Figure 2

**Figure 3**

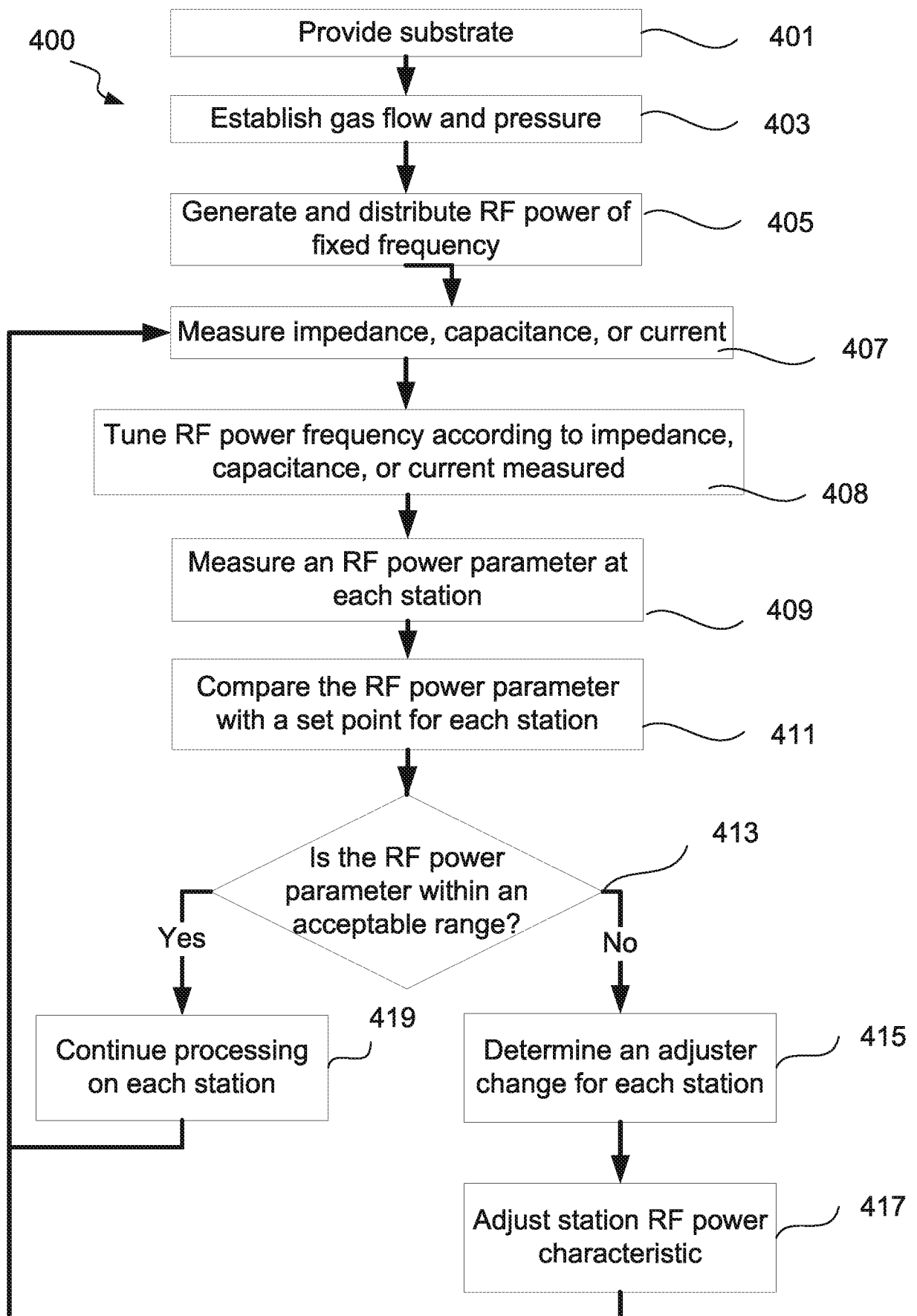


Figure 4A

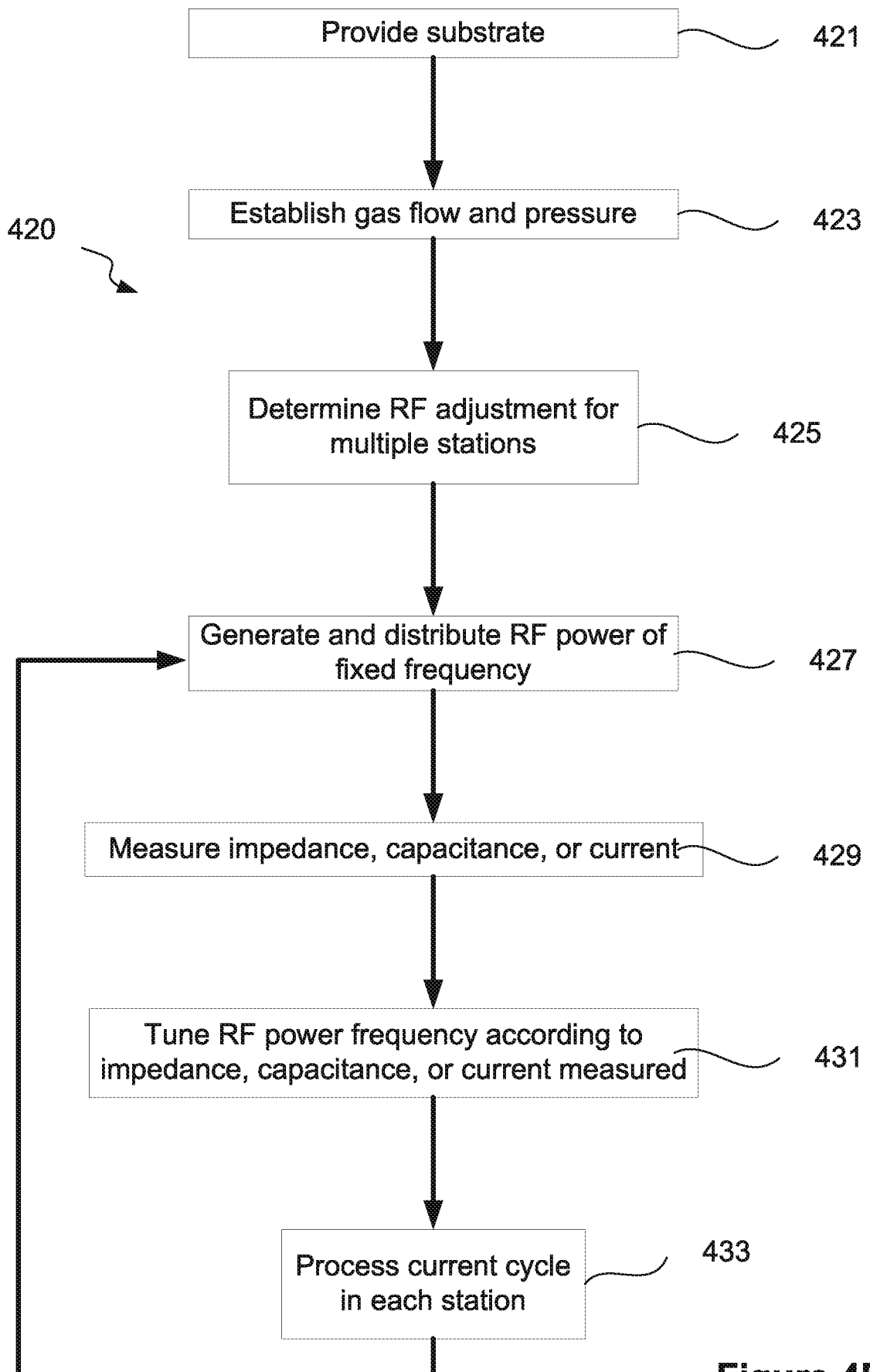
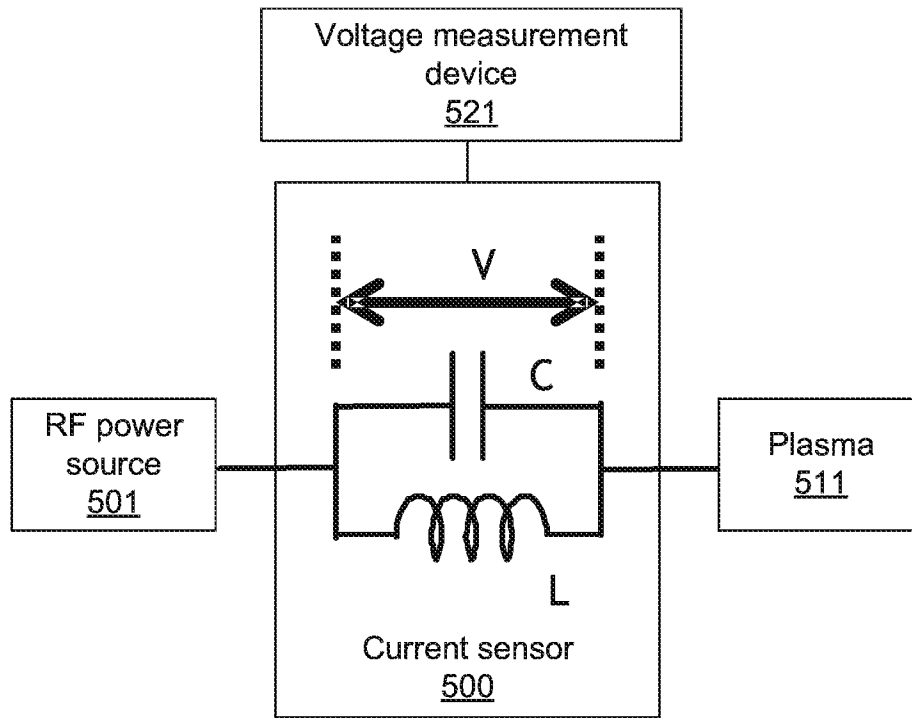


Figure 4B

**Figure 5**

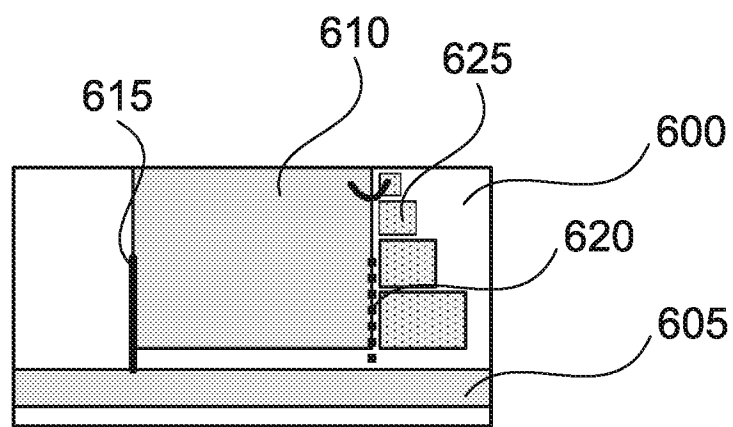
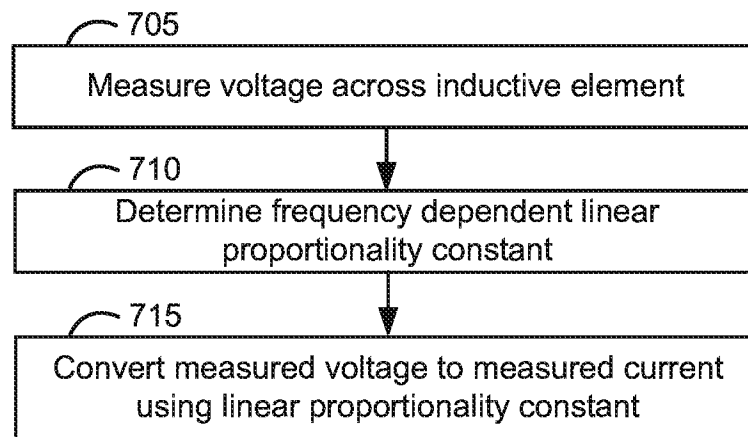


Figure 6

**FIGURE 7**

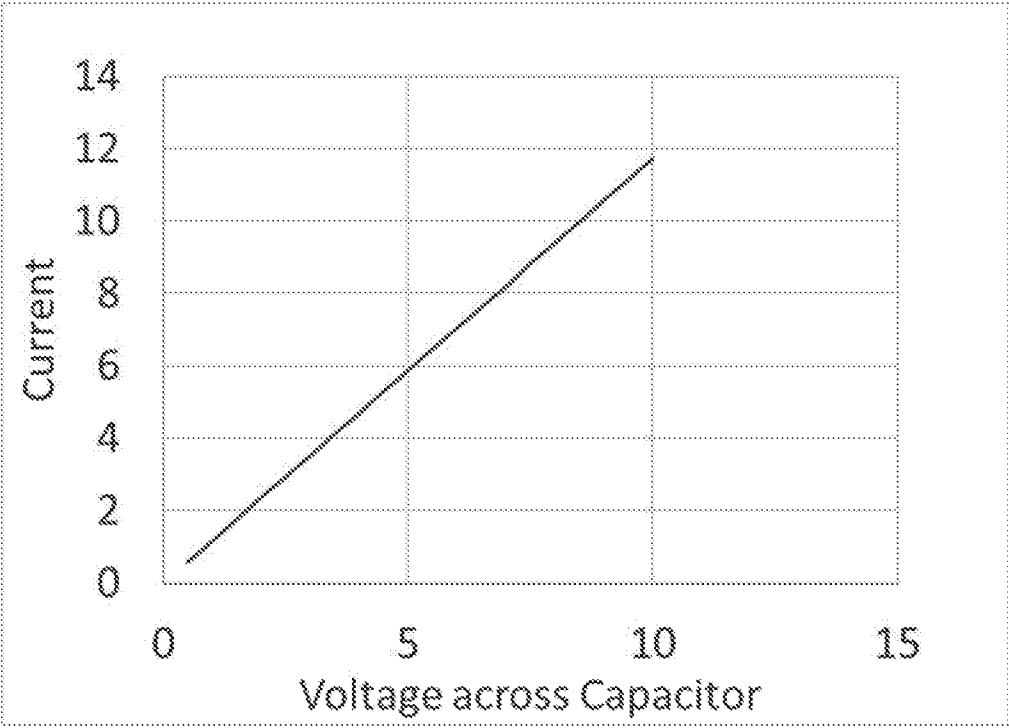
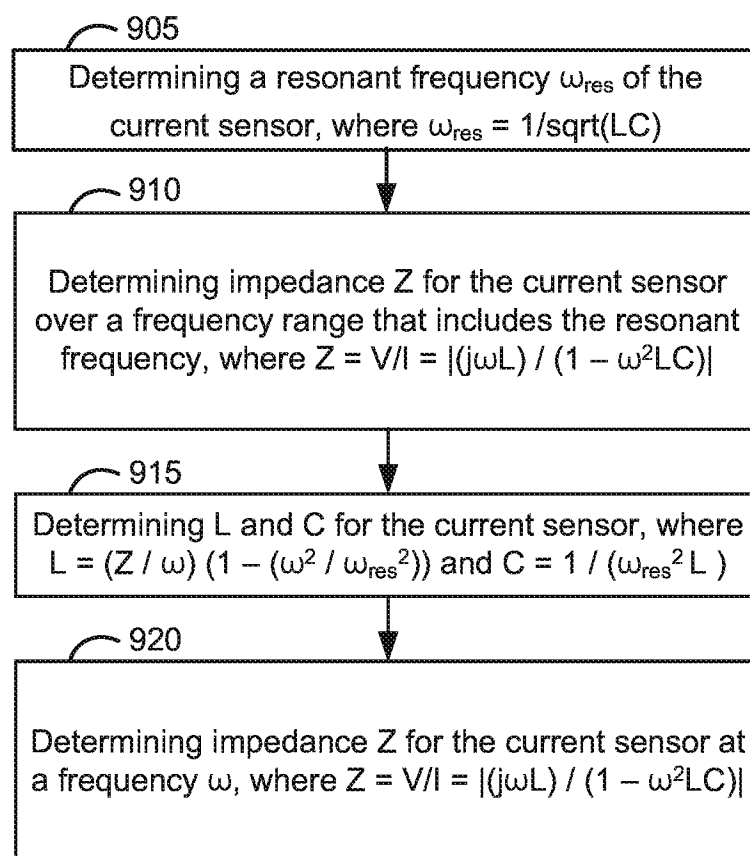
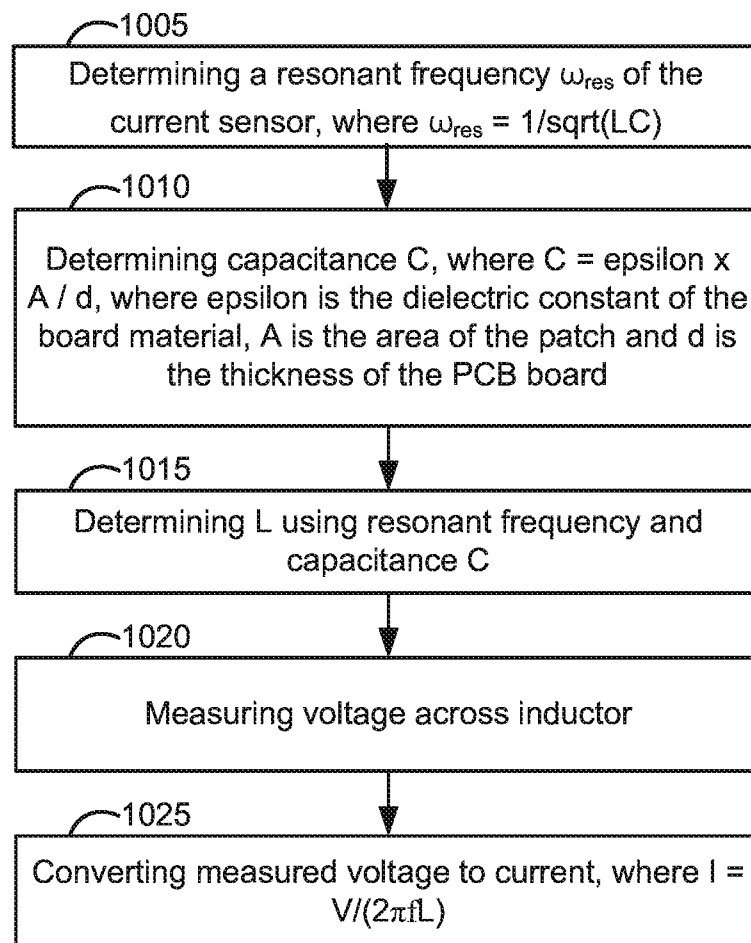


Figure 8

**FIGURE 9**

**FIGURE 10**

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/019278**A. CLASSIFICATION OF SUBJECT MATTER****H01J 37/32(2006.01)i, H01L 21/3065(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01J 37/32; C23C 16/455; C23C 16/458; C23C 16/505; G01R 31/14; H01L 21/02; H01L 21/3065; H01L 21/683; H05H 1/46

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: multiple stations, RF, tune, current sensor, voltage

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2016-0168701 A1 (LAM RESEARCH CORPORATION) 16 June 2016 See paragraphs [0003], [0069], [0079] and claim 1.	1, 2
A		3-47
A	US 2017-0338085 A1 (LAM RESEARCH CORPORATION) 23 November 2017 See paragraphs [0041], [0055] and figure 3.	1-47
A	US 2012-0074951 A1 (JIAN J. CHEN et al.) 29 March 2012 See claims 1, 2.	1-47
A	US 2017-0140968 A1 (LAM RESEARCH CORPORATION) 18 May 2017 See paragraphs [0076]-[0079].	1-47
A	JP 2016-105489 A (TOKYO ELECTRON LTD. et al.) 09 June 2016 See paragraphs [0038]-[0045].	1-47

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

03 June 2019 (03.06.2019)

Date of mailing of the international search report

03 June 2019 (03.06.2019)

Name and mailing address of the ISA/KR

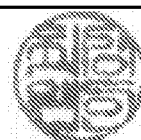
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2019/019278

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2016-0168701 A1	16/06/2016	CN 105321792 A	10/02/2016
		CN 105321792 B	24/04/2018
		CN 108461376 A	28/08/2018
		KR 10-2015-0139461 A	11/12/2015
		SG 10201504057 A	28/01/2016
		TW 201611153 A	16/03/2016
		US 10145010 B2	04/12/2018
		US 2015-0348854 A1	03/12/2015
		US 2018-0163302 A1	14/06/2018
		US 9263350 B2	16/02/2016
		US 9840776 B2	12/12/2017
US 2017-0338085 A1	23/11/2017	JP 2017-098224 A	01/06/2017
		KR 10-2017-0035772 A	31/03/2017
		TW 201720237 A	01/06/2017
		US 2017-0076921 A1	16/03/2017
		US 9754769 B2	05/09/2017
		US 9875883 B2	23/01/2018
US 2012-0074951 A1	29/03/2012	CN 103120032 A	22/05/2013
		JP 2013-543636 A	05/12/2013
		KR 10-2013-0099976 A	06/09/2013
		TW 201215246 A	01/04/2012
		US 8587321 B2	19/11/2013
		WO 2012-039885 A2	29/03/2012
		WO 2012-039885 A3	31/05/2012
US 2017-0140968 A1	18/05/2017	CN 106992107 A	28/07/2017
		CN 106992107 B	19/02/2019
		CN 107039255 A	11/08/2017
		KR 10-2017-0066215 A	14/06/2017
		KR 10-2017-0066216 A	14/06/2017
		KR 10-2017-0066223 A	14/06/2017
		KR 10-2017-0066224 A	14/06/2017
		SG 10201609439 A	29/06/2017
		TW 201729235 A	16/08/2017
		TW 201729243 A	16/08/2017
		TW 201729244 A	16/08/2017
		TW 201731014 A	01/09/2017
		US 10121708 B2	06/11/2018
		US 10128160 B2	13/11/2018
		US 2017-0141000 A1	18/05/2017
		US 2017-0141001 A1	18/05/2017
		US 2017-0141002 A1	18/05/2017
		US 2018-0076100 A1	15/03/2018
		US 9824941 B2	21/11/2017
		US 9997422 B2	12/06/2018
JP 2016-105489 A	09/06/2016	JP 6055537 B2	27/12/2016