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(54) **CONTROL OF PLASMA FORMATION BY RF COUPLING STRUCTURES**

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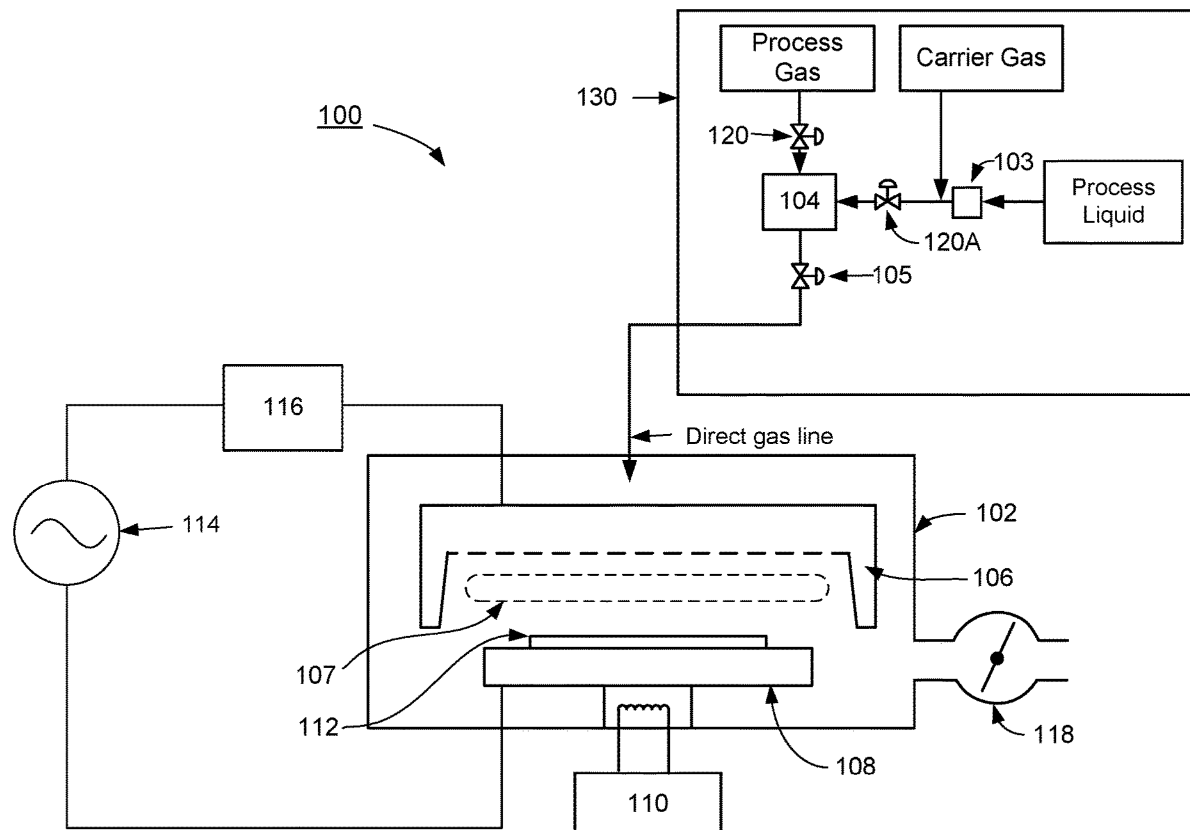
(57) **ABSTRACT**

An apparatus for forming a plasma may include one or more coupling ports to accept a radiofrequency (RF) current. The apparatus may additionally include one or more coupling structures which may include one or more conductive loops to permit the RF current to conduct from at least a first portion of the one or more coupling ports to at least a second port of the one or more coupling ports. The one or more conductive loops may each be configured to exhibit a first value of inductance in the absence of the plasma and to exhibit a second value of inductance in the presence of the plasma. The one or more coupling structures may each include a reactive element, in which each reactive element is coupled to a corresponding one of the one or more conductive loops so as to form a corresponding number of coupling structures. Each RF coupling structure may have a resonant frequency that increases in response to the presence of the plasma.



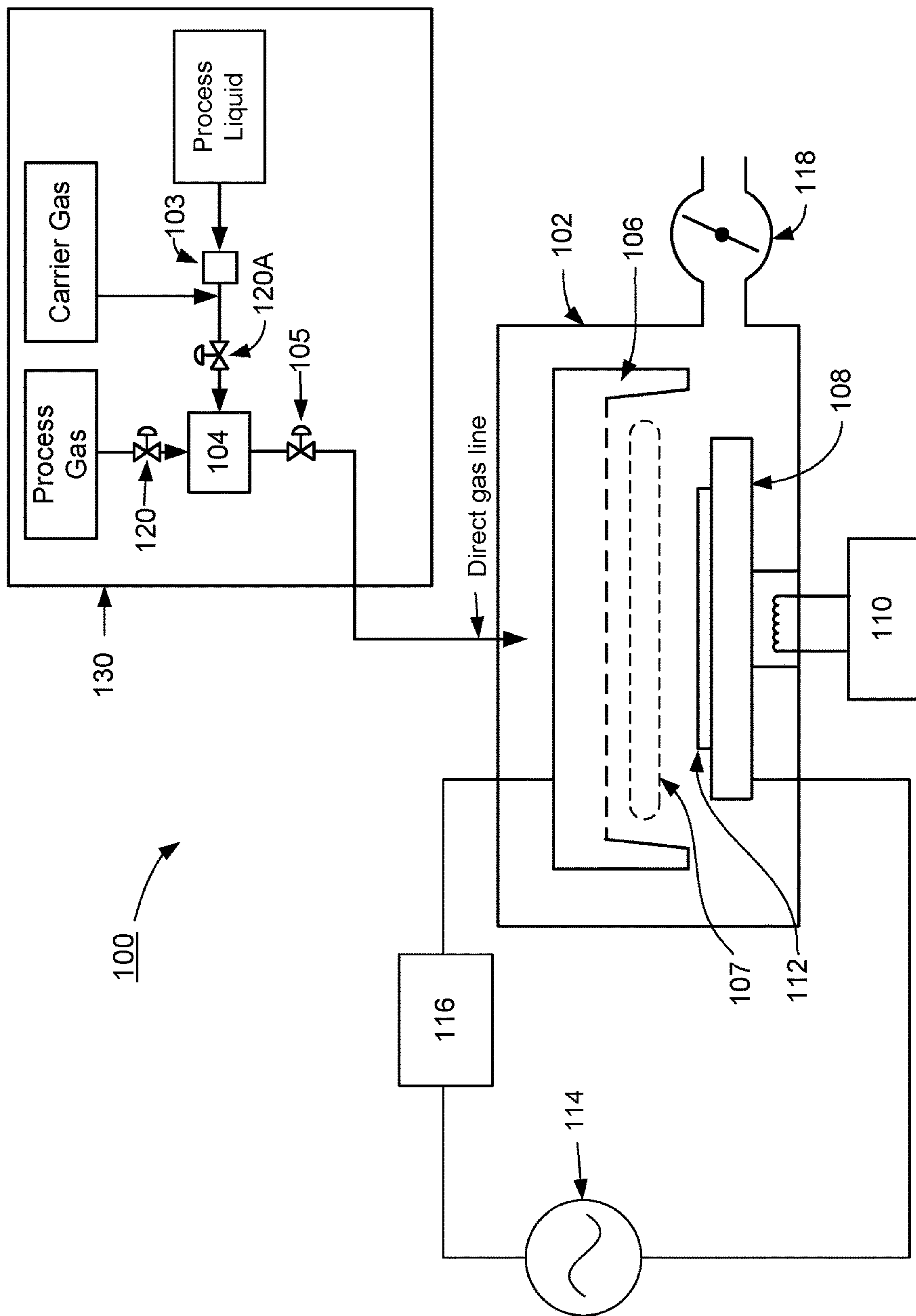


FIG. 1

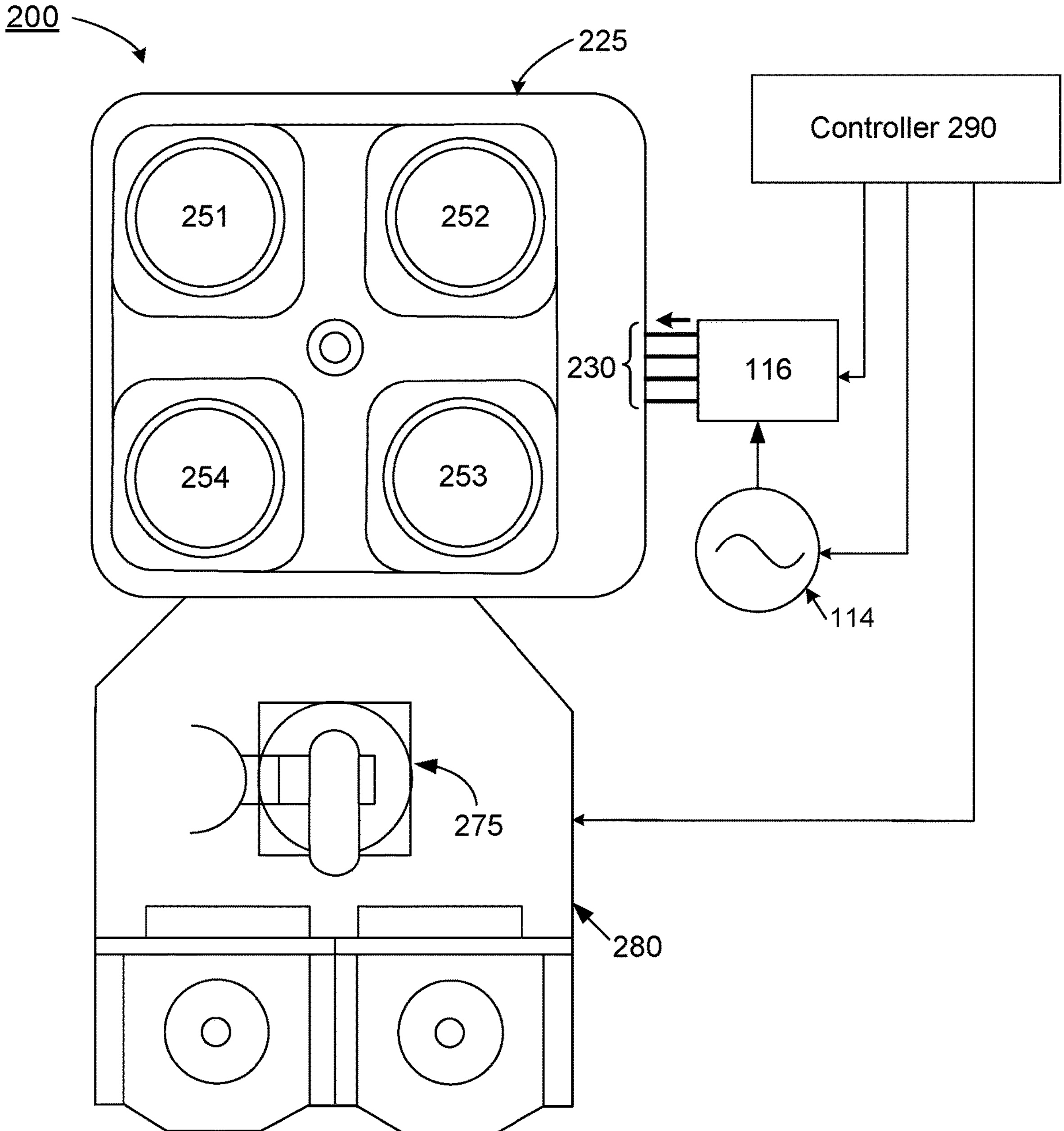


FIG. 2

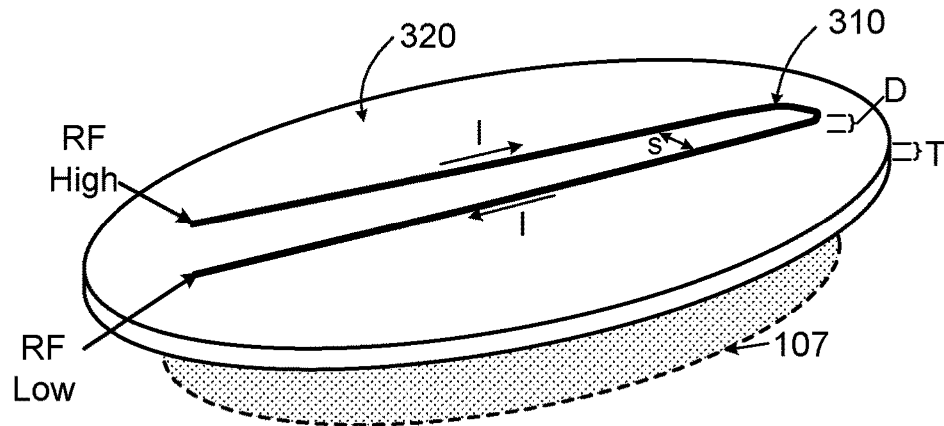


FIG. 3

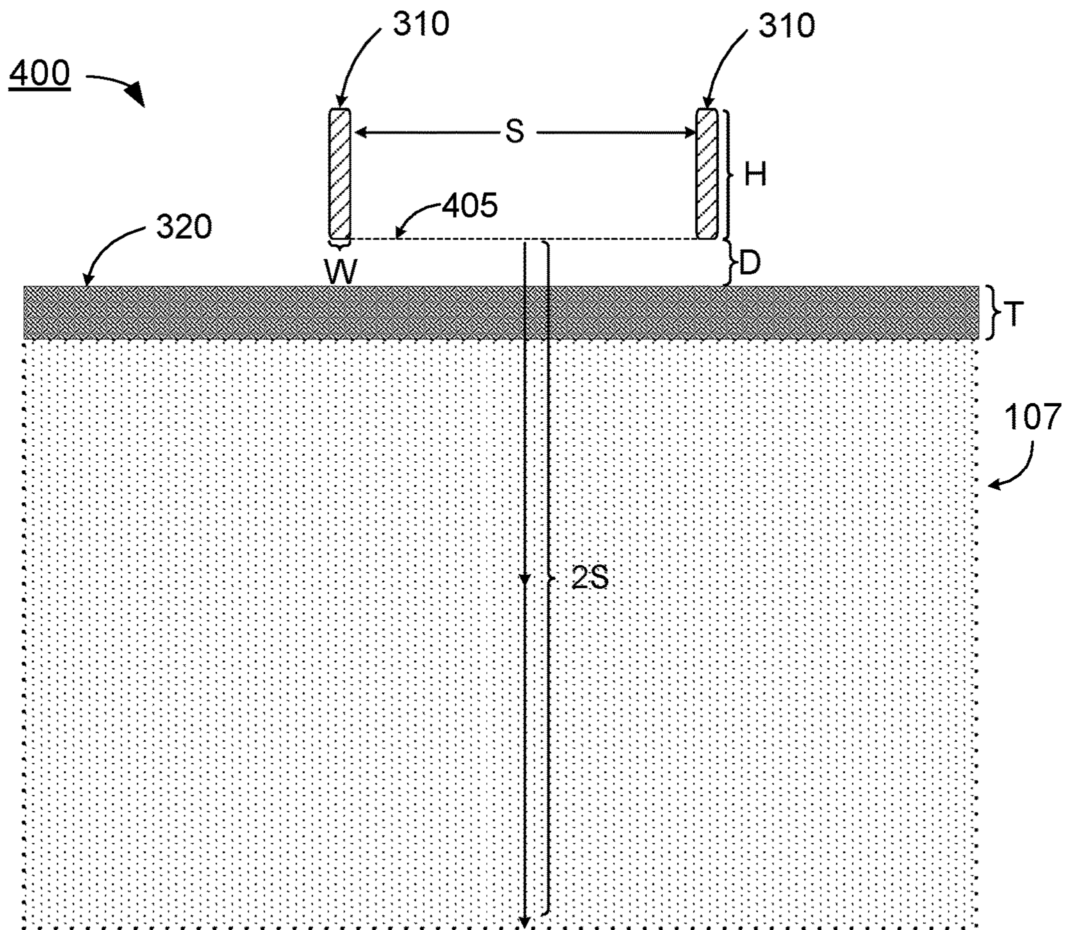


FIG. 4

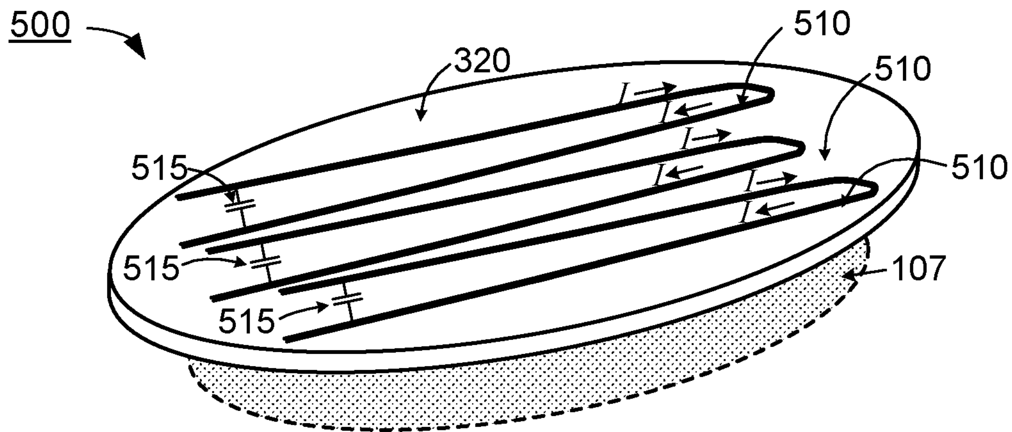


FIG. 5

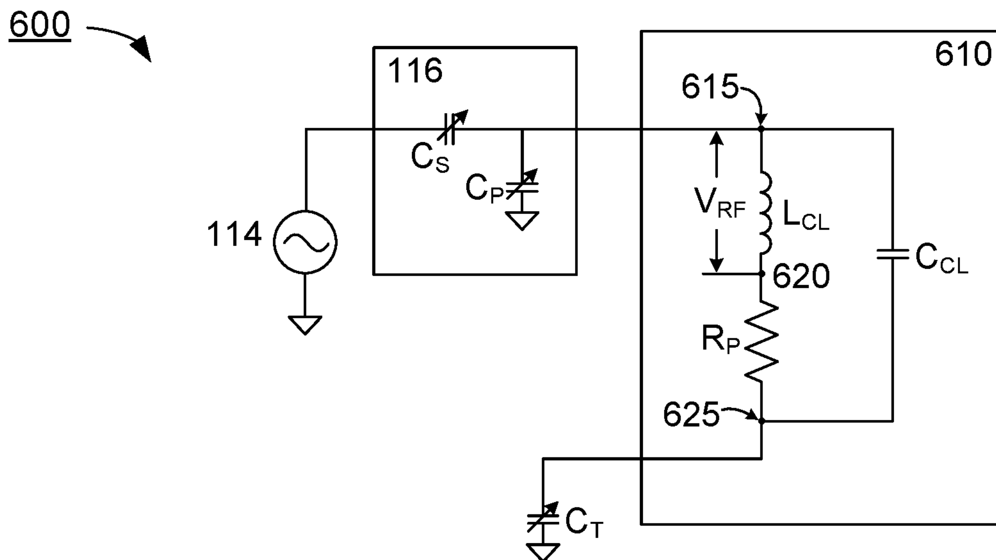


FIG. 6

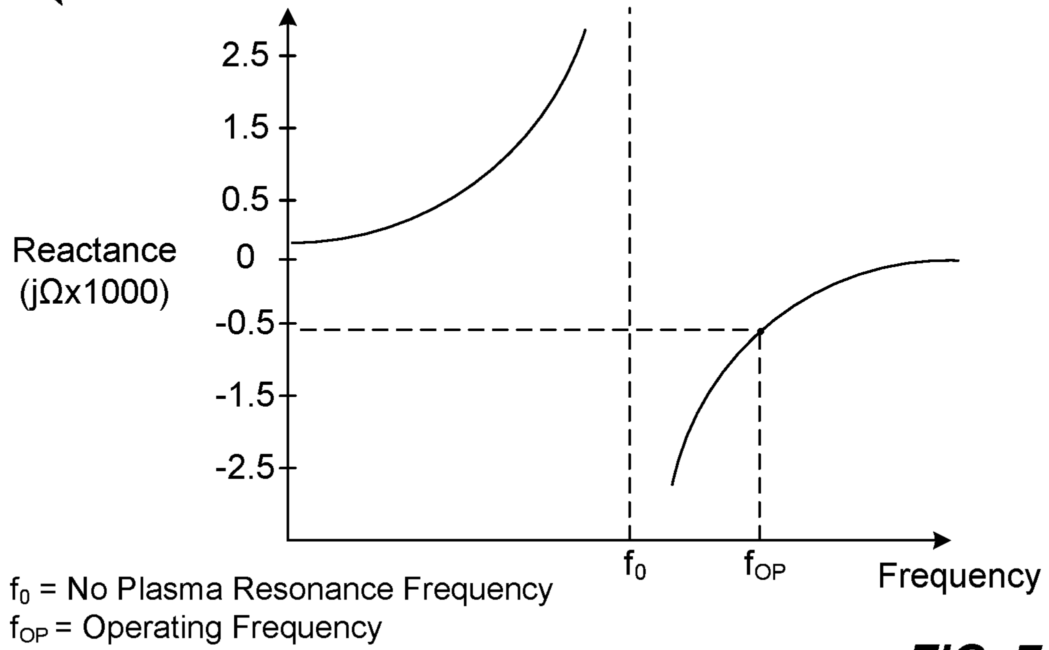


FIG. 7

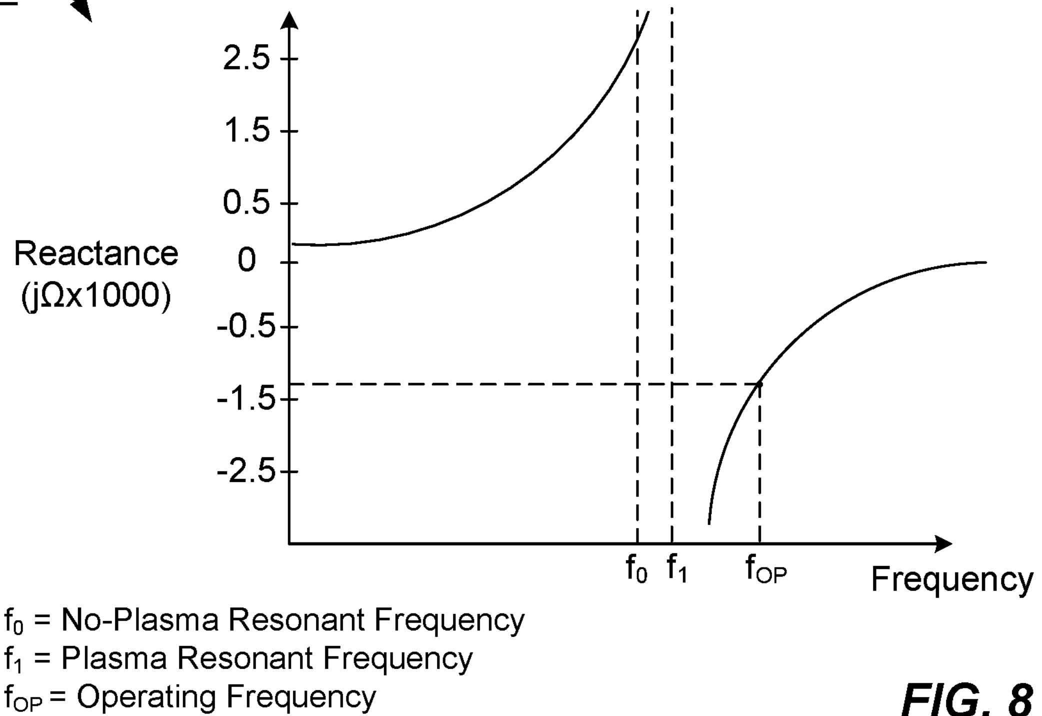


FIG. 8

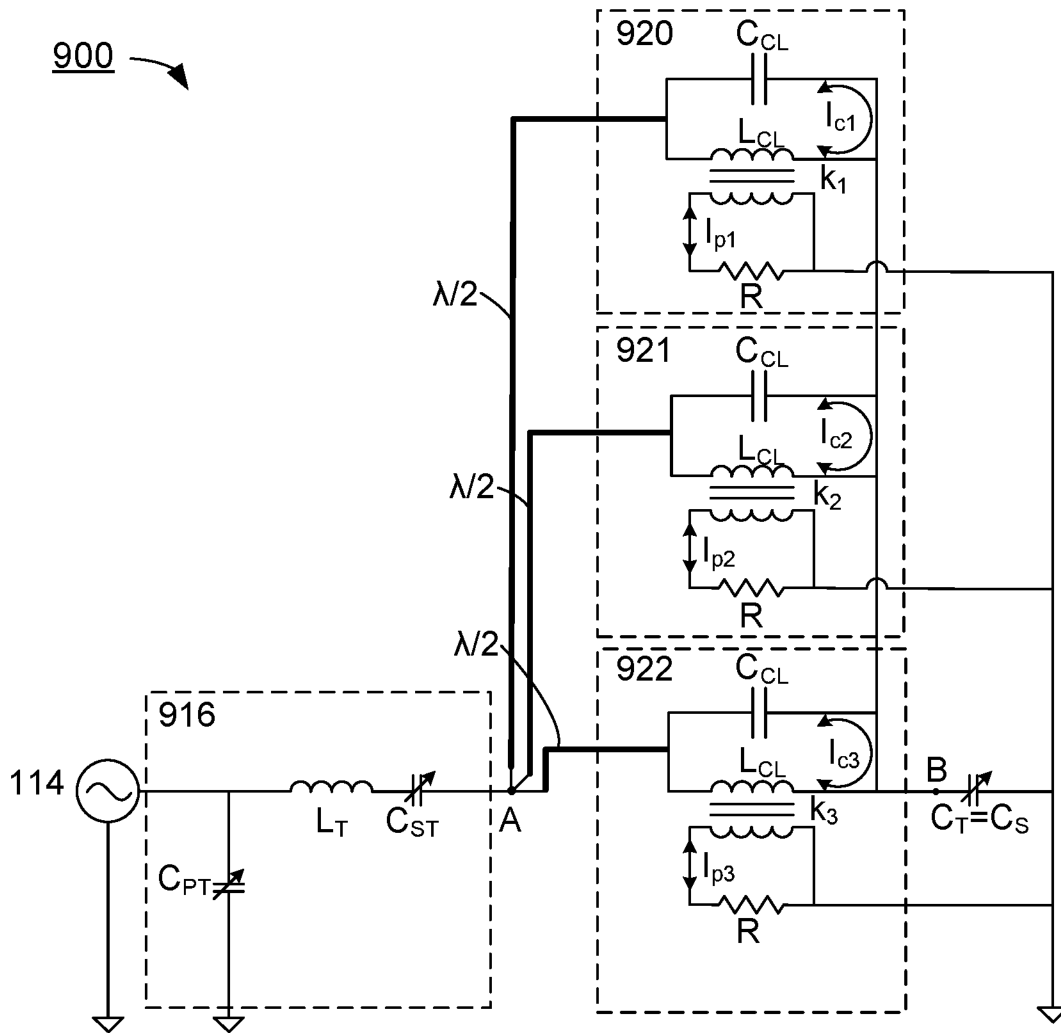


FIG. 9

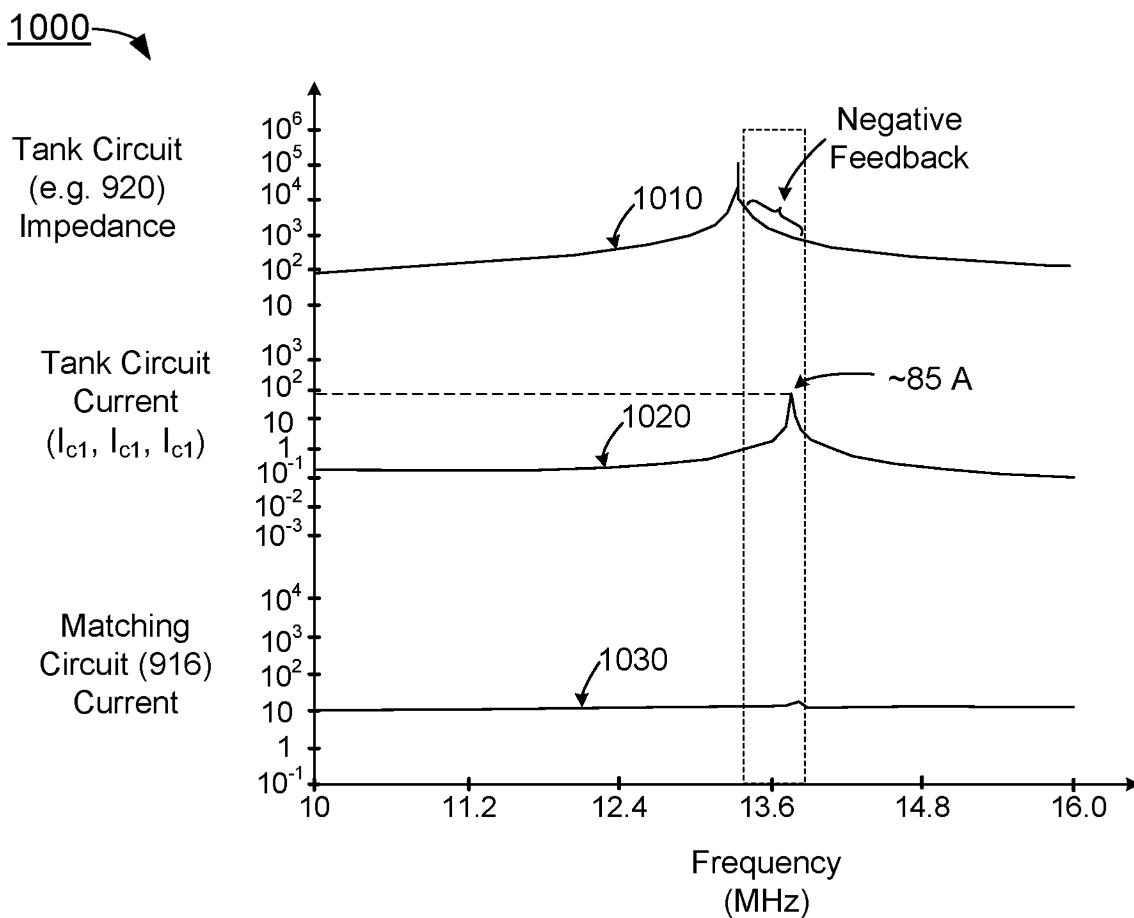
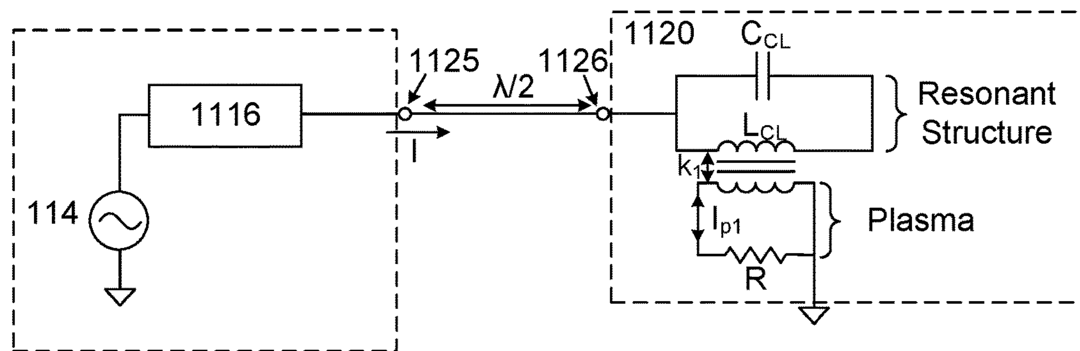


FIG. 10

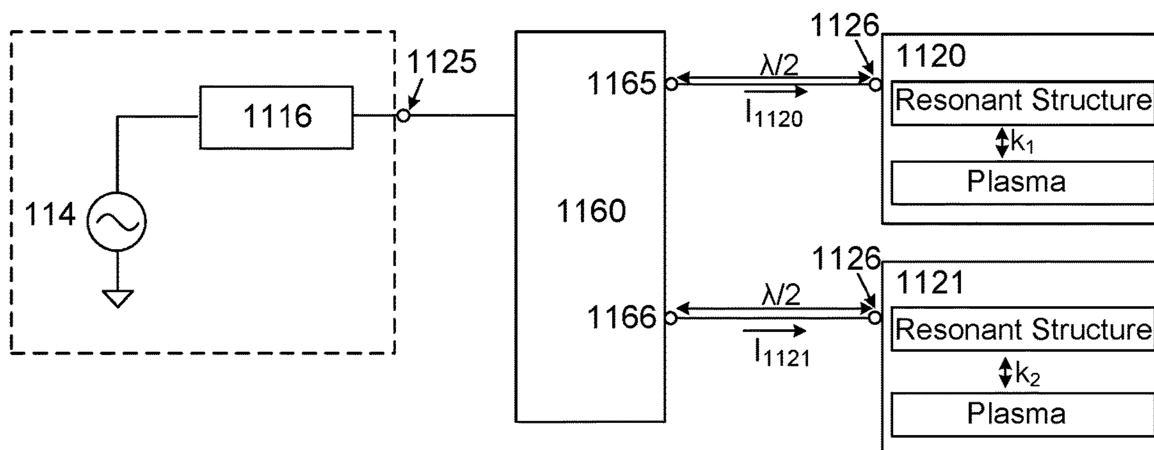
1100



$Z_{1120}\downarrow \Rightarrow I\uparrow \Rightarrow V_{1125}\downarrow \Rightarrow I\downarrow$

FIG. 11A

1150



$$\left.\begin{array}{l} Z_{1120}\downarrow \Rightarrow I_{1120}\uparrow \Rightarrow V_{1165}\downarrow \Rightarrow I_{1120}\downarrow \\ Z_{1121}\downarrow \Rightarrow I_{1121}\uparrow \Rightarrow V_{1166}\downarrow \Rightarrow I_{1121}\downarrow \end{array}\right\} I_{1120} \approx I_{1121}$$

FIG. 11B

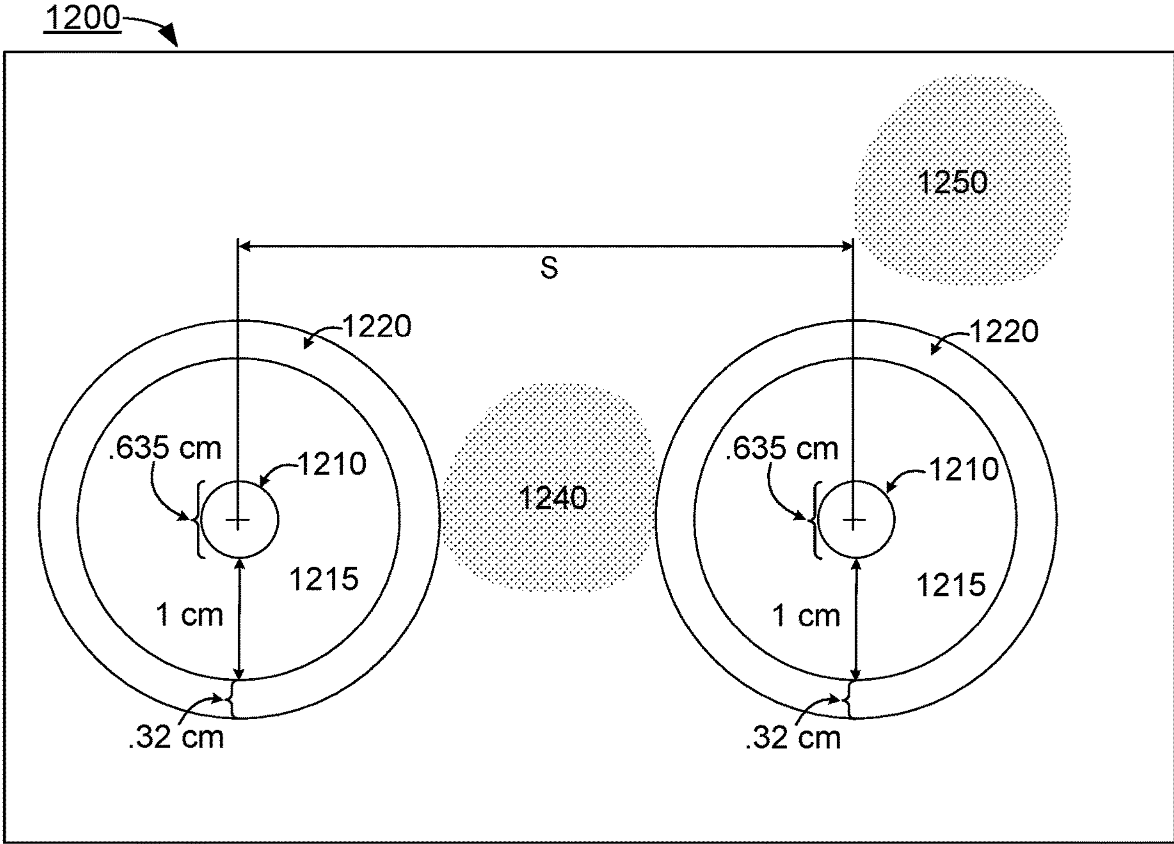


FIG. 12

CONTROL OF PLASMA FORMATION BY RF COUPLING STRUCTURES

CROSS REFERENCE

[0001] A PCT Request Form is filed concurrently with this specification as part of the present application. Each application that the present application claims benefit of or priority to as identified in the concurrently filed PCT Request Form is incorporated by reference herein in its entirety and for all purposes.

BACKGROUND

[0002] During wafer fabrication processes, such as deposition of a film on a substrate utilizing a multi-station integrated circuit fabrication chamber, one or more radiofrequency (RF) currents may be coupled into process stations of the chamber. Coupling of RF currents of sufficient energy into a process station may bring about or enhance formation of an ionized plasma material. The ionized plasma material may operate to form radical species of gaseous precursors to enable such precursors to be adsorbed, for example, by an exposed surface of a semiconductor wafer. Through a buildup of multiple layers, which may number into the hundreds or thousands, of very thin layers of material, an integrated circuit may be built on or over a semiconductor substrate. However, in some instances, formation of an ionized plasma material in a fabrication chamber may involve a delicate procedure in which certain parameters are rigidly controlled so as to bring about highly repeatable and consistent results. Thus, approaches toward improving control over various aspects of the formation of ionized plasma materials continues to be an active area of investigation.

[0003] The background description provided herein is for the purposes of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

SUMMARY

[0004] One general aspect includes an apparatus for forming a plasma, including: one or more coupling ports to accept a radiofrequency (RF) current. The apparatus also includes one or more conductive loops configured to permit the RF current to conduct from at least a first port of the one or more coupling ports to at least a second port of the one or more coupling ports, the one or more conductive loops each configured to exhibit a second value of inductance in the presence of the plasma. The apparatus also includes one or more reactive elements, each coupled to a corresponding one of the one or more conductive loops, to form a corresponding number of coupling structures. Each coupling structure of the apparatus may have a resonant frequency configured to increase in response to the presence of the plasma.

[0005] In some embodiments, the one or more conductive loops of the apparatus are configured to form a plasma operating in an inductive mode. The one or more conductive loops of the apparatus can include two or more conductive loops. The one or more reactive elements can include one or more capacitive elements that cooperate with a corresponding conductive loop of the one or more conductive loops to bring about resonance at a frequency that is lower than the frequency of the RF current. The resonant frequency of the conductive loops can be a value that is within about 10% of the frequency of the RF current. The forming of the plasma can bring about a second value of inductance that is less than the first value of inductance. The coupling factor of the apparatus can be between a value of between about 0.35 and about 0.5. At least a portion of the formed plasma can be located in a region between segments of each of the one or more conductive loops. The formed plasma can be located in a region less than twice the separation distance between adjacent segments of each of the one or more conductive loops. At least one of the one or more conductive loops can include a hairpin shape. The apparatus can further include a delay network configured to maintain current conduction within the one or more conductive loops at a value that is at least twice the value of the current conducted to the first port of the one or more coupling ports. The delay network can be further configured to introduce a delay of about one-half wavelength between an output port of an RF matching network and the first port of the one or more coupling ports.

[0006] Another general aspect includes an apparatus that includes one or more input ports to receive an RF current. The apparatus can also include one or more conductive loops coupled to a corresponding one of the one or more input ports, each of the one or more conductive loops configured to exhibit inductance. The apparatus also includes one or more capacitive elements, each of the one or more capacitive elements coupled to a corresponding one of the one or more conductive loops so as to resonate at a first frequency that is below the frequency of the RF current. The apparatus can also include the conductive loops configured to convert a gas, proximate to the conductive loops, to a plasma in response to conduction of the RF current.

[0007] Embodiments can include an apparatus in which the first frequency differs from the frequency of the RF current by less than about 10%. The gas can at least partially surround the one or more conductive loops. The gas can be located within a distance of two times the spacing between adjacent segments of the one or more conductive loops. One or more conductive loops can be configured to resonate at a frequency below about 13.56 MHz. At least one of the one or more conductive loops can include a hairpin shape. The apparatus can further include a time-delay network configured to maintain peak current conduction within the one or more conductive loops at a value that is at least twice the value of the current conducted a first input port of the one or more input ports.

[0008] Another general aspect includes a multi-station integrated circuit fabrication chamber, including: a matching network to receive an RF current from an output port of an RF current generator. The multi-station integrated circuit fabrication chamber can also include one or more coupling structures to receive a current from the matching network, in which the one or more coupling structures includes at least one conductive loop and at least one capacitive element, and in which the one or more coupling structures are configured to resonate at a frequency that is less than the frequency of the RF current. The multi-station integrated circuit fabrication chamber can also include a volume configured to permit conversion of one or more gases to a plasma to conduct one or more fabrication operations within the multi-station integrated circuit fabrication chamber.

[0009] Embodiments may include the multi-station integrated circuit fabrication chamber having a time-delay network configured to maintain peak current conduction within the one or more conductive loops at a value that is at least twice the value of the current received from the matching network. In an embodiment, the fabrication chamber may include a time-delay network configured to introduce a delay of about one-half wavelength between an output port of the RF matching network and input ports of the one or more coupling structures. The gases within the multi-station integrated circuit fabrication chamber can at least partially surround the one or more conductive loops. At least a portion of the one or more gases can be located within a distance of two times the spacing between adjacent segments of the one or more conductive loops. A coupling factor between the one or more conductive loops and the formed plasma can include a value of between about 0.2 and about 0.5. The first frequency of the RF current and the resonant frequency of each of the one or more coupling structures can differ by less than about 10%. The one or more coupling structures can include three or more RF coupling structures.

[0010] Another general aspect includes an system for forming a that includes a radiofrequency (RF) current generator. The system also includes a first RF coupling structure configured to receive current generated by the RF current generator and to convert a gaseous material, at least partially surrounding the first RF coupling structure, to an ionized plasma. The first RF coupling structure is configured to exhibit an impedance that decreases responsive to an increased density of the ionized plasma. The RF current generator configured to decrease output current delivered to the first RF coupling structure responsive to the decreased impedance.

[0011] In an embodiment, the system can further include a second RF configured to receive current generated by the RF current generator and to convert a gaseous material, at least partially surrounding the second RF coupling structure to an ionized plasma. The system may also include an RF current divider having an input port coupled to an output port of the RF current generator and having a first output port coupled the first RF coupling structure and a second output port coupled to the second RF coupling structure, the second RF coupling structure configured to exhibit an impedance that decreases responsive to an increased density of the ionized plasma. In an embodiment, the current delivered to the first RF coupling may involve the use of an RF power divider in which the current delivered to the second RF coupling structure by the RF power divider are configured to be approximately equal during the increased density of the ionized plasma converted by the first RF coupling structure and during the increased density of the ionized plasma converted by the second RF coupling structure. The first RF coupling structure and the second RF coupling structure can include a conductive loop configured to form the ionized plasma in an H mode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The various embodiments disclosed herein are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings, in which like reference numerals refer to similar elements.

[0013] FIG. **1** shows an example apparatus for depositing or etching a film on or over a substrate utilizing any number of processes, according to an embodiment.

[0014] FIG. **2** is a schematic view of a multi-station integrated circuit fabrication chamber that utilizes active components, according to an embodiment.

[0015] FIG. **3** shows a single conductive loop for forming an ionized plasma material, according to an embodiment.

[0016] FIG. **4** shows an end view of the conductor of a conductive loop for forming an ionized plasma material, according to an embodiment.

[0017] FIG. **5** shows three conductive loops for forming an ionized plasma material, according to an embodiment.

[0018] FIG. **6** shows an RF generator, matching network, and equivalent circuit representing a conductive loop and capacitor combination, according to an embodiment.

[0019] FIG. **7** shows a graph of impedance versus frequency for the equivalent circuit corresponding to the conductive loop and capacitor combination of FIG. **6** prior to formation of a plasma material, according to an embodiment.

[0020] FIG. **8** shows a graph of impedance versus frequency for the equivalent circuit corresponding to the conductive loop and capacitor combination of FIG. **6** after formation of a plasma material, according to an embodiment.

[0021] FIG. **9** shows an RF current generator, matching network, transmission line and equivalent circuit for three conductive loops for forming an ionized plasma material, according to an embodiment.

[0022] FIG. **10** shows a graph of tank circuit impedance, tank circuit current, and matching network current for a single hairpin-shaped conductive loop for forming an ionized plasma material, utilizing a common frequency scale, according to an embodiment.

[0023] FIG. **11**A shows an equivalent circuit of a resonant RF coupling structure coupled to an ionized plasma material, according to an embodiment.

[0024] FIG. **11**B shows equivalent circuits of resonant RF coupling structures coupled an ionized plasma material, according to an embodiment.

[0025] FIG. **12** shows a side view of conductors of a conductive loop immersed within an ionized plasma material, according to an embodiment.

DETAILED DESCRIPTION

[0026] In certain types of integrated circuit fabrication chambers, a radiofrequency (RF) power source may be utilized to provide a signal having sufficient current and voltage to bring about formation of a plasma, which may include ionized gaseous compounds and/or elements, within the fabrication chamber. In some instances, RF energy may be coupled into a fabrication chamber utilizing an RF coupling structure, such as a conductive loop. In response to sufficient coupling of RF energy into a fabrication chamber, ionized gaseous materials within the chamber may react with one another to permit formation of one or more radicalized specie of precursor gases. When such radicalized specie of precursor gases are allowed to come into contact with a material present on a surface of a semiconductor substrate, deposition of a thin layer (e.g., a layer having a thickness comparable to that of a single atom or molecule) of a material at the surface of the semiconductor substrate may occur. After exposure of a substrate to an ionized

plasma material, the fabrication chamber may be purged and a second gaseous material may be allowed to enter the fabrication chamber to bring about exposure of the semiconductor substrate to the second gaseous material. Following purging of the second gaseous precursor material from the fabrication chamber, ionized gaseous materials may again be introduced into the fabrication chamber, which may give rise to formation of an additional thin (e.g., atomic) layer of material. In certain instances, such processes may be repeated over hundreds or thousands of cycles (or an even greater number of cycles) until a film of a desired thickness has been formed or deposited on or over a semiconductor substrate.

[0027] However, formation of a plasma material for use in integrated circuit fabrication chambers utilizing an RF source may represent a delicate process. For instance, under certain circumstances, responsive to the presence of a discontinuity at an inner surface of a fabrication chamber, such as a slot valve, hole, or other type of orifice, RF current from the RF coupling structure may be disproportionately drawn toward the discontinuity. Such disproportionate drawing of RF energy in the direction of the discontinuity may give rise to a nonuniform formation of an ionized plasma material in which plasma may be formed with greater density at particular regions of a fabrication chamber in relation to other regions of the fabrication chamber. In some instances, variations in plasma density within the fabrication chamber may bring about nonuniform distribution of ionized precursor gases which may, in turn, result in unwanted variations in material deposition rates across a semiconductor substrate undergoing processing.

[0028] To introduce further complexity, in some instances, even a minuscule variation in the distribution of RF energy within a fabrication chamber may give rise to larger and larger variations after only a short period of time. Such positive feedback, in which small variations in distribution of RF energy quickly bring about larger variations in the distribution or density of RF energy in a fabrication chamber, may result in the introduction of a number of unwanted consequences. For example, variations in the distribution or density of RF energy in a fabrication chamber may give rise to changes in voltage and/or current magnitudes present at an RF coupling structure within the fabrication chamber. Such changes in voltage and/or current magnitudes may give rise to an abrupt plasma mode transition such as a transition from a high-density, inductive (or "H" mode) to a low-density, capacitive (or "E" mode). To transition plasma generation back to an inductive mode, the output power of the RF current generator may be decreased, or may be interrupted completely. Such occasional power decreases and/or interruptions in RF output current may diminish plasma generation which may, in turn, necessitate unwanted increases in semiconductor processing times and/or may impact wafer-to-wafer process repeatability, for example.

[0029] Changes to RF power coupled to a coupling structure at a process station of a multi-station integrated circuit fabrication chamber may additionally affect operations conducted at other process stations. For example, if power from a single RF current generator is distributed to two or more stations, an increase in RF power coupled to a first process station may bring about reductions in power coupled to other stations. In some instances, in response to an increase in power coupled to a first station of a multi-station fabrication chamber, power to a second station of the fabrication chamber may fall below a threshold amount, which may cause plasma extinction in the second station. In such an instance, fabrication processes at the second station may consume longer periods of time, which may increase cost, decrease equipment availability for other processing operations, and/or decrease film quality. In some instances, excessive occurrences of plasma extinction may bring about the need for additional processing and/or metrology to determine if quality of a fabricated wafer has been negatively impacted.

[0030] Accordingly, it may be appreciated that obtaining uniformity in plasma generation may be desirable in many integrated circuit fabrication operations. Thus, one approach toward obtaining uniformity in plasma generation within a fabrication chamber involves a use of multiple RF coupling structures, as opposed to use of a single RF coupling structure, which may operate to more evenly distribute RF energy within a fabrication chamber. A more even distribution of RF energy within a fabrication chamber may, in turn, give rise to a more evenly distributed generation of an ionized plasma material, which may serve to evenly distribute ionized precursor gases across a semiconductor wafer undergoing processing. However, despite advantages of multiple RF coupling structures in a fabrication chamber, such additional coupling structures may introduce further complexities by increasing opportunities for RF energy to be disproportionately coupled to certain regions of a fabrication chamber with respect to other regions. As previously noted, such disproportionate coupling of RF energy within a fabrication chamber may bring about positive feedback in which small spatial and/or temporal variations in RF power may bring about large variations in RF current and voltage distributions across an RF coupling structure.

[0031] Thus, for the above-identified reasons, and potentially others, it may be advantageous to implement plasma-forming arrangements of one or more RF coupling structures in which nonuniformities in RF power coupling within a fabrication chamber are controlled and/or reduced via negative feedback. In such an arrangement, responsive to the disproportionate coupling of RF energy to a region of a fabrication chamber, power coupled to a plasma-forming RF coupling structure may be quickly reduced. In particular embodiments, such reduction in current coupled to a plasma forming RF coupling structure may be brought about nearly instantaneously and as a consequence of the inherent design of the RF coupling structure. Accordingly, in particular embodiments, as an RF coupling structure begins to disproportionately couple RF energy to a region of a fabrication chamber, thereby increasing plasma density in the region, parameters of the RF power coupled to the coupling structure may be adjusted. Such adjustment in RF power parameters may decrease plasma density in the region, thereby returning the RF energy distribution within the chamber to a more uniform state.

[0032] In particular embodiments, such negative feedback may be introduced utilizing an inherent electrical characteristic, such as impedance of a resonant RF coupling structure. For example, as described herein, an increase in plasma density may bring about a reduction in impedance exhibited by a resonant RF coupling structure that is at least partially surrounded by an ionized plasma material. Such decrease in resonant RF coupling structure impedance may increase the demand for electrical current to be conducted by the resonant structure. Accordingly, an increased current may flow from an RF current generator to the RF coupling structure.

However, as the current demand of the resonant RF coupling structure increases, a voltage drop may occur at an output node of the RF current generator. Such voltage drop may occur in response to the RF current generator having a non-negligible source impedance. Thus, the voltage drop at the output port of the RF current generator may bring about a decreased current flow, which may operate to reduce the current delivered to the resonant circuit. Consequently, current conducted by the resonant RF coupling structure may be quickly (e.g., virtually instantaneously) returned to a nominal level.

[0033] It may be appreciated that the above-described approach toward maintaining a substantially constant current flow to an RF coupling structure represents a negative-feedback control system having a negligible or virtually zero (0) response time. This is to say that a momentary increase in current conduction to a resonant structure, such as in response to a localized increase in density of an ionized plasma material formed by the resonant structure, can be nearly instantaneously returned to a steady-state value. In some instances, current conduction to a resonant RF coupling structure may be returned to a nominal operating point in less than about 1.0 μs. In particular embodiments, a transmission line length, such as a length corresponding to one half of the wavelength of an RF current in the transmission line medium, may be utilized to transform impedances of a resonant structure. Such impedance transformation may provide additional control over an impedance presented to an RF current generator.

[0034] In other instances, a single RF current generator may be coupled to two or more resonant RF coupling structures at least partially immersed within an ionized plasma material. In such instances, negative feedback may bring about substantially constant current flow to each resonant structure, even as plasma density local to one of the resonant RF coupling structures increases. For example, in an arrangement involving first and second resonant RF coupling structures , a momentary increase in current conduction to the first resonant RF coupling structure may be followed by an immediate return to nominal current conduction. Meanwhile, current conduction to the second resonant RF coupling structure may remain steady and unvarying.

[0035] Particular embodiments may additionally make possible the coupling of relatively large RF currents within an individual coupling structure without necessitating correspondingly large currents at an output port of an RF current generator. For example, in particular embodiments, an RF coupling structure may operate as a circuit in which an RF current oscillates at a signal frequency (e.g., 13.56 MHz) utilizing a much smaller input current. In an example, such as described in reference to FIG. **10** herein, an oscillating current having a magnitude of approximately 85 A may be formed utilizing an input current of approximately 10 A. In such a circuit, for example, an increase in plasma density reduces the inductance exhibited by the circuit, which, in turn, increases the capacitance of the circuit. Accordingly, in response to the circuit exhibiting greater capacitance, power coupled to plasma-forming RF coupling structures may be reduced.

[0036] In particular embodiments, plasma-forming RF coupling structures may operate while being at least partially immersed in an ionized plasma material. Such partial or total immersion within an ionized plasma material serves to increase coupling between an RF coupling structure. In certain embodiments, increased coupling between an RF coupling structure and an ionized plasma material may serve to strengthen the negative feedback relationship between the increased plasma density and the capacitance exhibited by a resonant circuit. Accordingly, small spatial and/or temporal variations in plasma density at regions of a fabrication chamber may bring about even faster correction of such spatial and temporal variations in plasma density.

[0037] Certain embodiments may be utilized in connection with a number of wafer fabrication processes, such as various plasma-enhanced atomic layer deposition (PEALD) processes (e.g., PEALD1, PEALD2), various plasma-enhanced chemical vapor deposition (e.g., PECVD1, PECVD2, PECVD3) processes, or may be utilized on-the-fly during single deposition processes. In certain embodiments, a RF current generator having multiple output ports may be utilized at any frequency, such as at frequencies between 300 kHz and 60 MHz, which may include frequencies of about 400 kHz, about 440 kHz, about 1 MHz, about 2 MHz, about 4 MHz, about 13.56 MHz, about 20 MHz and about 27.12 MHz. However, in other embodiments, RF current generators having multiple output ports may operate at any frequency, which may include relatively low frequencies, such as between 50 kHz and 300 kHz, as well as higher frequencies, such as frequencies of between about 60 MHz and about 100 MHz, virtually without limitation.

[0038] Particular embodiments described herein may show and/or describe multi-station semiconductor fabrication chambers comprising 4 process stations. However, the disclosed embodiments are intended to embrace multi-station integrated circuit fabrication chambers that include any number of process stations. Thus, in certain embodiments, an output signal of a RF current generator may be divided among, for example, 2 process stations or 3 process stations of a fabrication chamber. An output current from a RF current generator may be divided among a larger number of process stations virtually without limitation, such as 5 process stations, 6 process stations, 8 process stations, 10 process stations. Particular embodiments described herein may show and/or describe utilization of a single, relatively low-frequency RF signal, such as a frequency of between about 300 kHz and about 2 MHz, as well as a single, relatively high-frequency RF current, such as a frequency of between 2 MHz and 100 MHz. However, the disclosed embodiments are intended to embrace the use of any number of radio frequencies, such as frequencies below about 2 MHz as well as radio frequencies above about 2 MHz.

[0039] Manufacture of semiconductor devices may involve depositing or etching of one or more thin films on or over a planar or non-planar substrate in connection with an integrated circuit fabrication process. In some aspects of an integrated circuit fabrication process, it may be useful to deposit thin films that conform to unique substrate topography. One type of reaction that is useful in many instances may involve chemical vapor deposition (CVD). In certain CVD processes, gas phase reactants introduced into stations of a reaction chamber simultaneously undergo a gas-phase reaction. The products of the gas-phase reaction deposit on the surface of the substrate. A reaction of this type may be driven by, or enhanced by, presence of a plasma, in which case the process may be referred to as a plasma-enhanced

chemical vapor deposition (PECVD) reaction. As used herein, the term CVD is intended to include PECVD unless otherwise indicated.

[0040] In another example, as previously alluded to, some deposition processes involve multiple film deposition cycles, each producing a discrete film thickness. For example, in atomic layer deposition (ALD), thickness of a deposited layer may be limited by an amount of one or more film precursor reactants, which may adsorb onto a substrate surface, so as to form an adsorption-limited layer, prior to the film-forming chemical reaction itself. Thus, a feature of ALD involves the formation of thin layers of film, such as layers having a width of a single atom or molecule, which are used in a repeating and sequential matter. As device and feature sizes continue to be reduced in scale, and as three-dimensional devices and structures become more prevalent in integrated circuit (IC) design, the capability of depositing thin conformal films (e.g., films of material having a uniform thickness relative to the shape of the underlying structure) continues to gain in importance. Thus, in view of ALD being a film-forming technique in which each deposition cycle operates to deposit a single atomic or molecular layer of material, ALD may be well-suited to the deposition of conformal films. In some instances, device fabrication processes involving ALD may include multiple ALD cycles, which may number into the hundreds or thousands, may then be utilized to form films of virtually any desired thickness. Further, in view of each layer being thin and conformal, a film that results from such a process may conform to a shape of any underlying device structure. In certain embodiments, an ALD cycle may include the following steps:

[0041] Exposure of the substrate surface to a first precursor.

[0042] Purge of the reaction chamber in which the substrate is located.

[0043] Activation of a reaction of the substrate surface, such as by exposing the substrate surface with a plasma and/or a second precursor.

[0044] Purge of the reaction chamber in which the substrate is located.

[0045] The duration of each ALD cycle may, at least in particular embodiments, be less than about 25 seconds or less than about 10 seconds or less than about 5 seconds. The plasma exposure step (or steps) of the ALD cycle may be of a short duration, such as a duration of about 1 second or less.

[0046] Turning now to the figures, FIG. **1** shows an example apparatus suitable for depositing or etching a film on or over a substrate utilizing any number of processes, according to various embodiments. Processing apparatus **100** of FIG. **1** depicts single process station **102** of a process chamber with a single substrate holder **108** (e.g., a pedestal) in an interior volume, which may be maintained under vacuum by vacuum pump **118**. Showerhead **106** and gas delivery system **130**, which may be fluidically coupled to the process chamber, may permit the delivery of film precursors, for example, as well as carrier and/or purge and/or process gases, secondary reactants, etc. Equipment utilized in the generation of plasma within the process chamber is also shown in FIG. **1**. The apparatus schematically illustrated in FIG. **1** may be adapted for performing, in particular, plasma-enhanced CVD.

[0047] In FIG. **1**, gas delivery system **130** 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**. Particular reactants may be stored in liquid form prior to vaporization and subsequent delivery to process station **102** of a process chamber. The embodiment of FIG. **1** includes a vaporization point **103** for vaporizing liquid reactant to be supplied to mixing vessel **104**. In some embodiments, vaporization point **103** may include a heated liquid injection module. In some other embodiments, vaporization point **103** may include a heated vaporizer. In yet other embodiments, vaporization point **103** may be eliminated from the process station. In some embodiments, 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 process station **102**.

[0048] Showerhead **106** may operate to distribute process gases and/or reactants (e.g., film precursors) in the direction of substrate **112** at the process station, the flow of which may be controlled by one or more valves upstream from the showerhead (e.g., valves **120**, **120**A, **105**). In the embodiment of FIG. **1**, substrate **112** is depicted as located beneath showerhead **106**, and is shown resting on a pedestal **108**. Showerhead **106** may be of any suitable shape, and may include any suitable number and arrangement of ports for distributing process gases to substrate **112**. In some embodiments involving 2 or more stations, gas delivery system **130** includes valves or other flow control structures upstream from the showerhead, which can independently control the flow of process gases and/or reactants to each station so as to permit gas flow to one station while prohibiting gas flow to a second station. Furthermore, gas delivery system **130** may be configured to independently control process gases and/or reactants delivered to each station in a multi-station apparatus such that the gas composition provided to different stations is different (e.g., the partial pressure of a gas component may vary between stations at the same time).

[0049] In FIG. **1**, gas volume **107** is depicted as being located beneath showerhead **106**. In some embodiments, pedestal **108** may be raised or lowered to expose substrate **112** to gas volume **107** and/or to vary the size of gas volume **107**. Optionally, pedestal **108** may be lowered and/or raised during portions of the deposition process to modulate process pressure, reactant concentration, etc., within gas volume **107**. Showerhead **106** and pedestal **108** are depicted as being electrically coupled to RF current generator **114** and matching network **116** for providing an RF current of sufficient magnitude to a plasma-forming structure. However, in other embodiments, showerhead **106** may not be utilized in connection with a plasma-forming structure. In such embodiments, showerhead **106** may be replaced by (or supplemented with) a conductive loop, which may be immersed within gas volume **107**. In such embodiments, the plasma density is controlled (e.g., via a system controller having appropriate machine-readable instructions and/or control logic) by controlling one or more of a process station pressure, a gas concentration, output current of an RF current generator, and so forth. For example, RF current generator **114** and matching network **116** may be operated at any suitable RF power level, which may operate to bring about formation of a an ionized plasma material having a desired composition of radical gaseous species. In addition, RF current generator **114** may provide RF power having more than one frequency component, such as a low-frequency component (e.g., less than about 2 MHz) as well as

a high frequency component (e.g., greater than about 2 MHz). Use of a conductive loop as a plasma-forming RF coupling structure is discussed, for example, in relation to FIGS. **3-12**, hereinbelow.

[0050] In the embodiment of FIG. **1**, heater **110** may be placed beneath pedestal **108**. Heater **110**, which may utilized a resistive heating coil, may bring about heating of pedestal **108** as well as substrate **112**. Thus, in certain embodiments, showerhead **106** (and/or an alternative plasma-forming RF coupling structure) and heater **110** may cooperate to enhance formation of an ionized plasma material which may, consequently, accelerate material deposition and/or material removal (e.g., etching) processes occurring within process station **102**.

[0051] In some embodiments, conditions to bring about the formation and maintenance of an ionized plasma material are controlled via appropriate hardware and/or appropriate machine-readable instructions accessible to a system controller. Machine-readable instructions may include a non-transitory sequence of input/output control (IOC) instructions encoded on a computer-readable media. In one example, the instructions for generating or maintaining an ionized plasma material are provided in the form of a plasma activation recipe of a process recipe. In some cases, process recipes may be sequentially arranged, so that at least some instructions for the process can be executed concurrently. In some embodiments, instructions for setting one or more plasma parameters may be included in a recipe preceding a plasma formation process. For example, a first recipe may include instructions for setting a flow rate of an inert (e.g., helium) and/or a reactant gas, instructions for setting an RF current generator to a power set point and time delay instructions for the first recipe. In some deposition processes, a duration of a plasma strike may correspond to a duration of a few seconds, such as from about 3 seconds to about 15 seconds, or may involve longer durations, such as durations of up to about 30 seconds, for example. In certain embodiments described herein, much shorter plasma strikes may be applied during a processing cycle.

[0052] For simplicity, processing apparatus **100** is depicted in FIG. **1** as a standalone station (**102**) of a process chamber for maintaining a low-pressure environment. However, it may be appreciated that a plurality of process stations may be included in a multi-station processing tool environment, such as shown in FIG. **2**, which depicts a schematic view of an example multi-station processing tool, according to various embodiments. Processing tool **200** employs an integrated circuit fabrication chamber **225** that includes multiple process stations. Process stations may be utilized to perform processing operations on a substrate retained via a wafer holder, such as pedestal **108** of FIG. **1**, at a particular process station. In the example of FIG. **2**, integrated circuit fabrication chamber **225** is shown as including 4 process stations **251**, **252**, **253**, and **254**. Other similar multi-station processing apparatuses may include more or fewer process stations depending on the implementation and, for instance, the desired level of parallel wafer processing, size/space constraints, cost constraints, etc. Also shown in FIG. **1**B is substrate handler robot **275**, which operates under the control of system controller **290**, is configured or adapted to move substrates from a wafer cassette (not shown in FIG. **2**). Substrates from a wafer cassette may be moved from loading port **280** and into multi-station integrated circuit fabrication chamber **225** and onto one of process stations **251**, **252**, **253**, and/or **254**.

[0053] FIG. **2** also depicts an embodiment of a system controller **290** employed to control process conditions and operating states of processing tool **200**. System controller **290** may include one or more memory devices, one or more mass storage devices, and one or more processors. The one or more processors may include a central processing unit, analog and/or digital input/output connections, stepper motor controller circuitry, etc. In some embodiments, system controller **290** controls all of the activities of process tool **200**. System controller **290** executes system control software stored in a mass storage device, which may be loaded into a memory device, and executed by a processor of the system controller. Software to be executed by a processor of system controller **290** may include instructions for controlling the timing, mixture of gases, fabrication chamber and/or station pressure, fabrication chamber and/or station temperature, wafer temperature, substrate pedestal, chuck and/or susceptor position, number of cycles performed on one or more substrates, and other parameters of a particular process performed by process tool **200**. These programmed processes may include various types of processes including, but not limited to, processes related to determining an amount of accumulation on a surface of the chamber interior, processes related to the deposition of film on substrates including numbers of ALD cycles, determining and obtaining a number of compensated cycles, and processes related to cleaning the chamber. System control software, which may be executed by one or more processors of system controller **290**, 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 necessary to carry out various tool processes.

[0054] In some embodiments, software for execution by way of a processor of system controller **290** may include input/output control (IOC) sequencing instructions for controlling the various parameters described above. For example, each phase of deposition and deposition cycling of a substrate may include one or more instructions for execution by system controller **290**. The instructions for setting process conditions for an ALD conformal film deposition process phase may be included in a corresponding ALD conformal film deposition recipe phase. In some embodiments, the recipe phases may be sequentially arranged, so that all instructions for a process phase are executed concurrently with that process phase.

[0055] Other computer software and/or programs stored on a mass storage device of system controller **290** and/or a memory device accessible to system controller **290** may be employed in some embodiments. Examples of programs or sections of programs for this purpose can include a substrate positioning program, a process gas control program, a pressure control program, a heater control program, and a plasma control program. A substrate positioning program may include program code for process tool components utilized to load a substrate onto pedestal **108** (of FIG. **1**) and to control the spacing between the substrate and other portions of process tool **200**. A positioning program can include instructions for appropriately moving substrates into and out of the reaction chamber as necessary to deposit films on substrates, etch substrates, and to clean the chamber.

[0056] A process gas control program may include code for controlling gas composition and/or flow rates and for controlling the flow of gas into one or more process stations prior to deposition, which may bring about stabilization of the pressure in the process station. In some embodiments, the process gas control program includes instructions for introducing gases during formation of a film on a substrate in the reaction chamber. This may include introducing gases for a different number of cycles for one or more substrates within a batch of substrates. A pressure control program may include code for controlling the pressure in the process station by regulating, for example, a throttle valve in an exhaust system of the process station, a gas flow into the process station, etc. The pressure control program may include instructions for maintaining the same pressure during the deposition of a differing number of cycles on one or more substrates during the processing of the batch.

[0057] System controller **290** may additionally control and/or manage the operations of RF current generator **114**, which may generate and transmit RF power to multi-station integrated circuit fabrication chamber **225** via RF power input ports **230**. Such operations may relate to determining upper and lower thresholds for RF power to be delivered to integrated circuit fabrication chamber **225**, RF power activation/deactivation times, RF power on/off duration, duty cycle, operating frequencies, and so forth. Additionally, system controller **290** may determine a set of normal operating parameters of RF power to be delivered to integrated circuit fabrication chamber **225** by way of RF power input ports **230**. Such parameters may include upper and lower thresholds of, for example, RF power reflected from integrated circuit fabrication chamber **225** in the direction of matching network **116** in terms of a reflection coefficient (e.g., the scattering parameter S_{11}) and/or a voltage standing wave ratio. Such parameters may also include upper and lower thresholds of a voltage applied to RF power input ports **230**, upper and lower thresholds of current conducted through RF power input ports **230**, as well as an upper threshold for a magnitude of a phase angle between a voltage and a current conducted through RF power input ports **230**. Such thresholds may be utilized in defining "out-of-range" RF current characteristics. For example, reflected power greater than an upper threshold may indicate an out-of-range RF power parameter. Likewise, an applied voltage or conducted current having a value below a lower threshold or greater than an upper threshold may indicate out-of-range RF current characteristics.

[0058] In certain embodiments, RF current generator **114** may operate to generate two frequencies, such as a first frequency of about 400 kHz and a second frequency of about 13.56 MHz. It should be noted, however, that RF current generator **114** may be capable of generating additional frequencies, such as frequencies of between about 300 kHz and about 100 MHz, and embodiments are not limited in this respect. In particular embodiments, currents generated by RF current generator **114** may include at least one low frequency (LF), which may be defined as a frequency of between about 300 kHz and about 2 MHz, and at least one high frequency (HF), which may be defined as a frequency greater than about 2 MHz but less than about 100 MHz.

[0059] In some embodiments, there may be a user interface associated with system controller **290**. The user interface may include a display screen, graphical software displays of the processing tool and/or process conditions, and user input devices such as pointing devices, keyboards, touch screens, microphones, etc.

[0060] In some embodiments, parameters adjusted by system controller **290** may relate to process conditions. Non-limiting examples may include process gas composition and flow rates, temperature, pressure, plasma conditions, etc. These parameters may be provided to the user in the form of a recipe, which may be entered utilizing the user interface. The recipe for an entire batch of substrates may include compensated cycle counts for one or more substrates within the batch in order to account for thickness trending over the course of processing the batch.

[0061] Signals for monitoring a fabrication process may be provided by analog and/or digital input connections of system controller **290** from various process tool sensors. Signals for controlling the process may be transmitted by way of 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, pressure sensors (such as manometers), thermocouples, etc. Sensors may also be included and used to monitor and determine the accumulation on one or more surfaces of the interior of the chamber and/or the thickness of a material layer on a substrate in the chamber. Appropriately programmed feedback and control algorithms may be used with data from these sensors to maintain process conditions.

[0062] System controller **290** may provide program instructions for implementing the above-described deposition processes. The program instructions may control a variety of process parameters, such as DC power level, pressure, temperature, number of cycles for a substrate, amount of accumulation on at least one surface of the chamber interior, etc. The instructions may control the parameters to operate in-situ deposition of film stacks according to in embodiment described herein.

[0063] For example, system controller **290** may include control logic for performing the techniques described herein, such as determining (a) an amount of accumulated deposition material currently on at least an interior region of the deposition chamber interior. In addition, system controller **290** may include control logic for applying the amount of accumulated deposition material determined in (a), or a parameter derived therefrom, to a relationship between (i) a number of ALD cycles required to achieve a target deposition thickness, and (ii) a variable representing an amount of accumulated deposition material, in order to obtain a compensated number of ALD cycles for producing the target deposition thickness given the amount of accumulated deposition material currently on the interior region of the deposition chamber. System controller **290** may include control logic for performing number of ALD cycles on one or more substrates in the batch of substrates. System controller **290** may also include control logic for determining that the accumulation in the chamber has reached an accumulation limit and stopping the processing of the batch of substrates in response to that determination, and for initiating a cleaning operation of the chamber interior.

[0064] Although FIGS. **1** and **2** are discussed in the context of showerhead **106** being utilized as an RF coupling structure to bring about formation of an ionized plasma material within a fabrication chamber, an ionized plasma material may be formed utilizing RF coupling structures in place of (or in addition to) showerhead **106**. Accordingly, FIG. **3** a shows a single conductive loop for forming an

ionized plasma material, according to an embodiment **300**. In FIG. **3**, conductive loop **310** may be formed from a metallic conductor (e.g., copper) and may be capable of conducting a current of, for example, between 25 A and 150 A. Conductive loop **310** may be elongated so as to conform to the shape of a hairpin in which an input current and a return current (I) conduct in opposite directions, such as between the RF High coupling port and the RF Low coupling port of conductive loop **310**. Portions of the hairpin-shaped conductor of conductive loop **310** are indicated as being separated from each other by a pitch (S). Conductive loop **310** is positioned at a first (e.g., upper) side of window **320** while gas volume **107** is exposed to a second (e.g., lower) side of window **320**. Accordingly, responsive to an RF current (I) having a sufficient magnitude, which generates a magnetic (or "H") field proximate to the conductive loop, at least a portion of the gas within gas volume **107** may be converted to an ionized plasma material. In certain embodiments, the thickness (T) and pitch (S) of conductive loop **310**, RF drive current (I), voltage of the coupling port labeled RF High relative to the coupling port labeled RF Low, distance (D) between conductive loop **310** and the first (e.g., upper) surface of window **320** may be selected so as to bring about plasma formation within a region of gas volume **107** that is up to 2 times the pitch (S) shown in FIG. **3**.

[0065] FIG. **4** shows an end view of the conductor of a conductive loop for forming an ionized plasma material, according to an embodiment **400**. As shown in FIG. **4**, portions of conductive loop **310**, each having a width (W) and a height (H), are separated from each other by pitch (S). The plane of conductive loop **310**, which is indicated by a dotted line **405**, is separated from window **320** by a distance (D). As previously described in relation to FIG. **3**, an RF current (I) having a sufficient magnitude may generate a magnetic field, which brings about formation of a plasma within a region of gas volume **107**. In the embodiment of FIG. **4**, plasma may be generated within a portion of gas volume **107** that extends to a distance (2S) from the plane of conductive loop **310** (indicated by dotted line **405**).

[0066] From the arrangement of FIGS. **3-4**, it may be appreciated that a single hairpin-shaped conductive loop, such as conductive loop **310**, may be capable of converting perhaps only a relatively small portion of gas within gas volume **107** to an ionized plasma. Accordingly, FIG. **5** shows three conductive loops for forming an ionized plasma material, according to an embodiment **500**. The arrangement of FIG. **5** may represent an improvement over the single conductive loop of FIGS. **3-4** by bringing about formation of an ionized plasma material within a larger portion of gas volume **107**. In the embodiment of FIG. **5**, use of 3 conductive loops **510** may bring about plasma formation in a region that is (nominally) 3 times the size of the region provided by a single conductive loop. Although not shown explicitly in FIG. **5**, elements of each of conductive loops **510** are coupled to an RF High and an RF Low coupling port, each of which provides a current (I). Each of conductive loops **510**, along with the positioning of each conductive loop relative to gas volume **107** and window **320**, is similar to that described in relation to conductive loop **310** of FIG. **3**.

[0067] In addition to utilizing a greater number of conductive loops to bring about formation of an ionized plasma material, such as from 1 conductive loop to 3 conductive loops, capacitor **515** may be coupled to each of conductive loops **510**. In particular embodiments, by way of coupling of a capacitor having value of capacitance, each of conductive loops **510** may resonate at a predetermined frequency. At such a resonant frequency, or perhaps within between 5 and 15% of the resonant frequency, an increased current (I) may be permitted to flow within each conductive loop. Such increased current flow may give rise to generation of increased magnetic field (H) by each conductive loop, which, in turn, may bring about formation of plasma within a larger region of gas volume **107**.

[0068] FIG. **6** shows RF current generator **114**, matching network **116**, and equivalent circuit **610** representing a conductive loop and capacitor combination, according to an embodiment **600**. Although equivalent circuit **610** may correspond to a single conductive loop **510** and capacitor **515**, circuit elements of equivalent circuit **610** may be modified to correspond to any number of conductive loops **510**. The circuit elements of equivalent circuit **610** may additionally be modified to correspond to an RF coupling structure other than a hairpin-shaped loop, such as an elliptical loop, a rectangular loop (perhaps having rounded corners), and so forth. Thus, in view of conductive loop **510** exhibiting an inductance, at least at particular frequencies, such as frequencies below about 30 MHz, circuit elements of matching network **116** may correspond to capacitors (e.g., capacitors C_S and C_P). Such capacitances may be inserted into the circuit between RF current generator **114** an equivalent circuit **610** so as to present a substantially matched load to the RF current generator. Termination capacitance C_T operates to raise the voltage at node **625** to a value above a reference potential, which may reduce voltage swings within equivalent circuit **610**. As described in reference to FIG. **2**, RF current generator **114** and RF matching network **116** may operate under the control of controller **290**.

[0069] With respect to equivalent circuit **610**, circuit element L_{CL} corresponds to an inductor having a value exhibited by conductive loop **510**. In an example, inductance of circuit element L_{CL} may correspond to a value of about 482 nH. However, in other examples, circuit element L_{CL} may correspond to any other value, such as a value of less than about 482 nH (e.g., 475 nH, 450 nH, 400 nH, and so forth) or may correspond to a value greater than about 482 nH (e.g., 500 nH, 525 nH, 600 nH, and so forth). Circuit element C_{CL} of FIG. **6**, which corresponds to capacitor **515** of FIG. **5**, may correspond to a value of about 300 pF. However, circuit element C_{CL} of FIG. **6** may include any other value, such as values of less than about 300 pF (e.g., 275 pF, 250 pF, 200 pF, and so forth) or may correspond to a value greater than about 300 pF (e.g., 325 pF, 350 pF, and so forth). In the example of FIG. **6**, selection of a capacitance of about 300 pF and an inductance of about 482 nH may permit the combination of conductive loop **510** and capacitor **515** to resonate at a frequency of about 13.24 MHz, which may be computed substantially in accordance with expression (1), below:

$$f_{resonance} = \frac{1}{2\pi\sqrt{(482\times10^{-9})(300\times10^{-12})}} = 13.24 \text{ MHz} \quad (1)$$

Thus, at a frequency of 13.24 MHz, a maximum current may conduct within conductive loop **310**.

[0070] Prior to formation of an ionized plasma source within a fabrication chamber, resistance R_P of FIG. **6** may comprise a negligible value. Thus, the voltage (V_{RF}) across equivalent circuit element L_{CL} (e.g., between nodes **615** and **620**) may exhibit a relatively high value. In addition, the resonant circuit formed by L_{CL} and C_{CL} may correspond to a circuit having a relatively high quality factor (Q). As an ionized plasma material is formed within the fabrication chamber, via conduction of a sufficient current with the in the resonant of circuit formed by L_{CL} and C_{CL}, resistance R_P exhibits a larger value. Accordingly, the voltage (V_{RF}) across equivalent circuit element L_{CL} decreases in magnitude. Resistance R_P may be characterized as a plasma-induced resistance that increases as RF power is coupled from conductive loop **310** and into a gaseous volume to form an ionized plasma material. An increase in resistance R_P also brings about a lowering of the quality factor (Q) of the resonant circuit formed by L_{CL} and $C_{CL.}$

[0071] It should be noted that the circuit of FIG. **6** permits a relatively high current to flow between circuit elements L_{CL} and C_{CL} without requiring a large current to be coupled to the resonant circuit, such as from RF current generator **114**. Accordingly, it may be appreciated that an advantage of the circuit of FIG. **6** is to provide a significant magnetic field, thereby giving rise to an ionized plasma material distributed throughout a large portion of a gas volume (e.g., gas volume **107**), but without necessitating excessively large currents from an RF current generator and/or an RF matching network.

[0072] In addition to increasing resistance R_P, generation of an ionized plasma material in a fabrication chamber may bring about a change in an inductance exhibited by a conductive loop. Thus, in an example, generation of an ionized plasma material may reduce an inductance exhibited by a conductive loop from about 482 nH to about 467 nH. Accordingly, the resonance of equivalent circuit **610** operating under plasma-generating conditions may be increased from about 13.24 MHz to about 13.45 MHz as computed substantially in accordance with expression (2) below:

$$f_{resonance} = \frac{1}{2\pi\sqrt{(467\times10^{-9})(300\times10^{-12})}} = 13.45\ \text{MHz} \tag{2}$$

[0073] FIG. **7** depicts reactance versus frequency for the equivalent circuit corresponding to the conductive loop and capacitor combination of FIG. **6** prior to formation of a plasma material, according to an embodiment **700**. The vertical axis of FIG. **7** corresponds to reactance (series inductance) while the horizontal axis corresponds to frequency. At relatively low frequencies, the reactance of equivalent circuit **610** corresponds to a relatively low or negligible value of positive reactance. At increased frequencies, the positive reactance increases monotonically to reach a maximum value at a resonant frequency (f_0). At frequencies greater than the resonant frequency (f_0), the reactance comprises a large negative value (capacitance), which approaches a relatively low value as frequency increases. Thus, as shown, at frequencies lower than the resonant frequency (f_0), the inductance (such as the inductance L_{CL}) of equivalent circuit **610** dominates. However, at frequencies greater than the resonant frequency (f_0) the capacitance (such as the capacitance C_{CL}) of equivalent circuit **610** dominates.

[0074] In an example in which plasma formation has not occurred, the resonant frequency (f_0) of equivalent circuit **610** corresponds to approximately 13.24 MHz (f_0=13.24 MHz) as computed in accordance with expression (1) above. Accordingly, responsive to operation of equivalent circuit **610** at a frequency greater than 13.24 MHz, such as at 13.56 MHz (indicated as fop in FIG. **7**), the capacitive reactance exhibited by capacitance C_{CL} dominates. For example, prior to plasma formation (the "No-Plasma Resonance Frequency" of FIG. **7**), the reactance of equivalent circuit **610** operating at a frequency of about 13.56 MHz comprises a value of about −j500 Ω.

[0075] However, as previously alluded to, generation of an ionized plasma material may reduce an inductance exhibited by a conductive loop from about 482 nH to a lower value, such as a value of about 467 nH. Thus, FIG. **8** shows a graph of impedance versus frequency for the equivalent circuit corresponding to the conductive loop and capacitor combination of FIG. **6** after formation of a plasma material, according to an embodiment **800**. The resonance of equivalent circuit **610** after the formation of a plasma is computed substantially in accordance with expression (2) above. Accordingly, as indicated in expression (2), after formation of an ionized plasma material, the resonance of equivalent circuit **610** increases from about 13.24 MHz to about 13.45 MHz. Such increase is indicated as f_1 on the horizontal axis of FIG. **8**. Thus, responsive to operation of equivalent circuit **610** at a frequency of 13.56 MHz (f_{OP} in FIG. **8**), the reactance exhibited by capacitance C_{CL} increases negatively. For example, as shown in FIG. **8**, following plasma formation, the reactance of equivalent circuit **610** comprises a value of about −j1500 Ω.

[0076] As shown in FIGS. **7** and **8**, in response to the formation of plasma in a fabrication chamber, the inductive reactance exhibited by a conductive loop coupled to a capacitive element decreases. Such decrease in inductive reactance renders the conductive loop/capacitive element combination to exhibit greater capacitance (i.e., negative reactance). Accordingly, in a fabrication chamber, increases in plasma density operate to increase the capacitance of the RF coupling structure formed from a conductive loop/capacitive element combination. Responsive to increasing the capacitance of the RF coupling structure, a negative feedback loop may be introduced. In such an arrangement, a disproportionate coupling of RF energy to a region of a fabrication chamber brings about a reduction in current coupled to the RF coupling structure. Such passive compensation may be capable of rapidly compensating for nonuniformities in plasma density within the fabrication chamber.

[0077] FIG. **9** shows an RF current generator, matching network, transmission line, and equivalent circuit for conductive loops for forming an ionized plasma material, according to an embodiment **900**. In FIG. **9**, matching circuit **916** performs a function similar to matching network **116** of FIG. **6**, with the exception that matching circuit **916** incorporates transmission line effects. Accordingly, matching circuit **916** includes inductor L_T, which corresponds to a lumped-element series inductance of a length of, for example, a coaxial cable (e.g., 50-ohm) transmission line. Thus, the capacitance of capacitor C_{ST} may be increased

from C_S of FIG. **6** to compensate for the presence of series inductor L_T. Additionally, capacitor C_{PT} may be reduced to compensate for a series capacitance present in length of a coaxial cable (e.g., 50-ohm) transmission line. Capacitor C_T corresponds to capacitor C_T of FIG. **6**, in which C_T operates to raise the voltage at node B to a value above a reference potential, which may reduce voltage swings within conductive loops **920**, **921**, and **922**. Although not shown in FIG. **9**, adjustment of capacitors C_{PT} and C_{ST}, may be performed by a controller, such as controller **290** of FIG. **2**.

[0078] In particular embodiments, capacitors C_{PT} and C_{ST} may be adjusted to accommodate a transmission line length of about one-half wavelength (λ/2) of an operating frequency (e.g., f_{OP}), such as 13.5 MHz. In certain embodiments, computer simulations utilizing a transmission line of various length, which bring about corresponding delays (such as a delay of about 35.8 ns) in currents between RF current generator **114** and conductive loops **920**, **921**, and **922**, have been shown to impact the operating frequency at which a maximum current can be induced to flow within the conductive loops. In an example, a transmission line having a length of one-half wavelength, which corresponds to a full rotation around the Smith chart, serves to bring about maximum current flow through conductive loop at a frequency slightly higher than a resonant frequency of a conductive loop.

[0079] Between nodes A and B of FIG. **9**, conductive loops **920**, **921**, and **922** correspond to RF structures for forming an ionized plasma material. Presence of resistance (R) indicates that each of conductive loops **920**, **921**, and **922** operate in a plasma-forming state. Loop currents I_{C1}, I_{C2}, and I_{C3} correspond to currents flowing within, for example, conductive loops **510** of FIG. **5**.

[0080] Inductors L_{CL} correspond to inductances of each of loops **510** while plasma is being formed. Coupling factors k_1, k_2, and k_3 indicate a relationship between a loop current and current conduction through resistance (R), such as I_{P1}, I_{P2}, and I_{P3}. Thus, at least in particular embodiments, it may be desirable for a relatively strong relationship to exist between a loop current and current conduction through resistance (R). In certain embodiments, presence of a relatively large coupling factor, such as a coupling factor between about 0.35 and 0.45 coupling factor may serve to strengthen the negative feedback relationship between the increased plasma density and the capacitance exhibited by a resonant circuit.

[0081] In FIG. **9**, a one-half wavelength transmission line is utilized to couple output node A, which corresponds to the output side of matching circuit **916**, with each of conductive loops **920**, **921**, and **922**. In particular embodiments, use of a one-half wavelength (λ/2) transmission line, such as a 50-ohm coaxial cable, introduces a one-half wavelength time delay in a current conducting from output node A to conductive loops **920**, **921**, and **922**. In the embodiment of FIG. **9**, such a time delay operates to provide uniformity in power coupled between matching circuit **916** and conductive loops **920**, **921**, and **922**. Accordingly, even if varying line lengths, parasitic capacitances or inductances, bring about differing values for L_{CL} and C_{CL} of conductive loops **920**, **921**, and **922**, a one-half wavelength transmission line can operate to bring about equal, or at least substantially equal, power coupling to each conductive loop.

[0082] FIG. **10** shows graphs of tank circuit impedance, tank circuit current, and matching network current for a single hairpin-shaped conductive loop for forming an ionized plasma material, utilizing a common frequency scale, according to an embodiment **1000**. The graphs of FIG. **10** result from use of a coaxial cable transmission line that is about one-half wavelength of the operating frequency of 13.56 MHz. As mentioned with respect to FIG. **9**, a one-half wavelength transmission line brings about maximum current flow through a conductive loop at a frequency at or near 13.56 MHz.

[0083] In the top portion of FIG. **10**, graph **1010** shows monotonically increasing impedance of an example conductive loop, such has any one of conductive loops **920**, **921**, and **922**. Graph **1010** indicates real impedance peaking at a resonant frequency of approximately 13.45 MHz, which corresponds to operation of a conductive loop/capacitor combination during plasma formation. When conductive loop **920**, for example, is operated at a frequency that is slightly greater than the 13.45 MHz resonance frequency (e.g. 13.56 MHz), the conductive loop/capacitor combination operates in a negative feedback region. In the negative feedback region, impedance of the conductive loop/capacitor combination increases as the operating frequency becomes incrementally closer to the resonant frequency. For example, as depicted in graph **1010**, operation of the conductive loop/capacitor combination at a frequency of slightly greater than 13.45 MHz indicates an impedance of 10,000 ohms or greater. However, as the operating point of the conductive loop/capacitor combination assumes a value slightly greater than 13.45 MHz (e.g., 13.56 MHz), the impedance assumes a value of about 1000 ohms or less. In particular embodiments, the negative feedback region may include a range of frequencies within about 10% of the resonant frequency of a conductive loop/capacitor combination. However, in other embodiments, the negative feedback region may include a broader range of frequencies, such as frequencies within about 15% or about 20% of the resonant frequency. In still other embodiments, the negative feedback region may include a narrower range of frequencies, such as frequencies within about 8%, 5%, or 2% of the resonant frequency.

[0084] FIG. **10** also depicts graph **1020**, which corresponds to current conducted within any one of conductive loop **920**, **921**, and **922**, each of which corresponds to a conductive loop/capacitor combination. As indicated at graph **1020**, at a frequency of approximately 13.6 MHz, current conduction reaches a maximum of about 85 A. Such relatively high current flow may encourage plasma formation using a conductive loop. However, as indicated at graph **1030**, current conduction through matching circuit **916** assumes a nominal value of about 10 A with a slight increase at approximately 13.6 MHz.

[0085] Although graph **1020** indicates a current conduction through a conductive loop of 85 A and a current conduction through matching circuit **916** comprises a value of about 10 A, indicating a current through conductive loop that is more than 8.5 times the current conduction through a matching network, the disclosed embodiments are not so limited. For example, in other embodiments, current conduction through a conductive loop may be, perhaps, only twice, three times, or four times that of the current conduction through a matching network. In still other embodiments, current conduction through a conductive loop may be greater than 8.5 times the current conduction through a

matching network, such as 9 times, or 10 times, or may be related to current conduction through a matching network by an even larger factor.

[0086] FIG. **11**A shows an equivalent circuit of a resonant RF coupling structure coupled to an ionized plasma material, according to an embodiment **1100**. In the equivalent circuit of embodiment **1100**, RF current generator **114** provides an RF current to matching network **1116**.

[0087] Matching network **1116** may include reactive components operating to match the output impedance of RF current generator **114**. In the embodiment of FIG. **11**A, RF current generator **114** and reactive components of matching network **1116** include a non-negligible real impedance (e.g., resistance) such that an increased current flow (I) through node **1125** brings about a decrease in the voltage present at node **1125**. Equivalent circuit **1120** includes a resonant structure, which may be implemented as a hairpin-shaped conductive loop, for example. Responsive to current conduction within the resonant RF coupling structure of equivalent circuit **1120**, a plasma may be formed. In equivalent circuit **1120**, coupling between the resonant RF coupling structure and the plasma may be represented by the coupling factor k_1. Thus, an increase in the density of an ionized plasma material may be represented as an increase in coupling factor k_1. In particular embodiments, coupling factor k_1 may vary from between about 0.35 and about 0.45, for example. In some embodiments, coupling factor k_1 may assume different values, such as between about 0.25 and about 0.5.

[0088] In the embodiment of FIG. **11**A, as the coupling factor (k_1) between the plasma and the resonant RF coupling structure of equivalent circuit **1120** increases, indicating an increase in plasma density, the impedance of equivalent circuit **1120** may decrease. Such a decrease in the impedance of equivalent circuit **1120**, shown as $Z_{1120}\downarrow$ in FIG. **11**A, may be brought about by increased current flow (I_{P1}) within the plasma of equivalent circuit **1120**. Accordingly, current conduction through node **1125** may increase, as indicated by $I\uparrow$ in FIG. **11**A. However, as current conduction through node **1125** increases, the voltage at node **1125** is reduced in response to increased resistive losses through matching network **1116**. Such reduction in voltage at node **1125** is indicated as $V_{1251}\downarrow$, in FIG. **11**A. Consequently, as indicated as $I\downarrow$ current delivered to equivalent circuit **1120** is reduced. In some embodiments, such a reduction in the current delivered to equivalent circuit **1120** returns the delivered current to a nominal or steady-state value. Responsive to reducing the current delivered to equivalent circuit **1120** to a nominal or steady-state value, coupling between the resonant RF coupling structure and the plasma may be decreased, thereby increasing the impedance of equivalent circuit **1120**. Such an increase in the impedance of equivalent circuit **1120**, along with the attendant decrease in current delivered to the equivalent circuit, may return the voltage of output node **1125** to a steady-state value.

[0089] In the embodiment of FIG. **11**A, node **1125** is separated from input node **1126** by a transmission line length corresponding to one half of the wavelength of an RF signal in the transmission line medium. A half-wavelength transmission line may be utilized to transform impedances of the resonant structure. Such impedance transformation may provide additional control over the impedance of equivalent circuit **1120** as reflected at node **1125**.

[0090] FIG. **11**B shows equivalent circuits of resonant RF coupling structures coupled an ionized plasma material, according to an embodiment **1150**. In the embodiment of FIG. **11**B, equivalent circuit **1121** is arranged in parallel with equivalent circuit **1120** (of FIG. **11**A). Power divider **1160** operates to divide power generated by RF current generator **114** into approximately equal portions. In this context, approximately equal portions refers to portions within 5% of one another. Power divider **1160** exhibits a real impedance (e.g., resistance) in which an increased current flow brings about a decrease in the voltage present at nodes **1165** and **1166**. Equivalent circuit **1121** may operate in a manner similar to that of equivalent circuit **1120**, in which power may be coupled from a resonant RF coupling structure to a plasma. A coupling factor, such as k_2, may indicate a level of coupling between the resonant RF coupling structure and the plasma.

[0091] In the embodiment of FIG. **11**B, as the coupling factor (k_1) between the plasma and the resonant RF coupling structure of equivalent circuit **1120** increases, the impedance of equivalent circuit **1120** may decrease. Such a decrease in the impedance of equivalent circuit **1120**, shown as $Z_{1120}\downarrow$ in FIG. **11**B, may be brought about by increased current flow within the plasma of equivalent circuit **1120**. Accordingly, current conduction through node **1165** of power divider **1160** may increase, as indicated by $I_{1120}\downarrow$ in FIG. **11**A. However, as current conduction through node **1165** increases, the voltage at node **1165** is reduced in response to increased resistive losses within power divider **1160**. Such reduction in voltage at node **1165** is indicated as $V_{1165}\downarrow$ in FIG. **11**B. Consequently, as indicated as $I_{1120}\downarrow$, current delivered to equivalent circuit **1120** is reduced. Responsive to reducing the current delivered to equivalent circuit **1120** to a nominal or steady-state value, coupling between the resonant RF coupling structure and the plasma may be decreased, thereby increasing the impedance of equivalent circuit **1120**. Such an increase in the impedance of equivalent circuit **1120**, along with the attendant decrease in current delivered to the equivalent circuit, may return the voltage of output node **1125** to a steady-state value.

[0092] In some embodiments, such a reduction in the current delivered to equivalent circuit **1120** returns the delivered current to a nominal or steady-state value. In the embodiment of FIG. **11**A, node **1165** and input node **1126** to equivalent circuit **1120** are separated by a transmission line length corresponding to one half of the wavelength of an RF signal in the transmission line medium. A half-wavelength transmission line may be utilized to transform impedances of the resonant structure.

[0093] Equivalent circuit **1121** operates in a manner similar to equivalent circuit **1120**. Such operation involves an increase in coupling between the resonant RF coupling structure of equivalent circuit **1121** and a plasma of the equivalent circuit. The increase in coupling brings about a decrease in impedance presented by equivalent circuit **1121** ($Z_{1121}\downarrow$). Consequently, an increased current ($I_{1121}\downarrow$) may be conducted from output node **1166** which, in turn, operates to reduce the voltage at output node **1166** ($V_{1166}\downarrow$). Responsive to a reduction in the voltage at output node **1166**, the output current conducted from power divider **1160** to equivalent circuit **1121** is reduced to a nominal value.

[0094] FIG. **12** shows a side view of conductors of a conductive loop immersed within an ionized plasma material, according to an embodiment **1200**. Conductors **1210** of

FIG. **12** conduct current in opposite directions similar to current conduction (I) in conductive loop **310** of FIG. **3**. In the embodiment of FIG. **12**, conductors **1210** each comprise a thickness of about 0.635 cm (about ¼ inch). Conductors **1210** are surrounded by air gap **1215**, which comprises a thickness of about 1 cm (about 0.4 inch). Conductors **1210** and air gap **1215** are surrounded by ceramic tube **1220**, which comprises a thickness of about 0.32 cm (about 0.125 inch).

[0095] Responsive to current conduction in opposite directions through conductors **1210**, similar to current conduction (I) in conductive loop **310** of FIG. **3**, a magnetic field between conductors **1210**, such as at region **1240**, may assume a relatively high value. Accordingly, a relatively dense plasma may form at region **1240**. However, at region **1250**, which corresponds to a region away from region **1240**, a less dense plasma may form. In particular embodiments, immersion of a plasma-forming conductive loop, such as shown in FIG. **12**, may result in a coupling factor greater than a coupling factor provided by other arrangements of a conductive loop. For example, the arrangement of conductors in FIG. **12** may provide a coupling factor of between 0.35 and 0.5 (e.g., about 0.4), which may represent increased coupling over the conductive loop arrangement of, for example, FIG. **3** and FIG. **4**.

[0096] Returning now to FIG. **2**, in general controller **290** may be defined as electronics having various integrated circuits, logic, memory, and/or software that receive instructions, issue instructions, control operation, enable cleaning operations, enable endpoint measurements, and the like. The integrated circuits may include chips in the form of firmware that store program instructions, digital signal processors (DSPs), chips defined as application specific integrated circuits (ASICs), and/or one or more microprocessors, or microcontrollers or field-programmable gate arrays (FPGA) or FPGA with system-on-a-chip (SoC) that that execute program instructions (e.g., software). Program instructions may be instructions communicated to the controller in the form of various individual settings (or program files), defining operational parameters for carrying out a particular process on or for a semiconductor wafer or to a system. The operational parameters may, in some implementations, be part of a recipe defined by process engineers to accomplish one or more processing steps during the fabrication of one or more layers, materials, metals, oxides, silicon, silicon dioxide, surfaces, circuits, and/or dies of a wafer.

[0097] The controller, in some embodiments, may be a part of or coupled to a computer that is integrated with, coupled to the system, otherwise networked to the system, or a combination thereof. For example, the controller may be in the "cloud" or all or a part of a fab host computer system, which can allow for remote access of the wafer processing. The computer may enable remote access to the system to monitor current progress of fabrication operations, examine a history of past fabrication operations, examine trends or performance metrics from a plurality of fabrication operations, to change parameters of current processing, to set processing steps to follow a current processing, or to start a new process. In some examples, a remote computer (e.g. a server) can provide process recipes to a system over a network, which may include a local network or the Internet. The remote computer may include a user interface that enables entry or programming of parameters and/or settings, which are then communicated to the system from the remote computer. In some examples, the controller receives instructions in the form of data, which specify parameters for each of the processing steps to be performed during one or more operations. It should be understood that the parameters may be specific to the type of process to be performed and the type of tool that the controller is configured to interface with or control. Thus, as described above, the controller may be distributed, such as by comprising one or more discrete controllers that are networked together and working towards a common purpose, such as the processes and controls described herein. An example of a distributed controller for such purposes would be one or more integrated circuits on a chamber in communication with one or more integrated circuits located remotely (such as at the platform level or as part of a remote computer) that combine to control a process on the chamber.

[0098] In the foregoing detailed description, numerous specific details are set forth to provide a thorough understanding of the presented embodiments or implementations. The disclosed embodiments or implementations may be practiced without some or all of these specific details. In other instances, well-known process operations have not been described in detail so as to not unnecessarily obscure the disclosed embodiments or implementations. While the disclosed embodiments or implementations are described in conjunction with the specific embodiments or implementations, it will be understood that such description is not intended to limit the disclosed embodiments or implementations.

[0099] The foregoing detailed description is directed to certain embodiments or implementations for the purposes of describing the disclosed aspects. However, the teachings herein can be applied and implemented in a multitude of different ways. In the foregoing detailed description, references are made to the accompanying drawings. Although the disclosed embodiments or implementation are described in sufficient detail to enable one skilled in the art to practice the embodiments or implementations, it is to be understood that these examples are not limiting; other embodiments or implementation may be used and changes may be made to the disclosed embodiments or implementation without departing from their spirit and scope. Additionally, it should be understood that the conjunction "or" is intended herein in the inclusive sense where appropriate unless otherwise indicated; for example, the phrase "A, B, or C" is intended to include the possibilities of "A," "B," "C," "A and B," "B and C," "A and C," and "A, B, and C."

[0100] In this application, the terms "semiconductor wafer," "wafer," "substrate," "wafer substrate," and "partially fabricated integrated circuit" are used interchangeably. One of ordinary skill in the art would understand that the term "partially fabricated integrated circuit" can refer to a silicon wafer during any of many stages of integrated circuit fabrication thereon. A wafer or substrate used in the semiconductor device industry may include a diameter of 200 mm, or 300 mm, or 450 mm. The foregoing detailed description assumes embodiments or implementations are implemented on a wafer, or in connection with processes associated with forming or fabricating a wafer. However, disclosed embodiments are not limited to such. The work piece may be of various shapes, sizes, and materials. In addition to semiconductor wafers, other work pieces that may take advantage of claimed subject matter and may

include various articles such as printed circuit boards, or the fabrication of printed circuit boards, and the like.

[0101] Unless the context of this disclosure clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," and the like are to be construed in an inclusive sense as opposed to an exclusive or exhaustive sense; that is to say, in a sense of "including, but not limited to." Words using the singular or plural number also generally include the plural or singular number respectively. When the word "or" is used in reference to a list of 2 or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list. The term "implementation" refers to implementations of techniques and methods described herein, as well as to physical objects that embody the structures and/or incorporate the techniques and/or methods described herein.

1. An apparatus for forming a plasma, comprising:
one or more coupling ports configured to accept a radiofrequency (RF) current;
one or more conductive loops configured to permit the RF current to conduct from at least a first port of the one or more coupling ports to at least a second port of the one or more coupling ports, the one or more conductive loops each configured to exhibit a first value of inductance in an absence of the plasma and to exhibit a second value of inductance in a presence of the plasma; and
one or more reactive elements, each coupled to a corresponding one of the one or more conductive loops, to form a corresponding number of coupling structures, each coupling structure having a resonant frequency configured to increase in response to the presence of the plasma.

2. The apparatus of claim **1**, wherein the one or more conductive loops are configured to form a plasma operating in an inductive mode.

3. The apparatus of claim **1**, wherein the one or more conductive loops comprises two or more conductive loops.

4. The apparatus of claim **1**, wherein each of the one or more reactive elements comprises one or more capacitive elements that cooperate with a corresponding conductive loop of the one or more conductive loops to bring about resonance at a frequency that is lower than the frequency of the RF current.

5. The apparatus of claim **4**, wherein the resonant frequency is a value that is within about 10% of the frequency of the RF current.

6. The apparatus of claim **4**, wherein the forming of the plasma brings about a second value of inductance that is less than the first value of inductance.

7. The apparatus of claim **1**, wherein a coupling factor between the one or more conductive loops and the formed plasma comprises a value of between about 0.35 and about 0.5.

8. The apparatus of claim **7**, wherein at least a portion of the formed plasma is located in a region between segments of each of the one or more conductive loops.

9. The apparatus of claim **7**, wherein at least a portion of the formed plasma is located in a region less than twice a separation distance between adjacent segments of each of the one or more conductive loops.

10. The apparatus of claim **1**, wherein at least one of the one or more conductive loops comprises a hairpin shape.

11. The apparatus of claim **1**, further comprising a delay network configured to maintain current conduction within the one or more conductive loops at a value that is at least twice the value of the RF current conducted to the first port of the one or more coupling ports.

12. The apparatus of claim **11**, wherein the delay network is further configured to introduce a delay of about one-half wavelength between an output port of an RF matching network and the first port of the one or more coupling ports.

13. An apparatus, comprising:
one or more input ports to receive an RF current;
one or more conductive loops coupled to a corresponding one of the one or more input ports, each of the one or more conductive loops configured to exhibit inductance; and
one or more capacitive elements, each of the one or more capacitive elements coupled to a corresponding one of the one or more conductive loops so as to resonate at a first frequency that is below a frequency of the RF current,
the one or more conductive loops configured to convert a gas, proximate to the one or more conductive loops, to a plasma in response to conduction of the RF current.

14. The apparatus of claim **13**, wherein the first frequency differs from the frequency of the RF current by less than about 10%.

15. The apparatus of claim **13**, wherein the gas at least partially surrounds the one or more conductive loops.

16. The apparatus of claim **13**, wherein the gas is located within a distance of two times a spacing between adjacent segments of the one or more conductive loops.

17. The apparatus of claim **13**, wherein the one or more conductive loops are configured to resonate at a frequency below about 13.56 MHz.

18. The apparatus of claim **13**, wherein at least one of the one or more conductive loops comprises a hairpin shape.

19. The apparatus of claim **13**, further comprising a time-delay network configured to maintain peak current conduction within the one or more conductive loops at a value that is at least twice the value of the RF current conducted a first input port of the one or more input ports.

20. A multi-station integrated circuit fabrication chamber, comprising:
a matching network to receive an RF current from an output port of an RF current generator;
one or more coupling structures to receive a current from the matching network, the one or more coupling structures having at least one conductive loop and at least one capacitive element, the one or more coupling structures configured to resonate at a resonant frequency that is less than the frequency of the RF current; and
a volume configured to permit conversion of one or more gases into a plasma to conduct one or more fabrication operations within the multi-station integrated circuit fabrication chamber.

21. The multi-station integrated circuit fabrication chamber of claim **20**, further comprising a time-delay network configured to maintain peak current conduction within the one or more conductive loops at a value that is at least twice a value of the RF current received from the matching network.

22. The multi-station integrated circuit fabrication chamber of claim **20**, further comprising a time-delay network configured to introduce a delay of about one-half wavelength between an output port of the matching network and input ports of the one or more coupling structures.

23. The multi-station integrated circuit fabrication chamber of claim **20**, wherein the one or more gases at least partially surround the one or more conductive loops.

24. The multi-station integrated circuit fabrication chamber of claim **20**, wherein at least a portion of the one or more gases are located within a distance of two times a spacing between adjacent segments of the one or more conductive loops.

25. The multi-station integrated circuit fabrication chamber of claim **20**, wherein a coupling factor between the one or more conductive loops and the plasma comprises a value of between about 0.2 and about 0.5.

26. The multi-station integrated circuit fabrication chamber of claim **20**, wherein a first frequency of the RF current and the resonant frequency differ by less than about 10%.

27. The multi-station integrated circuit fabrication chamber of claim **20**, wherein the one or more coupling structures comprises three or more coupling structures.

28. A system for forming a plasma, comprising:

a radiofrequency (RF) current generator; and

a first RF coupling structure configured to receive power generated by the RF current generator and to convert a gaseous material, at least partially surrounding the first RF coupling structure, to an ionized plasma, the first RF coupling structure configured to exhibit an impedance that decreases responsive to an increased density of the ionized plasma, the RF current generator configured to decrease output current delivered to the first RF coupling structure responsive to the decreased impedance.

29. The system of claim **28**, further comprising:

a second RF coupling structure, the second RF coupling structure configured to receive a current conducted from the RF current generator and to convert a gaseous material, at least partially surrounding the second RF coupling structure, to an ionized plasma; and

an RF power divider having an input port coupled to an output port of the RF current generator and having a first output port coupled to the first RF coupling structure and a second output port coupled to the second RF coupling structure, the second RF coupling structure configured to exhibit an impedance that decreases responsive to an increased density of the ionized plasma.

30. The system of claim **29**, wherein power delivered to the first RF coupling structure by the RF power divider and the power delivered to the second RF coupling structure by the RF power divider are configured to be approximately equal during the increased density of the ionized plasma converted by the first RF coupling structure and during the increased density of the ionized plasma converted by the second RF coupling structure.

31. The system of claim **29**, wherein the first RF coupling structure and the second RF coupling structure comprise a conductive loop configured to form the ionized plasma in an H mode.

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