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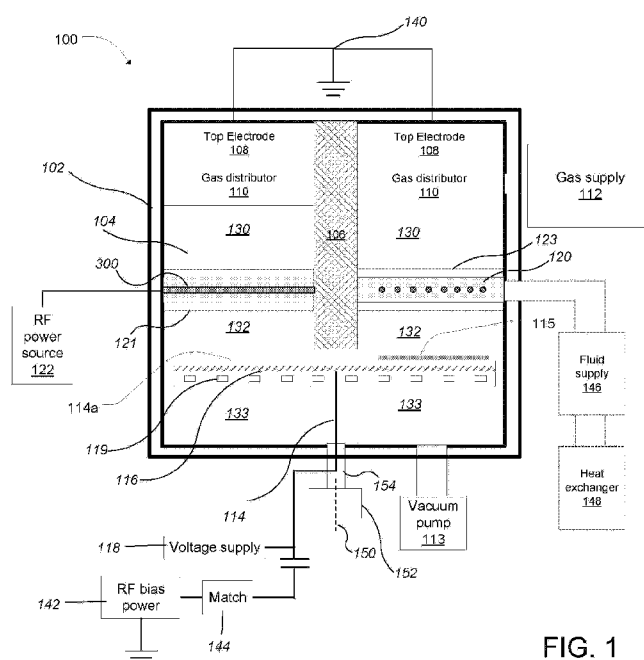


FIG. 1

(57) **Abstract:** A processing tool for a plasma process includes a chamber body that has an interior space that provides a plasma chamber and that has a ceiling and an opening on a side opposite the ceiling, a workpiece support to hold a workpiece such that at least a portion of a front surface of the workpiece faces the opening, an actuator to generate relative motion between the chamber body and the workpiece support such that the opening moves laterally across the workpiece, a gas distributor to deliver a processing gas to the plasma chamber, an electrode assembly comprising a plurality of coplanar filaments extending laterally through the plasma chamber between the workpiece support and the ceiling, each of the plurality of filaments including a conductor, and a first RF power source to supply a first RF power to the conductors of the electrode assembly to form a plasma.



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PLASMA CHAMBER WITH ELECTRODE ASSEMBLY

TECHNICAL FIELD

The present disclosure relates to a processing tool that includes a plasma chamber, e.g. for depositing a film on, etching, or treating a workpiece such as a semiconductor wafer.

BACKGROUND

5 Plasma is typically generated using a capacitively-coupled plasma (CCP) source or an inductively-coupled plasma (ICP) source. A basic CCP source contains two metal electrodes separated by a small distance in a gaseous environment similar to a parallel plate capacitor. One of the two metal electrodes are driven by a radio frequency (RF) power supply at a fixed frequency while the other electrode is connected to an RF ground, generating an RF electric
10 field between the two electrodes. The generated electric field ionizes the gas atoms, releasing electrons. The electrons in the gas are accelerated by the RF electric field and ionizes the gas directly or indirectly by collisions, producing plasma.

A basic ICP source typically contains a conductor in a spiral or a coil shape. When an RF electric current is flowed through the conductor, RF magnetic field is formed around the
15 conductor. The RF magnetic field accompanies an RF electric field, which ionizes the gas atoms and produces plasma.

Plasmas of various process gasses are widely used in fabrication of integrated circuits. Plasmas can be used, for example, in thin film deposition, etching, and surface treatment.

20 Atomic layer deposition (ALD) is a thin film deposition technique based on the sequential use of a gas phase chemical process. Some ALD processes use plasmas to provide necessary activation energy for chemical reactions. Plasma-enhanced ALD processes can be performed at a lower temperature than non-plasma-enhanced (e.g., 'thermal') ALD processes.

SUMMARY

25 In one aspect, a processing tool for a plasma process includes a chamber body that has an interior space that provides a plasma chamber and that has a ceiling and an opening on a side opposite the ceiling, a workpiece support to hold a workpiece such that at least a

portion of a front surface of the workpiece faces the opening, an actuator to generate relative motion between the chamber body and the workpiece support such that the opening moves laterally across the workpiece, a gas distributor to deliver a processing gas to the plasma chamber, an electrode assembly comprising a plurality of coplanar filaments extending
5 laterally through the plasma chamber between the workpiece support and the ceiling, each of the plurality of filaments including a conductor, and a first RF power source to supply a first RF power to the conductors of the electrode assembly to form a plasma.

Implementations may include one or more of the following features.

The workpiece support may be rotatable about an axis of rotation, and the actuator
10 may rotate the workpiece support such that rotation of the support carries the workpiece across the opening.

The plurality of coplanar filaments may extend across a wedge-shaped area. The workpiece may fit entirely within the wedge-shaped area such that in operation an entirety of the front surface of the workpiece is exposed to plasma. The workpiece may be larger than
15 the wedge-shaped area such that in operation a wedge-shaped portion of the front surface of the workpiece is exposed to plasma. The opening may be wedge-shaped.

The plurality of coplanar filaments may be linear filaments, and different filaments may have different lengths so as to define the wedge-shaped area. The plurality of coplanar filaments may extend in parallel. The plurality of coplanar filaments may be uniformly
20 spaced apart. Different filaments may be oriented at different angles. The plurality of coplanar filaments may be oriented such that a plasma density generated in the wedge-shaped area is lower at an apex of the wedge-shaped area than at a base of the wedge-shaped area. The plurality of coplanar filaments may be oriented to have longitudinal axes at a non-zero angle relative to a direction of motion of the portion of the substrate below the opening. The
25 non-zero angle may be greater than 10°.

A spacing between the coplanar filaments may be sufficient to avoid pinching of a plasma region between regions above and below the intra-chamber electrode assembly. A bottom of the chamber may be open. The tool may include a top electrode on the ceiling of the chamber.

30 Ends of conductors of the plurality of coplanar filaments may be connected to the first RF power source by a recursive RF feed structure. Opposite ends of conductors of the

plurality of coplanar filaments may be connected to a common bus. The bus may be connected to the first RF power source at two opposing locations.

A first multiplicity of conductors of the plurality of coplanar filaments may be connected to the first RF power source and a second multiplicity of conductors of the plurality of coplanar filaments may be floating or grounded. First ends of conductors of the plurality of coplanar filaments may be connected to the first RF power source by a common bus. The conductors of the first group and the conductors of the second group may be arranged to alternate along a direction perpendicular to a longitudinal axis of the filaments.

In another aspect, a plasma reactor includes a chamber body having an interior space that provides a plasma chamber, a gas distributor to deliver a processing gas to the plasma chamber, a workpiece support to hold a workpiece, an electrode assembly comprising a plurality of conductors spaced apart from and extending laterally across the workpiece support in a parallel coplanar array, a first RF power source to supply a first RF power to the electrode assembly, and a dielectric bottom plate between the electrode assembly and the workpiece support, the dielectric bottom plate providing an RF window between the electrode assembly and the plasma chamber.

Implementations may include one or more of the following features.

The plurality of conductors may be positioned between a dielectric top plate and the dielectric window. The dielectric top plate may be a ceramic body and the dielectric bottom plate may be quartz or silicon nitride.

A lower surface of the bottom plate may have a plurality of parallel grooves, and the plurality of parallel coplanar conductors may be positioned in the plurality of parallel grooves. A plurality of filaments may be positioned in the plurality of grooves. Each filament may include a conductor and a non-metallic shell surrounding the conductor. The shell may form a conduit and the conductor may be suspended in and extends through the conduit. The conductor may include a hollow conduit.

The plurality of conductors may be coated on the dielectric top plate. The plurality of conductors may be embedded in the dielectric top plate.

The plurality of conductors may be uniformly spaced apart. A spacing between the workpiece support and the plurality of conductors may be 2 mm to 50 cm.

The plurality of conductors may include a first multiplicity of conductors and a second multiplicity of conductors arranged in an alternating pattern with the first multiplicity of conductors. The RF power source may be configured to apply a first RF input signal to the first multiplicity of conductors, and to apply a second RF input signal to the second multiplicity of conductors. The RF power source may be configured to generate the first RF signal and the second RF signal with same frequency. The RF power source may be configured to generate the first RF signal and the second RF signal such that a phase difference between the first RF signal and the second RF signal is 180°. The RF power source may be configured to provide an adjustable phase difference between the first RF signal and the second RF signal.

The plurality of conductors may have a plurality of first ends at a first side of the plasma chamber and a plurality of second ends at an opposite second side of the plasma chamber. The RF power source may be configured to apply the first RF input signal to the first ends of the first multiplicity of conductors and to apply the second RF input signal to the second ends of the second multiplicity of conductors. The second ends of the first multiplicity of conductors may be floating and first ends of the second multiplicity of conductors may be floating. The first ends of the first multiplicity of conductors may be connected to a first common bus, and the second ends of the second multiplicity of conductors may be connected to a second common bus. The first multiplicity of filaments may be grounded and the first ends of the second multiplicity of filaments may be grounded.

The first ends of the first multiplicity of conductors may be connected to a first common bus located outside the plasma chamber on the first side of the chamber, and the second ends of the second multiplicity of conductors may be connected to a second common bus located outside the plasma chamber on the second side of the chamber. The second ends of the first multiplicity of conductors may be connected to a third common bus located outside the plasma chamber on the second side of the chamber, and the first ends of the second multiplicity of conductors may be connected to a fourth common bus located outside the plasma chamber on the first side of the chamber.

In another aspect, a plasma reactor includes a chamber body having an interior space that provides a plasma chamber, a gas distributor to deliver a processing gas to the plasma chamber, a pump coupled to the plasma chamber to evacuate the chamber, a workpiece

support to hold a workpiece, an intra-chamber electrode assembly comprising a plurality of filaments extending laterally through the plasma chamber between a ceiling of the plasma chamber and the workpiece support, each filament including a conductor surrounded by a cylindrical insulating shell, wherein the plurality of filaments includes a first multiplicity of filaments and a second multiplicity of filaments arranged in an alternating pattern with the first multiplicity of filaments, a first bus coupled to the first multiplicity of filaments and a second bus coupled to the second multiplicity of filaments, an RF power source to apply an RF signal the intra-chamber electrode assembly, and at least one RF switch configured to controllably electrically couple and decouple the first bus from one of i) ground, ii) the RF power source, or iii) the second bus.

Implementations may include one or more of the following features.

The at least one RF switch may include a plurality of RF switches connected in parallel between the first bus and the one of i) ground, ii) the RF power source, or iii) the second bus.

The at least one RF switch may be configured to controllably electrically couple and decouple the first bus from the second bus. The at least one RF switch may include a plurality of switches connected in parallel between different pairs of locations on the first bus and the second bus to controllably electrically couple and decouple the first bus from the second bus.

The at least one RF switch may include a first switch configured to controllably electrically couple and decouple the first bus from ground, and include at least one second RF switch configured to controllably electrically couple and decouple the second bus from ground. The at least one RF switch may include a first plurality of switches connected in parallel between different locations on the first bus and ground, and the at least one second switch may include a second plurality of switches connected in parallel between different locations on the second bus and ground. The different locations on the first bus may include opposing ends of the first bus and the different locations on the second bus may include opposing ends of the second bus.

The at least one RF switch may include a first plurality of switches connected in parallel between different locations on the first bus and the RF power source, and the at least one second switch may include a second plurality of switches connected in parallel between

different locations on the second bus and the RF power source. The different locations on the first bus may include opposing ends of the first bus and the different locations on the second bus may include opposing ends of the second bus. The at least one RF switch may include a first plurality of switches connected in parallel between different locations on the first bus and the RF power source, and the at least one second switch may include a second plurality of switches connected in parallel between different locations on the second bus and ground. The different locations on the first bus may include opposing ends of the first bus and the different locations on the second bus may include opposing ends of the second bus.

The at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from the RF power source, and includes at least one second switch configured to controllably electrically couple and decouple the second bus from the RF power source.

Some implementations may include a third bus coupled to the first multiplicity of filaments, and a fourth bus coupled to the second multiplicity of filaments, wherein the plurality of filaments have a plurality of first ends and a plurality of second ends and a first end of each respective filament is closer to a first sidewall of the plasma chamber than a second end of the respective filament, and wherein the first bus is coupled to the first ends of the first multiplicity of filaments, the second bus is coupled to the first ends of the second multiplicity of filaments, the third bus is coupled to the second ends of the first multiplicity of filaments, and the fourth bus is coupled to the second ends of the second multiplicity of filaments.

The at least one RF switch may be configured to controllably electrically couple and decouple the first bus from the second bus, and may include at least one second RF switch configured to controllably electrically couple and decouple the third bus from the fourth bus.

The at least one RF switch may include a first switch configured to controllably electrically couple and decouple the first bus from ground, and may include at least one second RF switch configured to controllably electrically couple and decouple the third bus from ground.

The RF source may be coupled by a first tap to the fourth bus and by a second tap to the second bus.

Some implementations may include at least one third RF switch configured to controllably electrically couple and decouple the third bus from ground, and include at least one fourth RF switch configured to controllably electrically couple and decouple the fourth bus from ground. The at least one RF switch may include a first switch configured to controllably electrically couple and decouple the first bus from ground, and include at least one second RF switch configured to controllably electrically couple and decouple the second bus from the RF source, at least one third RF switch configured to controllably electrically couple and decouple the third bus from ground, and include at least one fourth RF switch configured to controllably electrically couple and decouple the fourth bus from the RF source.

The at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from the RF source, and include at least one second RF switch configured to controllably electrically couple and decouple the second bus from the RF source, at least one third RF switch configured to controllably electrically couple and decouple the third bus from the RF source, and include at least one fourth RF switch configured to controllably electrically couple and decouple the fourth bus from the RF source.

In another aspect, a plasma reactor includes a chamber body having an interior space that provides a plasma chamber, a gas distributor to deliver a processing gas to the plasma chamber, a pump coupled to the plasma chamber to evacuate the chamber, a workpiece support to hold a workpiece, an intra-chamber electrode assembly comprising a plurality of filaments extending laterally through the plasma chamber between a ceiling of the plasma chamber and the workpiece support, each filament including a conductor surrounded by a cylindrical insulating shell, a bus outside the chamber and coupled to opposing ends of plurality of filaments, an RF power source to apply an RF signal the intra-chamber electrode assembly, and a plurality of RF switch configured to controllably electrically couple and decouple a plurality of different locations on bus from one of i) ground or ii) the RF power source.

Certain implementations may have one or more of the following advantages. Plasma uniformity may be improved. Plasma process repeatability may be improved. Metal contamination may be reduced. Particle generation may be reduced. Plasma charging damage

may be reduced. Uniformity of plasma may be maintained over different process operating conditions. Plasma power coupling efficiency may be improved. Plasma region size may be reduced for a given size of a workpiece. Plasma process throughput may be improved. The workpiece may be carried through multiple chambers in succession while remaining on a support. Effects of relative velocity during exposure to plasma may be compensated, and thus within-wafer uniformity may be improved. Effects of local non-uniformity of the plasma region may be reduced through switching, and thus within-wafer uniformity may be improved. Low impedance RF ground may be provided. Particle generation may be reduced. Plasma charging damage may be reduced. Uniformity of plasma may be maintained over different process operating conditions. Plasma power coupling efficiency may be improved. A grounded top electrode integrated with a gas distributing showerhead may be implemented for introducing gas in a uniform manner without undesirable gas breakdown in showerhead holes.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a schematic side view diagram of an example of a processing tool that includes a plasma chamber.

FIG. 2A is a schematic top view diagram of an example of a processing tool that includes a plasma chamber.

FIGS. 2B-2C are cross sectional side view diagrams of the processing tool of FIG. 2A along section lines B-B and C-C, respectively.

FIGS. 3A-3C are schematic cross-sectional perspective view diagrams of various examples of a filament of an intra-chamber electrode assembly.

FIG. 4A is a schematic top view diagram of a portion of an intra-chamber electrode assembly.

FIGS. 4B-C are cross-sectional schematic side view diagrams of an intra-chamber electrode assembly with different plasma region states.

FIGS. 5A-D are schematic top view diagrams of various examples of intra-chamber electrode assembly configurations.

FIG. 6A is a schematic top view diagram of an example of a processing tool.

FIG. 6B is a schematic top view diagram of an example of a wedge-shaped electrode assembly.

FIG. 6C is a schematic top view diagram of an example of a frame of a wedge-shaped electrode assembly.

FIG. 6D is a cross sectional side view diagram of an example of a frame of a wedge shaped electrode assembly.

FIG. 6E is a schematic top view diagram of an example of a wedge-shaped electrode assembly.

FIGS. 7A-7D are conceptual schematic diagrams of examples of electrical configurations of a wedge-shaped electrode assembly.

FIG. 8A is a schematic top view diagram of an example of an electrode assembly.

FIGS. 8B-8F are conceptual schematic diagrams of examples of electrical configurations of switched electrode assembly

FIGS. 9A-9B are conceptual schematic diagrams of examples of a mode-selectable switched electrode systems.

FIG. 10 is a conceptual schematic diagram of an example of a switched wedge-shaped electrode system.

FIG. 11A is a schematic diagram of an example of a PIN diode switch.

FIG. 11B is a schematic diagram of an example of a saturable inductor switch.

FIG. 12A is a schematic diagram of an example of a frequency-based switch.

FIGS. 12B-C are conceptual schematic diagrams of examples of electrical configurations of frequency-switched electrode systems.

FIG. 13 is a schematic side view of an example of a plasma reactor.

FIG. 14A is a schematic top view of another example of a plasma reactor.

FIGS. 14B and 14C are schematic side views of the plasma reactor of FIG. 14A along lines 14B-14B and 14C-14C, respectively.

FIGS. 15A-15C are schematic cross-sectional views of an electrode assembly.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

In a conventional plasma reactor, a workpiece remains stationary within the reactor chamber. A plasma region is generated above the stationary workpiece, which then treats the workpiece surface. However, some plasma processing applications can benefit from having
5 the workpiece move through a plasma region, i.e., a relative motion between the plasma region and the workpiece. In addition, for some tools the substrate is moved between different chambers for a sequence of processing steps.

One way of achieving relative motion between the workpiece and the plasma region is by placing the workpiece on a workpiece support that moves along a linear path, e.g., a
10 conveyor belt. In such a configuration, the workpiece may make a single pass in one direction through the plasma region and exit the other side of the chamber. This may be advantageous for some sequential processes in which workpiece travels through multiple chambers of different types as part of a fabrication process.

Another way of achieving relative motion between the workpiece and the plasma
15 region is by placing the workpiece on a rotating workpiece support. Rotating workpiece support enables multiple passes through the plasma region without changing the direction of travel, which can improve throughput as the workpiece support does not need to continuously change its direction of travel. However, if the support is rotating, then different regions of the workpiece may be moving at different velocities relative to the region plasma.

20 Plasma uniformity in a conventional CCP source is typically determined by electrode(s) size and inter-electrode distance, as well as by gas pressure, gas composition, and applied RF power. At higher radio frequencies, additional effects may become significant or even dominate non-uniformities due to the presence of standing waves or skin effects. Such additional effects becomes more pronounced at higher frequencies and plasma
25 densities.

Plasma uniformity in a conventional ICP source is typically determined by the configuration of ICP coil(s) including its size, geometry, distance to workpiece, and associated RF window location, as well as by gas pressure, gas composition, and power. In case of multiple coils or coil segments, the current or power distribution and their relative
30 phase, if driven at same frequency, might also be a significant factor. Power deposition tends to occur within several centimeters under or adjacent to ICP coils due to skin effect, and such

localized power deposition typically leads to process non-uniformities that reflect the coil geometries. Such plasma non-uniformity causes a potential difference across a workpiece, which can also lead to plasma charging damage (e.g., transistor gate dielectric rupture).

A large diffusion distance is typically needed for improved uniformity of ICP source. However, a conventional ICP source with a thick RF window is typically inefficient at high gas pressures due to low power coupling, which leads to high drive current resulting in high resistive power losses. In contrast, an intra-chamber electrode assembly does not need to have an RF window, but only a cylindrical shell. This can provide better power coupling and better efficiency.

In a plasma chamber with a moving workpiece support, the moving workpiece support may be DC grounded through, for example, a rotary mercury coupler, brushes, or slip rings. However, the moving workpiece support may not be adequately grounded at radio frequencies. The RF ground path should have substantially lower impedance than the plasma for it to be an adequate RF ground. The lack of an adequate RF ground path may make it difficult to control ion energy at the workpiece and reduce the repeatability of the process.

A plasma source with the following properties is thus desired: it can efficiently produce a uniform plasma with the desired properties (plasma density, electron temperature, ion energy, dissociation, etc.) over the workpiece size; it is tunable for uniformity over the operating window (e.g. pressure, power, gas composition); it has stable and repeatable electrical performance even with a moving workpiece; and it does not generate excessive metal contaminants or particles. An intra-chamber electrode assembly might be better able to provide one or more of these properties.

FIG. 1 is a schematic side view diagram of an example of a processing tool. A processing tool 100 has a chamber body 102 enclosing an interior space 104. The interior space 104 can be cylindrical, e.g., to contain a circular workpiece support. At least some of the interior space is used as a plasma chamber or a plasma reactor. The chamber body 102 has a support 106 for providing mechanical support for various components within the interior space 104. For example, the support 106 can provide support for a top electrode 108. The top electrode can be suspended within the interior space 104 and spaced from the ceiling, about the ceiling, or form a portion of the ceiling. Some portions of the side walls of the chamber body 102 can be grounded independent of the top electrode 108.

A gas distributor 110 is located near the ceiling of the plasma reactor portion of the processing tool 100. In some implementations, the gas distributor 110 is integrated with the top electrode 108 as a single component. The gas distributor 110 is connected to a gas supply 112. The gas supply 112 delivers one or more process gases to the gas distributor 110, the composition of which can depend on the process to be performed, e.g., deposition or etching.

A vacuum pump 113 is coupled to the interior space 104 to evacuate the processing tool. For some processes, the chamber is operated in the Torr range, and the gas distributor 110 supplies argon, nitrogen, oxygen and/or other gases.

A workpiece support 114 for supporting a workpiece 115 is positioned in the processing tool 100. The workpiece support 114 has a workpiece support surface 114a facing the ceiling of the processing tool 100. For example, the workpiece support surface 114a can face the top electrode 108. The workpiece support 114 is operable to rotate about an axis 150. For example, an actuator 152 can turn a drive shaft 154 to rotate the workpiece support 114. In some implementations, the axis 150 is coincident with the center of the workpiece support 114.

In some implementations, the workpiece support 114 includes a workpiece support electrode 116 inside the workpiece support 114. In some implementations, the workpiece support electrode 116 may be grounded or connected to an impedance or circuit which is grounded. In some implementations, an RF bias power generator 142 is coupled through an impedance match 144 to the workpiece support electrode 116. The workpiece support electrode 116 may additionally include an electrostatic chuck, and a workpiece bias voltage supply 118 may be connected to the workpiece support electrode 116. The RF bias power generator 142 may be used to generate plasma, control electrode voltage or electrode sheath voltage, or to control ion energy of the plasma.

Additionally, the workpiece support 114 can have internal passages 119 for heating or cooling the workpiece 115. In some implementations, an embedded resistive heater can be provided inside the internal passages 119.

In some implementations, the workpiece support 114 is heated through radiation, convection, or conduction from a heating element located within a bottom interior space 133.

An intra-chamber electrode assembly 120 is positioned in the interior space 104 between the top electrode 108 and the workpiece support 114. This electrode assembly 120

includes one or more coplanar filaments 300 that extend laterally in the chamber over the support surface 114a of the workpiece support 114. At least a portion of the coplanar filaments of the electrode assembly 120 over the workpiece support 114 extends parallel to the support surface 114a. Although the left side of FIG. 1 illustrates filaments 300 as parallel to the direction of motion of the workpiece 115 (into and out of the page), the filaments 300 can be at a non-zero angle relative to direction of motion, e.g., substantially perpendicular to direction of motion.

A top gap 130 is formed between the top electrode 108 and the intra-chamber electrode assembly 120. A bottom gap 132 is formed between the workpiece support 114 and the intra-chamber electrode assembly 120.

The interior space 104 can be segmented into one or more zones 101a, 101b by barriers, at least one of which serves as the plasma chamber. The barriers define one or more openings 123 above the workpiece support. In some implementations, the electrode assembly 120 is positioned inside the opening 123. In some implementations, the electrode assembly is placed above the opening 123. In some implementations, the barriers are integrally formed by the support 106, and the openings 123 are formed on the support 106. In some implementations, the opening 123 formed on the support 106 is configured to support the electrode assembly 120.

The electrode assembly 120 is driven by an RF power source 122. The RF power source 122 can apply power to the one or more coplanar filaments of the electrode assembly 120 at frequencies of 1 MHz to over 300 MHz. For some processes, the RF power source 120 provides a total RF power of 100W to more than 2kW at a frequency of 60 MHz.

In some implementations, it may be desirable to select the bottom gap 132 to cause plasma generated radicals, ions or electrons to interact with the workpiece surface. The selection of gap is application-dependent and operating regime dependent. For some applications wherein it is desired to deliver a radical flux (but very low ion/electron flux) to the workpiece surface, operation at larger gap and/or higher pressure may be selected. For other applications wherein it is desired to deliver a radical flux and substantial plasma ion/electron flux to the workpiece surface, operation at smaller gap and/or lower pressure may be selected. For example, in some low-temperature plasma-enhanced ALD processes, free radicals of process gases are necessary for the deposition or treatment of an ALD film. A

free radical is an atom or a molecule that has an unpaired valence electron. A free radical is typically highly chemically reactive towards other substances. The reaction of free radicals with other chemical species often plays an important role in film deposition. However, free radicals are typically short-lived due to their high chemical reactivity, and therefore cannot
5 be transported very far within their lifetime. Placing the source of free radicals, namely the intra-chamber electrode assembly 120 acting as a plasma source, close to the surface of the workpiece 115 can increase the supply of free radicals to the surface, improving the deposition process.

The lifetime of a free radical typically depends on the pressure of the surrounding
10 environment. Therefore, a height of the bottom gap 132 that provides satisfactory free radical concentration can change depending on the expected chamber pressure during operation. In some implementations, if the chamber is to be operated at a pressure in the range of 1 - 10 Torr, the bottom gap 132 is less than 1cm. In other low(er) temperature plasma-enhanced ALD processes, exposure to plasma ion flux (and accompanying electron flux) as well as
15 radical flux may be necessary for deposition and treatment of an ALD film. In some implementations, if the chamber is to be operated at a pressure in the range of 1 - 10 Torr, the bottom gap 132 is less than 0.5 cm. Lower operating pressures may operate at larger gaps due to lower volume recombination rate with respect to distance. In other applications, such as etching, lower operating pressure is typically used (less than 100 mTorr) and gap may be
20 increased.

In such applications where bottom gap 132 is small, the plasma generated by the electrode assembly 120 can have significant non-uniformities between the filaments, which may be detrimental to processing uniformity of the workpiece. By moving the workpiece through the plasma having spatial non-uniformities, the effect of the plasma spatial non-
25 uniformities on the process can be mitigated by a time-averaging effect, i.e., the cumulative plasma dose received by any given region of the workpiece after a single pass through the plasma is substantially similar.

The top gap may be selected large enough for plasma to develop between intra-chamber electrode assembly and top electrode (or top of chamber). In some implementations,
30 if the chamber is to be operated at a pressure in the range of 1 - 10 Torr, the top gap 130 may be between 0.5 – 2 cm, e.g., 1.25 cm.

The top electrode 108 can be configured in various ways. In some implementations, the top electrode is connected to an RF ground 140. In some implementations, the top electrode is electrically isolated ('floating'). In some implementations, the top electrode 108 is biased to a bias voltage. The bias voltage can be used to control characteristics of the generated plasma, including the ion energy. In some implementations, the top electrode 108 is driven with an RF signal. For example, driving the top electrode 108 with respect to the workpiece support electrode 116 that has been grounded can increase the plasma potential at the workpiece 115. The increased plasma potential can cause an increase in ion energy to a desired value.

The top electrode 108 can be formed of different process-compatible materials. Various criteria for process-compatibility include a material's resistance to etching by the process gasses and resistance to sputtering from ion bombardment. Furthermore, in cases where a material does get etched, a process-compatible material preferably forms a volatile, or gaseous, compound which can be evacuated by the vacuum pump 113, and not form particles that can contaminate the workpiece 115. Accordingly, in some implementations, the top electrode is made of silicon. In some implementations, the top electrode is made of silicon carbide.

In some implementations, the top electrode 108 may be omitted. In such implementations, RF ground paths may be provided by the workpiece support electrode, a subset of coplanar filaments of the electrode assembly 120, or by a chamber wall or other ground-referenced surfaces in communication with plasma.

In some implementations, a fluid supply 146 circulates a fluid through channels in the intra-chamber electrode assembly 120. In some implementations, a heat exchanger 148 is coupled to the fluid supply 146 to remove or supply heat to the fluid.

Depending on chamber configuration and supplied processing gasses, the plasma reactor in the processing tool 100 could provide an ALD apparatus, an etching apparatus, a plasma treatment apparatus, a plasma-enhanced chemical vapor deposition apparatus, a plasma doping apparatus, or a plasma surface cleaning apparatus.

FIG. 2A is a schematic top view diagram of an example of a processing tool 200. The processing tool 200 is similar to the processing tool 100 except as described. The processing tool 200 has a cylindrical chamber body 202, an interior space 204 having a cylindrical

shape, a support 206, electrode assemblies 220, and precursor stations 260. The support 206 is located at the center of the processing tool 200, and multiple radial partitions 270 are formed to partition the interior space 204 into multiple processing zones. For example, the multiple processing zones can be configured to have a shaped of a wedge, e.g., a circular section or an equilateral triangle, either possibly cut off at the apex. Processing zones can be configured in various ways to achieve various functions necessary for operation of the processing tool 200.

A precursor processing zone is configured to treat the workpiece 115 with one or more precursors, e.g., for an ALD process. For example, a first precursor station 260a positioned within a precursor processing zone 280a can be configured to flow or pump a chemical precursor A, treating the workpiece 115 as the workpiece 115 moves under the precursor station 260a. Then, the precursor station 260a can treat the workpiece 115 with a chemical precursor B, preparing the surface of the workpiece 115, e.g., for an ALD film-forming plasma treatment of the surface.

In some implementations, the precursor processing zone 280 includes multiple subzones having respective precursor station 260 for respective chemical precursors. In some implementations, the subzones are sequentially arranged along a path of the workpiece 115. In some implementations, the movement of workpiece 115 is halted during a precursor surface treatment. In some implementations, the workpiece 115 moves continuously through the precursor processing zone 280.

A gas isolation zone 281 is configured to provide spatial isolation of respective processing environments of multiple processing zones, e.g., a first processing zone and a second processing zone. The gas isolation zone 281 can include a first pumping zone 282, a purging zone 283, and a second pumping zone 284, each separated by a respective radial partitions 270. In a conventional system, the isolation of processing environments may be provided by a gas-tight seal between the first and second processing zones. However, due to the rotating workpiece support 114, providing such seal may not be practical. Instead, a level of isolation sufficient for plasma processing applications, e.g., ALD, can be provided by inserting the gas isolation zone 281 between the first and the second processing zones.

Referring to FIG. 2B, a cross sectional view of a portion of the processing tool 200 along a cross section line B is illustrated. During operation, the first pumping zone 282

adjacent to the first processing zone (e.g., precursor processing zone 280a) creates a negative pressure differential relative to the first processing zone. For example, the negative pressure differential can be generated using a vacuum pump. This negative pressure differential causes the process gasses leaking out of the first processing zone to be pumped out through
5 the first pumping zone 282, as indicated by an arrow. Similarly, the second pumping zone 284 adjacent to the second processing zone provides a negative pressure differential relative to the second processing zone (e.g., plasma treatment zone 285a).

The purging zone 283 positioned between the first pumping zone 282 and the second pumping zone 284 supplies a purging gas. Examples of the purging gas include non-reactive
10 gases such as argon and nitrogen. Due to the negative pressure differentials created by the first and second pumping zones, the purging gas supplied by the purging zone 283 is pumped into the first and second pumping zones, as indicated by the arrows. The presence of the purging gas can prevent the respective process gasses of the first and the second processing zones from mixing with one another, which may cause unwanted chemical reaction that
15 results in unwanted deposition, etching, or debris generation.

A first gap height H_1 provides clearance between the radial partitions 270 and the workpiece support 114. The first gap height can be determined based on providing sufficient clearance for the workpiece 115 to pass through, while reducing process gas leakage into the pumping zones 282 and 284. For example, the first gap height can range from 2 – 4 mm, e.g.,
20 3 mm.

Referring back to FIG. 2A, a plasma treatment zone 285 is configured to treat the workpiece 115 with plasma. For example, the electrode assembly 220a positioned within the plasma treatment zone 285a can generate plasma for treating the surface of the workpiece 115. The precursor-treated surface of the workpiece 115, which have moved through the gas
25 isolation zone 281, is treated with the plasma generated by the electrode assembly 220a. In some implementations, the plasma treatment completes a deposition cycle of a single atomic layer of a first ALD film.

In some implementations, the electrode assembly 220 is formed in a rectangular shape as shown. In some implementations, the electrode assembly 220 is formed in a wedge
30 shape.

Referring back to FIG. 2B, in some implementations, process gasses for the plasma treatment zone 285 is provided through gas inlets 210 formed adjacent to the electrode assembly 220. In particular, the gas inlet 210 can be provided at the edge of the gas isolation zone 281 adjacent the plasma processing region 285a. For example, a passage can be formed
5 between one of the partitions 270 and an outer wall 221 of the electrode assembly 220a.

A second gap height H_2 provides clearance between the electrode assembly 220 and the workpiece support 114. The second gap height can be determined based on providing sufficient clearance for the workpiece 115 to pass through and providing process gas to an interior region of the electrode assembly 220, while reducing process gas flow into the
10 pumping zones 282 and 284. For example, the second gap height can range from 1 – 3 mm, e.g., 2 mm. In some implementations, the gas inlet is formed on the ingress side of the workpiece 115. In some implementations, the gas inlet is formed towards the radial outer edge of the electrode assembly, near the chamber wall 202. In some implementations, the gas inlet is formed towards the center of the workpiece support 114, e.g., near the axis 150.

15 In some implementations, a top electrode 208 is formed as a part of or supported by the electrode assembly 220a. For example, the top electrode 208 can be supported by a ceiling plate 221a.

Referring to FIG. 2C, a cross sectional view of a portion of the processing tool 200 along a cross section line C is illustrated. In some implementations, the support 206 is
20 configured to provide mechanical support for the electrode assemblies 220a and 220b as shown.

In some implementations, the processing tool 200 includes a second precursor processing zone 280b and a second plasma treatment zone 285b. The zones 280b and 285b can be configured to deposit a second ALD film. In some implementations, the second ALD
25 film is the same as the first ALD film deposited by zones 280a and 285a. Such implementations may provide improved deposition speed of a single ALD film. In some implementations, the second ALD film is different from the first ALD. In such implementations, two different ALD films can be deposited in an alternating fashion. In general, the processing tool 200 can be configured to deposit 2, 3, 4, or more types of ALD
30 films.

In general, the workpiece 115 may make a single pass or may make multiple passes through the processing zones. For example, direction of rotation may be alternated to make multiple pass through a specific processing zone.

In general, processing zones can be arranged in any sequence. For example, a precursor processing zone can be followed by 2 different plasma treatment zones having same or different plasma characteristics.

With respect to either FIG. 1 or FIGS. 2A-2C, the electrode assembly 120 or 220 includes one or more coplanar filaments 300 that extend laterally in the chamber over the support surface of the workpiece support. At least a portion of the coplanar filaments of the electrode assembly over the workpiece support extends parallel to the support surface. The filaments 300 can be at a non-zero angle relative to direction of motion, e.g., substantially perpendicular to direction of motion.

The electrode assembly can include side walls 221 that surround the electrode plasma chamber region. The side walls can be formed of a process-compatible material, e.g., quartz. In some implementations, the filaments project laterally out the side walls. In some implementations, the ends of the filaments 300 extend out of the ceiling of the electrode assembly and turn to provide the portion that is parallel to the support surface for the workpiece (see FIG. 2C).

FIGS. 3A-C are schematic diagrams of various examples of a filament of an intra-chamber electrode assembly. Referring to FIG. 3A, a filament 300 of the intra-chamber electrode assembly 120 is shown. The filament 300 includes a conductor 310 and a cylindrical shell 320 that surrounds and extends along the conductor 310. A channel 330 is formed by the gap between the conductor 310 and the cylindrical shell 320. The cylindrical shell 320 is formed of a non-metallic material that is compatible with the process. In some implementations, the cylindrical shell is semiconductive. In some implementations, the cylindrical shell is insulative.

The conductor 310 can be formed of various materials. In some implementations, the conductor 310 is a solid wire, e.g., a single solid wire with a diameter of 0.063".

Alternatively, the conductor 310 can be provided by multiple stranded wires. In some implementations, the conductor contains 3 parallel 0.032" stranded wires. Multiple stranded

wires can reduce RF power losses through skin effect. In some implementations, the conductor 310 is formed from Litz wires, which can further reduce skin effect.

A material with high electrical conductivity, e.g., above 10^7 Siemen/m, is used, which can reduce resistive power losses. In some implementations, the conductor 310 is made of
5 copper or an alloy of copper. In some implementations, the conductor is made of aluminum.

Undesired material sputtering or etching can lead to process contamination or particle formation. Whether the intra chamber electrode assembly 120 is used as a CCP or an ICP source, undesired sputtering or etching can occur. The undesired sputtering or etching may be caused by excessive ion energy at the electrode surface. When operating as a CCP source,
10 an oscillating electric field around the cylindrical shell is necessary to drive the plasma discharge. This oscillation leads to sputtering or etching of materials, as all known materials have a sputtering energy threshold that is lower than the corresponding minimum operating voltage of a CCP source. When operated as an ICP source, capacitive coupling of the filament 300 to the plasma creates an oscillating electric field at nearby surfaces, which also
15 causes sputtering of materials. The problems resulting from undesired material sputtering or etching may be mitigated by using a process-compatible material for the outer surface of the filament 300 exposed to the interior space 104 (e.g., the cylindrical shell 320).

In some implementations, the cylindrical shell 320 is formed of a process-compatible material such as silicon, e.g., a high resistivity silicon, an oxide material, a nitride material, a
20 carbide material, a ceramic material, or a combination thereof. Examples of oxide materials include silicon dioxide (e.g., silica, quartz) and aluminum oxide (e.g., sapphire). Examples of carbide materials include silicon carbide. Ceramic materials or sapphire may be desirable for some chemical environments including fluorine-containing environments or fluorocarbon containing environments. In chemical environments containing ammonia, dichlorosilane,
25 nitrogen, and oxygen, use of silicon, silicon carbide, or quartz may be desirable.

In some implementations, the cylindrical shell 320 has a thickness of 0.1 mm to 3 mm, e.g., 2 mm.

In some implementations, a fluid is provided in the channel 330. In some implementations, the fluid is a non-oxidizing gas to purge oxygen to mitigate oxidization of
30 the conductor 310. Examples of non-oxidizing gases are nitrogen and argon. In some

implementations, the non-oxidizing gas is continuously flowed through the channel 330, e.g., by the fluid supply 146, to remove residual oxygen or water vapor.

The heating of conductor 310 can make the conductor more susceptible to oxidization. The fluid can provide cooling to the conductor 310, which may heat up from supplied RF power. In some implementations, the fluid is circulated through the channel 330, e.g., by the fluid supply 146, to provide forced convection temperature control, e.g., cooling or heating.

In some implementations, the fluid may be near or above atmospheric pressure to prevent breakdown of the fluid. For example, gas breakdown or unwanted plasma formation in the tube may be prevented by providing fluid pressure above 100 Torr.

Referring to FIG. 3B, in some implementations of the filament 300, the conductor 310 has a coating 320. In some implementations, the coating 320 is an oxide of the material forming the conductor (e.g., aluminum oxide on an aluminum conductor). In some implementations, the coating 320 is silicon dioxide. In some implementations, the coating 320 is formed in-situ in the plasma reactor of the processing tool 100 by, for example, a reaction of silane, hydrogen, and oxygen to form a silicon dioxide coating. In-situ coating may be beneficial as it can be replenished when etched or sputtered. In-situ coating can have a range of thicknesses, ranging from 100 nm to 10 μ m.

Referring to FIG. 3C, in some implementations of the filament 300, the conductor 310 is hollow, and a hollow channel 340 is formed inside the conductor 310. In some implementations, the hollow channel 340 can carry a fluid as described in FIG. 3A. A coating of the process-compatible material can cover the conductor 310 to provide the cylindrical shell 320. In some implementations, the coating 320 is an oxide of the material forming the conductor (e.g., aluminum oxide on an aluminum conductor). In some implementations, the hollow conductor 310 has an outer diameter of 2 mm, with a wall thickness of 0.5 mm.

FIG. 4A is a schematic diagram of a portion of an intra-chamber electrode assembly. An intra-chamber electrode assembly 400 includes multiple coplanar filaments 300 attached at a support 402. An electrode array is formed by the multiple coplanar filaments 300. The electrode assembly 400 can provide the electrode assembly 120. In some implementations, at

least over the region corresponding to where the workpiece is processed, the filaments 300 extend in parallel to each other.

The filaments 300 are separated from one another by a filament spacing 410. The spacing 410 can impact plasma uniformity. If the spacing is too large, then the filaments can create shadowing and non-uniformity. On the other hand, if the spacing is too small, the plasma cannot migrate between the top gap 130 and the bottom gap 132, and non-uniformity will be increased or free radical density will be reduced.

In general, a desired value for filament spacing 410 is dependent on several factors. Examples of such factors include chamber pressure, RF power, distance between the filament 300 to the workpiece 115, and process gas composition. For example, when operating at lower pressure, e.g., below 2 Torr, and with large distance between the filament and the workpiece, e.g., greater than 3 mm, the filament spacing 410 may be increased.

In some implementations, the filament spacing 410 is uniform across the assembly 400. The filament spacing 410 can range from 3 mm to 20 mm, e.g., 8 mm.

FIGS. 4B-C are cross-sectional schematic diagrams of an intra-chamber electrode assembly with different plasma region states. Referring to FIG. 4B, in some operating conditions, a plasma region 412 surrounds the filaments 300. Examples of such operating conditions can include all filaments being driven with the same RF signal (i.e., “monopolar”), with a grounded top electrode. The plasma region 412 has an upper plasma region 414 and a lower plasma region 416. The upper plasma region 414 can be located at the top gap 130 and the lower plasma region 416 can be located at the bottom gap 132. As shown in FIG. 4B, the upper plasma region 414 and the lower plasma region 416 is connected through the gaps between the filaments 300, forming a continuous plasma region 412. This continuity of the plasma regions 412 is desirable, as the regions 414 and 416 ‘communicate’ with each other through exchange of plasma. The exchanging of plasma helps keep the two regions electrically balanced, aiding plasma stability and repeatability.

Referring to FIG. 4C, in this state, the upper plasma region 414 and the lower plasma region 416 are not connected to each other. This ‘pinching’ of the plasma region 412 is not desirable for plasma stability. The shape of the plasma region 412 can be modified by various factors to remove the plasma region discontinuity or improve plasma uniformity.

In general, the regions 412, 414, and 416 can have a wide range of plasma densities, and are not necessarily uniform. Furthermore, the discontinuities between the upper plasma region 414 and the lower plasma region 416 shown in FIG. 4C represents a substantially low plasma density relative to the two regions, and not necessarily a complete lack of plasma in the gaps.

In some operating conditions, e.g., top electrode is absent or floating, and the workpiece support electrode is grounded, plasma region 414 may not be formed, or have low plasma density.

In some implementations, the intra-chamber electrode assembly 400 can include a first group and a second group of filaments 300. The first group and the second group can be spatially arranged such that the filaments alternate between the first group and the second group. For example, the first group can include the filament 302, the second group can include the filaments 300 and 304. The first group can be driven by a first terminal 422a of an RF power supply 422 and the second group can be driven by a second terminal 422b of the RF power supply 422. The RF power supply 422 can be configured to provide a first RF signal at the terminal 422a and a second RF signal at terminal 422b. The first and second RF signals can have a same frequency and a stable phase relationship to each other. For example, the phase difference between the first and second RF signals can be 0 or 180 degrees. In some implementations, the phase relationship between the first and the second RF signals provided by the RF power supply 422 can be tunable between 0 and 360. In some implementations, the RF supply 422 can include two individual RF power supplies that are phase-locked to each other.

In some operating conditions, e.g., when the phase difference between the first and second RF signals is 180, the resulting plasma region may be concentrated between the filaments.

The top gap 130 is a factor affecting the shape of the plasma region. When the top electrode 108 is grounded, reducing the top gap 130 typically leads to a reduction of plasma density in the upper plasma region 414. Specific values for the top gap 130 can be determined based on computer modelling of the plasma chamber. For example, the top gap 130 can be 3 mm to 8 mm, e.g., 4.5 mm.

The bottom gap 132 is a factor affecting the shape of the plasma region. When the workpiece support electrode 116 is grounded, reducing the bottom gap 132 typically leads to a reduction of plasma density in the lower plasma region 416. Specific values for the bottom gap 132 can be determined based on computer modelling of the plasma chamber. For
5 example, the bottom gap 132 can be 3 mm to 9 mm, e.g., 4.5 mm.

In general, the chamber pressure is a factor affecting the shape of the plasma region.

FIGS. 5A and 5B are schematic diagrams of various examples of intra-chamber electrode assembly configurations. Referring to FIGS. 5A and 5B, in some implementations the electrode assembly 106 can include a first group of conductors 120a and a second group
10 of conductors 120b. At least within the plasma chamber 104, the conductors 120a, 120b of the first group and the second group can be arranged in an alternating pattern. The first group can be driven by a first terminal 122a of the RF power supply 122, and the second group can be driven by a second terminal 122b of the RF power supply 122. The RF power supply 122 can be configured to provide a first RF signal at the terminal 122a and a second
15 RF signal at terminal 122b. The first and second RF signals can have a same frequency and a stable phase relationship to each other. For example, the phase difference between the first and second RF signals can be 180 degrees. By driving the conductors 120a, 120b with RF signals that have 180 degrees of phase difference, the resulting plasma distribution can be less sensitive to imperfect RF grounding of the electrode 116. Without being limited to any
20 particular theory, this can be because the RF current is returned through the adjacent electrodes due to the differential nature of the driving signals. In some implementations, the phase relationship between the first and the second RF signals provided by the RF power supply 122 can be tunable between 0 and 360.

To generate the signals, an unbalanced output signal from an oscillator of the RF
25 power supply can be coupled to a balun (a balance-unbalance transformer) 124 that outputs balanced signals on the terminals 122a, 122b. Alternatively, the RF supply 122 can include two individual RF power supplies that are phase-locked to each other.

Referring to FIG. 5A, the electrode assembly 120 includes a first electrode subassembly 510 that includes the first group of conductors 120a, and a second electrode
30 subassembly 520 that includes the second group of conductors 120b. The conductors 120a of

the first electrode subassembly 510 are interdigitated with the conductors 120b of the second electrode subassembly 520.

The subassemblies 510, 520 each has multiple parallel conductors 120a, 120b that extend across the chamber 104. Every other electrode 120, e.g., the electrodes 120a, is
5 connected to a first bus 530 on one side of the chamber 104. The remaining (alternating) electrodes 120, i.e., the electrodes 120b, are each connected to a second bus 540 on the other side of the chamber 104. The end of each conductor 120 that is not connected to an RF power supply bus can be left unconnected, e.g., floating.

The first bus 530 can be connected to the first terminal 122a, and the second bus can
10 be connected to the second terminal 122b. The first electrode subassembly 510 and the second electrode subassembly 520 are oriented parallel to each other such that the conductors of the subassemblies 510 and 520 are parallel to each other.

In some implementations, the buses 530, 540 connecting the conductors 120a, 120b are located outside of the interior space 104. This is preferable for improved uniformity
15 within the chamber 104. However, in some implementations, the buses 530, 540 connecting the conductors 120a, 120b are located in the interior space 104.

FIG. 5B illustrates an electrode assembly 106 that is similar to the implementation shown in FIG. 5A, but the end of each conductor 120 that is not connected to an RF power supply bus can be grounded, e.g., connected to a bus that is grounded. For example, the
20 electrodes 120a can be connected to a third bus 550 on the side of the chamber 104 as the second bus 550, and the electrodes 120b can be connected to a fourth bus 560 on the same side of the chamber 104 as the first bus 530. Each bus 550, 560 can be grounded through an adjustable impedance 580, e.g., an impedance matching network.

For either FIG. 5A or FIG. 5B, optionally a low frequency common mode bias can be
25 applied between the electrode subassemblies 510, 520. This can controllably increase the plasma potential.

FIG. 5C illustrates an intra-chamber electrode assembly 106 that includes a first electrode subassembly 522 and a second electrode subassembly 532 configured such that the filaments of the subassemblies 522 and 532 extend at a non-zero angle, e.g., perpendicular, to
30 each other.

The intra-chamber electrode assembly 106 can be driven with RF signals in various ways. In some implementations, the subassembly 522 and subassembly 532 are driven with a same RF signal with respect to an RF ground. In some implementations, the subassembly 522 and subassembly 532 are driven with a differential RF signal. In some implementations, the subassembly 522 is driven with an RF signal, and subassembly 532 is connected to an RF ground.

FIG. 5D illustrates an intra-chamber electrode assembly 106 that includes a first electrode subassembly 524 and a second electrode subassembly 534 that are overlaid. The first electrode subassembly 524 and the second electrode subassembly 534 each have multiple parallel filaments 300 that are connected by buses 530, 540, 550 and 560 at respective ends of respective busses. The first electrode subassembly 524 and the second electrode subassembly 534 are configured such that the filaments of the subassemblies 524 and 534 are parallel to each other, with the filaments of the subassemblies 524, 534 arranged in alternating pattern.

The intra-chamber electrode assembly 106 can be driven with RF signals in various ways. In some implementations, the subassembly 524 and subassembly 534 are driven with a same RF signal with respect to an RF ground. In some implementations, the subassembly 524 and subassembly 534 are driven with a differential RF signal. In some implementations, the subassembly 524 is driven with an RF signal, and the subassembly 534 is connected to an RF ground.

In some implementations, the intra-chamber electrode assembly 106 is driven in a single-ended manner with an RF signal using a center-feed 590. The center-feed 590 is connected to an X-shaped current splitter 592 at the center. The four corners of the subassemblies 524 and 534 are connected to the X-shaped current splitter 592 using vertical feed structures.

In general, differential driving of the subassemblies 510, 522, 524 and the respective subassemblies 520, 532, 534 can improve plasma uniformity or process repeatability when an adequate RF ground cannot be provided (e.g., RF ground through a rotary mercury coupler, brushes, or slip rings).

FIG. 6A is a schematic top view diagram of the interior region of an example of the processing tool 650. In a processing tool 650, the workpiece support 114 is rotating about the

axis 150, and the rotation of the workpiece support 114 causes the workpiece 115 to move under an electrode assembly 600, through the plasma region generated by the electrode assembly 600. The processing tool 650 is similar to the processing tool 200, and the electrode assembly 600 is similar to the electrode assembly 400, except as described.

5 When the workpiece 115 rotates through the plasma region around the axis 150, velocities experienced by different surface regions of the workpiece varies as a function of their radial distance from the axis 150. For example, a regions of the workpiece further away from the axis 150 moves faster than a region closer to the axis 150. For a rectangular or linear plasma region, the regions of the workpiece that are further away from the axis 150
10 experiences a correspondingly shorter dwell time in the plasma region. This radial non-uniformity in dwell time leads to a non-uniformity in received plasma dose across the workpiece, resulting in undesirable process non-uniformities.

 One method of compensating for the foregoing dwell time non-uniformity is to vary the local density of the plasma region in proportion to the local velocity of the wafer. For
15 example, the local plasma density can be increased in proportion to the radial distance from the axis 150. By increasing the plasma density at the regions of higher local velocity, those regions receive an equal dose of plasma integrated over their respective shorter dwell times. However, spatial non-uniformity in plasma density can lead to non-uniform charging of the workpiece surface, generating an electric potential difference across the workpiece surface.
20 Depending on the die size and device sensitivity, sufficiently large electric potential difference across the surface (e.g., greater than 2 volts, 5 volts, 10 volts, 15 volts, 25 volts) can lead to damages to devices being fabricated on the workpiece, e.g., dielectric breakdown of thin transistor gate dielectric layer.

 Another way of compensating for the dwell time non-uniformity is by modifying the
25 geometry of the plasma region. The plasma region geometry can be modified such that regions of higher local velocity travel through correspondingly longer sections of the plasma region to equalize dwell times of different regions of the workpiece surface. For the configuration shown in FIG. 6A, dwell time equalization can be achieved with a wedge-shaped plasma region. In such a configuration, the radial increase in local velocity by moving
30 away from the axis 150 can be canceled out by a proportional increase in the arc length of the wedge-shaped plasma region over the respective regions.

The foregoing wedge-shaped plasma region can be formed by configuring the coplanar filaments of the electrode assembly 600 and an opening 627 in various ways. One way is to configure an electrode array formed by the filaments of the electrode assembly 600 in the shaped of a wedge. For example, the respective lengths of the individual coplanar
5 filaments of the electrode array can be modified so that an overall contour of the electrode array defines a wedge. In some implementations, the support 206 can provide support at the respective two ends of the coplanar filaments of the electrode array.

Another way to form the wedge-shaped plasma region is by forming the opening 627 to have the wedge shape and forming a plasma region larger than the size of the opening 627
10 using the electrode array of the electrode assembly 600 that is larger than the opening 627 (e.g., electrode assembly 400). Then, portions of the generated plasma region can be blocked by the wedge-shaped opening to generate the wedge-shaped plasma region. For example, the support 206 can provide the wedge-shaped opening 627.

In general, various factors can affect the sizing of the wedge-shaped plasma region. In
15 some applications, partial or incomplete plasma coverage over the surface of the workpiece can lead to detrimental results. For example, workpiece 115 can contain devices sensitive to charging damage, e.g., transistors with thin gate dielectric layer. In such cases, the electric potential developed between a region of workpiece 115 exposed to the plasma and a region unexposed to the plasma can lead to dielectric breakdown of the gate dielectric layers,
20 resulting in permanent damage of the sensitive devices. Such problem can be mitigated by sizing the plasma region to be larger than the workpiece to achieve complete plasma coverage over the entire workpiece surface. In some implementations, the plasma region is sized to enable movement of the workpiece through the plasma region while maintaining complete plasma coverage.

In some implementations, e.g., with the plasma region larger than the workpiece, the
25 timing of the application of RF power to the electrode assembly 600 can be coordinated with the movement of the workpiece 115 to ensure that the entire surface of the workpiece experience is uniformly exposed to the plasma. For example, the plasma can be generated (ignited) after the entire workpiece moves under the opening 627 or the electrode assembly
30 600, and turned off (extinguished) before the workpiece leaves the plasma region. In this case, the plasma region need not be wedge-shaped.

In some cases, however, creating a large plasma region (e.g., larger than 300 mm x 300 mm) using the electrode assembly 600 can be challenging. If the workpiece to be processed can withstand an incomplete plasma coverage over its surface, the plasma region can be sized to be smaller than the workpiece surface in one direction of the workpiece. For example, as shown in FIG. 6A, the wedge-shaped electrode assembly 600 (and hence the plasma region) is smaller than the workpiece diameter in the direction of travel of the workpiece 115, but is larger than the workpiece diameter along the radial direction with respect to the axis 150 to achieve complete coverage in the radial direction.

Other considerations for sizing of the plasma region include workpiece movement speed, target processing rate, and target plasma exposure time to achieve desired process duration or throughput.

In some implementations, the plasma can be coordinated with the movement of the workpiece to ensure that a stable plasma is established before the workpiece enters the plasma region. For example, in processes requiring relatively short plasma exposure time, the time spent in striking on of the plasma can be a significant portion of the entire plasma exposure time. Because the plasma is relatively unstable during the striking phase, the resulting process repeatability may suffer. By establishing a stable plasma before introducing the workpiece, the plasma exposure time and dose can be precisely controlled by controlling the speed of the workpiece as it moves through the plasma region. For such implementations, regardless of whether the plasma region is larger or smaller than the workpiece, it is advantageous for the plasma region to be wedge-shaped to compensate for differences in exposure time. In some implementations, the generated plasma is maintained over processing of multiple workpieces.

Given the processing tool 650 having a fixed plasma region size, various process parameters can be controlled to achieve desired plasma processing characteristics. Examples of the process parameters that can be controlled include processing rate, exposure time, workpiece movement speed profile, number of plasma exposure passes, and total plasma exposure dose. For example, the workpiece may make multiple passes through the plasma region, or may oscillate in position within the plasma region.

FIG. 6B is a schematic top view diagram of an example of a wedge-shaped electrode assembly for generating a wedge-shaped plasma region. A wedge-shaped electrode assembly

600 has multiple coplanar filaments 610 and a frame 620. The electrode assembly 600 is similar to the electrode assembly 120, 220 and 400, except as described. The frame 620 has a first end 602, a second end 604, a central angle θ_{ca} , an inner radius R_1 , an outer radius R_2 , and a bisector 605. The first end 602 is the short end of the electrode assembly 600, sometimes called an apex. The second end 604 is the longer end of the electrode assembly 600, sometime called a base. The multiple coplanar filaments 610 are similar to the filaments 300, except as described. Each coplanar filament 610 has a respective length L , respective angle θ (theta) with respect to the bisector 605. Length L is defined to be a linear portion of the coplanar filaments 610 in a region parallel and adjacent to the workpiece support surface, e.g., 114a. Each adjacent pair of coplanar filaments 610 are separated by respective separations S , defined as the center-to-center distance between the adjacent filaments. For non-parallel filaments, the separation S is defined as the smallest center-to-center spacing along the lengths of the adjacent filament pair.

There are various considerations for determining angle theta of the filaments 610. One consideration for determining the angle theta is the trajectory of workpiece 115 as it moves under the electrode assembly 600. In some situations, the plasma generated by the electrode assembly 600 can have non-uniformities in plasma that extend along the direction of the filaments 610. For example, an elongated region of reduced plasma density may exist between a pair of filaments 610 in certain operating conditions. If a point on the surface of the workpiece travels along such region of reduced plasma density, the point will receive reduced plasma exposure dose, resulting in process non-uniformity. By arranging the filaments to have an appropriate value of theta (e.g., smaller or larger than 90° , excluding 90°), such tangential travel along regions of reduced plasma density can be reduced, improving process uniformity. For example, by setting the theta to 60° , points on the surface of the workpiece pass under multiple filaments, being exposed to local plasma regions having reduced density as well as nominal density along the way, resulting in time-averaging of the plasma exposure dose. In some implementations, the respective theta of the multiple coplanar filaments 610 are equal, i.e., the filaments are parallel.

In some implementations, the respective theta of the filaments 610 are different based on their respective locations within the electrode assembly 600. For example, the respective theta monotonically increases for filaments near the apex 602 to filaments near the base 604

of the assembly 600 to maintain equal lengths of the filaments 610 across the electrode assembly 600. Having filaments of equal lengths may improve uniformity when the assembly 600 is operated as an ICP source.

In general, the number of coplanar filaments 610 is determined by the size of the plasma region, the theta, and the separation S to achieve desired plasma region characteristics, e.g., plasma density, uniformity.

In general, the separation S can be determined based on considerations discussed in FIG. 4 regarding the filament spacing 410.

The frame 620 defines the shapes of electrode assembly 600 and the shape of the plasma region formed by the electrode assembly 600. The inner radius, the outer radius and the central angle determines the size of the wedge-shaped electrode, which in turn defines the size of the plasma region. The size of the frame can be determined based on foregoing discussion of plasma region sizing in relation to FIG. 6B.

The frame 620 can be formed of different process-compatible materials. Suitable process-compatible materials include those described in relation to cylindrical shell 320 e.g., quartz. Other examples of process-compatible materials include ceramics (e.g., Aluminum Oxide, Aluminum Nitride), and various nitrides of silicon (e.g., SiN, Si₃N₄).

While frame 620 has been described in relation to the wedge-shaped electrode assembly 600, the filaments 610 can be formed and arranged to have the described wedge shape without the frame 620 to achieve similar results.

An example of the wedge-shaped electrode assembly has the following design properties: $R_1 = 91$ mm, $R_2 = 427$ mm, central angle = 31° , theta = 60° , filament center-to-center separation = 15 mm, number of filaments = 20, frame material = quartz.

Referring to FIG. 6C, in some implementations, the frame 620 has a cutout 622. The cutout 622 can be shaped to fit a wedge-shaped top electrode 624. The wedge-shaped top electrode 624 can be grounded or biased to a bias voltage. The wedge-shaped top electrode 624 can be formed of various process compatible materials, e.g., silicon. In some implementations, the wedge-shaped electrode is shaped to be inserted into the cutout 622 to fill the cutout 622.

Referring to FIG. 6D, a cross sectional view of a portion of the frame 620 along a cross section line A is illustrated. In some implementations, the frame has an upper portion 625, an inner sidewall 626, and an opening 627.

In general, the respective lengths L of the multiple coplanar filaments 610 are set to generate a plasma region of desired shape. The frame 620 can be shaped to provide support to the coplanar filaments 610. In some implementations, the ends of the coplanar filaments 610 are supported by the inner sidewall 626 of the frame 620, similar to the configuration shown in FIG. 6B. In some implementations, the ends of the coplanar filaments 610 are bent (e.g. 90°) to be supported by the upper portion 625 of the frame 620, as shown in the electrode assembly 220a of FIG. 2B. In some implementations, the opening 627 of the frame 620 can determine the shape of the plasma region.

In some implementations, the theta is close to 0, e.g., $< 20^\circ$. Referring to FIG. 6E, the assembly 601 has two filaments, and the filaments are arranged with $\theta = 0^\circ$, i.e., the filaments are parallel to the bisector 605. The frame 620 of the assembly 601 has the cutout 622, and the wedge-shaped electrode 624. The wedge-shaped electrode 624 can be grounded. In such a configuration, the shape of the plasma region generated by the electrode assembly 601 is affected by the interaction between the filaments 610 and the wedge-shaped electrode 624, resulting in a wedge-shaped plasma region. In configuration where theta is close to 0° , the effects of plasma non-uniformity parallel to the filament 610 can be reduced as the direction of travel of the workpiece 115 is substantially close to 90° with respect to the orientation of the filaments 610.

FIGS. 7A-7D are conceptual schematic diagrams of various electrical configurations of a wedge-shaped electrode assembly. The filaments of the electrode assembly can be electrically connected in various different configurations. Referring to FIG. 7A, an electrode assembly 700 similar to the electrode assembly 600, and has a first bus 730 and a second bus 740. The first bus 730 and the second bus 740 can be located on opposite sides of the chamber body 102, e.g., outside the chamber.

The first bus 730 has a first end 750 and a second end 751 opposite to the first end 750. The first bus 730 and the second bus 740 are electrically connected to the respective opposite ends of each filament 710 of the electrode assembly 700. The filament 710 is similar

to the filament 300, except as described. The electrode assembly 700 can be driven in various ways using one or more RF power sources.

In some implementations, a first RF power source drives the first bus 730, and the second bus 740 is connected to an RF ground. In such a configuration, RF current flows
5 across the filaments 710, and the electrode assembly may work as a predominantly ICP plasma source.

In some implementations, the first RF power source drives the first bus 730, and the second bus 740 is electrically floating. In such a configuration, the electrode assembly may work as a predominantly CCP plasma source. The RF current return path may be provided by
10 the chamber body 102, top electrode 108, the wedge-shaped top electrode 624, or by the workpiece support electrode 116.

In some implementations, the first RF power source drives the first bus 730 at the first end 750, a second RF power source drives the first bus 730 at the second end 751, and the second bus 740 is connected to an RF ground. In such a configuration, the electrode
15 assembly may work as a predominantly ICP plasma source.

In some implementations, the first RF power source drives the first bus 730, and the second RF power source drives the second bus 740.

In general, a RF driving point at which the RF power source connects to a bus is selected to optimized uniformity of the resulting plasma. For example, the driving point
20 location can be selected based on minimizing non-uniformity in RF signal amplitude experienced by individual filaments 710.

In some implementations, the intra-chamber electrode assembly can include a first group and a second group of coplanar filaments. The filaments of the first group and the second group can be arranged in an alternating pattern along the direction perpendicular to
25 their longitudinal axis. As such, that the coplanar filaments alternate between the first group and the second group.

Referring to FIG. 7B, an electrode assembly 702 similar to the electrode assembly 600 has a first group can include the coplanar filaments 710 and 714, and a second group that include the coplanar filaments 712. The first group is electrically connected to a first bus 732,
30 and the second group is electrically connected to a second bus 742. An end of each filament farther from the bus to which it is connected can be “floating” or grounded. If the ends of the

filaments are floating, the two groups of filaments can be considered to form an interdigitated array.

The first bus 732 can have a first end 752 and a second end 753 opposite to the first end 752. In some implementations, the first RF power source drives the first bus 732 with a first RF signal, and the second RF power source drives the second bus 742 with a second RF signal. The first and second RF signals may have the same frequency and a stable phase relationship to each other. For example, the phase difference between the first RF signal and the second RF signal can be 0 degrees or 180 degrees. In some implementations, the phase relationship between the first and the second RF signals provided by the RF power supply 422 can be tunable between 0 and 360. In some implementations, the RF supply 422 can include two individual RF power supplies 422a and 422b that are phase-locked to each other.

In some implementations, the first RF power source drives the first bus 732, and the second bus 742 is connected to an RF ground. In such cases, the second bus 742 and the even group of filaments connected to the second bus 742 can serve as an RF current return path.

In some implementations, the first RF power source drives the first bus 732 at the first end 752, and a second RF power source drives the first bus 732 at the second end 753, and the second bus 742 is connected to an RF ground.

In some implementations, the first RF power source drives the first bus 732, and the second RF power source drives the second bus 742. In such cases, the electrode assembly 702 may work as a predominantly CCP plasma source. The RF current return path may be provided by the chamber body 102, the top electrode 108, the wedge-shaped top electrode 624, or by the workpiece support electrode 116.

Referring to FIG. 7C, an electrode assembly 704 similar to the electrode assembly 600 has a single bus 734. The bus 734 is electrically connected to the both ends of the filaments 710.

In some implementations, the first RF power source drives the first bus 734. The first bus 734 can have a first end 754 and a second end 755, and in some implementations, the first RF power source drives the first bus 734 at the first end 754, and the second RF power source drives the first bus 734 at the second end 755. In such a configuration, the electrode assembly may work as a predominantly CCP plasma source. The RF current return path may

be provided by the chamber body 102, the top electrode 108, the wedge-shaped top electrode 624, or by the workpiece support electrode 116.

Referring to FIG. 7D, an electrode assembly 706 similar to the electrode assembly 600 has a first bus 736 and a second bus 746. The first bus 736 and the second bus 746 are electrically connected to the respective opposite ends of filaments 710 of the electrode assembly 706. The first RF power source drives the first bus 736 at a driving point 756. The second bus 746 can be connected to an RF ground.

The first RF signal generated by the first RF power source may be attenuated by various sources of RF loss. For example, an RF transmission line that forms the bus 736 is lossy due to finite electrical conductivity of the conductor, or dielectric loss tangent due to a dielectric material forming the transmission line. As another example, the plasma loading of the RF transmission line affects RF losses. Therefore, filaments 710 connected at different locations along the direction of propagation of the RF signal may experience different RF signal amplitude. For example, referring to FIG. 7A, an RF signal launched at the first end 750 will be attenuated as it propagates down the length of the first bus 730. As a result, the RF signal amplitude at the filaments 710 near the second end 751 will be smaller than the RF signal amplitude at the filaments 710 near the first end 750, where the RF signal is being launched.

Standing waves resulting from reflections of RF signals due to imperfect RF impedance matching / termination can also create non-uniformities in RF signal amplitude along the length of the first bus 730. For example, an RF signal launched at the first end 750, upon reaching the second end 751, may get reflected back towards the first end 750 due to a lack of impedance matched termination, creating a standing wave along the length of the first bus 730.

Such non-uniformity in RF signal amplitude across the length of the first bus 730 may result in plasma non-uniformity.

Non-uniformity in RF signal amplitude across the first bus 730 can be reduced by using a recursive RF feed structure. Referring back to FIG. 7D, the first bus 736 is configured to form a recursive RF feed structure to deliver the first RF signal generated by the first RF power source to the filaments 710 such that the signal path lengths, and hence the loss experienced by the RF signal, from the driving point 756 to each filaments 710 is

approximately equal for all filaments 710. Such approximately equal path lengths can enable approximately equal RF signal amplitudes at the driven ends (i.e., ends connected to the first bus 736) of the filament 710. In some implementations, the non-uniformity in RF signal amplitude is further mitigated by configuring the recursive RF feed structure such that each
5 branch of the structure is connected to an approximately equal total length of filaments. For example, from left to right, 7,6,5,4 filaments, respectively, are connected to the respective branch of the recursive RF feed structure. Such approximately equal total lengths per branch may help improve uniformity when the electrode assembly 706 is operated as an ICP source. In some implementations, each level of recursion of the feed structure is shielded by
10 respective ground planes, and a vertical via penetrating the ground plane connected the respective levels of the structure.

In cases where the electrode assembly is driven by two RF signal sources, various factors affects the shape of the generated plasma region. Examples of factors include the frequency and the phase relation of the two RF signals. Referring to FIG. 7B, for example,
15 when the frequency of the first and second RF signals driving the first bus 732 and the second bus 742 is the same and the phase difference is set to 0 degrees ('monopolar', or 'singled-ended'), the plasma region is pushed out from the gaps between the coplanar filaments 710, leading to discontinuity or non-uniformity, e.g., in some cases where the spacing between the cylindrical shells is small. When the phase difference of the RF signals
20 driving the adjacent coplanar filaments 710 is set to 180 degrees ('differential'), the plasma region is more strongly confined between the coplanar filaments 710. Any phase difference between 0 and 360 degrees can be used to affect the shape of the plasma region.

In general, the grounding of the workpiece support electrode 116 is a factor affecting the shape of the plasma region. Imperfect RF grounding of the electrode 116 in combination
25 with 0 degrees of phase difference between the RF signals driving the adjacent coplanar filaments pushes the plasma region towards the top gap. However, if adjacent coplanar filaments, e.g., coplanar filaments are driven with RF signals that have 180 degrees of phase difference, the resulting plasma distribution is much less sensitive to imperfect RF grounding of the electrode 116. Without being limited to any particular theory, this can be because the
30 RF current is returned through the adjacent electrodes due to the differential nature of the driving signals.

The electrical configurations and characteristics of the foregoing electrode assemblies (e.g., 400, 500, 502, 504, 600, 601, 700, 702, and 704) can be dynamically changed using RF switches coupled to various locations of the electrode assembly in various configurations.

Referring to FIG. 8A, an electrode assembly 800 includes filaments 810, a first bus 820, and a second bus 824. The buses 820 and 824 can have respective third ends 821 and respective fourth ends 822 as shown. The filaments 810 are similar to filaments 610 and 300, except as described. Each filaments 810 has a respective first end 811 and a respective second end 812. The first bus 820 and the second bus 824 can be located inside of the chamber body 102, in the chamber ceiling, or outside of the chamber, and electrical connections can be made between the respective ends of the filaments 810 to various locations along (e.g., along the length of) the buses 820 and 824.

The filaments 810 may be divided into a first multiplicity 816 of filaments and a second multiplicity 817 of filaments. In some implementations, the filaments 810 of the first multiplicity 816 and the second multiplicity 817 can be arranged in an alternating pattern along the direction perpendicular to their longitudinal axis such that the coplanar filaments alternate between the first group and the second group as shown.

The first ends 811 of the filaments of the first multiplicity 816 can be coupled to the first bus 820. The first ends 811 of the filaments of the second multiplicity 817 can be coupled to the second bus 822. The coupling between the filaments 810 and the busses can be achieved using simple wires or metal straps (if the length is short relative to a small fraction of a wavelength at the RF frequency), or by using RF transmission lines, e.g., coaxial cables.

In some implementations, the electrode assembly 800 additionally includes a third bus 826 and a fourth bus 828. In such implementations, the second ends 812 of the filaments of the first multiplicity 816 can be coupled to the third bus 824. The second ends 812 of the filaments of the second multiplicity 817 can be coupled to the fourth bus 826.

The buses 820, 824, 826, and 828 are configured electrically couple the respective filaments 810 coupled to it. The RF transmission lines that form the buses may have a length that is comparable to or greater than a significant fraction of a wavelength of the RF frequency (e.g., $> 1/10$ wavelength), and are lossy due to deliberate plasma loading of the filament array, i.e., absorption of RF power. Therefore, filaments 810 connected at different

locations along the direction of propagation of the RF signal may experience different RF signal amplitude. For example, an RF signal launched at the third end 821 of the first bus 820 will be attenuated as it propagates down the length of the first bus 820. As a result, the RF signal amplitude at the filaments 810 near the second end 822 will be smaller than the RF signal amplitude at the filaments 810 near the first end 821, where the RF signal is being launched. Such non-uniformity in RF signal amplitude across the length of the first buses 820 or 824 may result in plasma non-uniformity.

In general, plasma region generated by the electrode assembly 800 over a substantially large area may contain substantial non-uniformities in plasma densities. For example, for a plasma region that is 40 cm long by 40 cm wide, a substantial difference in plasma uniformity may be observed between RF signal frequency of 13.56 MHz and 60 MHz. When driven at a lower frequency, e.g., 13.56 MHz, the plasma density may decrease towards the central portions of the filaments 810 away from the ends 811 and 812. However, along the direction perpendicular to the longitudinal axis of the filaments, the time-average of the plasma density remain substantially spatially uniform. When driven at a higher frequency, e.g., 60 MHz, the plasma density becomes less uniform both along the filaments and perpendicular to the longitudinal axes of the filaments. For example, periodic distribution of local maxima and minima may form along the two directions. Without wishing to be bound by theory, such patterns of non-uniformities may be caused at least in part by a presence of standing waves.

It may be possible to mitigate such non-uniformities by dynamically changing the electrical characteristics of the electrode assembly 800 using RF switches. It may also be possible to intentionally introduce non-uniformities in the voltage signal to compensate for other sources of non-uniformity in the workpiece, e.g., non-uniform layer thickness, or the plasma density, e.g., non-uniform gas distribution.

Referring to FIG. 8B, a switched electrode system 802 includes a first RF switch 830, a second RF switch 834, a third RF switch 836, a fourth RF switch 838, a first tap 840 and a second tap 842. In general, the first and second taps 840 and 842 can be connected to various signals and potentials to generate plasma, e.g., a first and second RF signal, an RF ground.

Each RF switch includes a first terminal 831 and a second terminal 832. In general, the RF switch 830 operates bidirectionally, and first and second end 831 and 832 is not tied

to a specific physical terminal of the RF switch, but used rather to refer to the two different terminals of the RF switch. The RF switches 830,834,836, and 838 can be provided using various RF switching components. Examples of RF switching components include mechanical relays or switches, PIN diodes, saturable inductor/reactors, MOSFETS,
5 electronic circuits including such components, and frequency-dependent impedance circuits when combined with an RF power generator with tunable RF signal frequency.

In general, the first and second taps 840 and 842 may be located along respective lengths of the buses 820, 824, 826, and 828, e.g., at the middle of the bus. In some implementations, the first tap 840 is located at the middle of the first bus 820, and the second
10 tap 842 is located at the middle of the fourth bus 828.

In some implementations, the first and second taps 840 and 842 are differentially driven by two RF signals having a same frequency (e.g., 60 MHz) and a relative phase difference of 180 degrees.

In general, the first and second terminals 831 and 832 of the RF switches can be
15 coupled to the busses in various ways to achieve various effects. For example, the respective first terminals of the RF switches 830,834,836, and 838 are connected to ends of the busses 820, 824, 826, and 828 as shown. In such a configuration, closing of any one of the RF switches 830, 834, 836 and 838 electrically connects, or “shorts”, the respective ends of the busses (the “corners”). Shorting of the corners can cause a change in a RF reflection
20 coefficient at that location, resulting in reduced RF signal amplitude and power coupling at a local region of the filaments 810 near the shorted corner, and thus reducing local plasma generation. Shorting of the corners can also move and / or change the spatial distribution of the maxima and minima in plasma density.

In general, electrical connections and couplings can be provided by conductive wires,
25 coaxial cables, waveguides, or by physical contact (e.g., welding, soldering, one-piece fabrication).

In general, process uniformity of the workpiece can be improved by time-averaging of the plasma exposure. One way of achieving time-averaging of the plasma exposure is through moving of the spatial distribution of non-uniformities in the plasma region. For
30 example, by opening and closing of (“modulating”) RF switches coupled to the four corners

of the electrode assembly, the plasma density distribution (non-uniformities) can be moved around.

The RF switches 830, 834, 836, and 838 can be modulated in various ways to achieve desired time-averaged plasma density. An example of a sequence for modulating the RF switches is to cyclically connect pairs of points on different buses. For example, the system could be operated as follows: (1) close RF switch 830 for a first duration then open, (2) close RF switch 834 for a second duration, then open, (3) close RF switch 836 for a third duration, then open, (4) close RF switch 838 for a fourth duration. The first through fourth duration can be determined based on desired repetition rate of the sequence. Repetition rate can be set, for example, to be substantially faster than timescale of certain effects, e.g., device charging. For example, in a sequence with 4 states, the individual state durations, including dead time, can be set to 50 μ s to achieve a repetition rate of 5 kHz.

In some implementations, a dead time between the steps of the sequence is inserted. The dead time may provide a “break before make” contact to prevent shorting of two or more generators in certain configurations. In some implementations, closing of the switches can overlap in time. For example, two switches can be modulated in synchrony, e.g., pairs of diagonally opposed switches (830 – 838, 834-836), pairs of adjacent switches (830-834 and 836-838, 832-836 and 834-838). As another example, all four switches can be opened and closed in synchrony.

Referring to FIG. 8C, an example of a switched electrode system 804 is shown. The switched electrode system 804 is similar to system 802, except as described. The switched electrode system 804 includes a first group of RF switches 850, a second group of RF switches 854, a third group of RF switches 856, and a fourth group of RF switches 858. The first group of RF switches 850 includes sub-switches 860a and 860b, the second group of RF switches 854 includes sub-switches 860c and 860d, the third group of RF switches 836 includes sub-switches 860e and 860f, and the fourth group of RF switches 838 includes sub-switches 860g and 860h. The sub-switches are similar to RF switch 830.

The first terminals 831 of the sub-switches are connected to ends of the busses 820, 824, 826, and 828. In some implementations, the second terminals 832 of the sub-switches are connected to an RF ground. In such a configuration, closing of any one of the sub-switches electrically connects the respective ends of the busses to the RF ground, or grounds

the ends of the busses. Grounding of an end of a bus can lead to reduced RF signal amplitude in a local region of the filaments 810 near the RF grounded end of the bus, and results in a reduced squared amplitude of the electric field in that region, or lower power coupling. A reduced squared amplitude of the electric field can lead to reduced plasma generation in that region.

The groups of RF switches and individual sub-switches can be modulated in various ways to provide modulation of plasma density distribution. For example, each group of RF switches can be operated as a single unit in which the sub-switches of the group of RF switches are opened and closed as a single unit. As another example, the sub-switches of each group of RF switches can be independently opened and closed.

Switches can be modulated in various different sequences in manners similar to various sequences described in relation to FIG. 8B. For example the switched electrode system can be operated by cyclically closing one group of switches at a time (optionally with a time delay), cyclically closing groups of switches with overlap in times that the different groups are closed, alternating groups of switches, or opening and closing all switches in synchronicity.

As another example, the system could be operated as follows: (1) close first and third group of RF switches 850 and 856 for a first duration then open, (2) open all switches, (3) close second and fourth group of RF switches 854 and 858 for a second duration then open.

As yet another example, the system could be operated as follows: (1) close first group of switches 850 for a first duration then open, (2) close second group of switches 854 for a second duration then open, (3) close third group of switches 856 for a third duration then open, (4) close fourth group of switches 858 for a fourth duration then open, (5) open all group of switches, (6) close all group of switches.

In some implementations, the feeding of the RF signal to various locations on the bus can be dynamically reconfigured using RF switches. Referring to FIG. 8D, an example of a switched electrode system 806 is shown. The switched electrode system 806 is similar to system 804 and can be operated in a similar manner, except as described.

The first multiplicity 816 is driven with an RF signal at taps 844 and 846. The RF signals driving the taps 844 and 846 can be at the same frequency or at a different frequency. For cases when the frequency is the same, the phase relationship of the two signals can be 0,

180, or any value between 0 and 360. For some implementations, the phase relationship can be modulated over time. The second terminals 832 of the sub-switches 860a, 860c, 860f, and 860h are connected to the respective taps 844 and 846 as shown.

In such a configuration, the grounding characteristics of the second multiplicity 817
5 can be modulated using the respective sub-switches, and RF signals can be launched in to the buses 820 and 826 from different locations, such as from ends 821 and 822. The combination of modulation of grounding characteristics and RF signal distribution can be used to modulate the plasma density to improve processing uniformity by time-averaging.

In such a configuration, it may be advantageous to maintain at least one of the sub-
10 switches 860 in a closed state to provide a continuous supply of RF signal to the assembly 800.

Referring to FIG. 8E, an example of a switched electrode system 808 is shown. The switched electrode system 808 is similar to system 804 and can be operated in a similar manner, except as described. The second terminals 832 of the sub-switches are connected to
15 a single tap 848. A symmetric distribution network as shown can be used to improve uniformity of the RF signal delivered to the four corners of the system 808. The sub-switches can be modulated in various ways a previously described to change plasma distribution and improve process uniformity.

In some implementations, the switches can be distributed across buses to allow finer
20 control of instantaneous plasma uniformity and thereby improve time average plasma uniformity. Referring to FIG. 8F, an example of a switched electrode system 801 is shown. The switched electrode system 801 is similar to system 808 and can be operated in a similar manner, except as described. The first bus 820 is coupled to a first group of RF switches 870, e.g., three or more sub-switches. Each group of RF switches includes multiple sub-switches
25 860. The first terminals of the sub-switches 860 of the first group of RF switches 870 are electrically coupled to the first bus at various locations across the length of the first bus 820. In some implementations, the coupling points are approximately equally spaced as shown. The second terminals of the sub-switches 860 of the first group of RF switches 870 are electrically coupled to the tap 848 to receive the RF signal.

The second, third, and fourth buses 824, 826 and 828 are connected to a second, third, and fourth group of RF switches 874, 876, and 878, respectively, each in a manner similar to the first bus 820 and first group of RF switches 870 as shown.

In such a configuration, the additional level of control over the launching locations of the RF signals along the lengths of the busses can lead to improved time-averaged plasma uniformity.

In general, the number of sub-switches included in a group of RF switches can be determined based on, for example, the lengths of the buses, size of the plasma region, RF signal frequency and power, and chamber pressure.

In some implementations, the RF signal feeding and grounding location can be dynamically reconfigured using RF switches to provide a mode-selectable plasma source that can switch between a predominantly CCP mode and predominantly ICP mode. Referring to FIG. 9A, an example of a switched electrode system 900 is shown. The switched electrode system 900 is similar to the system 802 and can be operated in a similar manner, except as described. The first terminals 831 of the RF switches 830 and 834 are connected to the respective third end 821 and fourth end 822 of the second bus 824, and the first terminals 831 of the RF switches 836 and 838 are connected to the respective third end 821 and fourth end 822 of the third bus 826 as shown. The second terminals 832 are connected to an RF ground.

The RF switches 830, 834, 836, and 838 can be controlled in various ways to change the dominant mode of plasma generation by the switched electrode assembly 900. For example, by closing all four RF switches, RF current flows along the lengths of the filaments 810, creating magnetic fields and producing a predominantly inductively coupled plasma. By opening all four switches, RF current flow is reduced, and the assembly 900 creates a predominantly capacitively coupled plasma.

In some implementations, the first and second RF signals driving the respective taps 840 and 842 have a phase difference of 180 degrees, i.e., differentially driven. In such cases, alternating filaments 810 belonging to the first and second multiplicity 816 and 817 are fed from opposite ends with RF signals having approximately 180 degrees of phase difference, resulting in generation of aiding RF magnetic fields. In some implementations, the first and second RF signals driving the respective taps 840 and 842 have a phase difference of approximately 0 degrees. In such cases, alternating filaments 810 belonging to the first and

second multiplicity 816 and 817 are fed from opposite ends with RF signals having approximately 0 degrees of phase difference, resulting in generation of opposing RF magnetic fields.

In some implementations, the switches can be distributed across buses to allow finer control of instantaneous plasma uniformity and thereby improve time average plasma uniformity. Referring to FIG. 9B, an example of a switched electrode assembly 902 is shown. The switched electrode assembly 902 is similar to system 801, except as described. The first bus 820 is coupled to a first group of RF switches 870 that includes multiple sub-switches 860.

The first terminals of the sub-switches 860 of the first group of RF switches 870 are electrically coupled to the first bus at various locations across the length of the first bus 820. In some implementations, the coupling points are approximately equally spaced as shown. The second terminals of the sub-switches 860 of the first group of RF switches 870 are electrically coupled to the tap 940 to receive a first RF signal.

The second bus is connected to the second group of RF switches 874 at the first terminals of the sub-switches, and the second terminals of the sub-switches are connected to an RF ground.

The third bus is connected to the third group of RF switches 876 at the first terminals of the sub-switches 860, and the second terminals 832 of the sub-switches 860 of the third group of RF switches 876 are connected to an RF ground.

The fourth bus is connected to the fourth group of RF switches 878 at the first terminals of the sub-switches, and the second terminals of the sub-switches are electrically coupled to the tap 942 to receive a second RF signal.

The first and second RF signals driving the taps 940 and 942 can be at the same frequency or at a different frequency. For cases when the frequency is the same, the phase relationship of the two signals can be 0, 180, or any value between 0 and 360. For some implementations, the phase relationship can be modulated over time.

The groups of RF switches 870, 874, 876, and 878 can be controlled in various ways to change the dominant mode of plasma generation by the switched electrode assembly 902. For example, by closing at least one of the sub-switches from each of the first group 870 and

the fourth group 878, and opening the second and third groups of RF switches 874 and 876, the assembly 902 creates a predominantly capacitively coupled plasma.

As another example, by closing at least one of the sub-switches from each of the first group 870 and the fourth group 878, and closing all sub-switches of the second and third groups of RF switches 874 and 876, the assembly 902 creates a predominantly inductively coupled plasma. In some implementations, the first and second RF signals driving the respective taps 940 and 942 have a phase difference of 180 degrees, i.e., differentially driven. In such cases, alternating filaments 810 belonging to the first and second multiplicity 816 and 817 are fed from opposite ends with RF signals having approximately 180 degrees of phase difference, resulting in generation of aiding RF magnetic fields. In some implementations, the first and second RF signals driving the respective taps 940 and 942 have a phase difference of approximately 0 degrees. In such cases, alternating filaments 810 belonging to the first and second multiplicity 816 and 817 are fed from opposite ends with RF signals having approximately 0 degrees of phase difference, resulting in generation of opposing RF magnetic fields.

In some processing applications, ICP generation using opposing RF magnetic field which can deposit RF power into plasma in strips generally parallel to the filaments, may provide a more uniform plasma, particularly when the workpiece is close to the plasma source (e.g., electrode assembly), i.e., small bottom gap 132. Therefore, having the capability of changing the phase relationship of the first and second RF signal may be beneficial.

In general, the individual sub-switches of the first and fourth group 870 and 878 can be modulated to vary the plasma density distribution. In addition, in cases where the switched electrode assembly 902 is configured to create predominantly inductively coupled plasma, the sub-switches of the second and third group 874 and 876 can be individually modulated to further modify the plasma density distribution.

In general, while figures shows buses driven near center and ends floating or with ground terminations, depending on application, RF configuration, frequency and operating region (plasma load) it may be advantageous to drive or terminate at other locations e.g. driven ends, terminate ends or center.

In general, in cases where the second terminals of RF switches are connected to an RF ground, a variable impedance can be placed in series to the RF ground to provide a variable RF termination impedance to further control the modification of plasma density.

In general, while figures illustrated taps connected to the center of the respective buses, the taps for applying RF power to the electrode assembly could be located at one or more ends, the center, or other positions on the bus.

Switches can be used to improve time-averaged plasma uniformity of a wedge-shaped electrode assembly. Referring to FIG. 10, an example of a switched electrode assembly 1000 is shown. The switched electrode assembly 1000 includes the wedge-shaped electrode assembly 1010. The wedge-shaped electrode assembly 1010 is similar to wedge-shaped electrode assembly 704, except as described. The assembly 1010 includes wedge-shaped top electrode 624, which can be grounded. The switched electrode assembly 1000 includes a first RF switch 1030, a second RF switch 1034, a third RF switch 1036, a fourth RF switch 1038, and a tap 1040. The RF switches are similar to RF switch 830. The first terminals of RF switches 1030 and 1034 are connected to the first end 754 of the assembly 1010, and the first terminals of RF switches 1036 and 1038 are connected to the second end 755 of the assembly 1010. The second terminals of first and fourth RF switches 1030 and 1038 are connected to each other and to a tap 1040, and the second terminals of the second and the third RF switches 1034 and 1036 are connected to an RF ground.

The first and fourth RF switches 1030 and 1038 can be opened and closed to selectively feed RF signal to the first end 754, the second end 755, or both ends of the assembly 1010. The second and third RF switches 1034 and 1036 can be opened and closed to selectively ground the first end 754 or the second end 755 of the assembly 1010.

The RF switches can be modulated in various ways to improve time-averaged plasma uniformity. Following is an example of a sequence: (1) close RF switch 1030 for a first duration, and open switches 1034, 1036 and 1038 (e.g., for 30 microseconds), (2) close 1030, 1036, open 1034, 1038 (e.g., for 40 microseconds), then (3) close 1036, open 1030, 1034, and 1036 (e.g., for 30 microseconds). Optionally either unpowered end may be grounded after a short delay after applying RF signal to the other end, and the grounded end may be ungrounded prior to applying RF signal to that end.

Following is another example of a sequence: (1) 1030 = ON, 1038,1034,1036 = OFF for 30 microseconds, (2) 1030,1038 = ON, 1034,1036 = OFF for 40 microseconds, (3) 1038 = ON, 1034,1030,1036 = OFF for 30 microseconds, then the cycle is repeated multiple times until the process step is completed or alternately reversed cyclically. Optionally either
5 unpowered end may be grounded after a short delay after applying power to the other end, and the grounded end may be ungrounded prior to applying power to that end.

In general, a wedge-shaped electrode assembly 1010 can be similar to the electrode. In general, the switches can be applied to other electrode assemblies, e.g., 600, 601, 700, 702, 704.

10 RF switches suitable for switching RF signals for plasma generation can be provided using various circuit implementations. Various considerations exist for implementing RF switches (e.g., RF switch 830, sub-switch 860) to be used in switched electrode systems. Examples of such considerations include RF power handling capacity, switching speed, ON-state impedance, OFF-state impedance, and bidirectionality.

15 In general, a switch is considered to be in an “ON”, or closed, state when the impedance presented between the two terminals of the switch is low, and in an “OFF”, or open, state when the impedance is high.

A PIN diode switch may be used to provide a suitable RF switch. Referring to FIG. 11A, a PIN diode switch 1100 includes a PIN diode 1110, a first capacitor 1120 having
20 capacitance C1, a second capacitor 1122 having capacitance C2, and an inductor 1140 having inductance L1. The switch 1100 has a first terminal 1131, a second terminal 1132, and a control terminal 1134. The first terminal 1131 can provide the first terminal 831, and the second terminal 1132 can provide the second terminal 832 of the RF switch 830.

The first capacitor 1120 and inductor 1150 can be connected in parallel between the
25 first terminal 1131 and the second capacitor 1122. Then the PIN diode 1110 can be connected in parallel with the first capacitor 1120, inductor 1150 and second capacitor 1122 between the first terminal 1131 and the second terminal 1132. The control terminal 1134 can be connected between the second capacitor and 1122 and the first capacitor 1120.

The PIN diode 1110 is a diode with a wide, undoped intrinsic semiconductor region
30 between a p-type semiconductor and an n-type semiconductor region, and can be well suited for fast switching of high power RF signals. The PIN diode has an anode (+) and a cathode (-

), and can provide a low impedance conduction path, e.g., < 1 ohm, for RF signals when a forward bias is established between the anode and the cathode (e.g., > 0.7 V and / or diode current > 100 mA).

The PIN diode switch 1100 operates based on the following working principle. The impedance of the PIN diode 1110 can be controlled by providing a control signal to the control terminal 1134. The control signal is a quasi-static voltage switching between a first level (e.g., 0.7 V), and a second level (e.g., -2 kV). Due to the quasi-static nature of the control signal, the control voltage and any resulting diode current can conduct through the inductor 1140. Additionally, the second capacitor 1122 blocks the control voltage from reaching the cathode. By providing a sufficiently large negative control voltage (e.g., -2 kV) to the anode with respect to the cathode, the PIN diode 1110 can be set to an “OFF” state, presenting a high impedance across its cathode and anode. When a sufficiently large positive control voltage (e.g., 0.7 V) is applied, the PIN diode 1110 can be set to an “ON” state, presenting a low impedance path (e.g., < 1 ohm) for the RF signal between the terminals 1131 and 1132.

The first capacitor 1120 and the inductor 1140 connected in parallel as shown form a parallel LC resonator 1150. The resonator 1150 has a resonance frequency determined by the equation $f_0 = \frac{1}{2\pi\sqrt{L1*C1}}$. At the resonance frequency f_0 , the resonator 1150 presents a high impedance approximating an open circuit (e.g., > 1000 ohms), depending on the quality factor of the resonator. By selecting the values for C1 and L1 such that the resonance frequency aligns with the frequency of the RF signal present at the terminals 1131 or 1132, the RF signal can be prevented from passing through the resonator 1150.

In general, the capacitance C2 of the second capacitor 1122 can be set to provide a low impedance path at the frequency of the RF signal.

In some implementations, the first capacitor 1120 is a variable capacitor (“a varactor”) with tunable capacitance C1 that can be varied to optimize the resonance of the parallel LC circuit formed by the first capacitor 1120 and the inductor 1140 to align with the frequency of the RF signal.

In some implementations, a control signal buffer amplifier 1136 can be provided to buffer and / or amplify the control signal applied at the control terminal 1134 to the anode of the PIN diode 1110.

In general, multiple PIN diode switches may be used in combination to achieve a range of impedance values between the first and the second terminals 1131 and 1132. The control signal may also be set between the first and second level to provide a variable impedance.

5 In some implementations, the first terminal 1131 is connected to a bus (e.g., bus 820), and the second terminal 1132 is connected to an RF ground, forming a path to the RF ground. In some implementations, the first terminal is connected to a first bus (e.g., bus 820) and the second terminal 1132 is connected to a second bus (e.g., bus 824), in which case the switch may be considered to be “floating”, the potential of the second terminal 1132 is defined by
10 external factors.

As another example, a saturable inductor switch may be used to provide a suitable RF switch. Referring to FIG. 11B, a saturable inductor switch 1102 includes a saturable inductor 1160, a first capacitor 1124 having capacitance C1, and a second capacitor 1126 having
15 capacitance C2. The switch 1102 has a first terminal 1131, a second terminal 1132, and a control terminal 1135. The first terminal 1131 can provide the first terminal 831, and the second terminal 1132 can provide the second terminal 832.

The saturable inductor 1160 has a primary winding 1162 having inductance L1, and a control winding 1164 having inductance L2. The saturable inductor may also be called a saturable reactor or a magnetic amplifier in some literatures. A saturable inductor is a type of
20 inductor having a magnetic core that can be deliberately saturated by a current flowing through the control winding 1164. Once saturated, the primary winding 1162 experiences a substantial drop in its inductance L1. The decreased inductance of the primary windings leads to reduction of impedance presented to the RF signal, which can be used to achieve switching.

25 The primary winding 1162 of the inductor 1160 can be connected in series with the second capacitor 1126, and the first capacitor 1124 can be connected in parallel with the primary winding 1162 and second capacitor 1126 between the first terminal 1131 and the second terminal 1131. The control terminal 1135 is connected to the control winding 1164, which can be connected in turn to ground.

30 The saturable inductor switch 1102 operates based on the following working principle. The first capacitor 1124 in parallel with a series combination of the primary

winding 1162 and the second capacitor 1126 form a parallel LC resonator that operates similarly to the LC resonator 1150. For example, the values for C1, C2, and L1 can be set such that the resonance of the switch 1102 occurs at the RF signal frequency, e.g., 60 MHz, when the control signal is set to an “OFF”, or low, state in which there is no current flowing through the control winding 1164. In such a state, the switch 1102 is in an “open” state, presenting a high impedance between the first and second terminals 1131 and 1132. When the control signal applied to the control terminal 1135 is set to an “ON”, or high, state, the magnetic field generated by the current flowing through the secondary winding 1164 saturates the magnetic core of the saturable inductor 1160, reducing the inductance L1 of the primary winding 1162. The reduction of inductance L1 modifies the resonance frequency of the switch 1102, presenting a low impedance between the first and second terminal 1131 and 1132 at the same RF signal frequency. This low impedance state can be used as a closed state of the switch 1102.

In some implementations, a control signal buffer amplifier 1137 can be provided to amplify and / or buffer the control signal applied at the control terminal 1135 so that a current sufficient to saturate the saturable inductor 1160 can be applied to the control winding 1164.

In some implementations, a low pass filter 1138 can be provided between the control signal terminal 1135 and the control winding 1164 to mitigate noise coupling from the control signal and / or RF signal propagating towards the control signal terminal.

In general, the impedance of the switch presented between the first terminal 1131 and the second terminal 1132 can be controlled between the “ON” state and the “OFF” state by adjusting the control signal to provide a range of current to the control winding 1164.

In some implementations, the first terminal 1131 is connected to a bus (e.g., bus 820), and the second terminal 1132 is connected to an RF ground. In some implementations, the first terminal is connected to a first bus (e.g., bus 820) and the second terminal 1132 is connected to a second bus (e.g., bus 824).

The impedance, and therefore the switching state, presented by the foregoing switches 1100 and 1102 are controlled by an application of a control signal. However, in some implementations, the characteristics of a switch can remain static, and instead the frequency of the RF signal can be modulated so that a switch presents an “open” or “closed”

state to RF signals having different frequencies. For example, a frequency dependent impedance of a circuit can be used to provide such a frequency-based switch.

Referring to FIG. 12A, a frequency-based switch 1200 includes a first capacitor 1220 having capacitance C1, a second capacitor 1222 having capacitance C2, a first inductor 1240 having inductance L1, and a second inductor 1242 having inductance L2. The switch 1200 has a first terminal 1231, and a second terminal 1232.

The first capacitor 1220 and the first inductor 1240 can be connected in series, and the second capacitor 1222 and the second inductor 1242 can be connected in series. This pair of circuits can be connected in parallel between the first terminal 1231 and the second terminal 1232.

The combination of L1, C1, L2, and C2 can be set such that at a first frequency, e.g., 58 MHz, a low impedance (e.g., < 0.1 ohm) is presented between the first and second terminals 1231 and 1232, and at a second frequency, e.g., 62 MHz, a high impedance (e.g., > 100 ohm) is presented. For example, the following values of $L1 = L2 = 0.1$ μ H, $C1 = 75.3$ pF, $C2 = 58.6$ pF can provide a low impedance resonance at 58 MHz, and a high impedance resonance at 62 MHz.

Without wishing to be bound by theory, the low impedance resonance may be provided by a series LC resonance and the high impedance resonance may be provided by a parallel LC resonance.

The capacitances and inductances can be set to form a frequency-based switch that has an approximately complementary response to the example provided above. For example, the following values of $L1 = L2 = 0.1$ μ H, $C1 = 65.9$ pF, $C2 = 87.8$ pF can provide a low impedance resonance at 62 MHz, and a high impedance resonance at 58 MHz, presenting an approximately complementary, or opposite, response relative to the first example. Such complementary behavior can be used to form various frequency-switched electrode systems.

In some implementations, the discrete capacitors and inductors can be implemented with distributed circuit elements, e.g. transmission line segments, stubs.

Referring to FIG. 12B, a frequency-switched electrode system 1202 includes an electrode assembly 800, a first frequency-based switch 1200a, a second frequency-based switch 1200b, and a tap 1260. RF signals of different frequencies can be provided to the tap

1260, for example, using a variable-frequency RF generator with a matching network and isolator or circulator in series.

In this configuration, the frequency of the RF signal supplied through the tap 1260 can alternate from a first frequency to a second frequency to cause more RF signal to couple to the left side of the electrode assembly 800 through the switch 1200a, or to the right side of the electrode assembly 800 through the switch 1200b. Alternatively, the frequency of the RF signal supplied through the tap 1260 can be driven, e.g., with a ramp function, to vary between a first frequency and a second frequency.

For example, by setting the components values to $L1a = L2a = 0.1 \mu\text{H}$, $C1a = 75.3 \text{ pF}$, $C2a = 58.6 \text{ pF}$, the first switch 1200a can provide a low impedance resonance at 58 MHz, and a high impedance resonance at 62 MHz. The component values of the second switch 1200b can be set to $L1 = L2 = 0.1 \mu\text{H}$, $C1 = 65.9 \text{ pF}$, $C2 = 87.8 \text{ pF}$ to provide a low impedance resonance at 62 MHz, and a high impedance resonance at 58 MHz. In such a configuration, by switching the frequency of the RF signal to the first frequency, e.g., 58 MHz, a majority of RF signal can be coupled to the left side of the electrode assembly 800 through the first switch 1200a, and by switching the frequency of the RF signal to the second frequency, e.g., 62 MHz, the majority of RF signal can be coupled to the right side of the assembly 800 through the second switch 1200b. When frequency is mid-way in between the two frequencies, broadly around 60 MHz, then power is coupled approximately similarly to both ends and a high center non-uniformity may result.

In some implementations, the frequency dependent impedance of the switch 1200 can be modified using a transmission line segment. For example, a transmission line segment that is a quarter-wavelength in length, accounting for the velocity factor of the transmission line, can be used to connect the corners of the electrode assembly 800 to the terminal of the switches 1200a and 1200b. By using a quarter-wavelength transmission line, the presented impedance at the first and second frequencies may be swapped. For example, the low impedance at the series resonance may be transformed to a high impedance of about 1000 ohms, and the high impedance at the parallel resonance may be transformed to a low impedance of about 1 ohm.

In some implementations, the frequency-based switch 1200 can be used as a frequency-selective termination to provide impedance-matched termination at different

frequencies to control coupling of the RF signal into the electrode assembly. Referring to FIG. 12C, a frequency-switched electrode system 1204 includes an electrode assembly 800, a first frequency-selective termination 1250a, a second frequency-selective termination 1250b, and a tap 1260. The frequency selective terminations 1250a and 1250b can be provided by
5 the frequency-based switch 1200, and operated in a similar manner, except as described.

In some implementations, the component values of the frequency-selective terminations 1250a and 1250b can be set such that at the first frequency, termination 1250a presents a characteristic impedance of the RF generator and the transmission line, while the termination 1250b presents a high impedance. In such a configuration, termination 1250a
10 provides an impedance-matched termination to an RF ground, minimizing RF signal reflection and RF signal coupling to the left side of the electrode assembly 800. At the same time, the high impedance presented by the termination 1200b allows the RF signal to be coupled into the right side of the electrode assembly 800.

In some implementations, the component values of the frequency-selective terminations 1250a and 1250b can be set such that at the first frequency, termination 1250a presents a low impedance path to an RF ground while the termination 1250b presents a high impedance. In such a configuration, the low impedance path to the RF ground provided by termination 1250a minimizes RF signal coupling to the left side of the electrode assembly
15 800. At the same time, the high impedance presented by the termination 1200b allows the RF
20 signal to be coupled into the right side of the electrode assembly 800.

In general, frequency-based switches and frequency-selective terminations can be coupled to various locations along the busses. For example, an additional pair of coupling points to the tap may be provided at approximately the center of the busses, and additional switches or terminations can be provided at those coupling points.

25 In general, the frequency switching is not limited to the 2 states corresponding to high and low impedance states, but may advantageously be operated continuously between, or beyond the first and second switching frequencies.

In general, various combination of frequency-based switches having various resonance frequencies can be used to expand the frequency-based switching to 3, 4, or more
30 frequencies.

In some plasma chambers, a workpiece is moved through a plasma processing region on, for example, a linear or rotating workpiece support. In such a chamber, the moving workpiece support may be DC grounded through, for example, a rotary mercury coupler, brushes, or slip rings. However, the moving workpiece support may not be adequately grounded at radio frequencies. The RF ground path should have substantially lower impedance than the plasma for it to be an adequate RF ground. The lack of an adequate RF ground path may make it difficult to control ion energy at the workpiece and reduce the repeatability of the process.

A plasma source with the following properties is thus desired: it can efficiently produce a uniform plasma with the desired properties (plasma density, electron temperature, ion energy, dissociation, etc.) over the workpiece size; it is tunable for uniformity over the operating window (e.g. pressure, power, gas composition); it has stable and repeatable electrical performance even with a moving workpiece; and it does not generate excessive metal contaminants or particles.

FIG. 13 is a schematic side view diagram of another example of a plasma reactor. A plasma reactor 2100 has a chamber body 2102 enclosing an interior space for use as a plasma chamber. The chamber body 2102 can have one or more side walls 2102a, a ceiling 2102b and a floor 2102c. The interior space 2104 can be cylindrical, e.g., for processing of circular semiconductor wafers. The plasma reactor includes a top electrode array assembly 2106 located at the ceiling of the plasma reactor 2100. The top electrode array assembly 2106 can abut the ceiling (as shown in FIG. 13), or be suspended within the interior space 2104 and spaced from the ceiling, or form a portion of the ceiling. Some portions of the side walls of and floor of the chamber body 2102 can be separately grounded.

A gas distributor is located near the ceiling of the plasma reactor 2100. The gas distributor can include one or more ports 2110 in the side walls 2102 that are connected to a process gas supply 2112. Alternatively or in addition, the gas distributor can be integrated with the top electrode assembly 2106 as a single component. For example, passages connected to the process gas supply 2112 can be formed through a dielectric plate in the assembly 2112 to provide openings in the ceiling of the plasma chamber. The gas supply 2112 delivers one or more process gases to the gas distributor 2110, the composition of which can depend on the process to be performed, e.g., deposition or etching.

A vacuum pump 2113 is coupled to the interior space 2104 to evacuate the plasma reactor. For some processes, the chamber is operated in the Torr range, and the gas distributor supplies argon, nitrogen, oxygen and/or other gases.

Depending on chamber configuration and supplied processing gasses, the plasma reactor 100 could provide an ALD apparatus, an etching apparatus, a plasma treatment apparatus, a plasma-enhanced chemical vapor deposition apparatus, a plasma doping apparatus, or a plasma surface cleaning apparatus.

The plasma reactor 2100 includes a workpiece support 2114, such as a pedestal, for supporting a workpiece with a top surface exposed to plasma formed in the chamber 2104. The workpiece support 2114 has a workpiece support surface 2114a facing the top electrode 2108. In some implementations, the workpiece support 2114 includes a workpiece support electrode 2116 inside the support 2114, and a workpiece bias voltage supply 2118 is connected to the workpiece support electrode 2116. The voltage supply 2118 can apply a voltage to chuck the workpiece 2115 to the support 2114 and/or supply a bias voltage to control characteristics of the generated plasma, including the ion energy. In some implementations, an RF bias power generator 2142 is AC-coupled through an impedance match 2144 to the workpiece support electrode 2116 of the workpiece support 2114.

Additionally, the support 2114 can have internal passages 2119 for heating or cooling the workpiece 2115, and/or an embedded resistive heater (2119).

The electrode assembly 2106 is positioned at the ceiling of the chamber 2104. This electrode assembly 2106 includes a plurality of conductors 2120 that extend laterally over the workpiece support 2114. At least in the region over the expected position of the workpiece on the support 2114, the conductors 2120 be coplanar. For example, in this region the conductors can extend parallel to the support surface 2114a. The plurality of conductors 2120 may be arranged as an array of parallel lines. In some implementations, conductors could have a “U-shape” with both ends connected to respective buses on the same side of the chamber 2104. Alternatively, the conductors could be arranged as interleaved spirals (either interleaved circular spirals or interleaved rectangular spirals). The longitudinal axis of the conductors 2120 can be arranged at a non-zero angle, e.g., an angle greater than 20 degrees, to the direction of motion of the workpiece 10 below the electrode assembly 2106. For

example, the longitudinal axis of the conductors 2120 can be substantially perpendicular to the direction of motion of the workpiece 10.

A gap 2132 is formed between the workpiece support 2114 and the electrode assembly 2106. For high pressure, e.g., 1-10 torr, the gap 2132 may be 2-25mm. A stationary workpiece may requiring greater minimum gap, e.g., about 5mm, depending on electrode-to-electrode spacing on source, and thickness of dielectric cover. At lower pressure, e.g., less than 100 mTorr, the gap 2132 may be 1 cm to 50 cm..

In some implementations, a fluid supply 2146 circulates a fluid through the electrode assembly 2106. In some implementations, a heat exchanger 2148 is coupled to the fluid supply 2146 to remove or supply heat to the fluid.

The electrode assembly 2106 is driven by an RF power source 2122. The RF power source 2122 can apply power to the conductors 2120 of the electrode assembly 2106 at frequencies of, e.g., 1 to 300 MHz. For some processes, the RF power source 2122 provides a total RF power of more than 2kW at a frequency of 60 MHz.

In some implementations, a heat sink 2150, e.g., an aluminum plate, is attached to the ceiling 2102b of the chamber body 2102. Passages 2152 can be formed through the heat sink 2150, and coolant can circulate through the passages 2152. A heat exchanger 2154 can be coupled to the passages 152 to remove or supply heat to the coolant.

FIGS. 14A-14C are schematic views of another example of a plasma reactor. In this example, which operates the same as FIG. 13 except as described, a multi-chamber processing tool 200 includes a plasma reactor 100.

The processing tool 2200 has a body 2202 enclosing an interior space 2204. The body 2102 can have one or more side walls 2202a, a ceiling 2202b and a floor 2202c. The interior space 2204 can be cylindrical.

The processing tool 2200 includes a workpiece support 2214, such as a pedestal, for supporting one or more workpieces 10, e.g., a plurality of workpieces. The workpiece support 2214 has a workpiece support surface 2214a. The workpiece support 2214 can include the workpiece support electrode 2116, and a workpiece bias voltage supply 2118 can be connected to the workpiece support electrode 2116.

A space between the top of the workpiece support 2214 and the ceiling 2202b can be divided into a plurality of chambers 2204a-2204d by barriers 2270. The barriers 2270 can

extend radially from a center of the workpiece support 2214. Although four chambers are illustrated, there could be two, three or more than four chambers.

The workpiece can be rotatable about an axis 2260 by a motor 2262. As a result, any workpiece 10 on the workpiece support 2214 will be carried sequentially through the chambers 2204a-2204d.

The chambers 2204a-2204d can be at least partially isolated from each other by a pump-purge system 2280. The pump-purge system 2280 can include multiple passages formed through the barrier 2210 that flow a purge gas, e.g., an inert gas such as argon, into a space between adjacent chambers, and/or pump gas out of a space between adjacent chambers. For example, the pump-purge system 2280 can include a first passage 2282 through which a purge gas is forced, e.g., by a pump, into the space 2202 between the barrier 2272 and the workpiece support 2214. The first passage 2282 can be flanked on either side (relative to direction of motion of the workpiece support 2214) by a second passage 2284 and a third passage 2286 which are connected to a pump to draw gas, include both the purge gas and any gas from the adjacent chamber, e.g., chamber 2204a. Each passage can be an elongated slot that extends generally along the radial direction.

At least one of the chambers 2204a-2204 provides a plasma chamber of a plasma reactor 2100. The plasma reactor includes the top electrode array assembly 2106 and RF power source 2122, and can also include the fluid supply 2146 and/or heat exchanger. Process gas can be supplied through a port 2210 located along one or both barriers 2270 to the chamber 2104. In some implementations, the port 2210 is positioned only on the leading side of the chamber 2104 (relative to direction of motion of the workpiece support 2214). Alternatively or in addition, process gas can be supplied through ports the side wall 2202a of the tool body 2202.

FIG. 15A illustrates an example of an electrode assembly 2106. The electrode assembly 2106 includes a dielectric top plate 2130, a plurality of conductors 2120, and a dielectric bottom plate 2132. As noted above, the conductors 2120 can be arranged as parallel linear stripes that extend laterally over the workpiece support 2114. The dielectric top plate 2130 can be a ceramic material.

The dielectric bottom plate 2132 provides a window for RF power, i.e., is substantially transparent to RF radiation of the frequency used to generate the plasma. For

example, the bottom plate 2132 can be quartz or silicon nitride. The bottom plate can protect the plasma process and workpiece environment from metal contamination or particle formation that may otherwise occur if the conductors or ceramic were exposed to plasma. The bottom plate 2132 can be a consumable part that is replaced periodically. The bottom
5 plate can be relatively thin, e.g., 0.25mm – 2mm, such as 0.5 mm.

The conductors can have a width of 1-5 mm, and a separation W between the conductors 120 can be 0.5 to 3 mm. The conductors can be wider than the separation, e.g., about twice as wide.

The thickness T of the lower dielectric plate 2132 should be less than twice the
10 separation W between conductors 2120, e.g., less than the separation W between conductors. A gap between the lower dielectric plate 2132 and the upper dielectric plate 2130 should be “small”, e.g., less than 0.5mm, e.g., less than 0.25mm, at higher pressure to avoid plasma occurring behind plate.

The conductors 2120 can be formed directly on a lower surface of the dielectric top
15 plate surface 2130. For example, the conductors 2120 can be formed by deposition (e.g. plating, sputtering or CVD) of a thin layer across the bottom surface followed by patterning by etching, to form a stripline structure. The conductors can then be covered by the dielectric bottom dielectric plate 2132.

The conductors 2120 can also be embedded in, i.e., be buried below the surface of,
20 the dielectric top plate. For example, the top plate 2130 can be a ceramic structure, similar in construction to an electrostatic wafer chuck. For the buried conductor, the dielectric bottom plate becomes optional, but can still be used as a dielectric cover, e.g., of quartz, to protect the bottom surface of the top plate.

In an exemplary implementation, 45 pairs (90 total) of parallel conductors 2120 are
25 deposited on a square structural ceramic top plate 2130. The linewidth of the conductors 2120 is 3mm each, with 1.5mm separation (so the conductors are arranged at a pitch of 4.5 mm). The conductors can be 400 mm long, with vertical feedthroughs through the ceramic top plate 2130, and electrical connections made on backside at atmospheric pressure. Every other electrode is connected to a bus on one side, and the remaining (alternating) electrodes
30 are each connected to a bus on the other side, thus forming two arrays. RF power at 60 MHz and 180 degree phase difference is connected across the 2 arrays.

Referring to FIG. 15B, a plurality of grooves 2136 can be formed in a bottom surface 2130a of the dielectric top plate 2130, and the conductors 2120 can fit into the grooves. The grooves 2136 can be arranged as parallel linear stripes.

In some implementations, each conductor 2120 is part of a filament 2150. The filament 2150 can fit into its respective groove 2136. The filament 2150 can include a shell that surrounds and protects the conductor 2120. The filament 2150 can be provided by the various filaments 300 described with reference to FIGS. 3A-C.

Referring to FIG. 15C, in some implementations, the conductors 2120 can be provided by a conductive coating on the top plate 2130. For example, the conductor 2120 can be a stripline electrode plated on the ceramic top plate 2130. Each conductor 2120 can be a coating on one or more interior surfaces of a respective groove 2136. A space between the conductor 2120 and the bottom plate 2132 can provide a conduit 2450. The conduit 2450 can carry a fluid as described for FIG. 3A.

Plasma simulation, using a 2-D model, was performed to investigate plasma parameter dependence on gas pressure. The computational domain was over two half-pairs of electrodes. Process conditions were assumed to be 1450 sccm Argon + 50 sccm N₂ per source, 6 torr, 200W per pair of half electrodes. Simulation indicated plasma densities generally would be higher in the region below the electrodes. Ar⁺ density and electron density were similar (much lower N₂⁺ density, primarily due to high ratio of Argon to N₂ gas supply).

Particular embodiments of the invention have been described. While this specification contains many specific implementation details, many other variations are possible. For example:

- Rather than a rotating platform, the workpiece may be moved linearly through a sequence of chambers, e.g., on a belt or linearly actuated platform. In addition, the workpiece could be stationary, e.g., the workpiece support does not move relative to the filaments.

- Connection of the RF power to the conductor busses at the center, ends, or other position or combination of positions on the bus.

- Grounding of electrode busses can be performed at the center, ends, or other position or combination of positions on the bus.

- The RF power supply can apply signals in the RF, VHF, UHF or microwave range.

Other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A processing tool for a plasma process, the processing tool comprising:
a chamber body having an interior space that provides a plasma chamber, the chamber body having a ceiling and an opening on a side opposite the ceiling,
a workpiece support to hold a workpiece such that at least a portion of a front surface of the workpiece faces the opening;
an actuator to generate relative motion between the chamber body and the workpiece support such that the opening moves laterally across the workpiece;
a gas distributor to deliver a processing gas to the plasma chamber;
an electrode assembly comprising a plurality of coplanar filaments extending laterally through the plasma chamber between the workpiece support and the ceiling, each of the plurality of filaments including a conductor; and
a first RF power source to supply a first RF power to the conductors of the electrode assembly to form a plasma.
2. The processing tool of claim 1, wherein the workpiece support is rotatable about an axis of rotation and the actuator rotates the workpiece support such that rotation of the support carries the workpiece across the opening.
3. The processing tool of claim 2, wherein the plurality of coplanar filaments extend across a wedge-shaped area.
4. The processing tool of claim 3, wherein the workpiece fits entirely within the wedge-shaped area such that in operation an entirety of the front surface of the workpiece is exposed to plasma.
5. The processing tool of claim 3, wherein the workpiece is larger than the wedge-shaped area such that in operation a wedge-shaped portion of the front surface of the workpiece is exposed to plasma.
6. The processing tool of claim 3, wherein the opening is wedge-shaped.

7. The processing tool of claim 3, wherein the plurality of coplanar filaments comprise linear filaments, and different filaments have different lengths so as to define the wedge-shaped area.

8. The processing tool of claim 7, wherein the plurality of coplanar filaments extend in parallel.

9. The processing tool of claim 3, wherein the plurality of coplanar filaments are oriented to have longitudinal axes at a non-zero angle relative to a direction of motion of the portion of the substrate below the opening.

10. The processing tool of claim 1, wherein a bottom of the chamber is open.

11. The processing tool of claim 1, wherein ends of conductors of the plurality of coplanar filaments are connected to the first RF power source by a recursive RF feed structure.

12. A plasma reactor comprising:
a chamber body having an interior space that provides a plasma chamber;
a gas distributor to deliver a processing gas to the plasma chamber;
a pump coupled to the plasma chamber to evacuate the chamber;
a workpiece support to hold a workpiece;
an intra-chamber electrode assembly comprising a plurality of filaments extending laterally through the plasma chamber between a ceiling of the plasma chamber and the workpiece support, each filament including a conductor surrounded by a cylindrical insulating shell, wherein the plurality of filaments includes a first multiplicity of filaments and a second multiplicity of filaments arranged in an alternating pattern with the first multiplicity of filaments,
a first bus coupled to the first multiplicity of filaments and a second bus coupled to the second multiplicity of filaments;

an RF power source to apply an RF signal the intra-chamber electrode assembly; and
at least one RF switch configured to controllably electrically couple and decouple the first bus from one of i) ground, ii) the RF power source, or iii) the second bus.

13. The plasma reactor of claim 12, wherein the at least one RF switch is configured to controllably electrically couple and decouple the first bus from the second bus, and wherein the at least one RF switch comprises a plurality of switches connected in parallel between different pairs of locations on the first bus and the second bus to controllably electrically couple and decouple the first bus from the second bus.

14. The plasma reactor of claim 12, wherein the at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from ground, and comprising at least one second RF switch configured to controllably electrically couple and decouple the second bus from ground.

15. The plasma reactor of claim 14, wherein the at least one RF switch comprises a first plurality of switches connected in parallel between different locations on the first bus and ground, and the at least one second switch comprises a second plurality of switches connected in parallel between different locations on the second bus and ground.

16. The plasma reactor of claim 12, wherein the at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from the RF power source, and comprising at least one second switch configured to controllably electrically couple and decouple the second bus from the RF power source.

17. The plasma reactor of claim 16, wherein the at least one RF switch comprises a first plurality of switches connected in parallel between different locations on the first bus and the RF power source, and the at least one second switch comprises a second plurality of switches connected in parallel between different locations on the second bus and the RF power source.

18. The plasma reactor of claim 12, comprising:
a third bus coupled to the first multiplicity of filaments, and a fourth bus coupled to the second multiplicity of filaments,
wherein the plurality of filaments have a plurality of first ends and a plurality of second ends and a first end of each respective filament is closer to a first sidewall of the plasma chamber than a second end of the respective filament, and
wherein the first bus is coupled to the first ends of the first multiplicity of filaments, the second bus is coupled to the first ends of the second multiplicity of filaments, the third bus is coupled to the second ends of the first multiplicity of filaments, and the fourth bus is coupled to the second ends of the second multiplicity of filaments.

19. The plasma reactor of claim 18, wherein the at least one RF switch is configured to controllably electrically couple and decouple the first bus from the second bus, and comprising at least one second RF switch configured to controllably electrically couple and decouple the third bus from the fourth bus.

20. The plasma reactor of claim 18, wherein the at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from ground, and comprising at least one second RF switch configured to controllably electrically couple and decouple the third bus from ground.

21. The plasma reactor of claim 18, wherein the at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from ground, and comprising at least one second RF switch configured to controllably electrically couple and decouple the second bus from the RF source, at least one third RF switch configured to controllably electrically couple and decouple the third bus from ground, and comprising at least one fourth RF switch configured to controllably electrically couple and decouple the fourth bus from the RF source.

22. The plasma reactor of claim 18, wherein the at least one RF switch includes a first switch configured to controllably electrically couple and decouple the first bus from the

RF source, and comprising at least one second RF switch configured to controllably electrically couple and decouple the second bus from the RF source, at least one third RF switch configured to controllably electrically couple and decouple the third bus from the RF source, and comprising at least one fourth RF switch configured to controllably electrically couple and decouple the fourth bus from the RF source.

23. A plasma reactor comprising:

a chamber body having an interior space that provides a plasma chamber;

a gas distributor to deliver a processing gas to the plasma chamber;

a pump coupled to the plasma chamber to evacuate the chamber;

a workpiece support to hold a workpiece;

an intra-chamber electrode assembly comprising a plurality of filaments extending laterally through the plasma chamber between a ceiling of the plasma chamber and the workpiece support, each filament including a conductor surrounded by a cylindrical insulating shell,

a bus outside the chamber and coupled to opposing ends of plurality of filaments;

an RF power source to apply an RF signal the intra-chamber electrode assembly; and

a plurality of RF switch configured to controllably electrically couple and decouple a plurality of different locations on bus from one of i) ground or ii) the RF power source.

24. A plasma reactor comprising:

a chamber body having an interior space that provides a plasma chamber;

a gas distributor to deliver a processing gas to the plasma chamber;

a workpiece support to hold a workpiece;

an electrode assembly comprising a plurality of conductors spaced apart from and extending laterally across the workpiece support in a parallel coplanar array;

a first RF power source to supply a first RF power to the electrode assembly; and

a dielectric bottom plate between the electrode assembly and the workpiece support, the dielectric bottom plate providing an RF window between the electrode assembly and the plasma chamber.

25. The plasma reactor of claim 24, comprising a dielectric top plate, wherein the plurality of conductors are positioned between the dielectric top plate and the dielectric window.

26. The plasma reactor of claim 25, wherein a lower surface of the bottom plate has a plurality of parallel grooves, and wherein the plurality of parallel coplanar conductors positioned in the plurality of parallel grooves.

27. The plasma reactor of claim 26, wherein the shell forms a conduit and the conductor is suspended in and extends through the conduit, or wherein the conductor comprises a hollow conduit, or comprising a plurality of filaments in the plurality of grooves with each filament comprising a conductor and a non-metallic shell surrounding the conductor.

28. The plasma reactor of claim 25, wherein the plurality of conductors are coated on the dielectric top plate.

29. The plasma reactor of claim 25, wherein the plurality of conductors are embedded in the dielectric top plate.

30. The plasma reactor of claim 24, wherein the plurality of conductors includes a first multiplicity of conductors and a second multiplicity of conductors arranged in an alternating pattern with the first multiplicity of conductors, and the RF power source is configured to apply a first RF input signal to the first multiplicity of conductors, and to apply a second RF input signal to the second multiplicity of conductors.

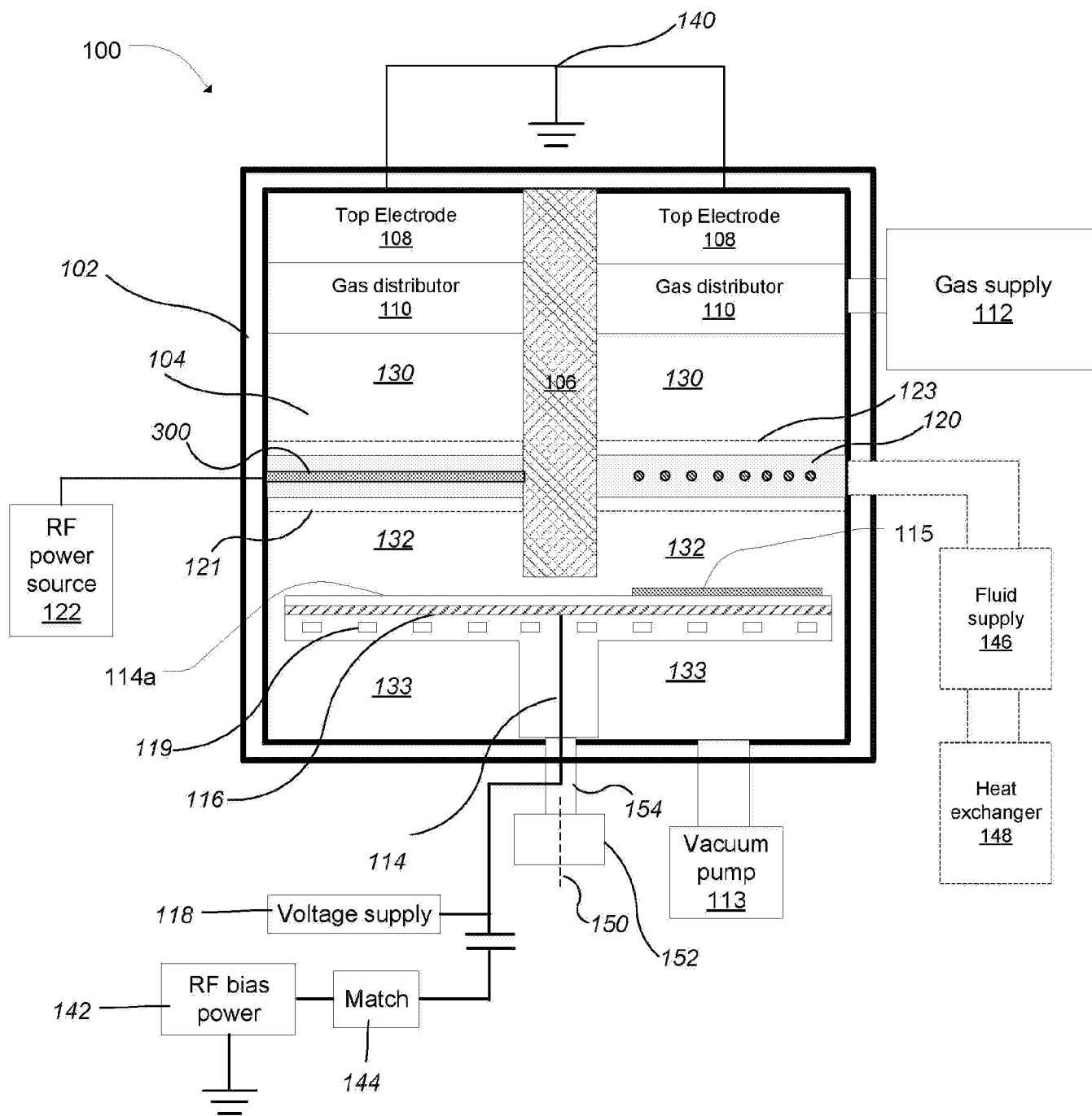


FIG. 1

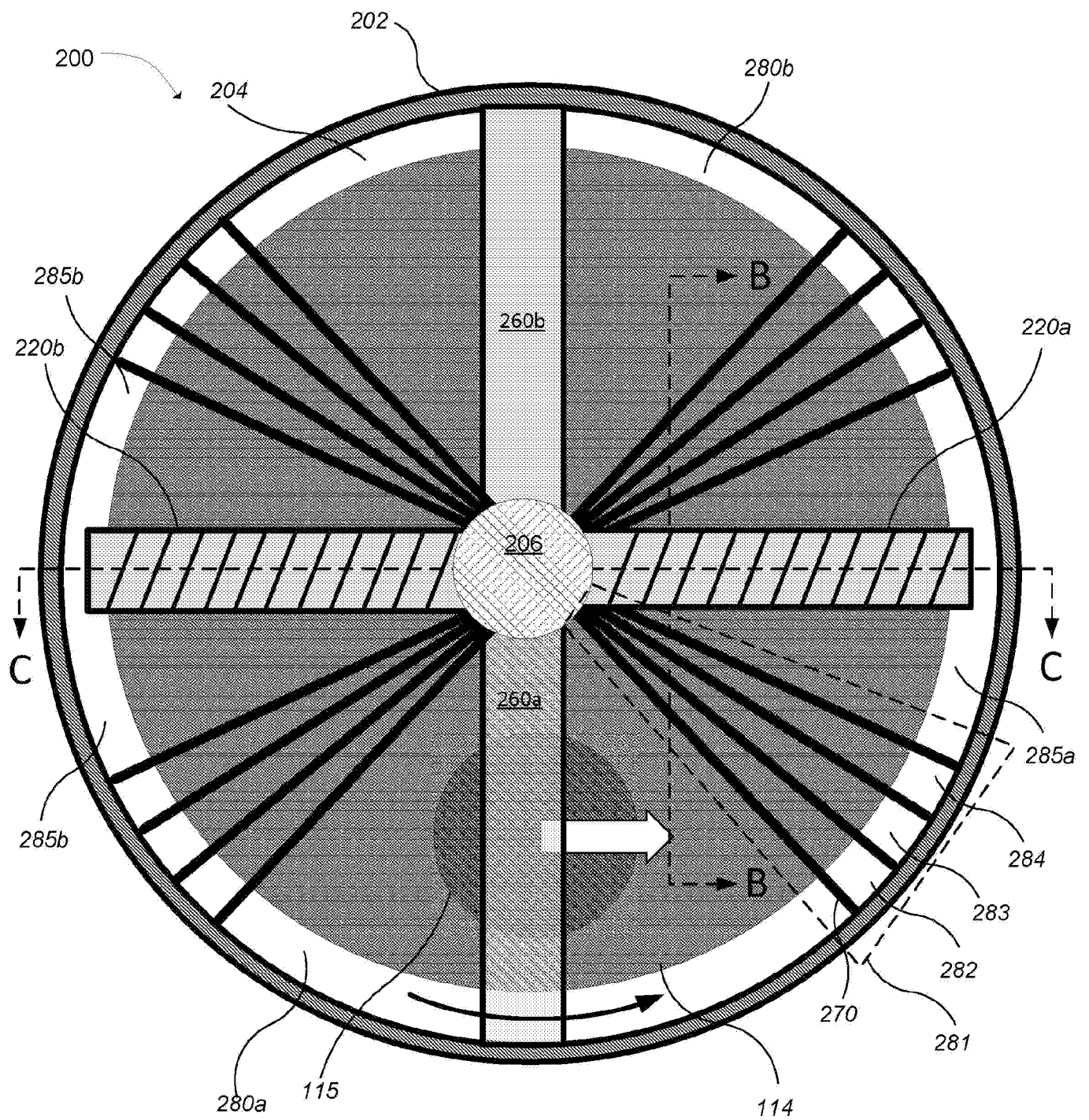


FIG. 2A

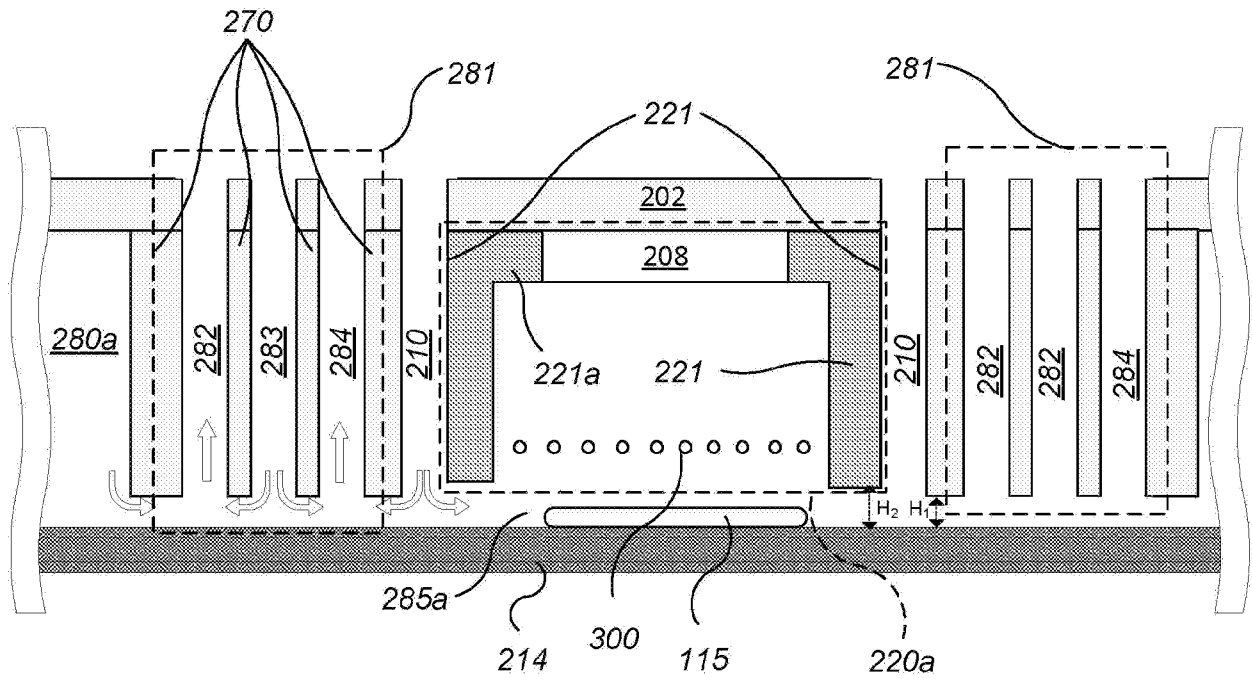


FIG. 2B

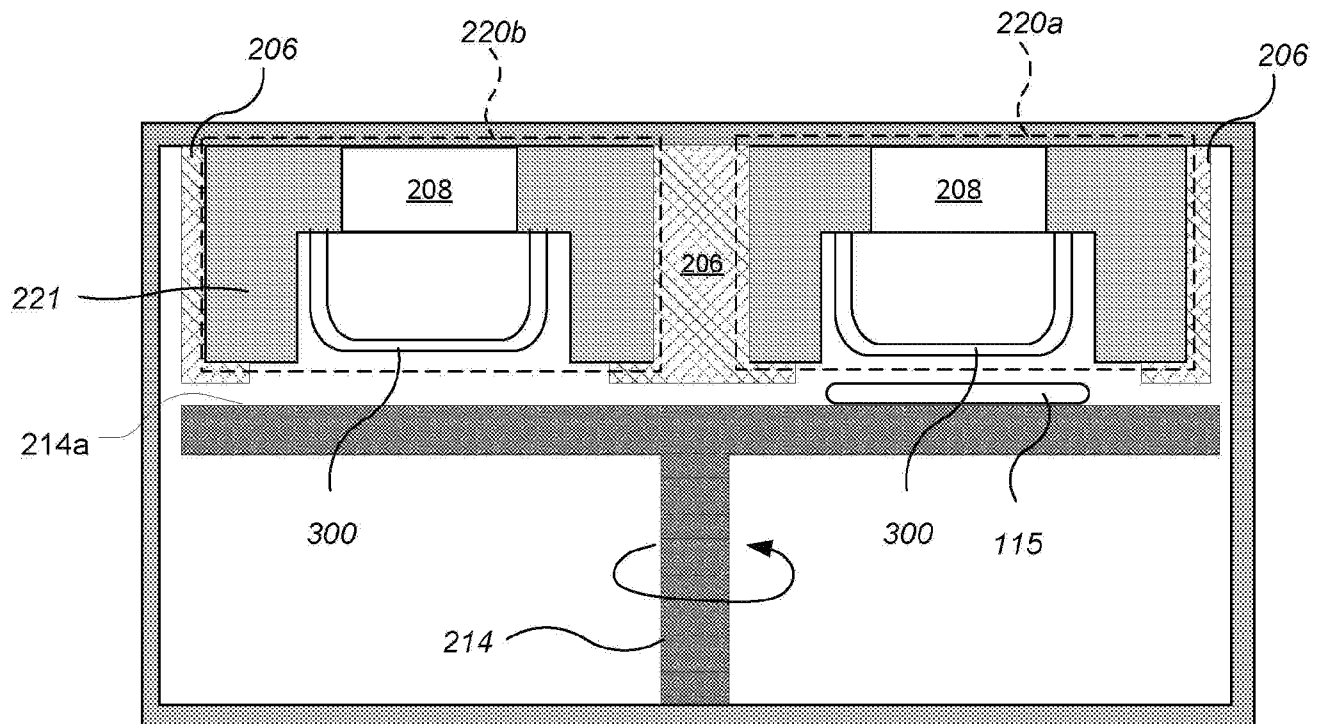


FIG. 2C

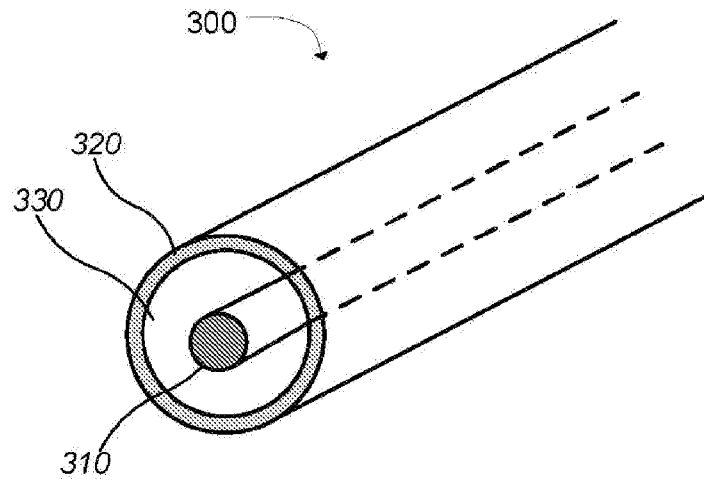


FIG. 3A

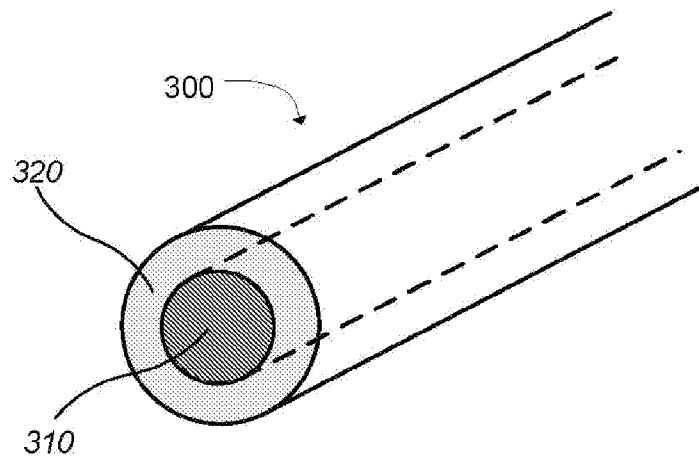


FIG. 3B

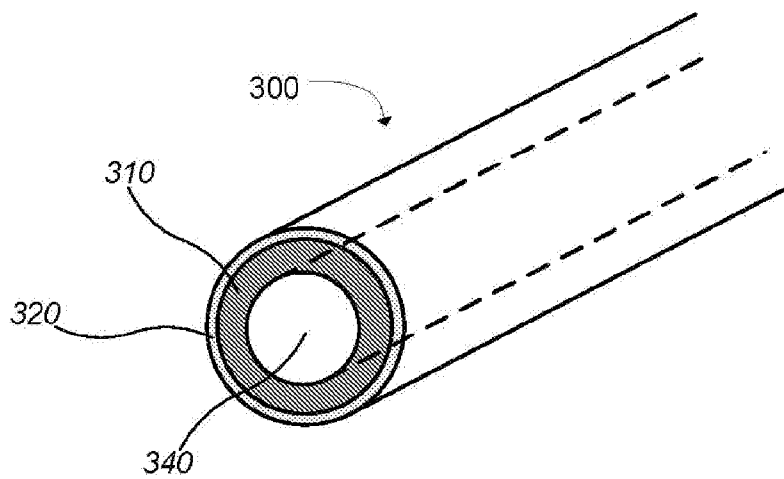


FIG. 3C

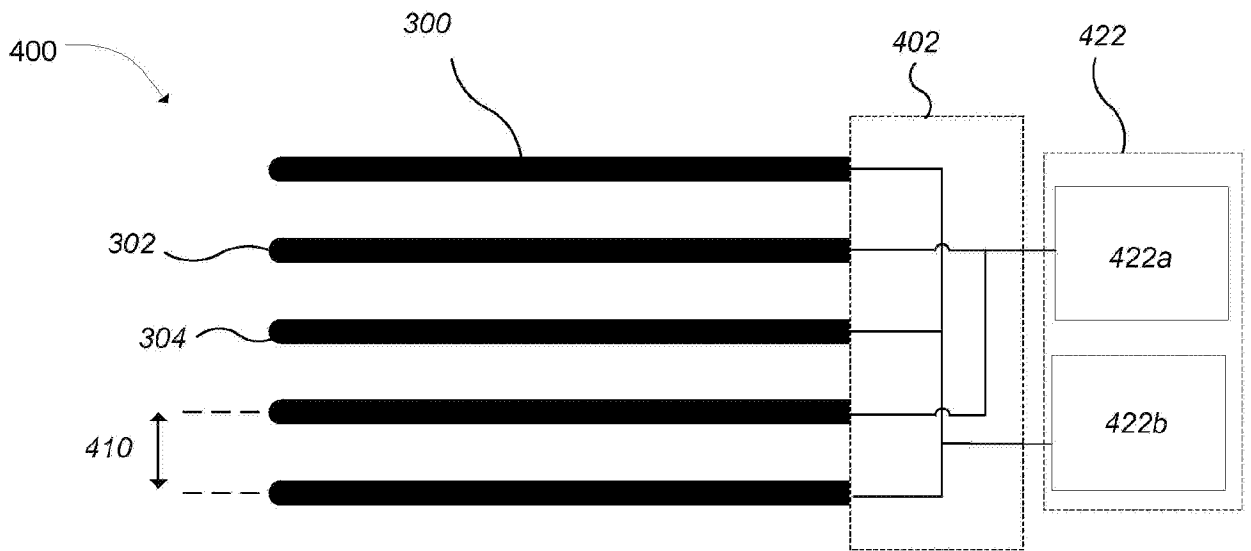


FIG. 4A

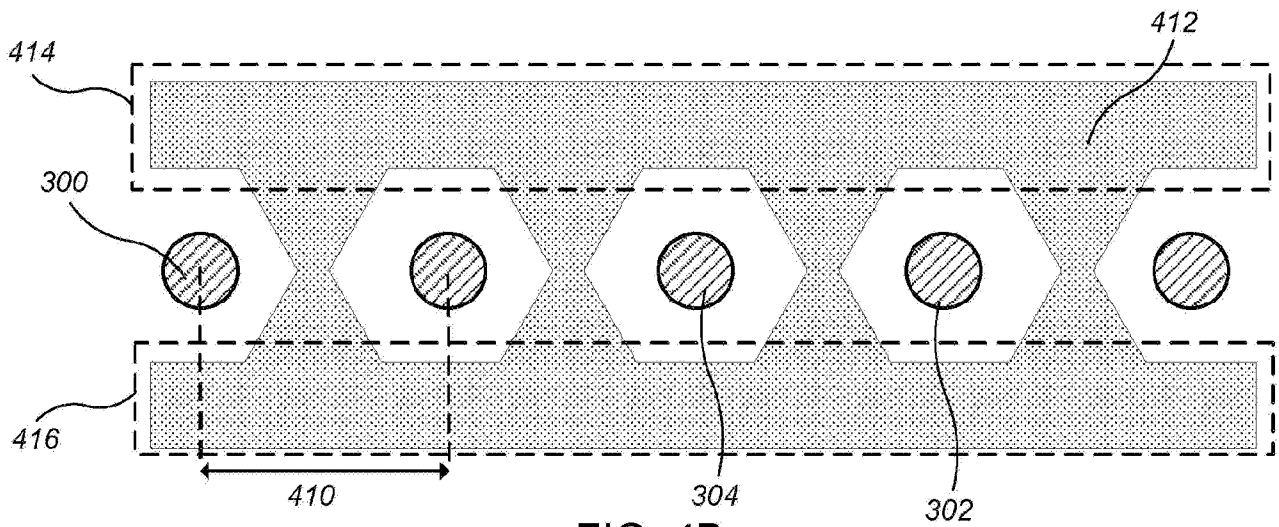


FIG. 4B

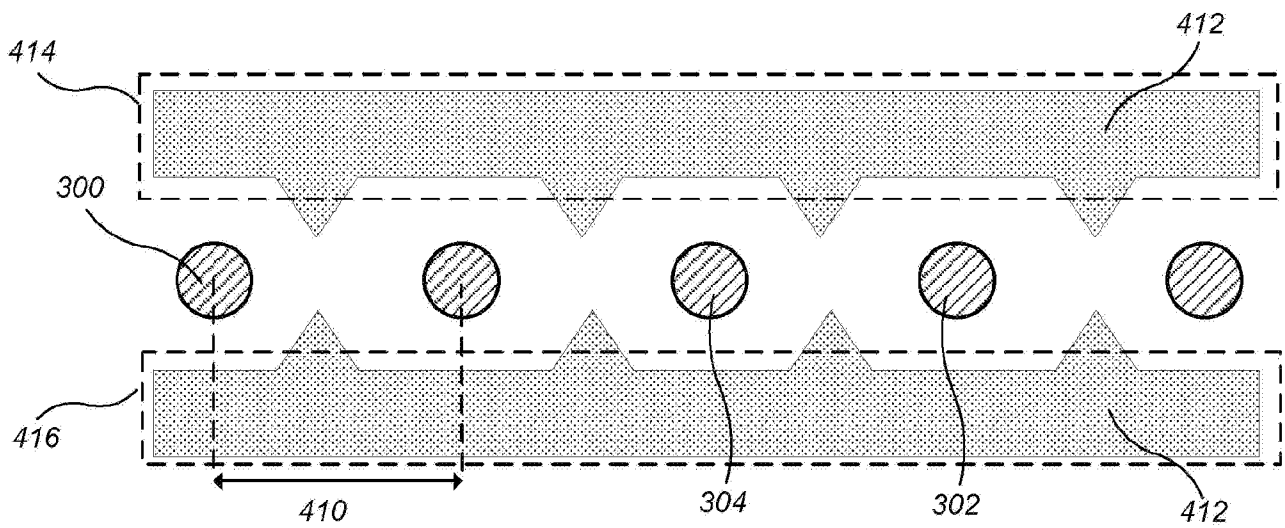


FIG. 4C

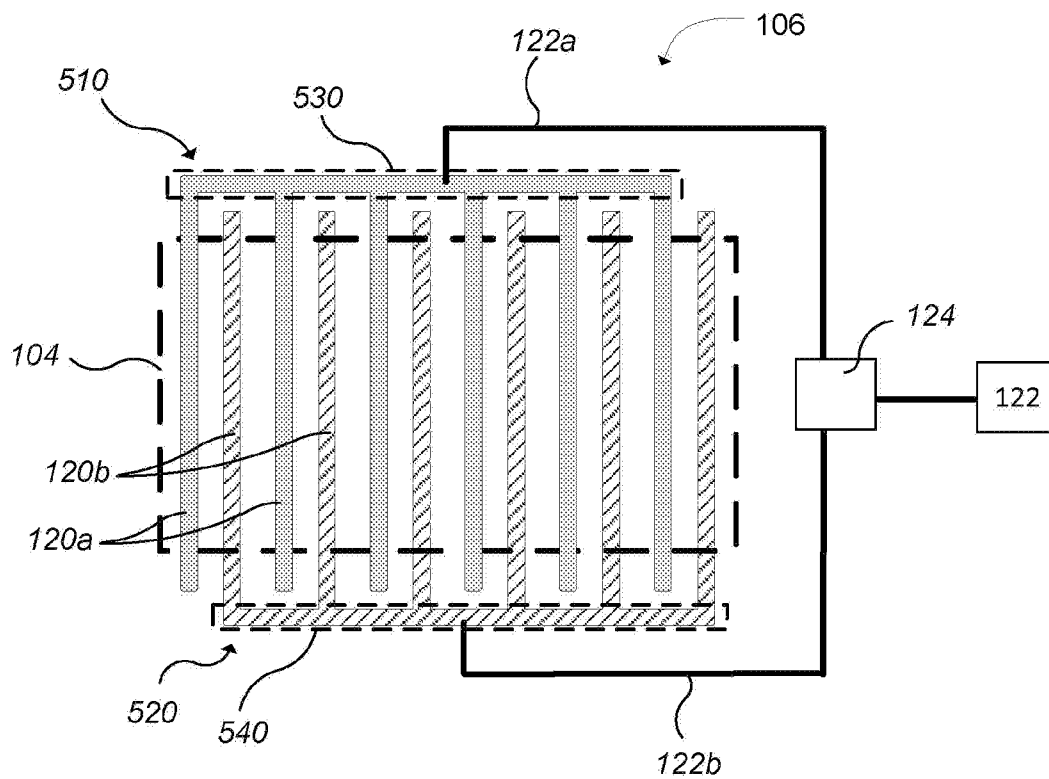


FIG. 5A

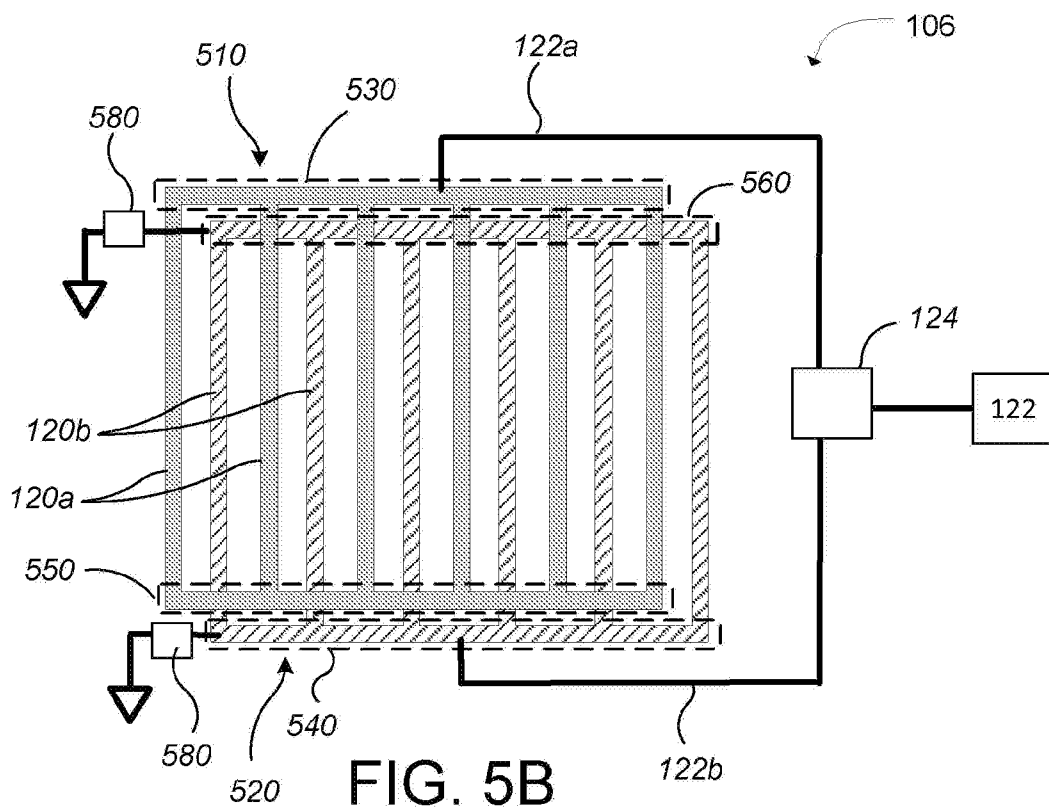


FIG. 5B

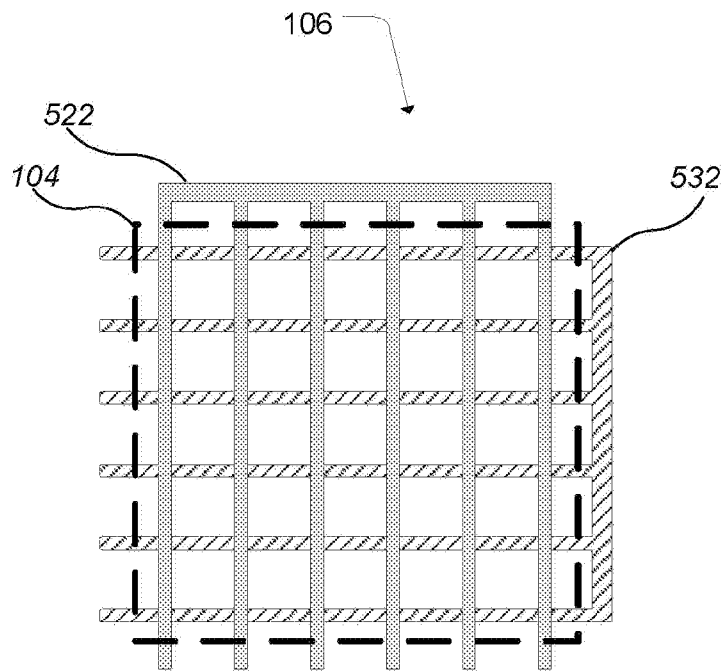


FIG. 5C

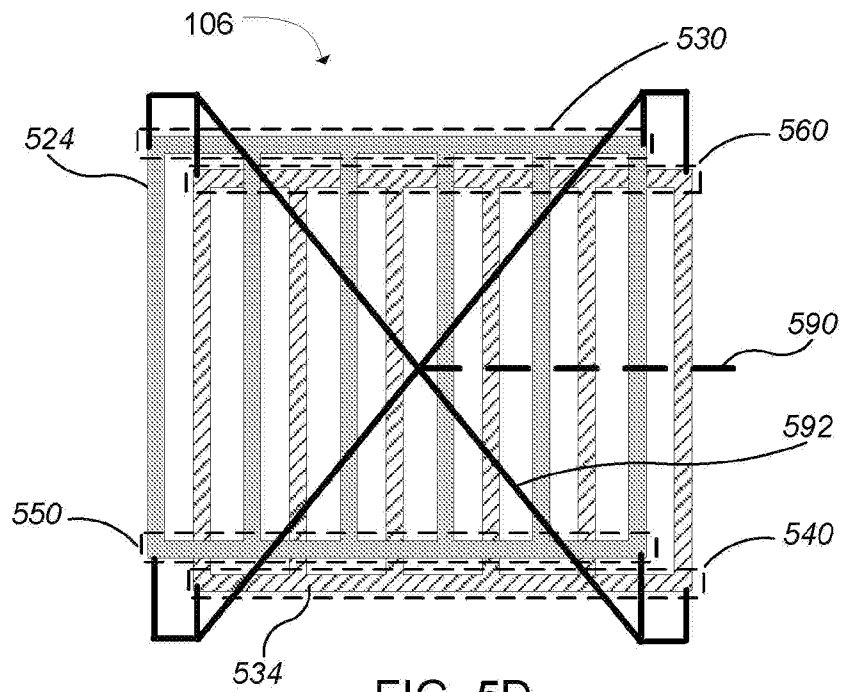


FIG. 5D

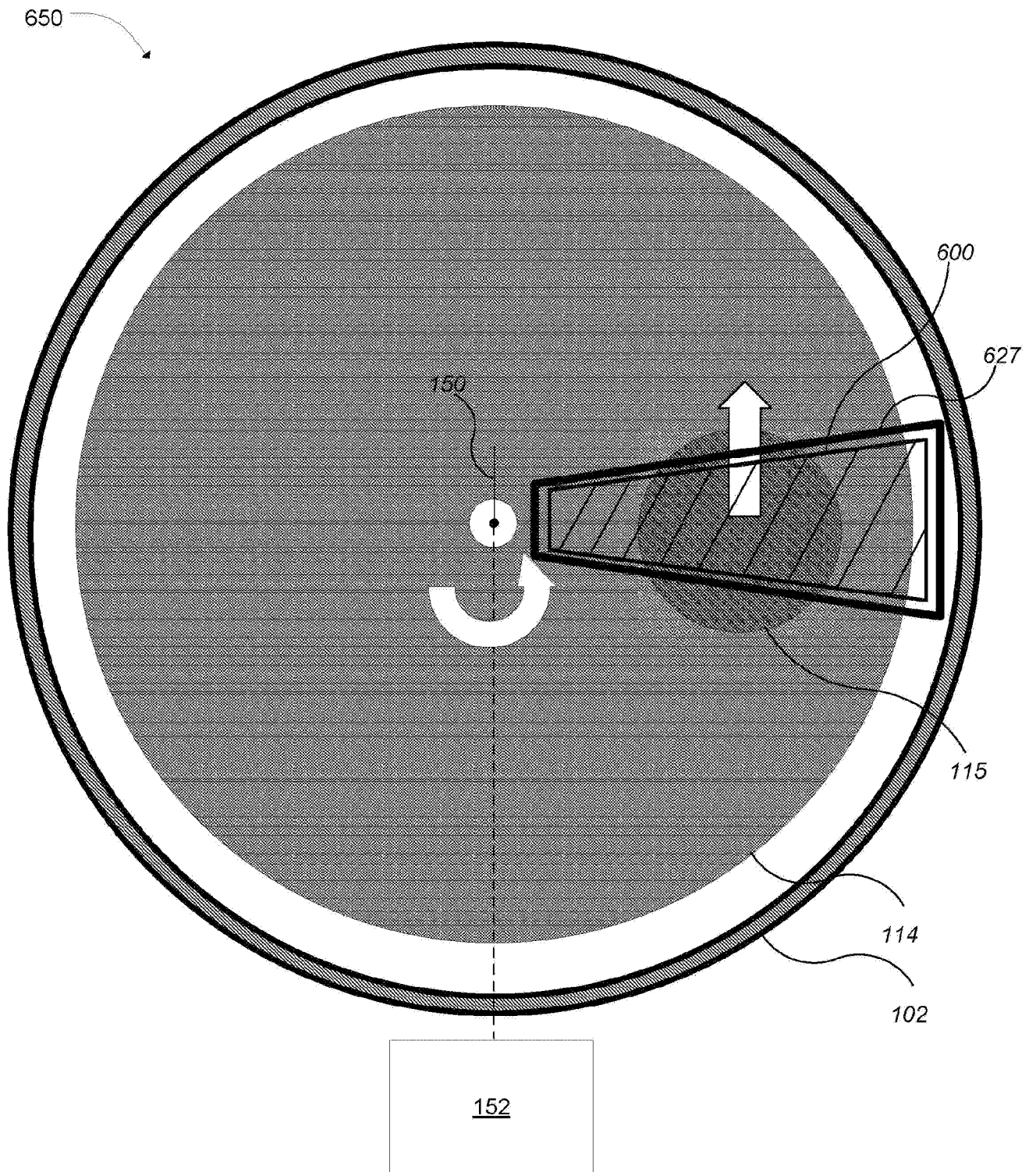


FIG. 6A

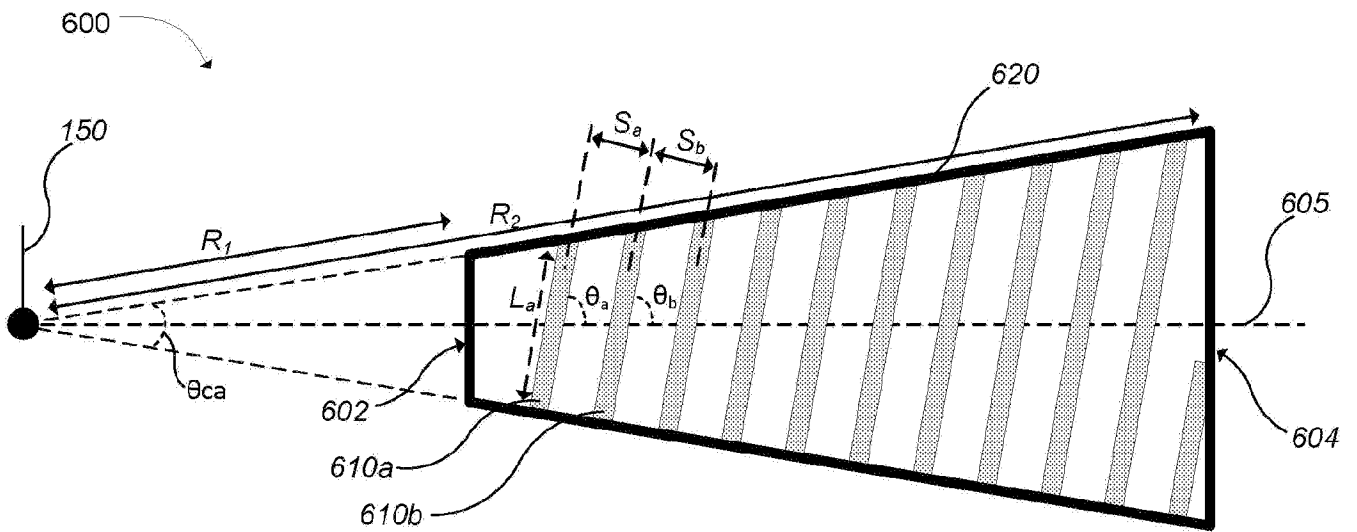


FIG. 6B

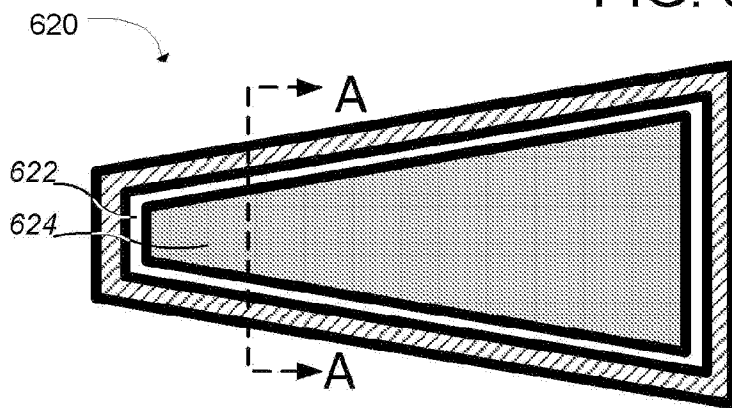


FIG. 6C

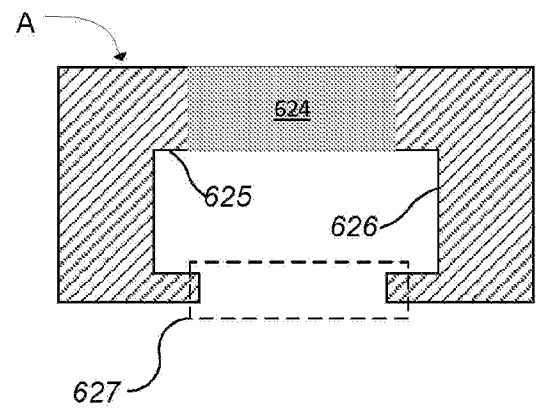


FIG. 6D

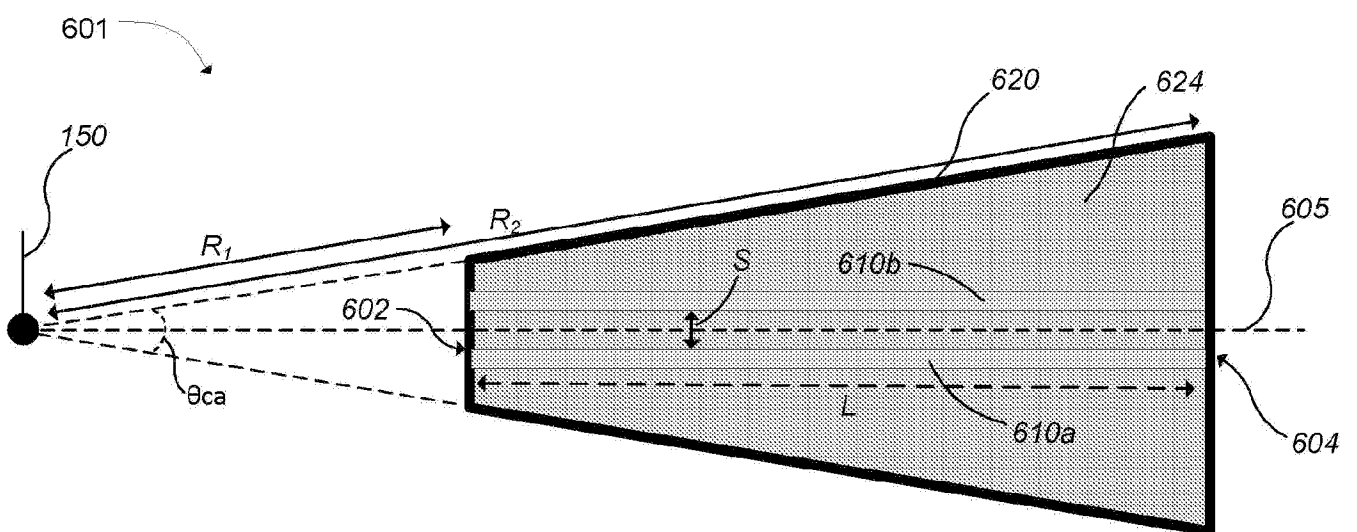


FIG. 6E

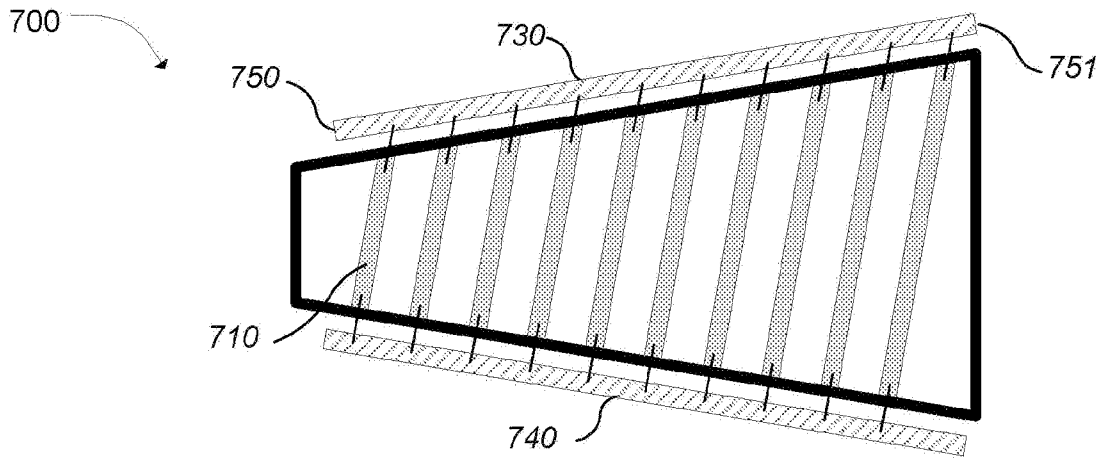


FIG. 7A

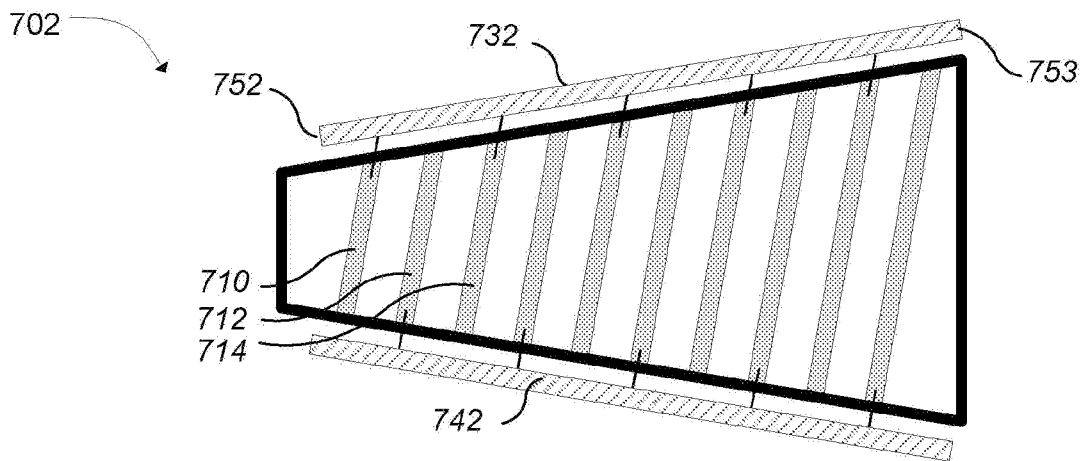


FIG. 7B

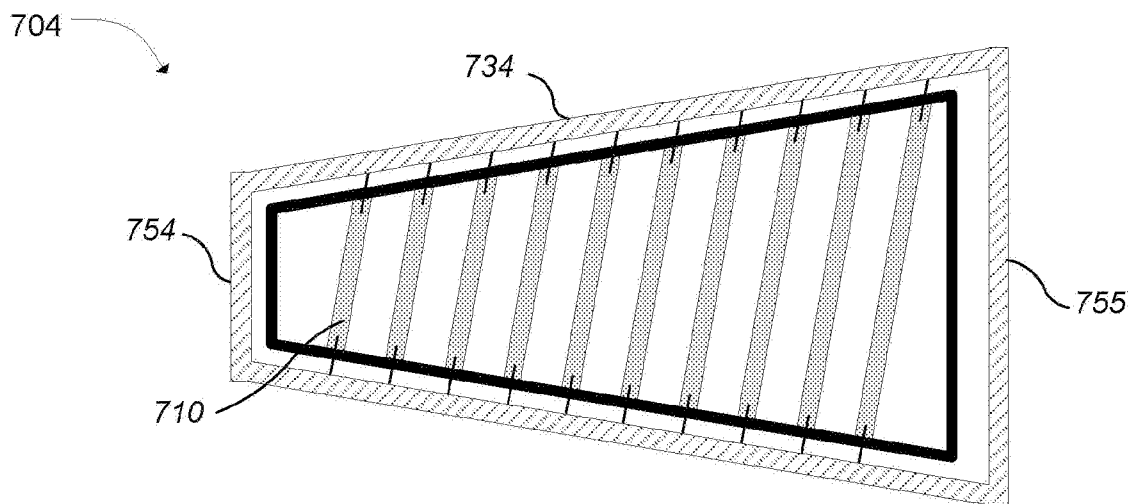


FIG. 7C

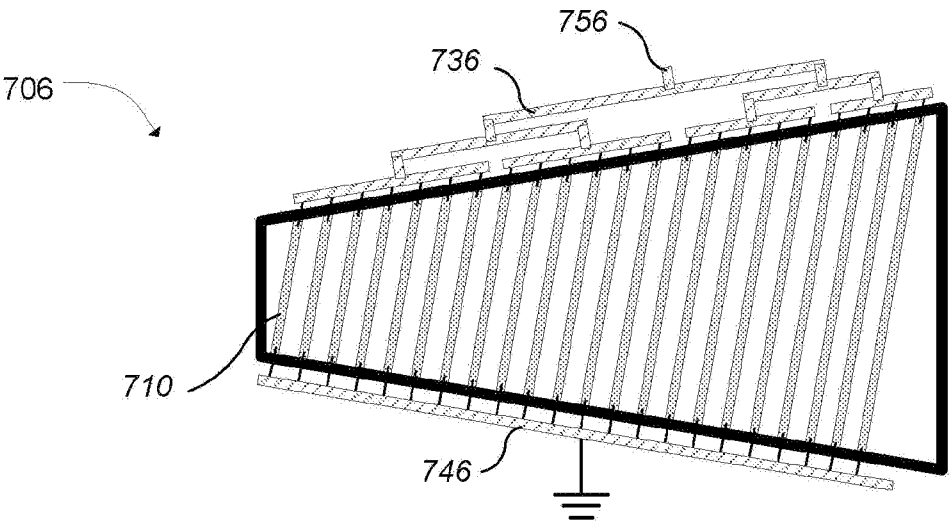


FIG. 7D

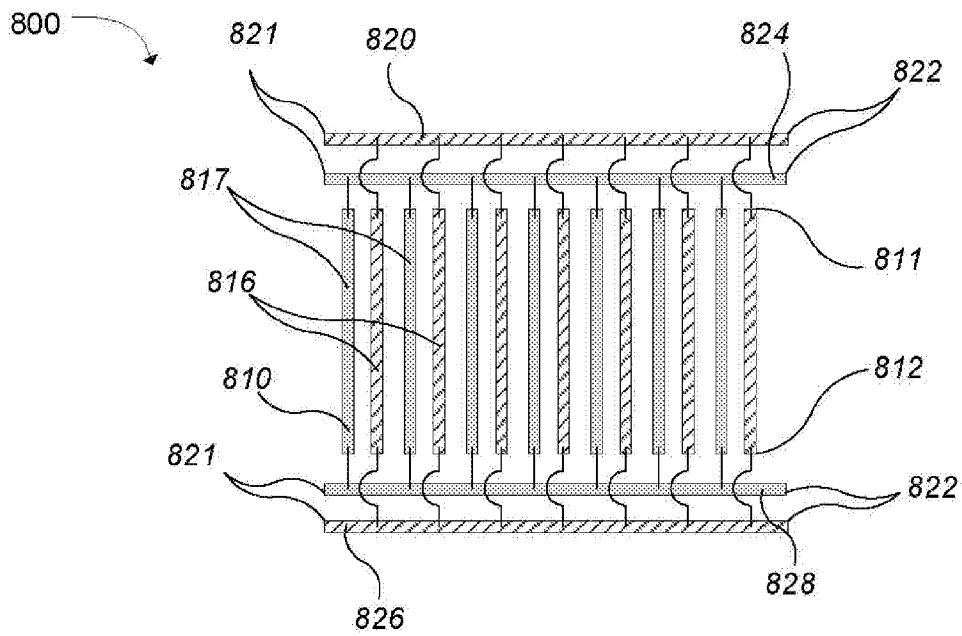


FIG. 8A

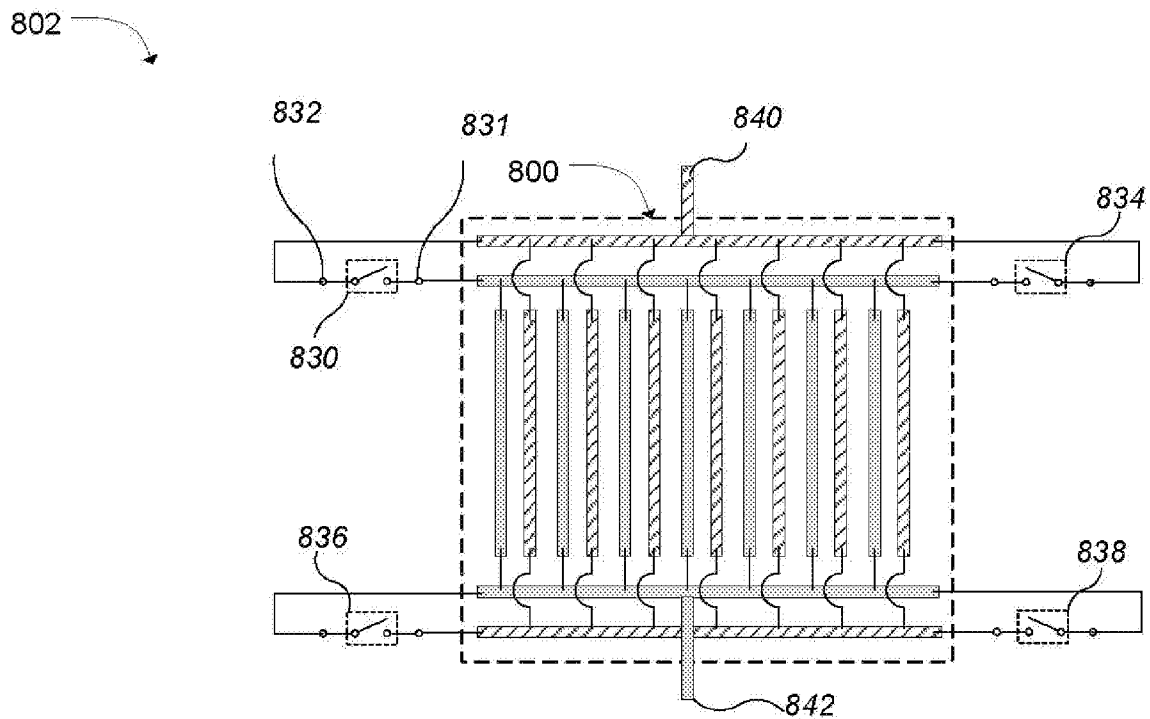


FIG. 8B

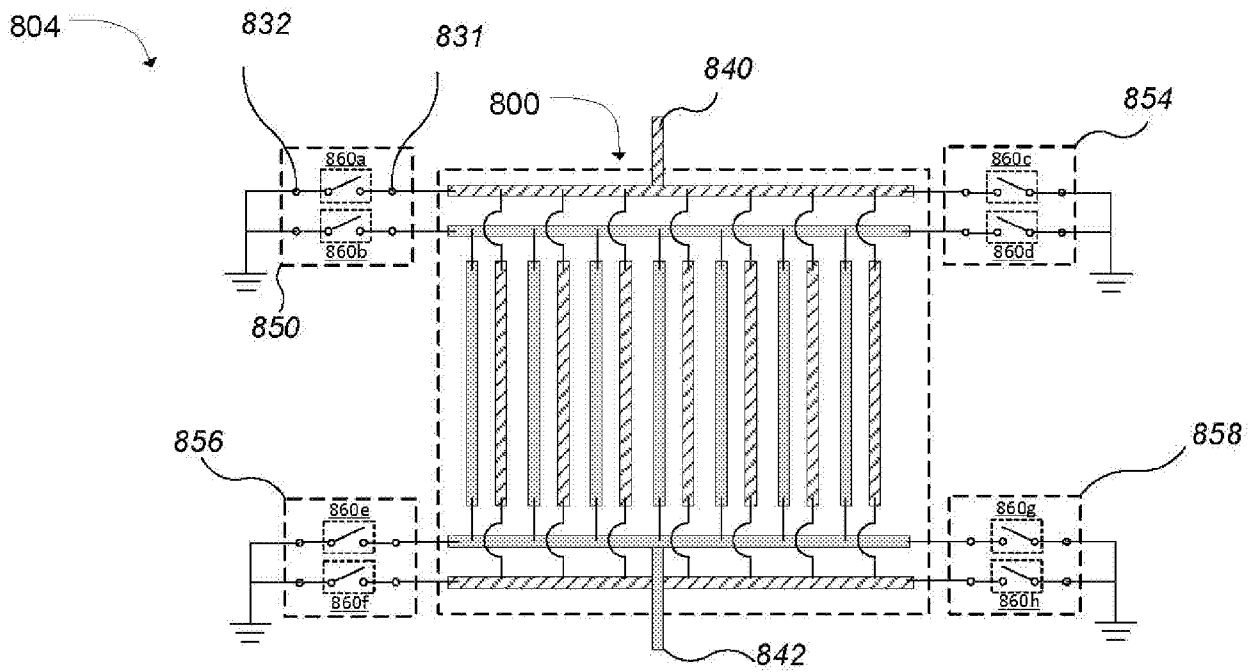


FIG. 8C

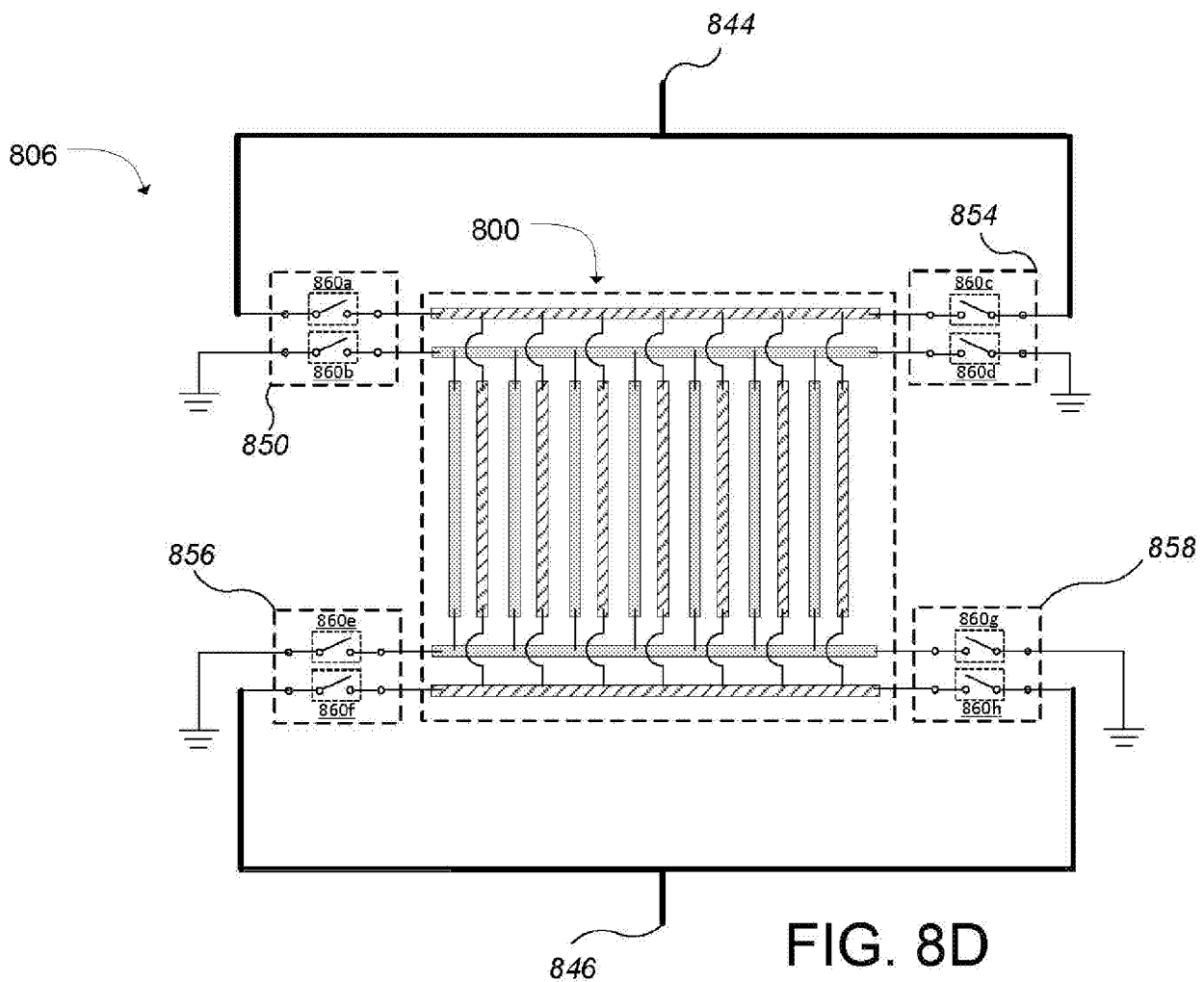
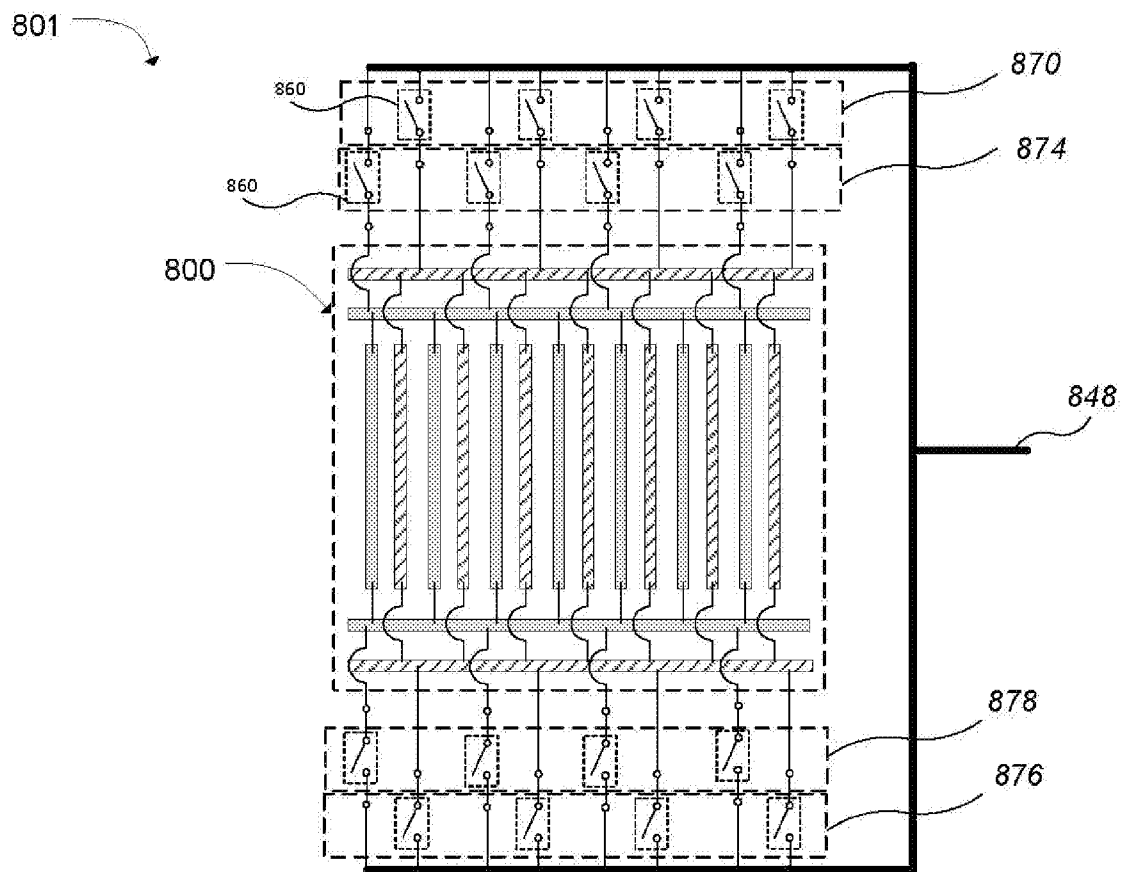
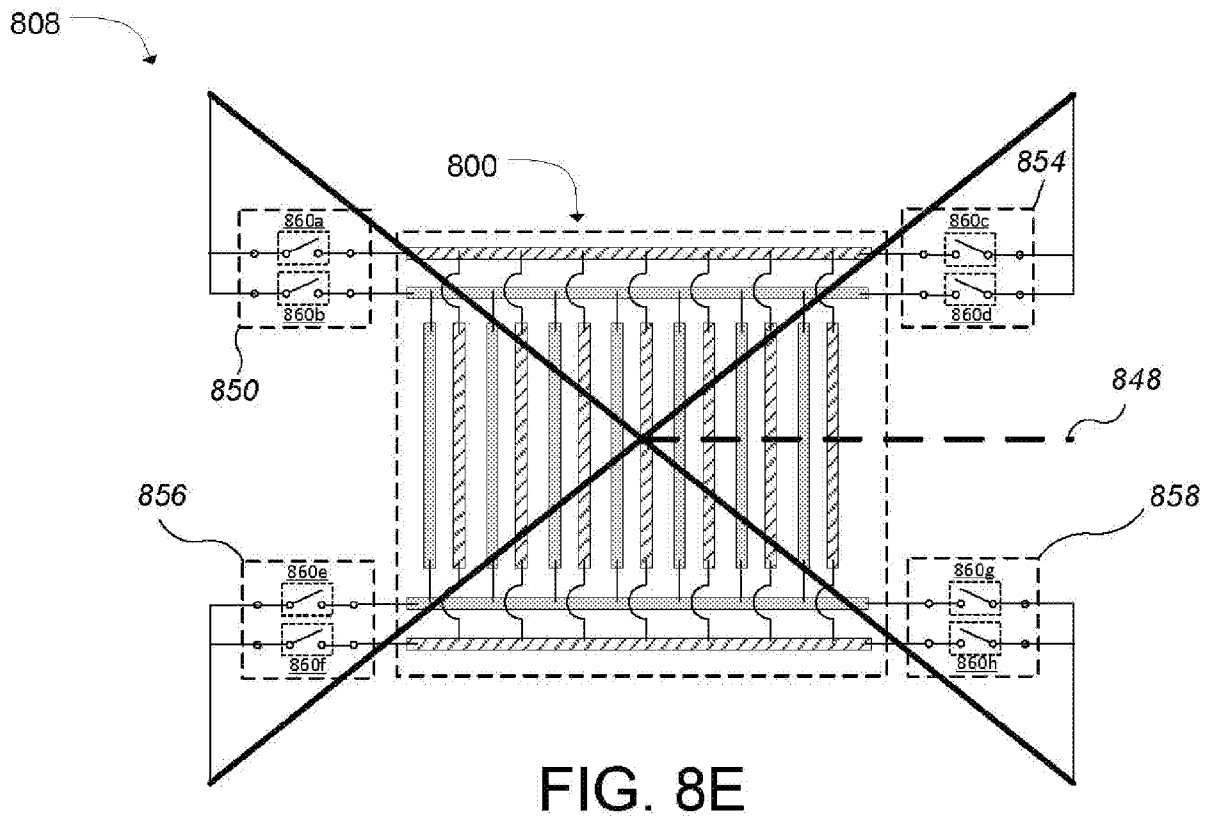


FIG. 8D



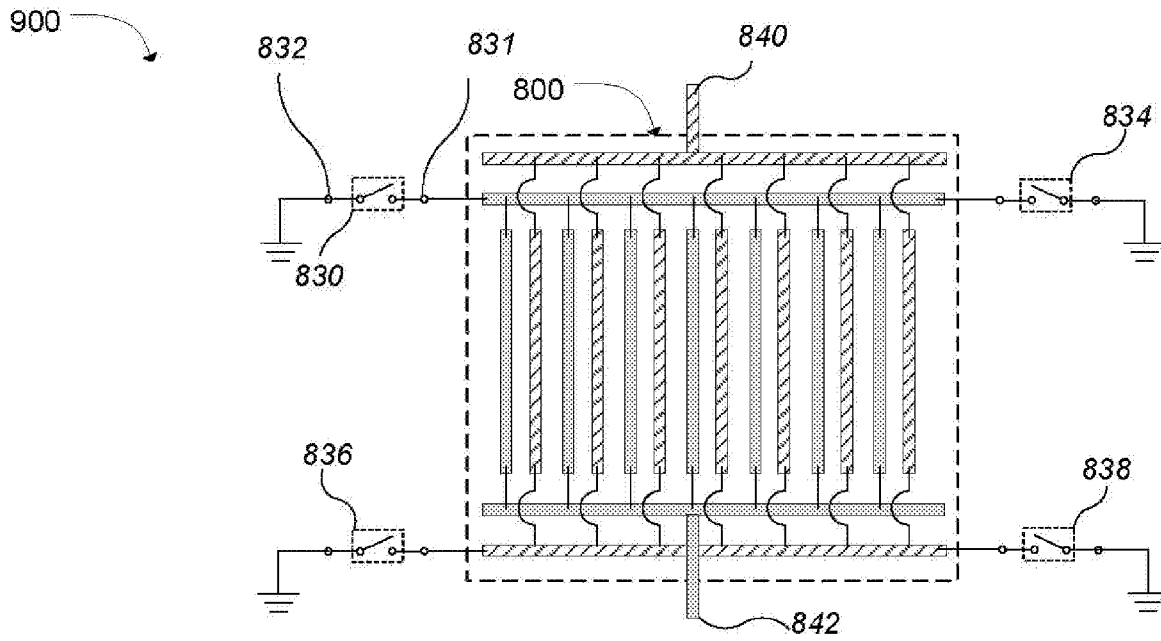


FIG. 9A

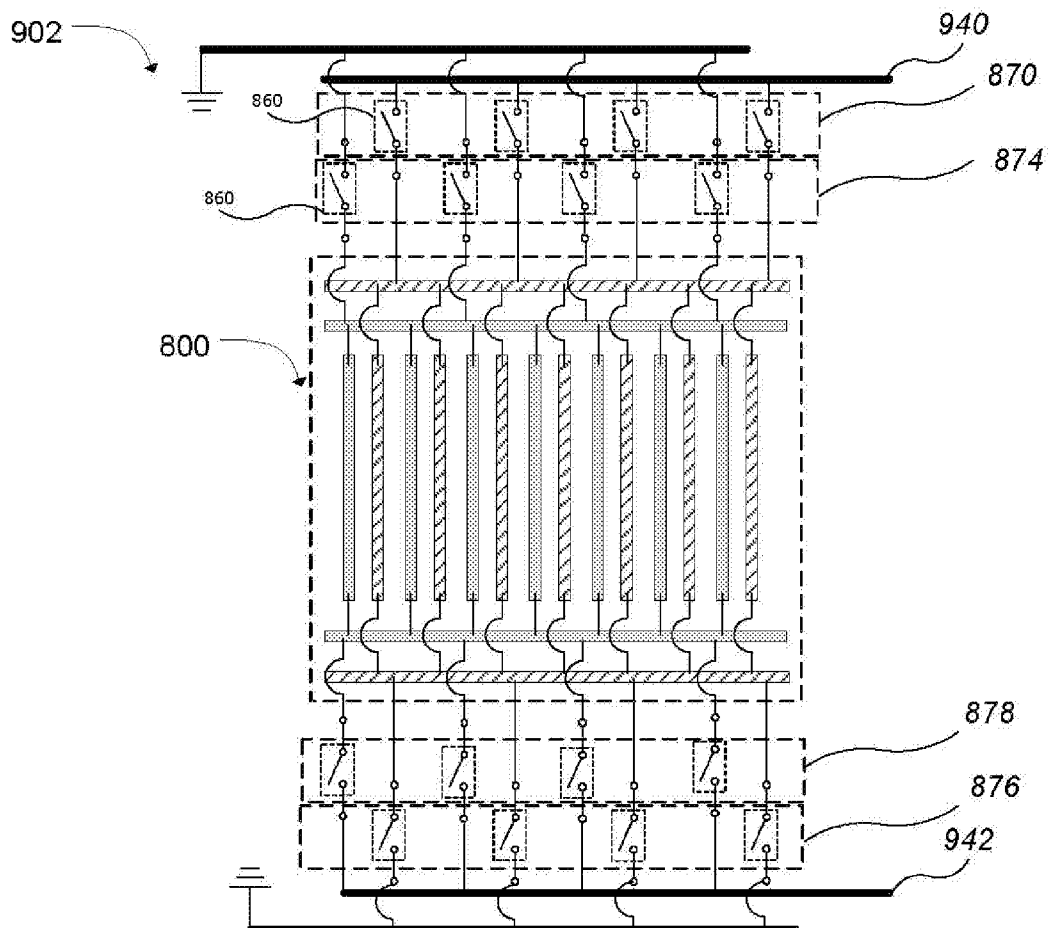


FIG. 9B

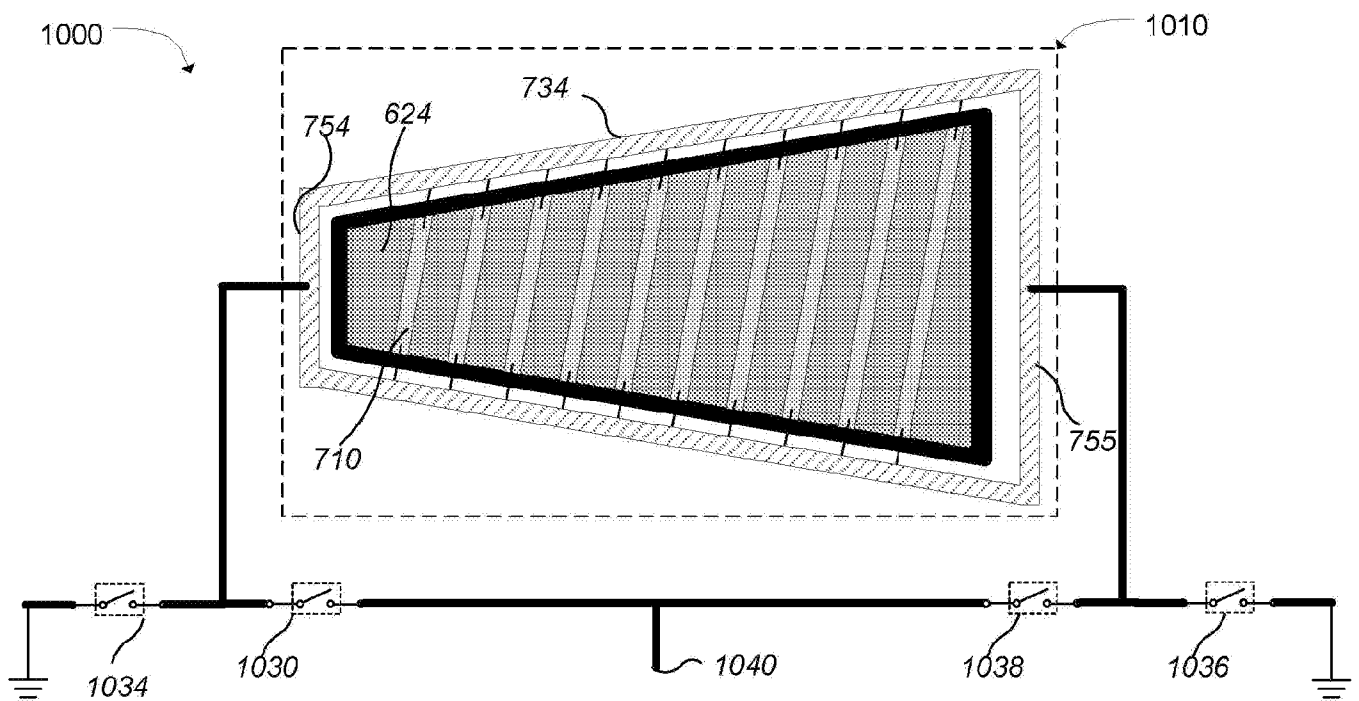


FIG. 10

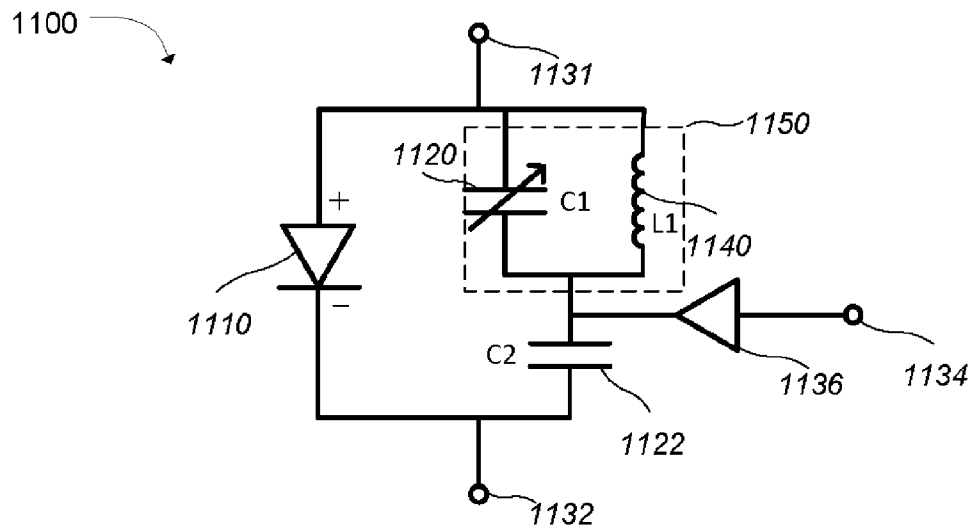


FIG. 11A

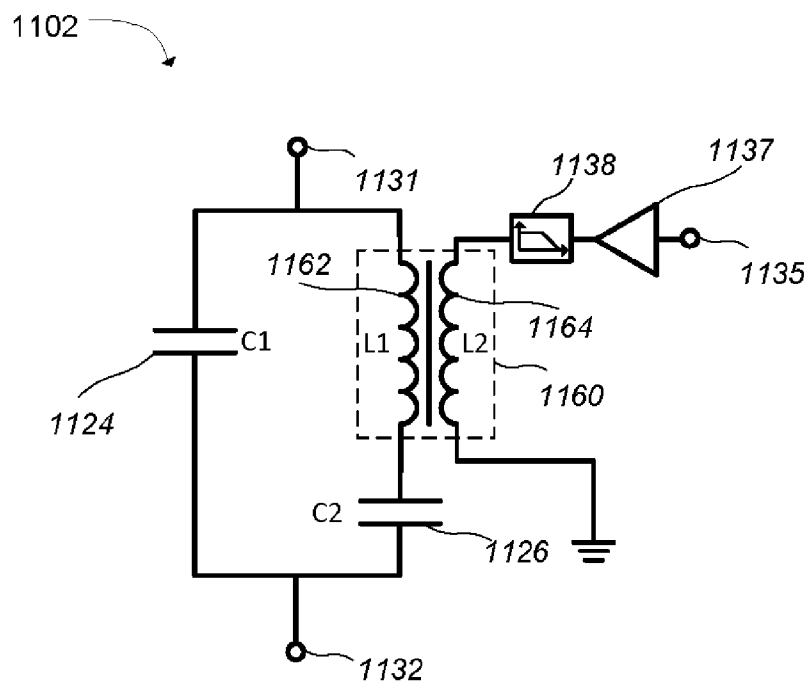


FIG. 11B

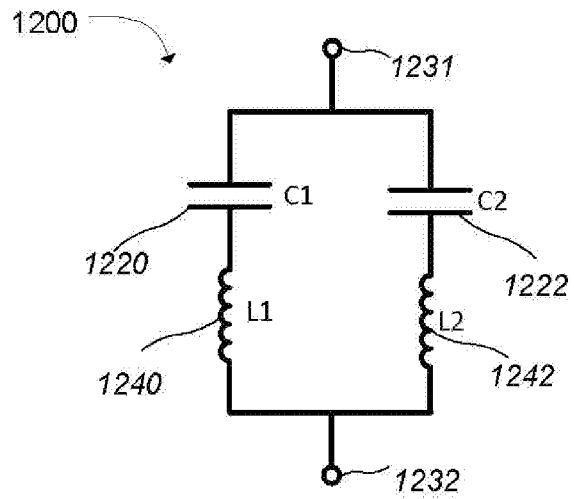


FIG. 12A

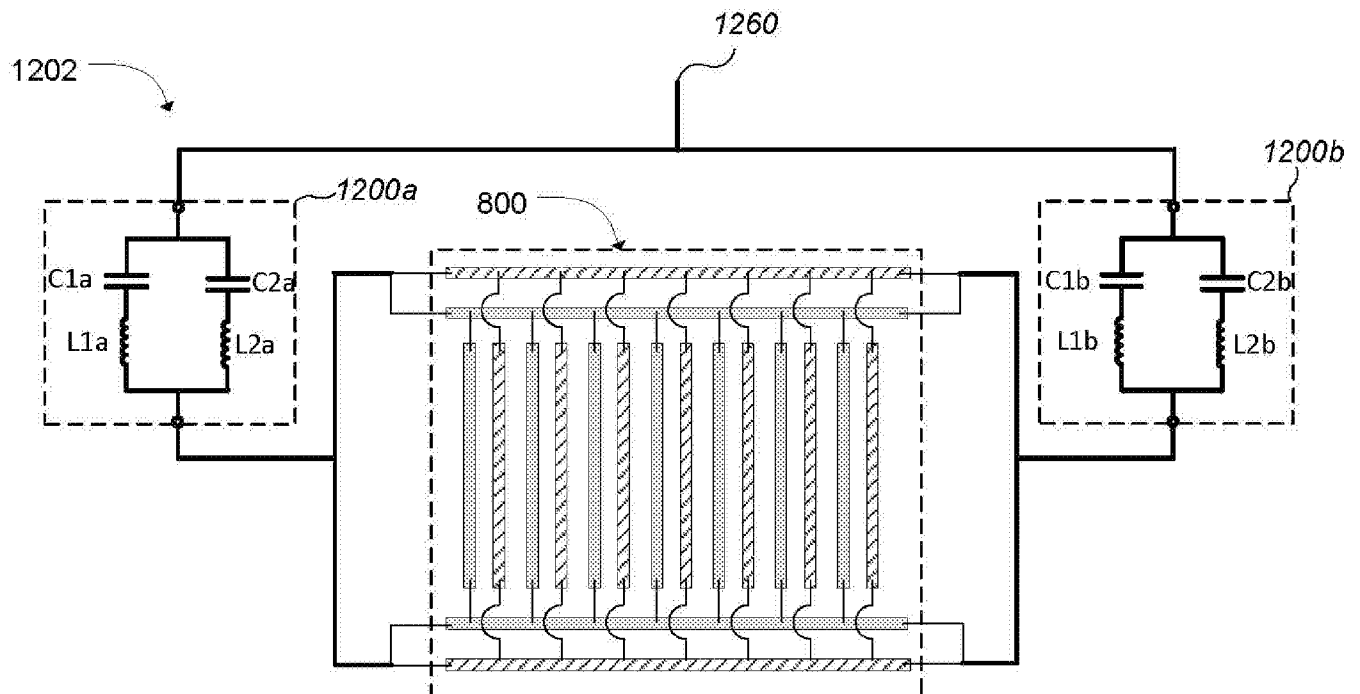


FIG. 12B

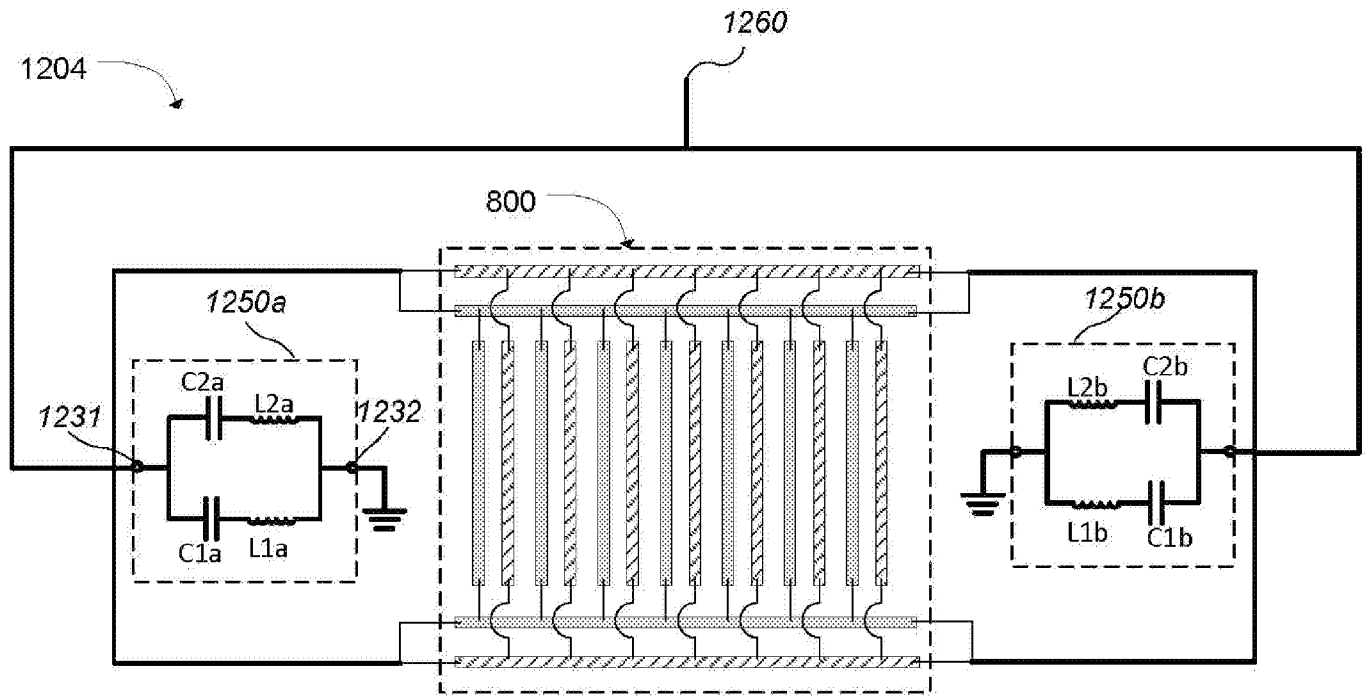


FIG. 12C

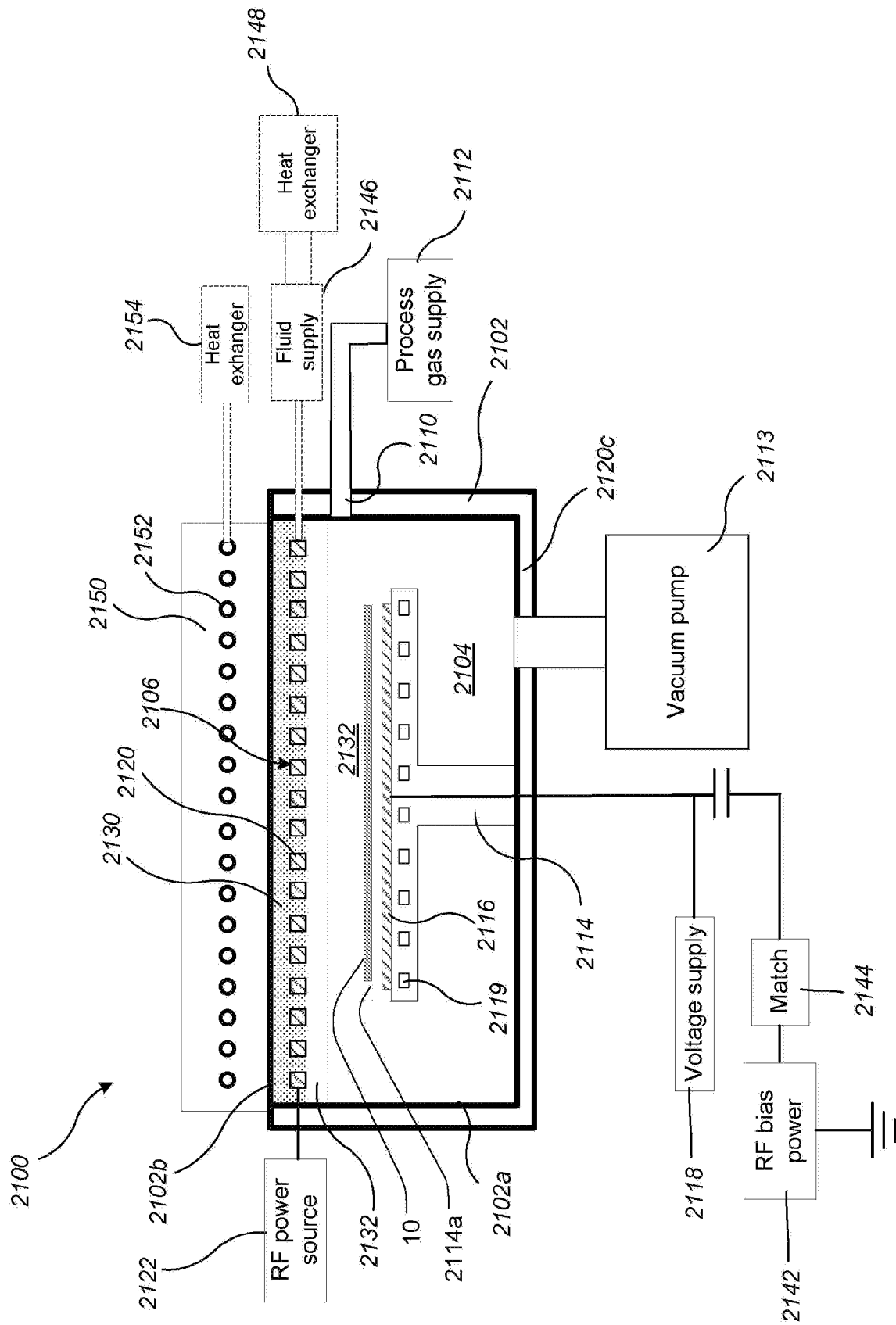


FIG. 13

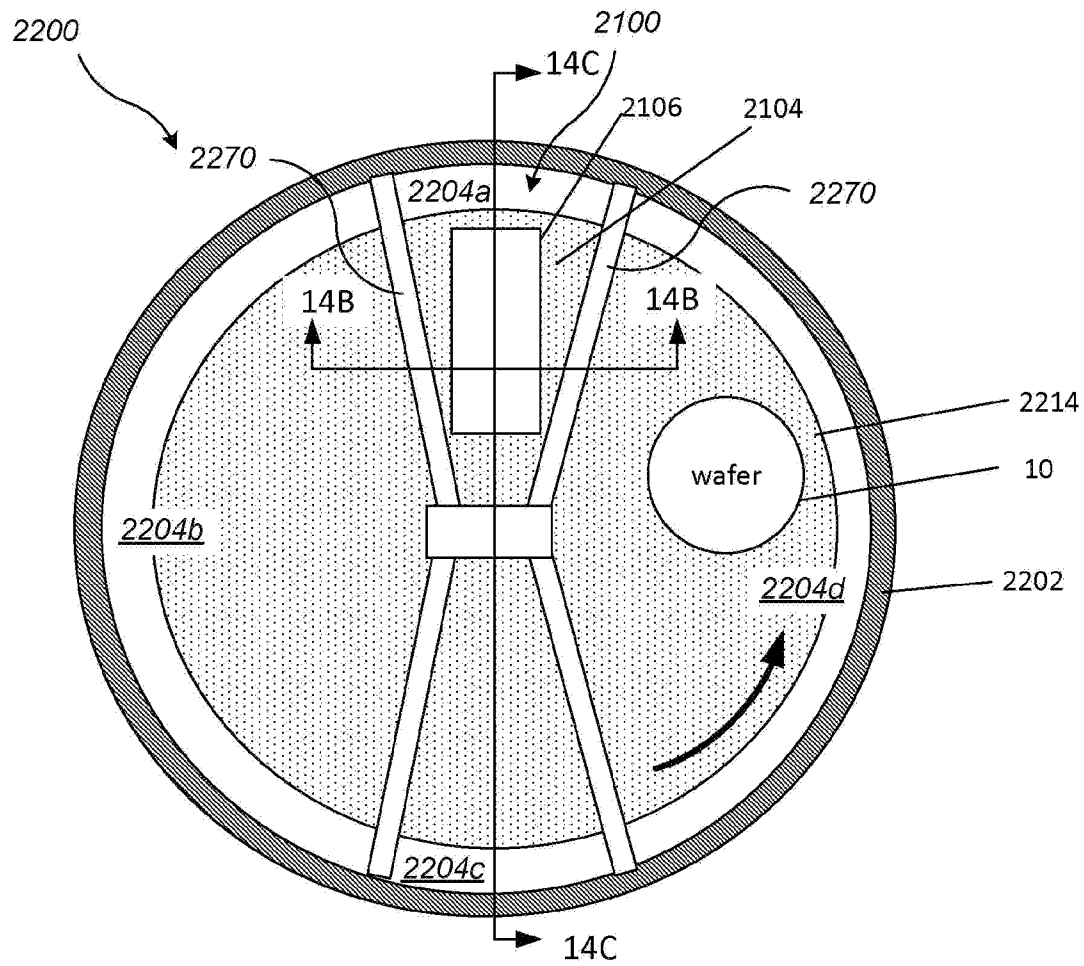


FIG. 14A

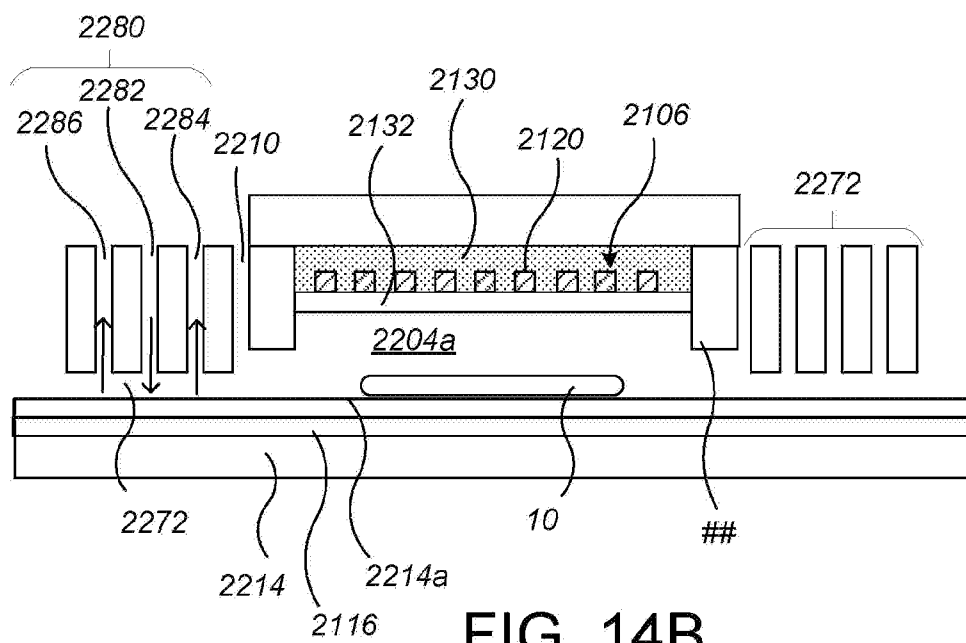


FIG. 14B

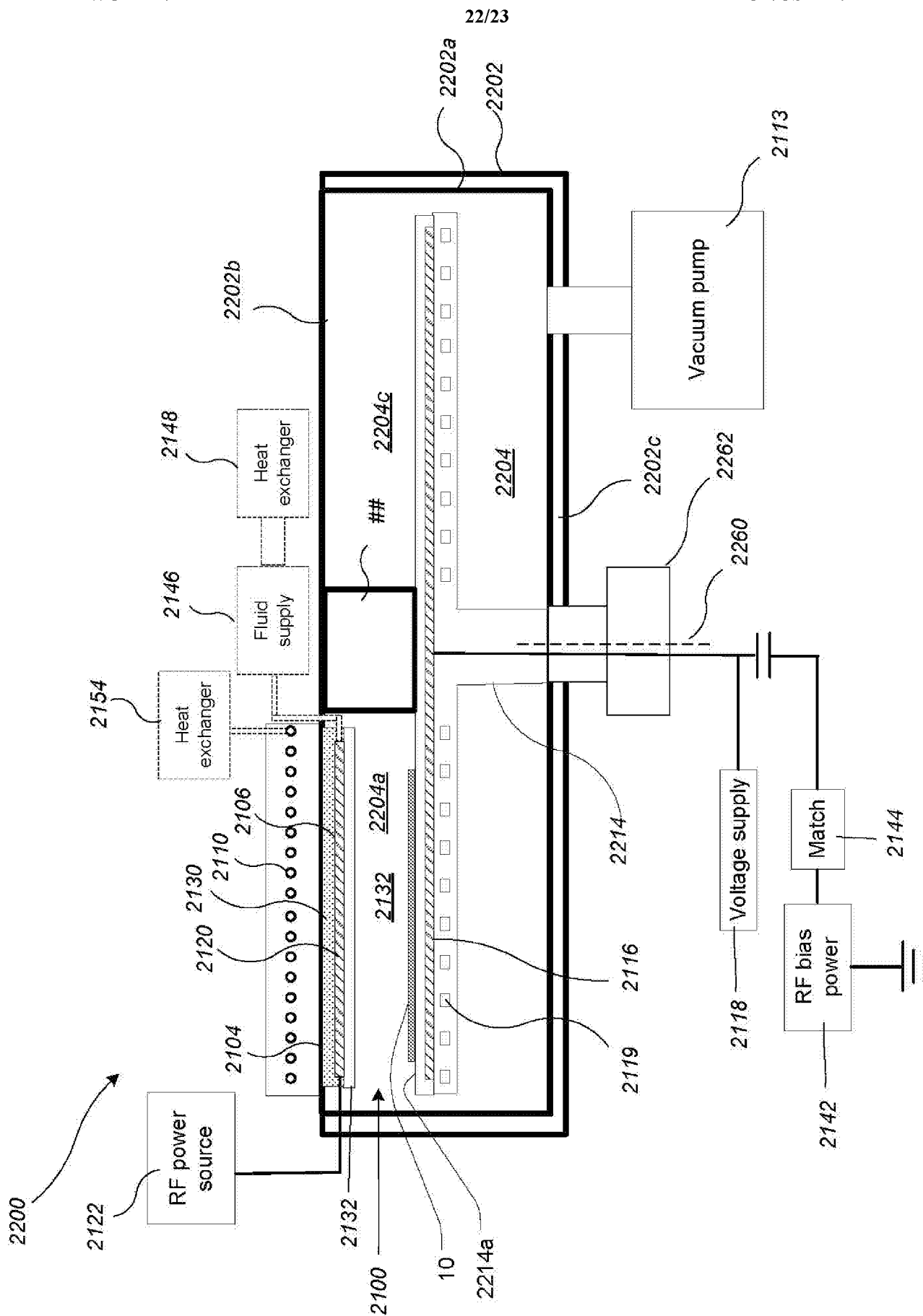


FIG. 14C

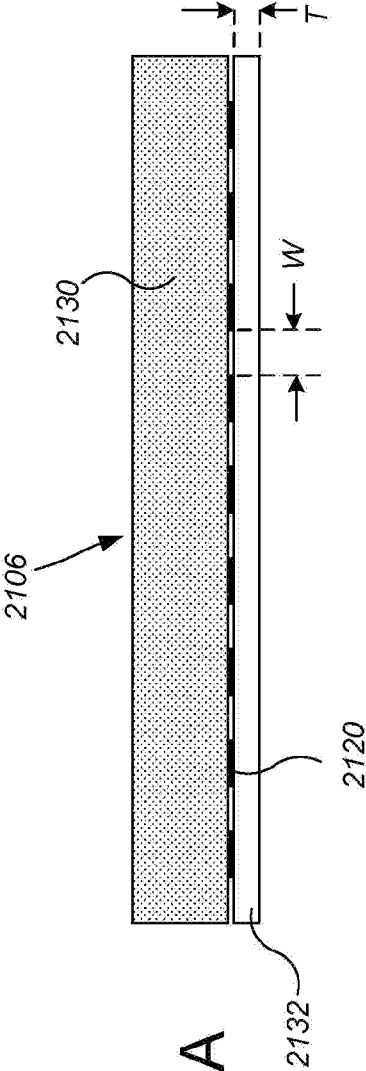


FIG. 15A

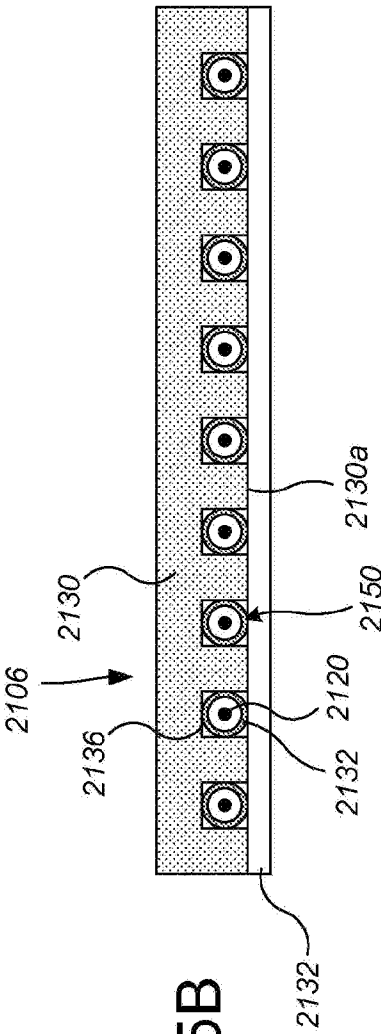


FIG. 15B

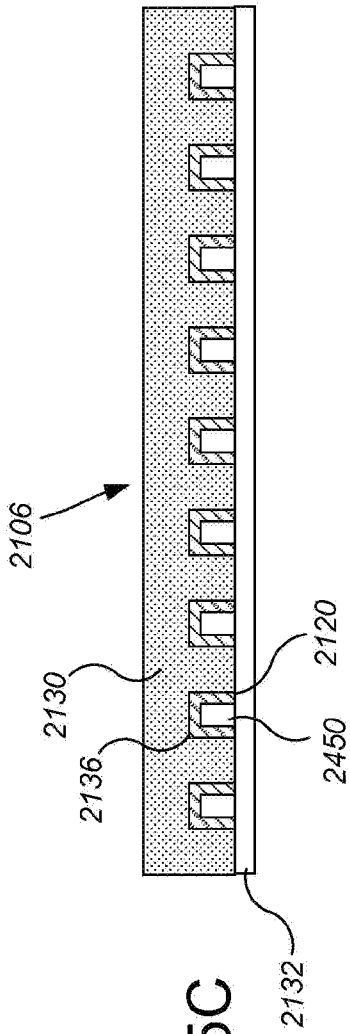


FIG. 15C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/038696**A. CLASSIFICATION OF SUBJECT MATTER****H01J 37/32(2006.01)i**

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01J 37/32; A61N 5/00; C23C 16/458; H01L 21/3065; H01L 21/67

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & keywords: chamber, plasma, conductor, filament, coplanar, electrode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2017-0076917 A1 (APPLIED MATERIALS, INC.) 16 March 2017 See paragraphs [0034]–[0090]; claim 1; and figures 1–14.	1–30
A	US 2015-0075719 A1 (APPLIED MATERIALS, INC.) 19 March 2015 See paragraphs [0003], [0016]–[0030]; and figures 1A–5.	1–30
A	US 2009-0001290 A1 (TAKATOSHI YAMASHITA) 01 January 2009 See paragraphs [0040]–[0047]; and figures 1–4.	1–30
A	US 2014-0238608 A1 (NOVELLUS SYSTEMS, INC.) 28 August 2014 See paragraphs [0031]–[0050]; and figures 1A–2B.	1–30
A	US 2016-0254124 A1 (APPLIED MATERIALS, INC.) 01 September 2016 See paragraphs [0036]–[0053]; and figures 2–5.	1–30
A	US 2014-0057447 A1 (APPLIED MATERIALS, INC.) 27 February 2014 See paragraphs [0026]–[0063]; and figures 1–5.	1–30



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

26 October 2018 (26.10.2018)

Date of mailing of the international search report

26 October 2018 (26.10.2018)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

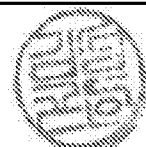
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Authorized officer

KIM, Sung Gon

Telephone No. +82-42-481-8746



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/038696

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