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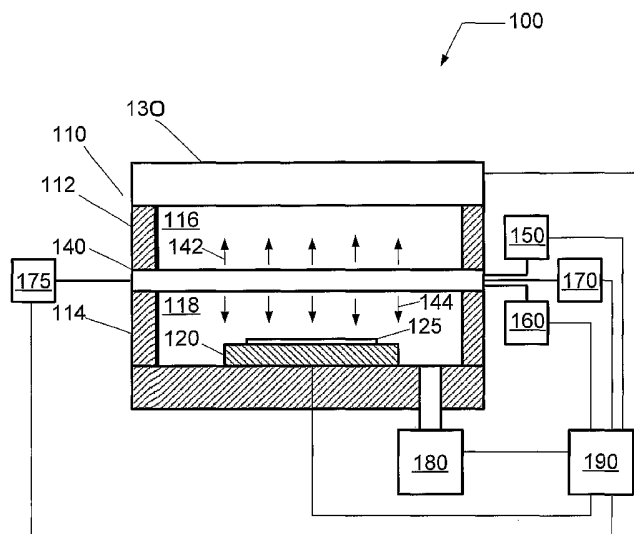
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(54) Title: METHOD AND SYSTEM FOR IMPROVING COUPLING BETWEEN A SURFACE WAVE PLASMA SOURCE AND A PLASMA SPACE



(57) Abstract: A method and system for improving the coupling between a surface wave plasma (SWP) source and a plasma space is described. The surface wave plasma source comprises an electromagnetic wave launcher, such as a slot antenna having a resonator plate, wherein at a plasma surface between the resonator plate and the plasma, a mode scrambler is utilized to improve coupling to the plasma.



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METHOD AND SYSTEM FOR IMPROVING COUPLING BETWEEN A SURFACE WAVE PLASMA SOURCE AND A PLASMA SPACE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to co-pending United States patent application serial no. 10/XXX,XXX, entitled "Surface wave plasma processing system and method of using", Attorney docket no. YYYYYY, filed on even date herewith; co-pending United States patent application serial no. 10/XXX,XXX, entitled "Plasma processing system for treating a substrate and method of using", Attorney docket no. YYYYYY, filed on even date herewith; and co-pending United States patent application serial no. 10/XXX,XXX, entitled "Method and system for controlling uniformity in a surface wave plasma", Attorney docket no. YYYYYY, filed on even date herewith. The entire contents of all of those applications are herein incorporated by reference in their entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a method and apparatus for improving coupling between a surface wave plasma (SWP) source and plasma and, more particularly, to a method and apparatus for improving the coupling between the SWP source and plasma using a mode scrambler.

Description of Related Art

[0003] Typically, during semiconductor processing, a (dry) plasma etch process is utilized to remove or etch material along fine lines or within vias or contacts patterned on a semiconductor substrate. The plasma etch process generally involves positioning a semiconductor substrate with an overlying patterned, protective layer, for example a photoresist layer, into a processing chamber. Once the substrate is positioned within the chamber, an ionizable, dissociative

gas mixture is introduced within the chamber at a pre-specified flow rate, while a vacuum pump is throttled to achieve an ambient process pressure. Thereafter, a plasma is formed when a fraction of the gas species present are ionized following a collision with an energetic electron. Moreover, the heated electrons serve to dissociate some species of the ambient gas species and create reactant specie(s) suitable for the exposed surface etch chemistry. Once the plasma is formed, any exposed surfaces of the substrate are etched by the plasma. The process is adjusted to achieve optimal conditions, including an appropriate concentration of desirable reactant and ion populations to etch various features (e.g., trenches, vias, contacts, etc.) in the exposed regions of substrate. Such substrate materials where etching is required include silicon dioxide (SiO_2), poly-silicon and silicon nitride.

[0004] Conventionally, various techniques have been implemented for exciting a gas into plasma for the treatment of a substrate during semiconductor device fabrication, as described above. In particular, ("parallel plate") capacitively coupled plasma (CCP) processing systems, or inductively coupled plasma (ICP) processing systems have been utilized commonly for plasma excitation. Among other types of plasma sources, there are microwave plasma sources (including those utilizing electron-cyclotron resonance (ECR)), surface wave plasma (SWP) sources, and helicon plasma sources. However, many of the commonly used plasma processing systems suffer from a number of deficiencies including, but not limited to, process chemistry control (i.e., control of chemistry dissociation), substrate damage due to interaction with energetic electrons, and process uniformity.

Summary of the Invention

[0005] One aspect of the invention is to reduce or eliminate any or all of the above-described problems.

[0006] Another aspect of the invention is to provide a method and system for improving coupling between a surface wave plasma (SWP) source and plasma.

[0007] Another aspect of the invention is to provide a method and system for preventing mode jumps between a desired electromagnetic (EM) wave mode and another EM wave mode in a SWP source.

[0008] According to one aspect, a surface wave plasma (SWP) source is described comprising: an electromagnetic (EM) wave launcher configured to couple EM energy in a desired EM wave mode to plasma by generating a surface wave on a plasma surface adjacent the plasma; a power coupling system coupled to the EM wave launcher, and configured to provide the EM energy to the EM wave launcher for forming the plasma; and a mode scrambler coupled to the plasma surface of the EM wave launcher, and configured to prevent mode jumping between the desired EM wave mode and another EM wave mode due to changes in the plasma.

Brief Description of the Drawings

[0009] In the accompanying drawings:

[0010] FIG. 1 presents a simplified schematic representation of a plasma processing system according to an embodiment of the invention;

[0011] FIG. 2 presents a simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0012] FIG. 3 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0013] FIG. 4 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0014] FIG. 5 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0015] FIG. 6 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0016] FIG. 7 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0017] FIG. 8 presents another simplified schematic representation of a plasma source for the plasma processing system depicted in FIG. 1;

[0018] FIGs. 9A and 9B provide schematic representations of electromagnetic wave propagation in a medium;

[0019] FIG. 10 provides an exploded view of a portion of a processing chamber according to an embodiment;

[0020] FIG. 11 provides an exploded view of a portion of a processing chamber according to another embodiment;

[0021] FIG. 12 provides an exploded view of a portion of a processing chamber according to another embodiment;

[0022] FIG. 13 illustrates a top view of a gas injection grid according to an embodiment;

[0023] FIG. 14 illustrates a top view of a gas injection grid according to another embodiment;

[0024] FIG. 15 provides a method of operating a plasma processing system according to an embodiment; and

[0025] FIG. 16 provides a method of controlling the uniformity in a plasma processing system according to an embodiment.

Detailed Description of Exemplary Embodiments

[0026] In the following description, to facilitate a thorough understanding of the invention and for purposes of explanation and not limitation, specific details are set forth, such as a particular geometry of the plasma processing system and various descriptions of the system components. However, it should be understood that the invention may be practiced with other embodiments that depart from these specific details.

[0027] Nonetheless, it should be appreciated that, contained within the description are features which, notwithstanding the inventive nature of the general concepts being explained, are also of an inventive nature.

[0028] Referring now to the drawings, wherein like reference numerals designate identical or corresponding parts throughout the several views, FIG. 1 illustrates a plasma processing system 100 according to an embodiment. The plasma processing system 100 comprises a processing chamber 110 having an upper chamber portion 112 configured to define a plasma space 116, and a lower chamber portion 114 configured to define a process space 118. In the lower chamber portion 114, the processing chamber 110 comprises a substrate holder 120 configured to support a substrate 125. Therein, the substrate 125 is exposed to process chemistry in process space 118. Furthermore, the plasma processing

system 100 comprises a plasma source 130 coupled to the upper chamber portion 112, and configured to form plasma in the plasma space 116.

[0029] Additionally, the plasma processing system 100 comprises a gas injection grid 140 coupled to the upper chamber portion 112 and the lower chamber portion 114, and located between the plasma space 116 and the process space 118. The gas injection grid 140 is configured to introduce a first gas 142 to the plasma space for forming plasma, and to introduce a second gas 144 to the process space for forming process chemistry. A first gas supply system 150 is coupled to the gas injection grid 140, and it is configured to supply the first gas 142. Moreover, a second gas supply system 160 is coupled to the gas injection grid 140, and it is configured to supply the second gas 144.

[0030] Additionally, the temperature of the gas injection grid 140 can be controlled using a temperature control system 170, and the electric potential of the gas injection grid 140 can be controlled using an electric bias control system 175.

[0031] Furthermore, the plasma processing system 100 includes a pumping system 180 coupled to the processing chamber 110, and configured to evacuate the processing chamber 110, as well as control the pressure within the processing chamber 110. Optionally, the plasma processing system 100 further includes a control system 190 coupled to the processing chamber 110, substrate holder 120, plasma source 130, gas injection grid 140, the first gas supply system 150, the second gas supply system 160, the temperature control system 170, the electric bias control system 175, and the pumping system 180. The control system 190 can be configured to execute a process recipe for performing at least one of an etch process, and a deposition process in the plasma processing system 100.

[0032] Referring still to FIG. 1, the plasma processing system 100 may be configured to process 200 mm substrates, 300 mm substrates, or larger-sized substrates. In fact, it is contemplated that the plasma processing system may be configured to process substrates, wafers, or LCDs regardless of their size, as would be appreciated by those skilled in the art. Therefore, while aspects of the invention will be described in connection with the processing of a semiconductor substrate, the invention is not limited solely thereto.

[0033] As described above, the processing chamber 110 is configured to facilitate the generation of plasma in plasma space 116, and generate process chemistry in

process space 118 adjacent a surface of the substrate 125. The first gas 142, which is introduced to the plasma space 116, comprises plasma forming gas, or an ionizable gas or mixture of gases. The first gas 142 can include an inert gas, such as a Noble gas. The second gas 144, which is introduced to the process space 118, comprises a process gas or mixture of process gases. For example, in an etch process, the process gas can include molecular constituents that when dissociated are reactive with the material being etched on the substrate surface. Once plasma is formed in the plasma space 116, some of the plasma can diffuse into the process space 118 through the gas injection grid 140. The heated electrons having diffused into the process space 118, can collide with molecules in the process gas causing dissociation and the formation of reactive radicals for performing an etch process, for example. Therefore, the use of a gas injection grid 140, as described above, can, for example, affect the formation of a dense, high temperature (electron temperature, T_e) plasma in the plasma space, while producing a lower temperature plasma in the process space.

[0034] In doing so, the split injection scheme for the first and second gases affects a reduction in the dissociation of the molecular composition in the second gas that is utilized for forming the process chemistry. Additionally, for instance, as an inert gas (first gas), such as argon (Ar), is introduced to the plasma space, plasma is formed and neutral Ar atoms are heated. The heated Ar neutral atoms diffuse downwards through the gas injection grid 140, and enter the cooler, process space proximate the substrate. This diffusion of neutral gas can eliminate back-diffusion of the molecular composition in the process gas (second gas).

[0035] In one example, the plasma source can include a surface wave plasma (SWP) source. Referring now to FIG. 2, a plasma source 230 is illustrated comprising a slot antenna, such as a radial line slot antenna (RLSA), with a coaxial feed 238 having an inner conductor 240, an outer conductor 242, and insulation 241. Additionally, the plasma source 130 includes an electromagnetic (EM) wave launcher 243 comprising a slow wave plate 244, a slot antenna 246 having slots 248, and a resonator plate 250. The number of slots, geometry of the slots, the size of the slots, and the distribution of the slots are all factors that can contribute to the spatial uniformity of the plasma formed in plasma space 116. For

instance, the exact dimensions of the resonator plate 250 (i.e., thickness, and diameter) can be calculated numerically.

[0036] The wave launcher 243 includes a microwave launcher configured to radiate microwave power into plasma space 116. The microwave launcher can be coupled to a microwave source, such as a 2.45 GHz microwave power source, wherein microwave power is coupled to the microwave launcher via the coaxial feed 238. Microwave energy generated by the microwave source is guided through a waveguide (not shown) to an isolator (not shown) for absorbing microwave energy reflected back to the microwave oscillator, and thereafter it is converted to a coaxial TEM mode via a coaxial converter (not shown). A tuner may be employed for impedance matching, and improved power transfer. The microwave energy is coupled to the microwave launcher via the coaxial feed 238, where another mode change occurs from the TEM mode in the coaxial feed 238 to a TM mode.

[0037] Referring still to FIG. 2, the plasma source 230 is coupled to the upper chamber portion 112 of processing chamber 110, wherein a vacuum seal can be formed between the upper chamber wall 252 and the plasma source 230 using a sealing device 254. The sealing device 254 can include an elastomer O-ring.

[0038] In general, the inner conductor 240 and the outer conductor 242 of the coaxial feed 238 comprise a conductive material, such as a metal, while the slow wave plate 244 and the resonator plate 250 comprise a dielectric material. In the latter, the slow wave plate 244 and the resonator plate 250 comprise the same material. The dielectric material can, for example, include quartz. Additional details regarding the design of the coaxial feed and the wave launcher can be found in US Patent No. 5,024,716, entitled "Plasma processing apparatus for etching, ashing, and film-formation"; the contents of which are herein incorporated by reference in its entirety.

[0039] The material selected for fabrication of the slow wave plate 244 and the resonator plate 250 is chosen to reduce the wavelength of the propagating electro-magnetic (EM) wave relative to the free-space wavelength, and the dimensions of the slow wave plate 244 and the resonator plate 250 are chosen to ensure the formation of a standing wave effective for radiating EM energy into the plasma space 116.

[0040] When the slow wave plate 244 and the resonator plate 250 are fabricated from quartz (silicon dioxide), several issues can arise, particularly when the plasma processing system is utilized for etch process applications. Firstly, the selection of quartz is often chosen for compatibility with the etch process. Secondly, the critical dimensions of the quartz resonator and quartz slow wave plate are very important, therefore, leading to a high cost consumable item. Additionally, the onset of the standing wave electric field must remain adjacent the quartz-plasma interface for low power plasma processes. Additionally, shifts in plasma parameters affect the decaying electric field in the quartz resonator. If the electric field strength in the dielectric resonator is not sufficiently larger than the change in the electric field due to the shift in plasma parameters, such a shift can cause a voltage standing wave ratio (VSWR) jump, or standing wave mode jump. The inventor has observed that the use of a quartz resonator plate with the standing wave at the quartz-plasma interface can be prone to such mode jumps as plasma parameters shift. Also, when using quartz as the material for the manufacture of the resonator plate and the slow wave plate, the design of the slot antenna (i.e., number of slots, their size, geometry and distribution) is less effective for affecting spatially uniform plasma in the plasma space 116. Therefore, a special shape can be required for forming uniform plasma.

[0041] In yet another example, a plasma source 231 is depicted in FIG. 3 comprising many of the same elements illustrated in FIG. 2. However, plasma source 231 can further include one or more concentric grooves 260 configured to improve the spatial uniformity of plasma in the plasma space 116.

[0042] Alternatively, the slow wave plate 244 and the resonator plate 250 can be fabricated from a high dielectric constant (high-k) material. Herein, high dielectric constant can be utilized to refer to materials having a dielectric constant equal to or greater than that of silicon dioxide (approximately a value of 3.9). The use of a high-k material can, for example, lead to reduced dissociation of the molecular constituent in the process chemistry, reduced risk of mode jumping due to shifts in plasma parameters, and improved effectiveness of controlling the spatial uniformity of plasma formed in plasma space 116. For example, the high-k material can include intrinsic crystal silicon, alumina ceramic, aluminum nitride, and sapphire. When the resonator plate 250 is fabricated from intrinsic crystal

silicon, the plasma frequency exceeds 2.45 GHz at a temperature of 45C. Therefore, intrinsic crystal silicon is appropriate for low temperature processes (i.e., less than 45C). For higher temperature processes, the resonator plate 250 can be fabricated from alumina (Al₂O₃), or sapphire.

[0043] However, due to the erosive nature of plasma in plasma space 116 and the requirement for maintaining critical dimensions of the resonator plate 250, a cover plate can be used to protect the more expensive resonator plate 250. According to yet another example, a cover plate 265, coupled to a lower surface of the resonator plate 250, is illustrated in FIG. 4. The cover plate thickness is selected to be sufficiently thin such that it does not support standing wave modes within it (i.e., the thickness is not electromagnetically critical); however, it is sufficiently thick for mechanical stability. For example, the cover plate 265 can include a quartz cover plate that is 1 to 5 mm in thickness, or desirably 2 to 3 mm in thickness. Furthermore, the lower surface (or contact surface) of the resonator plate 250 and the upper surface (or contact surface) of the cover plate 265 can be polished to ensure a good contact between the resonator plate 250 and the cover plate 265. Moreover, a thin film may be deposited on the lower surface of the resonator plate 250, and polished in order to provide a good contact. For instance, the thin film can include a thin film of SiO₂, and it may include up to 2 micron thermal SiO₂, or up to 6 micron physical vapor deposition (PVD) SiO₂.

[0044] Assuming a simple geometric interface, such as an infinite slab model, for the resonator plate 250 and the cover plate 265, as depicted in FIG. 9A, analytical expressions of the electric and magnetic fields can be determined using the homogeneous Helmholtz equation, viz.

$$\mathbf{[0045]} \quad E_z = A \sin(k_{250}x) e^{-j\beta z}, \quad (1)$$

$$\mathbf{[0046]} \quad E_x = -j \frac{\beta}{k_{250}} A \cos(k_{250}x) e^{-j\beta z}, \text{ and} \quad (2)$$

$$\mathbf{[0047]} \quad H_y = -j \frac{\kappa_{250} k_0 Y_0}{k_{250}} A \cos(k_{250}x) e^{-j\beta z}, \quad (3)$$

[0048] where x, y, and z are the Cartesian coordinates as shown in FIG. 8A, E_z is the electric field in the z direction, E_x is the electric field in the x direction, H_y is the magnetic field in the y direction, k₂₅₀ is the cut-off wave number in the resonator plate, κ₂₅₀ is the dielectric constant of the resonator plate material, κ₂₆₅

is the dielectric constant of the cover plate material, β is the propagation constant from the basic dispersion relation (i.e., $\beta^2 = k^2 - k_c^2 = \kappa_{250}k_0^2 - k_{250}^2 = \kappa_{265}k_0^2 + h^2$, where k is the medium wave number, k_c is the medium cut-off wave number, h is the field damping constant, k_0 is the vacuum wave number and $k_{265} = jh$), and Y_0 is the vacuum wave admittance ($Y_0 = (\epsilon_0/\mu_0)^{1/2} = Z_0^{-1}$). For example, the resonator plate can be fabricated from intrinsic crystal silicon, and the cover plate can be fabricated from silicon dioxide. Therefore, the subscript "250" refers to the material properties of intrinsic crystal silicon, and the subscript "265" refers to the material properties of silicon dioxide.

[0049] The primary surface wave exists between the resonator plate and cover plate interface, and the onset of the evanescent electric field occurs at this interface, as shown in FIG. 9A. Electromagnetic waves, represented by k_1 and k_2 , are depicted as two exemplary modes in FIG. 9A. Waves $k_{1,2}$ and $k_{2,2}$ represent the surface waves at this interface, traveling with a phase velocity between the phase velocity in intrinsic crystal silicon (e.g., $\kappa \sim 12$, and $\lambda_{Si} \sim 1$ cm), and the phase velocity in silicon dioxide ($\kappa \sim 4$, and $\lambda_{SiO2} \sim 3$ cm). If the thickness of the cover plate is much larger than the wavelength of the EM wave, then the infinite slab model field solutions for $x > s$ are:

$$\textbf{[0050]} \quad E_z = A \sin(k_{250}s) e^{-hx} e^{hs} e^{-j\beta z}, \quad (4)$$

$$\textbf{[0051]} \quad E_x = -j \frac{\beta}{h} \sin(k_{250}s) e^{-hx} e^{hs} e^{-j\beta z}, \text{ and} \quad (5)$$

$$\textbf{[0052]} \quad H_y = -j \frac{\kappa_{265}k_0Y_0}{h} A \sin(k_{250}s) e^{-hx} e^{hs} e^{-j\beta z}, \quad (6)$$

[0053] (where $kY = k_0Y_0$, when in vacuum; and $kY = \kappa_{265}k_0Y_0$, for a surface wave in the cover plate). However, since the thickness of the cover plate is only a fraction of the wavelength and, hence, a smaller fraction of the decay depth of the electric field, the above set of solutions are incomplete. For instance, an additional reflection at the interface between the cover plate and the plasma will occur, and there will exist a different decay constant for $x > q$. Since the propagation constant will have to be the same for the resonator plate, the cover plate, and the plasma, there will exist a new β . More importantly, the new β leads to a new phase velocity straddling that in the resonator plate, the cover plate, and the plasma. Therefore, as a result of the cover plate, it is possible that plasma instability can

occur as a result of a shift in plasma parameters. Although the dielectric constant for the plasma is approximately a value of unity for a wide range of plasma parameters, EM wave dispersion is strongly affected by the electron density (n_e), the electron temperature (T_e), etc. When the dispersion relation changes in the plasma, the surface wave propagation constant changes. Consequently, the field solutions change. The immediate consequence can include an increase in the VSWR, and a possible mode jump.

[0054] Therefore, in order to mitigate the effects of mode jumping, a mode scrambler can be coupled to the plasma source. The cavity mode in the wave launcher 243 can be dependent upon the geometry of the wave launcher cavity as well as the material properties of the wave launcher cavity, and it can also be dependent upon the plasma parameters. The use of a mode scrambler reduces the effect of changes in the plasma parameters on the resultant cavity mode. According to yet another example, a mode scrambler 270, coupled to a lower surface of the resonator plate 250 in plasma source 233, is illustrated in FIG. 5. Herein, the mode scrambler 270 comprises one or more gas holes 274 coupled to one or more gas plenums 272. The one or more gas plenums 272, and the one or more gas holes 274 are configured to introduce a gas, such as the first gas, or inert gas. Although the one or more gas holes 274 are shown to be coupled to the one or more gas plenums 272, wherein they are configured to introduce a gas, one or more of the one or more gas holes 274 do not have to be coupled to one or more of the one or more gas plenums 272. Alternatively, one or more of the one or more gas holes 274 can be evacuated.

[0055] Referring still to FIG. 5, the plasma source 233 is coupled to the upper chamber portion 112 of processing chamber 110, wherein a vacuum seal can be formed between the upper chamber wall 252 and the plasma source 230 using a sealing device 254. The sealing device 254 can include an elastomer O-ring. Furthermore, a second and third sealing device, 255A and 255B, are utilized to provide a vacuum seal in the coaxial feed 238.

[0056] According to yet another example, a mode scrambler 270, coupled to a lower surface of the resonator plate 250 in plasma source 233, is illustrated in FIG. 6. Herein, the mode scrambler 270 comprises one or more blind holes 276. As illustrated in FIG. 9B, electromagnetic waves, represented by k_1 , k_2 , and k_3 , are

depicted as three exemplary modes. Surface waves $k_{1,2}$ ($k_{1,3}$) and $k_{2,2}$ ($k_{2,3}$) represent effective coupling of energy to plasma in plasma space 116. However, wave k_3 does not contribute to plasma heating, and it is reflected by the plasma.

[0057] The number, geometry, distribution, and size of the one or more blind holes 276 can be selected in order to provide uniform plasma in plasma space 116. Additionally, the one or more blind holes 276 can be opened to plasma. However, the size of each blind hole, such as the diameter of each hole, should be sufficiently small so as to avoid the formation of plasma in the hole. For example, the diameter of each blind hole can be less than or equal to 2 mm for process pressures less than 100 mTorr. As the pressure is increased, the size of the blind hole should be decreased in order to prevent the formation of plasma therein (e.g., when $p=200$ mTorr, the diameter should be less than or equal to 1 mm). Additionally, for example, a blind hole diameter of less than 1 mm can be effective for scrambling cavity modes for $\lambda_{Si} \sim 1$ cm.

[0058] The one or more blind holes can be fabricated using drilling or milling techniques, sonic milling, laser milling, or etching processes, or any combination thereof. The etching processes can include dry or wet etching processes that can be utilized for forming the blind hole in the resonator plate 250. Additionally, a thin SiO_2 layer, such as a 2 micron layer of thermal SiO_2 or a 6 micron layer of physical vapor deposition (PVD) SiO_2 , can be deposited on the lower surface of the resonator plate 250. Thereafter, the thin SiO_2 layer can be patterned using, for example, an etching process, and the pattern can be transferred into the resonator plate 250 using an etching process, whereby the thin SiO_2 layer serves as a hard mask and defines the geometry of the one or more blind holes. Furthermore, the remaining thin SiO_2 layer can serve to ensure a good interface between the resonator plate 250 and the cover plate 265.

[0059] Alternatively, according to yet another example, the mode scrambler 270, depicted in FIG. 6, having one or more blind holes 276 can be filled with a material in order to prevent the formation of plasma. For example, referring to FIG. 7, a coating 278 can be applied to the lower surface of the resonator plate 250 in order to fill the one or more blind holes 276. The coating 278 comprises a material having a dielectric constant less than the dielectric constant of the resonator plate 250. For example, the coating can include SiO_2 , having a dielectric constant of

approximately 4. Alternatively, the coating can include a low dielectric constant (low-k) material, having a dielectric constant less than that of SiO_2 . Alternatively, the coating 278 can include a low-k material, having a coefficient of thermal expansion that is compatible with the expansion coefficient for the resonator plate. For example, the low-k material can include at least one of an organic, inorganic, and inorganic-organic hybrid material. Furthermore, the low-k material can include a porous, or non-porous coating. Additionally, for example, the coating 278 may include an inorganic, silicate-based material, such as oxidized organosilane (or organo siloxane), deposited using CVD techniques. Examples of such coatings include Black DiamondTM CVD organosilicate glass (OSG) films commercially available from Applied Materials, Inc., or CoralTM CVD films commercially available from Novellus Systems. Additionally, for example, the coating 278 can include single-phase materials, such as a silicon oxide-based matrix having CH_3 bonds that are broken during a curing process to create small voids (or pores). Additionally, for example, the coating 278 can include dual-phase materials, such as a silicon oxide-based matrix having pores of organic material (e.g., porogen) that is evaporated during a curing process. Alternatively, the coating 278 may include an inorganic, silicate-based material, such as hydrogen silsesquioxane (HSQ) or methyl silsesquioxane (MSQ), deposited using SOD techniques. Examples of such coatings include FOX HSQ commercially available from Dow Corning, XLK porous HSQ commercially available from Dow Corning, and JSR LKD-5109 commercially available from JSR Microelectronics. Still alternatively, the coating 278 can include an organic material deposited using SOD techniques. Examples of such coatings include SiLK-I, SiLK-J, SiLK-H, SiLK-D, and porous SiLK semiconductor dielectric resins commercially available from Dow Chemical, and FLARETM, and Nano-glass commercially available from Honeywell.

[0060] Additionally, for example, the coating 278 can be formed using chemical vapor deposition (CVD) techniques, or spin-on dielectric (SOD) techniques such as those offered in the Clean Track ACT 8 SOD and ACT 12 SOD coating systems commercially available from Tokyo Electron Limited (TEL). The Clean Track ACT 8 (200 mm) and ACT 12 (300 mm) coating systems provide coat, bake, and cure tools for SOD materials. The track system can be configured for

processing substrate sizes of 100 mm, 200 mm, 300 mm, and greater. Other systems and methods for forming a coating on a substrate are well known to those skilled in the art of both spin-on technology and vapor deposition technology. Once the coating 278 is applied, it can be polished in order to, for example, provide an improved interface with the cover plate 265. The polishing process can, for instance, include chemical-mechanical polishing (CMP).

[0061] Alternatively, according to yet another example, the mode scrambler 270, depicted in FIG. 6, having one or more blind holes 276 can be filled with a plasma arrester in order to prevent the formation of plasma. For example, referring to FIG. 8, the one or more blind holes 276 are filled with a spherical pellet 280. The spherical pellets 280 can, for example, comprise SiO_2 , or a low-k material, as described above. Once the one or more blind holes are loaded with the spherical pellets 280, each pellet is secured by press-fitting each pellet into each blind hole or by retaining each pellet within the blind hole by coupling the cover plate 265 to the resonator plate 250. The pellet's physical presence reduces the accelerated free electron path (electrons collide into pellet), thus, inhibiting avalanche ionization. In one example, each blind hole 276 can include a 2mm diameter by a 2mm depth, and each pellet 280 can have a diameter of 2 mm, and less (such that it is sufficiently small to fit within the blind hole). Additionally, in order to ensure a good interface between the resonator plate 250 and the cover plate 265, a thin SiO_2 layer, such as a 2 micron layer of thermal SiO_2 or a 6 micron layer of physical vapor deposition (PVD) SiO_2 , can be deposited on the contact surfaces of the resonator plate 250.

[0062] Referring now to FIG. 10, a portion of a processing system is illustrated. A processing chamber 310 is depicted comprising an upper chamber portion 312 that encloses a plasma space 316, and a lower chamber portion 314 that encloses a process region 318. A plasma source 330, such as a surface wave plasma source as described above, is coupled to the upper chamber portion 312, and is configured to form plasma in plasma space 316. A gas injection grid 340 is coupled to the upper chamber portion 312 and the lower chamber portion 314, and located between the plasma space 316 and the process space 318. As illustrated in FIG. 10, the gas injection grid 340 is coupled to the upper chamber portion 312, and it is sealed for use in vacuum using an upper sealing device 344,

such as an elastomer O-ring. Also, as illustrated in FIG. 10, the gas injection grid 340 is coupled to the lower chamber portion 314, and it is sealed for use in vacuum using a lower sealing device 346, such as an elastomer O-ring.

[0063] The gas injection grid 340 comprises one or more passageways 342 coupling the plasma space 316 to the process space 318. Additionally, gas injection grid 340 is configured to introduce a first gas to the plasma space 316 through one or more gas injection orifices (not shown) that are coupled to a first gas channel array 356. The first gas channel array 356 can include one gas channel coupled to a first gas supply system, or a plurality of gas channels forming multiple zones in the gas injection grid 340 that are independently coupled to the first gas supply system. In the latter, the composition of the first gas, or the flow rate of the first gas, or both can be varied from one gas channel to the next. Additionally, gas injection grid 340 is configured to introduce a second gas to the process space 318 through one or more gas injection orifices (not shown) that are coupled to a second gas channel array 366. The second gas channel array 366 can include one gas channel coupled to a second gas supply system, or a plurality of gas channels independently coupled to the second gas supply system. In the latter, the composition of the second gas, or the flow rate of the second gas, or both can be varied from one gas channel to the next. Furthermore, the temperature of the gas injection grid 340 can be controlled by circulating a heat transfer fluid through a fluid channel array 376 in order to transfer heat from the gas injection grid 340 to a heat exchanger (not shown) when cooling, or to transfer heat to the gas injection grid 340 from the heat exchanger when heating. The fluid channel array 376 can include one fluid channel coupled to a temperature control system, or a plurality of fluid channels independently coupled to the temperature control system. In the latter, the composition of the heat transfer fluid, or the temperature of the heat transfer fluid, or the flow rate of the heat transfer fluid, or any combination thereof can be varied from one fluid channel to the next.

[0064] As illustrated in FIG. 10, the first gas is coupled to the first gas channel array 356 via a first array of gas lines 354. The first gas is coupled to the first array of gas lines 354 through a first array of gas fittings 352, which permits a point for coupling a first gas supply system, such as the first gas supply system

150 depicted in FIG. 1. For example, the first array of gas fittings 352 can be located in the upper chamber portion 312, and the first array of gas lines 354 can pass through the upper chamber portion 312 into the gas injection grid 340, whereby a first array of gas sealing devices 358 are utilized to prevent leakage of the first gas. For example, the first array of gas sealing devices 358 can include one or more elastomer O-rings.

[0065] As illustrated in FIG. 11, the second gas is coupled to the second gas channel array 366 via a second array of gas lines 364. The second gas is coupled to the second array of gas lines 364 through a second array of gas fittings 362, which permits a point for coupling a second gas supply system, such as the second gas supply system 160 depicted in FIG. 1. For example, the second array of gas fittings 362 can be located in the upper chamber portion 312, and the second array of gas lines 364 can pass through the upper chamber portion 312 into the gas injection grid 340, whereby a second array of gas sealing devices 368 are utilized to prevent leakage of the second gas. For example, the second array of gas sealing devices 368 can include one or more elastomer O-rings.

[0066] Additionally, as illustrated in FIG. 12, the heat transfer fluid is coupled to the fluid channel array 376 via an array of fluid lines 374. The heat transfer fluid is coupled to the array of fluid lines 374 through an array of fluid fittings 372, which permits a point for coupling a temperature control system, such as the temperature control system 170 depicted in FIG. 1. For example, the array of fluid fittings 372 can be located in the upper chamber portion 312, and the array of fluid lines 374 can pass through the upper chamber portion 312 into the gas injection grid 340, whereby an array of fluid sealing devices 378 are utilized to prevent leakage of the heat transfer fluid. For example, the array of fluid sealing devices 378 can include one or more elastomer O-rings.

[0067] Referring now to FIGs. 13 and 14, a top down view of a gas injection grid is shown. In FIG. 13, a gas injection grid 340A is depicted, wherein the gas injection grid comprises a rectangular distribution of passageways 342A. For example, as shown in FIG. 13, the first gas is independently coupled to three gas channels 356A, 356B, and 356C via three separate gas lines 354A, 354B, and 354C. Although not shown, a separate mass flow controller, or separate array of mass flow controllers can be coupled to each gas line.

[0068] In FIG. 14, a gas injection grid 340B is depicted, wherein the gas injection grid comprises a circular distribution of passageways 342B. For example, as shown in FIG. 14, the first gas is independently coupled to three gas channels 356A, 356B, and 356C via three separate gas lines 354A, 354B, and 354C. Although not shown, a separate mass flow controller, or separate array of mass flow controllers can be coupled to each gas line.

[0069] The first gas comprises plasma forming gas, or an ionizable gas. For example, the first gas can include an inert gas, such as a Noble gas (i.e., helium, argon, xenon, krypton, neon). The second gas comprises a process gas. For example, the second gas can include a halogen containing gas, such as Cl_2 , HBr , SF_6 , NF_3 , etc. Additionally, for example, the second gas can include a C_xF_y containing gas, such as CF_4 , C_4F_6 , C_4F_8 , C_5F_8 , where x and y are integers greater than or equal to unity.

[0070] The gas injection grid 340 (340A, 340B), depicted in FIGs. 10 through 14 can be fabricated from a metal, such as aluminum, or a ceramic, such as alumina. Alternatively, the gas injection grid 340 can be fabricated from quartz, silicon, silicon carbide, silicon nitride, aluminum nitride, or carbon. Additionally, the gas injection grid 340 can be protected with a coating. For example, the coating can comprise one of a surface anodization, a coating formed using plasma electrolytic oxidation, or a spray coating such as a thermal spray coating. In an example, the coating can comprise at least one of Al_2O_3 and Y_2O_3 . In another example, the coating comprises at least one of a III-column element (column III of periodic table) and a Lanthanone element. In another example, the III-column element comprises at least one of Yttrium, Scandium, and Lanthanum. In another example, the Lanthanone element comprises at least one of Cerium, Dysprosium, and Europium. In another embodiment, the compound forming the coating comprises at least one of Ytria (Y_2O_3), Sc_2O_3 , Sc_2F_3 , YF_3 , La_2O_3 , CeO_2 , Eu_2O_3 , and DyO_3 . In another example, the coating can comprise Keronite (surface coating treatment commercially available from Keronite Limited, Advanced Surface Technology, PO Box 700, Granta Park, Great Abington, Cambridge CB1 6ZY, UK). In another example, the coating can comprise at least one of silicon, silicon carbide, alumina, Teflon, Vespel, or Kapton.

[0071] Referring again to FIG. 1, substrate 125 can be affixed to the substrate holder 120 via a mechanical clamping system, or an electrical clamping system, such as an electrostatic clamping system. Furthermore, substrate holder 120 can further include a cooling system including a re-circulating coolant flow that receives heat from substrate holder 120 and transfers heat to a heat exchanger system (not shown), or when heating, transfers heat from the heat exchanger system. Moreover, gas can be delivered to the back-side of substrate 125 via a backside gas system to improve the gas-gap thermal conductance between substrate 125 and substrate holder 120. Such a system can be utilized when temperature control of the substrate is required at elevated or reduced temperatures. For example, the backside gas system can comprise a two-zone gas distribution system, wherein the helium gas gap pressure can be independently varied between the center and the edge of substrate 125. In other embodiments, heating/cooling elements, such as resistive heating elements, or thermo-electric heaters/coolers can be included in the substrate holder 120, as well as the chamber wall of the processing chamber 110 and any other component within the plasma processing system 100.

[0072] Furthermore, substrate holder 120 can comprise an electrode through which radio frequency (RF) power is coupled to the processing plasma in process space 118. For example, substrate holder 120 can be electrically biased at a RF voltage via the transmission of RF power from a RF generator (not shown) through an impedance match network (not shown) to substrate holder 120. A typical frequency for the RF bias can range from about 0.1 MHz to about 100 MHz. RF bias systems for plasma processing are well known to those skilled in the art.

[0073] Alternately, RF power is applied to the substrate holder electrode at multiple frequencies. Furthermore, impedance match network serves to improve the transfer of RF power to plasma in plasma processing chamber 10 by reducing the reflected power. Match network topologies (e.g. L-type, π -type, T-type, etc.) and automatic control methods are well known to those skilled in the art.

[0074] The temperature control system 170 can include components necessary for controlling the temperature of the gas injection grid 130. For example, the temperature control system 170 can include a heat exchanger for controlling the

temperature of a heat transfer fluid, a pump and mass flow controller for delivering and controlling the flow rate of the heat transfer fluid to one or more channels in the gas injection grid 130, temperature sensing devices, a controller, etc.

[0075] The electric bias control system 175 can include components necessary for electrically biasing the gas injection grid 130. The electric bias can include a direct current (DC) electrical bias, or an alternating current (AC) electrical bias, or a combination thereof. For example, the electrical bias may include a radio frequency (RF) electric bias. The electric bias control system 175 can include a voltage/current source or power source, voltage or current or impedance measuring devices, a controller, etc.

[0076] The pumping system 180 can include a turbo-molecular vacuum pump (TMP) capable of a pumping speed up to about 5000 liters per second (and greater) and a gate valve for throttling the chamber pressure. In conventional plasma processing devices utilized for dry plasma etch, a 1000 to 3000 liter per second TMP is generally employed. Moreover, a device for monitoring chamber pressure (not shown) can be coupled to the processing chamber 110. The pressure measuring device can be, for example, a Type 628B Baratron absolute capacitance manometer commercially available from MKS Instruments, Inc. (Andover, MA).

[0077] Still referring to FIG. 1, control system 190 can comprise a microprocessor, memory, and a digital I/O port capable of generating control voltages sufficient to communicate and activate inputs to plasma processing system 100 as well as monitor outputs from plasma processing system 100. Moreover, the controller 190 may be coupled to and may exchange information with the processing chamber 110, substrate holder 120, plasma source 130, gas injection grid 140, first gas supply 150, second gas supply 160, temperature control system 170, electric bias control system 175, and pumping system 180. For example, a program stored in the memory may be utilized to activate the inputs to the aforementioned components of the plasma processing system 100 according to a process recipe in order to perform an etching process, or a deposition process. One example of the controller 190 is a DELL PRECISION WORKSTATION 610™, available from Dell Corporation, Austin, Texas.

[0078] The controller 190 may be locally located relative to the plasma processing system 100, or it may be remotely located relative to the plasma processing system 100. For example, the controller 190 may exchange data with the plasma processing system 100 using at least one of a direct connection, an intranet, the Internet and a wireless connection. The controller 190 may be coupled to an intranet at, for example, a customer site (i.e., a device maker, etc.), or it may be coupled to an intranet at, for example, a vendor site (i.e., an equipment manufacturer). Additionally, for example, the controller 190 may be coupled to the Internet. Furthermore, another computer (i.e., controller, server, etc.) may access, for example, the controller 190 to exchange data via at least one of a direct connection, an intranet, and the Internet. As also would be appreciated by those skilled in the art, the controller 190 may exchange data with the plasma processing system 100 via a wireless connection.

[0079] Referring now to FIG. 15, a method of operating a plasma processing system is described. The method includes a flow chart 500 beginning in 510 with disposing a substrate in a plasma processing system, such as the plasma processing system described in FIGs. 1 through 14. For example, a substrate can be disposed in a processing chamber having an upper chamber portion configured to define a plasma space and a lower chamber portion configured to define a process space.

[0080] In 520, a first gas is introduced to the plasma space from a gas injection grid positioned between the upper chamber portion and the lower chamber portion. In 530, a second gas is introduced to the process space from the gas injection grid.

[0081] In 540, plasma is formed in the plasma space from the first gas using a plasma source coupled to the upper chamber portion. In 550, process chemistry is formed in the process space to treat the substrate by coupling the process space to the plasma space through the gas injection grid.

[0082] Referring now to FIG. 16, a method of controlling the uniformity in a plasma processing system is provided according to an embodiment. The method comprises a flow chart 600 beginning in 610 with disposing a substrate in a plasma processing system, such as the plasma processing system described in FIGs. 1 through 14. For example, a substrate can be disposed in a processing

chamber having an upper chamber portion configured to define a plasma space and a lower chamber portion configured to define a process space.

[0083] In 620, a first gas is introduced to the plasma space from a gas injection grid positioned between the upper chamber portion and the lower chamber portion. The introduction of the first gas into the plasma space occurs from multiple zones formed in the gas injection grid as described above. Each zone for introducing the first gas includes a gas channel formed in the gas injection grid having one or more injection orifices, and the gas channel is independently coupled to a first gas supply system. Each zone can, for example, be formed in the radial directions, as illustrated in FIGs. 13 and 14.

[0084] In 630, a second gas is introduced to the process space from the gas injection grid. Optionally, the introduction of the second gas into the plasma space occurs from multiple zones formed in the gas injection grid as described above. Each zone for introducing the second gas includes a gas channel formed in the gas injection grid having one or more injection orifices, and the gas channel is independently coupled to a second gas supply system. Each zone can, for example, be formed in the radial directions, similar to the scheme illustrated for the first gas in FIGs. 13 and 14.

[0085] In 640, the flow of the first gas into the plasma space is adjusted in order to provide spatially uniform processing of the substrate. The local flow rate of the first gas into the plasma space can either raise or lower the local plasma density. For example, during high power operation of the plasma source, the hot plasma can be super heated, and therefore an increase in flow rate can lead to an excess of ionization of the first gas (i.e., plasma density increases). Alternatively, for example, during low power operation of the plasma source, the hot plasma is sustaining itself, and an increase in the flow rate can lead to quenching of the electron temperature (i.e., quenching of the collisions between neutrals and electrons), thus leading to a reduction in the plasma density. In one example, the gas injection grid can include, as described above, multiple zones for introducing the first gas into the plasma space. The flow rate for each zone can be utilized within the process recipe, for an etch or deposition process, in order to achieve the optimal spatial distribution of the plasma density in the plasma space for the specific process. For instance, a design of experiment (DOE) can be performed

to determine the optimal set of flow rates for each of the zones to produce the optimal results.

[0086] Optionally, the flow of the second gas into the process space is adjusted in order to provide spatially uniform processing of the substrate.

[0087] In 640, plasma is formed in the plasma space from the first gas using a plasma source coupled to the upper chamber portion. In 650, process chemistry is formed in the process space to treat the substrate by coupling the process space to the plasma space through the gas injection grid.

[0088] Although only certain exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention.

CLAIMS:

What is claimed is:

1. A surface wave plasma (SWP) source comprising:
an electromagnetic (EM) wave launcher configured to couple EM energy in a desired EM wave mode to a plasma by generating a surface wave on a plasma surface of the EM wave launcher adjacent said plasma;
a power coupling system coupled to said EM wave launcher, and configured to provide said EM energy to said EM wave launcher for forming said plasma; and
a mode scrambler coupled to said plasma surface of said EM wave launcher, and configured to reduce mode jumping between said desired EM wave mode and another EM wave mode.
2. The SWP source of claim 1, wherein said EM wave launcher is configured to couple said desired EM wave mode as a TM_{01} mode.
3. The SWP source of claim 1, wherein said mode scrambler comprises one or more holes coupled to said plasma surface of said EM wave launcher.
4. The SWP source of claim 3, wherein said one or more holes comprises one or more gas holes configured to flow gas therethrough.
5. The SWP source of claim 3, wherein said one or more holes comprises one or more blind holes.
6. The SWP source of claim 5, wherein at least one of a size, a geometry, a number, or a distribution of said one or more blind holes is selected to produce spatially controlled plasma.
7. The SWP source of claim 5, wherein said one or more blind holes are characterized by a width and a depth.

8. The SWP source of claim 7, wherein said width of said one or more blind holes and said depth of said one or more blind holes are substantially equivalent.

9. The SWP source of claim 7, wherein said width of said one or more blind holes and said depth of said one or more blind holes are less than or equal to 1 mm.

10. The SWP source of claim 5, wherein said one or more blind holes are filled with a material comprising SiO₂.

11. The SWP source of claim 5, wherein said one or more blind holes are filled with a material comprising a low dielectric constant material having a dielectric constant less than to SiO₂.

12. The SWP source of claim 5, wherein said one or more blind holes are filled with a plasma arrestor.

13. The SWP source of claim 12, wherein said plasma arrestor comprises a spherical pellet.

14. The SWP source of claim 13, wherein said spherical pellet comprises SiO₂, or a low dielectric constant material having a dielectric constant less than SiO₂.

15. The SWP source of claim 1, wherein said power coupling system comprises a radio frequency (RF) power coupling system.

16. The SWP source of claim 1, wherein said power coupling system comprises a microwave power coupling system.

17. The SWP source of claim 16, wherein said microwave power coupling system comprises:
a microwave source configured to produce microwave energy at 2.45 GHz;

a waveguide coupled to an outlet of said microwave source;
an isolator coupled to said waveguide and configured to prevent propagation of microwave energy back to said microwave source; and
a coaxial converter coupled to said isolator and configured to couple said microwave energy to a coaxial feed, wherein said coaxial feed is further coupled to said EM wave launcher.

18. The SWP source of claim 17, wherein:

said power coupling system comprises a coaxial feed for coupling EM energy to said EM wave launcher,

said EM wave launcher comprises a slot antenna with one end coupled to an inner conductor of said coaxial feed and another end coupled to an outer conductor of said coaxial feed, and

said slot antenna includes one or more slots configured to couple said EM energy from a first region above said slot antenna between said inner conductor and said outer conductor, to a second region below said slot antenna.

19. The plasma processing system of claim 18, wherein said EM wave launcher further comprises:

a slow wave plate positioned in said first region and configured to reduce the effective wavelength of said EM energy relative to the wavelength in free space; and

a resonator plate positioned in said second region and having a lower surface including said plasma surface of the EM wave launcher.

20. The SWP source of claim 19, wherein said slow wave plate and said resonator plate comprise substantially the same material composition.

21. The SWP source of claim 19, wherein said slow wave plate and said resonator plate comprise different material compositions.

22. The SWP source of claim 20, wherein said slow wave plate and said resonator plate consist essentially of quartz.

23. The SWP source of claim 22, wherein said resonator plate comprises at least one concentric groove configured to improve spatial uniformity of a plasma.

24. The SWP source of claim 19, wherein said resonator plate comprises a high dielectric constant (high-k) material, said high dielectric constant material having a dielectric constant greater than a value of 4.

25. The SWP source of claim 19, wherein said resonator plate comprises one or more of quartz, intrinsic crystal silicon, alumina, and sapphire.

26. The SWP source of Claim 1, further comprising a cover plate attached to said EM wave launcher and configured to reduce erosion of said SWP source.

27. A surface wave plasma (SWP) source comprising:
an electromagnetic (EM) wave launcher configured to couple EM energy in a desired EM wave mode to a plasma by generating a surface wave on a plasma surface of the EM wave launcher adjacent said plasma;

a power coupling system coupled to said EM wave launcher, and configured to provide said EM energy to said EM wave launcher for forming said plasma; and

means for reducing mode jumping between said desired EM wave mode and another EM wave mode.

28. The SWP source of Claim 27, further comprising means, attached to said EM wave launcher, for reducing erosion of said SWP source.

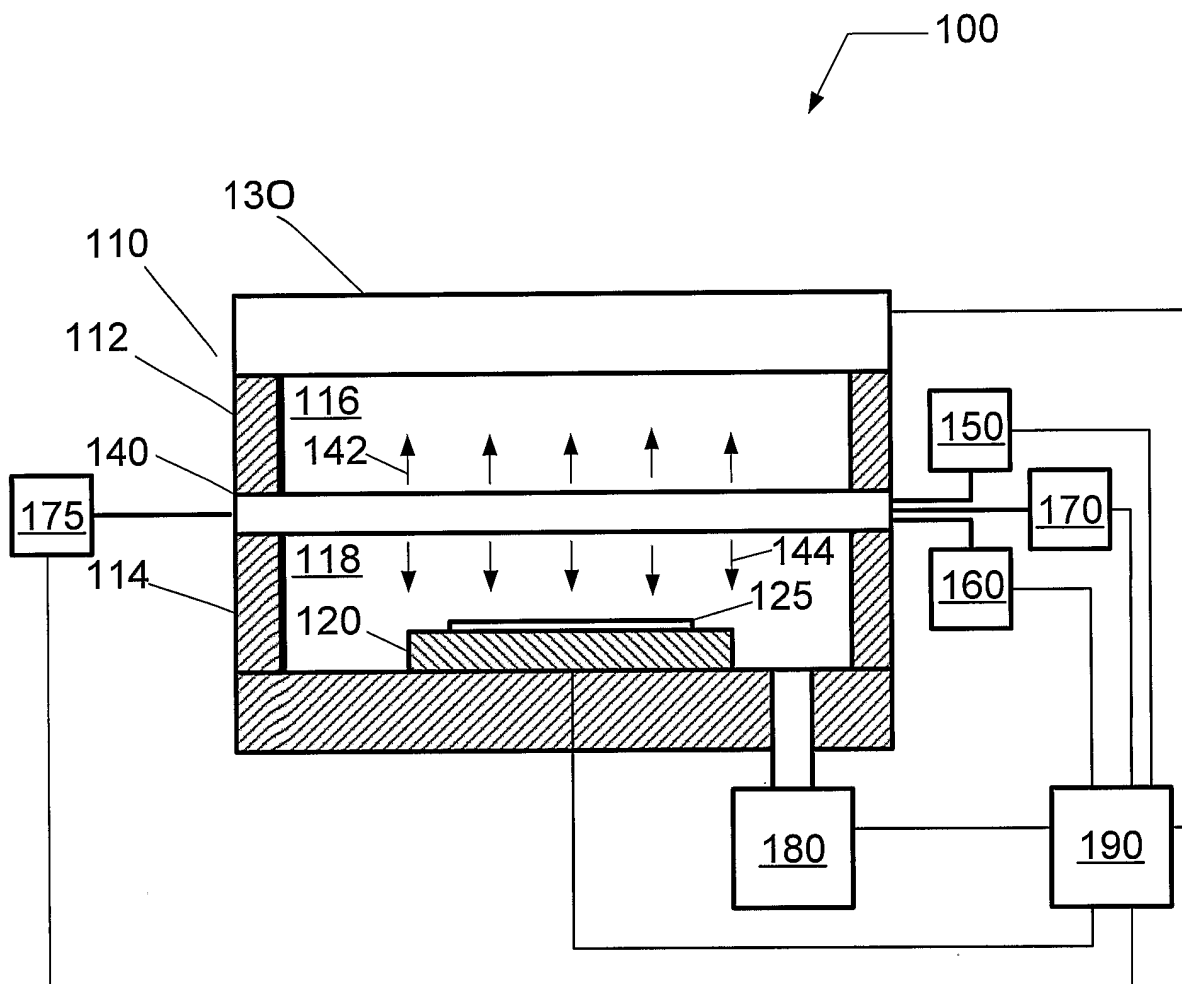


FIG. 1

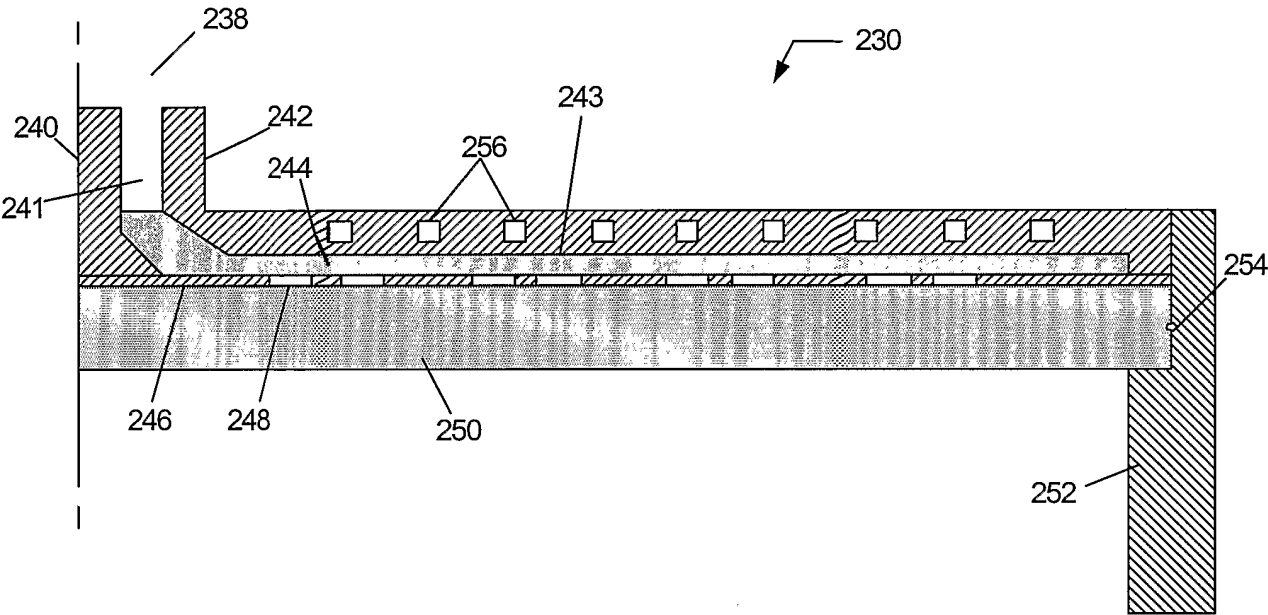


FIG. 2

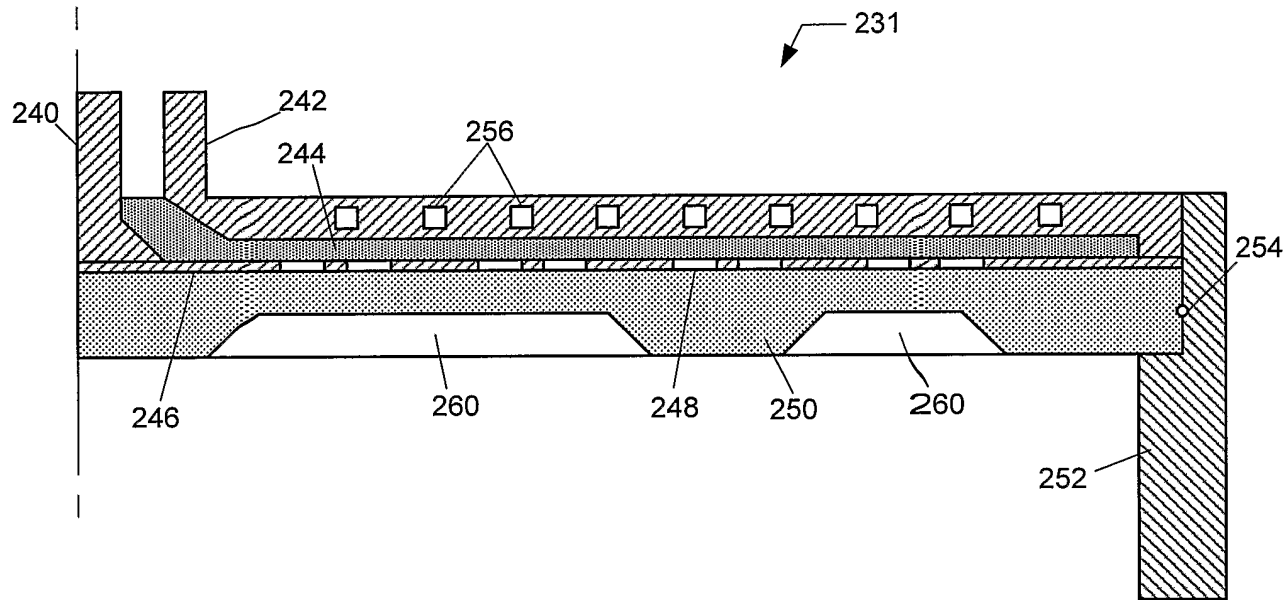


FIG. 3

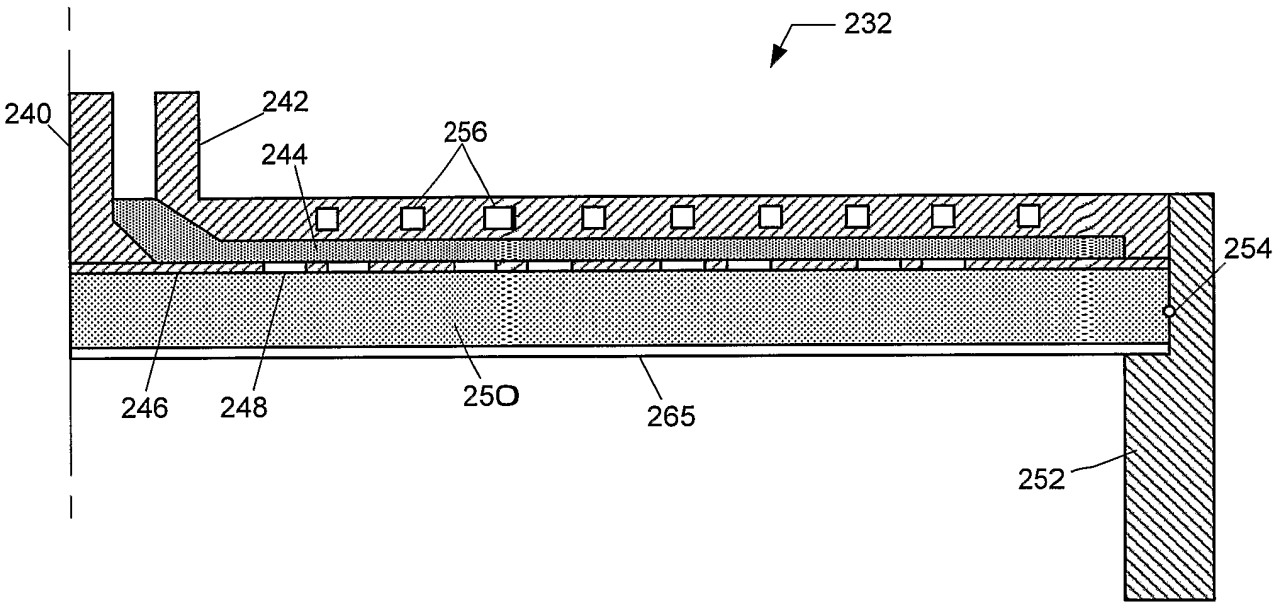


FIG. 4

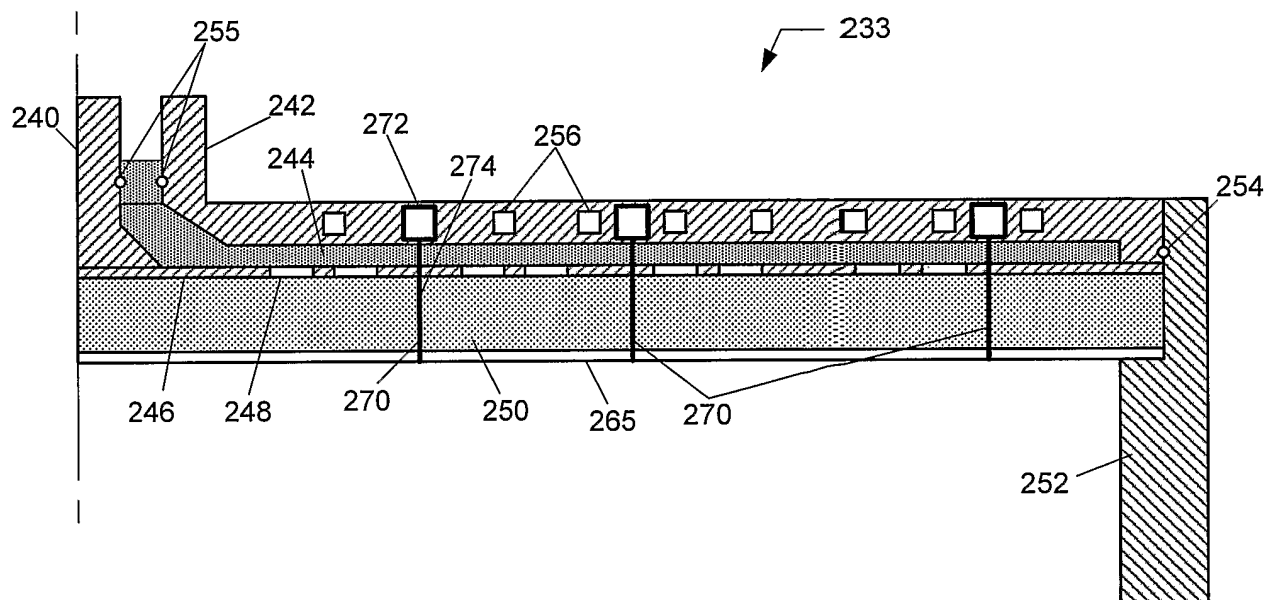


FIG. 5

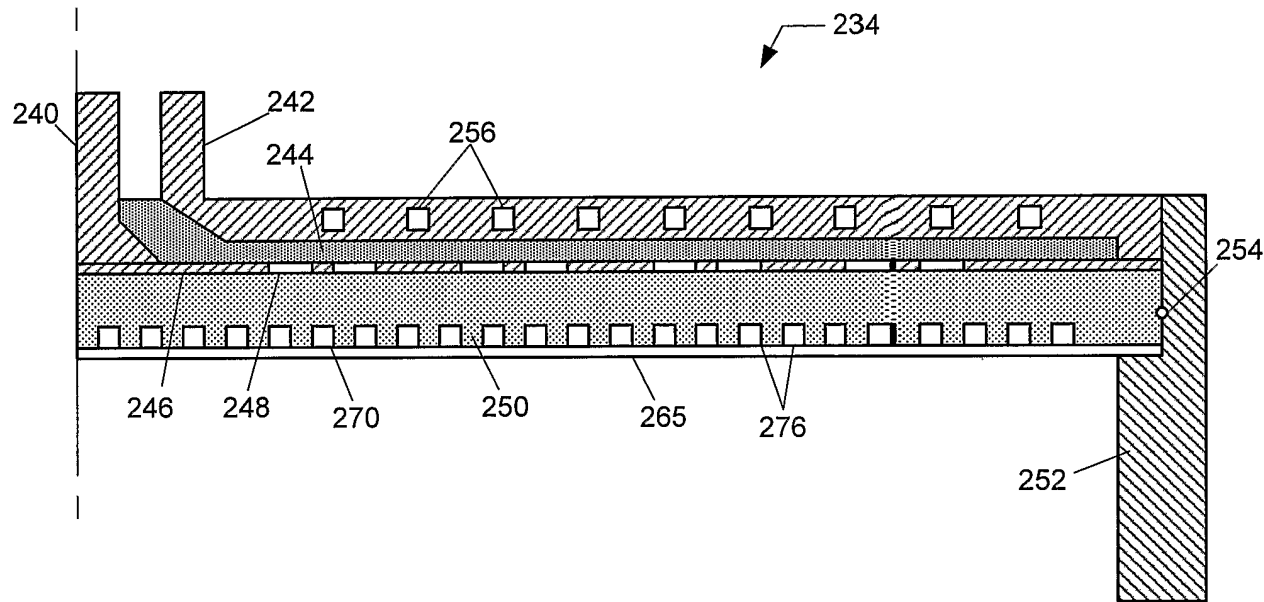


FIG. 6

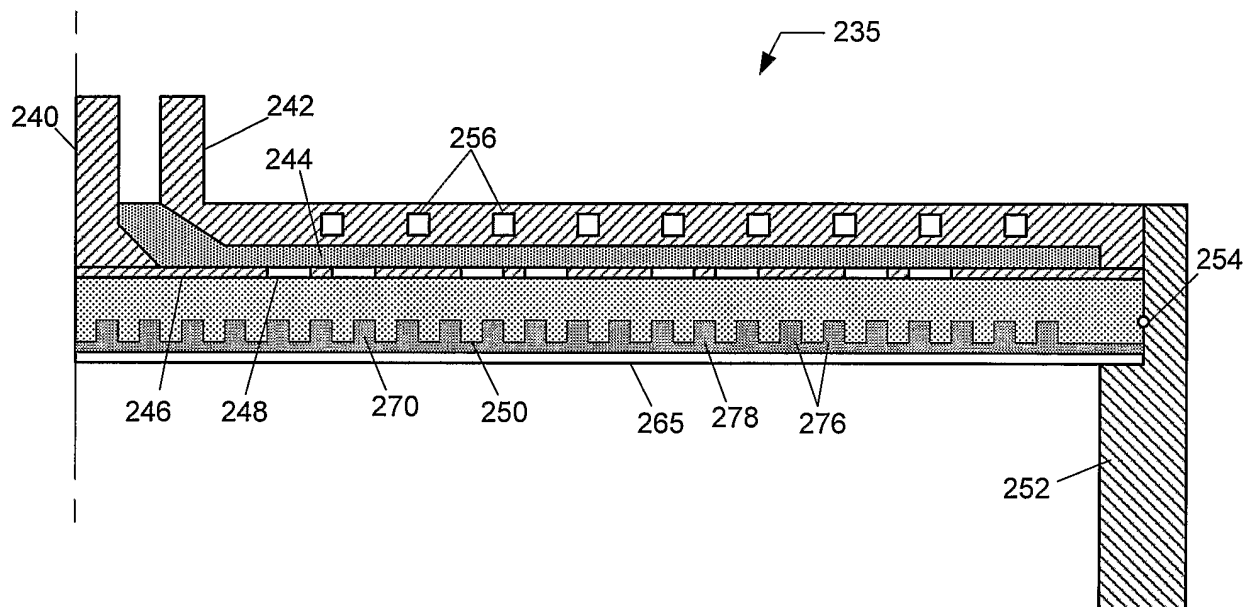


FIG. 7

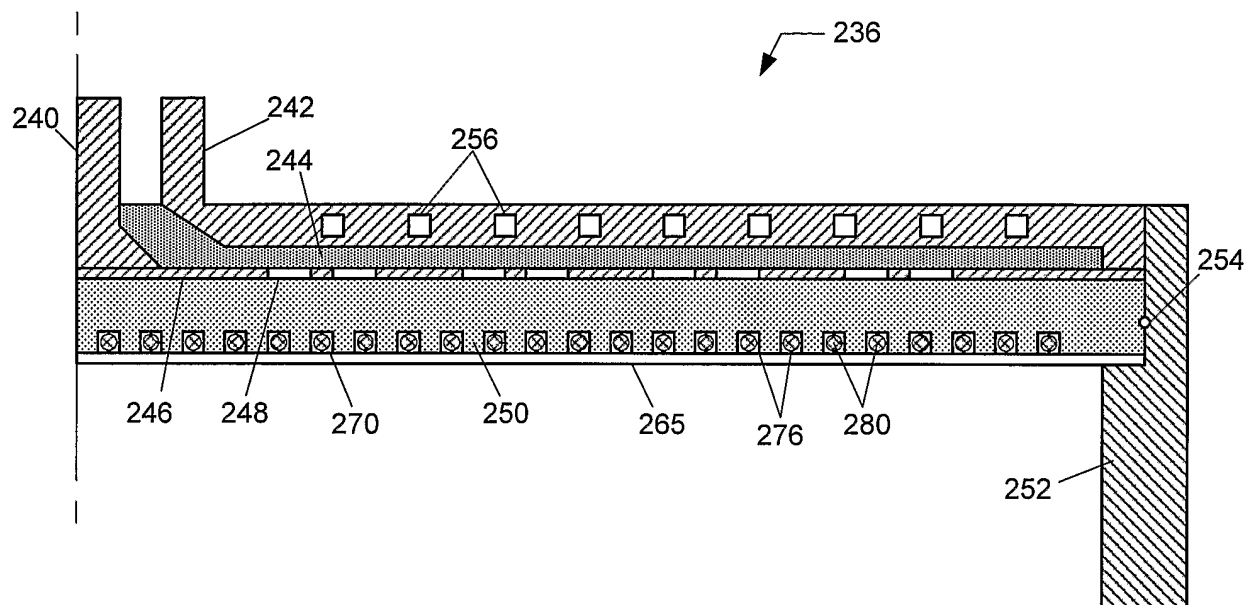


FIG. 8

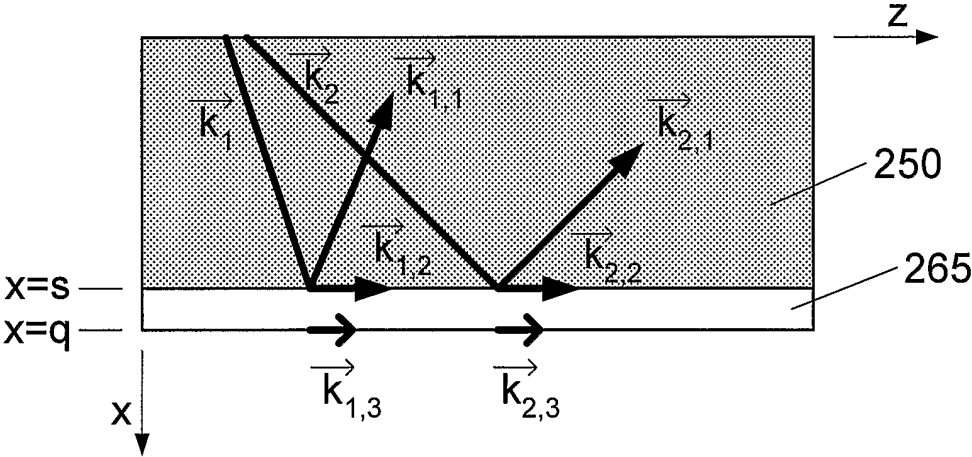


FIG. 9A

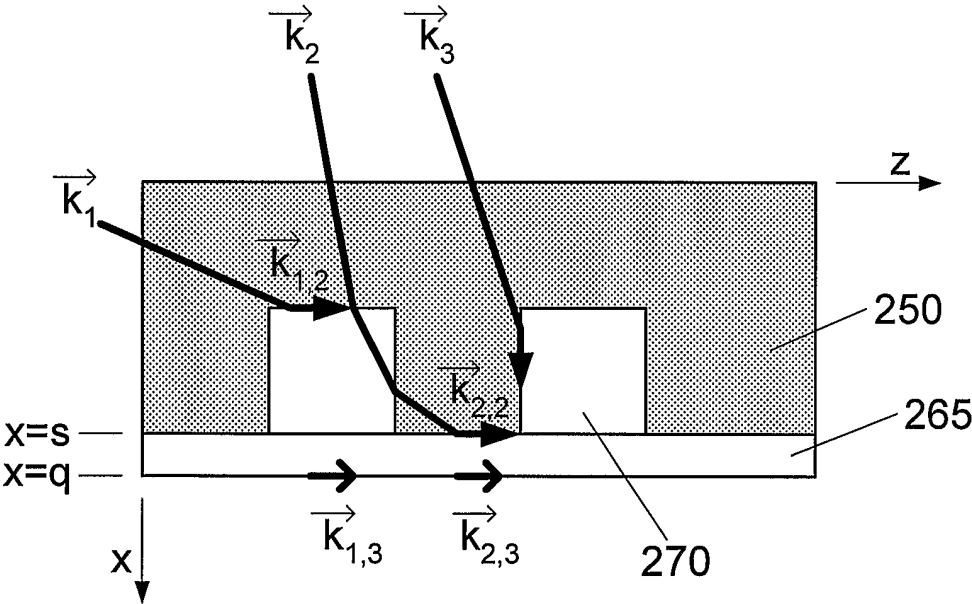


FIG. 9B

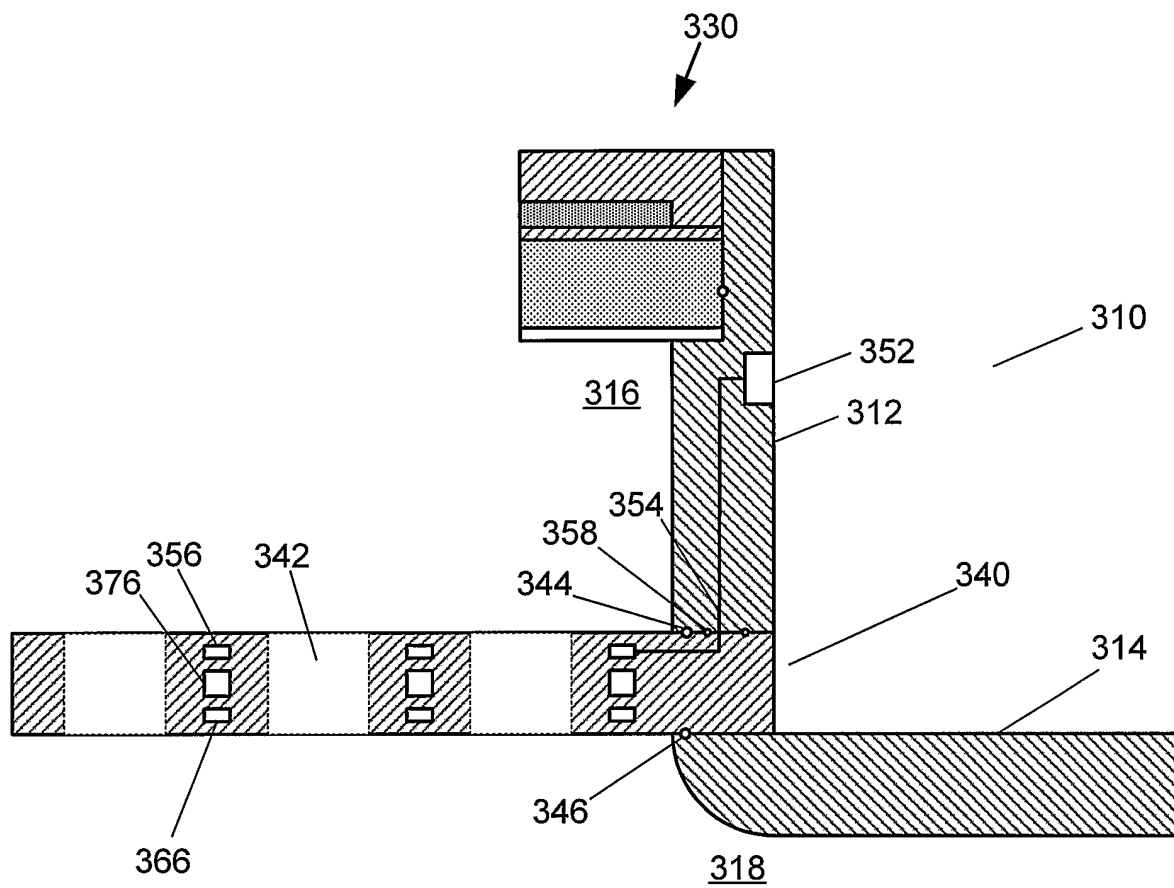


FIG. 10

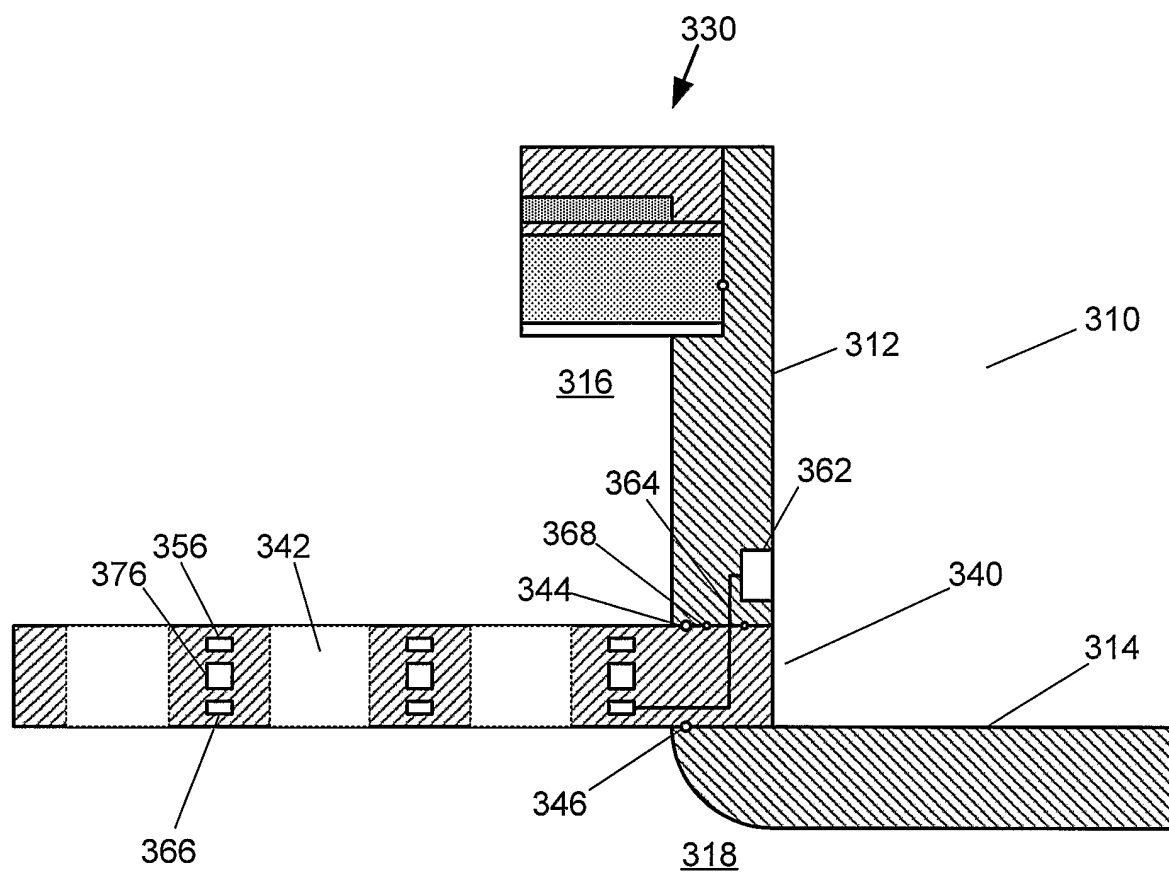


FIG. 11

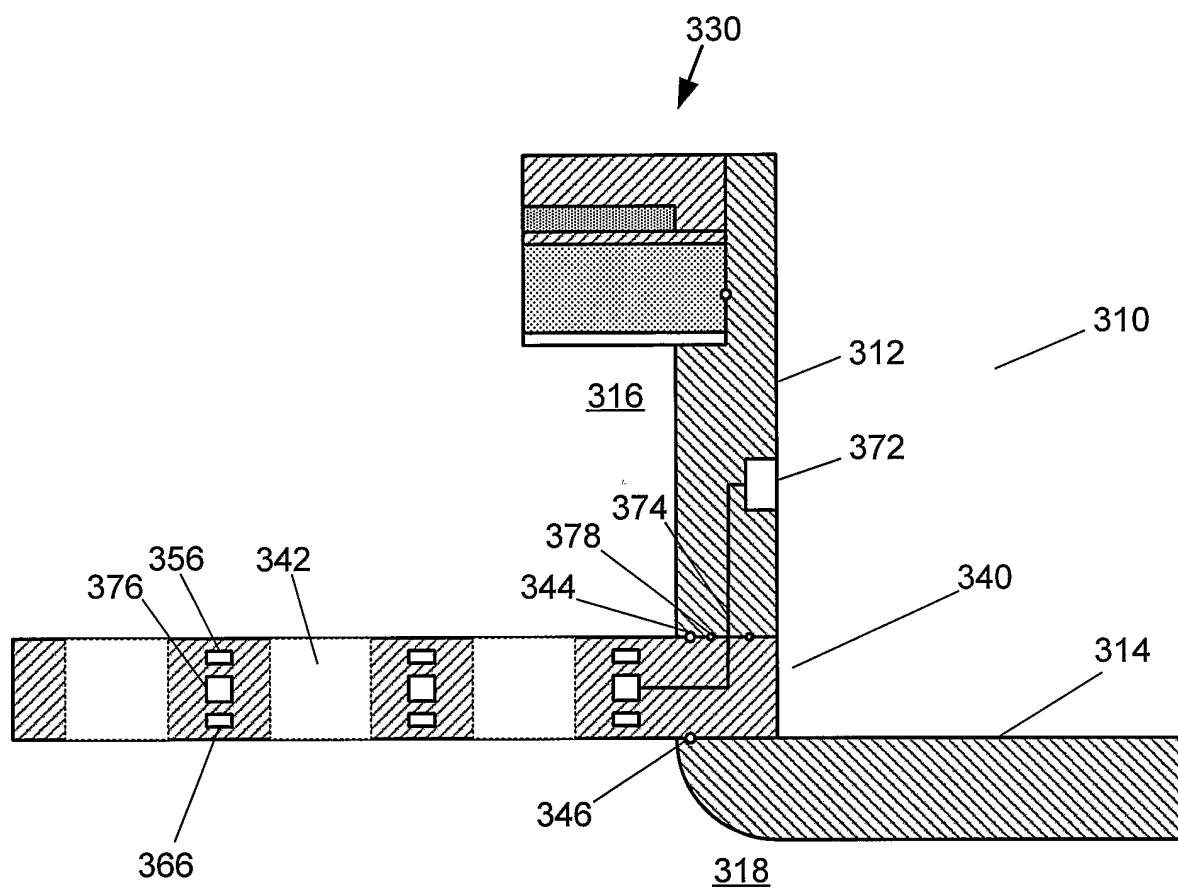


FIG. 12

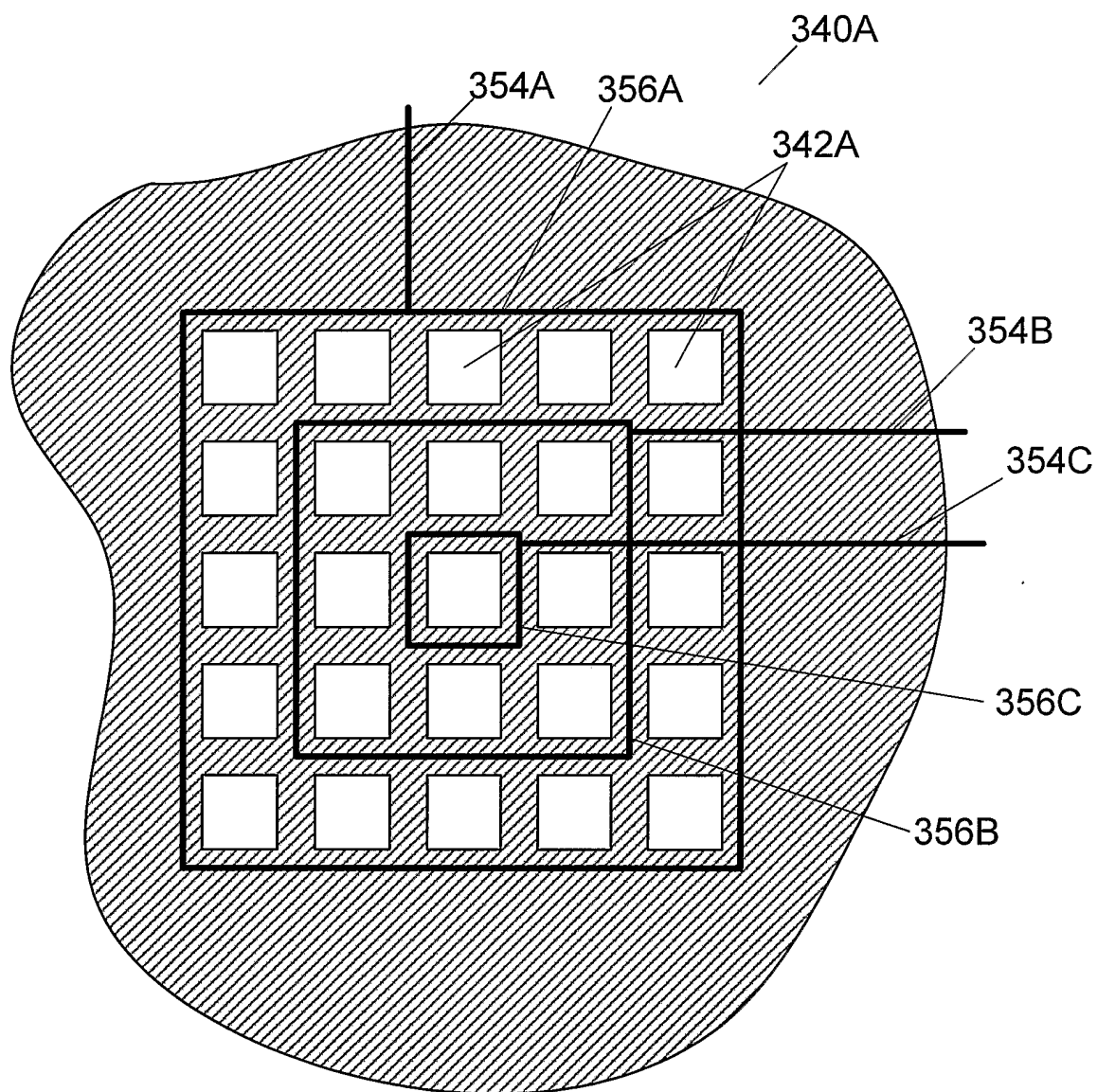


FIG. 13

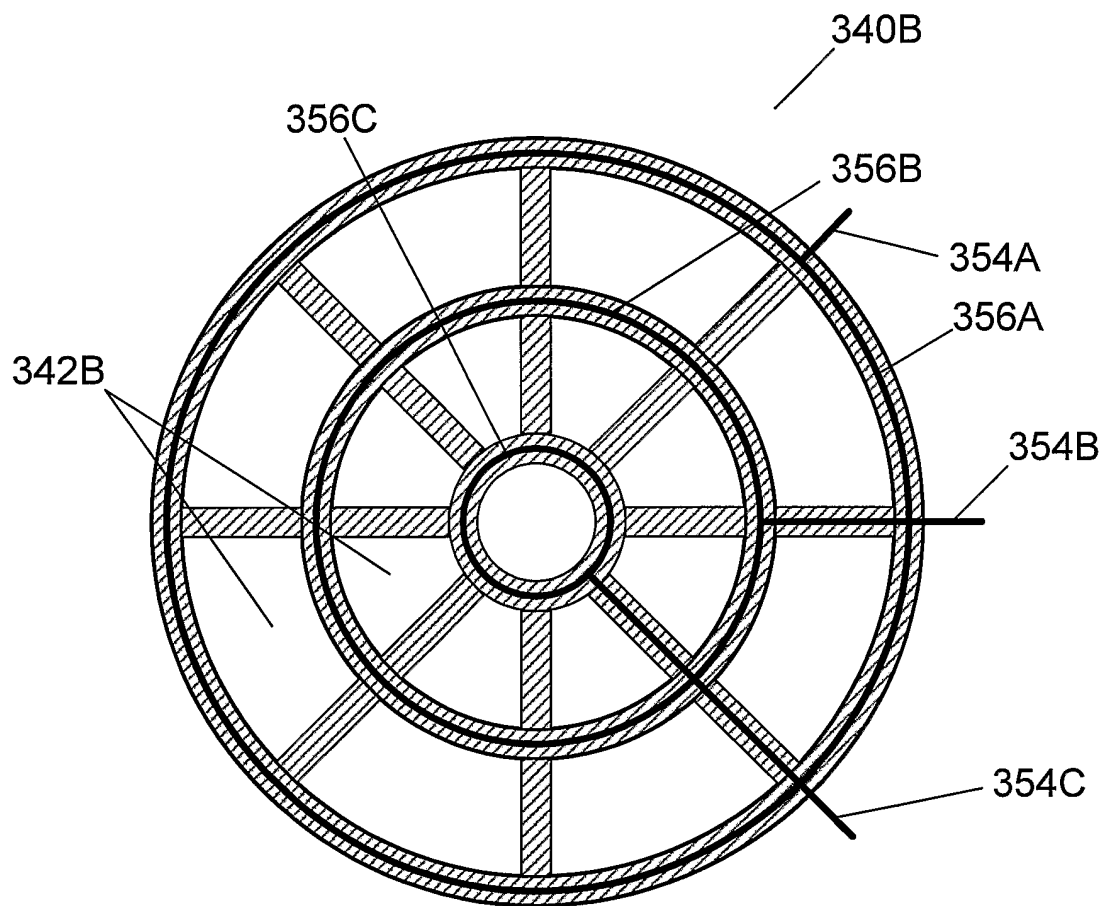


FIG. 14

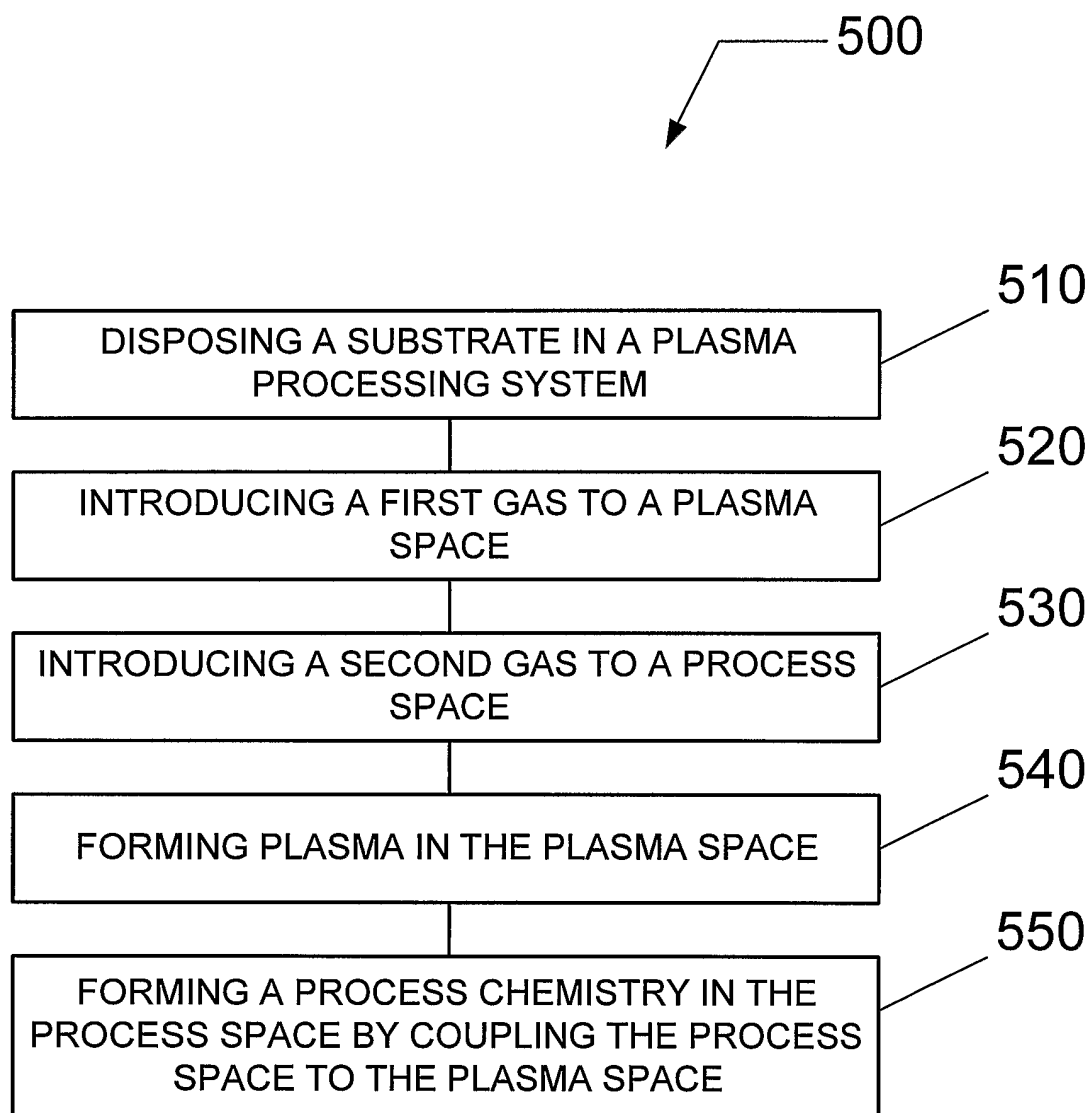


FIG. 15

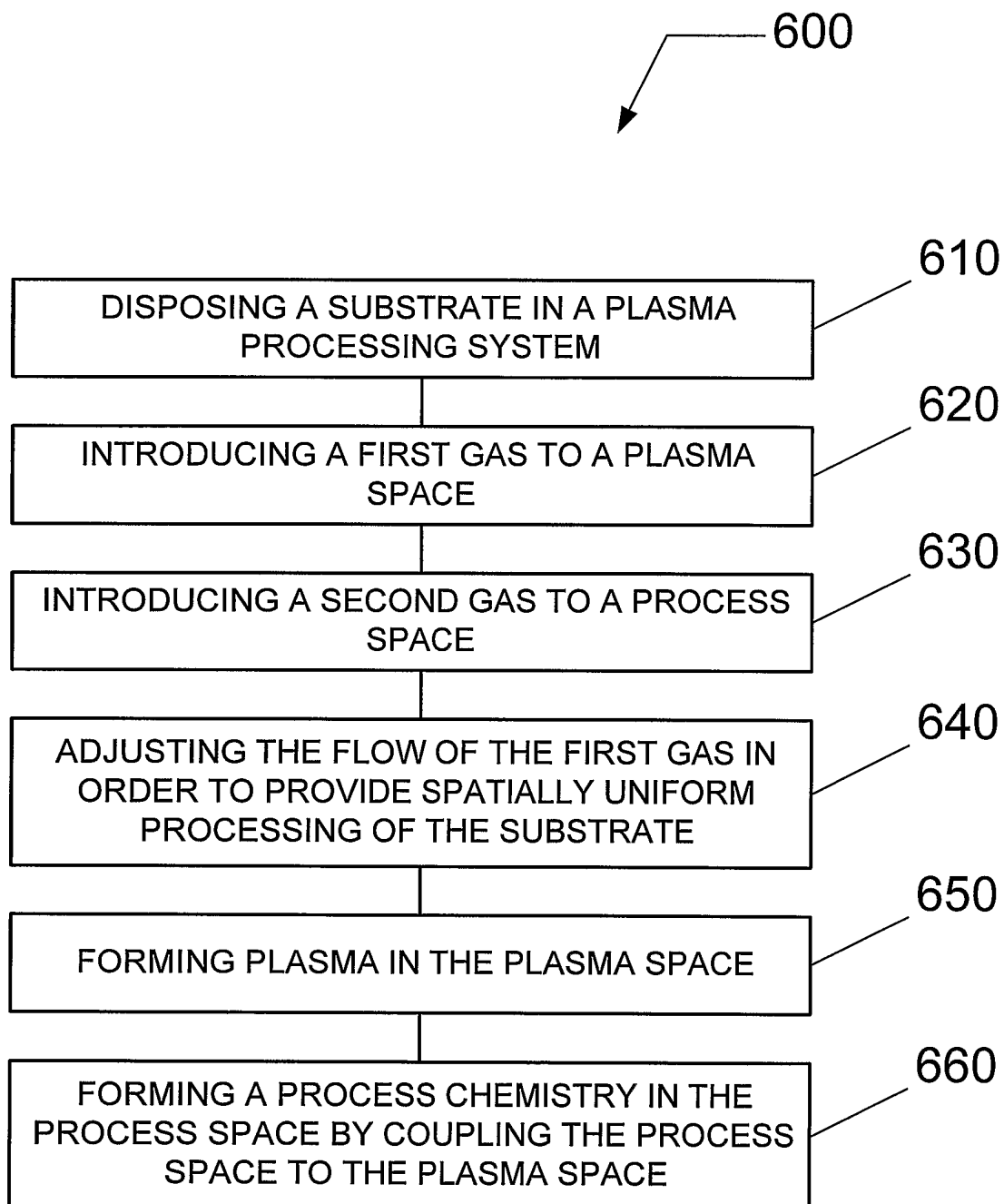


FIG. 16