

FIG. 1B

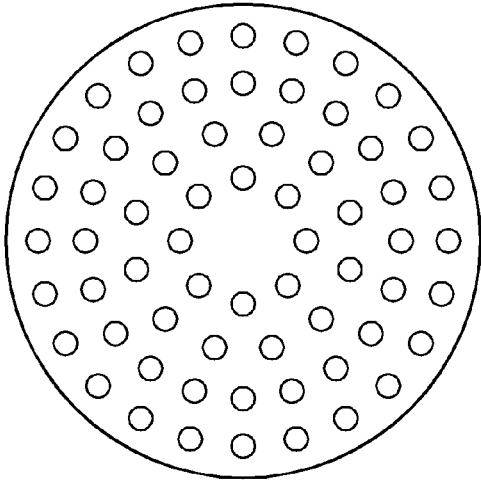


FIG. 2A

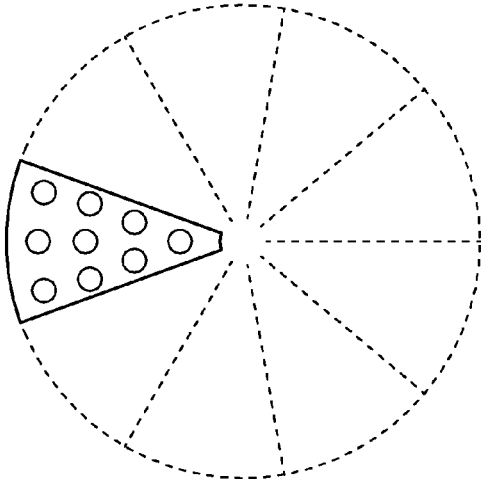
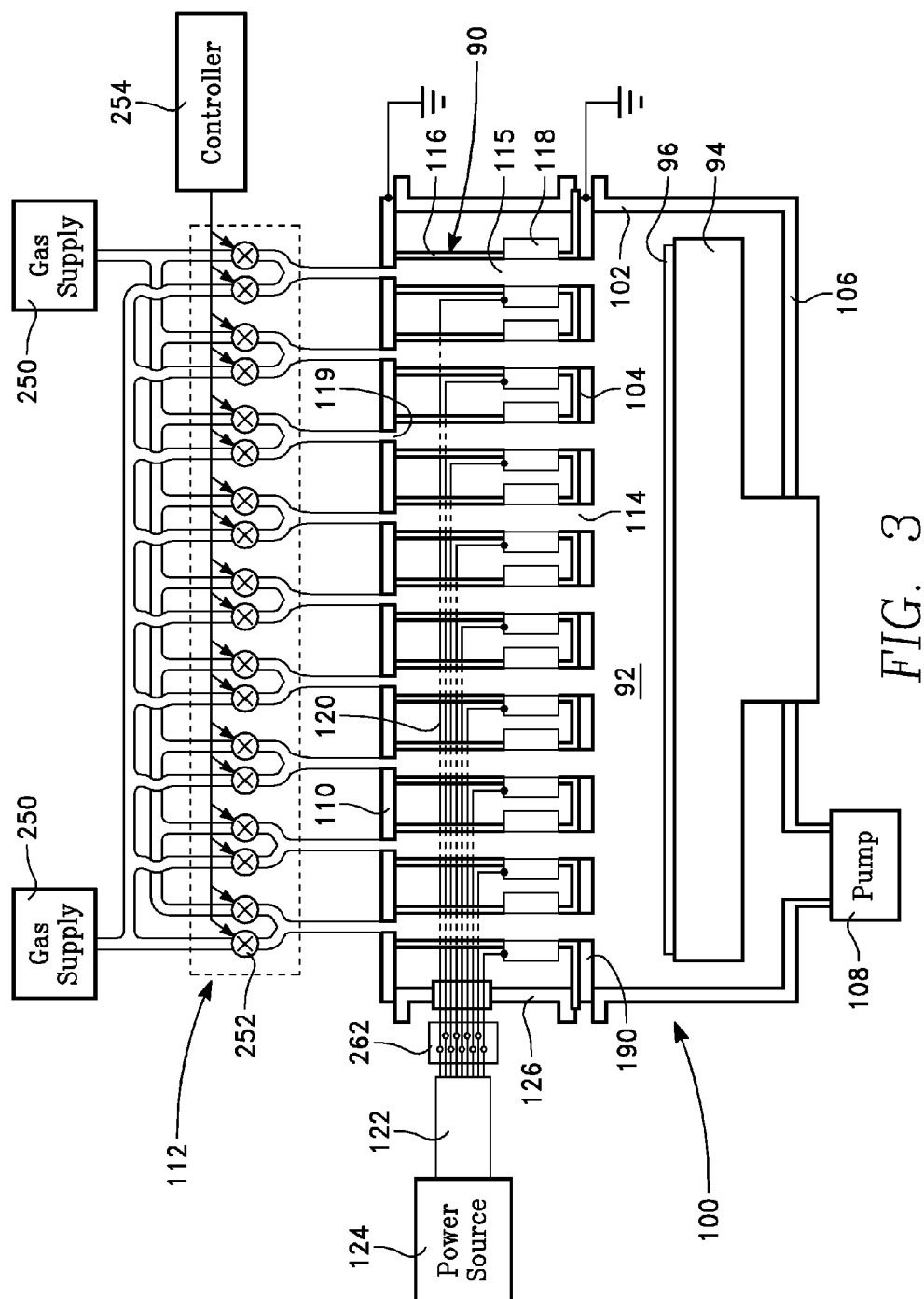


FIG. 2B



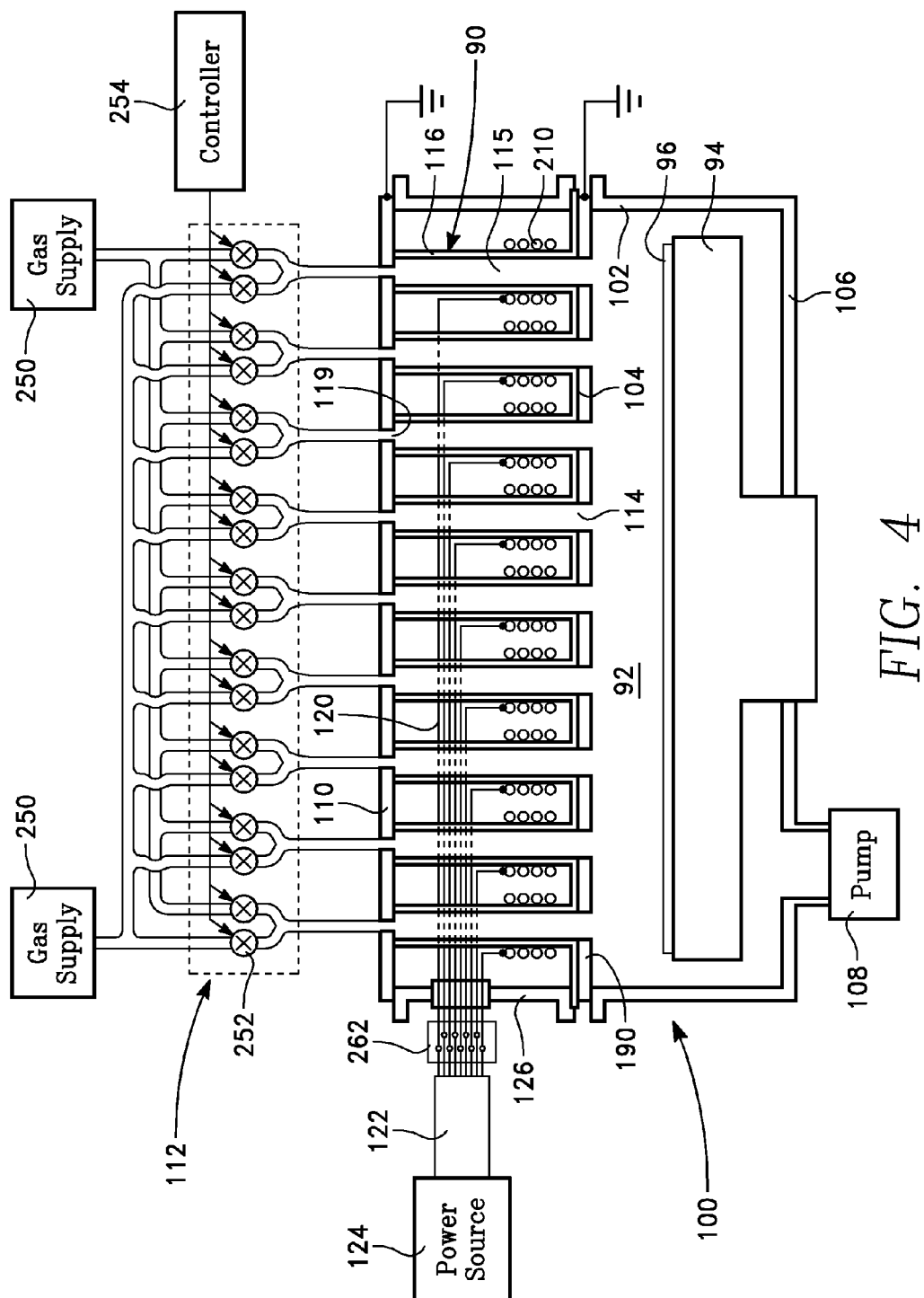


FIG. 4

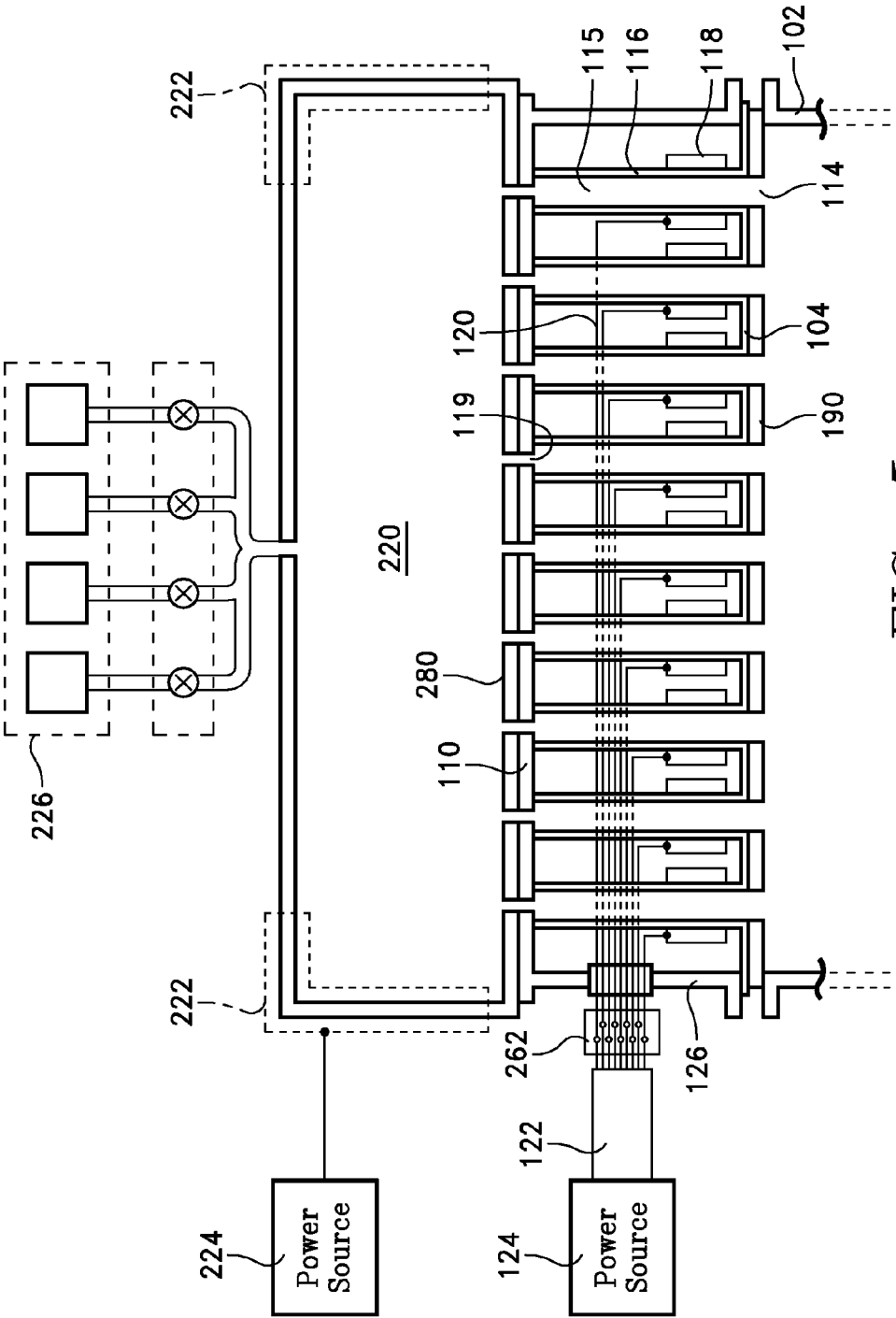


FIG. 5

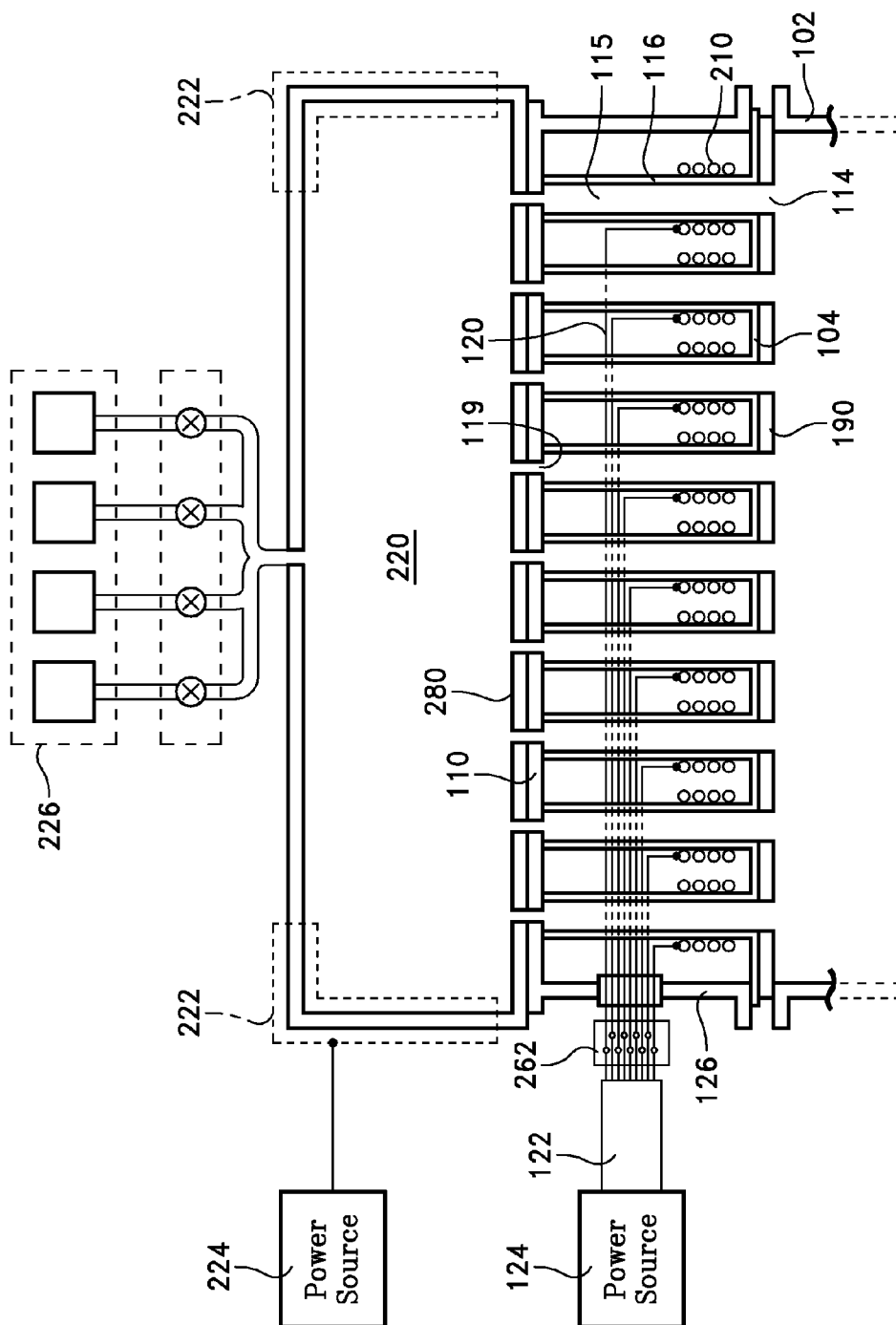
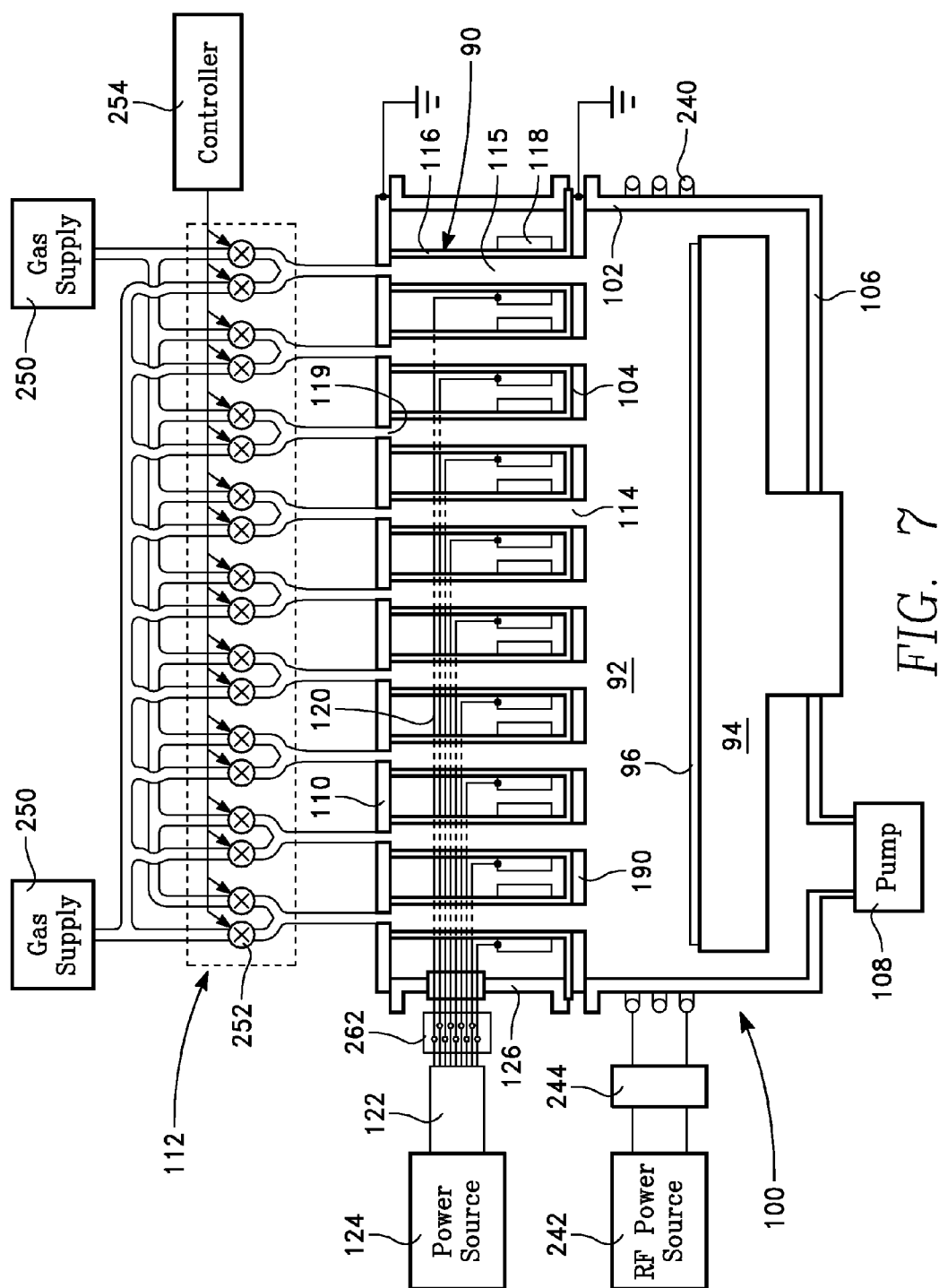


FIG. 6



PLASMA REACTOR FOR PROCESSING A WORKPIECE WITH AN ARRAY OF PLASMA POINT SOURCES

BACKGROUND

[0001] Technical Field

[0002] The disclosure concerns plasma processing of a workpiece such as a semiconductor wafer, and reduction in process non-uniformities.

[0003] Background Discussion

[0004] In conventional plasma processing, the processed wafers may suffer from local non uniformities—due non-uniform stress, non-uniform film composition (for a deposition process), non-uniform CD's (critical dimensions of features) due to different etch environments. This could be due to differences among incoming wafers or differences in the characteristic of the processing chamber (e.g., in a carousel style processing chamber where the rotating wafer sees a leading edge and a trailing edge radical dwell time difference or different local temperature).

SUMMARY

[0005] A plasma reactor comprises: a processing chamber and a workpiece support in the processing chamber, the chamber comprising a lower ceiling facing the workpiece support; an upper ceiling overlying and facing the lower ceiling and a gas distributor overlying the upper ceiling; plural cavity walls defining plural cavities between the upper and lower ceilings, the gas distributor comprising plural gas flow paths to respective ones of the plural cavities; plural outlet holes in the lower ceiling aligned with respective ones of the plural cavities; and respective power applicators adjacent respective ones of the plural cavities, a power source, plural power conductors coupled to respective ones of the power applicators, and a power distributor coupled between the power source and the plural power conductors.

[0006] In one embodiment, the plural cavity walls comprise dielectric cavity walls.

[0007] In a further embodiment, the power source comprises an RF power generator and wherein each one of the respective power applicators is separated from an interior of a corresponding one of the plural cavities by the corresponding one of the plural cavity walls.

[0008] In one embodiment, the power applicator comprises an electrode for capacitively coupling RF power into the corresponding one of the plural cavities. In this embodiment, each electrode may surround a section of the corresponding one of the plural cavities.

[0009] In another embodiment, the power applicator comprises a coil antenna for inductively coupling RF power into the corresponding one of the plural cavities. In this embodiment, the coil antenna may comprise a conductor coiled around a section of the corresponding one of the plural cavities.

[0010] In a yet further embodiment, the power source is a D.C. power generator, each one of the power applicators comprises an electrode for D.C. discharge, and wherein each one of the dielectric cavity walls is configured to expose the corresponding electrode to the interior of the corresponding one of the plural cavities.

[0011] In one embodiment, the power distributor comprises plural switches coupled between an output of the power generator and respective ones of the power conductors.

[0012] In one embodiment, the plasma reactor further comprises a processor controlling the plural switches individually in accordance with user-defined instructions.

[0013] In one embodiment, the plasma reactor further comprises a process gas source and a gas distributor comprising plural valves coupled between the process gas source and respective ones of the plural cavities. The process gas source may comprise plural gas sources of different gas species, wherein respective ones of the plural valves are coupled between respective ones of the plural gas sources and respective ones of the plural cavities. In one embodiment, the plasma reactor further comprises a processor controlling the plural valves individually in accordance with user-defined instructions.

[0014] In one embodiment, the plasma reactor further comprises a remote plasma source coupled to deliver plasma by-products to the plural cavities.

[0015] In one embodiment, the processing chamber further comprises a cylindrical side wall, the reactor further comprising an inductively coupled plasma source comprising a coil antenna wound around the cylindrical side wall and an RF power generator coupled to the coil antenna through an impedance match.

[0016] In one embodiment, a plasma reactor comprises: a processing chamber and a workpiece support in the processing chamber; a gas distributor overlying the workpiece support; plural cavity walls defining plural cavities underlying the gas distributor, the gas distributor comprising plural gas flow paths to respective ones of the plural cavities; respective power applicators adjacent respective ones of the plural cavities, a power source, plural power conductors coupled to respective ones of the power applicators, and a power distributor coupled between the power source and the plural power conductors; and a process gas source and a gas distributor comprising plural valves coupled between the process gas source and respective ones of the plural cavities.

[0017] In a further embodiment, a method of processing a workpiece in a plasma reactor comprising an array of plasma point sources distributed over a surface of the workpiece, comprises: performing a plasma process on the workpiece; observing a non-uniformity in a spatial distribution of process rate across the surface of the workpiece; and reducing the non-uniformity by performing at least one of:

- (a) adjusting an apportionment of plasma source power levels among the array of plasma point sources, or
- (b) adjusting an apportionment of gas flows among the array of plasma point sources.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] So that the manner in which the exemplary embodiments of the present invention are attained can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings. It is to be appreciated that certain well known processes are not discussed herein in order to not obscure the invention.

[0019] FIG. 1A is a simplified diagram of a first embodiment having an array of plasma point sources.

[0020] FIG. 1B is an enlarged plan view of a plasma point source in the embodiment of FIG. 1A.

[0021] FIGS. 2A and 2B depict different arrangements of an array of plasma point sources.

[0022] FIG. 3 depicts an embodiment in which the plasma point sources employ plasma D.C. discharge.

[0023] FIG. 4 depicts an embodiment in which the plasma point sources employ inductive coupling.

[0024] FIG. 5 depicts a modification of the embodiment of FIG. 1A employing a remote plasma source.

[0025] FIG. 6 depicts a modification of the embodiment of FIG. 4 employing a remote plasma source.

[0026] FIG. 7 depicts a modification of the embodiment of FIG. 1A having a chamber-wide inductively coupled source in addition to the array of plasma point sources.

[0027] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

DETAILED DESCRIPTION

Introduction

[0028] A plasma source consists of a multitude or array of independently controlled local plasma point sources, which allows the spatial and temporal control of charged particle species (electrons, negative and positive ions) and radicals over a user defined region.

[0029] Using a plasma source that enables spatial and temporal control enables correction of local non-uniformities. This may be accomplished by switching ON or OFF plasma generation in different plasma point sources where the charged particles and radicals are generated. Alternatively or in addition, this may be accomplished by changing process gas flows to the different plasma point sources. For example, the gas flow may be switched ON or OFF and/or the gas mixture for each plasma point source may be changed. The user can select the gas to be ionized or broken down in the local plasma point source. The user can further select the time or duration of the discharge.

[0030] One can alter the local discharge chemistry by either operating in parallel different gas chemistries in different simultaneous local gas discharges (spatial control) or by alternating gas chemistry locally in the same local discharge.

[0031] One can subject the entire workpiece (wafer) to a constant negative DC bias but attract ions locally to implant, or etch or deposit.

[0032] The array of plasma point sources can be combined with a conventional non-local plasma source (such as a capacitively coupled large electrode plasma source or an inductively coupled plasma source) and, in real time, correct for local non-uniformities in plasma generation.

[0033] The array of plasma point sources can be combined with a remote plasma source (e.g., a remote radical source). The radical processing step could be followed by a plasma treatment step where one can vary the composition and local dwell time. Past solutions have focused on local variation of

temperature by varying current through local heating elements in the substrate holders. Embodiments described herein add to the existing solution, and enable local chemistries, and affect the generation of charged particles and radicals rather than depending upon only temperatures to speed up reactions.

Embodiments

[0034] FIGS. 1A and 1B depict an embodiment having multiple plasma point sources **90** that are capacitively coupled using an RF frequency. The point sources **90** can be arranged in various configurations, such as circular (FIG. 2A) or pie shaped (FIG. 2B). The embodiment of FIG. 1A includes a process chamber body **100** having a processing zone **92** enclosed by a cylindrical side wall **102**, a lower ceiling **104** and a floor **106**. A workpiece support **94** supports a workpiece **96** within the processing zone **92**. A vacuum pump **108** may be coupled to the processing zone **92** through the floor **106**. An upper ceiling **110** supported on an upper cylindrical side wall **126** overlies the lower ceiling **104** and supports a gas distributor **112**. The lower ceiling **104** includes an array of gas outlet holes **114**. In the embodiment of FIG. 1A, the point sources **90** are an array of cylindrical cavities **115** enclosed by dielectric cylindrical cavity walls **116**, each being parallel to an axis of symmetry of the cylindrical side wall **102** and aligned with a respective one of the gas outlet holes **114**. The dielectric cylindrical cavity walls **116** are ringed by respective cylindrical electrodes **118**.

[0035] Each plasma point source **90** is local, in that the area of each gas outlet hole **114** is small relative to the area of the lower ceiling **104** or the upper ceiling **110** or relative to the diameter of the chamber body **100**. In one embodiment, the area of each gas outlet hole **114** does not exceed 5% of the area of the lower ceiling **104** or the upper ceiling **110** or area of the chamber body **100**.

[0036] In the illustrated embodiment of FIGS. 1A and 1B, the shape of each gas outlet opening **114** is circular and conforms with the shape of the cylindrical cavity **115**. However, in other embodiments, each gas outlet hole **114** may be of any shape and may not conform with the shape of the cylindrical cavity **115**. For example, each gas outlet hole **114** may be of a non-circular shape (e.g., elliptical) or may be of a polygonal shape or a linear slot shape or combinations of some of the foregoing shapes. If the shape of the gas outlet hole **114** does not conform with the cylindrical cavity **115**, then an adapter (not illustrated) may be introduced to provide a gas seal between the gas outlet hole **114** and the cylindrical cavity **115**, in one embodiment.

[0037] The upper ceiling **110** has an array of gas inlet openings **119** each aligned with a respective one of the cylindrical cavities **115**. The gas distributor **112** furnishes process gases into the cylindrical cavities **115** through the gas inlet openings **119**. Individual power conductors **120** conduct power to individual ones of the respective cylindrical electrodes **118**. A power distributor **122** distributes power to the power conductors **120** from a power source **124**. In one embodiment, the power source **124** is an alternating current (AC) power generator or a radio frequency (RF) power generator with an RF impedance match. In related embodiments, the frequency of the power source **124** may be any from D.C. to UHF, for example. In one embodiment, plasma is produced in the cylindrical cavities **115** by capacitive coupling of RF power from the cylindrical electrodes

118 through the dielectric cylindrical cavity walls 116 into the cylindrical cavities 115. The lower ceiling 104 isolates the cylindrical electrodes 118 from plasma.

[0038] The gas distributor 112 receives different gas species from plural gas supplies 250 and apportions different gas mixtures to different ones of the cylindrical cavities 115 through the respective gas inlet openings 119 in accordance with different user-specified gas recipes for the different cylindrical cavities 115. For example, the gas distributor 112 may include an array of gas valves 252 individually controlled by a processor 254 in accordance with user-defined instructions that define gas mixtures for the individual cylindrical cavities 115. The array of gas valves 252 is coupled between the plural gas supplies 250 and the gas inlet openings 119 to the cylindrical cavities 115.

[0039] The power distributor 122, in one embodiment, controls the power supplied to each power conductor 120 individually. For example, the power distributor 122 may include an array of electrical switches 262 individually controlled by the processor 254 in accordance with user-defined instructions. The power may be controlled by pulse width modulation, and the user-defined instructions may define individual on/off durations (or duty cycles) of power for the individual cylindrical cavities 115. The array of electrical switches 262 is coupled between the power source 124 and the power conductors 120.

[0040] In a first embodiment, the lower ceiling 104 is formed of a dielectric material while the upper ceiling 110 is formed of a conductive material. In a second embodiment, the lower ceiling 104 is adjacent a lower plate 190 formed of a conductive material, and both the lower plate 190 and the upper ceiling 110 are grounded. In this way, the plasma source is located between two grounded plates, namely the lower plate 190 and the upper ceiling 110.

[0041] FIG. 3 depicts an embodiment in which plasma is produced by a D.C. discharge, and the power source 124 is a D.C. power generator. Each of the dielectric cylindrical cavity walls 116 is terminated above the corresponding one of the cylindrical electrodes 118. This feature can directly expose each cylindrical electrode 118 to plasma to facilitate the D.C. discharge.

[0042] FIG. 4 depicts a modification of the embodiment of FIG. 1A, in which the cylindrical electrodes 118 are replaced by individual inductive coils 210, to produce an inductively coupled plasma within each cylindrical cavity 115. Each inductive coil 210 is wrapped around a bottom section of the corresponding cylindrical dielectric wall 116, as depicted in FIG. 4. In the embodiment of FIG. 4, a changing magnetic field generates a changing electric field in the cylindrical cavity 115 which in turn generates a closed turn oscillating plasma current.

[0043] FIG. 5 depicts another modification of the embodiment of FIG. 1A that includes a remote plasma source 220 and a radical distribution plate 280. The radical distribution plate 280 directs radicals from the remote plasma source 220 into the individual cylindrical cavities 115. The remote plasma source 220 may include a plasma source power applicator 222 driven by a power source 224. The remote plasma source 220 may further include controlled gas sources 226 containing precursors of desired radical species. There are some processes in which chemically active radicals generated remotely play a critical role in the processing of wafers. However, there may be a need to follow the radical treatment with a plasma treatment step. Having a

spatially and temporally controllable plasma source helps in addressing radical non-uniformity. In the case of radicals which are short lived (recombine into inert neutrals), having a controllable plasma density can help regenerate important radicals.

[0044] FIG. 6 depicts a modification of the embodiment of FIG. 4 that includes a remote plasma source 220 and a radical distribution plate 280. In the embodiment of FIG. 6, the remote plasma source 220 is combined with the inductively coupled plasma sources (i.e., the inductively coupled coils 210) of FIG. 4. The inductively coupled plasma sources (the coils 210) enable operation in different (lower) pressure regimes (e.g., below 25 mTorr), compared to the capacitively coupled plasma source of the embodiment of FIG. 1A.

[0045] FIG. 7 depicts a modification of the embodiment of FIG. 1A, in which the array of plasma point sources 90 is combined with a larger non-local inductively coupled plasma source. The non-local inductively coupled plasma source of FIG. 7 includes a helically wound coil antenna 240 surrounding the cylindrical side wall 102. The helically wound coil antenna 240 is driven by an RF power generator 242 through an RF impedance match 244. In the embodiment of FIG. 7, the cylindrical side wall 102 is formed of a non-metallic material to enable inductive coupling of RF power through the cylindrical side wall 102. The lower plate 190 protects the individual plasma point sources (corresponding to the individual cylindrical cavities 115) from the larger inductively coupled plasma source (corresponding to the helically wound coil antenna 240).

[0046] The individual plasma point sources 90 (corresponding to the individual cylindrical cavities 115) are individually controllable. The enables spatial and temporal control of plasma distribution. Such control may be exercised in such a manner as to reduce plasma distribution non-uniformity.

Control Modes:

[0047] The power source 124 can power each plasma point source 90 in different modes. In a first mode, each plasma point source 90 dissipates a fixed amount of power and the control system switches on or off the power furnished to the plasma point source using the array of electrical switches 262. In one example, each point source dissipates a constant amount of about 3 watts when it is on. The array of electrical switches 262 essentially apply the power to individual plasma point sources 90 on command. The plasma density is a function of how many plasma point sources 90 are turned on. In this manner, the net power delivered to each plasma point source 90 may be controlled by pulse width modification.

[0048] In a second mode, what is controlled is the level of power delivered to each plasma point source 90. Also, gas composition to individual plasma point sources 90 (or groups of plasma point sources 90) can be varied by the gas distributor 112. Thus, the different plasma point sources 90 need not have the same gas discharge composition. Each plasma point source 90 has a fixed address. The power and/or gas flow to each plasma point source 90 can be targeted to turn on or off individually.

[0049] In accordance with one method, the spatial distribution of process rate across the surface of the workpiece is measured. The non-uniformities in the process rate distribution are compensated by establishing a spatial distribution of ON/OFF duty cycles of power supplied to the array of

plasma point sources **90** that is in effect an inverse of the measured process rate spatial distribution. In other words, the distribution of ON/OFF power duty cycles has maxima in locations where the measured process rate distribution has minima and has minima where the measured process rate distribution has maxima.

[0050] In accordance with another method, the non-uniformities in the process rate distribution are compensated by establishing a spatial distribution of ON/OFF duty cycles of process gas flows supplied to the array of plasma point sources **90** that is in effect an inverse of the measured process rate spatial distribution. In other words, the distribution of ON/OFF gas flow duty cycles has maxima in locations where the measured process rate distribution has minima and has minima where the measured process rate distribution has maxima.

Advantages:

[0051] A primary advantage is complete control spatially and temporally of the generation of charged particles and energetic radicals. This enables spatial and temporal control over distribution of local charged particles and energetic radicals.

[0052] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A plasma reactor comprising:
 - a processing chamber and a workpiece support in said processing chamber, said chamber comprising a lower ceiling facing said workpiece support;
 - an upper ceiling overlying and facing said lower ceiling and a gas distributor overlying said upper ceiling;
 - plural cavity walls defining plural cavities between said upper and lower ceilings, said gas distributor comprising plural gas flow paths to respective ones of said plural cavities;
 - plural outlet holes in said lower ceiling aligned with respective ones of said plural cavities;
 - respective power applicators adjacent respective ones of said plural cavities, a power source, plural power conductors coupled to respective ones of said power applicators, and a power distributor coupled between said power source and said plural power conductors.
2. The plasma reactor of claim **1** wherein said plural cavity walls comprise dielectric cavity walls.
3. The plasma reactor of claim **1** wherein said power source comprises an RF power generator and wherein each one of said respective power applicators is separated from an interior of a corresponding one of said plural cavities by the corresponding one of said plural cavity walls.
4. The plasma reactor of claim **3** wherein said power applicator comprises an electrode for capacitively coupling RF power into the corresponding one of said plural cavities.
5. The plasma reactor of claim **4** wherein said electrode surrounds a section of the corresponding one of said plural cavities.
6. The plasma reactor of claim **3** wherein said power applicator comprises a coil antenna for inductively coupling RF power into the corresponding one of said plural cavities.

7. The plasma reactor of claim **6** wherein said coil antenna comprises a conductor coiled around a section of the corresponding one of said plural cavities.

8. The plasma reactor of claim **1** wherein said power source is a D.C. power generator, each one of said power applicators comprises an electrode for D.C. discharge, and wherein each one of said cavity walls is configured to expose a corresponding electrode to an interior of a corresponding one of said plural cavities.

9. The plasma reactor of claim **1** wherein said power distributor comprises plural switches coupled between an output of said power source and respective ones of said power conductors.

10. The plasma reactor of claim **9** further comprising a processor controlling said plural switches individually in accordance with user-defined instructions.

11. The plasma reactor of claim **1** further comprising:

- a process gas source and a gas distributor comprising plural valves coupled between said process gas source and respective ones of said plural cavities.

12. The plasma reactor of claim **11** wherein said process gas source comprises plural gas sources of different gas species, wherein respective ones of said plural valves are coupled between respective ones of said plural gas sources and respective ones of said plural cavities.

13. The plasma reactor of claim **12** further comprising a processor controlling said plural valves individually in accordance with user-defined instructions.

14. The plasma reactor of claim **9** further comprising:

- a process gas source and a gas distributor comprising plural valves coupled between said process gas source and respective ones of said plural cavities.

15. The plasma reactor of claim **14** wherein said process gas source comprises plural gas sources of different gas species, wherein respective ones of said plural valves are coupled between respective ones of said plural gas sources and respective ones of said plural cavities.

16. The plasma reactor of claim **15** further comprising a processor controlling said plural valves individually and controlling said plural switches individually in accordance with user-defined instructions.

17. The plasma reactor of claim **1** further comprising a remote plasma source coupled to deliver plasma by-products to said plural cavities.

18. The plasma reactor of claim **1** wherein said processing chamber further comprises a cylindrical side wall below said lower ceiling, said reactor further comprising an inductively coupled plasma source comprising a coil antenna wound around said cylindrical side wall and an RF power generator coupled to said coil antenna through an impedance match.

19. A plasma reactor comprising:

- a processing chamber and a workpiece support in said processing chamber;
- a gas distributor overlying said workpiece support;
- plural cavity walls defining plural cavities underlying said gas distributor, said gas distributor comprising plural gas flow paths to respective ones of said plural cavities;
- respective power applicators adjacent respective ones of said plural cavities, a power source, plural power conductors coupled to respective ones of said power applicators, and a power distributor coupled between said power source and said plural power conductors;
- and

a process gas source and a gas distributor comprising plural valves coupled between said process gas source and respective ones of said plural cavities.

20. A method of processing a workpiece in a plasma reactor comprising an array of plasma point sources distributed over a surface of the workpiece, comprising:

performing a plasma process on the workpiece;
observing a non-uniformity in a spatial distribution of process rate across the surface of the workpiece; and
reducing said non-uniformity by performing at least one of:

- (a) adjusting an apportionment of plasma source power levels among said array of plasma point sources, or
- (b) adjusting an apportionment of gas flows among said array of plasma point sources.

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