

**INTERLACED, MULTI-ZONE GAS DISTRIBUTION
FOR ASYMMETRIC WAFER BOW COMPENSATION**

INCORPORATION BY REFERENCE

[0000] A PCT Request Form is filed concurrently with this specification as part of the present application. Each application that the present application claims benefit of or priority to as identified in the concurrently filed PCT Request Form is incorporated by reference herein in its entirety and for all purposes.

BACKGROUND

[0001] Semiconductor manufacturing typically involves one or more processes to deposit and pattern a structure on a wafer. As the complexity and/or non-uniformity of the structure and/or materials on or across the wafer increase, stress applied to the wafer can cause wafer deformation (e.g., bowing, twisting, etc.) impacting various aspects from structure formation to product yield. For example, in three-dimensional NOT-AND logic gate (3D-NAND) structure fabrication, multi-stacked films with thick, high stress carbon-based hard masks, metallization patterns, and substrate trenches can cause significant wafer warpage, leading to issues such as frontside lithographic overlay mismatches, wafer bow beyond chucking limits of an electrostatic chuck, etc.

[0002] The background provided herein is for the purposes of generally presenting the context of the disclosure. Work of the presently named inventors, to the extent that it is described in this background, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the disclosure.

SUMMARY

[0003] Details of one or more implementations of the subject matter described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings, and the claims. The following, non-limiting implementations are considered part of the disclosure; other implementations will be evident from the entirety of this disclosure and the accompanying drawings as well.

[0004] Some embodiments provide an apparatus capable of distributing one or more gases,

such as one or more process (or reactant) gases and/or one or more dilution gases, in an area adjacent to (e.g., over or under) a substrate in a process chamber.

[0005] Additional aspects will be set forth in the detailed description which follows, and, in part, will be apparent from the disclosure, or may be learned by practice of the disclosed embodiments and/or the claimed subject matter.

[0006] According to an embodiment, an apparatus includes a main body having a first surface, a second surface, a first gas passage, a second gas passage, first gas distribution ports, and second gas distribution ports. The second surface opposes the first surface in a first direction. The first gas passage is fluidically connected to one or more first gas inlets and extends in a second direction between the first surface and the second surface. The second direction is transverse to the first direction. The second gas passage extends in the second direction and is spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction. The second gas passage is fluidically connected to one or more second gas inlets. The first gas distribution ports are fluidically connected to the first gas passage. The second gas distribution ports are fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. At least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction.

[0007] According to some embodiments, when viewed in the first direction, the at least some of the first gas distribution ports and the at least some of the second gas distribution ports may be arranged between the first gas passage and the second gas passage.

[0008] According to some embodiments, the first gas distribution ports and the second gas distribution ports may form respective openings in the first surface.

[0009] According to some embodiments, the apparatus may further include a third gas passage, third gas distribution ports, and fourth gas distribution ports. The third gas passage may be fluidically connected to the one or more first gas inlets and may extend in the second direction between the first surface and the second surface. The third gas passage may be adjacent to the second gas passage in the third direction. The third gas distribution ports may be fluidically connected to the third gas passage. The fourth gas distribution ports may be fluidically connected to the second gas passage. At least some of the third gas distribution

ports and at least some of the fourth gas distribution ports may be arranged in an alternating manner with respect to the second direction. When viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports may be arranged between the second gas passage and the third gas passage.

[0010] According to some embodiments, the third gas distribution ports and the fourth gas distribution ports may form respective openings in the first surface.

[0011] According to some embodiments, the apparatus may further include one or more fourth gas passages, a fifth gas passage, fifth gas distribution ports, and sixth gas distribution ports. The one or more fourth gas passages may be fluidically connected to the one or more first gas inlets and may extend in the second direction between the first surface and the second surface. The one or more fourth gas passages may be adjacent to the first gas passage in a fourth direction opposite the third direction. The fifth gas passage may be fluidically connected to the one or more second gas inlets and may extend in the second direction between the first surface and the second surface. The fifth gas passage may be adjacent to the one or more fourth gas passages in the fourth direction. The fifth gas distribution ports may be fluidically connected to the one or more fourth gas passages. The sixth gas distribution ports may be fluidically connected to the fifth gas passage. A first some of the fifth gas distribution ports may be arranged with respect to the second direction. A second some of the fifth gas distribution ports and at least some of the sixth gas distribution ports may be arranged in an alternating manner with respect to the second direction. When viewed in the first direction, the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports may be arranged between the fifth gas passage and the one or more fourth gas passages.

[0012] According to some embodiments, the sixth gas passage may be directly adjacent to a first side of the one or more fourth gas passages, the one or more fourth gas passages may be directly adjacent to a first side of the first gas passage, and the second gas passage may be directly adjacent to a second side of the first gas passage and a first side of the third gas passage.

[0013] According to some embodiments, the first surface may include a plurality of zones of gas distribution ports, the first some of the fifth gas distribution ports may be arranged in a first zone among the zones, and the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports may be arranged in a second zone among the zones.

The at least some of the first gas distribution ports, the at least some of the second gas distribution ports, the at least some of the third gas distribution ports, and the at least some of the fourth gas distribution ports may be arranged in a third zone among the zones. The first zone may separate the second zone from the third zone.

[0014] According to some embodiments, first gas distribution flow paths may be configured to provide the one or more first gases to the first some of the fifth gas distribution ports such that an output of the one or more first gases from the first zone exhibits a first gas flow profile across the first zone. Second gas distribution flow paths may be configured to provide the one or more first gases to the second some of the fifth gas distribution ports and third gas distribution flow paths may be configured to provide the one or more second gases to the at least some of the sixth gas distribution ports such that a combined output of the one or more first gases and the one or more second gases from the second zones exhibits a second gas flow profile across the second zone. Fourth gas distribution flow paths may be configured to provide the one or more first gases to the at least some of the first gas distribution ports, fifth gas distribution flow paths may be configured to provide the one or more second gases to the at least some of the second gas distribution ports, and sixth gas distribution flow paths may be configured to provide the one or more first gases to the at least some of the third gas distribution ports such that a combined output of the one or more first gases and the one or more second gases in the third zone exhibits a third gas flow profile across the third zone. The first gas flow profile, the second gas flow profile, and the third gas flow profile may be different for identical inlet/outlet boundary conditions.

[0015] According to some embodiments, the first gas flow profile may be substantially uniform. The second gas flow profile may vary in at least one direction across the second zone. The third gas flow profile may vary in at least one direction across the third zone.

[0016] According to some embodiments, each of the second and third gas flow profiles may include increasing amount of the one or more second gases with increasing distance from the first gas flow profile.

[0017] According to some embodiments, the first zone may include a first arrangement of gas distribution ports having a first spatial relationship, and each of the second and third zones may include a second arrangement of gas distribution ports having a second spatial relationship different from the first spatial relationship.

[0018] According to some embodiments, the second spatial relationship may include more densely arranged gas distribution ports than the first spatial relationship.

[0019] According to some embodiments, each of the second and third zones may further include at least one third arrangement of gas distribution ports having at least one third spatial relationship, and the at least one third spatial relationship may be different from each of the first spatial relationship and the second spatial relationship.

[0020] According to some embodiments, the second arrangement of gas distribution ports may separate the at least one third arrangement of gas distribution ports from the first arrangement of gas distribution ports.

[0021] According to some embodiments, the at least one third arrangement of gas distribution ports may be closer to a periphery of the first surface than a center of the first surface.

[0022] According to some embodiments, the first surface may include a plurality of gas distribution ports, the plurality gas distribution ports may include the first gas distribution ports and the second gas distribution ports, the first gas passage and the second gas passage may be among a plurality of gas passages extending in the second direction between the first surface and the second surface, and each of the gas passages may be fluidically connected to one or more gas distribution ports among the gas distribution ports of the first surface.

[0023] According to some embodiments, respective cross-sectional areas of the gas passages in a plane perpendicular to the second direction may be substantially equivalent.

[0024] According to some embodiments, a cross-sectional area of at least one of the gas passages in a plane perpendicular to the second direction may be different from a cross-sectional area of at least another one of the gas passages in the plane perpendicular to the second direction.

[0025] According to some embodiments, corresponding pitches between adjacent gas passages among the gas passages may be substantially equivalent.

[0026] According to some embodiments, the first gas distribution flow paths, the second gas distribution flow paths, the fourth gas distribution flow paths, and the sixth gas distribution flow paths may define portions of a first plenum volume within the main body. The third gas distribution flow paths and the fifth gas distribution flow paths may define portions of a second

plenum volume within the main body. The second plenum volume may be fluidically separate from the first plenum volume within the main body. A first some of the gas passages that are directly adjacent to one another may be associated with different plenum volumes among the first plenum volume and the second plenum volume.

[0027] According to some embodiments, a second some of the gas passages that are directly adjacent to one another may be associated with a same plenum volume among the first plenum volume and the second plenum volume.

[0028] According to some embodiments, the second some of the gas passages may be associated with the second plenum volume and may be positioned closer to a periphery of the first surface than a center of the first surface.

[0029] According to some embodiments, the second some of the gas passages may be associated with the first plenum volume and may be positioned closer to a center of the first surface than a periphery of the first surface.

[0030] According to some embodiments, the at least some of the first gas distribution ports may be fluidically connected to the first gas passage via first gas risers, and the at least some of the second gas distribution ports may be fluidically connected to the second gas passage via second gas risers. The first gas risers may extend in a fifth direction transverse to each of the first direction, the second direction, the third direction, and the fourth direction. The second gas risers may extend in a sixth direction transverse to each of the first direction, the second direction, the third direction, the fourth direction, and the fifth direction.

[0031] According to some embodiments, the fifth direction may be angled by a first amount from the first direction in a reference plane defined by the first direction and the third direction, and the sixth direction may be angled by a second amount from the first direction in the reference plane.

[0032] According to some embodiments, absolute values of the first amount and the second amount may be equivalent.

[0033] According to some embodiments, the first some of the fifth gas distribution ports may be fluidically connected to a fourth gas distribution passage among the one or more fourth gas distribution passages via third gas risers. The third gas risers may extend in the first direction.

[0034] According to some embodiments, the gas distribution ports of the first surface may be

distributed into rows of gas distribution ports extending in the third direction and columns of gas distribution ports extending in the second direction. A first some of the gas distribution ports may be arranged in first rows among the rows, the first some of the gas distribution ports may be fluidically connected to a first plenum volume within the main body. A second some of the gas distribution ports may be arranged in second rows among the rows, the second some of the gas distribution ports may be fluidically connected to a second plenum volume within the main body that is fluidically separate from the first plenum volume within the main body. The first rows may alternate with the second rows along the second direction.

[0035] According to some embodiments, the apparatus may further include an outer wall surrounding the main body. The main body may further include a third surface, a plurality of first blind cavities, and a plurality of second blind cavities. The third surface may extend between the first surface and the second surface. The third surface may face an inner surface of the outer wall. The plurality of first blind cavities may recessed into the third surface and may be arranged about a perimeter of the main body. The first blind cavities may define portions of a first plenum volume within the main body. The plurality of second blind cavities may be recessed into the third surface and may be arranged about a perimeter of the main body. The second blind cavities may define portions of a second plenum volume within the main body. The first plenum volume and the second plenum volume may be fluidically separate within the main body. A first distal end of the first gas passage may be fluidically connected to a first blind cavity among the first blind cavities. A first distal end of the second gas passage may be fluidically connected to a second blind cavity among the second blind cavities.

[0036] According to some embodiments, a second distal end of the first gas passage may be fluidically connected to another first blind cavity among the first blind cavities. The first blind cavity may oppose the another first blind cavity relative to a central axis of the main body extending in the first direction. A second distal end of the second gas passage may be fluidically connected to another second blind cavity among the second blind cavities. The second blind cavity may oppose the another second blind cavity relative to the central axis.

[0037] According to some embodiments, at least some of the first blind cavities may alternate about the perimeter of the main body with at least some of the second blind cavities.

[0038] According to some embodiments, each first blind cavity among the first blind cavities

may have a first opening area facing the inner surface of the outer wall. The first opening areas may be substantially equivalent to one another.

[0039] According to some embodiments, each second blind cavity among the second blind cavities may have a second opening area facing the inner surface of the outer wall. The second opening areas may be substantially equivalent to one another.

[0040] According to some embodiments, the first opening areas and the second opening areas may be equivalent.

[0041] According to some embodiments, each first blind cavity among the first blind cavities may have a first opening area facing the inner surface of the outer wall, and at least one of the first opening areas may be different from at least another one of the first opening areas.

[0042] According to some embodiments, each second blind cavity among the second blind cavities may have a second opening area facing the inner surface of the outer wall, and at least one of the second opening areas may be different from at least another one of the second opening areas.

[0043] According to some embodiments, the apparatus may further include a plurality of plugs respectively filling portions of only corresponding first blind cavities among the first blind cavities or only corresponding second blind cavities among the second blind cavities.

[0044] According to some embodiments, the apparatus may further include a plurality of first elongated holes and a plurality of second elongated holes. The plurality of first elongated holes may be in the main body and extend radially from a first central region of the main body. Each of the first elongated holes may have a corresponding proximal end fluidically connected to at least one of the one or more first gas inlets and a corresponding distal end fluidically connected to a first blind cavity among the first blind cavities. The plurality of second elongated holes may be in the main body and may extend radially from a second central region of the main body. Each of the second elongated holes may have a corresponding proximal end fluidically connected to at least one of the one or more gas second inlets, and a corresponding distal end fluidically connected to a second blind cavity among the second blind cavities.

[0045] According to some embodiments, the first central region may be arranged between the second central region and a periphery of the main body.

[0046] According to some embodiments, each of the first elongated holes may extend in a

first planar region of the main body, each of the second elongated holes may extend in a second planar region of the main body different from the first planar region of the main body, and the second planar region may be closer to the first surface of the main body than the first planar region.

[0047] According to some embodiments, the first gas passage and the second gas passage may extend in a third planar region of the main body different from each of the first planar region and the second planar region.

[0048] According to some embodiments, the third planar region may be closer to the first surface than each of the first planar region and the second planar region.

[0049] According to some embodiments, respective cross-sectional areas of the first elongated holes and the second elongated holes in corresponding planes perpendicular to their respective directions of longitudinal extension may be equivalent.

[0050] According to some embodiments, at least one of the first elongated holes may have a different cross-sectional area in a plane perpendicular to its direction of longitudinal extension than at least one other one of the first elongated holes.

[0051] According to some embodiments, at least one of the second elongated holes may have a different cross-sectional area in a plane perpendicular to its direction of longitudinal extension than at least one other one of the second elongated holes.

[0052] According to some embodiments, the apparatus may further include a cooling conduit in thermal contact with the main body. The cooling conduit may have an inlet configured to receive clean dry air (CDA) at a first temperature and an outlet configured to output the CDA at a second temperature different from the first temperature. The main body may include a first groove recessed into the second surface and a portion of the cooling conduit may extend within the first groove.

[0053] According to some embodiments, the apparatus may further include a first cap structure enclosing the cooling conduit in the first groove in a compressed state.

[0054] According to some embodiments, the cooling conduit may be formed of stainless steel.

[0055] According to some embodiments, the cooling conduit may be sized to enable a flow rate of CDA up to about 140 standard liters per minute with a Reynolds number greater than

about 2000.

[0056] According to some embodiments, the apparatus may further include a resistive heating element. The main body may further include a second groove recessed into the second surface. A portion of the resistive heating element may extend within the second groove.

[0057] According to some embodiments, in the first direction, the second groove may extend farther into the second surface than the first groove. In a radial direction perpendicular to the first direction, an outermost portion of second groove may be closer to a periphery of the main body than an outermost portion of the first groove.

[0058] According to some embodiments, the apparatus may further include a process chamber configured to support the main body therein. The main body may form a portion of a showerhead.

[0059] According to some embodiments, the first gas distribution ports and the second gas distribution ports may be among a plurality of gas distribution ports forming openings in the first surface of the main body. The showerhead may be a showerhead pedestal configured to support a substrate thereover such that a majority of a backside of the substrate is exposed to the plurality of gas distribution ports.

[0060] According to some embodiments, the main body may be formed of an aluminum alloy.

[0061] The foregoing general description and the following detailed description are illustrative and explanatory and are intended to provide further explanation of the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0062] Various embodiments disclosed herein are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings, in which like reference numerals refer to similar elements.

[0063] FIG. 1 schematically illustrates a perspective view of a bowed semiconductor substrate exhibiting asymmetric bowing.

[0064] FIG. 2A schematically illustrates a plan view of a substrate exhibiting asymmetric bowing.

[0065] FIG. 2B schematically illustrates a cross-sectional view of the substrate of FIG. 2A taken along sectional line 2B–2B.

[0066] FIG. 2C schematically illustrates a cross-sectional view of the substrate of FIG. 2A taken along sectional line 2C–2C.

[0067] FIG. 3 is a flowchart of a process to mitigate asymmetric wafer bowing according to some embodiments.

[0068] FIGS. 4A, 4B1, 4B2, and 4C schematically illustrate various stages of forming a stress compensation layer to mitigate asymmetric wafer bowing according to some embodiments.

[0069] FIG. 5 is a graph illustrating a thickness profile and a stress profile for each of i) a compressive film, ii) a tensile film, and iii) a stress compensation layer combining the compressive film and the tensile film according to some embodiments.

[0070] FIG. 6A is a graph comparing a desired profile and simulated profiles for reactant gas flowing from variously configured gas distributors relative to a backside of a substrate according to some embodiments.

[0071] FIG. 6B is a graph comparing a desired profile and simulated profiles for dilution gas flowing from variously configured gas distributors relative to a backside of a substrate according to some embodiments.

[0072] FIGS. 7A and 7B schematically illustrate perspective views of a gas distributor according to some embodiments.

[0073] FIG. 8 schematically illustrates a partially exploded perspective view of the gas distributor of FIG. 7A according to some embodiments.

[0074] FIG. 9A schematically illustrates a plan view of a first surface of the gas distributor of FIG. 7A according to some embodiments.

[0075] FIG. 9B schematically illustrates an enlarged portion of FIG. 9A according to some embodiments.

[0076] FIGS. 10 and 11 schematically illustrate enlarged perspective views of negative space within respective portions of another gas distributor according to some embodiments.

[0077] FIGS. 12 and 13 schematically illustrate perspective sectional views of corresponding portions of one or more gas distributors according to some embodiments.

[0078] FIG. 14A schematically illustrates a side view of a portion of the gas distributor of FIG. 7A according to some embodiments.

[0079] FIG. 14B schematically illustrates an enlarged portion of FIG. 14A according to some embodiments.

[0080] FIGS. 15, 17, and 18 schematically illustrate cross-sectional views of the gas distributor of FIG. 14A respectively taken along sectional lines 15–15, 17–17, and 18–18 according to some embodiments.

[0081] FIG. 16 schematically illustrates an enlarged portion of FIG. 15 according to some embodiments.

[0082] FIG. 19 schematically illustrates a gas distribution flow path through the gas distributor of FIG. 7A according to some embodiments.

[0083] FIG. 20 schematically illustrates a partially exploded perspective view of the gas distributor of FIG. 7B according to some embodiments.

[0084] FIG. 21 is a graph demonstrating simulated temperature control of a gas distributor at various setpoint temperatures and duty cycles according to some embodiments.

[0085] FIG. 22 schematically illustrates a thermal management system configured to control the temperature of a gas distributor according to some embodiments.

[0086] FIG. 23 schematically illustrates a substrate processing system configured for backside wafer deposition according to some embodiments.

[0087] FIG. 24 schematically illustrates a multi-station processing tool configured for backside wafer deposition according to some embodiments.

DETAILED DESCRIPTION OF SOME EMBODIMENTS

[0088] In the following description, numerous specific details are set forth in order to provide a thorough understanding of various embodiments. The disclosed embodiments may be practiced without some or all of these specific details. In other instances, well-known process operations have not been described in detail to not unnecessarily obscure the disclosed embodiments. While the disclosed embodiments will be described in conjunction with specific embodiments, it will be understood that it is not intended to limit the disclosed embodiments.

[0089] In this application, the terms “semiconductor wafer,” “wafer,” “substrate,” “wafer substrate” and “partially fabricated integrated circuit” are used interchangeably. One of ordinary skill in the art would understand that the term “partially fabricated integrated circuit” can refer to a silicon wafer during any of many stages of integrated circuit fabrication thereon. A wafer or substrate used in the semiconductor device industry typically has a diameter of 200 mm, or 300 mm, or 450 mm. In addition to semiconductor wafers, other work pieces that may take advantage of the disclosed embodiments include various articles, such as printed circuit boards, magnetic recording media, magnetic recording sensors, mirrors, optical elements, micro-mechanical devices, and the like.

[0090] Semiconductor fabrication processes involve formation of various structures, many of which may be two-dimensional. As semiconductor device dimensions shrink and devices are scaled to be smaller, the density of features across a semiconductor substrate increases, resulting in layers of material etched and deposited in various ways, including in three dimensions. For example, a 3D-NAND structure is one technology that is becoming increasingly popular due to lower cost and increased memory density compared to other techniques, such as two-dimensional (2D)-NAND structure, and higher reliability in various applications. During the fabrication of a 3D-NAND structure, wafer bow can change drastically. For example, deposition of thick hard mask materials and etching of trenches along a wafer surface in fabricating a 3D-NAND structure can cause wafer bowing. As layers of films are stacked on top of each other during fabrication, more stress is introduced to the semiconductor wafer which can cause bowing. Moreover, stress fields along different axes of the wafer may become increasingly inhomogeneous, leading to multimodal bow shapes.

[0091] Bowing can be measured using an optical technique. Wafer bowing can be measured or evaluated by obtaining a wafer map or stress map. Bowing can be quantified using a bow value and/or a warpage value as described herein. In general, a “wafer bow value” measures the deviation of the center point of a median surface of a free, un-clamped wafer from the median surface to a reference plane, which is defined by three corners of an equilateral triangle having a base a specified amount less than the nominal diameter of the wafer, according to the American Society for Testing and Materials (ASTM) F534 standard. A “wafer warp value” is the difference between the maximum and the minimum distances of the median surface of a free, un-clamped wafer from the reference plane, according to the ASTM F657 and ASTM F1390 standards. It is noted, however, that the warpage value can be expressed along one or more

axes – for example, an asymmetrically warped wafer may have an x-axis warpage and/or a y-axis warpage. Further, “wafer flatness” is a measure of the deviation of the front surface of a wafer, expressed in total indicator reading or maximum focal plane deviation, relative to a specified reference plane when the back surface of the wafer is ideally flat, according to the ASTM F1530 standard.

[0092] In a bow-shaped wafer, the lowest point is the center of the wafer and the highest point is the edge of the wafer. In a dome-shaped wafer, the lowest point is the edge of the wafer and the highest point is the center of the wafer. Bow-shaped and dome-shaped wafers have symmetrical or largely symmetrical bowing. Wafers can also have asymmetric bowing. In asymmetric bowing, warpage is measured along an x-axis and a y-axis. An asymmetrically bowed wafer has different values for the x-axis warpage and y-axis warpage. In some cases, an asymmetrically bowed wafer has a negative x-axis warpage and a positive y-axis warpage. In some cases, an asymmetrically bowed wafer has a positive x-axis warpage and a negative y-axis warpage. In some cases, an asymmetrically bowed wafer has both a positive x-axis warpage and a positive y-axis warpage, but the warpage values are different. In some instances, an asymmetrically bowed wafer has both a negative x-axis warpage and a negative y-axis warpage, but the warpage values are different. One example of an asymmetrically bowed wafer is a saddle-shaped wafer. For a saddle-shaped wafer, in one example, the warpage on the x-axis may be +200 μm and the warpage on the y-axis may be -200 μm . Saddle-shaped wafers have two opposing edges of the wafer that are curved upward while another two opposing edges of the wafer are curved downward. As used herein, warpage can refer to any deviation from planarity exhibited by a wafer, where a bow-shaped wafer, dome-shaped wafer, and saddle-shaped wafer are examples of different types of substrate warpage.

[0093] Bowing can cause problems with subsequent processing, such as during lithography, as etching can be uneven if the semiconductor substrate is warped. High bowing can be caused by deposition of a thick, high-stress carbon hard mask layer(s). Additionally, due to multi-stacked films and the presence of thick, high-stress carbon-based hard masks used in such fabrication processes, etching can cause some asymmetric warpage and deposition processes can introduce significant wafer warpage of up to a variation between -1300 μm to +1300 μm bow. For example, an ashable hard mask may have a stress value of up to -1000 MPa and have a bow value of up to -1000 μm . In some cases, a high-aspect ratio slit etch and metal fill (e.g., tungsten fill) can induce large anisotropic stress on the semiconductor substrate.

[0094] Addressing such wafer warpage can be a challenge as subsequent or downstream processing may be affected by a wafer warpage exceeding, for example, about $\pm 150\ \mu\text{m}$, about $\pm 200\ \mu\text{m}$, about $\pm 300\ \mu\text{m}$, or about $\pm 500\ \mu\text{m}$. It, however, is recognized that as processes become more sensitive to wafer topology, lesser degrees of wafer warpage may need to be addressed. One example issue is that mechanical wafer handling may be affected due to wafer warpage, where wafers that are not flat may not be gripped or held effectively by a wafer robot or wafer handling mechanism. Additionally, wafer warpage may contribute to process non-uniformity, where downstream etch, deposition, or clean operations may be adversely affected due to processing non-uniformities across a surface of the wafer. For instance, wafer warpage may lead to poor thermal contact, which can cause non-uniform heating of a wafer that, in turn, can lead to non-uniform processing of the wafer. In some instances, processing of highly warped wafers may cause further warping. For example, etching of a trench in one direction can cause warping in asymmetric bowing due to asymmetric stress on the wafer. In addition, lithography operations may be adversely affected by wafer warpage as precise patterns are unable to be formed. When wafers are used in subsequent processing that involve chucking of the wafer to an electrostatic chuck, highly warped wafers may not be able to be processed in some tools. Many electrostatic chucks have a “chucking limit,” which is defined as the maximum warpage tolerated before the wafer cannot be effectively chucked. For example, some electrostatic chucks have a chucking limit of about $\pm 300\ \mu\text{m}$. Warped wafers that exceed the chucking limit may not be processed in such instances.

[0095] FIG. 1 schematically illustrates a perspective view of a bowed semiconductor substrate exhibiting asymmetric bowing.

[0096] Referring to FIG. 1, substrate 101 is shown relative to a three-dimensional coordinate system having reference plane 103 parallel to a plane defined by the x-axis direction and the y-axis direction. In this manner, an extent of deformation (e.g., warpage) of substrate 101 from reference plane 103 is indicated along the u axis-direction. Accordingly, substrate 101 is shown as being asymmetrically bowed. In other words, an extent of the bowing of substrate 101 along the x-axis direction is different from an extent of the bowing of substrate 101 along the y-axis direction. For instance, warpage in the x-axis direction reaches a first positive value and warpage in the y-axis direction reaches a second negative value, a magnitude of the second negative value being greater than a magnitude of the first positive value. Such deformation of substrate 101 may be referred to as “saddle-shaped” bowing of substrate 101. As used herein,

warpage refers to any deviation of a median surface of substrate 101 from reference plane 103, and, thereby, from planarity.

[0097] As 3D-NAND structures continue to scale up and high-aspect ratio features become increasingly more common, new challenges are emerging related to localized stress and inter-die stress variations on semiconductor substrates. Localized stress and inter-die stress variations may lead to block-bending, cell cross-talk, cell loss, and/or cell misalignments. Localized stress refers to stress changes that occur within a wafer in a non-uniform manner. Poorly compensated/corrected localized stress may lead to localized wafer topology changes, which in turn may lead to poor alignment during lithography. Such poor alignment is typically viewed in terms of in-plane distortion (IPD), which is a quantification of the vector displacement of on-wafer alignment marks from their expected positions due to wafer topology. High IPD during lithography may lead to undesirable changes in critical dimensions or any other feature that is defined in a lithographic step, and so the foregoing phenomena of block-blending, cell cross-talk, cell loss, and/or cell misalignments can arise due to lithographic errors.

[0098] FIGS. 2A–2C schematically illustrate various views of a substrate exhibiting asymmetric bowing. For instance, FIG. 2A schematically illustrates a plan view of substrate 201, whereas FIGS. 2B and 2C schematically illustrate cross-sectional views of substrate 201 taken along sectional lines 2B–2B and 2C–2C, respectively. As seen in FIG. 2A, substrate 201 may include various features (e.g., metallization pattern 203) formed on frontside 205 that cause, at least in part, substrate 201 to asymmetrically bow. For illustrative convenience, feature formations on frontside 205 of substrate 201 are not shown in FIGS. 2B and 2C. As can be appreciated from FIGS. 2B and 2C, substrate 201 exhibits parabolic bowing along the x-axis direction and anti-parabolic bowing along the y-axis direction, the combination of which can yield saddle-shaped bowing similar to the saddle-shaped bowing of substrate 101 in FIG. 1.

[0099] Various techniques may be employed to address the bowing of a substrate, such as substrate 201. For instance, one or more stress compensation layers may be formed on a backside of a semiconductor substrate, such as backside 207. The utilization of backside stress compensation layers has typically been limited to mitigating monotonic global wafer warpage. In other words, techniques to address the bowing of semiconductor substrates are usually limited to addressing axially symmetric or multi-axially symmetric bow profiles. In some instances, asymmetric bowing may be addressed through the formation of backside stress compensation layers using mask or precursor zoning techniques during layer formation. For

instance, localized stress modulation may be achieved through the delivery of precursor material to certain areas or regions of an asymmetrically bowed substrate using, for instance, a carrier ring mask. In other instances, localized stress modulation may be achieved using precursor zoning employing multiple plenums to control delivery of gas to different locations. However, such techniques have yielded limited success due, in part, to high IPD overlay and issues associated with chucking a bowed substrate. Such issues may be the result of sharp transitions in film stress between zones and the difficulty in designing a zone layout that minimizes local topography variation.

[0100] Accordingly, one or more embodiments seek to provide methods and apparatuses for mitigating asymmetric bowing of a substrate via backside deposition. Precursor control from a gas distributor (e.g., a showerhead, showerhead pedestal, etc.) may provide a desired thickness profile in one or more films deposited on a backside of a substrate. The one or more deposited films may be utilized to collectively form a stress compensation layer. A stress profile of the stress compensation layer may be characterized by a polynomial function. In this manner, the stress compensation layer may mitigate or even resolve localized stress in an asymmetrically bowed substrate. In some implementations, the stress compensation layer may be formed through a film stacking approach, which deposits multiple films having different thickness profiles. In some implementations, a combination of a compressive film having a non-linear thickness profile and a tensile film having a different non-linear thickness profile may be deposited on a backside of a bowed substrate. For instance, the compressive film may have a first parabolic-shaped profile and the tensile film may have a second parabolic-shaped profile opening in a direction opposite the first parabolic-shaped profile. In this manner, the compressive film and the tensile film can be collectively utilized to form a stress compensation layer. In some instances, the stress compensation layer may be flat or substantially flat. Such a film stacking technique via backside deposition may be utilized to minimize (or at least reduce) IPD overlay issues without impacting the ability to chuck the substrate.

[0101] Thickness tuning of the one or more films in a stress compensation layer may be achieved by controlling precursor and dilution gas concentration proximate (or adjacent) to a substrate during one or more deposition operations. According to various embodiments, precursor and dilution gas concentration adjacent to the substrate may be controlled by design features in a gas distributor. Such design features may influence flow dynamics of the precursor and dilution gases from the gas distributor. In an embodiment, the gas distributor

may be divided into multiple gas distribution groups (or zones). For example, one or more precursor gases may be delivered to (and, thereby, from) one or more first zones, one or more precursor gases and one or more one or more dilution gases may be delivered to (and, thereby, from) one or more second zones, and one or more precursor gases and one or more one or more dilution gases may be delivered to (and, thereby, from) one or more third zones. In some instances, gas output from (or a gas flow profile across) one zone may be uniform (or substantially uniform) and gas output from one or more other zones may be irregular, e.g., exhibit a gradient, such as a non-linear gradient increasing with increasing distance from the one zone, such as a parabolic gradient increasing with increasing distance from the one zone. It is noted that the gradient may be with respect to one or more different gases flowed in the one or more other zones. The term “uniform,” as used herein with respect to gas flows and gas flow profiles, refers to a gas flow or gas flow profile that is substantially uniform or similar; such gas flows or gas flow profiles may potentially include minor perturbations or deviations due to various localized effects, but would still be recognizable as generally uniform. To this end, the various gas flow profiles referred to herein may be considered an effect of the structure(s) of the gas distributor, and, thereby, understood as occurring under identical inlet/outlet boundary conditions, e.g., pressure, temperature, etc. In some cases, gas output from the one or more other zones may exhibit a stepped gradient increasing with increasing distance from the one zone or any other suitable gas output profile.

[0102] According to some embodiments, a combined gas flow profile of all the gas distribution ports may exhibit mirror symmetry about an axis, but not exhibit 3-fold or higher radial symmetry. Such multizone flow control can be utilized to modulate the concentration of precursor and dilution gas adjacent to a substrate during layer formation. It is also contemplated that one or more primary zones may include one or more sub-zones and the one or more sub-zones may, in some implementations, include one or more sub-portions to further tailor the concentration of precursor and dilution gas (or flow dynamics) adjacent to the substrate, such as the flow dynamics in proximity to an edge of the substrate. This may be achieved via different gas distribution port patterns (e.g., positions, densities, port sizes, etc.) between a primary zone, a sub-zone, and/or a sub-portion of a sub-zone. In some cases, additional and/or alternative control (e.g., smoothing of the concentration of precursor and dilution gas (or flow dynamics associated therewith)) within and/or between zones, sub-zones, and/or sub-portions of sub-zones) may be achieved via interlaced, alternating, or otherwise

integrated patterns of two or more types of gas distribution ports, such as gas distribution ports configured to flow precursor and gas distribution ports configured to flow dilution gas. In some cases, different gas distribution flow paths (e.g., sizes, amounts, flow conductance, etc.) supplying one or more precursor gases or one or more dilution gases to different zones, sub-zones, and/or sub-portions of sub-zones may be additionally or alternatively utilized to tailor the concentration of precursor and dilution gas (or flow dynamics) adjacent to the substrate.

[0103] FIG. 3 is a flowchart of a process to mitigate asymmetric wafer bowing according to some embodiments. FIGS. 4A, 4B1, 4B2, and 4C schematically illustrate various stages of forming a stress compensation layer to mitigate asymmetric wafer bowing according to some embodiments. Process 300 may be performed in a different order and/or with different, fewer, or additional operations. The operations of process 300 will be described in association with the various stages of forming a stress compensation layer shown in FIGS. 4A to 4C. Further, the operations of process 300 may be performed using an apparatus for film deposition, such as an apparatus described in association with one or more of FIGS. 7A–20 and 22–24. In some implementations, the operations of process 300 may be implemented, at least in part, according to software stored in one or more non-transitory computer readable media.

[0104] At block 301, a substrate exhibiting asymmetric bowing may be caused, at least in part, to be loaded into a deposition apparatus, such as an apparatus configured to deposit material on a backside of the substrate. A stress profile acting on the substrate may include one or more compressive regions and/or one or more tensile regions non-uniformly applied to the substrate. In general, tensile stress applied across a substrate induces warpage having positive values and causes, at least in part, concave bending of the substrate. Compressive stress applied across a substrate induces warpage having negative values and causes, at least in part, convex bending of the substrate. The combination of various tensile and compressive stresses across the substrate may result in the substrate including a surface (e.g., median surface) deviating from a reference plane representing an otherwise planar configuration. In some instances, warpage of the substrate may exceed $\pm 300\ \mu\text{m}$. Further, the asymmetric bowing may result in a saddle-shaped or reversed saddle-shaped substrate.

[0105] The substrate may be a silicon wafer, such as a 200-mm wafer, a 300-mm wafer, a 450-mm wafer, or the like, including one or more layers of material, such as dielectric, conducting, and/or semiconducting materials, deposited on a frontside of the substrate. Some of the one or more layers may be patterned. Non-limiting examples of layers include dielectric

layers and conductive layers, such as silicon oxides, silicon nitrides, silicon carbides, metal oxides, metal nitrides, metal carbides, and metal layers. In some instances, the substrate itself may be patterned. For example, the substrate may include a 3D-NAND structure having one or more trenches formed (e.g., etched) in the substrate. Accordingly, the one or more compressive regions and the one or more tensile regions of the stress profile may be attributable to, for instance, the one or more layers of materials on the substrate, the one or more patterns in the one or more layers, the one or more trenches in the substrate, etc.

[0106] The substrate may exhibit warpage, such as warpage of about $\pm 1000\ \mu\text{m}$. In some instances, the substrate may have warpage exceeding about $\pm 300\ \mu\text{m}$. In some cases, the substrate has warpage greater than about $\pm 300\ \mu\text{m}$ and less than about $\pm 1000\ \mu\text{m}$. The warpage may occur at one or more regions of the substrate. To this end, the warpage may have different values (or profiles) along an x-axis direction and a y-axis direction. The warpage may be a result of anisotropic stress distribution in the substrate.

[0107] As used herein, tensile regions create tensile stresses that induce warpage having positive values. Tensile regions cause concave bending of a substrate. As used herein, compressive regions create compressive stresses that induce warpage having negative values. Compressive regions cause convex bending of a substrate. The one or more compressive regions and the one or more tensile regions may be attributable to, for instance, the one or more layers of materials on the substrate, the one or more patterns in the one or more layers, the one or more trenches in the substrate, etc.

[0108] In some implementations, a center of the substrate has compressive stress and at least two opposing edges of the substrate have tensile stress. In some cases, a center of the substrate has tensile stress and at least two opposing edges of the substrate have compressive stress. A stress profile in the x-axis direction of the substrate may be described by a parabolic or other non-linear function. A stress profile in the y-axis direction of the substrate may be described by a parabolic or other non-linear function. To this end, the stress profile in the x-axis direction may be described by a polynomial function and the stress profile in the y-axis direction may be described by a polynomial function.

[0109] According to some embodiments, the substrate is caused, at least in part, to be provided in a process chamber (e.g., chamber 2303 of FIG. 23) for performing a deposition operation. The process chamber may be configured for backside and/or frontside deposition.

In some implementations, backside deposition may be achieved by delivering process gases to a backside of the substrate from a bottom showerhead, e.g., a showerhead pedestal, of the process chamber. In some implementations, the backside of the substrate is not patterned. Showerheads generally described herein refer to showerhead pedestals for delivering gases to a backside of the substrate.

[0110] FIG. 4A schematically illustrates a cross-sectional view of a substrate exhibiting asymmetric bowing. Although not visibly shown, substrate 401 is bowed. Frontside 401a of substrate 401 may be patterned with structures leading to anisotropic stress distribution in substrate 401. The anisotropic stress distribution may be characterized by a polynomial function, such as a parabolic function in one or both of the x-axis and y-axis directions, where the x-axis and y-axis define a reference plane of substrate 401. Substrate 401 may be asymmetrically bowed. For example, substrate 401 may exhibit saddle-shaped bowing. In some cases, substrate 401 may have warpage greater than or equal to about +300 μm or less than or equal to about -300 μm in one or both of the x-axis and y-axis directions. Substrate 401 may be caused, at least in part, to be provided in a process chamber for deposition, such as a process chamber for backside deposition.

[0111] Adverting back to FIG. 3, at block 303, a first film is caused, at least in part, to be deposited on backside 401b of substrate 401 utilizing a first gas flow configuration from a showerhead pedestal. The first film is caused, at least in part, to have a first non-linear thickness profile on backside 401b of substrate 401.

[0112] According to one embodiment, the first film is a compressive film, which is a thin film having an intrinsic compressive stress. The compressive film may have an intrinsic compressive stress, such as a negative stress value of up to -4000 MPa. A thickness profile is presented along an axial direction (e.g., x-axis or y-axis direction) of the film. A non-linear thickness profile is characterized by any deviation from linearity of the film along the axial direction. The non-linear thickness profile may be characterized by a parabolic function or other polynomial function. For instance, the non-linear thickness profile may be a first parabolic-shaped profile that opens upwards or downwards. Where the first parabolic-shaped profile opens upwards, the compressive film is thicker at the edges of substrate 401 and tapers at the center of substrate 401. Where the first parabolic-shaped profile opens downwards, the compressive film is thicker at the center of the substrate 401 and tapers at the edges. Depending on the warpage of substrate 401, the compressive film may have a non-linear thickness profile in one

or both of the x-axis and y-axis directions.

[0113] Depositing a compressive film according to a non-linear thickness profile may occur by controlling precursor and/or dilution gas concentration from a showerhead pedestal. The precursor and/or dilution gas concentration may be controlled to vary across backside 401b of substrate 401. For instance, thickness control may be achieved by controlling precursor and/or dilution gas concentration adjacent to backside 401b of substrate 401 during deposition. More precursor for depositing a compressive film is flowed in the compressive region(s). Less or no precursor for depositing the compressive film is flowed in the tensile region(s). Controlling precursor concentration to vary across backside 401b of substrate 401 may occur by influencing flow dynamics from the showerhead pedestal. Precursor and/or dilution gas concentration may vary along one or both of an x-axis and y-axis directions of substrate 401.

[0114] In some implementations, a compressive film may be a compressive silicon oxide, a compressive silicon nitride, a compressive silicon, or a compressive carbon film, but embodiments are not limited thereto. For instance, in some implementations, the compressive film is a compressive silicon oxide film or a compressive silicon nitride film. A selection of precursor gas, dilution gas, and process conditions can be used to tune the stress of the compressive film. In some implementations, the compressive film is deposited on backside 401b of substrate 401 using any suitable deposition technique, such as plasma enhanced chemical vapor deposition (PECVD), chemical vapor deposition (CVD), plasma enhanced atomic layer deposition (PEALD), or atomic layer deposition (ALD). For example, the compressive film may be caused, at least in part, to be deposited using PECVD.

[0115] As used herein, “silicon oxide” includes chemical compounds including silicon and oxygen atoms, including any and all stoichiometric possibilities for Si_xO_y , including integer values of x and y and non-integer values of x and y. Further, “silicon nitride” is referred to herein as including any and all stoichiometric possibilities for Si_xN_y , including integer values of x and y and non-integer values of x and y; for example, a ratio X:Y may be 3:4.

[0116] In some embodiments, a compressive silicon oxide film may be deposited using a mixture of a silicon-containing precursor and an oxygen-containing reactant. Examples of silicon-containing precursors include but are not limited to silanes and tetraethyl orthosilicate (TEOS). Examples of oxygen-containing reactants include but are not limited to oxygen and nitrous oxide. In PECVD, the silicon-containing precursor may react with the oxygen-containing

reactant exposed to plasma to form the compressive silicon oxide film. An inert gas, such as helium, may be present.

[0117] According to some implementations, a compressive silicon nitride film may be deposited using a mixture of a silicon-containing precursor and a nitrogen-containing reactant. Examples of silicon-containing precursors include but are not limited to silanes and TEOS. Examples of nitrogen-containing reactants include but are not limited to nitrogen and ammonia. In PECVD, the silicon-containing precursor may react with the nitrogen-containing reactant exposed to plasma to form the compressive silicon nitride film. An inert gas, such as helium, may be present.

[0118] The selection of a silicon-containing precursor and reactants, as well as the plasma type (dual or single frequency) and process conditions may affect the stress of the film being deposited. In some implementations, a flow rate of the silicon-containing precursor relative to other gases flowed during deposition may tune the stress. For example, in deposition of compressive silicon nitride, increase in silane flow may decrease stress, making what would be a compressive silicon nitride film less compressive. Thus, in some implementations, increase in silane flow causes the deposited film to be less compressive, and, in some implementations, substrate temperature may be tuned to modulate stress in the compressive film. For example, higher temperatures may be used to achieve higher stress or increase a stability of the film being deposited. In some implementations, substrate temperature for deposition on backside 401b of substrate 401 is greater than or equal to about 200°C and less than or equal to 650°C.

[0119] According to some embodiments, a compressive film may be used to compensate the one or more compressive regions of substrate 401. In some implementations, the thickness of the compressive film may vary based on location on substrate 401. For instance, the thickness of the compressive film at any given location may be greater than or equal to 0 nm and less than or equal to about 2000 nm. To this end, an average thickness of the compressive film may be about 1000 nm, but embodiments are not limited thereto. A thickness of the compressive film can affect wafer bow of the compressive film to compensate asymmetric bowing in substrate 401. Accordingly, a non-linear thickness profile in the compressive film achieves a desired wafer bow that compensates the one or more compressive regions of substrate 401.

[0120] FIG. 4B1 schematically illustrates a cross-sectional view of compressive film 403 having a parabolic thickness profile deposited on backside 401b of substrate 401. Compressive film

403 may be caused, at least in part, to be deposited by PECVD. Compressive film 403 may be a compressive silicon oxide film, a compressive silicon nitride film, a compressive silicon film, a compressive carbon film, or the like. Compressive film 403 may be thicker at a center of substrate 401 than at opposite edges of substrate 401. Although compressive film 403 is shown having a parabolic thickness profile, the thickness profile may match or substantially match a polynomial function, such as a second order or third order polynomial function. The parabolic thickness profile of compressive film 403 opens downwards. The parabolic thickness profile of compressive film 403 is depicted along an x-axis or y-axis direction.

[0121] According to some embodiments, the first film may be a tensile film having a second non-linear thickness profile on backside 401b of substrate 401. A tensile film refers to a thin film having an intrinsic tensile stress. The tensile film may have an intrinsic tensile stress, such as a positive stress value of up to +4000 MPa. The non-linear thickness profile may be characterized by a parabolic function or other polynomial function. Depending on the warpage in substrate 401, the tensile film may have a non-linear thickness profile in one or both of the x-axis and y-axis directions. In some implementations, the non-linear thickness profile may be a second parabolic-shaped profile that opens downwards or upwards. In some implementations, the second parabolic-shaped profile opens in a direction opposite the first parabolic-shaped profile.

[0122] Depositing a tensile film according to a non-linear thickness profile may occur by controlling precursor and/or dilution gas concentration from a showerhead pedestal. The precursor and/or dilution gas concentration may be controlled to vary across backside 401b of substrate 401. For instance, thickness control may be achieved by controlling precursor and/or dilution gas concentration adjacent to backside 401b of substrate 401 during deposition. More precursor for depositing the tensile film may be flowed in the tensile region(s), and less or no precursor for depositing the tensile film may be flowed in the compressive region(s). It is noted that controlling the precursor and/or dilution gas concentration to vary across backside 401b of substrate 401 may occur by influencing flow dynamics from the showerhead pedestal. To this end, the precursor and/or dilution gas concentration may vary along one or both of an x-axis and y-axis directions of the substrate 401.

[0123] In some implementations, the tensile film may be a tensile silicon oxide film, a tensile silicon nitride film, a tensile silicon film, a tensile carbon film, or the like. For instance, the tensile film may be a tensile silicon oxide film or a tensile silicon nitride film. Selection of

precursors, dilatation gas, and process conditions can be used to tune the stress of the tensile film. In some implementations, the tensile film is deposited on backside 401b of substrate 401 using any suitable deposition technique, such as PECVD, CVD, PEALD, or ALD. For example, the tensile film may be caused, at least in part, to be deposited using PECVD.

[0124] In some implementations, a tensile silicon oxide film may be deposited using a mixture of a silicon-containing precursor and an oxygen-containing reactant. In PECVD, the silicon-containing precursor may react with the oxygen-containing reactant exposed to plasma to form the tensile silicon oxide film. An inert gas, such as helium, may be present.

[0125] A tensile silicon nitride film may be deposited, in some embodiments, using a mixture of a silicon-containing precursor and a nitrogen-containing reactant. In PECVD, the silicon-containing precursor may react with the nitrogen-containing reactant exposed to plasma to form the tensile silicon nitride film. An inert gas, such as helium, may be present.

[0126] Selection of a silicon-containing precursor and reactants, as well as the plasma type (dual or single frequency) and process conditions may affect the stress of the film being deposited. In some implementations, a flow rate of the silicon-containing precursor relative to other gases flowed during deposition may tune the stress. In some implementations, substrate temperature may be tuned to modulate stress in the tensile film. For example, higher temperatures may be used to achieve higher stress or increase a stability of the film being deposited. In some implementations, substrate temperature for deposition on backside 401b of substrate 401 is greater than or equal to about 200°C and less than or equal to 650°C. Embodiments, however, are not limited thereto.

[0127] A tensile film may be used to compensate the one or more tensile regions of substrate 401. In some implementations, the thickness of the tensile film may vary based on location on substrate 401. For instance, the thickness of the tensile film at any given location may be greater than or equal to 0 nm and less than or equal to about 2000 nm. To this end, an average thickness of the tensile film may be about 1000 nm, but embodiments are not limited thereto. A thickness of the tensile film can affect wafer bow of the tensile film to compensate asymmetric bowing in substrate 401. Accordingly, a non-linear thickness profile in the tensile film achieves a desired wafer bow that compensates the one or more tensile regions of substrate 401.

[0128] FIG. 4B2 schematically illustrates a cross-sectional view of tensile film 405 having a

parabolic thickness profile deposited on backside 401b of substrate 401. Tensile film 405 may be deposited by PECVD. Tensile film 405 may be a tensile silicon oxide film, a tensile silicon nitride film, a tensile silicon film, a tensile carbon film, or the like. In some cases, tensile film 405 may be thicker at opposite edges of substrate 401 than at a center of substrate 401. Although tensile film 405 is shown having a parabolic thickness profile, the thickness profile may match or substantially match a polynomial function, such as a second order or third order polynomial function. The parabolic thickness profile of tensile film 405 opens upwards. The parabolic thickness profile of tensile film 405 is depicted along an x-axis or y-axis direction.

[0129] Adverting back to FIG. 3, at block 305, substrate 401 including the first film formed on backside 401b may be optionally caused, at least in part, to be rotated by a predetermined amount before formation of another film on the first film. For instance, substrate 401 may be caused, at least in part, to be rotated greater than about 0° and less than about 180°, such as greater than about 30° and less than about 150°, e.g., greater than about 60° and less than about 120°, for instance, greater than about 80° and less than about 100°. In one embodiment, the substrate 401 may be caused, at least in part, to be rotated by or about 90°. It is noted, however, that any other suitable rotation may be utilized.

[0130] According to some embodiments, rotation of substrate 401 may be achieved manually or via one or more automated methods. For instance, substrate 401 may be removed from a processing chamber, rotated using an external aligner, and loaded back into the processing chamber. In some implementations, substrate 401 may be rotated in a processing chamber via rotation of a support structure, e.g., a susceptor, a showerhead pedestal, etc. It is also contemplated that substrate 401 may be rotated within a processing chamber via a spindex, spider forks, or any other suitable wafer handling robot.

[0131] At block 307, a second film is caused, at least in part, to be formed on the first film utilizing a second gas flow configuration different from the first gas flow configuration. In some implementations, the second gas flow configuration may be opposite of the first gas flow configuration, as will become more apparent below. It is noted, however, that the first gas flow configuration may include one or more process gases being flowed in at least one first zone of a showerhead pedestal, and one or more process gases and one or more dilution gases being flowed in second and third zones of the showerhead pedestal that flank the first zone. In this manner, the second gas flow configuration may include one or more dilution gases being flowed in the first zone of the showerhead pedestal, and one or more process gases and one or

more dilution gases being flowed in the second and third zones of the showerhead pedestal. It is noted, however, that the one or more process gases flowed in the second and third zones during the second gas flow configuration may be flowed from those gas distribution ports having flowed the one or more dilution gases during the first gas flow configuration, and the one or more dilution gases flowed in the second and third zones during the second gas flow configuration may be flowed from those gas distribution ports having flowed the one or more process gases during the first gas flow configuration. Embodiments, however, are not limited thereto, and other and/or additional gas flow configurations are contemplated.

[0132] In some implementations, the second film may be configured to apply a second stress profile on substrate 401 that is different from a first stress profile applied by the first film. As such, deposition of the compressive film and the tensile film may occur interchangeably. That is, the compressive film may be deposited first followed by the tensile film, or the tensile film may be deposited first followed by the compressive film. In either case, the compressive film and the tensile film may be stacked and together achieve a flat or substantially flat surface forming a stress compensation layer. This flatness may result from the compressive film having a first non-linear thickness profile different from the tensile film having a second non-linear thickness profile. As a result, a stress compensation layer is formed on backside 401b of substrate 401 that is flat or substantially flat. In general, a stress compensation layer refers to the one or more films deposited on backside 401b of substrate 401 to correct or compensate wafer bowing in substrate 401. As used herein, the phrase “substantially flat” refers to wafer bowing or deviations from a flat reference plane that is less than about 100 μm . Having a flat or substantially flat stress compensation layer reduces IPD, where low IPD reduces overlay impact, ensures proper wafer chucking, and avoids defocusing.

[0133] According to various embodiments, a stress compensation layer is formed by stacking multiple films, e.g., the compressive film and the tensile film, with the stress compensation layer having a non-linear stress profile. The non-linear stress profile of the stress compensation layer may be largely characterized by a polynomial function, such as a parabolic function. In some implementations, additional films or layers may be stacked on the compressive film and tensile film for achieving a desired stress profile in the stress compensation layer. In some implementations, the stress compensation layer is removed. For instance, the stress compensation layer may be removed in further downstream processing operations.

[0134] FIG. 4C schematically illustrates a side view of stress compensation layer 407 formed

on backside 401b of substrate 401. Stress compensation layer 407 includes compressive film 403 and tensile film 405 stacked on one another. By stacking compressive film 403 and tensile film 405, stress compensation layer 407 achieves a flat or substantially flat surface 407a. At least because compressive film 403 and tensile film 405 open in opposite directions, combining the thickness profiles of compressive film 403 and tensile film 405 forms a flat or substantially flat profile. Different regions of stress compensation layer 407 have different stress values to locally modulate stress. The stress variation in stress compensation layer 407 may be characterized by a polynomial function, such as a parabolic function. In various embodiments, stress compensation layer 407 mitigates asymmetric bowing in substrate 401. Prior to depositing stress compensation layer 407, substrate 401 may have warpage greater than or equal to about +300 μm or less than or equal to about -300 μm in one or both of the x-axis and y-axis directions. After depositing stress compensation layer 407, substrate 401 may have warpage between about -300 μm and about +300 μm in both the x-axis and the y-axis directions. In some implementations, substrate 401 may have warpage between about -100 μm and about +100 μm in both the x-axis and the y-axis directions after depositing stress compensation layer 407. It, however, is also contemplated that formation of stress compensation layer 407 on backside 401b of substrate 401 may eliminate (or substantially eliminate) warpage in one or more of the x-axis and the y-axis directions, e.g., reduce warpage in one or more of the x-axis and the y-axis directions to or about 0 μm .

[0135] FIG. 5 is a graph illustrating a thickness profile and a stress profile for each of i) a compressive film, ii) a tensile film, and iii) a stress compensation layer combining the compressive film and the tensile film according to some embodiments.

[0136] As seen in FIG. 5, an upper portion of the graph provides a thickness profile as a function of position along the x-axis direction of a substrate. A lower portion of the graph provides a stress profile as a function of position along the x-axis direction of the substrate. Values in the stress profile are product values of stress multiplied by film thickness. The product value of stress multiplied by film thickness correlates with wafer bowing.

[0137] With respect to thickness profiles, first thickness profile 510 of a highly compressive film is depicted having a first parabolic-shaped curve. The thickness changes as a polynomial function such that the thickness in first thickness profile 510 increases parabolically towards the center of the substrate and parabolically decreases towards the edges of the substrate. Second thickness profile 520 of a highly tensile film is depicted as a second parabolic-shaped curve

opening in a direction opposite the first parabolic-shaped curve. For instance, the thickness changes as a polynomial function such that the thickness in second thickness profile 520 increases parabolically towards the edges of the substrate and decreases parabolically towards the center of the substrate. A combination of the highly compressive film and the highly tensile film yield third thickness profile 530, which is flat or uniform across the x-axis direction of the substrate.

[0138] With continued reference to FIG. 5, first stress profile 515 of the highly compressive film is depicted as a third parabolic-shaped curve. As the thickness of the highly compressive film parabolically increases towards the center of the substrate, the stress parabolically decreases, and, thereby, becomes more negative. As the thickness of the highly compressive film parabolically decreases at the edges of the substrate, the stress parabolically becomes less negative and crosses the neutral axis. Second stress profile 525 of the highly tensile film is depicted as a fourth parabolic-shaped curve. As the thickness of the highly tensile film parabolically increases towards the edges of the substrate, the stress parabolically increases. As the thickness of the highly tensile film parabolically decreases towards the center of the substrate, the stress parabolically decreases and reaches the neutral axis. Third stress profile 535 is a result, e.g., total stress, applied by the combination of the highly compressive film and the highly tensile film. Towards the edges of the substrate, the stress of third stress profile 535 parabolically increases, whereas towards the center of the substrate, the stress parabolically becomes more negative.

[0139] According to various embodiments, a thickness profile of a compressive or tensile film is modulated by controlling a concentration of precursor and dilution gas adjacent to a substrate during material deposition. This concentration of precursor and dilution gas may be controlled by varying how much precursor and dilution gas is flowed from a gas distributor, such as a showerhead or showerhead pedestal, along at least one of the x-axis and y-axis directions. Structural components of the gas distributor may be configured to vary precursor and/or dilution gas distribution therefrom.

[0140] For descriptive and illustrative convenience, various embodiments will be described in association with showerhead pedestal implementations configured to modulate precursor and dilution gas distribution adjacent to a backside of a substrate. It will be appreciated, however, that some embodiments are equally applicable to showerhead implementations, as well as other gas distributor implementations. The precursor and dilution gas distribution profile

adjacent to the substrate may match (or substantially match) a desired thickness profile of material deposited on a substrate. The desired thickness profile may be described by a polynomial function, such as a second or higher order polynomial function. Various features and/or designs of showerhead pedestals for providing such tailored thickness profiles will be described in association with FIGS. 7A–19. In some implementations, precursor and dilution gas output may be divided into multiple zones in order to produce a particular thickness profile, as will become more apparent below. It is also contemplated that precursor and dilution gas output may be interlaced, alternated, or otherwise integrated within one or more other zones to further control, e.g., smoothen a desired profile within and/or between one or more zones, etc.) to further produce a particular thickness profile, as will become more apparent below.

[0141] FIG. 6A is a graph comparing a desired profile and simulated profiles for reactant gas flowing from variously configured gas distributors relative to a backside of a substrate according to some embodiments. FIG. 6B is a graph comparing a desired profile and simulated profiles for dilution gas flowing from variously configured gas distributors relative to a backside of a substrate according to some embodiments.

[0142] Referring to FIGS. 6A and 6B, reactant and dilution gas concentration from a showerhead pedestal is shown relative to locations on a gas output surface of the showerhead pedestal. The locations extend along a radial direction, which may extend in the x-axis or y-axis direction. Gas concentration of desired profiles 601 and 603 for a first gas (e.g., a reactant gas) and a second gas (e.g., a dilution gas) generally follow respective parabolic curves. Desired profile 601 exhibits maximum concentration at a center of the showerhead pedestal and zero (or substantially zero) concentration an edge of the showerhead pedestal. Desired profile 603 exhibits maximum concentration at the edge of the showerhead pedestal and zero (or substantially zero) concentration at the center of the showerhead pedestal. Simulated profiles 605 and 607 may not perfectly match desired profiles 601 and 603, but may substantially match desired profiles 601 and 603 to achieve a sufficient deposition profile on a backside of a substrate. An observed or simulated curve may be considered to “substantially match” a parabolic or polynomial curve based upon fitting the observed curve to a polynomial function and evaluating the residuals therebetween to determine an acceptable level of correlation. For instance, when a statistical measure (such as R-square or an adjusted R-square) of the residuals reaches or exceeds a predetermined confidence level, the observed curve may be considered to “substantially match” the polynomial function. According to various embodiments, a gas

distributor may be configured to output a gas concentration profile that substantially matches a desired parabolic or polynomial function. Simulated profiles 605 and 607 will be described in more detail after various gas distribution features of some example showerhead pedestals are explored.

[0143] According to various embodiments, a gas distributor is used to distribute one or more gases, such as one or more process (or reactant) gases and/or one or more dilution gases, in an area adjacent to (e.g., over or under) a substrate in a process chamber. Generally, the gas distributor has a first surface and a second surface, each of which includes ports (or holes) that are fluidically interposed between an interior and an exterior of a main body of the gas distributor. The first surface defines a portion of the main body that, during a semiconductor process, faces towards a location in the process chamber where a wafer may be positioned during processing operations. The first surface may include a plurality of gas distribution ports, which are openings or apertures that permit gas to be delivered from within the gas distributor towards the substrate. The second surface defines a portion of the main body that faces away from the location in the process chamber where a wafer may be positioned during processing operations. In a plan view, each of the first and second surfaces may have a circular (or substantially circular) shape, but embodiments are not limited thereto. In other words, any other geometric or freeform configuration may be utilized. At least one third surface may extend between the first and second surfaces to enclose one or more volumes (e.g., plenum volumes) within the gas distributor. These one or more volumes may define portions of one or more gas distribution flow paths interior to the gas distributor and may be defined by one or more through-holes (or passages), cavities, recessed portions, risers, and/or elongated holes in an interior of the gas distributor. One or more gas inlets may interface with the second surface to deliver one or more gases for distribution. In some embodiments, the one or more gas inlets are provided in a stem connected to the second surface. Gas within the one or more volumes exits the gas distributor by flowing out of the plurality of gas distribution ports. Some example architectures of a gas distributor are described in association with FIGS. 7A–19 in the context of various showerhead pedestal implementations. As previously mentioned, a showerhead pedestal is a showerhead configured to deliver gas(es) to a backside of a substrate.

[0144] FIGS. 7A and 7B schematically illustrate perspective views of a gas distributor according to some embodiments. FIG. 8 schematically illustrates a partially exploded perspective view of the gas distributor of FIG. 7A according to some embodiments. FIG. 9A

schematically illustrates a plan view of a first surface of the gas distributor of FIG. 7A according to some embodiments. FIG. 9B schematically illustrates an enlarged portion of FIG. 9A according to some embodiments. FIGS. 10 and 11 schematically illustrate enlarged perspective views of negative space within respective portions of another gas distributor according to some embodiments. FIGS. 12 and 13 schematically illustrate perspective sectional views of corresponding portions of one or more gas distributors according to some embodiments. FIG. 14A schematically illustrates a side view of a portion of the gas distributor of FIG. 7A according to some embodiments. FIG. 14B schematically illustrates an enlarged portion of FIG. 14A according to some embodiments. FIGS. 15, 17, and 18 schematically illustrate cross-sectional views of the gas distributor of FIG. 14A respectively taken along sectional lines 15–15, 17–17, and 18–18 according to some embodiments. FIG. 16 schematically illustrates an enlarged portion of FIG. 15 according to some embodiments. FIG. 19 schematically illustrates a gas distribution flow path through the gas distributor of FIG. 7A according to some embodiments. FIG. 20 schematically illustrates a partially exploded perspective view of the gas distributor of FIG. 7B according to some embodiments.

[0145] Referring to FIGS. 7A–20, showerhead pedestal 700 includes main body 701, outer wall 703, and stem 705. Main body 701 has first surface 701a and second surface 701b opposing first surface 701a in a first direction, e.g., a direction extending parallel to the z-axis direction. Accordingly, a thickness of main body 701 is defined along the first direction. First surface 701a includes a plurality of gas distribution ports 707, which may be divided into a plurality of zones (or groups), such as zones 711, 713, and 715. Each of gas distribution ports 707 may include a corresponding outlet 707a, inlet 707b, and passageway (or riser, which may also be referred to, herein, as a gas riser) 707c fluidically interposed between outlet 707a and inlet 707b. Zones 711, 713, and 715 may longitudinally extend in a second direction transverse to the first direction (e.g., the second direction may extend parallel to the y-axis direction). In some cases, zones 711, 713, and 715 may be adjacent to one another along a third direction transverse to both the first direction and the second direction (e.g., the third direction may extend parallel or substantially parallel to the x-axis direction). In some embodiments, the longitudinal extension of zone 713 may separate zone 711 from zone 715. The first, second, and third directions cross one another, and, in some instances, the first, second, and third directions may be perpendicular to one another. Although three zones are depicted, embodiments are not limited thereto. For example, the gas distribution ports 707 may be

divided into two zones or divided into four or more zones. Further, although the outlets 707a of gas distribution ports 707 are shown having circular cross-sectional areas in planes perpendicular to their longitudinal directions of extension, any suitable shape may be utilized, e.g., elliptical, polygonal, freeform, etc. For convenience, gas distribution ports 707 will, hereinafter, be assumed to have circular cross-sectional areas for outlets 707a, inlets 707b, and passageways 707c.

[0146] In addition, one or more of the zones of gas distribution ports 707 may include at least one sub-zone of gas distribution ports. For instance, zone 711 may include sub-zones 711_1, 711_2, . . . , 711_n (where “n” is a natural number greater than or equal to one), 711_n1, and 711_n2, and zone 715 may include sub-zones 715_1, 715_2, . . . , 715_m (where “m” is a natural number greater than or equal to one), 711_n1, and 711_n2, such as depicted in FIGS. 9A and 9B. It is noted that sub-zones 711_n1, 711_n2, 715_m1, and 715_m2 may form respective sub-portions of sub-zones 711_n and 715_m. As such, sub-zones 711_n1, 711_n2, 715_m1, and 715_m2 will, hereinafter, be referred to as sub-portions 711_n1, 711_n2, 715_m1, and 715_m2. In another embodiment, sub-zones 711_n and 715_m may each respectively include one sub-portion or more than two sub-portions. For example, sub-zone 715_m may include sub-portions 715_m11, 715_m12, 715_m13, and 715_m14, such as depicted in FIG. 13. As will become more apparent below, each of the zones of gas distribution ports may have a same pattern (or spatial arrangement) of gas distribution ports, such as depicted in FIG. 9A, or at least one of the zones may have a different pattern, e.g., a more or less dense pattern. For instance, as seen in FIGS. 12 and 13, the gas distribution ports associated with zone 713 may be less densely arranged in the second direction than the gas distribution ports associated with zones 711 and 715, which may have equivalent (or substantially equivalent) patterns of gas distribution ports. To this end, the gas distribution ports associated with zone 713 may be more densely arranged in the third direction than the gas distribution ports associated with zones 711 and 715. Embodiments, however, are not limited to these examples.

[0147] According to one embodiment, not only does central axis 717 of showerhead pedestal 700 extend through a center of zone 713, but so do transverse axes 719 and 721 of first surface 701a. Transverse axis 719 may extend through the respective centers of zones 711 and 715, as well as the respective centers of sub-zones 711_1, 711_2, . . . , 711_n and 715_1, 715_2, . . . , 715_m. In this manner, corresponding shapes of zones 711, 713, and 715 may have maximum widths W_{711} , W_{713} , and W_{715} , as well as maximum lengths L_{711} , L_{713} , and L_{715} . The corresponding

shapes of sub-zones 711_1, 711_2, . . . , 711_n and 715_1, 715_2, . . . , 715_m may have maximum widths W_{711_1} , W_{711_2} , . . . , W_{711_n} and W_{715_1} , W_{715_2} , . . . , W_{715_m} , as well as maximum lengths L_{711_1} , L_{711_2} , . . . , L_{711_n} and L_{715_1} , L_{715_2} , . . . , L_{715_m} . Although not shown, each of the sub-portions (e.g., sub-portions 715_m11, 715_m12, 715_m13, and 715_m14) of a sub-zone may have corresponding maximum widths and maximum lengths. In some cases, lengths L_{711} , L_{713} , L_{715} , L_{711_1} , L_{711_2} , L_{715_1} , and L_{715_2} may be equivalent or substantially equivalent, but embodiments are not limited thereto. For instance, at least one of lengths L_{711} , L_{713} , L_{715} , L_{711_1} , L_{711_2} , L_{715_1} , and L_{715_2} may be different. Each of lengths L_{711} , L_{713} , L_{715} , L_{711_1} , L_{711_2} , L_{715_1} , and L_{715_2} may be greater than each of lengths L_{711_n} and L_{715_m} , which may be equivalent or substantially equivalent. In some cases, the lengths of sub-zones $L_{711_1-711_n}$ and $L_{715_1-715_m}$ may decrease with increasing distance from transverse axis 721 or may decrease in a step-wise manner with some adjacent sub-zones having equivalent or substantially equivalent lengths as one another. Width W_{713} may be smaller than each of widths W_{711} and W_{715} , which may be equivalent or substantially equivalent. Each of widths W_{711_1} , W_{711_2} , W_{715_1} , and W_{715_2} may be equivalent or substantially equivalent, as well as smaller than width W_{713} . Widths W_{711_n} and W_{715_m} may be equivalent or substantially equivalent, as well as greater than width W_{713} .

[0148] In various implementations, the shape of zone 713 may exhibit symmetry about each of transverse axes 719 and 721. The shapes of zones 711 and 715 and sub-zones 711_1, 711_2, . . . , 711_n and 715_1, 715_2, . . . , 715_m may exhibit symmetry about transverse axis 719. To this end, the shape of zone 711 may have mirror symmetry with the shape of zone 715 about transverse axis 721. The shapes of sub-zones 711_1, 711_2, . . . , 711_n may have mirror symmetry with the respective shapes of sub-zones 715_1, 715_2, . . . , and 715_m. Similarly, a pattern of gas distribution ports in zone 713 may have symmetry about each of transverse axes 719 and 721. The patterns of gas distribution ports in zones 711 and 715 and sub-zones 711_1, 711_2, . . . , 711_n and 715_1, 715_2, . . . , 715_m may have symmetry about transverse axis 719. In one or more embodiments, at least some of the gas distribution ports in zones 711, 713, and 715 may be distributed (or arranged) across a circular area. It is also noted that the combined patterns of gas distribution ports in zone 711 and sub-zones 711_1, 711_2, . . . , 711_n and the combined patterns of gas distribution ports in zone 715 and sub-zones 715_1, 715_2, . . . , 715_m may exhibit mirror symmetry about a transverse axis (e.g., transverse axis 721), but not exhibit 3-fold or higher radial symmetry.

[0149] With reference to FIGS. 9A and 9B, each of gas distribution ports 707 may have an

equivalent (or substantially equivalent) diameter 901 and may be spaced apart from one another by (or substantially by) pitch P_{903} in the second direction and by (or substantially by) pitch P_{905} in the third direction. Pitches P_{903} and P_{905} may, in some embodiments, be equivalent or substantially equivalent. It is contemplated, however, that the pitches and/or diameters of the gas distribution ports in one or more different zones, sub-zones, and/or sub-portions may be different. For instance, as shown in FIG. 12, the gas distribution ports of zone 713 may be spaced apart from one another by (or substantially by) pitch P_{1201} in the second direction and by (or substantially by) pitch P_{1203} in the third direction, whereas at least some of the gas distribution ports of zone 711 may be spaced apart from one another by (or substantially by) pitch P_{1205} in the second direction and by (or substantially by) pitch P_{1207} in the third direction. In some cases, pitch P_{1201} may be greater than pitch P_{1205} , and pitch P_{1203} may be smaller than pitch P_{1207} .

[0150] Although certain shapes, relative dimensions, and symmetries for the zones, sub-zones, and sub-portions of sub-zones have been described, embodiments are not limited thereto. For instance, the zones, sub-zones, and sub-portions of gas distribution ports 707 may have any suitable shape, relative dimensions, symmetries, and/or asymmetries that may enable a uniform (or substantially uniform) amount of gas flow within zone 713 and an increasing amount of gas flow in zones 711 and 715 as a distance from central axis 717 increases. Further, although certain patterns, pitches, diameters, offsets, symmetries, and/or asymmetries for the gas distribution ports in the zones, sub-zones, and sub-portions have been described, embodiments are not limited thereto. For example, the gas distribution ports in the zones, sub-zones, and sub-portions may have any suitable pattern, pitch, diameter, offset, symmetry, and/or asymmetry that may enable a uniform (or substantially uniform) amount of gas flow within (or across) zone 713 and an increasing amount of gas flow within (or across) zones 711 and 715 as a distance from central axis 717 increases. To this end, the gas distribution ports in a sub-zone or sub-portion of a sub-zone may have any suitable pattern, pitch, diameter, symmetry, and/or asymmetry that may enable an increasing amount of gas flow in (or across) zones 711 and 715 as a distance from central axis 717 increases. Further, the gas distribution ports in a sub-portion may have any suitable offset from an outermost gas distribution port of a corresponding zone including the sub-portion to enable gas flow at (or near) an edge portion of zones 711 and 715 to match (or substantially match) an intended gas flow profile across zones 711 and 715. Thus, the various gas flow profiles serve as a stand-in for all of the various

structural ways the gas distribution ports 707 may be configured to arrive at an intended result.

[0151] For example, in some implementations, the gas distribution ports of zones 711 and 715 may have a variable pitch in at least one of the second and third directions. For instance, in zones 711 and 715, the pitch between at least some of the gas distribution ports in at least one of the second and third directions may decrease or increase with increasing distance from central axis 717. For example, as seen in FIG. 13, the pitch between the gas distribution ports in the second direction of sub-zone 715_m-1 may be smaller than the pitch between the gas distribution ports in the second direction of sub-portion 715_m13 of sub-zone 715_m, and the pitch between the gas distribution ports in the second direction of sub-portion 715_m13 of sub-zone 715_m may be smaller than the pitch between the gas distribution ports in the second direction of sub-portion 715_m14 of sub-zone 715_m. In some cases, the pitch between the gas distribution ports of a zone, sub-zone, or sub-portion of a sub-zone may vary in at least one of the second and third directions. For example, a first sub-set of the gas distribution ports of sub-portion 715_m11 of sub-zone 715_m that are disposed closer to transverse axis 719 may be more densely arranged in the second direction than a second sub-set of the distribution ports of sub-portion 715_m11 that are positioned further away from transverse axis 719. The same may be true with respect to the relative spacing between the gas distribution ports of sub-portions 711_n11, 711_n12, 711_n13, and 711_n4 of sub-zone 711_n.

[0152] In some embodiments, the cross-sectional area in a plane perpendicular to a direction of longitudinal extension of some of gas distribution ports 707 may be different. For example, in zones 711 and 715, the cross-sectional area of some of the gas distribution ports may increase with increasing distance from central axis 717, such as along at least one of the second and third directions. For example, the cross-sectional area of the gas distribution ports of sub-zone 711_1 may be smaller than the cross-sectional area of the gas distribution ports of sub-zone 711_2, and the cross-sectional area of the gas distribution ports of sub-zone 711_2 may be smaller than the cross-sectional area of the gas distribution ports of sub-zone 711_n. The same may be true with respect to the relative cross-sectional areas of the gas distribution ports of sub-zones 715_1, 715_2, and 715_m.

[0153] According to various embodiments, gas distribution ports 707 may distribute one or more gases, such as one or more process (or reactant) gases and/or one or more dilution gases, in an area adjacent to a backside of a substrate in a process chamber. For instance, one or more first gases may be flowed from the gas distribution ports of zone 713, and one or more

first gases and one or more second gases may be flowed from the gas distribution ports of zones 711 and 715. In some embodiments, the output of the one or more first gases from the gas distribution ports of zones 711 and 715 may be interlaced, alternated, or otherwise integrated with the output of the one or more second gases flowed from the gas distribution ports of zones 711 and 715. For example, as seen in FIG. 10, one or more first gases may be output from first gas distribution ports (e.g., first gas distribution ports 1001) of sub-zone 715_2 and one or more second gases may be output from second gas distribution ports (e.g., second gas distribution ports 1003) of sub-zone 715_2, and the position of the second gas distribution ports of sub-zone 715_2 may alternate with the position of the first gas distribution ports of sub-zone 715_2 along or otherwise in association with the second direction. The same or similar arrangements may not only be true with respect to the output of the one or more first gases and the one or more second gases from the gas distribution ports of the other sub-zones of zone 715, e.g., sub-zones 715_1 and 715_m, and/or sub-portions of, for instance, sub-zone 715_m, but may be true with respect to the output of the one or more first gases and the one or more second gases from the gas distribution ports of sub-zones 711_1, 711_2, and 711_n of zone 711, and/or sub-portions of, for instance, sub-zone 711_n. Embodiments, however, are not limited to the above-noted examples. For instance, the gas distribution ports of a zone, sub-zone, or sub-portion may be interlaced, alternated, or otherwise integrated in any suitable manner to achieve a desired gas distribution profile, such as interlaced, alternated, or otherwise integrated in groups of gas distribution ports of the one or more first gases and the one or more second gases along, for instance, at least one of the second and third directions with each group including one or more gas distribution ports. In some cases, the groups may have at least one of a linear, geometric, variable, etc., arrangement of gas distribution ports. Whatever the case, the interlaced, alternated, or otherwise integrated arrangement of gas distribution ports configured to output one or more first gases and one or more second gases in various zones, sub-zones, and/or sub-portions may enable more precise control over the gas distribution profile across first surface 701a of main body 701.

[0154] According to some embodiments, gas distribution ports 707 may be distributed across first surface 701a of main body 701 in a matrix arrangement, which may include a plurality of rows (e.g., rows 1004, 1005, 1007, 1009, and 1011) extending in the third direction and a plurality of columns (e.g., columns 1013, 1015, 1017, 1019, 1021, 1023, and 1025) extending in the second direction. In some cases, the gas distribution ports arranged in a same column may

form a portion of a same zone, sub-zone, or sub-portion of main body 701, and the gas distribution ports arranged in a same row may form portions of one or more zones, sub-zones, or sub-portions.

[0155] For instance, zone 713 may include a plurality of columns of gas distribution ports, such as columns 1013, 1015, 1017, and 1019. Zones 711 and 715 may also include respectively pluralities of columns. For example, zone 715 may include columns 1021 and 1023 of gas distribution ports. The columns of gas distribution ports in zones 711 and 715 may correspond to at least some of the sub-zones of zones 711 and 715 in a one-to-one relationship. For instance, columns 1021 and 1023 of gas distribution ports may respectively correspond to sub-zones 1015_1 and 1015_2. Similar arrangements may not only exist with respect to other sub-zones of zone 715 (e.g., sub-zone 715_3), but also with respect to sub-zones 711_1, 711_2, . . . , and 711_n of zone 711. The same may be true with respect to at least some of the sub-portions of a sub-zone, such as sub-portion 715_m13. It is contemplated, however, that some of the sub-portions of a sub-zone may be configured differently. For example, sub-portions 715_m12 and 715_m14 may respectively include two and three columns of gas distribution ports. As another example, sub-portion 715_m11 may include one column of gas distribution ports in a first area and two columns of gas distribution ports in a second area. Embodiments, however, are not limited to these examples and the various zones, sub-zones, and sub-portions may include any suitable number of columns of gas distribution ports.

[0156] With respect to the rows of gas distribution ports, some rows may only include gas distribution ports arranged in a same zone, sub-zone, or sub-portion (e.g., row 1004 may only include gas distribution ports arranged in zone 713). Other rows of gas distribution ports (e.g., rows 1005, 1007, 1009, and 1011) may include gas distribution ports from multiple zones, sub-zones, and/or sub-portions. For instance, row 1007 is at least shown in FIG. 10 including gas distribution ports arranged in zone 713 and zone 715, but may also include gas distribution ports arranged in zone 711. The same may be true with respect to other rows of gas distribution ports, such as row 1011. Hereinafter, rows including gas distribution ports from each of zones 711, 713, and 715 will be referred to as first rows 1027. As another example, row 1005 is at least shown in FIG. 10 including gas distribution ports arranged in zone 715, but may also include gas distribution ports arranged in zone 711. The same may be true with respect to other rows of gas distribution ports, such as row 1009. Hereinafter, rows including gas distribution ports from zones 711 and 715, but not zone 713 will be referred to as second rows

1029. In some instances, the positioning of respective first rows 1027 may alternate with the positioning of respective second rows 1029 along or otherwise in association with the second direction. To this end, corresponding rows of only gas distribution ports from zone 713 (e.g., row 1004) may bound the arrangement of first and second rows 1027 and 1029 in the second direction. In some cases, the gas distribution ports of first rows 1027 may be configured to flow the one or more first gases and the gas distribution ports of second rows 1029 may be configured to flow the one or more second gases. Embodiments, however, are not limited to the aforementioned examples.

[0157] As such, showerhead pedestal 700 may modulate a concentration of precursor gas delivered across a backside of a substrate by flowing one or more dilution gases or one or more precursor gases zone 713 and flowing one or more precursor gases and one or more dilution gases in zones 711 and 715. In this manner, a flow of dilution gas in certain zones or regions adjacent to the substrate will dilute or otherwise limit a concentration of precursor gas in the regions adjacent to the substrate that is flowed from certain other zones or regions adjacent to the substrate. Example dilution gases include, but are not limited to, various inert gases or gas species, such as nitrogen gas (N₂), helium (He), argon (Ar), neon (Ne), or xenon (Xe). Example process (or precursor) gases include, but are not limited to, silicon-containing gases, oxygen-containing gases, and nitrogen-containing gases (although generally not pure N₂).

[0158] In some implementations, the dilution gas is flowed through main body 701 to mix with precursor gas in an environment adjacent to the substrate. According to some embodiments, the dilution gas is flowed through main body 701 to mix with precursor gas in an environment adjacent to the substrate, but without mixing within main body 701 of showerhead pedestal 700. As such, main body 701 may include one or more first gas distribution flow paths to distribute the one or more first gases to the gas distribution ports of zone 713, one or more second gas distribution flow paths to distribute the one or more first gases to some of the gas distribution ports of zone 711, one or more third gas distribution flow paths to distribute the one or more second gases to other gas distribution ports of zone 711, one or more fourth gas distribution flow paths to distribute the one or more first gases to some of the gas distribution ports of zone 715, and one or more fifth gas distribution flow paths to distribute the one or more second gases to other gas distribution ports of zone 715. As will become more apparent below, each of the first, second, and fourth gas distribution flow paths may establish routes through main body 701 starting at an inlet and ending at a gas distribution

port. In some cases, one or more interior volumes (e.g., plenum volumes) may be defined between the inlet and the gas distribution port, such as by one or more elongated holes, blind cavities, recessed portions, and/or through-holes (or passages). Before describing each of these interior volumes, gas concentration profiles from various simulated examples of gas distribution port arrangements will be addressed.

[0159] Adverting back to FIGS. 6A and 6B and with continued reference to FIGS. 9A–13, various configurations of gas distribution ports 707 of showerhead pedestal 700 may be utilized to tailor a gas concentration profile that matches or substantially matches a desired profile, such as a profile characterized by a parabolic or polynomial function. In a first simulated example of a showerhead pedestal similar to showerhead pedestal 700, gas distribution ports 707 were divided into multiple zones similar to zones 711, 713, and 715, and included multiple sub-portions. For instance, a zone similar to zone 715 included sub-portions similar to sub-portions 715_m11–715_m14 shown in FIG. 13, and a zone similar to zone 711 exhibited symmetry with the zone similar to zone 715 about transverse axis 721. Comparable to as shown in FIG. 13, the sub-portions similar to sub-portions 715_m11–715_m14 had respective maximum widths W_{1301} , W_{1303} , W_{1305} , and W_{1307} extending in the second direction and corresponding maximum lengths extending in the third direction. It is noted that width W_{1301} and W_{1303} were equivalent or substantially equivalent, and were greater than width W_{1305} and smaller than width W_{1307} . The maximum lengths of the sub-portions similar to sub-portions 715_m11–715_m14 and decreased with increasing distance from transverse axis 721. Further, the outermost gas distribution ports of the sub-portions similar to sub-portions 715_m11–715_m14 defined the respective outermost gas distribution ports of the zone similar to zone 715. The gas distribution flow paths in the simulated showerhead pedestal implementation were substantially similar to showerhead pedestal 700.

[0160] To determine simulated gas concentration profiles, a reactant gas (i.e., nitrous oxide (N_2O)) was simulated as being flowed from the zone similar to zone 713, and the reactant gas and a dilution gas were simulated as being flowed from the zones similar to zones 711 and 715 with the flow of the dilution gas alternating with the flow of the reactant gas. In this manner, the dilution gas was simulated as being flowed from each of the example showerhead pedestals simultaneously with the reactant gases for depositing a compressive or tensile film on a substrate. It is noted that the dilution gas reduces (or dilutes) a concentration of the reactant gas adjacent to the substrate. As such, more dilution gas at a periphery of the substrate

reduces a concentration of reactant gas at the periphery, and more dilution gas at a center of the substrate reduces a concentration of reactant gas at the center.

[0161] As can be appreciated from the results shown in FIGS. 6A and 6B, the configuration of the showerhead pedestal in association with the first simulated example yielded gas concentration profiles 605 and 607 with relatively high correlation with desired profiles 601 and 603, respectively. It is noted that profile 605 corresponds with the profile of the reactant gas from the simulated showerhead pedestal and profile 607 corresponds with the profile of the dilution gas from the simulated showerhead pedestal. As such, the utilization of one or more sub-portions in one or more primary zones and/or sub-zones may be utilized to further tailor a gas concentration profile such that the gas concentration profile more closely matches or even substantially matches a desired profile, such as a profile characterized by a parabolic or polynomial function. Further, the alternating output of the reactant gas and the dilution gas along, for example, the second direction enables gas concentration profiles 605 and 607 to smoothly transition from one zone, sub-zone, or sub-portion to another without substantial deviation. Dissimilarly, the slope of gas concentration profiles 609 and 611 (that are associated with different simulated arrangements of gas distribution ports in zones similar to zones 711, 713, and 715 and do not include alternating output of the reactant and dilution gases in zones 711 and 715), exhibit much steeper, more variable gas concentration profiles that deviate much further and more significantly from desired profiles 601 and 603 than gas concentration profiles 605 and 607. Hereinafter, each of various interior volumes in showerhead pedestal 700 that are configured to supply gas to a gas distribution port among gas distribution ports 707 will be described in more detail.

[0162] With reference to FIGS. 10–16, gas distribution ports 707 are fluidically connected to a plurality of through-holes (or passages, which may also be referred to, herein, as gas passages), such as through-holes 1501–1543, that may longitudinally extend in a fourth direction. The second and fourth directions may be equivalent. In some embodiments, through-holes 1501–1543 are gun-drilled through main body 701 at (or substantially at) distance H_{1401} from second surface 701b. Further, through-holes 1501–1543 may be spaced apart from one another in a fifth direction by (or substantially by) pitch P_{1401} . The fifth direction crosses the first and fourth directions, and, in some implementations, may be equivalent to the third direction. Although twenty-one through-holes are shown as an example, embodiments are not limited thereto. A dichotomy, however, exists between the structural integrity of main body 701 and the gas

distribution effect provided by a corresponding number of the through-holes. For instance, the structural integrity of main body 701 may decrease as the number of through-holes increases, but the gas distribution effect may increase.

[0163] According to various embodiments, each through-hole among through-holes 1501–1543 may be configured to provide gas to the gas distribution ports of one or more zones, sub-zones, and/or sub-portions of a sub-zone. To this end, each of through-holes 1501–1543 may define a portion of a plenum volume within main body 701. For instance, through-holes 1503, 1509, 1513, 1517, 1521, 1523, 1525, 1529, 1533, 1537, and 1541 may define portions of a first plenum volume in main body 701. The first plenum volume may be fluidically connected to one or more sources of first gases via one or more first inlets, such as first inlets 1701 and 1702 in FIG. 17. Through-holes 1501, 1505, 1511, 1515, 1519, 1527, 1531, 1535, 1539, and 1543 may define portions of a second plenum volume in main body 701, which may be separate (and, in some cases, fluidically isolated) from the first plenum volume within an interior of main body 701. The second plenum volume may be fluidically connected to one or more sources of second gases via one or more second inlets, such as second inlet 1801 shown in at least FIG. 18.

[0164] In some implementations, each of through-holes 1501–1543 may be configured to supply gas to one or more columns of gas distribution ports within a zone, sub-zone, or sub-portion of a sub-zone. For instance, through-holes 1521–1525 may be fluidically connected to the gas distribution ports of zone 711, which may include four columns of gas distribution ports, but embodiments are not limited thereto. As seen in FIG. 10, two central columns of gas distribution ports (e.g., columns 1015 and 1017) among the four columns may be fluidically connected to a same through-hole (e.g., through-hole 1523) among through-holes 1521–1525. Columns 1013 and 1015 of gas distribution ports may be fluidically and respectively connected to through-holes 1521 and 1525 in a one-to-one relationship. In this manner, through-holes 1521–1525 may supply each of the gas distribution ports of zone 713 with the one or more first gases by way of first gas risers (e.g., first gas risers 1002), which may extend in the first direction from corresponding portions of through-holes 1521–1525.

[0165] Through-holes 1503, 1509, 1513, 1517, and 1521 may be fluidically connected to first gas distribution ports among the gas distribution ports of zone 711, and through-holes 1501, 1505, 1511, 1515, and 1519 may be fluidically connected to second gas distribution ports among the gas distribution ports of zone 711. The first gas distribution ports of zone 711 may receive the one or more first gases by way of through-holes 1503, 1509, 1513, 1517, and 1521

and the second gas distribution ports of zone 711 may receive the one or more second gases by way of through-holes 1501, 1505, 1511, 1515, and 1519. In some cases, additional second gas distribution ports in zone 711 may be fluidically connected to one or more blind cavities (such as blind cavity 1545), and, thereby, configured to receive the one or more second gases therefrom. Blind cavity 1545 may, in some implementations, be fluidically connected to the one or more second inlets, e.g., second inlet 1801, and may be formed as a recess in third surface 701c of main body 701. In this manner, blind cavity 1545 may form a passageway extending in the fourth direction that is spaced apart from an adjacent through-hole (e.g., through-hole 1501) in the fifth direction.

[0166] As previously mentioned, some of the first and second gas distribution ports of zone 711 may be interlaced, alternated, or otherwise integrated with one another along the fourth direction. For instance, as seen in at least FIG. 11, the first gas distribution ports (e.g., first gas distribution ports 1101) and the second gas distribution ports (e.g., second gas distribution ports 1103) of sub-zone 711_{n-1} of zone 711 may form column 1105 of gas distribution ports extending along the fourth direction with the positions of the first and second gas distribution ports alternating along the fourth direction. The first gas distribution ports of sub-zone 711_{n-1} may be fluidically connected to through-hole 1509 by way of second gas risers (e.g., second gas riser 1107) and the second gas distribution ports of sub-zone 711_{n-1} may be fluidically connected to through-hole 1505 by way of third gas risers (e.g., third gas riser 1109). In some cases, column 1105 of gas distribution ports may be positioned between through-holes 1505 and 1509 in the fifth direction when viewed in the first direction. As such, and to facilitate uniform (or substantially uniform) spacing between adjacent gas distribution ports, the first gas distribution ports may be sloped in a first reference plane (e.g., a first plane parallel to the z-x plane) from the first direction by angle 1111 and the second gas distribution ports may be sloped in a second reference plane (e.g., a second plane parallel to the z-x plane) from the first direction by angle 1113. Absolute values of angles 1111 and 1113 may, in some cases, be equivalent or substantially equivalent. Similar configurations of alternating first and second gas distribution ports may be implemented in association with sub-zones 711₁–711_{n-2} and sub-portions 711_{n1} and 711_{n12}. Sub-portions 711_{n13} and 711_{n14} may be configured similar to the gas distribution ports of zone 713, but relative to through-hole 1501 and blind cavity 1545. In this manner, gas risers (e.g., gas risers 1115 and 1117) fluidically connecting the gas distribution ports of sub-portions 711_{n13} and 711_{n14} to through-hole 1501 and blind cavity

1545 may extend in (or substantially in) the first direction.

[0167] In a similar fashion as the through-holes associated with zone 711, through-holes 1525, 1529, 1533, 1537, and 1541 may be fluidically connected to third gas distribution ports among the gas distribution ports of zone 715, and through-holes 1527, 1531, 1535, 1539, and 1543 may be fluidically connected to fourth gas distribution ports among the gas distribution ports of zone 715. The third gas distribution ports of zone 715 may receive the one or more first gases by way of through-holes 1525, 1529, 1533, 1537, and 1541, and the fourth gas distribution ports of zone 715 may receive the one or more second gases by way of through-holes 1527, 1531, 1535, 1539, and 1543. In some cases, additional fourth gas distribution ports in zone 715 may be fluidically connected to one or more blind cavities (such as blind cavity 1547), and, thereby, configured to receive the one or more second gases therefrom. Blind cavity 1547 may, in some implementations, be fluidically connected to the one or more second inlets, e.g., second inlet 1801, and may be formed as a recess in third surface 701c of main body 701. In this manner, blind cavity 1547 may form a passageway extending in the fourth direction that is spaced apart from an adjacent through-hole (e.g., through-hole 1543) in the fifth direction.

[0168] According to various embodiments, some of the third and fourth gas distribution ports of zone 715 may be interlaced, alternated, or otherwise integrated with one another along the fourth direction. For instance, as seen in at least FIG. 10 and 13, the third gas distribution ports (e.g., third gas distribution ports 1001) and the fourth gas distribution ports (e.g., fourth gas distribution ports 1003) of sub-zone 715_2 of zone 715 may form column 1023 of gas distribution ports extending along the fourth direction with the positions of the third and fourth gas distribution ports alternating along the fourth direction. The third gas distribution ports of sub-zone 715_2 may be fluidically connected to through-hole 1529 by way of fourth gas risers (e.g., fourth gas riser 1031) and the second gas distribution ports of sub-zone 715_2 may be fluidically connected to through-hole 1527 by way of fifth gas risers (e.g., fifth gas riser 1033). In some cases, column 1023 of gas distribution ports may be positioned between through-holes 1527 and 1529 in the fifth direction when viewed in the first direction. As such, and to facilitate uniform (or substantially uniform) spacing between adjacent gas distribution ports, the third gas distribution ports may be sloped in a third reference plane (e.g., a third plane parallel to the z-x plane) from the first direction by angle 1035 and the second gas distribution ports may be sloped in a fourth reference plane (e.g., a fourth plane parallel to the z-x plane) from the first

direction by angle 1037. Absolute values of angles 1035 and 1037 may, in some cases, be equivalent or substantially equivalent, angle 1035 may be equivalent or substantially equivalent to angle 1111, and angle 1037 may be equivalent or substantially equivalent to angle 1113, but embodiments are not limited thereto. Similar configurations of alternating third and fourth gas distribution ports may be implemented in association with sub-zones 715_1 and 715_3–715_m-2 and sub-portions 715_m11 and 715_m12. Sub-portions 715_m13 and 715_m14 may be configured similar to the gas distribution ports of zone 713, but relative to through-hole 1543 and blind cavity 1547. In this manner, gas risers (e.g., gas risers 1307 and 1309) fluidically connecting the gas distribution ports of sub-portions 715_m13 and 715_m14 to through-hole 1543 and blind cavity 1547 may extend in (or substantially in) the first direction.

[0169] According to some embodiments, first distal ends of through-holes 1501–1543 may be fluidically connected to a first plurality of blind cavities, e.g., blind cavities 1549a–1589a, and second distal ends of through-holes 1501–1543 may be fluidically connected to a second plurality of blind cavities, e.g., blind cavities 1549b–1589b. Each of blind cavities 1549a–1589a and 1549b–1589b extend into third surface 701c of main body 701 to (or substantially to) depth D_{1601} and at (or substantially at) distance H_{1403} from second surface 701b of main body 701. Third surface 701c of main body 701 may be connected to second surface 701b of main body 701 and extend towards first surface 701a of main body 701. Fourth surface 701d (see FIG. 19) of main body 701 may connect third and fifth surfaces 701c and 701e of main body 701. Fifth surface 701e of main body 701 may connect first and fourth surfaces 701a and 701d of main body 701. In some embodiments, blind cavities 1549a–1589a and 1549b–1589b are arranged about perimeter 701p (see, e.g., FIG. 15) of main body 701. For instance, blind cavities 1549a–1589a and 1549b–1589b may be defined in third surface 701c of main body 701 and azimuthally arranged about central axis 717. Although forty-one blind cavities at (or substantially at) distance H_{1403} from second surface 701b of main body 701 are shown as an example, embodiments are not limited thereto. As previously mentioned, main body 701 may also include blind cavities 1545 and 1547 defined in third surface 701c of main body 701. In some cases, blind cavities 1545 and 1547 may also be azimuthally arranged about central axis 717 with blind cavities 1549a–1589a and 1549b–1589b.

[0170] As seen in FIGS. 14A–16, each of blind cavities 1549a–1589a and 1549b–1589b may respectively interface with a corresponding distal end of through-holes 1501–1543. For instance, first distal ends of through-holes 1501–1519 may respectively interface with blind

cavities 1549a–1565a, and second distal ends of through-holes 1501–1519 may respectively interface with blind cavities 1549b–1565b. First distal ends of through-holes 1521–1525 may respectively interface with blind cavities 1567a–1571a, and second distal ends of through-holes 1521–1525 may respectively interface with blind cavities 1567b–1571b. Also, first distal ends of through-holes 1527–1543 may respectively interface with blind cavities 1573a–1589a, and second distal ends of through-holes 1527–1543 may respectively interface with blind cavities 1573b–1589b. In this manner, blind cavities 1551a, 1551b, 1555a, 1555b, 1559a, 1559b, 1563a, 1563b, 1567a, and 1567b may be fluidically connected to the first gas distribution ports of zone 711, and blind cavities 1571a, 1571b, 1575a, 1575b, 1579a, 1579b, 1583a, 1583b, 1587a, 1587b may be fluidically connected to the third gas distribution ports of zone 715. Blind cavities 1549a, 1549b, 1553a, 1553b, 1557a, 1557b, 1561a, 1561b, 1565a, and 1565b may be fluidically connected to some of the second gas distribution ports of zone 711, and blind cavities 1581a, 1581b, 1585a, 1585b, 1589a, and 1589b may be fluidically connected to some of the fourth gas distribution ports of zone 715. Remaining second gas distribution ports of zone 711 may be fluidically connected to blind cavity 1545, and remaining fourth gas distribution ports of zone 715 may be fluidically connected to blind cavity 1547. Further, blind cavities 1567a, 1567b, 1569a, 1569b, 1571a, and 1571b may be fluidically connected to the gas distribution ports of zone 713. Embodiments, however, are not limited to the above-noted configuration between blind cavities and through-holes. For instance, at least one blind cavity among blind cavities 1549a–1589a and 1549b–1589b may interface with corresponding distal ends of two or more through-holes among through-holes 1501–1543 to achieve desired gas distribution profiles in and across zones 711, 713, and 715.

[0171] In some embodiments, respective sizes (e.g., at least one of openings, depths, widths, and volumes) of blind cavities 1549a–1589a and 1549b–1589b may be equivalent, and respective sizes of blind cavities 1545 and 1547 may be equivalent. To this end, each of the respective sizes of blind cavities 1545 and 1547 may be greater than each of the respective sizes of blind cavities 1549a–1589a and 1549b–1589b. Embodiments, however, are not limited thereto.

[0172] As seen in FIGS. 7A, 7B, 17, 18, and 19, outer wall 703 may be connected to main body 701 such that upper and inner surfaces 703a and 703b of outer wall 703 respectfully abut against fourth and third surfaces 701d and 701c of main body 701. In some implementations, a gap may exist between one or more of upper and inner surfaces 703a and 703b of outer wall

703 and fourth and third surfaces 701d and 701c of main body 701. It is noted, however, that a size of the gap(s) may be configured (or maintained within an acceptable tolerance) to produce a gas blocking effect preventing, minimizing, or at least reducing gas flow therethrough. For instance, a flow conductance associated with the gap(s) may be low enough relative to a flow conductance of a gas distribution flow path to discourage deviation from the gas distribution flow path. In this manner, blind cavities 1551a, 1551b, 1555a, 1555b, 1559a, 1559b, 1563a, 1563b, 1567a, 1567b, 1569a, 1569b, 1571a, 1571b, 1575a, 1575b, 1579a, 1579b, 1583a, 1583b, 1587a, 1587b may define corresponding portions of the first plenum volume in showerhead pedestal 700, and blind cavities 1545, 1547, 1549a, 1549b, 1553a, 1553b, 1557a, 1557b, 1561a, 1561b, 1565a, 1565b, 1581a, 1581b, 1585a, 1585b, 1589a, and 1589b may define corresponding portions of the second plenum volume in showerhead pedestal 700. In some embodiments, blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b may function as both gas intake plenums and gas distribution plenums. For instance, initial gas flow into blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b may help build a stabilized pressure of source gas within showerhead pedestal 700 that, in turn, can help build a stabilized pressure of distribution gas within blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b. The distribution gas in blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b is made available to the distal ends of through-holes 1501–1543 for output via gas distribution ports 707. This configuration may not only allow gas distribution ports antipodally arranged about central axis 717 to exhibit similar gas flow, but also allow showerhead pedestal 700 to reach steady-state gas flow without expending too much extraneous reactant and dilution gas.

[0173] As seen in FIG. 17, blind cavities 1551a, 1555a, 1559a, 1563a, 1567a, 1569a, 1571a, 1575a, 1579a, 1583a, and 1587a are respectively and fluidically connected to distal ends of elongated holes 1703, 1705, 1707, 1709, 1711, 1713, 1715, 1717, 1719, 1721, 1723, and 1725, whereas blind cavities 1551b, 1555b, 1559b, 1563b, 1567b, 1569b, 1571b, 1575b, 1579b, 1583b, and 1587b are respectively and fluidically connected to distal ends of elongated holes 1727, 1729, 1731, 1733, 1735, 1737, 1739, 1741, 1743, 1745, and 1747. Proximal ends of elongated holes 1703–1725 are fluidically connected to first inlet 1701 and proximal ends of elongated holes 1727–1747 are fluidically connected to first inlet 1702. First inlets 1701 and 1702 may be configured to receive the one or more first gases into main body 701. Although illustrated as two separate inlets, first inlets 1701 and 1702 may be formed as a single inlet or more than two inlets. As depicted in FIG. 17, however, elongated holes 1703–1725 outwardly

extend (such as radially extend) from first inlet 1701 in a first generally planar region of main body 701 at (or substantially at) distance H_{1405} from second surface 701b of main body 701, and elongated holes 1727–1747 outwardly extend (such as radially extend) from first inlet 1702 in the first generally planar region of main body 701 at (or substantially at) distance H_{1405} from second surface 701b of main body 701.

[0174] Based on the above-noted configuration, first inlets 1701 and 1702 and elongated holes 1703–1713 and 1727–1735 may be fluidically connected to the first gas distribution ports of zone 711, and, in particular, to the first gas distribution ports of sub-zones 711_1–711_m-1 and sub-portions 711_n11–711_n13 of zone 711. First inlets 1701 and 1702 and elongated holes 1713–1717 may be fluidically connected to the gas distribution ports of zone 713. Further, first inlets 1701 and 1702 and elongated holes 1717–1725 and 1739–1747 may be fluidically connected to the third gas distribution ports of zone 715, and, in particular, to the third gas distribution ports of sub-zones 715_1–715_m-1 and sub-portions 715_n11–715_n13 of zone 715.

[0175] Referring to FIG. 18, blind cavities 1549a, 1553a, 1557a, 1561a, 1565a, 1581a, 1585a, and 1589a are respectively and fluidically connected to distal ends of elongated holes 1803, 1805, 1807, 1809, 1811, 1813, 1815, 1817, 1819, and 1821, whereas blind cavities 1549b, 1553b, 1557b, 1561b, 1565b, 1581b, 1585b, and 1589b are respectively and fluidically connected to distal ends of elongated holes 1823, 1825, 1827, 1829, 1831, 1833, 1835, 1837, 1839, and 1841. Blind cavity 1545 is fluidically connected to distal ends of elongated holes 1843 and 1845, whereas blind cavity 1547 is fluidically connected to distal ends of elongated holes 1847 and 1849. Proximal ends of elongated holes 1803–1841 are fluidically connected to second inlet 1801, which may be configured to receive the one or more second gases into main body 701. Although illustrated as one inlet, second inlet 1801 may be formed as two or more inlets. As depicted, however, in FIG. 18, elongated holes 1803–1849 extend radially from second inlet 1801 in a second generally planar region of main body 701 at (or substantially at) distance H_{1407} from second surface 701b of main body 701. Distance H_{1405} may be, in some implementations, greater than distance H_{1407} . As such, elongated holes 1803–1849 may be closer to second surface 701b of main body 701 than elongated holes 1703–1747. It is also noted that distance H_{1401} may, in some embodiments, be greater than distance H_{1405} . As such, each of elongated holes 1703–1747 and 1803–1849 may be closer to second surface 701b of main body 701 than each of through-holes 1501–1543.

[0176] Based on the above-noted configuration, second inlet 1801 and elongated holes 1803–1811, 1823–1831, 1843, and 1845 may be fluidically connected to the second gas distribution ports of zone 711. Further, second inlet and elongated holes 1813–1821, 1833–1841, 1847, and 1849 may be fluidically connected to the fourth gas distribution ports of zone 715.

[0177] Accordingly, in various implementations, each of blind cavities 1549a–1589a and 1549b–1589b may interface with one elongated hole among elongated holes 1703–1747 and 1803–1841, and each of blind cavities 1545 and 1547 may interface with two elongated holes among elongated holes 1843–1849. As such, blind cavities 1545 and 1547 may receive more of the one or more second gases via elongated holes 1843–1849 than is received by blind cavities 1549a, 1549b, 1553a, 1553b, 1557a, 1557b, 1561a, 1561b, 1565a, 1565b, 1573a, 1573b, 1577a, 1577b, 1581a, 1581b, 1585a, 1585b, 1589a, and 1589b via elongated holes 1803–1841. In addition, blind cavities 1545 and 1547 may receive more of the one or more second gases via elongated holes 1843–1849 than the one or more first gases received by blind cavities 1551a, 1551b, 1555a, 1555b, 1559a, 1559b, 1563a, 1563b, 1567a, 1567b, 1569a, 1569b, 1571a, 1571b, 1575a, 1575b, 1579a, 1579b, 1583a, 1583b, 1587a, and 1587b via elongated holes 1703–1747. It is noted, however, that embodiments are not limited thereto. For instance, any given blind cavity may interface with any suitable number of elongated holes, such as one, two, three, four, five, or six or more elongated holes to enable, for instance, a uniform (or substantially uniform) amount of gas flow within zone 713 and an increasing amount of gas flow in zones 711 and 715 as a distance from central axis 717 increases.

[0178] According to some embodiments, respective cross-sectional areas of elongated holes 1703–1747 and 1803–1849 in planes perpendicular to their directions of longitudinal extension may be equivalent or substantially equivalent. However, in some implementations, at least one of elongated holes 1703–1747 and 1803–1849 may have a different cross-sectional area than at least another one of elongated holes 1703–1747 and 1803–1849. For instance, elongated holes 1711–1719 and 1733–1741 may have equivalent (or substantially equivalent) first cross-sectional areas, elongated holes 1705, 1709, 1721, 1723, 1729, 1731, 1743, and 1745 may have equivalent (or substantially equivalent) second cross-sectional areas, and elongated holes 1703, 1725, 1727, and 1747 may have equivalent (or substantially equivalent) third cross-sectional areas. Each of the first cross-sectional areas may be greater than each of the second cross-sectional areas, which may be greater than each of the third cross-sectional areas. In some

cases, the cross-sectional areas of elongated holes 1703–1747 may decrease in size with increasing angular offset of an associated elongated hole from transverse axis 721. As will become more apparent below, this may allow for less of the one or more first gases to flow from associated gas distribution ports among gas distribution ports 707 with increasing distance from transverse axis 721 in the third direction. It is also noted that the decrease in size of the cross-sectional areas of elongated holes 1703–1747 may exhibit a linear relationship, a step-wise relationship, a variable relationship, or any other suitable relationship.

[0179] As another example, elongated holes 1811, 1813, 1831, and 1833 may have equivalent (or substantially equivalent) fourth cross-sectional areas, elongated holes 1809, 1815, 1829, and 1835 may have equivalent (or substantially equivalent) fifth cross-sectional areas, elongated holes 1807, 1817, 1827, and 1837 may have equivalent (or substantially equivalent) sixth cross-sectional areas, elongated holes 1805, 1819, 1825, and 1839 may have equivalent (or substantially equivalent) seventh cross-sectional areas, elongated holes 1803, 1821, 1823, and 1841 may have equivalent (or substantially equivalent) eighth cross-sectional areas, and elongated holes 1843–1849 may have equivalent (or substantially equivalent) ninth cross-sectional areas. Each of the ninth cross-sectional areas may be greater than each of the eighth cross-sectional areas, which may be greater than each of the seventh cross-sectional areas. To this end, each of the seventh cross-sectional areas may be greater than each of the sixth cross-sectional areas, which may be greater than each of the fifth cross-sectional areas. Each of fifth cross-sectional areas may be greater than each of the fourth cross-sectional areas. In some cases, the cross-sectional areas of elongated holes 1803–1849 may increase in size with increasing angular offset of an associated elongated hole from transverse axis 721. As will become more apparent below, this may allow for more of the one or more second gases to flow from associated gas distribution ports among gas distribution ports 707 with increasing distance from transverse axis 721 in the third direction. It is also noted that the increase in size of the cross-sectional areas of elongated holes 1803–1849 may exhibit a linear relationship, a step-wise relationship, a variable relationship, or any other suitable relationship.

[0180] According to various embodiments, variance between the first to ninth cross-sectional areas may enable variable flow conductance within showerhead pedestal 700. For instance, decreasing the cross-sectional area of an elongated hole may decrease its flow conductance, and, thereby, increase the flow resistance experienced by gas(es) flowing therethrough. Increasing flow resistance, decreases throughput. The corollary is also true. In

other words, increasing the cross-sectional area of an elongated hole may increase its flow conductance, and, thereby, decrease the flow resistance experienced by gas(es) traversing the elongated hole. Decreasing flow resistance, increases throughput. Thus, variance between the first to ninth cross-sectional areas of corresponding elongated holes 1703–1747 and 1803–1849 may be utilized to vary the amount of gas(es) passed to blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b, and, to that end, output via the corresponding gas distribution ports fluidically connected thereto. Accordingly, the relative sizing of the first to ninth cross-sectional areas may be utilized to tailor a flow rate of gas supplied to different zones, sub-zones, and/or sub-portions of sub-zones of gas distribution ports. This, in turn, may be utilized to control precursor and dilution gas concentration proximate (or adjacent) to a substrate during one or more deposition operations utilizing showerhead pedestal 700.

[0181] According to various embodiments, the one or more first gases may be supplied to the first gas distribution ports of zone 711 via corresponding second gas distribution flow paths traversing at least one of first inlets 1701 and 1702, at least one of elongated holes 1703, 1705, 1709, 1711, 1713, 1727, 1729, 1731, 1733, and 1735, at least one of blind cavities 1551a, 1551b, 1555a, 1555b, 1559a, 1559b, 1563a, 1563b, 1567a, and 1567b, and at least one of through-holes 1503, 1509, 1513, 1517, and 1521. The one or more second gases may be supplied to the second gas distribution ports of zone 711 via corresponding third gas distribution flow paths traversing second inlet 1801, at least one of elongated holes 1803–1811, 1823–1831, 1843, and 1845, at least one of blind cavities 1545, 1549a, 1549b, 1553a, 1553b, 1557a, 1557b, 1561a, 1561b, 1565a, and 1565b, and at least one of through-holes 1501, 1505, 1511, 1515, and 1519. The one or more first gases may be supplied to the gas distribution ports of zone 713 via corresponding first gas distribution flow paths traversing at least one of first inlets 1701 and 1702, at least one of elongated holes 1713, 1715, 1717, 1735, 1737, and 1739, at least one of blind cavities 1567a, 1567b, 1569a, 1569b, 1571a, and 1571b, and at least one of through-holes 1521, 1523, and 1525. In addition, the one or more first gases may be supplied to the third gas distribution ports of zone 715 via corresponding fourth gas distribution flow paths traversing at least one of first inlets 1701 and 1702, at least one of elongated holes 1717, 1719, 1721, 1723, 1725, 1739, 1741, 1743, 1745, and 1747, at least one of blind cavities 1571a, 1571b, 1575a, 1575b, 1579a, 1579b, 1583a, 1583b, 1587a, and 1587b, and at least one of through-holes 1525, 1529, 1533, 1537, and 1541. Also, the one or more second gases may be supplied to the fourth gas distribution ports of zone 715 via corresponding fifth gas distribution

flow paths traversing second inlet 1801, at least one of elongated holes 1813, 1815, 1817, 1819, 1821, 1833, 1835, 1837, 1839, 1841, 1847, and 1849, at least one of blind cavities 1547, 1573a, 1573b, 1577a, 1577b, 1581a, 1581b, 1585a, 1585b, 1589a, and 1589b, and at least one of through-holes 1527, 1531, 1535, 1539, and 1543. Thus, at least some of the gas distribution flow paths formed between first inlets 1701 and 1702 and the gas distribution ports of zone 713, the first gas distribution ports of zone 711, and the third gas distribution ports of zone 715 may share a coincident portion, such as within a passageway of first inlet 1701 or second inlet 1702. Similarly, at least some of the gas distribution flow paths formed between second inlet 1801 and the second gas distribution ports of zone 711 and the fourth gas distribution ports of zone 715 may share a coincident portion, such as within a passageway of second inlet 1801. An illustrative gas distribution flow path will be described in more detail in association with FIG. 19.

[0182] Adverting to FIG. 19, gas distribution flow path 1901 may supply n^{th} gas distribution port 707n of, for instance, zone 715_2 with the one or more second gases received at second inlet 1801. In this manner, gas distribution flow path 1901 may flow from second inlet 1801 to elongated hole 1813, which allows the one or more second gases of gas distribution flow path 1901 to flow into blind cavity 1573a, which may function as an intake plenum and as a distribution plenum. As pressure builds in blind cavity 1573a, the one or more second gases of gas distribution flow path 1901 may be forced into through-hole 1527 and expelled via n^{th} gas distribution port 707n to an area proximate a substrate during a deposition operation. Each of the other gas distribution ports among gas distribution ports 707 may be similarly supplied with the one or more first gases or the one or more second gases via corresponding gas distribution flow paths routing between one of first inlets 1701 and 1703 or second inlet 1801 and a corresponding one of the other gas distribution ports among gas distribution ports 707.

[0183] In various implementations, the gas distribution flow paths extending from first inlets 1701 and 1703 may be fluidically separated or isolated from the gas distribution flow paths extending from second inlet 1801 in an interior of showerhead pedestal 700. However, as previously mentioned, given that at least one gap may exist between one or more of upper and inner surfaces 703a and 703b of outer wall 703 and fourth and third surfaces 701d and 701c of main body 701, some of blind cavities 1549a–1589a and 1549b–1589b may include a plug (e.g., plug 1903) filling respective portions of, for instance, their distal end portions interfacing with outer wall 703 to further discourage gas from leaking between adjacent blind cavities, which may be configured to flow different gases from one another. For instance, one or more of blind

cavities 1549a, 1549b, 1553a, 1553b, 1557a, 1557b, 1561a, 1561b, 1565a, 1565b, 1573a, 1573b, 1577a, 1577b, 1581a, 1581b, 1585a, 1585b, 1589a, and 1589b (which may be associated with the distribution of the one or more second gases within main body 701) may optionally include a plug (such as plug 1903) extending partially therein and arranged between inner surface 703b of outer wall 703 and a corresponding, remaining void space associated therewith, such as shown in FIG. 19 relative to blind cavity 1573a. In some cases, plugs may be additionally or alternatively arranged in distal end portions of one or more of blind cavities 1551a, 1551b, 1555a, 1555b, 1559a, 1559b, 1563a, 1563b, 1567a, 1567b, 1569a, 1569b, 1571a, 1571b, 1575a, 1575b, 1579a, 1579b, 1583a, 1583b, 1587a, and 1587b.

[0184] It is noted that a ratio of precursor gas flow rate to inert gas flow rate through one or more zones may be controlled by adjusting a concentration of precursor gas adjacent to a substrate. For instance, where the ratio is higher, more precursor gas is flowed along an axial length of showerhead pedestal 700, such as along an x-axis or y-axis direction of showerhead pedestal 700. As a result, a concentration of precursor gas will taper less (e.g., have a shallower slope) along the axial length. When the ratio is lower, less precursor gas is flowed along the axial length of showerhead pedestal 700. As a result, the concentration of precursor gas will taper more (e.g., have a steeper slope) along the axial length. The ratio of the precursor gas flow rate to the inert gas flow rate may be controlled by adjusting the relationships between and amongst gas distribution ports 707, through-holes 1501–1543, blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b, and elongated holes 1703–1747 and 1803–1849, as well as the relative sizing, amounts, arrangements, patterns, etc., of gas distribution ports 707, through-holes 1501–1543, blind cavities 1545, 1547, 1549a–1589a, and 1549b–1589b, and elongated holes 1703–1747 and 1803–1849. In one embodiment, the gas distribution ports of zone 713 may provide a uniform (or substantially uniform) output (or gas flow profile) of one or more first gases, and the gas distribution ports of zones 711 and 715 may provide a varying output (or gas flow profile) of the one or more first gases and the one or more second gases that increases in dilution of the one or more first gases with increasing distance from central axis 717. To this end, output of the one or more first gases and the one or more second gases within at least one of zones 711 and 715 may be interlaced, alternated, or otherwise integrated along one or more directions, such as at least one of the second and third directions. By additionally including the output of the one or more first gases within zones 711 and 715, more control of a combined gas distribution profile within and across zones 711, 713, and 715 may be

achieved. For instance, a slope of the combined gas distribution profile may be reduced and transitions between zones may be smoothed to better approximate an intended gas flow profile. As such, the various gas flow profiles mentioned herein may also serve as a stand-in for all of the various structural ways the internal volumes in showerhead pedestal 700 may be configured to arrive at an intended result. To the end, the various gas flow profiles mentioned herein may serve as a stand-in for all of the various structural ways the internal volumes in showerhead pedestal 700 may be configured and the various structural ways the gas distribution ports 707 may be configured to arrive at an intended result.

[0185] According to some embodiments, main body 701 is manufactured as a monolithic structure. For instance, one or more additive manufacturing techniques, such as direct laser metal sintering (or, if a ceramic showerhead is desired, a ceramic sintering process), may be utilized to form main body 701. It is also contemplated that main body 701 may be machined from solid stock, such as billet material. In other implementations, multiple plate structures may be stacked to form main body 701, and, to this end, one or more indexing pins or other similar features may be utilized to align the plate structures. In such instances, main body 701 may include one or more apertures extending through portions of the plate structures to allow the one or more indexing pins to align the plate structures with one another. Furthermore, in instances in which a multiple-plate structure is used, the various plates forming the overall structure of main body 701 may be brazed or diffusion bonded together along mating surfaces to prevent gas flow between contacting surfaces of the plates. It is also contemplated that, in some cases, main body 701 and outer wall 703 may be manufactured as a monolithic structure or formed as separate components that are coupled (or detachably coupled) together.

[0186] In some implementations, main body 701 may further include one or more apertures (such as apertures 725) in first surface 701a and extending through main body 701 in the first direction. In this manner, each aperture may interface with a corresponding blind bore (such as blind bore 727) in second surface 701b. The combination of the blind bores and apertures may be configured to interface with respective lift pins of a substrate processing system, e.g., substrate processing system 2300 of FIG. 23. For instance, the lift pins may be movably disposed through apertures 725 to enable a substrate supported over showerhead pedestal 700 to be raised or lowered relative to first surface 701a of main body 701.

[0187] It is also recognized that, in many semiconductor wafer processing applications, such as plasma-enhanced chemical vapor deposition (PECVD) processes, a deposition (or etching)

process may be negatively affected by variations in process parameters, such as temperatures of a target wafer and/or a gas distributor, such as a showerhead pedestal. These variations may appear during process initiation (e.g., before reaching steady state), cleaning cycles, idling, etc. For example, when a reactor is initially turned on, it may take a relatively long time before the temperature of the gas distributor is stabilized. For instance, a gas distributor may be heated by radiation from the wafer (or another gas distributor) and/or by plasma, which may be introduced at some point during processing and can cause other temperature fluctuation. In addition, a gas distributor may lose heat to the process and dilution gases flowed through the gas distributor and due to radiation from its external surfaces. It is also noted that temperature variation may be caused by other more permanent changes in a system, such as drifts in surface emissivity of the gas distributor. Variable temperature may cause, at least in part, substantial deviation of a profile of a deposited film or etched feature from a target profile. Moreover, operating a gas distributor at relatively high temperature can not only shorten the operational life of the gas distributor, but may also cause, at least in part, particle contamination on a gas distribution surface of the gas distributor. Such build up may flake off and contaminate a structure being formed on (or in) a substrate via the gas distributor. As such, embodiments of showerhead pedestal 700 may incorporate heating and/or cooling channels (or loops) to enable control (e.g., active control) of the temperature of showerhead pedestal 700. Some example structures and thermal management systems are described in association with FIGS. 7B, 19, 20, and 22.

[0188] FIG. 20 schematically illustrates an exploded perspective view of various components of the gas distributor of FIG. 7B according to some embodiments.

[0189] Referring to FIGS. 7B, 19, and 20, showerhead pedestal 700 may include one or more electrodes and/or heating elements (hereinafter, individually or collectively referred to as a heating loop) 2001, first cap (or cover) structure 2003, one or more cooling conduits and/or cooling elements (hereinafter, individually or collectively referred to as a cooling loop) 2005, and second cap (or cover) structure 2007. In various embodiments, main body 701 is formed of at least one conductive material, such as one or more metals and/or metal alloys. For example, main body 701 may be formed of an aluminum alloy, such as a precipitation-hardened aluminum alloy, e.g., AL6061. It is contemplated, however, that any other suitable material may be utilized. In this manner, main body 701 can be thermally conductive.

[0190] According to some embodiments, main body 701 includes heating loop 2001 coupled

to a power source (e.g., power supply 2237 of FIG. 22) to controllably heat showerhead pedestal 700 and a substrate (such as wafer 2301 of FIG. 23) supported thereon. Heating loop 2001 may be resistively heated and thermally coupled to (e.g., in thermal contact with) main body 701. Further, heating loop 2001 may be disposed on and/or at least partially embedded within main body 701. For example, main body 701 may include at least one slot (or groove) 2009 in second surface 701b that is configured to receive a lower section of heating loop 2001.

[0191] As depicted in FIGS. 7B, 19, and 20, first portion 2001a of heating loop 2001 may enter main body 701 through hollow 733 in stem 705, bend to form second portion 2001b in a first outer peripheral region of main body 701, bend to form third portion 2001c in a first inner peripheral region of main body 701, bend to form fourth portion 2001d in an inner central region of main body 701, bend to form fifth portion 2001e in a second inner peripheral region of main body 701, bend to form a sixth portion 2001f in a second outer peripheral region of main body 701, and bend to form seventh portion 2001g exiting main body 701 through hollow 733 in stem 705. It is noted that first distal end 2001h of heating loop 2001 may be coupled to a power source and second distal end 2001i of heating loop 2001 may be coupled to a reference level, such as ground, floating ground, or another relatively low potential.

[0192] In some implementations, second and sixth portions 2001b and 2001f of heating loop 2001 may follow generally “C” shaped paths in corresponding outer peripheral regions of main body 701 that face one another. Third and fifth portions 2001c and 2001e of heating loop 2001 may also follow generally “C” shaped paths, but in corresponding inner peripheral regions of main body 701 that face one another. The corresponding outer peripheral regions of main body 701 may at least partially surround the corresponding inner peripheral regions of main body 701. Fourth portion 2001d of heating loop 2001 may follow a generally “Ω” shaped path in the inner central region of main body 701 adjacent to distal end 801 of stem body 731, e.g., adjacent to first and second inlets 1701, 1703, and 1801. In addition, the inner central region of main body 701 may be at least partially surrounded by the corresponding inner peripheral regions of main body 701. It is also noted that first and seventh portions 2001a and 2001g of heating loop 2001 may generally extend in an axial direction along central axis 717 of showerhead pedestal 700, whereas second to sixth portions 2001b to 2001f of heating loop 2001 may generally meander in a transverse plane at (or substantially at) a first distance H_{1905} (see FIG. 19) from second surface 701b of main body 701. It is contemplated, however, that any other suitable path through and/or about main body 701 may be utilized.

[0193] The lower section of heating loop 2001 may be encased in main body 701 between a bottom surface of slot 2009 and first cap structure 2003, which may be formed of at least one thermally conductive material, such as one or more metals and/or metal alloys. For instance, first cap structure 2003 may be made of the same material as main body 701, such as an aluminum alloy, e.g., a precipitation-hardened aluminum alloy, for example, AL6061. It is contemplated, however, that any other suitable material may be utilized. In this manner, first cap structure 2003 may be pressed into slot 2009 and welded (e.g., friction stir welded) to main body 701. Pressure applied to first cap structure 2003 during welding may, in some instances, partially deform heating loop 2001. The applied pressure and/or partial deformation of heating loop 2001 may, in some cases, ensure contact between one or more inner surfaces of slot 2009 and one or more outer surfaces of heating loop 2001. This may improve conductive heat transfer between heating loop 2001 and main body 701.

[0194] Showerhead pedestal 700 may also include cooling loop 2005 configured to maintain temperature control and compensate for temperature variations, which may occur before, during, and/or after substrate processing. For instance, cooling loop 2005 may be utilized to compensate for temperature increases or spikes when reactant gases are excited to generate plasma inside a process chamber (such as chamber 2303 of FIG. 23) and/or when the plasma is struck. To this end, cooling loop 2005 may form a conduit (or tube) through which a conductive cooling fluid, such as gas, may flow. In some embodiments, cooling loop 2005 may be formed of a thermally conductive material, such as one or more metals and/or metal alloys. For example, cooling loop 2005 may be formed of stainless steel, but embodiments are not limited thereto. It is noted, however, that the material selection for cooling loop 2005 should be considered in the context of the process/process recipe utilizing showerhead pedestal 700. In some cases, a wall temperature of cooling loop 2005 may reach about 350°C to about 450°C, e.g., about 375°C to about 425°C, e.g., about 400°C, and, as such, a material of cooling loop 2005 should be selected that can withstand anticipated/potential wall temperatures.

[0195] Cooling loop 2005 may have an outer diameter ranging from about 0.125" to about 0.375", e.g., from about 0.1875" to about 0.3125." An inner diameter of cooling loop 2005 may range from about 0.069" to about 0.319", e.g., from about 0.132" to about 0.215." In some embodiments, cooling loop 2005 may have an outer diameter of about 0.25" and an inner diameter of about 0.18." Also, a length of cooling loop 2005 within main body 701 may be from about 10" to about 26", e.g., from about 13" to about 23", such as about 16" to about 20." In

some cases, the length of cooling loop 2005 within main body 701 may be about 18." Such a configuration may enable up to about 140 standard liters per minute (SLM) of clean dry air (CDA) with a relatively turbulent flow to pass through cooling loop 2005. For instance, the flow of CDA through cooling loop 2005 may exhibit a Reynolds number (Re) greater than 2000, such as about 2500 to about 35000. It is noted, however, that the sizes of the inner diameter, outer diameter, and length of cooling loop 2005 are not limited to these examples. For instance, the sizes the inner diameter, outer diameter, and the length of cooling loop 2005 may be dimensioned according to desired cooling metrics associated with one or more processes and/or process recipes to be performed in association with showerhead pedestal 700. The same is also true with respect to the flow rate of conductive cooling fluid through cooling loop 2005. To this end, the sizing of the inner diameter, outer diameter, and length of cooling loop 2005 may be chosen in consideration of material choice for cooling loop 2005 and main body 701, a length of cooling loop 2005 within main body 701, a path shape of cooling loop 2005 through main body 701, a type of conductive cooling fluid being utilized, a flow rate of the conductive cooling fluid, any imposed flow rate modulation techniques, etc.

[0196] According to various embodiments, cooling loop 2005 may be disposed on and/or at least partially embedded in main body 701. For example, main body 701 may include at least one slot (or groove) 2011 in second surface 701b that is configured to receive a lower section of cooling loop 2005. As depicted in FIGS. 7B, 19, and 20, first portion 2005a of cooling loop 2005 may enter main body 701 through hollow 733 in stem 705, bend to form second portion 2005b in an outer central region of main body 701, and bend to form third portion 2005c exiting main body 701 through hollow 733 in stem 705. In some implementations, second portion 2005b of cooling loop 2005 may follow a generally circular-shaped path in the outer central region of main body 701 adjacent to the inner central region of main body 701 through which heating loop 2001 extends. To this end, the inner central region of main body 701 may, in a plan view, be disposed between the outer central region of main body 701 and a portion of main body 701 coupled to distal end 801 of stem body 731. It is also noted that first and third portions 2005a and 2005c of cooling loop 2005 may generally extend in an axial direction along central axis 717 of showerhead pedestal 700, whereas second portion 2005b of cooling loop 2005 may generally meander in a transverse plane at (or substantially at) a second distance H_{1907} (see FIG. 19) from second surface 701b of main body 701. In some embodiments, first distance H_{1905} may be greater than second distance H_{1907} such that cooling loop 2005 is disposed closer to

second surface 701b of main body 701 than heating loop 2001. It is contemplated, however, that any other suitable path through and/or about main body 701 may be utilized.

[0197] The lower section of cooling loop 2005 may be encased in main body 701 between a bottom surface of slot 2011 and second cap structure 2007, which may be formed of at least one thermally conductive material, such as one or more metals and/or metal alloys. For instance, second cap structure 2007 may be made of the same material as main body 701, such as an aluminum alloy, e.g., a precipitation-hardened aluminum alloy, for example, AL6061. It is contemplated, however, that any other suitable material may be utilized. In this manner, second cap structure 2007 may be pressed into slot 2011 and welded (e.g., friction stir welded) to main body 701. Pressure applied to second cap structure 2007 during welding may, in some instances, partially deform cooling loop 2005. The applied pressure and/or partial deformation of cooling loop 2005 may, in some instances, ensure contact between one or more inner surfaces of slot 2011 and one or more outer surfaces of cooling loop 2005. This may improve conductive heat transfer between cooling loop 2005 and main body 701.

[0198] Although heating loop 2001 and cooling loop 2005 may generally meander in transverse planes at different distances from second surface 701b of main body 701, first and second cap structures 2003 and 2007 may cross paths. As such, at least one of first and second cap structures 2003 and 2007 may include one or more notched portions to allow passage of the other of the first and second cap structures 2003 and 2007. For instance, first cap structure 2003 may include notched portions 2003a to 2003d to allow passage of second cap structure 2007 therethrough.

[0199] In some embodiments, one of first and second distal ends 2005d and 2005e of cooling loop 2005 provides an inlet for conductive cooling fluid at a first temperature (e.g., a low temperature) and the other of first and second distal ends 2005d and 2005e serves as an outlet for the conductive cooling fluid at a second temperature (e.g., a high temperature). For instance, assuming CDA is utilized as the conductive cooling fluid with a flow rate of about 100 SLM to about 140 SLM, the CDA may enter inlet 2005d at about 20°C and exit outlet 2005e at about 275°C. Such metrics may enable about 620 watts (W) to about 775 W, such as 675 W to about 725 W, of thermal energy to be removed from showerhead pedestal 700 in association with a backside deposition process. This, in turn, can enable adequate temperature control over the setpoint temperature of showerhead pedestal 700 as demonstrated in FIG. 21.

[0200] FIG. 21 is a graph demonstrating simulated temperature control of a gas distributor at various setpoint temperatures and duty cycles according to some embodiments.

[0201] To determine an efficacy of cooling loop 2005, an implementation of showerhead pedestal 700 was simulated as part of a PECVD backside deposition process, but without the presence of a substrate. Main body 701, outer wall 703, stem 705, first and second cap structures 2003 and 2007, a processing chamber (e.g., chamber 2303 of FIG. 23), and a top plate of the processing chamber were each assumed as being formed of AL6061. An emissivity of main body 701, outer wall 703, stem 705, and first and second cap structures 2003 and 2007 was assumed to be 0.3, and an emissivity of the processing chamber and top plate was assumed to be 0.2. Cooling loop 2005 was assumed as being formed of stainless steel and CDA was utilized as the conductive cooling fluid. A showerhead opposing showerhead pedestal 700 in the processing chamber was assumed as being formed of an HA-12 variant of aluminum nitride provided by NGK Insulators, Ltd. As such, an emissivity of the showerhead was assumed to be 0.7. In addition, a top plate of the processing chamber was set at 75°C, the showerhead was set at 550°C, the processing chamber was set at 75°C, and an ambient environment of the processing chamber was set at 25°C. With these conditions, the efficacy of cooling loop 2005 flowing 140 SLM of CDA was determined in conjunction with various set point temperatures for showerhead pedestal 700, such as the setpoint temperatures shown in FIG. 21, e.g., 550°C, 600°C, 650°C, and 600°C with a higher RF power being applied to generate plasma, and assuming various RF duty cycles, e.g., 0%, 5%, 7%, 10%, 20%, and 25%. For each of cases 2101 to 2105, power utilized to generate plasma was 530 W. For case 2107, the power utilized to generate plasma was 2750 W. As seen in FIG. 21, dashed line 2111 demonstrates that, under most of the assumed processing conditions and despite heat transfer to showerhead pedestal 700, simulated temperatures for showerhead pedestal 700 were capable of being maintained at approximately 400°C. In other words, cooling loop 2005 may, in some embodiments, enable adequate temperature control over the setpoint temperature of showerhead pedestal 700.

[0202] According to various embodiments, operation of heating loop 2001 and cooling loop 2005 may be controlled via a thermal management system. FIG. 22 schematically illustrates a thermal management system configured to control the temperature of a gas distributor according to some embodiments.

[0203] Referring to FIG. 22, cooling may be provided during operation of a substrate processing system (e.g., substrate processing system 2300 of FIG. 23) by thermal management

system (or system) 2200 via introduction of a convective cooling fluid (e.g., atmospheric air, argon, helium, nitrogen, hydrogen, CDA, and/or the like) via inlet 2201 having valve 2203. In some embodiments, one or more additives may be introduced to the flow before and/or after valve 2203. The additive(s) may be utilized to increase the cooling efficiency and/or service life of cooling loop 2205, and, thereby, of gas distributor 2207. According to one or more implementations, the convective cooling fluid received at inlet 2201 is facilities-provided CDA at conventional facilities pressure. It will, therefore, be appreciated that different flow rates may be imposed based on different facilities pressures. For example, at a facilities pressure of about 80 psi, about 100 standard liters per minute (SLM) of CDA may be used. It is noted, however, that typical facilities pressure may range between about 80 psi to about 100 psi, and, therefore, flow rates through cooling loop 2205 may reach about 140 SLM. Hereinafter, it will be assumed that the convective cooling fluid is CDA.

[0204] Valve 2203 may be an electrically actuated valve capable of modulating the CDA flow through cooling loop 2205 to not only cool gas distributor 2207, but also to facilitate turbulent flow through cooling loop 2205. Such turbulent flow may increase thermal transfer from gas distributor 2207, and, thereby, the cooling efficiency of cooling loop 2205. For instance, modulation of the CDA flow may not only help impart a Reynolds number greater than or equal to about 2500, but it may compensate for some energy dissipation of the CDA flow along cooling loop 2205. It is also contemplated that the modulation of the CDA flow may be utilized to decrease a cooling effect of cooling loop 2205. In some implementations, valve 2203 may include one or more gas amplification features (e.g., constricting structures, such as Coanda profiles) that, in conjunction with a fluidic connection to a compressed gas source, can increase/decrease a flow rate (and, thereby, turbulence) of the CDA flow through cooling loop 2205. Additionally (or alternatively), one or more throttling valves, pendulum valves, and/or other flow modulators may be disposed upstream or downstream from cooling loop 2205 to increase/decrease turbulent flow through cooling loop 2205. Although valve 2203 has been described as an electrically actuated valve, it is contemplated that any other suitably controllable valve may be utilized as (or in addition to) valve 2203. An outlet of valve 2203 is fluidically connected to an inlet portion 2209 of cooling loop 2205.

[0205] System 2200 also includes outlet 2211 having heat exchanger 2213 and exhaust system 2215. A first inlet to heat exchanger 2213 is fluidically connected to an outlet portion 2217 of cooling loop 2205, and a first outlet of heat exchanger 2213 is fluidically connected to

an input conduit 2219 of exhaust system 2215. Coolant, e.g., liquid coolant, for heat exchanger 2213 may enter heat exchanger 2213 at second inlet 2221, follow coolant path 2223, and exit heat exchanger 2213 via second outlet 2225. The coolant may be water or any other suitable coolant, e.g., Freon. In one embodiment, the coolant may be facilities provided water. After exiting heat exchanger 2213 via second outlet 2225, the coolant may be compressed and recirculated back into heat exchanger 2213 in a closed-loop coolant system, but embodiments are not limited thereto. In this manner, the CDA flow from outlet portion 2217 of cooling loop 2205 may be cooled via heat exchanger 2213 and expelled via exhaust system 2215.

[0206] Although heat exchanger 2213 has been described as a gas-to-liquid heat exchanger, embodiments are not limited thereto. For instance, heat exchanger 2213 may be configured as a gas-to-gas heat exchanger, and, in such cases, aspects of second inlet 2221 and second outlet 2225 of heat exchanger 2213 reconfigured to correspondingly interface with a suitable cooling source and a suitable effluent waste, recycling, and/or feedback system. When configured as a gas-to-gas heat exchanger, the cooling fluid may be, for instance, a source of atmospheric air, argon, helium, nitrogen, hydrogen, CDA, and/or the like.

[0207] According to some embodiments, the CDA output from heat exchanger 2213 may be about or slightly above ambient temperature and pressure. In some implementations, the temperature of the CDA output from heat exchanger 2213 may be greater than or equal to about 20°C and less than or equal to about 65°C. It is noted, however, that heat exchanger 2213 may be configured to ensure that any residual heat in the effluent from cooling loop 2205 can be held within output-based environmental regulatory limits.

[0208] Conduit 2219 may be coupled to conduit 2227, which may be part of (or fluidically connected to) exhaust system 2215. In some implementations, exhaust system 2215 may be a scrubbed exhaust system. As such, any environmentally controlled components, constituents, by-products, etc., of the effluent from the first outlet of heat exchanger 2213 may be scrubbed via scrubber 2229 along with other effluents 2229 of the substrate processing system and/or ambient environment.

[0209] According to some embodiments, heating of gas distributor 2207 may be provided by thermal management system (or system) 2200 via heating loop 2233, such as heating loop 2001 described in association with FIG. 20. In this manner, input portion 2235 of heating loop 2233 may receive power from power supply 2237, and output portion 2239 of heating loop 2233

may be, for instance, coupled to reference level 2241, such as ground, floating ground, or another relatively low potential. In some instances, radio frequency (RF) power applied to gas distributor 2207 or at least one other component in a chamber (e.g., chamber 2303 of FIG. 23) of a semiconductor processing system may be above 100 W, sometimes above 1000 W. As such, an amplitude of RF voltages can exceed a kilovolt. Such RF power can affect operation of control and power circuits of heating loop 2233 without filtration or isolation. In some embodiments, an RF filter may be used to shunt the RF power away from control and power circuits. An RF filter may be a simple broad-band filter or a tuned-filter for predetermined RF frequencies used in a semiconductor processing system. An RF isolator, in contrast, eliminates direct electrical connection between any RF-coupled components and control and power circuits via, for example, an optical coupler or transformer. Thus, at least one RF component (e.g., filter, isolator, and/or the like) 2243 may be electrically connected between power supply 2237 and input portion 2235, and at least one RF component 2245 may be electrically connected between output portion 2239 and reference level 2241.

[0210] According to some embodiments, control module (or controller) 2247 is configured to operate various components of system 2200, such as valve 2203, power supply 2237, etc., to actively control the temperature of gas distributor 2207. In some embodiments, feedback information may be provided to controller 2247 from, for example, one or more sensors 2249, such as one or more thermocouples. Sensors 2249 may be configured to monitor temperature of at least one of cooling loop 2205, gas distributor 2207, and heating loop 2233. In some instances, at least one sensor 2249 may be configured to monitor temperature of conductive cooling fluid upstream, downstream, or within at least one portion of cooling loop 2205, such as inlet portion 2209, outlet portion 2217, etc. It is also contemplated that one or more of sensors 2249 may be thermally coupled to (or embedded within) various portions of gas distributor 2207, such as first surface 2207a, second surface 2207b, and body portion 2207c. As with power supply 2237 and reference level 2241, one or more RF components 2251 may be electrically connected between sensors 2249 and controller 2247 to mitigate or eliminate interference in signals from sensors 2249.

[0211] Controller 2247 may, in some implementations, receive feed forward information 2253 from at least one other controller (e.g., control module 2313 of FIG. 23, system controller 2423 of FIG. 24, etc.) of another system or tool and/or sensor associated with at least one other gas distributor of a multi-station processing tool (e.g., multi-station processing tool 2400). In

this manner, controller 2247 may utilize feed forward information 2253 to control the temperature of gas distributor 2207 in anticipation of a processing event. For example, controller 2247 may increase power input to heating loop 2233 in anticipation of a cooling event, e.g., chamber purge event, or decrease power input to heating loop 2233 in anticipation of a heating event, such as before or during process gas activation. Similarly, controller 2247 may increase cooling input to cooling loop 2205 by increasing conductive fluid flow in anticipation of a heating event or decrease the cooling input by decreasing conductive fluid flow in anticipation of a cooling event. As such, different combinations of various heating and/or cooling inputs may be used to accurately control the temperature of gas distributor 2207, whether proactively or reactively. Furthermore, one or more features or functions of controller 2247 may be shared with, assumed by, or negotiated amongst at least one other controller (e.g., control module 2313 of FIG. 23, system controller 2423 of FIG. 24, etc.).

[0212] FIG. 23 schematically illustrates substrate processing system (or system) 2300, which may be used to process wafer 2301 according to some embodiments.

[0213] System 2300 includes chamber 2303. A center column is configured to support a pedestal when a surface of wafer 2301 is being processed, e.g., a film is being formed on the surface of wafer 2301. The pedestal, in accordance with some embodiments, may be referred to as showerhead pedestal 2305. Showerhead 2307 is disposed over showerhead pedestal 2305. In an embodiment, showerhead 2307 is electrically coupled to power supply 2309 via match network 2311. As such, power supply 2309 may be controlled by control module 2313, e.g., a controller. In some embodiments, power may be provided to showerhead pedestal 2305 instead of (or in addition to) showerhead 2307. Control module 2313 is configured to operate system 2300 by executing one or more sequences of one or more instructions defining at least one process recipe. Depending on whether a frontside or backside of wafer 2301 is to receive a deposited film, control module 2313 may set various operational inputs for defining a process recipe, such as power levels, timing parameters, process gases, mechanical movement of wafer 2301, height of wafer 2301 from showerhead pedestal 2305, etc.

[0214] The center column may also include lift pins, which may be controlled by a lift pin control signal from, for instance, control module 2313. The lift pins may be used to raise wafer 2301 from showerhead pedestal 2305 to allow an end-effector to pick wafer 2301 and to lower wafer 2301 after being placed by the end end-effector. The end effector may also place wafer 2301 over spacers 2315. As will be described below, spacers 2315 are sized to provide a

controlled separation of wafer 2301 between a surface of showerhead 2307 facing wafer 2301 and a surface of showerhead pedestal 2305 facing wafer 2301.

[0215] System 2300 further includes gas sources 2317 and 2319, e.g., gas chemistry supplies from a facility and/or dilution (e.g., inert) gases. Depending on the processing being performed relative to a surface of wafer 2301, control module 2313 may control the delivery of gas sources 2317 to showerhead 2307 and/or showerhead pedestal 2305. In some embodiments, gas manifold 2321 may be fluidically interposed between gas sources 2317 and showerhead 2307 and gas manifold 2323 may be fluidically interposed between gas sources 2319 and showerhead pedestal 2305. Appropriate valving and mass flow control mechanisms may be employed and controlled via control module 2313 to ensure suitable gases are delivered during deposition and plasma treatment phases of a process. In some embodiments, chamber 2303 may include openings 2303a and 2303b through which portions of stems 2325 and 2327 respectively extend. Gas flow into showerhead 2307 and showerhead pedestal 2305 may be output, and, thereby, distributed in a space volume between wafer 2301 and a corresponding surface of showerhead 2307 and showerhead pedestal 2305 facing wafer 2301 via one or more gas distribution structures of showerhead 2307 and showerhead pedestal 2305. Example gas distribution structures were at least described in association with FIGS. 7A–20.

[0216] During substrate processing, spacers 2315 are configured to maintain a predetermined separation of wafer 2301 from a gas distribution surface of showerhead pedestal 2305 to facilitate (e.g., optimize) deposition to the backside of wafer 2301, while reducing (or even preventing) deposition on the frontside of wafer 2301. In some embodiments, while deposition is targeted for the backside of wafer 2301, one or more inert gases may be flowed over the frontside of wafer 2301 via showerhead 2307 to push reactant gas away from the frontside of wafer 2301 and enable reactant gas(es) output from showerhead pedestal 2305 to be directed to the backside of wafer 2301.

[0217] In various embodiments, process and/or dilution gases exit chamber 2303 via an outlet fluidically coupled to, for instance, vacuum pump 2329, which may be a one or two stage mechanical dry pump and/or a turbomolecular pump. In this manner, process and/or dilution gases may be drawn out of chamber 2303 to maintain a suitably low pressure therein. To this end, a closed-loop flow restriction device, such as a throttle valve or a pendulum valve, may be controlled via control module 2313 to further ensure a suitably low pressure in chamber 2303.

[0218] System 2300 may further include carrier ring 2331 encircling an outer region of showerhead pedestal 2305. When the frontside of wafer 2301 is being processed, e.g., a material is being deposited thereon, carrier ring 2331 is configured to sit over a carrier ring support region stepped down from a wafer support region in a center (or central portion) of showerhead pedestal 2305. Carrier ring 2331 includes an outer edge side of its disk structure, e.g., outer radius, and a wafer edge side of its disk structure, e.g., inner radius, that is closest to where wafer 2301 is supported. The wafer edge side of carrier ring 2331 may include a plurality of contact support structures configured to lift wafer 2301 when carrier ring 2331 is held by spacers 2315. In this manner, spider forks 2401 (see FIG. 24) may be used to lift and maintain carrier ring 2331 at a predetermined height during, for example, backside deposition processing, as well as utilized to rotate wafer 2301 about an axis perpendicular to a surface of, for instance, showerhead 2307 or showerhead pedestal 2305. Thus, carrier ring 2331 may also be lifted (or otherwise manipulated) along with wafer 2301 to be, for example, rotated to another station, e.g., in a multi-station system, such as multi-station processing tool 2400.

[0219] According to various embodiments, system 2300 may include or communicate with thermal management system 2333, such as thermal management system 2200 of FIG. 22, to actively control the temperature of showerhead 2307 and/or showerhead pedestal 2305.

[0220] FIG. 24 schematically illustrates a multi-station processing tool configured for backside wafer deposition according to some embodiments.

[0221] In some implementations, multi-station processing tool 2400 can include an inbound load lock 2403 and an outbound load lock 2405, either or both of which may include a plasma source and/or an ultraviolet (UV) source. Robot 2407, at atmospheric pressure, is configured to move wafers from a cassette loaded through pod 2409 into inbound load lock 2403 via an atmospheric port 2411. Wafer 2301 is placed by robot 2407 on pedestal 2413 in inbound load lock 2403, atmospheric port 2411 is closed, and inbound load lock 2403 is pumped down. In instances in which inbound load lock 2403 includes a remote plasma source, wafer 2301 may be exposed to a remote plasma treatment in inbound load lock 2403 prior to being introduced into processing chamber 2415. Further, wafer 2301 may be heated in inbound load lock 2403 to, for example, remove moisture and/or adsorbed gases. Next, chamber transport port 2417 to processing chamber 2415 is opened, and another robot 2419 places wafer 2301 into the reactor on a pedestal of a first station shown in the reactor for processing. While the implementation depicted in FIG. 24 includes load locks, it will be appreciated that, in some implementations,

direct entry of wafer 2301 into a processing station may be provided.

[0222] As seen in FIG. 24, processing chamber 2415 includes four process stations, numbered 1 to 4. Each station has a temperature-controlled pedestal (such as temperature-controlled pedestal 2421 of station 1), and gas line inlets. It will be appreciated that, in some cases, each process station may have different or multiple purposes. For example, in some embodiments, a process station may be switchable between a CVD and PECVD process mode. In another example, deposition operations, such as PECVD operations, may be performed in one station, while exposure to UV radiation for UV curing may be performed in another station. In some embodiments, deposition and UV curing may be performed in the same station. Further, although processing chamber 2415 shown as including four stations, embodiments are not limited thereto. For example, processing chamber 2415 may have any suitable number of stations, such as five or more stations, or three or less stations.

[0223] As previously mentioned, multi-station processing tool 2400 may include a wafer handling system (e.g., robot 2419 including spider forks 2401) for transferring and/or positioning wafers within processing chamber 2415. In some embodiments, the wafer handling system may transfer wafers between various process stations and/or between a process station and a load lock. It is contemplated, however, that any suitable wafer handling system may be employed, such as, for example, wafer carousels, other wafer handling robots, etc. Further, multi-station processing tool 2400 may include (or otherwise be coupled to) a system controller 2423 employed to control process conditions and hardware states of multi-station processing tool 2400. System controller 2423 may include one or more memory devices 2425, one or more mass storage devices 2427, and one or more processors 2429. Each processor 2429 may include a central processing unit (CPU) or computer, analog, and/or digital input/output connections, stepper motor controller boards, etc.

[0224] In some embodiments, system controller 2423 controls each of the activities of multi-station processing tool 2400. For instance, system controller 2423 may execute system control software 2431 stored in mass storage device 2427, loaded into memory device 2425, and executed by processor 2429. Alternatively, control logic may be hard coded in system controller 2423. Application specific integrated circuits (ASIC), programmable logic devices (e.g., field-programmable gate arrays (FPGAs)) and/or the like may be used for these purposes. In the following discussion, wherever “software” or “code” is used, functionally comparable hard coded logic may be used in its place. System control software 2431 may

include instructions for controlling the timing, mixture of gases, gas flow rates, chamber and/or station pressure, chamber and/or station temperature, wafer temperature, target power levels, RF power levels, substrate pedestal, chuck and/or susceptor position, and other parameters of a particular process performed by multi-station processing tool 2400. System control software 2431 may be configured in any suitable way. For example, various process tool component subroutines or control objects may be written to control operation of the process tool components used to carry out various process tool processes. System control software 2431 may be coded in any suitable computer readable programming language.

[0225] In some embodiments, system control software 2431 may include input/output control (IOC) sequencing instructions for controlling the various parameters described above. Other computer software and/or programs stored on mass storage device 2427 and/or memory device 2425 associated with system controller 2423 may be employed in some embodiments. Examples of programs or sections of programs for this purpose include a substrate positioning program, a process gas control program, a pressure control program, a heater control program, a cooler control program, and a plasma control program.

[0226] A substrate positioning program may include program code for process tool components that are used to load and orientate wafer 2301 on pedestal 2421 and to control the spacing between wafer 2301 and other parts of multi-station processing tool 2400.

[0227] A process gas control program may include code for controlling gas composition (e.g., silicon-containing gases, oxygen-containing gases, nitrogen-containing gases, dilution (or inert) gases, etc., as described herein) and flow rates and optionally for flowing gas into one or more process stations prior to deposition to stabilize the pressure in the process station. A pressure control program may include code for controlling the pressure in the process station by regulating, for example, a throttle valve in an exhaust system of the process station, a gas flow into the process station, etc.

[0228] A heater control program may include code for controlling current to a heating unit (e.g., heating loop 2001 of FIG. 20) used to heat a gas distributor (e.g., showerhead 2307, showerhead pedestal 2305, etc.), and, thereby, heat wafer 2301. Alternatively, the heater control program may control delivery of a heat transfer gas (such as helium) to a gas distributor, and, thereby, wafer 2301.

[0229] A cooler control program may include code for controlling a flow rate of fluid (e.g.,

CDA) through a cooling unit (e.g., cooling loop 2005 of FIG. 20) used to extract heat from a gas distributor, such as showerhead 2307, showerhead pedestal 2305, etc., and transfer such thermal energy to, for instance, a waste heat capturing, storage, recycling, and/or disposing system.

[0230] A plasma control program may include code for setting RF power levels applied to the process electrodes in one or more process stations in accordance with various embodiments.

[0231] A pressure control program may include code for maintaining pressure in a reaction chamber in accordance with various embodiments.

[0232] In some embodiments, a user interface may be provided in association with system controller 2423. The user interface may include a display screen, graphical software displays of the apparatus and/or process conditions, and user input devices, such as pointing devices, keyboards, touch screens, microphones, etc.

[0233] In some embodiments, parameters adjusted by system controller 2423 may relate to process conditions. Non-limiting examples include process gas composition and flow rates, temperature, pressure, plasma conditions (such as RF bias power levels), pressure, temperature, etc. These parameters may be provided to the user in the form of a recipe, which may be entered utilizing the user interface.

[0234] Signals for monitoring the process may be provided by analog and/or digital input connections of system controller 2423 from various process tool sensors. The signals for controlling the process may be output on analog and/or digital output connections of multi-station process tool 2400. Non-limiting examples of process tool sensors that may be monitored include mass flow controllers, pressure sensors (such as manometers), thermocouples, etc. Appropriately programmed feedback and control algorithms may be used with data from the sensors to maintain process conditions.

[0235] System controller 2423 may provide program instructions for implementing one or more of the above-described processes. The program instructions may control a variety of process parameters, such as DC power level, RF bias power level, pressure, temperature, etc. The instructions may control the parameters to operate deposition of film stacks of a stress compensation layer according to various embodiments.

[0236] The system controller 2423 will typically include one or more memory devices and one or more processors configured to execute the instructions so that the apparatus will perform a

method in accordance with some embodiments. In some instances, machine-readable media containing instructions for controlling process operations in accordance with various embodiments may be coupled to system controller 2423.

[0237] In some embodiments, system controller 2423 may be part of a system, which may be part of at least one of the above-described examples. Such systems may include semiconductor processing equipment, including a processing tool or tools, a chamber or chambers, a platform or platforms for processing, and/or specific processing components (e.g., a wafer pedestal, a gas flow system, a thermal management system, etc.). The systems discussed above may be integrated with electronics for controlling their operation before, during, and/or after processing of a semiconductor wafer or substrate. The electronics may be referred to as the “controller,” which may control various components or subparts of the system or systems. For instance, system controller 2423, depending on the processing requirements and/or the type of system, may be programmed to control any of the processes disclosed herein, including the delivery of processing gases, temperature settings (e.g., heating and/or cooling), valve operation, light source control for radiative heating, pressure settings, vacuum settings, power settings, radio frequency (RF) generator settings, RF matching circuit settings, frequency settings, flow rate settings, fluid delivery settings, positional and operational settings, wafer transfers into and out of a tool or chamber and other transfer tools and/or load locks connected to or interfaced with a specific system. In this manner, system controller 2423 may be configured to control, among other systems, the various actuators and motors of a backside wafer processing system.

[0238] Broadly speaking, system controller 2423 may be defined as electronics having various integrated circuits, logic, memory, and/or software that receive instructions, issue instructions, control operation, enable cleaning operations, enable endpoint measurements, and/or the like. The integrated circuits may include chips in the form of firmware that store program instructions, digital signal processors (DSPs), chips defined as application specific integrated circuits (ASICs), and/or one or more microprocessors, or microcontrollers that execute program instructions (e.g., software). Program instructions may be instructions communicated to system controller 2423 in the form of various individual settings (or program files), defining operational parameters for carrying out a particular process on or for a semiconductor wafer or to a system. The operational parameters may, in some embodiments, be part of a recipe defined by process engineers to accomplish one or more processing steps during the fabrication

of one or more layers, materials, metals, oxides, silicon, silicon oxide, surfaces, circuits, dies of a wafer, etc.

[0239] System controller 2423, in some implementations, may be a part of or coupled to a computer that is integrated with, coupled to the system, otherwise networked to the system, or a combination thereof. For example, system controller 2423 may be in the “cloud” or all or a part of a fab host computer system, which can allow for remote access of wafer processing. The computer may enable remote access to the system to monitor current progress of fabrication operations, examine a history of past fabrication operations, examine trends or performance metrics from a plurality of fabrication operations, to change parameters of current processing, to set processing steps to follow a current processing, or to start a new process. In some examples, a remote computer (e.g., a server) can provide process recipes to a system over a network, which may include a local network or the Internet. The remote computer may include a user interface that enables entry or programming of parameters and/or settings, which are then communicated to the system from the remote computer. In some examples, the controller receives instructions in the form of data, which specify parameters for each of the processing steps to be performed during one or more operations. It is to be understood that the parameters may be specific to the type of process to be performed and the type of tool that the controller is configured to interface with or control. Thus, as described above, system controller 2423 may be distributed, such as by including one or more discrete controllers that are networked together and working towards a common purpose, such as the processes and controls described herein. An example of a distributed controller for such purposes would be one or more integrated circuits on a chamber in communication with one or more integrated circuits located remotely (such as at the platform level or as part of a remote computer) that combine to control a process on the chamber.

[0240] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports

fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. In some cases, the apparatus further comprises a third gas passage fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the third gas passage being adjacent to the second gas passage in the third direction; third gas distribution ports fluidically connected to the third gas passage; and fourth gas distribution ports fluidically connected to the second gas passage. The at least some of the third gas distribution ports and at least some of the fourth gas distribution ports are arranged in an alternating manner with respect to the second direction. Also, when viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports are arranged between the second gas passage and the third gas passage. In some cases, the sixth gas passage is directly adjacent to a first side of the one or more fourth gas passages; the one or more fourth gas passages are directly adjacent to a first side of the first gas passage; and the second gas passage is directly adjacent to a second side of the first gas passage and a first side of the third gas passage. In one of these cases, the first surface comprises a plurality of zones of gas distribution ports; the first some of the fifth gas distribution ports are arranged in a first zone among the zones; the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports are arranged in a second zone among the zones; the at least some of the first gas distribution ports, the at least some of the second gas distribution ports, the at least some of the third gas distribution ports, and the at least some of the fourth gas distribution ports are arranged in a third zone among the zones; and the first zone separates the second zone from the third zone. According to one aspect of this one case, first gas distribution flow paths are configured to provide the one or more first gases to the first some of the fifth gas distribution ports such that an output of the one or more first gases from the first zone exhibits a first gas flow profile across the first zone; second gas distribution flow paths are configured to provide the one or more first gases to the second some of the fifth gas distribution ports and third gas distribution flow paths are configured to provide the one or more second gases to the at least some of the sixth gas distribution ports such that a combined output of the one or more first gases and the one or more second gases from the second zones exhibits a second gas flow profile across the second zone; fourth gas distribution flow paths are configured to provide the one or more first gases to the at least some of the first gas distribution ports, fifth gas distribution flow

paths are configured to provide the one or more second gases to the at least some of the second gas distribution ports, and sixth gas distribution flow paths are configured to provide the one or more first gases to the at least some of the third gas distribution ports such that a combined output of the one or more first gases and the one or more second gases in the third zone exhibits a third gas flow profile across the third zone; and the first gas flow profile, the second gas flow profile, and the third gas flow profile are different for identical inlet/outlet boundary conditions. In one example, the first gas flow profile is substantially uniform; the second gas flow profile varies in at least one direction across the second zone; and the third gas flow profile varies in at least one direction across the third zone. In another example, each of the second and third gas flow profiles comprises increasing amount of the one or more second gases with increasing distance from the first gas flow profile. According to another aspect of the one case, the first zone comprises a first arrangement of gas distribution ports having a first spatial relationship; and each of the second and third zones comprises a second arrangement of gas distribution ports having a second spatial relationship different from the first spatial relationship. In one example, the second spatial relationship comprises more densely arranged gas distribution ports than the first spatial relationship. In another example, each of the second and third zones further comprises at least one third arrangement of gas distribution ports having at least one third spatial relationship and the at least one third spatial relationship is different from each of the first spatial relationship and the second spatial relationship. In this example, according to one aspect, the second arrangement of gas distribution ports separates the at least one third arrangement of gas distribution ports from the first arrangement of gas distribution ports. According to another aspect, the at least one third arrangement of gas distribution ports is closer to a periphery of the first surface than a center of the first surface.

[0241] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically

separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. In some cases, the apparatus further comprises a third gas passage fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the third gas passage being adjacent to the second gas passage in the third direction; third gas distribution ports fluidically connected to the third gas passage; and fourth gas distribution ports fluidically connected to the second gas passage. The at least some of the third gas distribution ports and at least some of the fourth gas distribution ports are arranged in an alternating manner with respect to the second direction. Also, when viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports are arranged between the second gas passage and the third gas passage. The sixth gas passage is directly adjacent to a first side of the one or more fourth gas passages; the one or more fourth gas passages are directly adjacent to a first side of the first gas passage; and the second gas passage is directly adjacent to a second side of the first gas passage and a first side of the third gas passage. The first surface comprises a plurality of zones of gas distribution ports; the first some of the fifth gas distribution ports are arranged in a first zone among the zones; the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports are arranged in a second zone among the zones; the at least some of the first gas distribution ports, the at least some of the second gas distribution ports, the at least some of the third gas distribution ports, and the at least some of the fourth gas distribution ports are arranged in a third zone among the zones; and the first zone separates the second zone from the third zone. First gas distribution flow paths are configured to provide the one or more first gases to the first some of the fifth gas distribution ports such that an output of the one or more first gases from the first zone exhibits a first gas flow profile across the first zone; second gas distribution flow paths are configured to provide the one or more first gases to the second some of the fifth gas distribution ports and third gas distribution flow paths are configured to provide the one or more second gases to the at least some of the sixth gas distribution ports such that a combined output of the one or more first gases and the one or more second gases from the second zones exhibits a second gas flow profile across the second zone; fourth gas distribution flow paths are configured to provide the one or more first gases to the at least some of the first gas distribution ports, fifth gas distribution flow paths are configured to provide the one or more second gases to the at least some of the second gas distribution ports, and sixth gas distribution flow paths are

configured to provide the one or more first gases to the at least some of the third gas distribution ports such that a combined output of the one or more first gases and the one or more second gases in the third zone exhibits a third gas flow profile across the third zone; and the first gas flow profile, the second gas flow profile, and the third gas flow profile are different for identical inlet/outlet boundary conditions. The first gas distribution flow paths, the second gas distribution flow paths, the fourth gas distribution flow paths, and the sixth gas distribution flow paths define portions of a first plenum volume within the main body; the third gas distribution flow paths and the fifth gas distribution flow paths define portions of a second plenum volume within the main body, the second plenum volume being fluidically separate from the first plenum volume within the main body; and a first some of the gas passages that are directly adjacent to one another are associated with different plenum volumes among the first plenum volume and the second plenum volume. In some cases, a second some of the gas passages that are directly adjacent to one another are associated with a same plenum volume among the first plenum volume and the second plenum volume. In one of these cases, the second some of the gas passages are associated with the second plenum volume and is positioned closer to a periphery of the first surface than a center of the first surface. In another one of these cases, the second some of the gas passages are associated with the first plenum volume and is positioned closer to a center of the first surface than a periphery of the first surface.

[0242] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. The at least some of the first gas distribution ports are fluidically connected to the first gas passage via first gas risers. The at least some of the second gas distribution ports are fluidically connected to the second gas passage via

second gas risers. The first gas risers extend in a fifth direction transverse to each of the first direction, the second direction, the third direction, and the fourth direction. The second gas risers extend in a sixth direction transverse to each of the first direction, the second direction, the third direction, the fourth direction, and the fifth direction. In some cases, the fifth direction is angled by a first amount from the first direction in a reference plane defined by the first direction and the third direction; the sixth direction is angled by a second amount from the first direction in the reference plane. In one of these cases, absolute values of the first amount and the second amount are equivalent. In other cases, the first some of the fifth gas distribution ports are fluidically connected to a fourth gas distribution passage among the one or more fourth gas distribution passages via third gas risers, the third gas risers extending in the first direction.

[0243] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. In some cases, the apparatus further comprises a third gas passage fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the third gas passage being adjacent to the second gas passage in the third direction; third gas distribution ports fluidically connected to the third gas passage; and fourth gas distribution ports fluidically connected to the second gas passage. The at least some of the third gas distribution ports and at least some of the fourth gas distribution ports are arranged in an alternating manner with respect to the second direction. Also, when viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports are arranged between the second gas passage and the third gas passage. In some cases, the sixth gas passage is directly adjacent to a first side of the one or more fourth gas passages; the one or more fourth

gas passages are directly adjacent to a first side of the first gas passage; and the second gas passage is directly adjacent to a second side of the first gas passage and a first side of the third gas passage. In one of these cases, the first surface comprises a plurality of zones of gas distribution ports; the first some of the fifth gas distribution ports are arranged in a first zone among the zones; the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports are arranged in a second zone among the zones; the at least some of the first gas distribution ports, the at least some of the second gas distribution ports, the at least some of the third gas distribution ports, and the at least some of the fourth gas distribution ports are arranged in a third zone among the zones; and the first zone separates the second zone from the third zone. According to one aspect of this one case, first gas distribution flow paths are configured to provide the one or more first gases to the first some of the fifth gas distribution ports such that an output of the one or more first gases from the first zone exhibits a first gas flow profile across the first zone; second gas distribution flow paths are configured to provide the one or more first gases to the second some of the fifth gas distribution ports and third gas distribution flow paths are configured to provide the one or more second gases to the at least some of the sixth gas distribution ports such that a combined output of the one or more first gases and the one or more second gases from the second zones exhibits a second gas flow profile across the second zone; fourth gas distribution flow paths are configured to provide the one or more first gases to the at least some of the first gas distribution ports, fifth gas distribution flow paths are configured to provide the one or more second gases to the at least some of the second gas distribution ports, and sixth gas distribution flow paths are configured to provide the one or more first gases to the at least some of the third gas distribution ports such that a combined output of the one or more first gases and the one or more second gases in the third zone exhibits a third gas flow profile across the third zone; and the first gas flow profile, the second gas flow profile, and the third gas flow profile are different for identical inlet/outlet boundary conditions. The gas distribution ports of the first surface are distributed into rows of gas distribution ports extending in the third direction and columns of gas distribution ports extending in the second direction. A first some of the gas distribution ports are arranged in first rows among the rows, the first some of the gas distribution ports being fluidically connected to a first plenum volume within the main body. A second some of the gas distribution ports are arranged in second rows among the rows, the second some of the gas distribution ports being fluidically connected to a second plenum volume within the main body that is fluidically separate from the first plenum volume within the main body. The first rows alternate with the second rows along the second

direction.

[0244] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. The apparatus further comprises an outer wall surrounding the main body. The main body further comprises: a third surface extending between the first surface and the second surface, the third surface facing an inner surface of the outer wall; a plurality of first blind cavities recessed into the third surface and arranged about a perimeter of the main body, the first blind cavities defining portions of a first plenum volume within the main body; and a plurality of second blind cavities recessed into the third surface and arranged about a perimeter of the main body, the second blind cavities defining portions of a second plenum volume within the main body. The first plenum volume and the second plenum volume are fluidically separate within the main body. A first distal end of the first gas passage is fluidically connected to a first blind cavity among the first blind cavities and a first distal end of the second gas passage is fluidically connected to a second blind cavity among the second blind cavities. In some cases, a second distal end of the first gas passage is fluidically connected to another first blind cavity among the first blind cavities, the first blind cavity opposing the another first blind cavity relative to a central axis of the main body extending in the first direction; and a second distal end of the second gas passage is fluidically connected to another second blind cavity among the second blind cavities, the second blind cavity opposing the another second blind cavity relative to the central axis. In other cases, each first blind cavity among the first blind cavities has a first opening area facing the inner surface of the outer wall and at least one of the first opening areas is different from at least another one of the first opening areas. In yet other cases, each second blind cavity among the second blind cavities has

a second opening area facing the inner surface of the outer wall; and at least one of the second opening areas is different from at least another one of the second opening areas.

[0245] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. The first surface comprises a plurality of gas distribution ports. The plurality gas distribution ports comprise the first gas distribution ports and the second gas distribution ports. The first gas passage and the second gas passage are among a plurality of gas passages extending in the second direction between the first surface and the second surface. Each of the gas passages is fluidically connected to one or more gas distribution ports among the gas distribution ports of the first surface. Respective cross-sectional areas of the gas passages in a plane perpendicular to the second direction are substantially equivalent. Each of the first elongated holes extends in a first planar region of the main body. Each of the second elongated holes extends in a second planar region of the main body different from the first planar region of the main body and the second planar region is closer to the first surface of the main body than the first planar region. In some cases, the first gas passage and the second gas passage extend in a third planar region of the main body different from each of the first planar region and the second planar region. In one of these cases, the third planar region is closer to the first surface than each of the first planar region and the second planar region.

[0246] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first

gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. In some cases, the apparatus further comprises a third gas passage fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the third gas passage being adjacent to the second gas passage in the third direction; third gas distribution ports fluidically connected to the third gas passage; and fourth gas distribution ports fluidically connected to the second gas passage. The at least some of the third gas distribution ports and at least some of the fourth gas distribution ports are arranged in an alternating manner with respect to the second direction. Also, when viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports are arranged between the second gas passage and the third gas passage. The sixth gas passage is directly adjacent to a first side of the one or more fourth gas passages; the one or more fourth gas passages are directly adjacent to a first side of the first gas passage; and the second gas passage is directly adjacent to a second side of the first gas passage and a first side of the third gas passage. The first surface comprises a plurality of zones of gas distribution ports; the first some of the fifth gas distribution ports are arranged in a first zone among the zones; the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports are arranged in a second zone among the zones; the at least some of the first gas distribution ports, the at least some of the second gas distribution ports, the at least some of the third gas distribution ports, and the at least some of the fourth gas distribution ports are arranged in a third zone among the zones; and the first zone separates the second zone from the third zone. The first zone comprises a first arrangement of gas distribution ports having a first spatial relationship and each of the second and third zones comprises a second arrangement of gas distribution ports having a second spatial relationship different from the first spatial relationship. The apparatus further comprises a plurality of first elongated holes in the main body that extend radially from a first central region of the main body, each of the first elongated holes having: a corresponding proximal end fluidically connected to at least one of the one or more first gas inlets; and a corresponding distal end fluidically connected to a first blind cavity among the first

blind cavities. The apparatus further comprises a plurality of second elongated holes in the main body that extend radially from a second central region of the main body, each of the second elongated holes having: a corresponding proximal end fluidically connected to at least one of the one or more gas second inlets; and a corresponding distal end fluidically connected to a second blind cavity among the second blind cavities. In one example, respective cross-sectional areas of the first elongated holes and the second elongated holes in corresponding planes perpendicular to their respective directions of longitudinal extension are equivalent. In another example, at least one of the first elongated holes has a different cross-sectional area in a plane perpendicular to its direction of longitudinal extension than at least one other one of the first elongated holes. In another example, at least one of the second elongated holes has a different cross-sectional area in a plane perpendicular to its direction of longitudinal extension than at least one other one of the second elongated holes.

[0247] Certain embodiments pertain to an apparatus comprising a main body comprising: a first surface; a second surface opposing the first surface in a first direction; a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction; a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets; first gas distribution ports fluidically connected to the first gas passage; and second gas distribution ports fluidically connected to the second gas passage. The one or more first gas inlets are fluidically separate from the one or more second gas inlets within the main body. Also, at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction. The apparatus further comprises a cooling conduit in thermal contact with the main body, the cooling conduit having an inlet being configured to receive clean dry air (CDA) at a first temperature and an outlet being configured to output the CDA at a second temperature different from the first temperature, wherein the main body comprises a first groove recessed into the second surface, a portion of the cooling conduit extending within the first groove. The apparatus further comprises a resistive heating element, wherein the main body further comprises a second groove recessed into the second surface, a portion of the resistive heating element extending within the second groove. In the first direction, the second groove extends farther into the second surface than the first groove. In a radial

direction perpendicular to the first direction, an outermost portion of second groove is closer to a periphery of the main body than an outermost portion of the first groove.

[0248] Without limitation, example systems may include a plasma etch chamber or module, a deposition chamber or module, a spin-rinse chamber or module, a metal plating chamber or module, a clean chamber or module, a bevel edge etch chamber or module, a physical vapor deposition (PVD) chamber or module, a chemical vapor deposition (CVD) chamber or module, an atomic layer deposition (ALD) chamber or module, an atomic layer etch (ALE) chamber or module, an ion implantation chamber or module, a track chamber or module, and/or any other semiconductor processing system that may be associated or used in the fabrication and/or manufacturing of semiconductor wafers.

[0249] As noted above, depending on the process step or steps to be performed by the tool, system controller 2423 might communicate with one or more of other tool circuits or modules, other tool components, cluster tools, other tool interfaces, adjacent tools, neighboring tools, tools located throughout a factory, a main computer, another controller, and/or tools used in material transport that bring containers of wafers to and from tool locations and/or load ports in a semiconductor manufacturing factory.

[0250] Unless otherwise specified, the illustrated embodiments are to be understood as providing example features of varying detail of some embodiments. Thus, unless otherwise specified, the features, components, modules, layers, films, regions, aspects, structures, etc. (hereinafter individually or collectively referred to as an “element” or “elements”), of the various illustrations may be otherwise combined, separated, interchanged, and/or rearranged without departing from the teachings of the disclosure.

[0251] The terminology used herein is for the purpose of describing some embodiments and is not intended to be limiting. As used herein, the singular forms, “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It is to be understood that the phrases “for each <item> of the one or more <items>,” “each <item> of the one or more <items>,” and/or the like, if used herein, are inclusive of both a single-item group and multiple-item groups, i.e., the phrase “for . . . each” is used in the sense that it is used in programming languages to refer to each item of whatever population of items is referenced. For example, if the population of items referenced is a single item, then “each” would refer to only that single item (despite dictionary definitions of “each” frequently defining

the term to refer to “every one of two or more things”) and would not imply that there must be at least two of those items. Similarly, the term “set” or “subset” should not be viewed, in itself, as necessarily encompassing a plurality of items—it is to be understood that a set or a subset can encompass only one member or multiple members (unless the context indicates otherwise). The terms “comprises,” “comprising,” “includes,” and/or “including,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, components, and/or groups thereof, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. It is also noted that, as used herein, the terms “substantially,” “about,” and other similar terms, are used as terms of approximation and not as terms of degree, and, as such, are utilized to account for inherent deviations in measured, calculated, and/or provided values that would be recognized by one of ordinary skill in the art. Accordingly, the term “substantially” as used herein, unless otherwise specified, means within 5% of a referenced value. For example, substantially perpendicular means within $\pm 5\%$ of parallel. Further, as used herein, the terms “proximal” and “distal” refer, respectively, to directions closer to and farther away from a particular reference point, such as a source of gas flow. In this sense, an element referred to as being “proximal” may conversely be referred to as being “distal” depending on the particular reference point chosen without departing from the teachings of the disclosure.

[0252] The use of cross-hatching and/or shading in the accompanying drawings is generally provided to clarify boundaries between adjacent elements. As such, neither the presence nor the absence of cross-hatching or shading conveys or indicates any preference or requirement for particular materials, material properties, dimensions, proportions, commonalities between illustrated elements, and/or any other characteristic, attribute, property, etc., of the elements, unless specified. Further, in the accompanying drawings, the size and relative sizes of elements may be exaggerated for clarity and/or descriptive purposes. As such, the sizes and relative sizes of the respective elements are not necessarily limited to the sizes and relative sizes shown in the drawings. When an embodiment may be implemented differently, a specific process order may be performed differently from the described order. For example, two consecutively described processes may be performed substantially at the same time or performed in an order opposite to the described order.

[0253] When an element, such as a layer, is referred to as being “on,” “connected to,” or “coupled to” another element, it may be directly on, directly connected to, or directly coupled

to the other element or at least one intervening element may be present. When, however, an element is referred to as being “directly on,” “directly connected to,” or “directly coupled to” another element, there are no intervening elements present. Other terms and/or phrases if used herein to describe a relationship between elements should be interpreted in a like fashion, such as “between” versus “directly between,” “adjacent” versus “directly adjacent,” “on” versus “directly on,” etc. Further, the term “connected” may refer to physical, electrical, and/or fluid connection. To this end, for the purposes of this disclosure, the phrase “fluidically connected” is used with respect to volumes, plenums, holes, etc., that may be connected to one another, either directly or via one or more intervening components or volumes, to form a fluidic connection, similar to how the phrase “electrically connected” is used with respect to components that are connected to form an electric connection. The phrase “fluidically interposed,” if used, may be used to refer to a component, volume, plenum, hole, etc., that is fluidically connected with at least two other components, volumes, plenums, holes, etc., such that fluid flowing from one of those other components, volumes, plenums, holes etc., to the other or another of those components, volumes, plenums, holes, etc., would first flow through the “fluidically interposed” component before reaching that other or another of those components, volumes, plenums, holes, etc.. For example, if a pump is fluidically interposed between a reservoir and an outlet, fluid flowing from the reservoir to the outlet would first flow through the pump before reaching the outlet. The phrase “fluidically adjacent,” if used, refers to placement of a fluidic element relative to another fluidic element such that no potential structures fluidically are interposed between the two elements that might potentially interrupt fluid flow between the two fluidic elements. For example, in a flow path having a first valve, a second valve, and a third valve arranged sequentially therealong, the first valve would be fluidically adjacent to the second valve, the second valve fluidically adjacent to both the first and third valves, and the third valve fluidically adjacent to the second valve.

[0254] For the purposes of this disclosure, “at least one of X, Y, . . . , and Z” and “at least one selected from the group consisting of X, Y, . . . , and Z” may be construed as X only, Y only, . . . , Z only, or any combination of two or more of X, Y, . . . , and Z, such as, for instance, XYZ, XYY, YZ, and ZZ. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

[0255] Although the terms “first,” “second,” “third,” etc., may be used herein to describe various elements, these elements should not be limited by these terms. These terms are used

to distinguish one element from another element. Thus, a first element discussed below could be termed a second element without departing from the teachings of the disclosure. To this end, use of such identifiers, e.g., “a first element,” should not be read as suggesting, implicitly or inherently, that there is necessarily another instance, e.g., “a second element.” Further, the use, if any, of ordinal indicators, such as (a), (b), (c), . . . , or (1), (2), (3), . . . , or the like, in this disclosure and accompanying claims, is to be understood as not conveying any particular order or sequence, except to the extent that such an order or sequence is explicitly indicated. For example, if there are three steps labeled (i), (ii), and (iii), it is to be understood that these steps may be performed in any order (or even concurrently, if not otherwise contraindicated), unless indicated otherwise. For example, if step (ii) involves the handling of an element that is created in step (i), then step (ii) may be viewed as happening at some point after step (i). In a similar manner, if step (i) involves the handling of an element that is created in step (ii), the reverse is to be understood.

[0256] Spatially relative terms, such as “beneath,” “below,” “under,” “lower,” “above,” “upper,” “over,” “higher,” “side” (e.g., as in “sidewall”), and the like, may be used herein for descriptive purposes, and, thereby, to describe one element’s spatial relationship to at least one other element as illustrated in the drawings. Spatially relative terms are intended to encompass different orientations of an apparatus in use, operation, and/or manufacture in addition to the orientation depicted in the drawings. For example, if the apparatus in the drawings is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” or “over” the other elements or features. Thus, the term “below” can encompass both an orientation of above and below. Furthermore, the apparatus may be otherwise oriented (e.g., rotated 90 degrees or at other orientations), and, as such, the spatially relative descriptors used herein interpreted accordingly.

[0257] The term “between,” as used herein and when used with a range of values, is to be understood, unless otherwise indicated, as being inclusive of the start and end values of that range. For example, between 1 and 5 is to be understood as inclusive of the numbers 1, 2, 3, 4, and 5, not just the numbers 2, 3, and 4.

[0258] As used herein, the phrase “operatively connected” is to be understood as referring to a state in which two components and/or systems are connected, either directly or indirectly, such that, for example, at least one component or system can control the other. For instance, a controller may be described as being operatively connected with (or to) a resistive heating unit,

which is inclusive of the controller being connected with a sub-controller of the resistive heating unit that is electrically connected with a relay that is configured to controllably connect or disconnect the resistive heating unit with a power source that is capable of providing an amount of power that is able to power the resistive heating unit so as to generate a desired degree of heating. The controller itself likely will not supply such power directly to the resistive heating unit due to the current(s) involved, but it is to be understood that the controller is nonetheless operatively connected with the resistive heating unit.

[0259] As used herein, the singular forms, “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It is also to be understood that the phrases “for each <item> of the one or more <items>,” “each <item> of the one or more <items>,” and/or the like, if used herein, are inclusive of both a single-item group and multiple-item groups, i.e., the phrase “for . . . each” is used in the sense that it is used in programming languages to refer to each item of whatever population of items is referenced. For example, if the population of items referenced is a single item, then “each” would refer to only that single item (despite dictionary definitions of “each” frequently defining the term to refer to “every one of two or more things”) and would not imply that there must be at least two of those items. Similarly, the term “set” or “subset” should not be viewed, in itself, as necessarily encompassing a plurality of items—it is to be understood that a set or a subset can encompass only one member or multiple members (unless the context indicates otherwise). In addition, the terms “comprises,” “comprising,” “includes,” and/or “including,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, components, and/or groups thereof, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0260] Various embodiments are described herein with reference to sectional views, isometric views, perspective views, plan views, and/or exploded illustrations that are schematic depictions of idealized embodiments and/or intermediate structures. As such, variations from the shapes of the illustrations as a result of, for example, manufacturing techniques and/or tolerances, are to be expected. Thus, embodiments disclosed herein should not be construed as limited to the particular illustrated shapes of regions, but are to include deviations in shapes that result from, for instance, manufacturing. To this end, regions illustrated in the drawings may be schematic in nature and shapes of these regions may not reflect the actual shapes of

regions of a device, and, as such, are not intended to be limiting.

[0261] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure is a part. Terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and are not to be interpreted in an idealized or overly formal sense, unless expressly so defined herein.

[0262] As customary in the field, some embodiments are described and illustrated in the accompanying drawings in terms of functional blocks, units, and/or modules. Those skilled in the art will appreciate that these blocks, units, and/or modules are physically implemented by electronic (or optical) circuits, such as logic circuits, discrete components, microprocessors, hard-wired circuits, memory elements, wiring connections, and the like, which may be formed using semiconductor-based fabrication techniques or other manufacturing technologies. In the case of the blocks, units, and/or modules being implemented by microprocessors or other similar hardware, they may be programmed and controlled using software (e.g., microcode) to perform various functions discussed herein and may optionally be driven by firmware and/or software. It is also contemplated that each block, unit, and/or module may be implemented by dedicated hardware, or as a combination of dedicated hardware to perform some functions and a processor (e.g., one or more programmed microprocessors and associated circuitry) to perform other functions. Also, each block, unit, and/or module of some embodiments may be physically separated into two or more interacting and discrete blocks, units, and/or modules without departing from the inventive concepts. Further, the blocks, units, and/or modules of some embodiments may be physically combined into more complex blocks, units, and/or modules without departing from the teachings of the disclosure.

[0263] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing the processes, systems, and apparatuses of the disclosed embodiments. Accordingly, embodiments are to be considered as illustrative and not as restrictive, and embodiments are not to be limited to the details given herein.

CLAIMS

What is claimed is:

1. An apparatus comprising:
a main body comprising:
a first surface;
a second surface opposing the first surface in a first direction;
a first gas passage fluidically connected to one or more first gas inlets and extending in a second direction between the first surface and the second surface, the second direction being transverse to the first direction;
a second gas passage extending in the second direction and spaced apart from the first gas passage in a third direction transverse to each of the first direction and the second direction, the second gas passage being fluidically connected to one or more second gas inlets;
first gas distribution ports fluidically connected to the first gas passage; and
second gas distribution ports fluidically connected to the second gas passage,
wherein:
at least one of the one or more first gas inlets is fluidically separate from the one or more second gas inlets within the main body; and
at least some of the first gas distribution ports and at least some of the second gas distribution ports are arranged in an alternating manner with respect to the second direction.
2. The apparatus of claim 1, wherein, when viewed in the first direction, the at least some of the first gas distribution ports and the at least some of the second gas distribution ports are arranged between the first gas passage and the second gas passage.
3. The apparatus of either claim 1 or claim 2, wherein the first gas distribution ports and the second gas distribution ports form respective openings in the first surface.

4. The apparatus of any one of claims 1–3, further comprising:

a third gas passage fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the third gas passage being adjacent to the second gas passage in the third direction;

third gas distribution ports fluidically connected to the third gas passage; and

fourth gas distribution ports fluidically connected to the second gas passage,

wherein:

at least some of the third gas distribution ports and at least some of the fourth gas distribution ports are arranged in an alternating manner with respect to the second direction; and

when viewed in the first direction, the at least some of the third gas distribution ports and the at least some of the fourth gas distribution ports are arranged between the second gas passage and the third gas passage.

5. The apparatus of claim 4, wherein the third gas distribution ports and the fourth gas distribution ports form respective openings in the first surface.

6. The apparatus of any one of claims 1–3, further comprising:

one or more fourth gas passages fluidically connected to the one or more first gas inlets and extending in the second direction between the first surface and the second surface, the one or more fourth gas passages being adjacent to the first gas passage in a fourth direction opposite the third direction;

a fifth gas passage fluidically connected to the one or more second gas inlets and extending in the second direction between the first surface and the second surface, the fifth gas passage being adjacent to the one or more fourth gas passages in the fourth direction;

fifth gas distribution ports fluidically connected to the one or more fourth gas passages; and

sixth gas distribution ports fluidically connected to the fifth gas passage,

wherein:

a first some of the fifth gas distribution ports are arranged with respect to the second direction;

a second some of the fifth gas distribution ports and at least some of the sixth

gas distribution ports are arranged in an alternating manner with respect to the second direction; and

when viewed in the first direction, the second some of the fifth gas distribution ports and the at least some of the sixth gas distribution ports are arranged between the fifth gas passage and the one or more fourth gas passages.

7. The apparatus of claim 1, wherein:

the first surface comprises a plurality of gas distribution ports;

the plurality gas distribution ports comprise the first gas distribution ports and the second gas distribution ports;

the first gas passage and the second gas passage are among a plurality of gas passages extending in the second direction between the first surface and the second surface; and

each of the gas passages is fluidically connected to one or more gas distribution ports among the gas distribution ports of the first surface.

8. The apparatus of claim 7, wherein respective cross-sectional areas of the gas passages in a plane perpendicular to the second direction are substantially equivalent.

9. The apparatus of claim 7, wherein a cross-sectional area of at least one of the gas passages in a plane perpendicular to the second direction is different from a cross-sectional area of at least another one of the gas passages in the plane perpendicular to the second direction.

10. The apparatus of any one of claims 7–9, wherein corresponding pitches between adjacent gas passages among the gas passages are substantially equivalent.

11. The apparatus of claim 1, wherein:

the at least some of the first gas distribution ports are fluidically connected to the first gas passage via first gas risers;

the at least some of the second gas distribution ports are fluidically connected to the second gas passage via second gas risers;

the first gas risers extend in a fifth direction transverse to each of the first direction, the second direction, the third direction, and a fourth direction opposite the third direction; and

the second gas risers extend in a sixth direction transverse to each of the first direction, the second direction, the third direction, the fourth direction, and the fifth direction.

12. The apparatus of claims 1, further comprising:

an outer wall surrounding the main body,

wherein the main body further comprises:

a third surface extending between the first surface and the second surface, the third surface facing an inner surface of the outer wall;

a plurality of first blind cavities recessed into the third surface and arranged about a perimeter of the main body, the first blind cavities defining portions of a first plenum volume within the main body; and

a plurality of second blind cavities recessed into the third surface and arranged about a perimeter of the main body, the second blind cavities defining portions of a second plenum volume within the main body,

wherein:

the first plenum volume and the second plenum volume are fluidically separate within the main body;

a first distal end of the first gas passage is fluidically connected to a first blind cavity among the first blind cavities; and

a first distal end of the second gas passage is fluidically connected to a second blind cavity among the second blind cavities.

13. The apparatus of claim 12, wherein at least some of the first blind cavities alternate about the perimeter of the main body with at least some of the second blind cavities.

14. The apparatus of claim 12, wherein:

each first blind cavity among the first blind cavities has a first opening area facing the inner surface of the outer wall; and

the first opening areas are substantially equivalent to one another or at least one of the first opening areas is different from at least another one of the first opening areas.

15. The apparatus of claim 14, wherein:

each second blind cavity among the second blind cavities has a second opening area facing the inner surface of the outer wall; and

the second opening areas are substantially equivalent to one another or at least one of the first opening areas is different from at least another one of the first opening areas.

16. The apparatus of claim 15, wherein the first opening areas and the second opening areas are equivalent.

17. The apparatus of claim 12, further comprising:

a plurality of plugs respectively filling portions of only corresponding first blind cavities among the first blind cavities or only corresponding second blind cavities among the second blind cavities.

18. The apparatus of claim 12, further comprising:

a plurality of first elongated holes in the main body that extend radially from a first central region of the main body, each of the first elongated holes having:

a corresponding proximal end fluidically connected to at least one of the one or more first gas inlets; and

a corresponding distal end fluidically connected to a first blind cavity among the first blind cavities;

a plurality of second elongated holes in the main body that extend radially from a second central region of the main body, each of the second elongated holes having:

a corresponding proximal end fluidically connected to at least one of the one or more gas second inlets; and

a corresponding distal end fluidically connected to a second blind cavity among the second blind cavities.

19. The apparatus of claim 18, wherein the first central region is arranged between the second central region and a periphery of the main body.

20. The apparatus of either claim 18 or claim 19, wherein:

each of the first elongated holes extends in a first planar region of the main body;

each of the second elongated holes extends in a second planar region of the main body different from the first planar region of the main body; and

the second planar region is closer to the first surface of the main body than the first planar region.

21. The apparatus of claim 1, further comprising:

a cooling conduit in thermal contact with the main body, the cooling conduit having an inlet being configured to receive clean dry air (CDA) at a first temperature and an outlet being configured to output the CDA at a second temperature different from the first temperature,

wherein the main body comprises a first groove recessed into the second surface, a portion of the cooling conduit extending within the first groove.

22. The apparatus of claim 21, further comprising:

a first cap structure enclosing the cooling conduit in the first groove in a compressed state.

23. The apparatus of either claim 21 or claim 22, wherein the cooling conduit is formed of stainless steel.

24. The apparatus of any one of claims 21-23, wherein the cooling conduit is sized to enable a flow rate of CDA up to about 140 standard liters per minute with a Reynolds number greater than about 2000.

25. The apparatus of any one of claims 21-24, further comprising:

a resistive heating element,

wherein the main body further comprises a second groove recessed into the second surface, a portion of the resistive heating element extending within the second groove.

26. The apparatus of any one of claims 1–25, further comprising:
a process chamber configured to support the main body therein,
wherein the main body forms a portion of a showerhead.

27. The apparatus of claim 26, wherein:
the first gas distribution ports and the second gas distribution ports are among a plurality of gas distribution ports forming openings in the first surface of the main body; and
the showerhead is a showerhead pedestal configured to support a substrate thereover such that a majority of a backside of the substrate is exposed to the plurality of gas distribution ports.

28. The apparatus of any one of claims 1–27, wherein the main body is formed of an aluminum alloy.