System, Method and Apparatus for Coordinating Pressure Pulses and RF Modulation in a Small Volume Confined Process Reactor

By Inventors:

Rajinder Dhindsa and Harmeet Singh

BACKGROUND

[1] The present invention relates generally to plasma etch processes, and more particularly, to methods and systems for controlling plasma etch processes.

[2] Semiconductor device dimensions are pressed to ever smaller dimensions to enable more devices per wafer with higher performance. As semiconductor device dimensions become smaller, new challenges are presented in the process technology needed to form the smaller, more densely packed devices with high yield. These process requirements demand a precise control of plasma chemistry (radical, neutral and ions) to meet both on die as well as across semiconductor wafer etch requirements.

[3] Fig. 1 is a side view of a simplified schematic drawing of a typical narrow gap plasma processing chamber 100. Process gases ~~102~~ are injected through a substantially central location 104 of the top portion 108 of the plasma processing chamber 100. The process gases ~~102~~ are injected into the plasma processing volume 110 defined as being over the semiconductor wafer 101 to be processed. The semiconductor wafer 101 is supported on a wafer support 106.

[4] The process gases ~~102~~ flow in a substantially radial direction 112 through the plasma processing volume 110 toward a plasma confinement structure 114 at the periphery of the plasma processing volume. The process gases ~~102~~ and plasma process byproducts are pumped out at the periphery ~~114~~ through peripheral vents 116 to one or more vacuum pumps 118.

[5] Typical plasma processes are performed at fixed process gas ~~102~~ pressure and flow. The fixed process gas ~~102~~ pressure and flow often causes radial pressure

SUMMARY

[7] Broadly speaking, the present invention fills these needs by providing a system, method and apparatus for dynamically changing and controlling the peripheral conductance of the process gases so as to induce a fast change in the pressure in the plasma processing volume. It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, computer readable media, or a device. Several inventive embodiments of the present invention are described below.

[8] One embodiment provides a plasma processing system and method that includes a processing chamber, and a plasma processing volume included therein. The plasma processing volume having a volume less than the processing chamber. The plasma processing volume being defined by a top electrode, a substrate support surface opposing the surface of the top electrode and a plasma confinement structure including at least one outlet port. A conductance control structure is movably disposed proximate to the at least one outlet port and capable of controlling an outlet flow through the at least one outlet port between a first flow rate and a second flow rate, wherein the conductance control structure controls the outlet flow rate and an at least one RF source is modulated and at least one process gas flow rate is modulated corresponding to a selected processing state set by the controller during a plasma process.

[9] Another embodiment provides a method of modulating a pressure in-situ in a plasma processing volume of a chamber, the plasma processing volume defined between a surface of a top electrode, a supporting surface of a substrate support and an outer region defined by a plasma confinement structure. The plasma confinement structure including at least one outlet port. The method including injecting at least one processing gas into the plasma processing volume, forming a plasma within the plasma processing volume and modulating a pressure and an RF signal applied to the plasma processing volume during a period of time when the plasma is formed in the plasma processing volume. The modulating of the pressure being controlled by at least one of a first outlet flow out of the plasma processing volume from the at least one outlet port,

conductance control ring can provide a corresponding pressure modulation within the plasma processing volume relative to time.

[45] Variations in pressure in the plasma processing volume can vary or modulate several parameters including, ions to neutral ratio, ion energy, IEDF and IADF. At low pressure there is less collision between the ions entering the plasma sheath (voltage drop) above the wafer surface. Reducing ion collisions causes more of the ions to exit the plasma sheath in a substantially perpendicular direction to the plasma sheath and to the surface of the substrate being processed. As a result, reducing the ion collisions improves the directionality of the ions entering any features present in the surface of the substrate being processed.

[46] Further, as the pressure changes the effective plasma density as well an area ratio changes. Changing the effective plasma density and/or the area ratio also changes the ion energy distribution function (IEDF) from a low ion energy ratio to a high ion energy ratio. The ion energy distribution function can be adjusted to affect the plasma processing performance of the process within the plasma processing volume.

[47] By way of example, a precise control of ion to neutral flux is one important operational parameter used to maintain a good mask profile during etch. A good mask profile during etch directly impacts the quality of the final etch profile.

[48] A fast pressure pulse in the plasma processing volume can also be synchronized with RF power delivery and/or process gas chemistry modulation and/or wafer temperature ~~provide~~ profile to further enhance the desired control of ion to neutral flux along with difference process chemistry, to meet the requirement of next generation etch processes. A pressure pulse within the plasma processing volume can also provide a plasma chemistry control to the feature being etched and thus provide improved selectivity, profile control and radial uniformity.

[49] Figs. 2A and 2B are schematic diagrams of a small volume plasma processing chamber system 200, in accordance with one embodiment of the present invention. The small volume plasma processing chamber system 200 includes a processing chamber 201, one or more gas sources 102, one or more RF sources 117A, 117B and a controller 119 coupled to the processing chamber and the gas sources. The processing

chamber 201 is defined by inner walls 201A-D and includes a substrate support 106 for supporting a substrate 101.

[50] The processing chamber 201 also includes a plasma processing volume 110. The plasma processing volume 110 is defined by an inner surface 108A of the top 108 of the plasma processing chamber (e.g., a surface of a top electrode coupled to RF source 117B), the surface 106A, 106B of the substrate support 106 (e.g., a bottom electrode coupled to RF source 117A), if the substrate 101 is not present, and the surface 106A and the surface 101A of the substrate 101, when the substrate is present. The plasma processing volume 110 is typically less than about 10 percent of the total volume of the processing chamber 201. A plasma confinement structure 114 defines an outer perimeter of the plasma processing volume 110.

[51] The plasma confinement structure 114 includes multiple outlet ports 116. A positioning actuator 207 is coupled to the conductance control structure 202 to apply a desired level of restriction to the outlet ports 116. The outlet ports 116 can be substantially fully restricted to minimize gas output flow through the outlet ports, as shown in Fig. 2A, by a conductance control structure 202 being placed immediately adjacent to the outlet ports 116. The restricted outlet ports 116 restrict the flow of the process gases and plasma byproducts ~~117~~ out of the plasma processing volume 110 and thus generates an increased pressure within the limited volume of only the plasma processing volume 110.

[52] When the outlet ports 116 are restricted, the pressure within the plasma processing volume 110 can increase at a rate of up to about 20 mtorr per 100ms. In many plasma processes a relatively small pressure increase in the plasma processing volume 110, as little as about 5 mtorr pressure, can be a sufficient pressure change to create the desired effects. The restricted outlet ports 116 can generate an increased pressure within the plasma processing volume 110 of about 50 mtorr or greater, with more time is allowed.

[53] By way of example, if only 5 mtorr pressure increase is desired, then the outlet ports 116 may only need to be restricted for about 25 ms, which is about 25 percent of the time required to increase the pressure 20 mtorr, within the plasma processing

volume 110. Alternatively, if a 40 mtorr pressure increase is desired, then the outlet ports 116 may need to be restricted about 200 ms, which is about 200 percent of the time required to increase the pressure 20 mtorr, within the plasma processing volume 110.

[54] Alternatively, as shown in Fig. 2B, the outlet ports 116 can be substantially fully unrestricted when the positioning actuator 207, moves the conductance control structure 202 a sufficient distance $\Delta 1$ away from the outlet ports 116, where distance $\Delta 1$ is between about 0.25 mm to about 25 mm (i.e., between about 0.01 inches and about 1.0 inches) and more specifically between about 0.25 mm to about 12.5 mm (i.e., between about 0.01 inches and about 0.5 inches).

[55] The substantially fully unrestricted outlet ports 116 can more freely allow flow the process gases and plasma byproducts ~~117~~ toward the vacuum pumps 118. When substantially fully unrestricted, the outlet ports 116 can generate a pressure decrease within the plasma processing volume 110 ~~of~~ at a rate of up to about 20 mtorr per 100ms. The conductance control structure 202 can be moved any desired more or less than distance $\Delta 1$ away from the outlet ports 116 to provide a corresponding selected amount of restriction to the outlet flow through the outlet ports.

[56] Modulating the amount of restriction of the outlet flow of the outlet ports 116 can be used to correspondingly modulate an increase and a decrease of the pressure within only the plasma processing volume 110 at a rate of about 10 Hz. The pressure in the remainder of the processing chamber 201, external of the plasma processing volume 110, remains substantially constant while the pressure within the plasma processing volume is varied.

[57] It should be understood that the above examples are mere exemplary embodiments and different structures of and control schemes of the conductance control structure 202 and the plasma confinement structure 114 will have correspondingly different pressure rate increases and decreases within the plasma processing volume 110 to correspond with the opening and closing of the ports 116.

[58] Figs. 3A-3D are schematic diagrams of an alternative small volume plasma processing chamber system 300, in accordance with one embodiment of the present

[62] Fig. 3F is a detailed perspective view the conductance control structure 302 and the plasma confinement structure 114, in accordance with one embodiment of the present invention. The plasma confinement structure 114 includes many radial slot shaped outlet ports 116' in the bottom facing portion 114A. The slot shaped outlet ports 116' extend outward from the interior portion 114A' toward the peripheral portion 114B.

[63] Figs. 4A and 4B are schematic diagrams of an alternative small volume plasma processing chamber system 400, in accordance with one embodiment of the present invention. The small volume plasma processing chamber system 400 is substantially similar to the small volume plasma processing chamber system 200 described in Fig. 2A and 2B, above. The primary difference is the multiple outlet ports 116' are formed between corresponding plasma confinement rings 402 in the outer periphery ~~114A~~ of the plasma confinement structure 114. The plasma confinement rings 402 are shown collapsed together or closed in Fig. 4A, thus with the outlet ports 116' being substantially fully restricted or closed.

[64] Operationally, the small volume plasma processing chamber system 400 is substantially similar to the small volume plasma processing chamber system 200. By way of example, separating the plasma confinement rings 402 reduces the restriction the outlet flow through the outlet ports 116' as a width W1 of the outlet ports is increased. Separating and collapsing the plasma confinement rings 402 in respective direction 404A, 404B can correspondingly modulate the pressure within the plasma processing volume 110.

[65] Figs. 5A and 5B are simplified cross-sectional views of an alternative small volume plasma processing chamber system 500, in accordance with one embodiment of the present invention. Figs. 5C and 5D are detailed views of a portion of the bottom facing or substantially horizontal portion 114A of the plasma confinement structure 114 in an alternative small volume plasma processing chamber system 500, in accordance with one embodiment of the present invention.

[66] The small volume plasma processing chamber system 500 is substantially similar to the small volume plasma processing chamber system 200 described in Fig.

2A and 2B, above. The primary difference is restriction of the outlet flow through the multiple outlet ports 116 is increased and decreased by shifting the conductance control structure ~~202~~ 202" in a rotational direction 504A or 504B to align or partially align the outlet ports 116 with the corresponding openings 516 in the conductance control structure.

[67] The positioning actuator 207' can move or shift or rotate the conductance control structure ~~202~~ 202" in rotational directions 504A and 504B. As shown in Figs. 5A and 5C, the outlet ports 116 are not aligned the corresponding openings 516 in the conductance control structure and thus the outlet flow through the ports is substantially fully restricted. As shown in Figs. 5B and 5D, the outlet ports 116 are aligned the corresponding openings 516 in the conductance control structure and thus the outlet ports are open and substantially fully unrestricted. It should be understood that the outlet ports 116 can be partially aligned with the corresponding openings 516 in the conductance control structure and thus the outlet flow through the outlet ports can be adjusted between substantially fully unrestricted and substantially fully restricted.

[68] Figs. 5E-G are simplified cross-sectional views of an alternative small volume plasma processing chamber system 550, in accordance with one embodiment of the present invention. The small volume plasma processing chamber system 550 is substantially similar to the small volume plasma processing chamber system 500 described in Fig. 5A-D, above. The primary difference is that the outlet flow through only a portion of the multiple outlet ports 116, 116', 116", 116'" are restricted or unrestricted at any one time and thus allowing an asymmetrical the outlet flow operation.

[69] By way of example, as shown in Fig. 5E all of the outlet ports 116, 116', 116", 116'" are substantially fully restricted. The openings 516 in the conductance control structure ~~202~~ 202" are shown offset in phantom because the openings are not aligned with the outlet ports 116.

[70] Referring to Fig. 5F, the openings 516 are shifted to align with outlet ports 116 and thus only the outlet flow through the outlet ports 116 are substantially fully unrestricted, while the outlet flow through the remaining outlet ports 116', 116", 116'"

[78] It should also be understood that the conductance control structure 602 can also include openings 616 in the substantially horizontal portion 602A. The openings 616 in the substantially horizontal portion 602A correspond to outlet ports 116 in the substantially horizontal portion 114A of the plasma confinement structure 114 as described in the preceding figures.

[79] Fig. 7 is a flowchart diagram that illustrates the method operations 700 performed in varying the pressure within the plasma processing volume 110, in accordance with embodiments of the present invention. In an operation 705, the outlet flow through at least one outlet port 116, 116' in the plasma confinement structure 114 is substantially fully unrestricted. The outlet flow through the least one port outlet 116, 116' in the plasma confinement structure 114 can be substantially fully unrestricted by moving the corresponding conductance control structure 202, 302, 402, ~~502~~ 202", 602 so as to align the at least one outlet port with or create corresponding openings 216, 316, 516 and/or 616.

[80] In an operation 710, one or more processing gases are injected into the plasma processing volume 110. In an operation 715, the process gases ~~102~~ flow in at least one substantially radial direction 112 through the plasma processing volume 110 toward one or more outlet ports 116, 116' in the plasma confinement structure 114 at the *periphery of the plasma processing volume.*

[81] In an operation 720, a plasma is formed in the plasma processing volume 110 by applying an RF signal to at least one of the top electrode 108 or the substrate support 106 (e.g. bottom electrode) from the respective RF sources 117B, 117A. The flow of the process gases ~~102~~ distribute the ions, radicals and neutrals generated by the plasma.

[82] In an operation 725, the pressure is increased in the plasma processing volume 110. The pressure in the plasma processing volume 110 can be increased by substantially fully restricting the outlet flow through least a portion of the at least one outlet port 116, 116'. The outlet flow through the at least one outlet port 116, 116' can be substantially fully restricted by shifting the conductance control structure 202, 302,

202",
402, ~~502~~, 602 to restrict or block the at least one outlet port as shown in the figures above.

[83] The pressure in the plasma processing volume 110 can increase at a rate of upto about 30 mtorr/100ms. The amount of pressure increase can also be controlled by varying the flowrate of the process gases from the process gas sources 102 into the plasma processing volume 110.

[84] As discussed above, as little as about 5 mtorr pressure change, either an increase or a decrease, can make significant process variations due to the corresponding changes in the plasma chemistries. By way of example, as the pressure changes in the plasma processing volume 110, the ratio of ions, radicals and neutrals and the plasma density varies.

[85] As the pressure reaches a desired set point, one or both of the RF sources 117A, 117B can optionally remain constant, be modulated, reduced, enabled or disabled operational state to also allow further selection of the ratios of ions, radicals and neutral species in the plasma.

[86] In an operation 730, the pressure is decreased in the plasma processing volume 110. The pressure in the plasma processing volume 110 can be decreased by reducing the restriction of the outlet flow through at least a portion of the outlet ports 116, 116'. The outlet flow through the outlet ports 116, 116' can be increased (e.g., less restricted) by shifting the conductance control structure 202, 302, 402, ~~502~~, 602 to align or create openings to correspond to the outlet ports 116, 116'. Reducing the restriction of the outlet flow through the outlet ports 116, 116' allows the process gases and the plasma byproducts to rush toward the outlet ports and the outlets, e.g., vacuum pumps, of the plasma processing chamber 201. The pressure in the plasma processing volume 110 can decrease at a rate of up to about 20 mtorr/100ms. The rate of change of the pressure can be selected from between about 1mtorr/100ms to about 20 mtorr/100ms with movement of the conductance control structure. For a rotary type configuration such as shown in Figs. 3F and 5A-6, the conductance change could be even faster than 20 mtorr/100ms. Reducing the pressure in the plasma processing volume 110 moves plasma byproducts away from a center region 120 of plasma

202",

processing volume. As a result, some radial non-uniformity effects of the plasma processing can be reduced or eliminated.

[87] As described above, an asymmetrical flow of the processing gases uses the non-uniform nature of asymmetrical venting, e.g., substantially fully unrestricted outlet flow through only a selected portion or segment of the outlet ports 116, 116', can vary the etch rate in a corresponding asymmetrical pattern. The asymmetrical ~~the~~ outlet flow through outlet ports ~~that~~ can be selectively moved around the surface being processed to counteract radial non-uniformities.

[88] As the pressure reaches a desired set point, one or both of the RF sources 117A, 117B can optionally remain constant, be modulated, reduced, enabled or disabled operational state to further select or control the ratios of ions, radicals and neutral species in the plasma.

[89] In an operation 735, the method operations can end if no additional pressure cycles are required in the plasma processing volume 110. Alternatively, if additional pressure cycles are required in the plasma processing volume 110 then the method operations can continue in an operation 725 above.

[90] Figs. 8A is graphical representation 800 of multiple pressure cycles within the plasma processing volume 110, in accordance with embodiments of the present invention. Figs. 8B is detailed view of a portion 830 of the graphical representation 800 of multiple pressure cycles within the plasma processing volume 110, in accordance with embodiments of the present invention. As described above, the pressure within the plasma processing volume 110 can be varied at a rate of about 10 Hz or more, depending on the desired pressure change and the possible rate of pressure change. Each cycle of the pressure change can be accomplished by a cycle of closing the ports 116, 116' and opening the ports. The conductance control structure 202, 302, 402, ~~502~~ 202", 602 of the various embodiments described above can be cycled through the port 116, 116' substantially fully unrestricted position and substantially fully restricted position and various positions between fully restricted and fully unrestricted to provide the desired cycle of the pressure change. By way of example, the positioning actuator 207 can alternate the conductance control structure 202 in directions 204A and 204B.

Similarly, conductance control structures ~~502~~ 202" and 602 can be rotated or stepped at a substantially continuous rate to provide the desired cycle and rate of the pressure change in the plasma processing volume 110. The flow rate of the process gases from the process gas source 102 into the plasma processing volume 110 can also be selected to increase or decrease the pressure within the plasma processing volume.

[91] Referring to Figs. 8A and 8B, a control signal graph 810 is shown superimposed to a pressure graph 820 of the pressure within the plasma processing volume 110. The control signal graph 810 shows the control signals to increase and decrease restriction on the outlet flow through the outlet ports 116, 116'. Time in seconds is shown across the horizontal axis. At time of about 3.15 sec, the control signal substantially fully restricts the outlet flow through the outlet ports 116, 116'. At about time 3.2 sec, the pressure begins a gradual increase from about 20 mtorr to about 90 mtorr at time 3.3 ~~m~~sec.

[92] Referring to Fig. 8B, time in seconds is shown across the horizontal axis. At end of 32nd second the pressure begins to change from 20mT and at end of 33rd second, the pressure has risen to about 90mT. This pressure change is 70mT/1sec or 70mT/1000ms. Fig. 8B shows a time delay error due to lack of fast pressure measurement instruments. However, the actual pressure change is proportional to change in conductance control structure position, such that the actual rate of change in pressure is about 70mT/500ms as is graphed in Fig 8C.

[93] The pressure is maintained at about 90 mtorr. At a time of about 33.6 ~~3.36~~ sec the control signal switches to reduce the restriction on the outlet flow through the outlet ports 116, 116'. At a time of about 33.7 ~~3.37~~ sec, the pressure begins to decrease to arrive at about 20 mtorr at a time of about 35 ~~3.5~~ sec. The pressure stabilizes at about 20 mtorr until the control signal increases the restriction on the outlet flow through the outlet ports 116, 116' at time about 36 ~~3.6~~ sec. The cycle then repeats.

[94] Fig. 8C is a graph representation 850 of the rate of pressure change, in accordance with embodiments of the present invention. As shown the rate of pressure change in the plasma processing volume 110 is about 17 mtorr per 100 msec. Thus allowing up to about a 17 mtorr pressure change cycle at a rate of about 10Hz.

[101] Pressure changes in the plasma processing volume 110 determine the ratios of ions, radicals and neutral species in the plasma. Fig. 10 is a graphical representation 1000 of ion and neutral flux densities, in accordance with embodiments of the present invention. The ion flux density graph 1010 is a substantially constant density, e.g., about 4.5, over a range of pressures between about 2 and about 20 mtorr. The neutral flux density graph 1020 varies widely from a density less than about 1 x 10^{14} to more than about 6.5 X 10^{14}. The neutral flux density ~~drops~~ increases substantially linearly with pressure.

[102] As shown in Fig. 10, a variation from 5 mtorr to 15 mtorr would have substantially the same ion flux density. In contrast, the neutral flux density would vary from about 1 to about 4, i.e., a factor of 4 times the density at the 15 mtorr, higher pressure, as compared to the 5 mtorr lower pressure. As a result, this 10 mtorr manipulation or modulation of the pressure gives a only limited selection of the ion flux density while at the same time gives broad selection to the neutral flux density. The etching performance of the different ratios can then be selected by the corresponding pressure of the plasma processing volume 110.

[103] Fig. 11A is a series ~~1100~~ of photos of prior art, constant pressure etch process results. The first view 1110 is a first etch process executed at a constant 12 mtorr. Each of the features 1112 has a tapered shape with the lower portion of the feature coming almost to a point when a wider, flatter bottom portion would be a much preferred result. A detailed view 1114 shows an acceptable profile in the mid depth of the feature. A preferred feature profile would have the acceptable profile of the mid depth (e.g., smooth, parallel sides) of the feature throughout the full depth of the feature.

[104] The second view 1120 is a second etch process executed at a constant 40 mtorr. Each of the features 1122 has a less tapered shape than the features 1112, however undesirable striation type non-uniformities are formed in the mid depth profile 1124. The third view 1130 is a third etch process executed at a constant 70 mtorr. Each of the features 1132 has a tapered shape similar to the features 1112, however undesirable striation type non-uniformities are also formed in the mid depth profile 1134.

[105] Fig 11B compares the constant pressure etch process 1120 to a pulsed pressure etch process 1150, in accordance with embodiments of the present invention. The pulsed pressure etch process 1150 varies the etch pressure within the plasma processing volume 110 from between about 12 mtorr and about 70 mtorr. The pulsed pressure etch process 1150 yields an improved profile similar to the 40 mtorr constant pressure etch process 1120 but also eliminates the undesireable striations as shown in the details view 1154 and further squares off the lower portions of the features 1152.

[106] Fig. 12A is a graph 1200 showing the relationship of pressure and lateral etching, *in accordance with embodiments of the present invention.* Fig. 12B is a simplified schematic diagram 1250 of high aspect ratio contact features, in accordance with embodiments of the present invention. In an etch process to form a high aspect ratio contact (HARC), such as for a DRAM device, as the critical dimension (i.e., width Fw of the features F1, ~~F1~~ F2) becomes smaller and the pitch P between the features F1, F2 is decreased (i.e., features are more closely spaced), an undesirable lateral etch can occur near the opening or top end of the features.

[107] The lateral etch etches into the sidewalls of the features F1, F2 to form a bowed sidewall 1260. If the lateral etch occurs too quickly, then the bowed sidewall 1260 can form a hole in the area 1262 between the adjacent features F1 and F2 and thus result in a short circuit between the two adjacent features. Therefore, the lateral etching needs to be minimized while also improving the bottom profile and depth Fd1 of the feature F1 as compared to the lesser depth Fd2 of feature F2.

[108] The graph 1200 as shown in Fig. 12A illustrates the effect of the operating pressure and the sidewall bowing 1260 and the depth and profile of the lower end of the features F1, F2. At lower pressures, fewer ions 1252, 1254 deflect off other ions due to the reduce density of ions present in the lower pressure. Thus, at lower pressures the directionality of the ions 1252, 1254 entering the features F1, F2 is improved and more ions reach the bottom of the feature to perform the desired directional etch. Further, as more ions 1252, 1254 enter the features, less ions deflect off the mask layer 1256 to impinge on the sidewall to produce the sidewall bowing 1260 (e.g., undesirable lateral etch)

The quantity of radicals 1406 present in the plasma processing volume 110 decays at a still slower rate, approaching zero at a time T1+ about 500 microseconds or more.

[116] As a result of the different decay rates the reactive specie varies over time. By way of example, at a time T0 steady state levels 1402A, 1404A, 1406A are shown. At a time T2, some time after T1 + about 50 microseconds, substantially all of the electrons 1402 are gone and yet the quantity of ions 1404 and radicals 1406 is substantially equal to the respective steady state levels 1404A, 1406A. Similarly, at a time T3, some time after T1 + about 200 microseconds, substantially all of the electrons 1402 and all of the ions 1404 have decayed to about zero, yet the quantity of radicals 1406 is still quite high and in some circumstances may be substantially equal to the radical steady state level 1406A. As the ratios of the reactive specie vary at times T0, T2 and T3, different processes can be more effectively applied at the respective times T0, T2 and T3.

[117] Insert examples of different processes at time T0, T2 and T3.

[118] Fig. 14B is a graphical representation of multiple timing sequences 1420-1470 of pressure pulse and RF modulation, in accordance with embodiments of the present invention. In timing graph 1420, the RF power modulation is approximately 180 degrees out of phase with process gas flow. As a result, at a time T1, the RF power is increased and the process gas flow is reduced. This timing graph 1420 can be termed 180 degrees out of phase, with the RF power modulation synchronized with the gas flow modulation. The resulting optical emission trace 1422 shows an argon (800 nm wavelength) trace proportional to both concentration and RF power. These graph illustrate a ~~synchronize~~ synchronized RF power and process gas modulation with a slight time offset due to instrumentation error.

[119] In timing graph 1430, the RF power modulation is approximately 200 degrees out of phase with process gas flow. As a result, at a time T1, the RF power is increased and an about 20 degree delay after T1, the process gas flow is reduced. This timing graph 1430 can be termed 180 degrees out of phase, with the RF power modulation leading the gas flow modulation. The resulting optical emission trace 1432 shows an argon (800 nm wavelength) trace proportional to both concentration

and RF power. Rising edge spikes indicate when the RF pulses are lagging the gas pulse. Falling edge spikes indicate when the RF pulses are leading the gas pulse. OES shows an actual transition time of a first process gas mixture to a second process gas mixture, while synchronizing with RF pulse and process gas pressure.

[120] In timing graph 1440, the RF power modulation is approximately 160 degrees out of phase with process gas flow. As a result, at a time about 20 degrees before T1, the process gas flow is reduced, and at time T1, the RF power is increased. This timing graph 1440 can be termed 180 degrees out of phase, with the gas flow modulation leading the RF power modulation. The resulting optical emission trace 1442 shows an argon (800 nm wavelength) trace proportional to both concentration and RF power. Rising edge spikes indicate when the RF pulses are lagging the gas pulse. Falling edge spikes indicate when the RF pulses are leading the gas pulse 1442. ~~shows...~~

[121] In timing graph 1450, the RF power modulation is approximately in-phase with process gas flow. As a result, at a time T1, the RF power is increased and the process gas flow is increased. This timing graph 1450 can be termed in-phase, with the RF power modulation synchronized with the gas flow modulation. The resulting optical emission trace 1452 shows an oxygen (770 nm wavelength) trace proportional to both concentration and RF power...

[122] In timing graph 1460, the RF power modulation is approximately 20 degrees out of phase with process gas flow. As a result, at a time T1, the RF power is increased and at a time of T1 plus about 20 degrees, the process gas flow is increased. This timing graph 1460 ~~1440~~ can be termed in-phase, with the RF power modulation leading the gas flow modulation. The resulting optical emission trace 1462 shows an oxygen (770 nm wavelength) trace proportional to both concentration and RF power. The steps indicate when the RF pulses are not in synch with the gas pulse ...

[123] In timing graph 1470, the RF power modulation is approximately negative 20 degrees out of phase with process gas flow. As a result, at a time of about 20 degrees before T1, the process gas flow is increased and at time T1, the RF power is increased. This timing graph 1470 can be termed in-phase, with the gas flow modulation leading

structure 114 can be substantially fully unrestricted by moving the corresponding conductance control structure 202, 302, 402, ~~502,~~ 202" 602 so as to align the at least one outlet port with or create corresponding openings 216, 316, 516 and/or 616.

[127] In an operation 1810, one or more processing gases are injected into the plasma processing volume 110. In an operation 1815, the process gases 102 flow in at least one direction 112 through the plasma processing volume 110 toward one or more outlet ports 116, 116' in the plasma confinement structure 114 at the periphery of the plasma processing volume.

[128] In an operation 1820, a plasma is formed in the plasma processing volume 110 by applying an RF signal to at least one of the top electrode 108 or the substrate support 106 (e.g. bottom electrode) from the respective RF sources 117B, 117A. The flow of the process gases 102 distribute the ions, radicals and neutrals generated by the plasma.

[129] In an operation 1825, the pressure is increased in the plasma processing volume 110. The pressure in the plasma processing volume 110 can be increased by substantially fully restricting the outlet flow through least a portion of the at least one outlet port 116, 116' as described in more detail above.

[130] As the pressure reaches a desired set point, one or both of the RF sources 117A, 117B can be modulated, reduced, enabled or disabled operational state to also allow further selection of the ratios of ions, radicals and neutral species in the plasma in an operation 1830.

[131] In an operation 1835, the pressure is decreased in the plasma processing volume 110. The pressure in the plasma processing volume 110 can be decreased by reducing the restriction of the outlet flow through at least a portion of the outlet ports 116, 116'as described in more detail above.

[132] As the pressure reaches a desired set point, one or both of the RF sources 117A, 117B can be modulated, reduced, enabled or disabled operational state to further select or control the ratios of ions, radicals and neutral species in the plasma in an operation 1840.

Claims

1. A plasma processing system comprising:

a processing chamber;

at least one gas source coupled to the processing chamber;

a controller coupled to the processing chamber and the at least one gas source;

the processing chamber including:

a top electrode disposed within a top portion of the processing chamber;

a substrate support disposed opposite from the top electrode;

a plasma processing volume having a volume less than a volume of the processing chamber, the plasma processing volume being defined by:

a surface of the top electrode;

a supporting surface of ~~a~~ the substrate support opposing the surface of the top electrode; and

an outer perimeter defined by a plasma confinement structure,

the plasma confinement structure including at least one outlet port;

at least one RF source coupled to at least one of the substrate support or the top electrode; and

a conductance control structure movably disposed proximate to the at least one outlet port, wherein the conductance control structure restricts an outlet flow through the at least one outlet port when disposed in a first position to a first flow rate and wherein the conductance control structure increases the outlet flow through the at least one outlet port when disposed in a second position to a second flow rate, wherein the conductance control structure moves between the first position and the second position corresponding to a selected processing state set by the controller during a plasma process and wherein the at least one RF source is modulated corresponding to the selected processing state set by the controller during the plasma process.

2. The system of claim 1, wherein the modulation of the at least one RF source is substantially in-phase with the selected processing state.

3. The system of claim 1, wherein the modulation of the at least one RF source is substantially 180 degrees out of phase with the selected processing state.

4. The system of claim 1, wherein the modulation of the at least one RF source lags the selected processing state.

5. The system of claim 1, wherein the modulation of the at least one RF source leads the selected processing state.

6. The system of claim 1, wherein the at least one RF source ~~i~~includes a high frequency RF source having an output of about 27 MHz.

7. The system of claim 1, wherein the at least one RF source includes a high frequency RF source having an output of about 60 MHz.

8. The system of claim 1, wherein the at least one RF source includes a high frequency RF source having an output of greater than about 27 MHz and low frequency RF source having an output of about 2 MHz.

9. The system of claim 1, wherein the controller coordinates an input flow rate of the at least one gas source into the processing volume with coordination of the movement of the conductance control structure and the modulation of the at least one RF source.

10. The system of claim 1, wherein the at least one outlet port in the plasma confinement structure is formed in a substantially horizontal portion of the plasma confinement structure.

11. The system of claim 1, wherein the at least one outlet port in the plasma confinement structure is formed in a substantially vertical portion of the plasma confinement structure.

12. A method of modulating a pressure in-situ in a plasma processing volume of a chamber, the plasma processing volume defined between a surface of a top electrode, a supporting surface of a substrate support and an outer region defined by a plasma confinement structure, the plasma confinement structure including at least one outlet port, the method comprising:

injecting at least one processing gas into the plasma processing volume;

forming a plasma within the plasma processing volume; and

modulating a pressure and modulating at least one RF source coupled to the plasma processing volume during a period of time when the plasma is formed in the plasma processing volume, the modulating of the pressure being controlled by at least one of,

a first outlet flow out of the plasma processing volume from the at least one outlet port, the first outlet flow through a restricted flow path out of the at least one outlet port, or

a second outlet flow out of the plasma processing volume from the at least one outlet port, the second outlet flow being greater than the first outlet flow, wherein the second outlet flow being through a less restricted flow path out of the at least one outlet port than the first outlet flow.

13. The method of claim 12, wherein the period of time when the plasma is formed corresponds to a processing recipe having one or more predefined pressure set points and RF modulation set points.

14. The method of claim 13, wherein each of the predefined pressure set points corresponds to one of the first outlet flow or the second outlet flow or an outlet flow between the first outlet flow and second outlet flow.

15. The method of claim 12, wherein the pressure in the plasma processing volume is increased when the restriction of the conductance path is increased and the pressure