the RF OFF period when the plasma shuts off. Typically, during the RF OFF period, the plasma potential collapses and electrons escape to the walls of the chamber. In the afterglow, the electron density drops and the negative ion density increases. Then ions to escape to the walls as well. The charged species dynamics determines the distribution of charges inside the chamber and, therefore, its etching properties, but unfortunately these dynamics and fluxes of charged species are mostly uncontrolled. The only controls available for the afterglow period are the frequency of the modulation and the duty cycle.

[0006] Another problem with pulsed plasma technology is plasma re-ignition when the RF power turns on. If the plasma and the afterglow are extinguished completely during the RF OFF period, re-striking the plasma requires high RF voltage levels. Further, there can be trouble with RF issues, especially when operating at low gas pressures.

[0007] It is in this context that embodiments arise.

SUMMARY

[0008] Embodiments of the present invention provide systems, methods, and computer programs for processing a semiconductor substrate in a pulsed plasma chamber in a dual chamber configuration.

[0009] It should be appreciated that the present invention can be implemented in numerous ways, such as a process, an apparatus, a system, a device or a method on a computer readable medium. Several inventive embodiments of the present invention are described below.

[0010] In one embodiment, a wafer processing apparatus with a top chamber and a bottom chamber separated by a plate that fluidly connects the top chamber to the bottom chamber includes a continuous wave (CW) controller, a pulse controller, and a system controller. The CW controller is operable to set the voltage and the frequency for a first radio frequency (RF) power source coupled to a top electrode in the top chamber. The pulse controller is operable to set voltage, frequency, ON-period duration, and OFF-period duration for a pulsed RF signal generated by a second RF power source coupled to the bottom electrode in the bottom chamber. Further, the system controller is operable to set parameters for the CW controller and the pulse controller to regulate the flow of species from the top chamber to the bottom chamber through the plate during operation of the chambers. The flow species assists in the negative ion density control during afterglow in the OFF period, and assists in the re-striking of the plasma in the bottom chamber during the ON period.

[0011] In another embodiment, a method, for processing a wafer in a wafer processing apparatus with a top chamber and a bottom chamber separated by a plate that fluidly connects

the top chamber to the bottom chamber, includes an operation for setting first parameters for a continuous radio frequency (RF) signal generated by a first RF power source coupled to a top electrode in the top chamber. The first parameters include a first voltage and a first frequency. Further, the method includes an operation for setting second parameters for a pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber. The second parameters include a second voltage, a second frequency, ON-period duration, and OFF-period duration. The continuous RF signal is applied to the top electrode, and the pulsed RF signal is applied to the bottom electrode. Setting the first parameters and the second parameters regulates the flow of species from the top chamber to the bottom chamber during operation of the chambers. The flow of species assists in a negative ion density control during afterglow in the OFF period, and assists in re-striking a plasma in the bottom chamber during the ON period.

[0012] In yet another embodiment, a wafer processing apparatus, with a top chamber and a bottom chamber separated by a plate that fluidly connects the top chamber to the bottom chamber, comprises a CW controller, a pulse controller, and a system controller. The CW controller is operable to set first parameters for a first radio frequency (RF) power source coupled to a top electrode in the top chamber, and the pulse controller is operable to set second parameters for a second pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber. The pulse controller is further operable to set third parameters for a third pulsed RF signal generated by a third RF power source coupled to the bottom electrode. Additionally, the system controller is operable to transfer the first, second, and third parameters to regulate a flow of species from the top chamber to the bottom chamber through the plate during operation of the chambers. The flow of species assists in the negtative ion density control during afterglow in the OFF period, and assists in re-striking the plasma in the bottom chamber during the ON period.

[0013] Other aspects will become apparent from the following detailed description, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The invention may best be understood by reference to the following description taken in conjunction with the accompanying drawings.

[0015] Figure 1 shows an etching chamber, according to one embodiment.

[0016] Figure 2 illustrates the behavior of a pulsed plasma chamber, according to one embodiment.

surface of the wafer. This is known as ion bombardment or ion sputtering. Some industrial plasmas, however, do not produce ions with enough energy to efficiently etch a surface by purely physical means. It has been proven that ~~that~~ the combined actions of both neutral-gas etching and ion bombardment produces a faster etch rate than simply adding the effects of each method.

[0028] In one embodiment, Fluorocarbon gases, such as CF_4 and C-C_4F_8, are used in the dielectric etch process for their anisotropic and selective etching capabilities, but the principles of the invention can be applied to other plasma-creating gases. The Fluorocarbon gases are readily dissociated into smaller molecular and atomic radicals. These chemically reactive by-products etch away the dielectric material, which in one embodiment can be SiO_2 or SiOCH for low-k devices.

[0029] The chamber of Figure 1 includes a top electrode 104 connected to ground, and a bottom electrode 108 powered by low-frequency RF generator 118 and high-frequency RF generator 116. The bottom electrode 108 is connected, via matching network 114, to the low-frequency RF generator 118 and to the high-frequency RF generator 116. In one embodiment, low-frequency RF generator 118 has an RF frequency of 2 MHz, and high-frequency RF generator 116 has an RF frequency of 27 MHz.

[0030] The chamber of Figure 1 includes a gas showerhead on the top electrode 104 to input gas in the chamber, and a perforated confinement ring 112 that allows the gas to be pumped out of the chamber. When substrate 106 is present in the chamber, silicon focus ring 110 is situated next to the substrate such that there is a uniform RF field at the bottom surface of the plasma 102 for uniform etching on the surface of the wafer.

[0031] In one embodiment, low-frequency RF generator 118 is pulsing while high-frequency RF generator 116 is not pulsing. In another embodiment, both RF generators are pulsing, and, in yet another embodiment, the high-frequency RF generator 116 is pulsing while low-frequency RF generator 118 is not pulsing, i.e., low-frequency RF generator 118 is always turned on while processing the wafer.

[0032] Figure 2 illustrates the behavior of a pulsed plasma chamber, according to one embodiment. The pulsed plasma chamber associated with Figure 1 includes one pulsing RF power source. Graph 202 illustrates the voltage of the RF power source, that includes an ON period, when the RF power source is turned on, and an OFF period, when the RF power source is turned off. The graph 204 illustrates that the power of the RF power source has two levels,

Charges can build up between the top and the bottom of a well during continues discharge, which can cause the deflection of ions. The charge buildup can be reduced in pulsed discharges because the low electron density in the afterglow regime allows more negative ions and electrons to be pulled to the well bottom, to neutralize the positive charges that might have accumulated at the bottom of the well.

[0039] Figure 3 illustrates the effect of RF power frequency and chamber pressure on the plasma density, according to one embodiment. Figure 3 illustrates some measurements taken on a non-pulsing plasma chamber under different conditions of RF power frequency and pressure in the chamber. The measurements were taken with a single RF power source at 400 W, in a chamber with oxygen and 5% Argon.

[0040] Line 302 charts the values for the positive ion flux at different levels of pressure and with an RF frequency of 2 MHz. As the pressure in the chamber increases, the ~~negative~~ positive ion flux increases to about a maximum positive ion flux at about 300 mTorr. Therefore, for a low RF frequency (2 MHz), the chamber is more efficient at high pressure. Line 306 charts the volumes when the RF frequency is 27 MHz. In this case, the flux gradually increases until the pressure is about 100 mTorr, and then remains substantially constant. Line 304 charts the values for the flux when using an RF frequency of 60 MHz. At this high frequency, the chamber is more efficient at low pressure, and less efficient as the pressure increases.

[0041] In general, when using a pulsed RF power, it is more desirable to run the chamber at low pressure, so the ions can penetrate deep in the holes. However, it is relatively hard to strike plasma in a low pressure plasma chamber, because there are fewer electrons when operating at low pressure than when operating at high pressure.

[0042] Embodiments of the invention utilize a dual chamber configuration, where the bottom chamber is pulsed ~~on~~ and the top chamber is not pulsed. As discussed in more detail below with reference to Figures 4-6, the two chambers are separated by a perforated grid that provides flow of species from the top chamber to the bottom chamber. Electrons escape the top plasma and flow to the bottom chamber to assist in the re-striking of the plasma. Since there are ~~have~~ more electrons in the bottom chamber, it is easier to re-strike the plasma. Therefore, the use of the dual chamber facilitates having a low pressure chamber and a pulsed RF power source at the same time.

[0043] Figure 4 shows a semiconductor wafer processing apparatus with two chambers, according to one embodiment of the invention. The semiconductor wafer processing apparatus includes a dual volume plasma source. Top chamber 414 is a Continuous Wave (CW) Radical

Control Plasma (RCP) chamber, separated from lower pulsed RF capacitive plasma chamber 420 by perforated grounded electrode 424, also referred to herein as plate or grid. The lower volume is a pulsing CCP plasma chamber, and the upper volume acts as a source of radicals, electrons, and ions that are injected into the lower volume.

[0044] During the afterglow in the OFF period of the pulsed lower-chamber RF, the flux of neutral and charged species in the lower chamber can be controlled by adjusting the parameters in the top chamber. Having charged species from the RCP top chamber flowing to the lower chamber also helps with re-striking the bottom plasma 418 during the RF ON period. In one embodiment, the afterglow and re-striking is controlled by using different plasma sources in the upper chamber. For example, using an inductively coupled or helicon plasma in the top chamber.

[0045] This configuration improves performance of the chamber, because the upper plasma 416 source provides control of the plasma afterglow in the bottom chamber, and provides control of the charged species dynamics for etching substrate 422. Furthermore, the RCP in the top chamber helps to re-ignite the plasma 418 in CCP bottom chamber by providing initial charged species to strike the CCP plasma.

[0046] In a single volume pulsing chamber, the only control for negative ion etching is the ON and OFF period cycles. In a dual-volume chamber, since the upper chamber is always on, there is a constant flow of species coming from the top chamber, even in the bottom chamber OFF period. Therefore, it is possible to control the etching process both in the ON and OFF periods. The electrons from the top plasma 416 go through the through-holes 426 that connect the top chamber to the bottom chamber. The electrons carry energy, so the through-holes 426 form electron beams into the bottom chamber.

[0047] In one embodiment, bottom chamber 420 is powered by a first pulsed RF power source 406 and by a second pulsed RF power source 410. The RF power sources are connected to the bottom electrode in chamber 420 via respective RF Matches 408 and 412. The top electrode in top chamber 414 is connected to a third RF power source 402 via matching network 404. In one embodiment, the third RF power source 402 provides a continuous wave RF power to top chamber 414.

[0048] A pulse controller 430 controls the parameters for the RF power generated by the first pulsed RF power source 406 and by the second pulsed RF power source 410. The parameters that control the first and the second RF power sources include the pulsing cycle (i.e., the duration of the ON and OFF periods) of the RF power sources, the frequency, the voltages, and

the power levels for the first and second RF power sources. By controlling the parameters of the RF power sources, the system controls, for example, the RF OFF period and the plasma afterglow in the bottom chamber. This control of the RF parameters also enables the system to control the flux of neutral and charged species from the top chamber. Having charged species from the top chamber traveling to the lower chamber also assists with the re-striking of the plasma at the beginning of the RF ON period, which means that plasma re-strikes faster than in the case of a single chamber device with the same RF power.

[0049] A continuous wave controller 428 controls the RF power generated by third RF power source 402. Thus, the continuous wave controller 428 controls the parameters of the RF power on the top chamber, which include frequency, voltage, and power. System controller 432 is in communication with pulse controller 430 and continuous wave controller 428, and system controller 432 sets the control parameters for the RF power in the top and bottom chambers. By controlling the parameters for the CW controller and the pulse controller, the system controller 432 is operable to regulate the flow of species from the top chamber to the bottom chamber through the plate during operation of the chambers, where the flow of species assists in the negative-ion etching and in neutralizing excessive positive charge on the wafer surface during afterglow in the OFF period, and assists in the re-striking of the plasma in the bottom chamber during the ON period. System controller 432 has plasma recipe setting 434 as an input. The plasma recipe setting 434 includes the parameters for the three RF power sources, including frequency, voltage, power, and ON/OFF cycles, and other parameters for the operation of the chambers. Other values in the plasma recipe setting may include the configuration of the plate separating the chambers (e.g., the number of through-holes, the thickness of the plate, the distribution of the through-holes, etc.), the pressure in the top chamber, the pressure in the bottom chamber, duration of the etching cycle, gas flow into the chambers, etc.

[0050] Besides controlling the RF power sources, system controller 432 is also operable to control other parameters of the chamber, such as the pressure in the top chamber, the pressure in the bottom chamber, and the configuration of the plate 424 situated between the top and bottom chambers.

[0051] The top and bottom chambers have independent controls for the gas flow into the respective chambers. There is a separate source of gas intake in the top chamber. The grid 424 also includes gas outlets that form a gas showerhead into the bottom chamber. Grid 424 has an outside surface which is an insulator dielectric, such as aluminum oxide. In one embodiment, grid 424 is made of aluminum and coated with aluminum oxide. In another embodiment, the

grid is made of silicon. Grid 424 is connected to ground. In one embodiment, grid is 27 mm thick, (i.e., the through-holes have the length of 27 mm), and the through-holes have a diameter of 2 mm, although other values are also possible.

[0052] Having dual volumes increases the amount of negative ions in the bottom chamber during the OFF period, which improves the etching with negative ions. As electrons from the top chamber arrive at the bottom chamber, the electrons attach to ions and create more negative ions in the chamber during the OFF period.

[0053] There are several parameters of the top chamber that affect the performance of the bottom chamber. First, the electron density in the top chamber. The higher the density, the higher the number of electrons traveling to the bottom chamber. Second, the voltage on the sheath of the top chamber, which defines the energy of some electrons, such as the secondary electrons. Third, the pressure in the chamber. The higher the pressure in the top chamber, the more particles (electrons, ions) that will travel to the bottom chamber. Fourth, the thickness of the plate 424 and the density of through-holes 426. The bigger the thickness of the plate, the less number of species that will travel to the bottom chamber. In addition, the higher the density of the through-holes 426, the more species that will travel to the bottom.

[0054] The embodiment of Figure 4 includes a first pulsed RF power source 406 at 2 MHz and a second pulsed RF power source 410 at 27 MHz. The RF power sources are connected to the bottom electrode in chamber 420 via respective RF Matches 408 and 412. The top electrode in top chamber 414 is connected to a third RF power source 402 via matching network 404. The third RF power source 402 is not pulsing.

[0055] It is noted that the embodiment illustrated in Figure 4 is exemplary. Other embodiments may utilize different types of chambers, different frequencies, only one RF power source in the bottom chamber, different size separation plates, different pressures in top and bottom chambers, etc. For example, in one embodiment, top chamber is a CCP plasma chamber. Furthermore, some of the modules described above in the semiconductor wafer processing apparatus may be combined into a single module, or the functionality of a single module may be performed by a plurality of modules. For example, in one embodiment, continuous wave controller 428 and pulse controller 430 are integrated within system controller 432, although other configurations are also possible. The embodiment illustrated in Figure ~~5~~ 4 should therefore not be interpreted to be exclusive or limiting, but rather exemplary or illustrative.

protective structure, may be secured to the gas distribution unit 515 by a pressure differential between the upper and lower plasma generation volumes 503 and 509, by a number of fasteners, or by a combination thereof. In various embodiments, the plasma resistant coating, the protective structure, used to protect the gas distribution unit 515 can be formed of silicon, silicon carbide, silicon oxide, yttrium oxide, or essentially any other material that provides adequate plasma resistance, electrical conduction, and thermal conduction for the plasma processes to which it is exposed.

[0069] Each of the gas supply ports 519 and through-holes 517 is defined to optimize fluid flow through it, while simultaneously preventing adverse intrusion of plasma into it. Fluid flow and plasma intrusion through each of the gas supply ports 519 and though-holes 517 is directly proportional to its size. Therefore, it is necessary to define each of the gas supply ports 519 and though-holes 517 such that its size is small enough to prevent adverse plasma intrusion into it, while remaining large enough to provide adequate fluid flow through it. In various embodiments, the diameter of the gas supply ports 519 is sized within a range extending from about 0.1 mm to about 3 mm. In various embodiments, the diameter of the through-holes 517 is sized within a range extending from about 0.5 mm to about 5 mm. It should be understood, however, that in various embodiments the gas supply ports 519 and through-holes 517 can be respectively defined with essentially any diameter size, so long as the diameter size provides for adequate fluid flow there through while simultaneously providing for adequate suppression of plasma intrusion therein.

[0070] A chuck 507 is disposed within the interior cavity 500D of the chamber 500 below the lower plasma generation volume 509. In one embodiment, the chuck 507 is cantilevered from the wall 500C of the chamber 500. In one embodiment, the chuck 507 is an electrostatic chuck and provides an electrode for transmitting RF power to the lower plasma generation volume 509. The chuck 507 is defined to hold a substrate 513, i.e., wafer 513, in exposure to the lower plasma generation volume 509. In one embodiment, a wafer edge ring 549 is disposed on the chuck 507 about the periphery of a substrate 513 holding area on the chuck 507. In various embodiments, the wafer edge ring is formed of quartz or silicon. Also, ~~in one embodiment, a conductor 548 is disposed below the wafer edge ring 549, and is connected to drive DC bias through the wafer edge ring 549.~~

[0071] A vertical distance across the lower plasma generation volume 509, as measured perpendicular to both the chuck 507 and the gas distribution unit 515, can be set and controlled by controlling the vertical position of the chuck 507. The vertical distance across the lower

Also, in one embodiment, a pressure manometer is disposed to measure the pressure within the lower plasma generation volume 509. In this embodiment, this measured pressure within the lower plasma generation volume 509 is used to generate feedback signals for controlling the position of the pressure control ring 531, which in turn provides active control of the pressure within the lower plasma generation volume 509.

[0079] It should be understood that both the upper plasma chamber 512 and the lower plasma chamber 514 enclose respective confined plasmas. A confined plasma is beneficial in that its residence time can be controlled by controlling volume, pressure, and flow within the plasma region, i.e., within the upper and lower plasma generation volumes 503 and 509. The plasma residence time affects the dissociation process, which is a factor in radical and neutron formation.

[0080] As previously discussed, the upper and lower plasma chambers 512 and 514 have respective RF power source controls, pressure controls, temperature controls, plasma process gas source controls, and gas flow controls. In various embodiments, a pressure within the upper plasma ~~processing~~ generation volume 503 can be controlled within a range extending from about 100 mTorr to about 1 Torr, or from about 200 mTorr to about 600 mTorr. In various embodiments, a pressure within the lower plasma ~~processing~~ generation volume 509 can be controlled within a range extending from about 5 mTorr to about 100 mTorr, or from about 10 mTorr to about 30 mTorr.

[0081] In the embodiment of Figure 5 with the showerhead electrode 501, the upper plasma chamber 512 is a capacitively coupled plasma chamber. In this embodiment, a vertical distance across the upper plasma generation volume 503, as measured perpendicularly between the lower surface of the showerhead electrode 501 and the upper surface of the gas distribution unit 515, is set within a range extending from about 1 cm to about 5 cm. In one embodiment, this vertical distance across the upper plasma generation volume 503 is about 2 cm. In another embodiment, the showerhead electrode 501 can be functionally replaced by an induction coil, such that the upper plasma chamber 512 is an inductively coupled plasma chamber. In this embodiment, the vertical distance across the upper plasma generation volume 503 can be up to about 12 cm.

[0082] The gas distribution unit 515 is disposed between the upper plasma generation volume 503 and the lower plasma generation volume 509. The gas distribution unit 515 is defined as a plate formed to separate the upper plasma generation volume 503 from the lower plasma generation volume 509, such that an upper surface of the gas distribution unit 515 plate provides a lower boundary of the upper plasma generation volume 503, and such that a lower surface of

the gas distribution unit 515 plate provides an upper boundary of the lower plasma generation volume 509.

[0083] The gas distribution unit 515 is held in a fixed position by the outer structural member 506 of the lower plasma chamber 514. The gas distribution unit 515 is defined to ~~defined to~~ supply a plasma process gas to the lower plasma generation volume 509 through an arrangement of gas supply ports 519. The gas distribution unit 515 is further defined to include an arrangement of through-holes 517 to provide controlled fluid communication between the upper plasma generation volume 503 and the lower plasma generation volume 509. Each of the through-holes 517 extends through the gas distribution unit 515 plate from its upper surface to its lower surface.

[0084] Figure 6 shows the chamber 500 of Figure 5 with an upper plasma ~~501~~ 601 and a lower plasma ~~503~~ 603, in accordance with one embodiment of the present invention. It should be understood that the independent control of the upper and lower plasma chambers 512 and 514 provides for extensive possibilities with regard to wafer processing recipes, particularly concerning the independent control of radical and neutral flux relative to ion flux. A couple of example wafer processes are provided below. However, it should be understood that the example wafer processes disclosed herein are provided as examples only and in no way represent any limitation on use of the dual plasma processing chamber 500 disclosed herein.

[0085] In one example embodiment, the chamber 500 is used to perform a wafer process that utilizes high fluorine radical and neutral flux with low dissociation of CxFy (C4F8, C4F6, etc.) in the wafer processing plasma. In this example embodiment, a mixture of Ar and NF3 is supplied as the plasma process gas to the upper plasma generation volume 503. The upper plasma generation volume 503 is operated at high pressure and high RF frequency (60 MHz). The high fluorine radical and neutral flux is generated in the upper plasma ~~chamber~~ generation volume 503 and is flowed through the through-holes 517 of the gas distribution unit 515. The ions generated in the upper plasma ~~processing~~ generation volume 503 are filtered by the gas distribution unit 515.

[0086] Also, in this example embodiment, a mixture Ar and CxFy gas is supplied as the plasma process gas to the lower plasma generation volume 509. The lower plasma generation volume 509 is operated at low pressure and low to medium RF frequency (2 MHz and 27 MHz) with pulsing RF power. The low RF frequency of the lower plasma generation volume 509 corresponds to low dissociation of CxFy in the plasma exposed to the wafer 513. It should be appreciated that the high power required in the upper plasma generation volume 503 to generate the necessary fluorine radical and neutral flux would cause high dissociation of CxFy if applied

to the lower plasma generation volume 509. Therefore, the dual plasma chamber 500 enables performance of the above described process.

[0087] In another example embodiment, the chamber 500 is used to perform a wafer process that utilizes high dissociation of CxFy (C4F8, C4F6, etc.) in a high pressure volume with a high density Ar plasma in a low pressure volume. In this example embodiment, a mixture of CxFy and Ar is supplied as the plasma process gas to the upper plasma generation volume 503. The upper plasma generation volume 503 is operated at high pressure and high RF frequency (60 MHz) to cause high dissociation of CxFy. The highly dissociated CxFy generated in the upper plasma ~~chamber~~ generation volume 503 flows through the through-holes 517 of the gas distribution unit 515. The ions generated in the upper plasma ~~processing~~ generation volume 503 are filtered by the gas distribution unit 515. Also, in this example embodiment, Ar gas is supplied as the plasma process gas to the lower plasma generation volume 509. The lower plasma generation volume 509 is operated at low pressure and low to medium RF frequency (2 MHz and 27 MHz) to generate a high density Ar plasma with high ion flux.

[0088] It should be appreciated that the dual plasma chamber 500 is defined to decouple radical and neutral flux generation from ionic plasma generation. Also, in one embodiment, the lower plasma chamber 514 can be inactive, i.e., exhaust only, such that radical and neutral flux from the upper plasma chamber 512 can be applied to the wafer 513 without exposing the wafer 513 to a plasma.

[0089] Figure 7 illustrates the normalized ion flux as a function of the plate thickness, according to one embodiment. One of the parameters that affect the interaction between the upper chamber ~~on~~ and the lower chamber is the configuration of the plate between the chambers. The thickness defines the length of the through-holes, and the longer the through-holes are, the bigger the obstacle for the ions and electrons to travel from the upper chamber to the lower chamber.

[0090] The chart in Figure 7 shows the measurements taken in a dual chamber for the normalized ion flux at different pressures in the lower chamber, with an RF frequency of 27 MHz at 300 W in argon chamber. As expected, the ion flux decreases as the length (depth) of the through-holes increases. In addition, the higher the pressure in the lower chamber, the lower the ion flux is because the higher pressure in the lower chamber increases the resistance for fluids and species to travel to the bottom chamber.

[0091] A second factor affecting the flow between the upper chamber and the lower chamber, is the diameter of the through-holes. As expected, the bigger the diameter of the through-holes

is, the bigger the flux of particles to the lower chamber. Another factors affecting the interaction between the upper chamber ~~on~~ and the lower chamber are the number and distribution of through-holes in the plate. The greater the number of through-holes is, the more electrons will travel from the upper chamber to the lower chamber, as there are more paths between the upper and lower chambers.

[0092] In one embodiment, grid is 27 mm thick, (i.e., the through-holes have a length of 27 mm), and the through-holes have a diameter of 2 mm, although other values are also possible. In one embodiment, the thickness of the grid is between 10 mm and 30 mm. In various embodiments, the diameter of the through-holes is sized within a range extending from about 0.5 mm to about 5 mm. It should be understood, however, that in various embodiments the through-holes can be respectively defined with essentially any diameter size, so long as the diameter size provides for adequate fluid flow there through while simultaneously providing for adequate suppression of plasma intrusion therein.

[0093] Figure 8 shows the flow of an algorithm for operating a semiconductor wafer processing apparatus, in accordance with one embodiment of the invention. The embodiment of Figure 8 illustrates the different operations that can be performed to control the flow of species between the upper chamber and the lower chamber.

[0094] In operation 802, the parameters for the top plasma chamber are set. These parameters include the operating frequency of the RF power source, the voltage and wattage of the RF power source, the pressure in the upper chamber, the gases injected in the upper chamber, etc. In operation 804, the parameters for the bottom plasma chamber are set. The same parameters described above for the upper chamber may also be adjusted for the bottom chamber. In addition, the parameters for the plate separating the upper chamber and the lower chamber are also defined. The parameters for the plate include the thickness of the plate, the number and distribution of through-holes in the plate, the diameter of the through-holes, etc.

[0095] In operation 806, a wafer is processed in the lower chamber with the parameters set in operations 802 and 804. After the wafer is processed, the operator may decide to adjust some of the parameters of the chamber to improve wafer processing. To determine the quality of etching in the chamber, probes can be used to measure the performance of the chamber. For example, a probe can be used to measure the ion flux from the top chamber to the bottom chamber.

[0096] In operation 810, a check is made to determine if the power is to be adjusted, and if the result of the check in operation 810 is that an adjustment is required, the method continues to operation 812. In operation 812, the wattage for the top or bottom chambers, or for both top and

bottom chambers, are set. As the power is increased in the chambers, the number of particles in the plasma will also increase.

[0097] In operation 814, a check is performed to determine if the voltage of the RF power sources is to be adjusted, and if the voltage is to be adjusted, new voltage levels for the top and/or bottom chambers are set, in operation 816. As previously discussed, the bottom chamber includes a pulsing RF power source. A check is performed to determine if the pulsing cycle of the RF power source is to be adjusted, in operation 820. In operation 826, the durations of the ON and OFF periods (i.e., the cycle of the RF signal) are set. For example, if negative ion etching needs to be increased, the OFF period may be increased to allow for a higher afterglow etching.

[0098] In operation 822, a check is made to determine if the pressure in the first chamber ~~of~~ or the second chamber is to be adjusted. If the pressure in either chamber is to be changed, in operation 828, the pressure from the top chamber, or the bottom chamber, or both chambers are adjusted. As described above with reference to Figure 7, the higher the pressure difference between the top chamber and the bottom chamber, the higher the flow of particles between the chambers.

[0099] Further, in operation 824, a check is made to determine if the parameters of the plate need to be changed. As previously discussed, several parameters of the plate can be changed, such as thickness of the plate, the number, distribution, and size of the through-holes, etc. If the parameters of the plate are to be adjusted, in operation 830, any of the aforementioned parameters of the plate can be adjusted.

[00100] After all the parameters of the chamber are adjusted, if any, the method flows back to operation 806 and continues with the processing of wafers. It is noted that the embodiments illustrated in Figure 8 are exemplary. Other embodiments may utilize different adjustments, or perform adjustments in a different order, or perform checks periodically, etc. The embodiments illustrated in Figure 8 should therefore not be interpreted to be exclusive or limiting, but rather exemplary or illustrative.

[00101] Figure 9 shows the flow of an algorithm for processing a wafer, in accordance with one embodiment of the invention. In operation 902, first parameters are set for a continuous radio frequency (RF) signal generated by a first RF power source coupled to a top electrode in the top chamber. The first parameters include a first voltage and a first frequency. Further, in operation 904, second parameters are set for a pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber, where the second parameters

include a second voltage, a second frequency, an ON-period duration, and an OFF-period duration.

[00102] In operation 906, the continuous RF signal is applied to the top electrode, and in operation 908, the pulsed RF signal is applied to the bottom electrode. Setting the first parameters and the second parameters regulates the flow of species from the top chamber to the bottom chamber during operation of the chambers. The flow of species assists in the negative-ion etching and in neutralizing excessive positive charge on the wafer surface during afterglow in the OFF period, and assists in re-striking the plasma in the bottom chamber during the ON period.

[00103] Figure 10 is a simplified schematic diagram of a computer system for implementing embodiments of the present invention. It should be appreciated that the methods described herein may be performed with a digital processing system, such as a conventional, general-purpose computer system. Special purpose computers, which are designed or programmed to perform only one function, may be used in the alternative. The computer system includes a central processing unit (CPU) 1004, which is coupled through bus 1010 to random access memory (RAM) 1028, read-only memory (ROM) 1012, and mass storage device 1014. Phase control program 1008 resides in random access memory (RAM) 1028, but can also reside in mass storage 1014 or ROM 1012.

[00104] Mass storage device 1014 represents a persistent data storage device such as a floppy disc drive or a fixed disc drive, which may be local or remote. Network interface 1030 provides connections via network 1032, allowing communications with other devices. It should be appreciated that CPU 1004 may be embodied in a general-purpose processor, a special purpose processor, or a specially programmed logic device. Input/Output (I/O) interface provides communication with different peripherals and is connected with CPU 1004, RAM 1028, ROM 1012, and mass storage device 1014, through bus 1010. Sample peripherals include display 1018, keyboard 1022, cursor control 1024, removable media device 1034, etc.

[00105] Display 1018 is configured to display the user interfaces described herein. Keyboard 1022, cursor control 1024, removable media device 1034, and other peripherals are coupled to I/O interface 1020 in order to communicate information in command selections to CPU 1004. It should be appreciated that data to and from external devices may be communicated through I/O interface 1020. The invention can also be practiced in distributed computing environments where tasks are performed by remote processing devices that are linked through a wire-based or wireless network.

CLAIMS

1. A wafer processing apparatus with a top chamber and a bottom chamber separated by a plate that fluidly connects the top chamber to the bottom chamber, comprising:

a continuous wave (CW) controller operable to set a voltage and a frequency for a first radio frequency (RF) power source coupled to a top electrode in the top chamber;

a pulse controller operable to set voltage, frequency, ON-period duration, and OFF-period duration for a pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber; and

a system controller operable to set parameters for the CW controller and the pulse controller to regulate a flow of species from the top chamber to the bottom chamber through the plate during operation of the chambers, wherein the flow of species assists in a negative-ion etching and in neutralizing excessive positive charge on ~~the~~ a wafer surface during afterglow in the OFF period, and assists in re-striking a plasma in the bottom chamber during the ON period.

2. The wafer processing apparatus as recited in claim 1, wherein the system controller is further operable to set a first pressure in the top chamber and a second pressure in the bottom chamber, and wherein the first pressure is higher than the second pressure.

3. The wafer processing apparatus as recited in claim 2, wherein a duration of the ON period is different from a duration of the OFF period.

4. The wafer processing apparatus as recited in claim 2, wherein a duration of the ON period is equal to a duration of the OFF period.

5. The wafer processing apparatus as recited in claim 1, wherein a frequency of the first RF power source has a value between 27 MHz and 100 MHz.

6. The wafer processing apparatus as recited in claim 1, wherein a frequency of the second RF power source has a value between 0.4 MHz and 25 MHz.

7. The wafer processing apparatus as recited in claim 1, wherein a voltage of the first RF power source has a value between 100 V and 600 V.

8. The wafer processing apparatus as recited in claim 1, wherein a voltage of the second RF power source has a value between 1000 V and 6000 V.

9. The wafer processing apparatus as recited in claim 1, wherein the top chamber is operable to form a top plasma in the top chamber while processing the wafer.

10. The wafer processing apparatus as recited in claim 1, wherein the top chamber is operable to have a first pressure between 20 mTorr and 60 mTorr during processing, and

wherein the bottom chamber is operable to have a second pressure between 10 mTorr and 19 mTorr during processing.

11. A method for processing a wafer in a wafer processing apparatus with a top chamber and a bottom chamber separated by a plate that fluidly connects the top chamber to the bottom chamber, the method comprising:

setting first parameters for a continuous radio frequency (RF) signal generated by a first RF power source coupled to a top electrode in the top chamber, wherein the first parameters include a first voltage and a first frequency;

setting second parameters for a pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber, wherein the second parameters include a second voltage, a second frequency, ON-period duration, and OFF-period duration;

applying the continuous RF signal to the top electrode; and

applying the pulsed RF signal to the bottom electrode, wherein setting the first parameters and the second parameters regulates a flow of species from the top chamber to the bottom chamber during operation of the chambers, wherein the flow of species assists in a negative-ion etching and in neutralizing excessive positive charge on ~~the~~ a wafer surface during afterglow in the OFF-period, and assists in re-striking a plasma in the bottom chamber during the ON period.

12. The method as recited in claim 11 further including:

setting a first pressure in the top chamber; and

setting a second pressure in the bottom chamber.

13. The method as recited in claim 12, further including:

increasing the first pressure to increase the flow of species from the top chamber to the bottom chamber.

14. The method as recited in claim 11 further including:

adjusting a length of through-holes in the plate separating the top chamber and the bottom chamber, wherein decreasing the length of the through-holes increases the flow of species from the top chamber to the bottom chamber.

15. The method as recited in claim 14 further including:

reducing a number of the through-holes in the plate to decrease the flow of species between the top chamber and bottom chamber.

16. The method as recited in claim 11, wherein setting the first parameters includes:

increasing the first voltage to increase the flow of species.

17. The method as recited in claim 11, wherein operations of the method are performed by a computer program when executed by one or more processors, the computer program being embedded in a non-transitory computer-readable storage medium.

18. A wafer processing apparatus with a top chamber and a bottom chamber separated by a plate that fluidly connects the top chamber to the bottom chamber, comprising:

a continuous wave (CW) controller operable to set first parameters for a first radio frequency (RF) power source coupled to a top electrode in the top chamber;

a pulse controller operable to set second parameters for a second pulsed RF signal generated by a second RF power source coupled to a bottom electrode in the bottom chamber, and to set third parameters for a third pulsed RF signal generated by a third RF power source coupled to the bottom electrode; and

a system controller operable to transfer the first, second, and third parameters to regulate a flow of species from the top chamber to the bottom chamber through the plate during operation of the chambers, wherein the flow of species assists in a negative-ion etching and in neutralizing excessive positive charge on ~~the~~ a wafer surface during afterglow in ~~the~~ an OFF period, and assists in re-striking a plasma in the bottom chamber during ~~the~~ an ON period.

19. The wafer processing apparatus as recited in claim 18, wherein the first RF power source has a frequency between 30 MHz and 100 MHz, the second RF power source has a frequency between 0.4 MHz and 4 MHz, and the third RF power source has a frequency between 20 MHz and 100 MHz.

20. The wafer processing apparatus as recited in claim 18, wherein the top chamber is operable to have a first pressure between 20 mTorr and 60 mTorr during processing, and wherein the bottom chamber is operable to have a second pressure between 10 mTorr and 19 mTorr during processing.