

Systems and Methods for Frequency Modulation of Radiofrequency Power Supply for Controlling Plasma Instability

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Background

1. Field of the Invention

[0001] The present invention relates to semiconductor device fabrication.

2. Description of the Related Art

10 **[0002]** Many modern semiconductor chip fabrication processes include generation of a plasma from which ions and/or radical constituents are derived for use in either directly or indirectly affecting a change on a surface of a wafer exposed to the plasma. For example, various plasma-based processes can be used to etch material from a wafer surface, deposit material onto a wafer surface, or modify a material already present on
15 a wafer surface. The plasma is often generated by applying radiofrequency (RF) power to a process gas in a controlled environment, such that the process gas becomes energized and transforms into the desired plasma. The characteristics of the plasma are affected by many process parameters including, but not limited to, material composition of the process gas, flow rate of the process gas, geometric features of the
20 plasma generation region and surrounding structures, temperatures of the process gas and surrounding materials, frequency and magnitude of the RF power applied, and bias voltage applied to attract charged constituents of the plasma toward the wafer, among others.

[0003] However, in some plasma processes, the above-mentioned process
25 parameters may not provide for adequate control of all plasma characteristics and behavior. In particular, in some plasma processes, an instability referred to as a

"plasmoid" may occur within the plasma, where the plasmoid is characterized by a small area of higher density plasma surrounded by larger volumes of normal density plasma. The formation of plasmoids can lead to non-uniformity in the processing results on the wafer. Therefore, it is of interest to mitigate and/or control plasmoid formation. It

5 is within this context that the present invention arises.

Summary

[0004] In an example embodiment, a method is disclosed for plasma processing of a wafer. The method includes positioning a wafer on a wafer support apparatus. The wafer support apparatus is positioned beneath an electrode such that a plasma generation region exists between the wafer and the electrode. The method includes
5 supplying radiofrequency signals of a first signal frequency to the plasma generation region to generate a plasma within the plasma generation region during multiple sequential plasma processing cycles of a plasma processing operation. The method includes detecting formation of a plasma instability within the plasma based on
10 supplying the radiofrequency signals of the first signal frequency to the plasma generation region. The method includes supplying radiofrequency signals of a second signal frequency to the plasma generation region to generate the plasma within the plasma generation region after detecting formation of the plasma instability. The radiofrequency signals of the second signal frequency are supplied in lieu of the
15 radiofrequency signals of the first signal frequency. The second signal frequency is greater than the first signal frequency. The second signal frequency causes a reduction in ion energy within the plasma and a corresponding reduction in secondary electron emission from the wafer caused by ion interaction with the wafer.

[0005] In an example embodiment, a method is disclosed for performing a plasma
20 process on a wafer. The method includes positioning a wafer on a wafer support apparatus. The wafer support apparatus is positioned beneath an electrode such that a plasma generation region exists between the wafer and the electrode. The method includes supplying radiofrequency signals having a signal frequency greater than 13.56 megaHertz to the electrode to generate a plasma within the plasma generation region.
25 The signal frequency keeps an ion energy within the plasma sufficiently low to maintain an acceptable amount of secondary electron emission from the wafer caused by ion

interaction with the wafer. The acceptable amount of secondary electron emission from the wafer is low enough to prevent formation of a secondary electron-induced instability within the plasma.

[0006] Other aspects and advantages of the invention will become more apparent from
5 the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the present invention.

Brief Description of the Drawings

[0007] Figure 1A shows a wafer processing system, in accordance with some embodiments of the present invention.

[0008] Figure 1B shows a wafer processing system, in accordance with some
5 embodiments of the present invention.

[0009] Figure 2 shows a top view of a multi-station processing tool that includes four processing stations, in accordance with some embodiments of the present invention.

[0010] Figure 3 shows a schematic view of an embodiment of the multi-station processing tool interfaced with an inbound load lock and an outbound load lock, in
10 accordance with some embodiments of the present invention.

[0011] Figure 4 shows an example of the pedestal configured to receive the wafer for a deposition process, in accordance with some embodiments of the present invention.

[0012] Figure 5A shows a vertical cross-section view of the pedestal, in accordance with some embodiments of the present invention.

15 [0013] Figure 5B shows a close-up view of the region 501 referenced in Figure 5A, in accordance with some embodiments of the present invention.

[0014] Figure 5C also shows a close-up view of the region 501 referenced in Figure 5A, in accordance with some embodiments of the present invention.

[0015] Figure 5D also shows a close-up view of the region 503 referenced in Figure
20 5A, in accordance with some embodiments of the present invention.

[0016] Figure 5E also shows a close-up view of the region 503 referenced in Figure 5A, in accordance with some embodiments of the present invention.

[0017] Figure 5F shows a top view of the electrically conductive layer corresponding to referenced view A-A as identified in Figure 5A, in accordance with some embodiments
25 of the present invention.

[0018] Figure 5G shows a top view of the electrically conductive layer corresponding to

referenced view A-A as identified in Figure 5A, in accordance with some embodiments of the present invention.

[0019] Figure 6 shows a schematic of DC electrical current flow from the DC power supply through the chamber, in accordance with some embodiments of the present invention.

[0020] Figure 7 shows an alternate schematic of DC electrical current flow from the DC power supply through the chamber, in accordance with some embodiments of the present invention.

[0021] Figure 8 shows a flowchart of a method for plasma processing of a wafer, in accordance with some embodiments of the present invention.

[0022] Figure 9 shows a chart that compares various aspects of using lower RF frequency, for example 13.56 MHz, and higher RF frequency, for example 27.12 MHz, in an example plasma process, in accordance with some embodiments of the present invention.

[0023] Figure 10 shows a plot of predicted normalized ion energy flux as a function of RF power for applied RF frequencies of 13.56 MHz and 27.12 MHz in the example plasma process, in accordance with some embodiments of the present invention.

[0024] Figure 11 shows a chart of plasmoid-free process windows for RF frequencies of 13.56 MHz and 27.12 MHz in the example plasma process, in accordance with some embodiments of the present invention.

[0025] Figure 12 shows a plot of normalized wet etch rate in the example plasma process as a function of RF power (Watts) for different process gas flow rates at RF signal frequencies of both 13.56 MHz and at 27.12 MHz, in accordance with some embodiments of the present invention.

[0026] Figure 13 shows a flowchart of a method for performing a plasma process on a wafer, in accordance with some embodiments of the present invention.

[0027] Figure 14 shows a flowchart of a method for plasma processing of a wafer, in accordance with some embodiments of the present invention.

Detailed Description

[0028] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

[0029] Deposition of films can be implemented in a plasma enhanced chemical vapor deposition (PECVD) system. The PECVD system may take many different forms. The PECVD system includes one or more chambers or “reactors” (sometimes including multiple stations) that house one or more wafers and are suitable for wafer processing. Each chamber may house one or more wafers for processing. The one or more chambers maintain the wafer in a defined position or positions (with or without motion within that position, e.g. rotation, vibration, or other agitation). A wafer undergoing deposition may be transferred from one station to another within a reactor chamber during the process. Of course, the film deposition may occur entirely at a single station or any fraction of the film may be deposited at any number of stations. While in process, each wafer is held in place by a pedestal, wafer chuck and/or other wafer holding apparatus. For certain operations, the apparatus may include a heater such as a heating plate to heat the wafer.

[0030] In an example embodiment, the term wafer as used herein refers to a semiconductor wafer. Also, in various embodiments, the wafer as referred to herein may vary in form, shape, and/or size. For example, in some embodiments, the wafer as referred to herein may correspond to a 200 mm (millimeters) semiconductor wafer, a 300 mm semiconductor wafer, or a 450 mm semiconductor wafer. Also, in some embodiments, the wafer as referred to herein may correspond to a non-circular substrate, such as a rectangular substrate for a flat panel display, or the like, among

other shapes.

[0031] Figure 1A illustrates a wafer processing system 100, which is used to process a wafer 101, in accordance with some embodiments of the present invention. The system includes a chamber 102 having a lower chamber portion 102b and an upper chamber portion 102a. A center column 141 is configured to support a pedestal 140 formed of an electrically conductive material. The electrically conductive the pedestal 140 is connected to receive RF signals from an RF power supply 104 by way of a match network 106, depending on a setting of an RF direction control module 250. Also, in the wafer processing system 100 of Figure 1A, a showerhead electrode 150 is configured and connected to receive RF signals from the RF power supply 104 by way of the match network 106, depending on the setting of the RF direction control module 250. In some embodiments, the RF direction control module 250 is configured to direct RF signals transmitted from the RF power supply 104 by way of the match network 106 to either the showerhead electrode 150 or to the pedestal 140. Also, the RF direction control module 250 is configured to electrically connect whichever one of the showerhead electrode 150 and the pedestal 140 that is not currently receiving RF signals to a reference ground potential. In this manner, at a given time, the RF direction control module 250 operates to ensure that either the showerhead electrode 150 will receive RF signals from the RF power supply 104 while the pedestal 140 is electrically connected to the reference ground potential, or the pedestal 140 will receive RF signals from the RF power supply 104 while the showerhead electrode 150 is electrically connected to the reference ground potential.

[0032] The RF power supply 104 is controlled by a control module 110, e.g., a controller. The control module 110 is configured to operate the wafer processing system 100 by executing process input and control instructions/programs 108. The process input and control instructions/programs 108 may include process recipes,

having directions for parameters such as power levels, timing parameters, process gases, mechanical movement of the wafer 101, etc., such as to deposit or form films over the wafer 101.

[0033] In some embodiments, the center column 141 can include lift pins, which are controlled by lift pin control 122. The lift pins are used to raise the wafer 101 from the pedestal 140 to allow an end-effector to pick up the wafer 101, and to lower the wafer 101 after being placed by the end-effector. The wafer processing system 100 further includes a gas supply system 112 that is connected to process gas supplies 114, e.g., gas chemistry supplies from a facility. Depending on the processing being performed, the control module 110 controls the delivery of process gases 114 via the gas supply system 112. The chosen process gases are then flowed into the showerhead electrode 150 and distributed in a processing volume defined between the showerhead electrode 150 and the wafer 101 disposed upon the pedestal 140.

[0034] Further, the process gases may be premixed or not. Appropriate valving and mass flow control mechanisms may be employed within the gas supply system 112 to ensure that the correct process gases are delivered during the deposition and plasma treatment phases of the process. Process gases exit the processing volume and flow through an exhaust outlet 143. A vacuum pump (such as a one or two stage mechanical dry pump, among other types) draws process gases out of the processing volume and maintains a suitably low pressure within the processing volume by a closed loop feedback controlled flow restriction device, such as a throttle valve or a pendulum valve.

[0035] Also shown is a carrier ring 200 that encircles an outer region of the pedestal 140. The carrier ring 200 is configured to support the wafer 101 during transport of the wafer 101 to or from the pedestal 140. The carrier ring 200 is configured to sit over a carrier ring support region that is a step down from a wafer support region in the center

of the pedestal 140. The carrier ring 200 has an annular shaped disc structure and includes an outer edge side of its disc structure, e.g., outer radius, and a wafer edge side of its disc structure, e.g., inner radius, that is closest to where the wafer 101 sits. The wafer edge side of the carrier ring 200 includes a plurality of contact support
5 structures which are configured to lift the wafer 101 when the carrier ring 200 is lifted by spider forks 180. The carrier ring 200 is therefore lifted along with the wafer 101 and can be rotated to another station, e.g., in a multi-station system. Carrier ring lift and/or rotate control signals 124 are generated by the control module 110 to control operation of the spider forks 180 to lift and/or rotate the carrier ring 200.

10 **[0036]** In some embodiments, the electrical insulating layer 507 is disposed on a top surface of the pedestal 140, and an electrically conductive layer 509 is disposed on the electrically insulating layer 507. The electrically conductive layer 509 is configured to support the wafer 101. Also, in these embodiments, the electrically conductive layer can be electrically connected to a positive terminal of a direct current (DC) power supply
15 521 by way of a low pass filter 525. The DC power supply 521 is also connected to be controlled by the control module 110. Therefore, in some embodiments, electrical current can be transmitted from the DC power supply 521 through the low pass filter 525 to the electrically conductive layer 509, in accordance with a prescribed recipe as provided by the process input and control instructions/programs 108 and as executed
20 by the control module 110.

[0037] Figure 1B illustrates a wafer processing system 100A that is configured to perform an atomic layer deposition (ALD) process on the wafer 101 (e.g. an ALD oxide process), in accordance with some embodiments of the present invention. Similar componentry as described with regard to Figure 1A is shown in Figure 1B. Specifically,
25 the wafer processing system 100A also includes the upper chamber portion 102a, the lower chamber portion 102b, the control module 110, the RF power supply 104, the

match network 106, the electrically conductive layer 509, the DC power supply 521, the low pass filter 525, the carrier ring 200, and the spider forks 180. In the wafer processing system 100A, a pedestal 140A is configured to include a dielectric body 251. In some embodiments, the dielectric body 251 is affixed directly to the column 141.

5 And, in some embodiments, the dielectric body 251 is supported by a conductive structure 252 that is affixed to the column 141. The electrically conductive layer 509 is disposed directly upon a top surface of the dielectric body 251 of the pedestal 140A.

[0038] In some embodiments, a heating component 253, such as a resistance heating element, is disposed with the dielectric body 251 of the pedestal 140A. The heating
10 component 253 is connected to a heater power supply 255, which is in turn connected to the control module 110. With the heating component 253 present, in some embodiments, the heater power supply 255 can be operated in accordance with a prescribed recipe as provided by the process input and control instructions/programs 108 and as executed by the control module 110. It should also be understood that
15 temperature measurement devices can be installed on/within the pedestal 140A and/or at other locations around the pedestal 140A to provide temperature measurement data to the control module 110, thereby enabling operation of a closed-loop temperature feedback control circuit between the control module 110 and the heater power supply 255.

20 **[0039]** The dielectric body 251 of the pedestal 140A includes an RF electrode 254 configured and connected to receive RF signals from the RF power supply 104 by way of the match network 106, depending on the setting of an RF direction control module 250. Also, in the wafer processing system 100A of Figure 1B, a showerhead electrode 150A is configured and connected to receive RF signals from the RF power supply 104
25 by way of the match network 106, depending on the setting of the RF direction control module 250. In some embodiments, the RF direction control module 250 is configured

to direct RF signals transmitted from the RF power supply 104 by way of the match network 106 to either the showerhead electrode 150A or to the RF electrode 254. Also, the RF direction control module 250 is configured to electrically connect whichever one of the showerhead electrode 150A and the RF electrode 254 that is not currently receiving RF signals to a reference ground potential. In this manner, at a given time, the RF direction control module 250 operates to ensure that either the showerhead electrode 150A will receive RF signals from the RF power supply 104 while the RF electrode 154 is electrically connected to the reference ground potential, or the RF electrode 154 will receive RF signals from the RF power supply 104 while the showerhead electrode 150A is electrically connected to the reference ground potential.

[0040] Figure 2 shows a top view of a multi-station processing tool 300 that includes four processing stations, in accordance with some embodiments of the present invention. This top view is of the lower chamber portion 102b (e.g., with the top chamber portion 102a removed for illustration). The four processing stations are accessed by spider forks 180. Each spider fork 180, or fork, includes a first and second arm, each of which is positioned around a portion of each side of the pedestal 140/140A. The spider forks 180, using an engagement and rotation mechanism 220 are configured to raise up and lift the carrier rings 200 (i.e., from a lower surface of the carrier rings 200) from the processing stations in a simultaneous manner, and then rotate a distance of at least one or more stations before lowering the carrier rings 200 (where at least one of the carrier rings supports a wafer 101) so that further plasma processing, treatment and/or film deposition can take place on respective wafers 101.

[0041] Figure 3 shows a schematic view of an embodiment of the multi-station processing tool 300 interfaced with an inbound load lock 302 and an outbound load lock 304, in accordance with some embodiments of the present invention. A robot 306, at atmospheric pressure, is configured to move wafers 101 from a cassette loaded

through a pod 308 into inbound load lock 302 via an atmospheric port 310. Inbound load lock 302 is coupled to a vacuum source/pump so that, when atmospheric port 310 is closed, inbound load lock 302 may be pumped down. Inbound load lock 302 also includes a chamber transport port 316 interfaced with processing chamber 102. Thus, when chamber transport 316 is opened, another robot 312 may move the wafer from inbound load lock 302 to the pedestal 140/140A of a first process station for processing.

[0042] The depicted processing chamber 102 comprises four process stations, numbered from 1 to 4 in the example embodiment shown in Figure 3. In some embodiments, processing chamber 102 may be configured to maintain a low pressure environment so that wafers may be transferred using the carrier ring 200 among the process stations 1-4 without experiencing a vacuum break and/or air exposure. Each process station 1-4 depicted in Figure 3 includes a pedestal 140/140A and showerhead electrode 150/150A and associated process gas supply connections. Also, it should be understood that in other embodiments the processing chamber 102 can include less than four process stations or more than four process stations.

[0043] Figure 3 also shows the spider forks 180 for transferring wafers within the processing chamber 102. As mentioned above, the spider forks 180 rotate and enable transfer of wafers from one processing station to another. The transfer occurs by enabling the spider forks 180 to lift the carrier rings 200 from an outer undersurface, which lifts the wafers 101, and rotates the wafers 101 and carrier rings 200 together to the next processing station. In one configuration, the spider forks 180 are made from a ceramic material to withstand high levels of heat during processing.

[0044] Figure 4 shows an example of the pedestal 140/140A configured to receive the wafer 101 for a deposition process, such as an atomic layer deposition (ALD) process, in accordance with some embodiments of the present invention. The pedestal 140/140A includes the electrically conductive layer 509 positioned on a central top

surface of the pedestal 140/140A, where the central top surface is defined by a circular area extending from a central axis 420 of the pedestal 140/140A to a top surface diameter 422 that defines the edge of the central top surface. The electrically conductive layer 509 includes a plurality of wafer supports 404a, 404b, 404c, 404d, 404e, and 404f, which are distributed across the electrically conductive layer 509 are which are configured to support the wafer 101. A wafer support level is defined by the vertical position of the bottom surface of the wafer 101 when seated on the wafer supports 404a, 404b, 404c, 404d, 404e, and 404f. In the example of Figure 4, there are six wafer supports 404a, 404b, 404c, 404d, 404e, and 404f symmetrically distributed about a periphery of the electrically conductive layer 509. However, in other embodiments there may be any number of wafer supports on the electrically conductive layer 509, and the wafer supports can be distributed across the electrically conductive layer 509 in any suitable arrangement for supporting the wafer 101 during deposition process operations. Figure 4 also shows recesses 406a, 406b, and 406c, which are configured to house lift pins. The lift pins can be utilized to raise the wafer 101 from the wafer supports 404a, 404b, 404c, 404d, 404e, and 404f to allow for engagement of the wafer 101 by an end-effector.

[0045] In some embodiments, each wafer support 404a, 404b, 404c, 404d, 404e, and 404f defines a minimum contact area structure (MCA). MCA's are used to improve precision mating between surfaces when high precision or tolerances are required, and/or minimal physical contact is desirable to reduce defect risk. Other surfaces in the system can also include MCA's, such as over the carrier ring 200 supports, and over the inner wafer support region of the carrier ring 200.

[0046] The pedestal 140/140A further includes an annular surface 410 extending from the top surface diameter 422 of the pedestal 140/140A to an outer diameter 424 of the annular surface 410. The annular surface 410 defines an annular region surrounding

the electrically conductive layer 509, but at a step down from the electrically conductive layer 509. That is, the vertical position of the annular surface 410 is lower than the vertical position of the electrically conductive layer 509. A plurality of carrier ring supports 412a, 412b, and 412c are positioned substantially at/along the edge (outer diameter) of the annular surface 410 and are symmetrically distributed about the annular surface 410. The carrier ring supports can in some embodiments define MCA's for supporting the carrier ring 200. In some implementations, the carrier ring supports 412a, 412b, and 412c extend beyond the outer diameter 424 of the annular surface 410, whereas in other implementations they do not. In some implementations, the top surfaces of the carrier ring supports 412a, 412b, and 412c have a height that is slightly higher than that of the annular surface 410, so that when the carrier ring 200 is resting on the carrier ring supports 412a, 412b, and 412c, the carrier ring 200 is supported at a predefined distance above the annular surface 410. Each carrier ring support 412a, 412b, and 412c may include a recess, such as recess 413 of carrier ring support 412a, in which an extension protruding from the underside of the carrier ring 200 is seated when the carrier ring 200 is supported by the carrier ring supports 412a, 412b, and 412c. The mating of the carrier ring extensions to the recesses (413) in the carrier ring supports 412a, 412b, and 412c provides for secure positioning of the carrier ring 200 and prevents the carrier ring 200 from moving when seated on the carrier ring supports 412a, 412b, and 412c.

[0047] In some implementations, the top surfaces of the carrier ring supports 412a, 412b, and 412c are flush with the annular surface 410. In other implementations, there are no carrier ring supports separately defined from the annular surface 410, so that the carrier ring 200 may rest directly on the annular surface 410, and such that no gap exists between the carrier ring 200 and the annular surface 410. In such implementations, a pathway between the carrier ring 200 and the annular surface 410

is closed, preventing precursor materials from reaching a backside/underside of the wafer 101 via this pathway.

[0048] In the example embodiment of Figure 4, there are three carrier ring supports 412a, 412b, and 412c positioned symmetrically along the outer edge region of the annular surface 410. However, in other implementations, there may be more than three carrier ring supports, distributed at any locations along the annular surface 410 of the pedestal 140/140A, to support the carrier ring 200 in a stable resting configuration.

[0049] When the wafer 101 is supported by the wafer supports 404a, 404b, 404c, 404d, 404e, and 404f, and when the carrier ring 200 is supported by the carrier ring supports 412a, 412b, and 412c, an edge region of the wafer 101 is disposed over an inner portion of the carrier ring 200. Generally speaking, the edge region of the wafer 101 extends from an outer edge of the wafer 101 inward by about 2 millimeters (mm) to about 5 mm. A vertical separation is thereby defined between the edge region of the wafer 101 and the inner portion of the carrier ring 200. In some embodiments, this vertical separation is about 0.001 inch to about 0.010 inch. The support of the carrier ring 200 at the predefined distance above the annular surface 410 and the vertical separation between the edge region of the wafer 101 and the inner portion of the carrier ring 200, can be controlled to limit deposition on a backside/underside of the wafer 101 in the edge region of the wafer 101.

[0050] Some plasmas used to deposit thin films or to treat the wafer surface are unstable under conditions that are preferred from a process standpoint. As an example, Ar/O₂ capacitively-coupled-plasma (CCP) discharge operated within a 1 to 3 Torr pressure range and at high RF power (>200 W per 300 mm diameter wafer processing station) shows instabilities within the plasma. One such plasma instability, referred to herein as a "plasmoid," is characterized by small areas of higher density (brighter) plasma surrounded by larger volumes of normal density plasma. When plasmoids are

formed, the deposited film is locally densified near the plasmoid due to interaction of the film with the local high density plasma corresponding to the plasmoid, which results in degraded film uniformity. A spatial distribution of plasmoids over the wafer 101 can vary from process-to-process, and within a given process. Also, the plasmoids can move
5 across the wafer 101 during a given process. It should be understood that the plasmoids cause a degradation in process uniformity across the wafer 101, such as by changing a thickness of a deposited film at different locations across the wafer 101. The non-uniformity in film thickness caused by the plasmoids can be about 1% to 2% of the total film thickness, which can be significant in some applications that require an ultra-
10 flat film profile.

[0051] During an example film deposition process, an operation is performed to apply a monolayer of a precursor gas, without applying any RF power. The precursor gas sticks to the wafer 101. In some embodiments, the precursor gas includes silicon to enable formation of silicon oxide on the wafer. An operation is then performed to flush
15 the precursor gas from the processing volume over the wafer 101, thereby leaving the monolayer of the precursor gas on the wafer 101. An oxidation process is then performed on the wafer 101. In the oxidation process, a process gas is flowed into the processing volume over the wafer 101 and RF power is applied to the process gas to generate a plasma within the processing volume. The plasma drives oxidation reactions
20 on the wafer 101. In some embodiments, the process gas will contain oxygen plus one or more other bombardment gases, such as argon, among others, where the bombardment gas(es) provide sufficient densification of the plasma. The bombardment gas is a gas that is effective in densifying a deposited film. Bombardment gases that densify the deposited film are those gases that can effectively transfer energy to the
25 deposited film. In some embodiments, the bombardment gases are monoatomic noble gases, such as argon, among others, that do not react chemically with the deposited

film and that lack vibrational or rotational molecular modes. For instance, in an example process, the process gas mixture can include about 5% to about 20% oxygen with the balance of the process gas mixture being argon. And, in other example processes, the percentage of oxygen to the bombardment gas in the process gas mixture can be less
5 than 5% or greater than 20%.

[0052] During the oxidation process, when a particular thickness of film is formed on the wafer 101, the plasmoids may begin to appear across the wafer 101. The number and size of the plasmoids has a direct correlation with the amount of the bombardment process gas, e.g., argon, in the process gas mixture. So, reducing of the amount of
10 bombardment process gas in the process gas mixture may serve to reduce the intensity of the plasmoids. However, the higher percentage of bombardment process gas is also typically necessary to provide sufficient plasma density to ensure proper film formation. Also, a large amount of RF power is needed to generate the plasma, because if there is not enough RF power applied, the plasma density will not be sufficient. However,
15 increasing the applied RF power leads to formation of more plasmoids. Some process applications use about 300 W of applied RF power per 300 mm diameter wafer processing station. However, other process applications may require higher RF power, such as 400 W, or even higher, per 300 mm diameter wafer processing station.

[0053] In view of the foregoing, one approach for suppressing plasmoid formation is to
20 reduce the applied RF power and/or increase the oxygen concentration within the gas mixture. More specifically, lower process power, i.e., lower applied RF power, or lower bombardment gas (typically argon) concentration within the process gas (with respect to oxygen) results in a lower plasma density, thus suppressing formation of plasmoids. Unfortunately, these conditions are not preferred from a deposited film quality
25 perspective. For example, film quality is degraded when ion bombardment from the plasma is not sufficient at lower process power or lower bombardment gas

concentration within the process gas. Therefore, it may not always be possible to maintain deposited film quality while suppressing plasmoid formation through lowering of the process power and/or lowering of the bombardment gas concentration, e.g., argon concentration, within the process gas.

5 **[0054]** Systems and methods are disclosed herein to prevent/suppress plasma instability by modulating electrical potential of the wafer 101. In some embodiments, a low positive DC bias is applied to the backside/underside of the wafer 101. This low positive DC bias is effective in suppressing the formation of plasmoids. The systems and methods disclosed herein for suppression and/or prevention of plasma instability
10 does not require changes in other process conditions, such as process gas flow rates, pressure, and/or applied RF power.

[0055] Figure 5A shows a vertical cross-section view of the pedestal 140 of Figure 1A, in accordance with some embodiments of the present invention. In some embodiments, the pedestal 140 is formed of an electrically conductive material, such as aluminum,
15 among other materials. In some embodiments, the pedestal 140 includes heating devices 505, such as electrical resistance heaters. The pedestal 140 includes a top surface 502. The electrical insulating layer 507 is disposed on the top surface 502 of the pedestal 140. The electrical insulating layer 507 is formed of a dielectric material that is compatible with the materials used in the processing of the wafer 101 and that is
20 stable with regard to thermal expansion during processing of the wafer 101. In various embodiments, during processing of the wafer 101, the pedestal 140 can be exposed to temperatures within a range extending up to about 100° Celsius (C), or within a range extending from about 20° C to about 100° C, or to temperatures within a range extending up to about 50° C, or to temperatures within a range extending up to about
25 250° C.

[0056] In some embodiments, the electrical insulating layer 507 is formed of a ceramic

material, such as a ceramic plate or ceramic coating. In some embodiments, the electrical insulating layer 507 is formed by anodizing the top surface 502 of the pedestal 140. In some embodiments, the electrical insulating layer 507 has a vertical thickness as measured in a direction perpendicular to the top surface 502 of the pedestal 140 within a range extending up to about 1 millimeter (mm), or within a range extending up to about 100 micrometers, or within a range extending from about 10 micrometers to about 50 micrometers, or of about 30 micrometers. It should be understood, however, that in other embodiments the vertical thickness of the electrical insulating layer 507 as measured in the direction perpendicular to the top surface 502 of the pedestal 140 can be different than the above-mentioned ranges and values. The vertical thickness of the electrical insulating layer 507 is defined to ensure that electrical current does not flow through the electrical insulating layer 507 to the pedestal 140.

[0057] The electrically conductive layer 509 is disposed on the electrically insulating layer 507. The electrically conductive layer 509 is configured to support the wafer 101.

In some embodiments, the electrically conductive layer 509 is formed to have a vertical thickness as measured perpendicular to the top surface 502 of the pedestal 140 within a range extending up to about 1 mm, or within a range extending up to about 0.25 inch, or within a range extending up to about 0.5 inch. It should be understood, however, that in other embodiments the vertical thickness of the electrically conductive layer 509 as measured in the direction perpendicular to the top surface 502 of the pedestal 140 can be different than the above-mentioned ranges and values. In some embodiments, the electrically conductive layer 509 is formed as a solid plate. In some embodiments, the electrically conductive layer 509 is formed as a laminated film. In some embodiments, the electrically conductive layer 509 is formed as a sprayed metal coating. In some embodiments, the electrically conductive layer 509 is formed of aluminum. However, it should be understood that in other embodiments the electrically conductive layer 509

can be formed of essentially any type of electrically conductive material that is compatible with the materials used in the processing of the wafer 101 and that is stable with regard to thermal expansion during processing of the wafer 101.

[0058] In some embodiments, the electrically conductive layer 509 includes a distribution of MCA's 511 configured to contact and support the wafer 101. In these 5 embodiments, the MCA's 511 are formed of electrically conductive material to provide for transmission of electrical current from the electrically conductive layer 509 to the wafer 101. In some embodiments, the MCA's 511 are formed of a same material as the electrically conductive layer 509. In some embodiments, the MCA's 511 are formed of a 10 different material than the electrically conductive layer 509, so long as the MCA's 511 are formed of an electrically conductive material. In some embodiments, the MCA's 511 are formed integrally with the electrically conductive layer 509. In some embodiments, the MCA's 511 are physically attached to the electrically conductive layer 509. In some 15 embodiments, the MCA's 511 are configured to have a rounded top surface that contacts the backside/underside of the wafer 101. In some embodiments, the MCA's 511 are configured to have a substantially flat top surface that contacts the backside/underside of the wafer 101.

[0059] The electrically conductive layer 509 is electrically connected to the DC power supply 521, through an electrical connection 523 that extends through the low pass 20 filter 525. The low pass filter 525 prevents RF signals from entering and damaging the DC power supply 521. A positive terminal of the DC power supply 521 is connected to the electrical connection 523, such that direct electrical current flows through the electrical connection 523, including through the low pass filter 525, to the electrically 25 conductive layer 509, and through the wafer 101 into the plasma within the processing volume overlying the wafer 101. A negative terminal of the DC power supply 521 is connected to an electrical current return structure within the chamber to provide for

completion of the circuit. In various embodiments, the electrical connection 523 can be connected to the electrically conductive layer 509 in different ways such as through a soldered connection, a brazed connection, a compression connection, a threaded connection, among others. Electrical conductors that form the electrical connection 523 and/or the contact with the electrically conductive layer 509 are electrically insulated from the pedestal 140 by one or more electrical insulating structures 527. Also, if the pedestal 140 includes heating devices 505, such as electrical resistance heaters, the electrical insulating structures 527 are formed to electrically insulate the heating devices 505 from the electrical connection 523.

[0060] Additionally, in some embodiments, at least one of the lift pins within the pedestal 140 is formed of an electrically conductive material, and is configured to electrically contact the electrically conductive layer 509 when retracted to its down position within the pedestal 140, and is electrically connected to the DC power supply 521 through the electrical connection 523 and the low pass filter 525. In these embodiments, the at least one DC powered lift pin can be used to provide electrical connection with the electrically conductive layer 509 in lieu of, or in addition to, forming a permanent contact between the electrically conductive layer 509 and the electrical connection 523.

[0061] Figure 5A also shows the carrier ring 200 which sits in the outer region of the pedestal 140 over a carrier support surface 513. The carrier ring 200 can include a plurality of extensions 515 which secure the carrier ring 200 to prevent the carrier ring 200 from shifting during processing of the wafer 101. The extensions 515 are configured to sit in the carrier ring supports 412a, 412b, and 412c, as shown in Figure 4A. Figure 5B shows a close-up view of the region 501 referenced in Figure 5A, in accordance with some embodiments of the present invention. Figure 5C also shows a close-up view of the region 501 referenced in Figure 5A, in accordance with some

embodiments of the present invention. In the example embodiment of Figure 5C, the pedestal 140 includes a retainer structure 142 configured to extend upward from the top surface 502 of the pedestal 140, and configured to circumscribe the region within which the electrical insulating layer 507 and the electrically conductive layer 509 are formed.

5 Also, in the example embodiment of Figure 5C the electrical insulating layer 507 is formed to extend upward along an inner surface of the retainer structure 142 to provide for electrical insulation between the retainer structure 142 and the electrically conductive layer 509.

[0062] Figure 5D also shows a close-up view of the region 503 referenced in Figure 10 5A, in accordance with some embodiments of the present invention. In the example embodiment of Figure 5D, an electrical connection 512 is shown as formed between the electrically conductive layer 509 and the electrical connection 523. In various embodiments, the electrical connection 523 can be a soldered connection, a brazed connection, a compression connection, a threaded connection, among others. Figure 15 5E also shows a close-up view of the region 503 referenced in Figure 5A, in accordance with some embodiments of the present invention. In the example embodiment of Figure 5E, the electrical connection 512 is formed as a wider, pad-type structure between the electrically conductive layer 509 and the electrical connection 523. In the example embodiment of Figure 5E, the electrical insulating layer 507 is 20 formed to wrap around the electrical connection 523.

[0063] During operation, the DC power supply 521 can be operated to cause a flow of DC electrical current from the DC power supply 521 through the electrical connection 523, including through the low pass filter 525, to the electrically conductive layer 509, through the MCA's 511 supporting the wafer 101, through the wafer 101, to the plasma 25 overlying the wafer 101, and through the plasma to an electrically conductive return structure in contact with the plasma. Positive electrical charges near the wafer 101

caused by the DC electrical current serve to repel positively charged ions within the plasma overlying the wafer 101, which serves to suppress formation of plasmoids at the wafer 101 surface. In some embodiments, the DC electrical current transmitted from the DC power supply 521 is within a range extending up to 100 milliAmperes (mA), or
5 within a range extending from about 30 mA to about 70 mA. It should be understood, however, that in some embodiments the DC electrical current transmitted from the DC power supply 521 can be different than the above-mentioned ranges and values. In some embodiments, a voltage applied by the DC power supply 521 to the electrical connection 523 is within a range extending up to about +30 volts (V), or within a range
10 extending from about -10 V to about +50 V, or within a range extending from about +20 V to about +40 V, or within a range extending from about +10 V to about +30 V. It should be understood, however, that in some embodiments the voltage applied by the DC power supply 521 can be different than the above-mentioned ranges and values.

[0064] Because the DC electrical current supplied from the DC power supply 521 flows
15 to the wafer 101 through the MCA's 511, the spatial arrangement of the MCA's 511 may have an effect on the spatial distribution of the DC electrical current flow from the wafer 101 to the plasma, and in turn have a spatial effect on the suppression of plasmoid formation across the wafer 101. Figure 5F shows a top view of the electrically
conductive layer 509 corresponding to referenced view A-A as identified in Figure 5A, in
20 accordance with some embodiments of the present invention. In the example embodiment of Figure 5F, the MCA's 511 (corresponding to the small circles denoted by 511 (typ.)) are distributed in a substantially uniform manner across the electrically
conductive layer 509 so as to contact the backside/underside of the wafer 101 with a
substantially uniform spatial arrangement. The spatial arrangement of the MCA's 511
25 can be used to increase/decrease electrical conductance to the wafer 101 in different spatial areas, and thereby provide for spatial control of the plasmoid suppression. For

example, in some embodiments, more MCA's 511 can be provided at locations where higher plasmoid formation is expected, so as to provide for increase flow of DC electrical current through the wafer 101 at those locations.

[0065] Figure 5G shows a top view of the electrically conductive layer 509 corresponding to referenced view A-A as identified in Figure 5A, in accordance with some embodiments of the present invention. In the example embodiment of Figure 5G, a spatial density of the MCA's 511 is increased toward an outer radial periphery of the electrically conductive layer 509. Therefore, the spatial arrangement of the MCA's 511 in the example embodiment of Figure 5G may be used in processing applications where increased plasmoid formation is expected near the outer radial region of the wafer 101. It should be understood that the MCA 511 spatial arrangements depicted in the example embodiments of Figures 5F and 5G are provided for purposes of description and do not represent all possible spatial arrangements of the MCA's 511 across the electrically conductive layer 509. In other embodiments, the MCA's 511 can have essentially any spatial arrangement that provides for adequate structural support of the wafer 101 and that provides for a suitable distribution of DC electrical current flow from the electrically conductive layer 509 to the wafer 101.

[0066] Figure 6 shows a schematic of DC electrical current flow from the DC power supply 521 through the chamber 102, in accordance with some embodiments of the present invention. Figure 6 shows the showerhead electrode 150/150A connected to receive RF signals from the RF power supply 104 by way of the match network 106 to generate a plasma 601 within the region overlying the wafer 101. In the example embodiment of Figure 6, the showerhead electrode 150/150A is connected to the return (negative terminal) of the DC power supply 521, as indicated by electrical connections 605, where the return (negative terminal) of the DC power supply 521 is electrically connected to a reference ground potential. In this manner, the DC electrical current (i)

flows from the DC power supply 521, through the low pass filter 525, to the electrically conductive layer 509, as indicated by electrical connection 523, and through the MCA's 511 to the wafer 101, and through the wafer 101 to the plasma 601, and through the plasma 601 to the showerhead electrode 150/150A, and from the showerhead electrode 150/150A through electrical connection 605 to the return (negative terminal) of the DC power supply 521.

[0067] Figure 7 shows an alternate schematic of DC electrical current flow from the DC power supply 521 through the chamber 102, in accordance with some embodiments of the present invention. The example embodiment of Figure 7 corresponds to a low pressure processing application in which the plasma 601 contacts the wall of the chamber 102. In the example embodiment of Figure 7, the wall of the chamber 102 functions as a return electrode for the DC electrical current (i) that flows from the DC power supply 521. More specifically, the wall of the chamber 102 is electrically connected to the return (negative terminal) of the DC power supply 521 through an electrical connection 701. During operation, the DC electrical current (i) flows from the DC power supply 521, through the low pass filter 525, to the electrically conductive layer 509, as indicated by electrical connection 523, and through the MCA's 511 to the wafer 101, and through the wafer 101 to the plasma 601, and through the plasma 601 to the wall of the chamber 102, and from the wall of the chamber 102 through the electrical connection 701 to the return (negative terminal) of the DC power supply 521.

[0068] As discussed above, in various wafer 101 processing applications, the wafer 101 is loaded onto a processing station, such as a deposition station, and is placed on the electrically conductive layer 509 of the pedestal 140/140A. The wafer 101 is supported by a set of conductive pins/structures, such as the MCA's 511, that are electrically connected to the electrically conductive layer 509. Then, DC voltage is applied from the external DC power supply 521 to the wafer 101 through the electrically

conductive layer 509 and through the conductive pins/structures, e.g., through the MCA's 511. The applied DC voltage is used to reduce the energy flux of (positive) ions within the plasma that are incident upon the wafer 101. Energetic ions from the plasma may eject secondary electrons from the film material deposited on the wafer 101. These
5 secondary electrons can be accelerated to high energy when pulled into the bulk plasma through the plasma sheath. These accelerated electrons may form regions of high-density, unstable plasma, such as the plasmoids. Such a behavior is observed in argon-rich gas mixtures when discharge interacts with specific surfaces (e.g., film of specific composition and thickness). In order to shift wafer potential, the applied DC
10 voltage generates a non-zero flow of DC electrical current. Without the non-zero flow of DC electrical current, application of the external DC voltage may be ineffective due to an ability of the plasma to shadow wafer 101 surface charge with charges of opposite sign, thereby restoring a floating potential of the wafer 101.

[0069] It should be appreciated that the system and methods disclosed herein for
15 suppressing plasma instabilities, such as plasmoids, adds a minimum perturbation to the processing system. The DC bias applied to the backside/underside of a wafer 101 serves as a process tuning parameter which may be adjusted to eliminate plasmoids while having minimal impact on the discharge and the process. Flow rate, pressure, RF power, and other parameters can remain the same with application of the DC bias to
20 the backside/underside of the wafer 101.

[0070] Application of DC bias to the wafer backside/underside of the wafer 101 is not common. In some situations, DC bias may be applied to the RF powered electrode, e.g., to the showerhead electrode 150/150A, to modulate global plasma structure. However, application of DC bias to the showerhead electrode 150/150A does not
25 suppress plasmoids because DC current primarily flows between showerhead electrode 150/150A and the wall of the chamber 102, with minimum effect on the plasma-to-wafer

interface. In contrast to applying DC bias to the showerhead electrode 150/150A, the systems and methods disclosed herein establish a DC electrical connection with the backside/underside of the wafer 101. And, in some embodiments, this DC electrical connection to the backside/underside of the wafer 101 is established by multiple
5 conductive wafer support structures, e.g., MCA's 511, distributed spatially across the backside/underside of the wafer 101. These multiple conductive wafer support structures create low electrical resistance contact with the wafer 101 and conduct DC current to the wafer 101 so as to modify the electric potential of the wafer 101. Generally speaking, various methods for increasing the electric potential of the wafer
10 101 may serve to reduce the likelihood of plasmoid formation. In an alternate embodiment, even DC grounding of the wafer 101 may serve to reduce some plasma instability, as opposed to having the wafer 101 be at a floating electric potential. Such an alternate embodiment may be considered a special case of DC biasing with zero voltage.

15 **[0071]** In view of the foregoing, it should be understood that an apparatus for supporting a wafer during a plasma processing operation is disclosed herein. The apparatus includes the pedestal 140/140A configured to have bottom surface and a top surface. The apparatus also includes the column 141 configured to support the pedestal 140/140A at a central region of the bottom surface of the pedestal 140/140A.

20 In some embodiments, the column 141 is configured to rotate. And, in these embodiments, the column 141 is fixed to the pedestal 140/140A such that rotation of the column 141 causes corresponding rotation of the pedestal 140/140A. The apparatus includes an electrical insulating layer 507 disposed over the top surface of the pedestal 140/140A. In some embodiments, the electrical insulating layer 507 is
25 formed integrally with the pedestal, such as shown in Figure 1B. The apparatus also includes an electrically conductive layer 509 disposed over the top surface of the

electrical insulating layer 507. The apparatus also includes at least three support structures 511 distributed on the electrically conductive layer 509. Each of the at least three support structures 511 is formed of electrically conductive material and is secured in electrical contact with the electrically conductive layer 509. The at least three support
5 structures 511 are configured to interface with a bottom surface of a wafer 101 to physically support the wafer 101 and electrically connect to the wafer 101. The apparatus also includes an electrical connection 523 extending from the electrically conductive layer 509 to a location outside of the pedestal 140/140A. The electrical connection 523 is electrically connected to the positive terminal of the direct current
10 power supply 521.

[0072] In some embodiments, the electrical insulating layer 507 has a vertical thickness as measured in a direction perpendicular to the top surface of the pedestal 140/140A at least large enough to prevent flow of electrical current from the electrically conductive layer 509 to an electrically conductive material located within the pedestal
15 140/140A below the electrical insulating layer 507. In some embodiments, the electrical insulating layer 507 has a vertical thickness as measured in a direction perpendicular to the top surface of the pedestal 140/140A within a range extending up to about 1000 micrometers, or within a range extending up to about 100 micrometers, or within a range extending from about 10 micrometers to about 50 micrometers, or of about 30
20 micrometers. It should be understood, however, that in other embodiments the vertical thickness of the electrical insulating layer 507 as measured in the direction perpendicular to the top surface of the pedestal 140/140A can be different than the above-mentioned ranges and values. In some embodiments, the electrically conductive layer 509 has a vertical thickness as measured in a direction perpendicular to the top
25 surface of the pedestal 140/140A within a range extending up to about 1 millimeter, or within a range extending up to about 7 millimeters, or within a range extending up to

about 13 millimeters. It should be understood, however, that in other embodiments the vertical thickness of the electrically conductive layer 509 as measured in the direction perpendicular to the top surface of the pedestal 140/140A can be different than the above-mentioned ranges and values. In various embodiments, the electrically
5 conductive layer 509 is formed as either a plate, or a laminated film, or a sprayed coating.

[0073] In some embodiments, the at least three support structures 511 are distributed in a substantially uniform manner across the electrically conductive layer 509, such as shown in Figure 5F, by way of example. In some embodiments, the at least three
10 support structures 511 are distributed in a non-uniform manner across the electrically conductive layer 509, such as shown in Figure 5G, by way of example. In some embodiments, a larger number of the at least three support structures 511 are positioned near a peripheral region of the electrically conductive layer 509 as compared to near a central region of the electrically conductive layer 509.

[0074] In some embodiments, both the at least three support structures 511 and the
15 electrically conductive layer 509 are formed of a same material. And, in some embodiments, the electrically conductive layer 509 is formed of a material different than a material of which the at least three support structures 511 are formed, with the at least three support structures 511 formed of an electrically conductive material. In some
20 embodiments, both the at least three support structures 511 and the electrically conductive layer 509 are formed as a single integral structure. In some embodiments, the at least three support structures 511 are attached to the electrically conductive layer 509. Also, in some embodiments, each of the at least three support structures 511 is configured to have a rounded top surface for interfacing with the bottom surface of the
25 wafer 101.

[0075] Also, in view of the foregoing, it should be understood that a system for plasma

processing of a wafer is disclosed herein. The system includes the direct current power supply 521 that has the positive terminal and the negative terminal. The system also includes a low pass filter circuit, e.g., low pass filter 525, that has an input connection and an output connection, with the input connection of the low pass filter circuit 525
5 electrically connected to the positive terminal of the direct current power supply 521. The system also includes a wafer support apparatus that includes at least three support structures 511 distributed to physically contact and support a bottom surface of the wafer 101. Each of the at least three support structures 511 is formed of electrically conductive material. And, each of the at least three support structures 511 is electrically
10 connected to the output connection of the low pass filter circuit 525.

[0076] In some embodiments, the wafer support apparatus includes the electrically conductive layer 509, with the at least three support structures 511 physically and electrically connected to the electrically conductive layer 509, and with the electrically conductive layer 509 being electrically connected to the output connection of the low
15 pass filter circuit 525. Also, in some embodiments, the wafer support apparatus includes the pedestal 140/140A configured to have a bottom surface and a top surface. And, the wafer support apparatus includes the electrical insulating layer 507 disposed below the electrically conductive layer 509. And, in some embodiments, the wafer support apparatus includes the column 141 configured to support the pedestal
20 140/140A at a central region of the bottom surface of the pedestal 140/140A. In some embodiments, the column 141 is configured to rotate, with the column 141 fixed to the pedestal 140/140A such that rotation of the column 141 causes corresponding rotation of the pedestal 140/140A.

[0077] The system also includes an electrode, such as the showerhead electrode
25 150/150A, by way of example, positioned above the wafer support apparatus. A plasma generation region is located between the electrode 150/150A and the wafer support

apparatus. The system also includes the radiofrequency power supply 104 connected to deliver radiofrequency power to the electrode 150/150A. The system also has the negative terminal of the direct current power supply 521 electrically connected to at least one electrically conductive structure exposed to the plasma generation region. In some embodiments, such as shown in Figure 6, the at least one electrically conductive structure exposed to the plasma generation region is the electrode 150/150A. In some embodiments, such as shown in Figure 7, the at least one electrically conductive structure exposed to the plasma generation region is a wall of the chamber 102 in which the electrode 150/150A and the wafer support apparatus are disposed.

[0078] Figure 8 shows a flowchart of a method for plasma processing of a wafer, in accordance with some embodiments of the present invention. The method includes an operation 801 for positioning a wafer (101) on at least three support structures (511) distributed to physically contact and support a bottom surface of the wafer (101). Each of the at least three support structures (511) is formed of electrically conductive material. Also, each of the at least three support structures (511) is electrically connected to a positive terminal of a direct current power supply (521).

[0079] The method also includes an operation 803 for providing an electrical current return path from a plasma generation region overlying the wafer (101) to a negative terminal of the direct current power supply (521). In some embodiments, such as shown in Figure 6, by way of example, the electrical current return path is provided from the plasma generation region through an electrode (such as the showerhead electrode 150/150A), and from the electrode (150/150A) to the negative terminal of the direct current power supply (521). In some embodiments, such as shown in Figure 7, by way of example, the electrical current return path is provided from the plasma generation region through a wall of a chamber (102) within which the plasma generation region is formed, and from the wall of the chamber (102) to the negative terminal of the direct

current power supply (521).

[0080] The method also includes an operation 805 for generating a plasma (601) within the plasma generation region overlying the wafer (101). In some embodiments, generating the plasma (601) within the plasma generation region in operation 805 includes supplying radiofrequency power to an electrode (such as showerhead electrode 150/150A) overlying the plasma generation region. The method also includes an operation 807 for operating the direct current power supply (521) to drive an electrical current through the at least three support structures (511), and from the at least three support structures (511) through the wafer (101), and from the wafer (101) through the plasma (601), and from the plasma (601) through the electrical current return path to the negative terminal of the direct current power supply (521). Driving of the electrical current in operation 807 is performed in conjunction with generating the plasma (601) in operation 805.

[0081] In some embodiments, operation 807 includes operating the direct current power supply (521) to generate an electrical current within a range extending up to about 100 milliAmperes, or within a range extending from about 30 milliAmperes to about 70 milliAmperes. It should be understood, however, that in some embodiments the DC electrical current transmitted from the DC power supply 521 can be different than the above-mentioned ranges and values. In some embodiments, operation 807 includes operating the direct current power supply (521) to generate an electrical voltage within a range extending up to about +30 volts, or within a range extending from about -10 volts to about +50 volts, or within a range extending from about +20 volts to about +40 volts, or within a range extending from about +10 volts to about +30 volts. It should be understood, however, that in some embodiments the voltage applied by the DC power supply 521 can be different than the above-mentioned ranges and values.

[0082] Many PECVD/ALD plasma processes use RF power supplied at a frequency of

13.56 MHz. The energy distribution of ions from the plasma that impact the wafer with RF power applied at a frequency of 13.56 MHz can be wide. High energy ions from the plasma that bombard the wafer can result in a higher rate of secondary electron emission from the wafer surface. In argon-rich processing, secondary electron emission from the wafer surface can initiate and sustain plasmoid formation. Also, plasmoids may form in other types of plasma processing operations that utilize relatively heavy process gases other than argon. In order to suppress plasmoid formation, the RF power can be reduced and/or heavier process gas concentration in the process gas mixture can be reduced. But, the deposited film quality (e.g., wet/dry etch rate) is degraded when the energy flux of the process gas ions is reduced. As a result, plasma-enhanced deposition processes that use RF power with the frequency of 13.56 MHz may not provide a wide enough process window to achieve both plasmoid-free processing (no plasma instability) and a required film quality (i.e., low wet/dry etch rate).

[0083] Because plasma instability can be driven by high energy ions bombarding the wafer, a method is disclosed herein for reducing ion energy and subsequent generation of secondary electrons from the wafer surface. The method includes use of higher RF frequency (e.g., 27.12 MHz) to achieve the reduction in ion energy while maintaining a sufficient high flux of ions incident upon the wafer surface. Figure 9 shows a chart that compares various aspects of using lower RF frequency, for example 13.56 MHz, and higher RF frequency, for example 27.12 MHz, in an example plasma process, in accordance with some embodiments of the present invention.

[0084] The comparison of Figure 9 is based on maintaining delivery of a fixed amount of RF power to the plasma for each RF frequency. As shown in Figure 9, the higher RF frequency plasma activation results in higher plasma density and lower sheath potential. Since the energy of ions impacting the wafer is approximately equal to the product of the sheath potential and the ion charge, lowering of the sheath potential

leads to lower ion energy. In the absence of a sufficient flux of secondary electrons emitted from the wafer surface through collision of energetic ions with the wafer surface, the plasma instability, e.g., plasmoid, is rapidly quenched and/or will not form.

[0085] Methods are disclosed herein for using an RF frequency higher than 13.56 MHz

5 to reduce ion energy flux incident upon the wafer and thereby suppress the formation of plasma instability, such as plasmoids. In some embodiments, an RF frequency of 27.12 MHz is used to generate the plasma. However, in some embodiments, RF frequencies other than 27.12 MHz and greater than 13.56 MHz may be used to generate the plasma. In some embodiments, the applied RF frequency can be much higher, such as
10 60 MHz or even higher.

[0086] Figure 10 shows a plot of predicted normalized ion energy flux as a function of RF power for applied RF frequencies of 13.56 MHz and 27.12 MHz in the example plasma process, in accordance with some embodiments of the present invention. As shown in Figures 9 and 10, when the RF frequency is increased from 13.56 MHz to
15 27.12 MHz, the energy of ions decreases while the flux of ions increases. This effect is attributed to an increase in the efficiency of electron heating in conjunction with a drop in the plasma potential, which corresponds to a reduction in applied RF voltage. The lower ion energy reduces the emission of secondary electrons from the wafer surface and thereby suppresses the formation of plasma instability, such as plasmoids.

20 **[0087]** Figure 11 shows a chart of plasmoid-free process windows for RF frequencies of 13.56 MHz and 27.12 MHz in the example plasma process, in accordance with some embodiments of the present invention. The plasma process corresponding to the chart of Figure 11 was performed at pressure within a range extending from about 1 Torr to about 3 Torr. Also, the plasma process corresponding to the chart of Figure 11 was
25 performed with about 10%-40% O₂ mixed in a flow of argon. For each frequency, the chart shows whether or not plasmoid formation occurs as a function of O₂ flow rate (in

standard cubic centimeters per minute (sccm)) and RF power (in Watts (W)). In Figure 11, the word "NO" for a given O₂ flow rate and RF power means that plasmoid formation did not occur. Also, in Figure 11, the word "YES" for a given O₂ flow rate and RF power means that plasmoid formation did occur. As shown in Figure 11, with the increase in RF frequency from 13.56 MHz to 27.12 MHz, the plasmoid-free process window expands significantly. For instance, at the O₂ flow rate of 1500 sccm and with the RF frequency of 13.56 MHz, there was no RF power that provided a plasmoid-free process window. However, at the O₂ flow rate of 1500 sccm and with the RF frequency of 27.12 MHz, a plasmoid-free process window expanded to include an RF power range extending from of about 250 W to about 600 W. And, within the O₂ flow rate range extending from about 3000 sccm to about 8000 sccm, changing from the RF frequency of 13.56 MHz to the RF frequency of 27.12 MHz expanded the plasmoid-free process window to include an RF power range extending from of about 250 W to about 500 W. Therefore, Figure 11 indicates that by increasing RF frequency, a plasmoid-free process window can be expanded with regard to both process gas flow rate and RF power.

[0088] Figure 12 shows a plot of normalized wet etch rate in the example plasma process as a function of RF power (Watts) for different process gas flow rates at RF signal frequencies of both 13.56 MHz and at 27.12 MHz, in accordance with some embodiments of the present invention. Figure 12 also shows the plasmoid-free process window with regard to wet etch rate and RF power and process gas flow rate for the higher RF signal frequency of 27.12 MHz. As shown in Figure 12, the plasmoid-free process window with regard to wet etch rate and RF power and process gas flow rate is significantly widened with the higher RF signal frequency of 27.12 MHz as compared to with the lower RF signal frequency of 13.56 MHz.

[0089] Figure 13 shows a flowchart of a method for performing a plasma process on a

wafer, in accordance with some embodiments of the present invention. It should be understood that the method of Figure 13 can be implemented using the wafer processing system 100/100A of Figures 1A/1B. In some embodiments, the plasma process is an atomic layer deposition process. In some embodiments, the plasma process is a plasma enhanced chemical vapor deposition process. The method includes an operation 1501 for positioning a wafer (101) on a wafer support apparatus (140/140A). The wafer support apparatus (140/140A) is positioned beneath an electrode (150/150A) such that a plasma generation region exists between the wafer (101) and the electrode (150/150A). The method also includes an operation 1503 for supplying radiofrequency signals having a signal frequency greater than 13.56 megaHertz to the electrode (150/150A) to generate a plasma within the plasma generation region. The signal frequency greater than 13.56 megaHertz keeps an ion energy within the plasma sufficiently low to maintain an acceptable amount of secondary electron emission from the wafer caused by ion interaction with the wafer. The acceptable amount of secondary electron emission from the wafer is low enough to prevent formation of a secondary electron-induced instability within the plasma. In some embodiments, the plasma instability is a plasmoid characterized by an area of higher density plasma surrounded by larger volumes of normal density plasma. In some embodiments, the signal frequency is within a range extending from 13.56 megaHertz up to about 60 megaHertz. In some embodiments, the signal frequency is 27.12 megaHertz.

[0090] Figure 14 shows a flowchart of a method for plasma processing of a wafer, in accordance with some embodiments of the present invention. It should be understood that the method of Figure 14 can be implemented using the wafer processing system 100/100A of Figures 1A/1B. In some embodiments, the plasma process is an atomic layer deposition process. In some embodiments, the plasma process is a plasma

enhanced chemical vapor deposition process. The method includes an operation 1601 for positioning a wafer (101) on a wafer support apparatus (140/140A). The wafer support apparatus (140/140A) is positioned beneath an electrode (150/150A) such that a plasma generation region exists between the wafer (101) and the electrode (150/150A). The method also includes an operation 1603 for supplying radiofrequency signals of a first signal frequency to the plasma generation region to generate a plasma within the plasma generation region during multiple sequential plasma processing cycles of a plasma processing operation.

[0091] The method also includes an operation 1605 for detecting formation of a plasma instability within the plasma based on supplying the radiofrequency signals of the first signal frequency to the plasma generation region. In some embodiments, the plasma instability is a plasmoid characterized by an area of higher density plasma surrounded by larger volumes of normal density plasma. In some embodiments, the plasma instability causes a non-uniformity in a deposited film thickness on the wafer.

[0092] The method also includes an operation 1607 for supplying radiofrequency signals of a second signal frequency to the plasma generation region to generate the plasma within the plasma generation region after detecting formation of the plasma instability in the operation 1605. In the operation 1607, the radiofrequency signals of the second signal frequency are supplied in lieu of the radiofrequency signals of the first signal frequency. The second signal frequency is greater than the first signal frequency. The second signal frequency causes a reduction in ion energy within the plasma and a corresponding reduction in secondary electron emission from the wafer caused by ion interaction with the wafer. In some embodiments, the first signal frequency is 13.56 megaHertz. In some embodiments, the second signal frequency is within a range extending from the first signal frequency up to about 60 megaHertz. In some embodiments, the first signal frequency is 13.56 megaHertz and the second signal

frequency is 27.12 megaHertz. It should be understood, however, that in other embodiments the first signal frequency can be less than 13.56 megaHertz or greater than 13.56 megaHertz, and the second signal frequency can be less than 27.12 megaHertz or greater than 27.12 megaHertz.

5 **[0093]** In some embodiments, detecting formation of the plasma instability within the plasma in the operation 1605 occurs during the plasma processing operation. In some of these embodiments, operation 1603 includes supplying radiofrequency signals of the first signal frequency to the electrode, with formation of the plasma instability being detected in the operation 1605 through measurement of a radiofrequency parameter on
10 the electrode. In some embodiments, the radiofrequency parameter is one or more of a radiofrequency voltage, a radiofrequency current, a radiofrequency impedance, a radiofrequency signal phase angle, and a radiofrequency power. Also, in some embodiments where detection of the plasma instability within the plasma in the operation 1605 occurs during the plasma processing operation, formation of the plasma
15 instability is detected through measurement of optical emissions from the plasma. Additionally, in some embodiments where detection of the plasma instability within the plasma in the operation 1605 occurs during the plasma processing operation, supplying radiofrequency signals of the second signal frequency to the plasma generation region in the operation 1607 occurs during a same plasma processing operation in which
20 formation of the plasma instability was detected.

[0094] In some embodiments, detecting formation of the plasma instability within the plasma in the operation 1605 occurs after the plasma processing operation. In some of these embodiments, detecting formation of the plasma instability within the plasma in the operation 1605 is done by measuring a non-uniformity in deposited film thickness
25 on the wafer. Also, in some embodiments in which detecting formation of the plasma instability within the plasma in the operation 1605 occurs after the plasma processing

operation, supplying radiofrequency signals of the second signal frequency to the plasma generation region in the operation 1607 occurs during a different plasma processing operation than that in which formation of the plasma instability was detected.

5 **[0095]** The methods disclosed herein for using radiofrequency signals of higher frequency to generate the plasma provides for suppression of plasma instability, such as plasmoid formation, and provides for maintaining film quality, e.g., for maintaining sufficiently low wet/dry etch rate. The ability to both suppress plasmoid formation and maintain film quality in a simultaneous manner is a distinguishing result of the methods
10 disclosed herein for using radiofrequency signals of higher frequency for plasma generation. Therefore, it should be appreciated that use of radiofrequency signals of higher frequency for plasma generation opens up a new process window with regard to plasmoid suppression during plasma-based deposition processes.

[0096] Although the foregoing invention has been described in some detail for
15 purposes of clarity of understanding, it will be apparent that certain changes and modifications can be practiced within the scope of the appended claims. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the described embodiments.

Claims

1. A method for plasma processing of a wafer, comprising:

positioning a wafer on a wafer support apparatus, the wafer support apparatus positioned beneath an electrode such that a plasma generation region exists between
5 the wafer and the electrode;

supplying radiofrequency signals of a first signal frequency to the plasma generation region to generate a plasma within the plasma generation region during multiple sequential plasma processing cycles of a plasma processing operation;

detecting formation of a plasma instability within the plasma based on supplying
10 the radiofrequency signals of the first signal frequency to the plasma generation region;
and

after detecting formation of the plasma instability, supplying radiofrequency signals of a second signal frequency to the plasma generation region to generate the plasma within the plasma generation region, the radiofrequency signals of the second
15 signal frequency supplied in lieu of the radiofrequency signals of the first signal frequency, the second signal frequency being greater than the first signal frequency, the second signal frequency causing a reduction in ion energy within the plasma while maintaining an existing flux of ions incident upon the wafer with a corresponding reduction in secondary electron emission from the wafer caused by ion interaction with
20 the wafer.

2. The method for plasma processing of the wafer as recited in claim 1, wherein the plasma instability is a plasmoid characterized by an area of higher density plasma surrounded by larger volumes of normal density plasma.

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3. The method for plasma processing of the wafer as recited in claim 1,

wherein the plasma instability causes a non-uniformity in a deposited film thickness on the wafer.

4. The method for plasma processing of the wafer as recited in claim 1,
5 wherein the plasma processing operation is an atomic layer deposition process.

5. The method for plasma processing of the wafer as recited in claim 1,
wherein the plasma processing operation is a plasma enhanced chemical vapor
deposition process.

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6. The method for plasma processing of the wafer as recited in claim 1,
wherein the first signal frequency is 13.56 megaHertz.

7. The method for plasma processing of the wafer as recited in claim 6,
15 wherein the second signal frequency is within a range extending from the first signal
frequency up to about 60 megaHertz.

8. The method for plasma processing of the wafer as recited in claim 6,
wherein the second signal frequency is 27.12 megaHertz.

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9. The method for plasma processing of the wafer as recited in claim 1,
wherein detecting formation of the plasma instability within the plasma occurs during the
plasma processing operation.

25 10. The method for plasma processing of the wafer as recited in claim 9,
wherein supplying radiofrequency signals of the first signal frequency to the plasma

generation region includes supplying radiofrequency signals of the first signal frequency to the electrode, and wherein formation of the plasma instability is detected through measurement of a radiofrequency parameter on the electrode.

5 11. The method for plasma processing of the wafer as recited in claim 10, wherein the radiofrequency parameter is one or more of a radiofrequency voltage, a radiofrequency current, a radiofrequency impedance, a radiofrequency signal phase angle, and a radiofrequency power.

10 12. The method for plasma processing of the wafer as recited in claim 9, wherein formation of the plasma instability is detected through measurement of optical emissions from the plasma.

15 13. The method for plasma processing of the wafer as recited in claim 9, wherein supplying radiofrequency signals of the second signal frequency to the plasma generation region occurs during a same plasma processing operation in which formation of the plasma instability was detected.

20 14. The method for plasma processing of the wafer as recited in claim 1, wherein detecting formation of the plasma instability within the plasma occurs after the plasma processing operation.

25 15. The method for plasma processing of the wafer as recited in claim 14, wherein detecting formation of the plasma instability within the plasma is done by measuring a non-uniformity in deposited film thickness on the wafer.

16. The method for plasma processing of the wafer as recited in claim 14, wherein supplying radiofrequency signals of the second signal frequency to the plasma generation region occurs during a different plasma processing operation than that in which formation of the plasma instability was detected.

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17. A method for performing a plasma process on a wafer, comprising:
positioning a wafer on a wafer support apparatus, the wafer support apparatus positioned beneath an electrode such that a plasma generation region exists between the wafer and the electrode; and

10 supplying radiofrequency signals having a signal frequency greater than 13.56 megaHertz to the electrode to generate a plasma within the plasma generation region;

adjusting the signal frequency to keep an ion energy within the plasma sufficiently low to maintain an acceptable amount of secondary electron emission from the wafer caused by ion interaction with the wafer, wherein the acceptable amount of secondary
15 electron emission from the wafer is low enough to prevent formation of a secondary electron-induced instability within the plasma, and wherein adjusting the signal frequency is performed to keep an ion flux incident upon the wafer at a level high enough to maintain a required deposited film quality on the wafer.

20 18. The method for performing the plasma process on the wafer as recited in claim 17, wherein the plasma process is either an atomic layer deposition process or a plasma enhanced chemical vapor deposition process.

19. The method for performing the plasma process on the wafer as recited in
25 claim 17, wherein the plasma instability is a plasmoid characterized by an area of higher density plasma surrounded by larger volumes of normal density plasma.

20. The method for performing the plasma process on the wafer as recited in claim 17, wherein the signal frequency is within a range extending from 13.56 megaHertz up to about 60 megaHertz.