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(19) **United States**(12) **Patent Application Publication****Chen et al.**(10) **Pub. No.: US 2006/0175015 A1**(43) **Pub. Date: Aug. 10, 2006**(54) **ETCH CHAMBER WITH DUAL FREQUENCY BIASING SOURCES AND A SINGLE FREQUENCY PLASMA GENERATING SOURCE**

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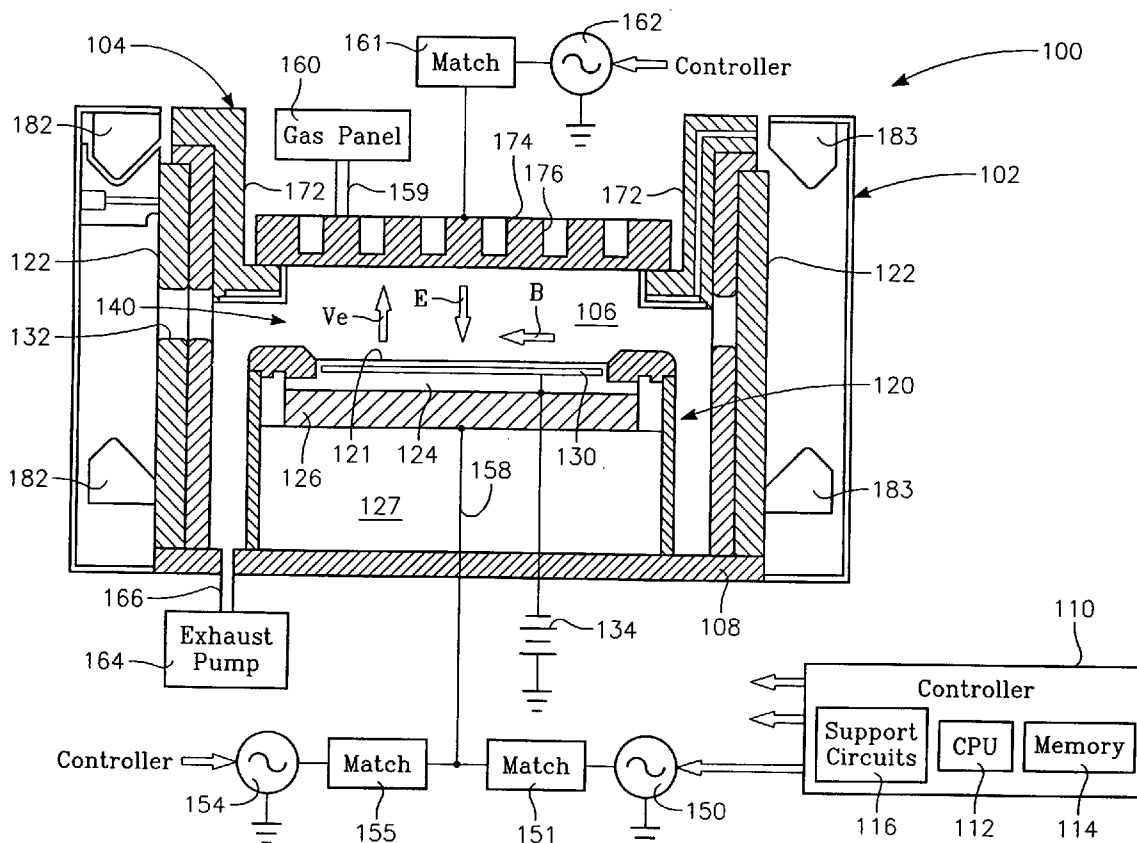
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**C23F 1/00** (2006.01)(52) **U.S. Cl.** ..... **156/345.44; 216/67**(57) **ABSTRACT**

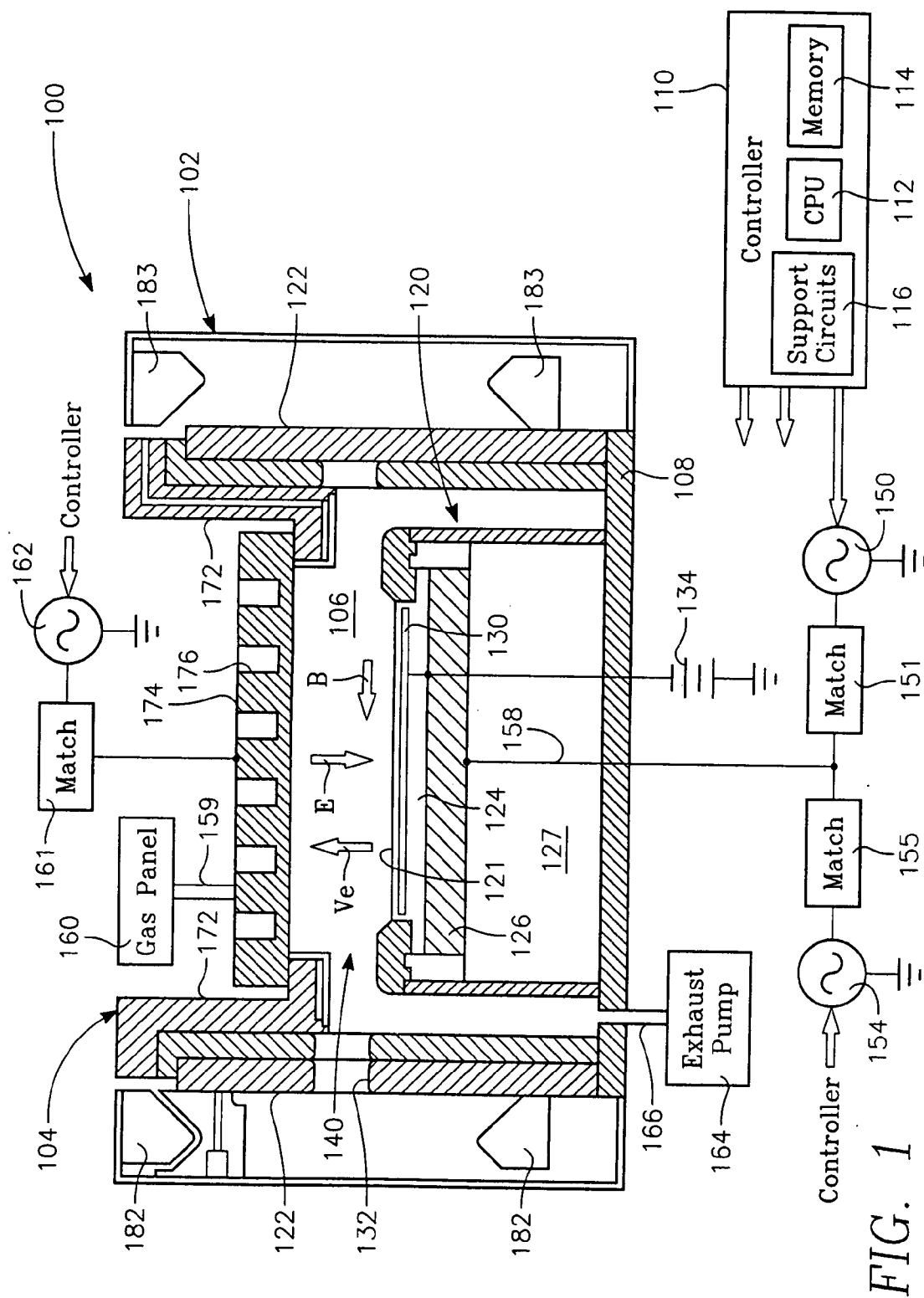
A method and apparatus for selectively controlling a plasma in a processing chamber during wafer processing. The method includes providing process gases into the chamber over a wafer to be processed, and providing high frequency RF power to a plasma generating element and igniting the process gases into the plasma. Modulated RF power is coupled to a biasing element, and wafer processing is performed according to a particular processing recipe. The apparatus includes a biasing element disposed in the chamber and adapted to support a wafer, and a plasma generating element disposed over the biasing element and wafer. A first power source is coupled to the plasma generating element, and a second power source is coupled to the biasing element. A third power source is coupled to the biasing element, wherein the second and third power sources provide a modulated signal to the biasing element.

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(63) Continuation of application No. 10/342,575, filed on Jan. 14, 2003.





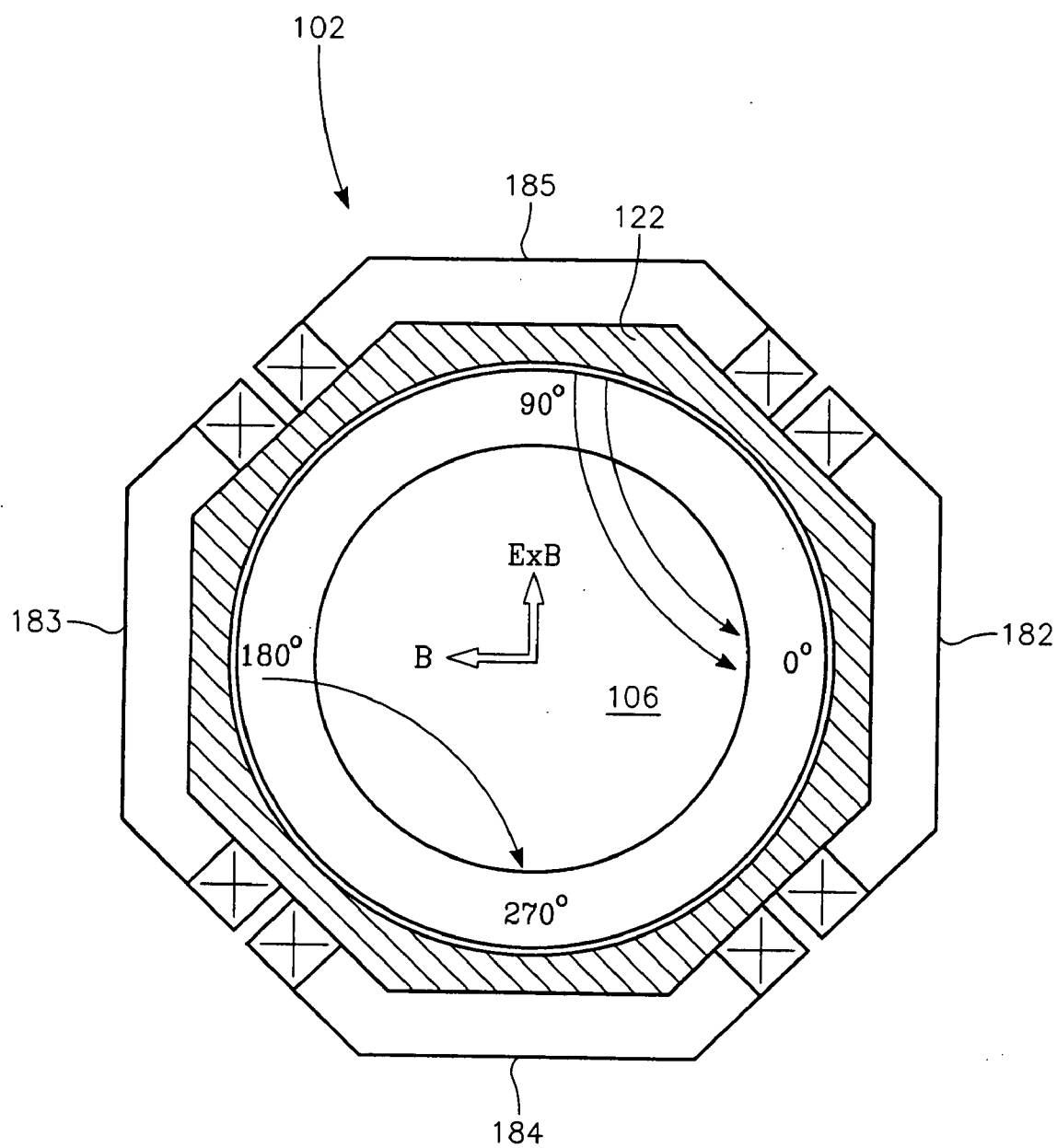
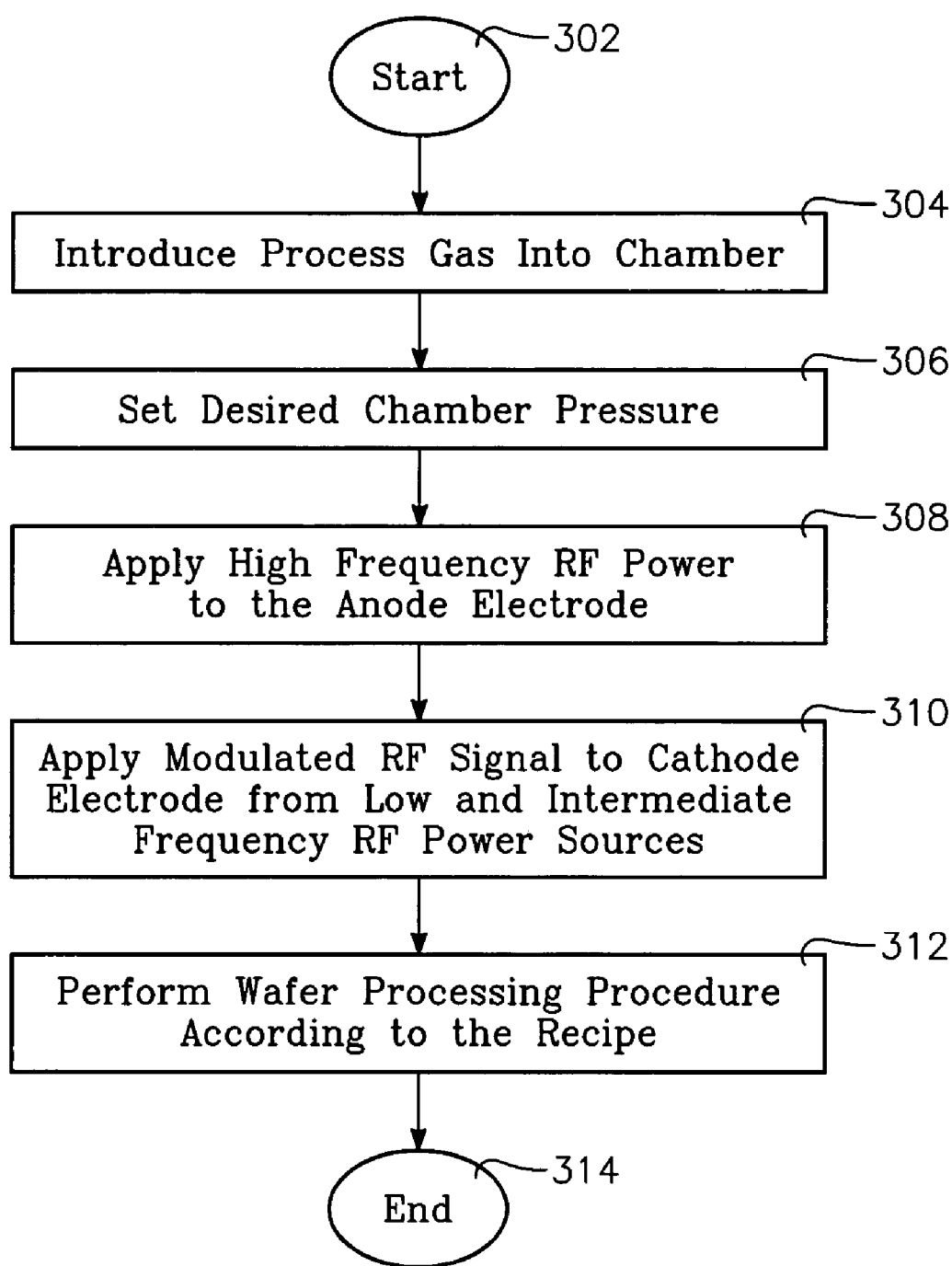


FIG. 2

*FIG. 3*

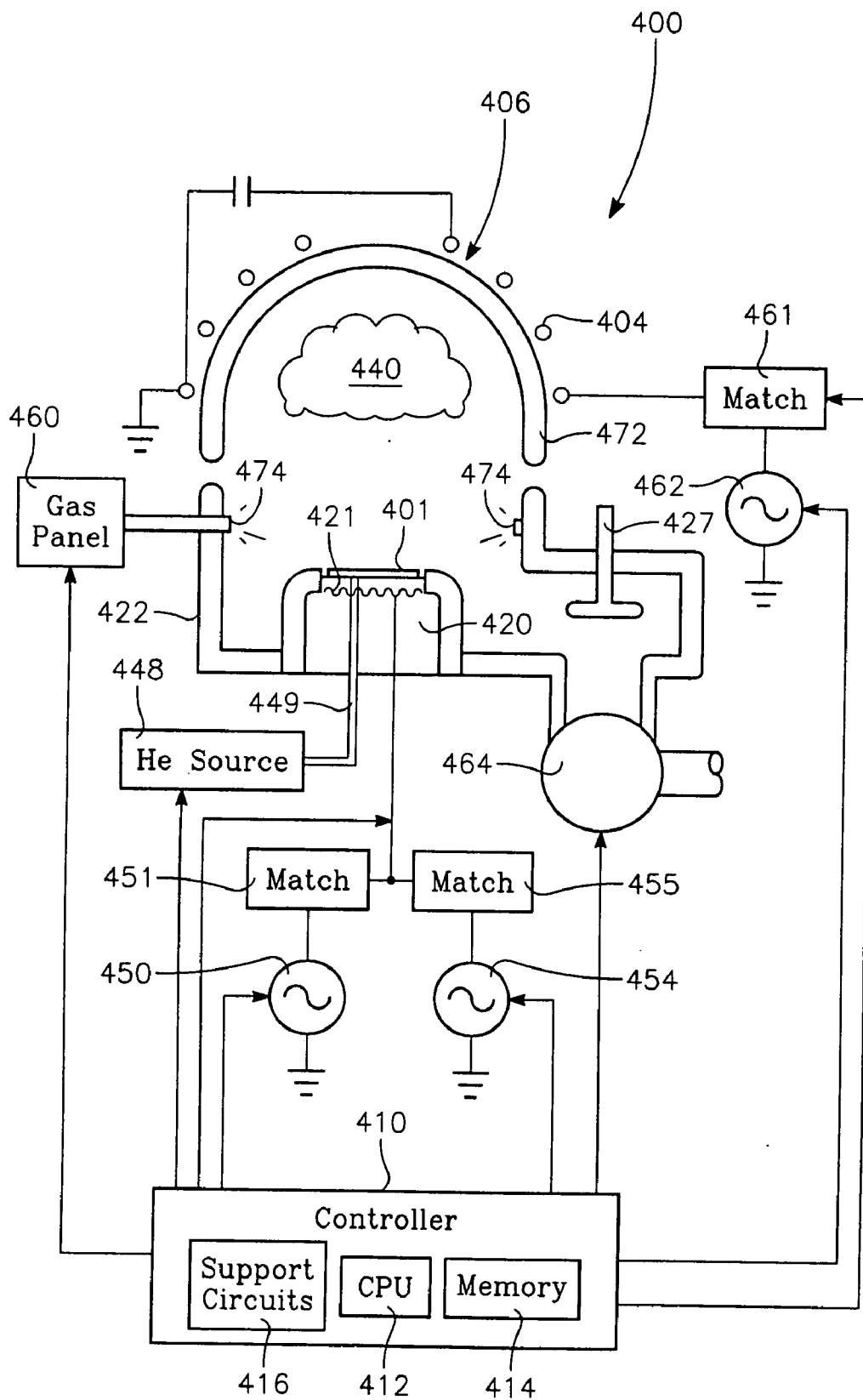
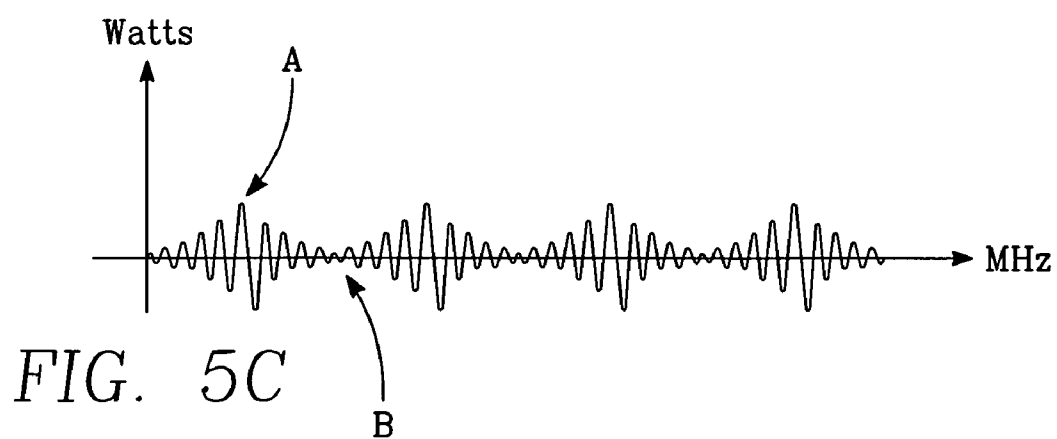
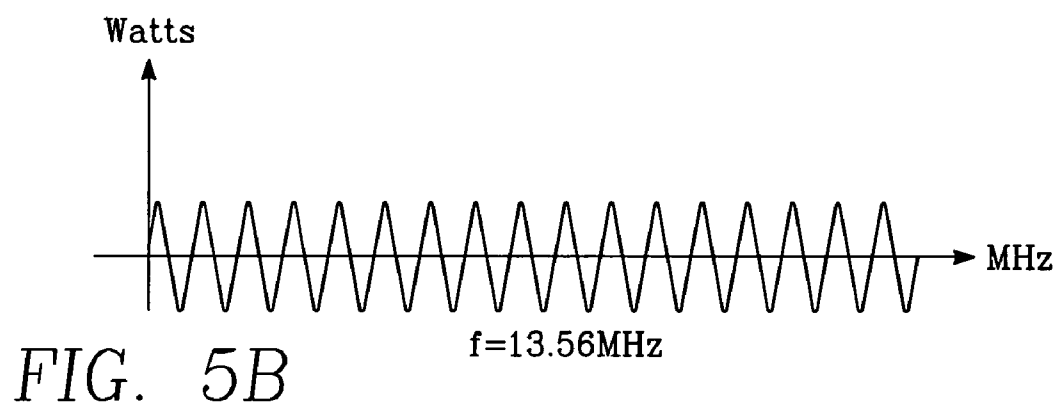
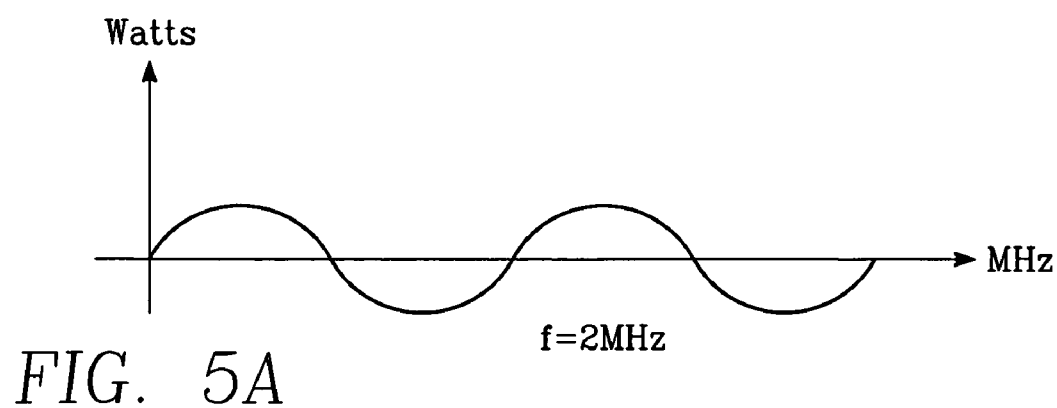
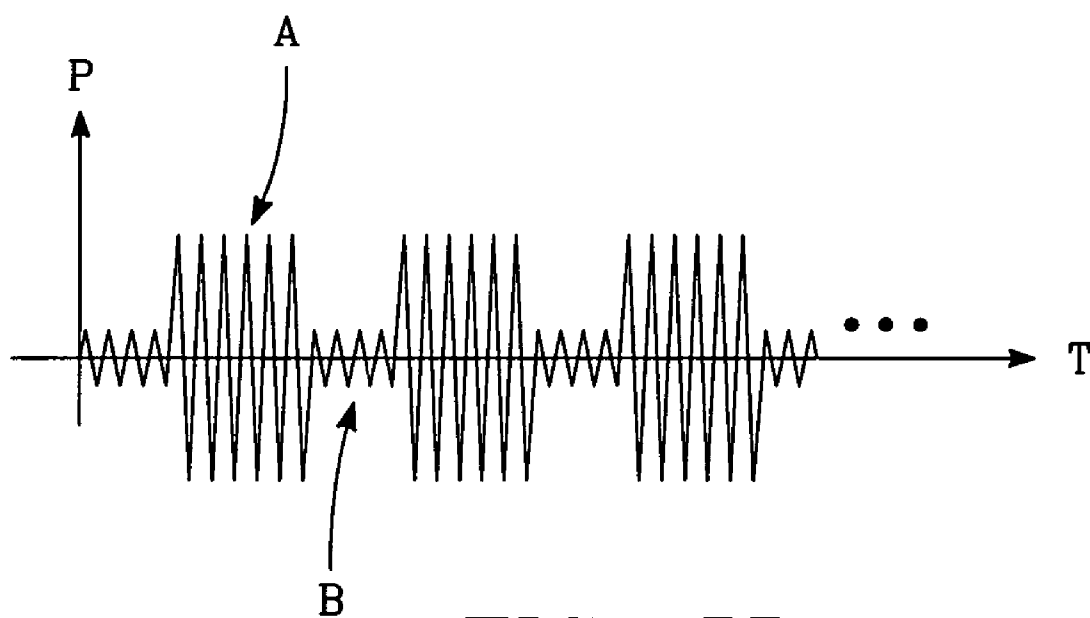


FIG. 4





*FIG. 5D*

# ETCH CHAMBER WITH DUAL FREQUENCY BIASING SOURCES AND A SINGLE FREQUENCY PLASMA GENERATING SOURCE

## CROSS REFERENCE TO RELATED APPLICATION

[0001] This patent application is a continuation of U.S. application Ser. No. 10/342,575 filed Jan. 14, 2003 by Jin-Yuan Chen, et al. entitled "ETCH CHAMBER WITH DUAL FREQUENCY BIASING SOURCES AND A SINGLE FREQUENCY PLASMA GENERATING SOURCE" and assigned to the present assignee.

## FIELD OF THE INVENTION

[0002] Embodiments of the invention generally relate to semiconductor wafer processing, and more particularly, to etch and plasma related integrated circuit manufacturing processes and related hardware.

## BACKGROUND OF THE INVENTION

[0003] Semiconductor fabrication wafer process chambers employing plasma to perform etching and deposition processes utilize various techniques to control plasma density and acceleration of plasma components. For example, magnetically-enhanced plasma chambers employ magnetic fields to increase the density of charged particles in the plasma, thereby further increasing the rate of plasma-enhanced deposition and etching processes. Increasing the process rate is highly advantageous because the cost of fabricating semiconductor devices is proportional to the time required for fabrication.

[0004] During a plasma-enhanced process, such as a reactive ion etch process, material on the wafer is removed in specific areas to subsequently form the components/features of the devices (e.g., transistors, capacitors, conductive lines, vias, and the like) on the wafer. A mask is formed over areas of the wafer that are to be protected from the etching process. Uniformity of the etching rate across the wafer during the entire etch process is very important for ensuring that features are etched with precision at any location on the wafer. The uniformity of the etching process is related to the ability to control the plasma throughout the etch process. For example, U.S. Pat. No. 6,354,240 includes disposing magnets around the reactor chamber to provide a magnetic confinement to sustain a high plasma density in a low pressure environment.

[0005] However, during "deep trench etching", the wafer may be exposed to the etchants for a long duration. During these long etching processes, the etch mask can be completely etched from the wafer surface to leave the surface unprotected. That is, the deep trench processes are limited by the selectivity between the material of the protective mask and the material to be etched, where the higher the selectivity, the deeper the trench may be etched.

[0006] Therefore, there is a need in the art for increasing the selectivity during deep trench etching, such that a sufficient portion of the masking material remains to cover areas of the wafer to be protected until the etch process is complete.

## SUMMARY OF THE INVENTION

[0007] The present invention provides an etch chamber that is driven with three RF frequencies: one frequency for

establishing and maintaining a plasma, and two frequencies for biasing a biasing element (e.g., wafer pedestal). Such triple frequency use provides improved plasma control that increases the process window for an etch process. Enhancing control of plasma density and ion energy improves the coverage of more etching applications and provides a wider window of processing.

[0008] In particular, the present invention provides an apparatus for controlling a plasma in a chamber during wafer processing. The apparatus comprises a biasing element disposed in the chamber and adapted to support a wafer, and a plasma generating element disposed proximate the biasing element. A plasma generating (top) power source is coupled to the plasma generating element, and a bottom (biasing) power source is coupled to the biasing element to provide a modulated signal that modulates the plasma.

[0009] A method for selectively controlling a plasma in the processing chamber during wafer processing comprises providing process gases into the chamber over a wafer to be processed, and providing high frequency RF power to the plasma generating element, which ignites the process gases into the plasma. A modulated RF power signal is provided to the biasing element, and wafer processing is performed according to a particular processing recipe.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0010] So that the manner in which the above recited features of the invention are attained can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof, which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention, and are therefore, not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

[0011] FIG. 1 depicts a cross-sectional view of a first embodiment of a dual frequency bias plasma chamber system;

[0012] FIG. 2 depicts a top cross-sectional view of the plasma chamber system of FIG. 1;

[0013] FIG. 3 depicts a flow diagram of a method for selectively controlling a plasma during wafer processing;

[0014] FIG. 4 depicts a cross-sectional view of a second embodiment of a dual frequency bias plasma chamber system; and

[0015] FIGS. 5A-5D depict graphs of exemplary RF waveforms used in the present invention.

[0016] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

## DETAILED DESCRIPTION OF THE INVENTION

[0017] One application of the present invention provides an apparatus for performing high aspect ratio deep trench etching. In particular, a processing chamber is equipped with dual frequency biasing sources and a single frequency plasma generating source. A wafer to be processed is secured



on a support pedestal in the chamber. The single frequency plasma generating source is coupled to a plasma generating element disposed over the wafer to be processed, while a pair of biasing sources having different frequencies are coupled to the support pedestal, such that the support pedestal serves as a biasing element.

[0018] **FIG. 1** depicts a cross sectional view of a first embodiment of a dual frequency bias plasma chamber system **100** of the present invention. Specifically, **FIG. 1** depicts an illustrative chamber system (system) **100** that can be used in high aspect ratio trench formation. The system **100** generally comprises a chamber body **102** and a lid assembly **104** that defines an evacuable chamber **106** for performing substrate processing. In one embodiment, the system **100** is an MxP type etch system available from Applied Materials, Inc. of Santa Clara, Calif. For a detailed understanding of an MxP type system, the reader is directed to U.S. Pat. No. 6,403,491, issued Jun. 11, 2002, the contents of which is incorporated by reference herein in its entirety. Further, other types of wafer processing systems are also contemplated, such as an eMAX type system, a PRODUCER e type system, HOT type system, and an ENABLER type system, among others, all of which are also available from Applied Materials, Inc. of Santa Clara, Calif.

[0019] The system **100** further comprises a gas panel **160** coupled to the chamber **106** via a plurality of gas lines **159** for providing processing gases, an exhaust stack **164** coupled to the chamber **106** via an exhaust passage **166** for maintaining a vacuum environment and exhausting undesirable gases and contaminants. Additionally, a controller **110** is coupled to the various components of the system **100** to facilitate control of the processes (e.g., deposition and etching processes) within the chamber **106**.

[0020] The chamber body **102** includes at least one of sidewall **122** and a chamber bottom **108**. In one embodiment, the at least one sidewall **122** has a polygon shaped (e.g., octagon or substantially rectangular) outside surface and an annular or cylindrical inner surface. Furthermore, at least one sidewall **122** may be electrically grounded. The chamber body **102** may be fabricated from a non-magnetic metal, such as anodized aluminum, and the like. The chamber body **102** contains a substrate entry port **132** that is selectively sealed by a slit valve (not shown) disposed in the processing platform.

[0021] A lid assembly **104** is disposed over the sidewalls **122** and defines a processing region **140** within the chamber **106**. The lid assembly **104** generally includes a lid **172** and a plasma generating element (e.g., source or anode electrode) **174** mounted to the bottom of the lid **172**. The lid **172** may be fabricated from a dielectric material such as aluminum oxide ( $\text{Al}_2\text{O}_3$ ), or a non-magnetic metal such as anodized aluminum. The plasma generating element **174** is fabricated from a conductive material such as aluminum, stainless steel, and the like.

[0022] Further, the plasma generating element **174** is coupled to a high frequency RF power source **162** via a matching network **161**. The high frequency power source (top power source) **162** provides RF power in a range between about 100 Watts to 7500 Watts, at a frequency in the range of about 40-180 MHz, and is used to ignite and maintain a plasma from a gas mixture in the chamber **106**.

[0023] The plasma generating element **174** may be provided with perforations or slits **176** to serve as a gas diffuser.

That is, the plasma generating element **174** may also serve as a showerhead, which provides processing gases that, when ignited, forms a plasma in the processing region **140**. The processing gases, (e.g.,  $\text{CF}_4$ , Argon (Ar),  $\text{C}_4\text{F}_8$ ,  $\text{C}_4\text{F}_6$ ,  $\text{C}_8\text{F}_4$ ,  $\text{CHF}_3$ ,  $\text{Cl}_2$ ,  $\text{HBr}$ ,  $\text{NF}_3$ ,  $\text{N}_2$ , He,  $\text{O}_2$  and/or combinations thereof) are provided to the plasma generating element/showerhead **174** from the external gas panel **160** via the gas conduit **159** coupled therebetween.

[0024] In another embodiment, a gas distribution ring (not shown) may be coupled to the lid assembly **104** to provide the processing gases into the chamber **106**. The gas distribution ring typically comprises an annular ring made of aluminum or other suitable material having a plurality of ports formed therein for receiving nozzles that are in communication with the gas panel **160**.

[0025] A substrate support pedestal **120** is disposed within the chamber **106** and seated on the chamber bottom **108**. A substrate (i.e., wafer, not shown) undergoing wafer processing is secured on an upper surface **121** of the substrate support pedestal **120**. The substrate support **120** may be a susceptor, a heater, ceramic body, or electrostatic chuck on which the substrate is placed during processing. The substrate support pedestal **120** is adapted to receive an RF bias signal, such that the substrate support pedestal serves as a biasing element (e.g., cathode electrode) with respect to the RF bias signal, as is discussed below in further detail.

[0026] In the embodiment of **FIG. 1**, the substrate support pedestal **120** comprises an electrostatic chuck **124** coupled to an upper surface of a cooling plate **126**. The cooling plate **126** is then coupled to an upper surface of the pedestal base **127**. The electrostatic chuck **124** may be fabricated from a dielectric material e.g., a ceramic such as aluminum nitride (AlN), silicon oxide (SiO), silicon nitride (SiN), sapphire, boron nitride, or it can be a plasma sprayed aluminum nitride, or aluminum oxide material on an anodized aluminum surface, or the like, and is generally shaped as a thin circular puck.

[0027] Furthermore, the electrostatic chuck **124** may be provided with one or more chucking electrodes **130**. The chucking electrodes **130** are, for example, fabricated from a conductive material, (e.g., tungsten). The chucking electrodes **130** are disposed relatively close to the top surface of the electrostatic chuck **124**. In this way, the chucking electrodes **130** provide the necessary electrostatic force to the backside of a wafer to retain (i.e., chuck) the wafer on the electrostatic chuck **124**. The chucking electrodes **130** may be in any configuration such as a monopolar configuration, bipolar configuration, zoned chucking configuration, or any other configuration suitable to retain the wafer to the chuck **124**. The chucking electrodes **130** are connected to a remote power source, i.e. a high voltage DC (HVDC) power supply **134**, which provides a chucking voltage sufficient to secure the wafer to the chuck **124**.

[0028] The cooling plate **126** assists in regulating the temperature of the electrostatic chuck **124**. Specifically, the cooling plate **126** is fabricated from a material that is a high conductor of RF power, such as molybdenum, a zirconium alloy (e.g., Zr—Hf), a metal matrix composite (e.g., Al—Si—SiC), among others. Furthermore, the materials used to fabricate the cooling plate **126** are selected from a group of materials that will have a thermal expansion coefficient value close to the thermal expansion coefficient

value of the electrostatic plate **124**. The cooling plate **126** comprises channels (not shown) formed therein to circulate a coolant to reduce the thermally conducted heat radiated from the wafer and the electrostatic chuck **124**.

[0029] Additional temperature control may be provided by a heating element embedded in the electrostatic chuck **124**. Moreover, a backside gas delivery system (not shown) is provided, such that a gas (e.g., helium) is provided between grooves (not shown), which are formed in the top surface of the chuck **124**, and the backside of the wafer.

[0030] As discussed above, the substrate support pedestal **120** also serves as a biasing electrode (e.g., cathode) for biasing the ionized gases towards the wafer during either a deposition or etching process. A first bias power supply **150** and a second bias power supply **154** are coupled in parallel between the substrate support pedestal **120** and ground via respective matching networks **151** and **155**. In one embodiment, the grounded sidewalls **122** and the plasma generating element **174** together define the anode with respect to the biasing element (cathode) in the substrate support pedestal **120**.

[0031] In particular, the first biasing power supply **150** provides RF power in the range of about 10 Watts to 7500 Watts (W), and at a frequency in the range of about 100 KHz to 6 MHz. The second biasing power supply **154** provides RF power in the range of about 10 W to 7500 W, at a frequency in the range of about 4 MHz to 60 MHz, and, for example, at a frequency of 13.56 MHz. As such, the signal from the first bias power supply **150** amplitude modulates the signal from the second bias power supply **154**. For example, a 13.56 MHz signal from the second bias power supply **154** is amplitude modulated with a 2 MHz signal from the first biasing power supply **150**. It is noted that one skilled in the art will appreciate that the power levels of the first and second biasing power supplies **150** and **154** are related to the size of the workpiece being processed. For example, a 300 mm wafer requires greater power consumption than a 200 mm wafer during processing.

[0032] In one embodiment, the chucking electrodes **130** may also function as the biasing element. In particular, the first and second bias power supplies **150** and **154** are coupled to the chucking electrode **130**, such that the bias signal (e.g., modulated RF signal) is applied to the electrodes **130** to create a bias voltage. In another embodiment, the first and second bias power supplies **150** and **154** are coupled to the cooling plate **126**, which thereby functions as a biasing element. Alternatively, the first and second bias power supplies **150** and **154** may be coupled to a base plate (not shown) disposed below the cooling plate **126**, or to another anode placed within the chuck **124**.

[0033] It is noted that the controller **110** may be utilized to control the bias power supplies **150** and **154**, as well as control the high frequency RF power source **162**. In particular, the controller **110** controls the power set points of the bias power supplies **150** and **154** to provide either the bias signal or the modulated signal. That is, the controller **110** may be used to control the low RF frequency bias signal (e.g., 2 MHz signal) provided by the first bias power supply **150**, as well as control the intermediate RF frequency bias signal (e.g., 13.56 MHz signal) provided by the second bias power supply **154**. Moreover, the controller **110** controls the set point of the high frequency RF signal from the high

frequency RF power source **162**. It is noted that a person skilled in the art will appreciate that the power levels set by the controller **110** for the power sources **150**, **154**, and **162** are related to the size of the wafer being processed (e.g., 200 millimeter (mm) and 300 mm wafers).

[0034] It is noted that the two bias input power signals from the bias power supplies **150** and **154** are not modulated until after the formation of the plasma. Specifically, the plasma acts as a non-linear device, such as a diode, so that the two bias power supplies **150** and **154** may be modulated in the plasma. The degree of modulation depends on the plasma condition, biasing signal power levels, and their respective frequencies.

[0035] Once the biasing signals are modulated in the plasma, the plasma density and acceleration may be changed in a controlled manner depending on the modulation scheme. During an etching process, the selectivity increases such that the protective mask (e.g., a photoresist mask) has a longer life that allows increased depth and aspect ratio when etching deep trenches (e.g., vias). The use of a modulated bias signal provides an increased process window for many etch processes.

[0036] FIG. 2 depicts a top cross-sectional view of the plasma chamber system **100** of FIG. 1. In particular, FIG. 2 depicts an embodiment where the plasma chamber system **100** is magnetically enhanced using a DC magnetic field in the processing region **140** between the plasma generating element **174** and the biasing element **120**. That is, the chamber (also referred to as a reactor) employs magnetic fields to increase the density of charged particles in the plasma, thereby further increasing the rate of the plasma enhanced fabrication process.

[0037] Typically, the direction of the magnetic field is traverse with respect to the longitudinal axis of the chamber **106**, that is, traverse to an axis extending between the electrodes **120** and **174**. Various arrangements of permanent magnets or electromagnets are conventionally used to provide such transverse magnetic field. One such arrangement is a first main pair of coils **182** and **183** disposed on opposite sides of the cylindrical chamber side wall **122**, and a second main pair of coils **184** and **185** disposed on opposite sides of the cylindrical chamber side wall **122**. Each pair of opposing main coils **182-185** are connected in series and in phase to a DC power supply (not shown), such that they produce transverse (adjacent) magnetic fields, which are additive in the region between the coil pairs. The transverse magnetic field is represented in FIGS. 1 and 2 by the vector "B" oriented along the negative X-axis. Variations on the magnetic fields may also be utilized, such as opposed magnetic fields as used in an etch MxP dielectric chamber, also available from Applied Materials Inc., of Santa Clara, Calif.

[0038] To facilitate control of the system **100** as described above, the controller **110** may be one of any form of general-purpose computer processor that can be used in an industrial setting for controlling various chambers and sub-processors. In general, the process controller **110** includes a central processing unit (CPU) **112** in electrical communication with a memory **114** and support circuits **116**. The support circuits **116** include various buses, I/O circuitry, power supplies, clock circuits, cache, among other components.

[0039] The memory **114**, or computer-readable medium, may be one or more of readily available memory such as

random access memory (RAM) read only memory (ROM), floppy disk, hard disk, or any other form of digital storage that are locally and/or remotely connected. Software routines are stored in memory 114. The software routines, when executed by the CPU 112, cause the reactor to perform processes of the present invention. The software routines may also be stored and/or executed by a second CPU (not shown) that is remotely located from the hardware being controlled by the CPU 112.

[0040] The software routines are executed after the wafer is positioned on the support pedestal 120. The software routines, when executed by the CPU 112, transform the general-purpose computer into a specific purpose computer (controller) 110 that controls the chamber operations such that the etching process is performed in accordance with the method of the present invention.

[0041] FIG. 3 depicts a flow diagram of a method 300 for selectively controlling a plasma during wafer processing. Specifically, the method 300 provides a technique for controlling plasma density and particle acceleration, which allows for greater depth and aspect ratios to be achieved on the wafer during deep trench etching.

[0042] The method 300 starts at step 302, where a substrate is loaded, moved into an appropriate processing position over the substrate support pedestal 106. At step 304, a process gas is introduced into the chamber 106 via the exemplary showerhead of FIG. 1 or at least one nozzle. The process gas may include Argon (Ar),  $\text{CF}_4$ ,  $\text{C}_4\text{F}_8$ ,  $\text{C}_4\text{F}_6$ ,  $\text{C}_8\text{F}_4$ ,  $\text{CHF}_3$ ,  $\text{Cl}_2$ ,  $\text{HBr}$ ,  $\text{NF}_3$ ,  $\text{N}_2$ ,  $\text{He}$ ,  $\text{O}_2$  and/or combinations thereof, and are introduced into the chamber 106 at rates of between about 1 sccm to about 2000 sccm.

[0043] At step 306, the pressure in the chamber 106 is brought to a desired processing pressure by adjusting a pumping valve (not shown) to pump the gas into the chamber 106 at a desired pressure. In one operational aspect of generating plasma, the pressure may be between about 1 milliTor and about 1000 milliTor.

[0044] Plasma may be generated via application of the source power by the top power supply 162 between the plasma generating element 174 and ground (e.g., the chamber sidewalls and/or bias element). At step 308, the top power supply 162 applies the source power between about 100 Watts and about 7500 Watts, at a frequency of about 40 MHz to about 180 MHz, which ignites the process gas or gases introduced into the processing region 140 into a plasma. In particular, the gas mixture (e.g., Ar) is introduced into the processing region 140 of the chamber 106. Once the pressure in the chamber reaches a pressure setpoint, the gas is ignited by the RF signal provided by the RF power source 162 to form the plasma. The wafer is then chucked to the substrate support pedestal 120, and then the other processing gases are provided to the chamber 106. The method 300 proceeds to step 308.

[0045] At step 310, the bias power supplies 150 and 154 are activated and the biasing element 120 is biased with the modulated bias signal. Recall that the biasing element may be formed by coupling the bias power supplies 150 and 154 to the chucking electrode 130, the cooling plate 126, cathode base plate, among other components in the substrate support pedestal 120. It is noted that the order of steps 308 and 310 of method 300 should not be considered as limiting, but rather, may be performed alternately or simultaneously.

[0046] In particular, the intermediate RF bias power source 150 and low RF bias power source 154 are turned on, and the biasing element 120 is biased to between about 10 Watts and about 7500 Watts. Furthermore, the RF signal from the two bias power sources 150 and 154 provide a modulated signal, such that the intermediate frequency signal (e.g., 13.56 MHz) is modulated by the low frequency signal (e.g., 400 KHz to 2 MHz).

[0047] The intermediate frequency RF source (second biasing power supply) 154 provides a sufficient energy level to accelerate the ions towards the biasing element 120, such that the particles bombard the wafer during the etching process. Further, the low frequency RF bias source 150 provides a wide energy band that increases the plasma density near the wafer. By increasing the plasma density, more particles are available for bombarding the wafer. As such, the modulated RF waveform provided by the bias power supplies 150 and 154 provides additional control of the energy used to accelerate the ions, as well as control the plasma density in the processing region 140.

[0048] At step 312, the wafer processing procedure (e.g., deep trench etching) is performed according to a particular recipe. The operation of the plasma process may be monitored by a process analysis system (not shown) to determine when the wafer processing has reached an endpoint value and is complete. Once the processing recipe is completed, at step 314, the plasma generation may be terminated and the wafer removed from the processing chamber for further processing, where the method 300 ends.

[0049] In one exemplary embodiment, a deep trench having a width of about 14 micrometers ( $\mu\text{m}$ ) and an aspect ratio of at least about 6:1 may be formed in a silicon wafer by providing the modulated waveform to the plasma during the etch step 312. In particular, process gases such as  $\text{NF}_3$  (at a rate of 80 sccm) and  $\text{HBr}$  (at a rate of 400 sccm) are provided to the reactor chamber 106. The flow ratio of  $\text{NF}_3$  to  $\text{HBr}$  is about 1:5. The pressure in the reaction chamber 106 is maintained at about 100 to 400 mTor. The top power supply 162 applies the source power at about 3000 Watts at a frequency of about 60 MHz, which ignites the process gases in the processing region 140 into a plasma. The intermediate RF bias power source 150 is set to provide power in a range of about 2000 to 3000 Watts at a frequency of 13.56 MHz, while the low RF bias power source (e.g., first biasing power supply) 154 provides power in a range of about 2000 to 3000 Watts at a frequency of 2 MHz. The RF signal from the two bias power sources 150 and 154 provide a RF signal modulated by about 10 to 80 percent.

[0050] FIGS. 5A-5D depict graphs of exemplary RF waveforms used in the present invention. FIG. 5A depicts a 2 MHz biasing signal, FIG. 5B depicts a 13.56 MHz biasing signal, and FIG. 5C depicts a modulated biasing signal. In FIGS. 5A-5C, each waveform graph has a y-axis representing magnitude of power, and an x-axis representing frequency. In particular, FIG. 5C shows the resultant amplitude modulated continuous wave (CW) signal, where the 13.56 MHz RF signal is modulated by the 2 MHz RF signal.

[0051] FIG. 5D depicts a graph illustrating a modulated pulsed waveform. In this instance, a square wave is used as a modulating signal, which produces the modulated signal shown in FIG. 5D, where the amplitude of the modulated signal varies in strength as a function of the modulating

waveform. The modulated pulsed waveform graph has a y-axis representing magnitude of power, and an x-axis representing time. Each pulse represents modulated power having a pulse peak of about  $\pm 3000$  W, and a duty cycle between about 10 to 90 percent. Note that **FIG. 5D** illustratively shows a 50% duty cycle, however, one skilled in the art will appreciate that the duty cycle may vary depending on the particular recipe used to form the features (e.g., deep trench). The controller **110** controls the pulsed power to the biasing element **120** based on the particular processing recipe requirements. The pulses are repeated during processing to emulate a modulated waveform. It is noted that only one biasing power source (e.g., **150** or **154**) is necessary to provide the modulated pulsed waveform shown in **FIG. 5D**.

[0052] At the peak magnitudes (higher energy levels) of the modulated CW (and pulsed) signal (point A) components of the plasma (e.g., ions) are accelerated toward the wafer, as compared to when the magnitude of the modulated CW signal (and modulated pulsed signal) approaches lower energy levels (point B). Further, the ion energy increases because of the low and medium frequency used for the bias power, as well as modulates as the amplitude modulates. Although the modulation waveforms are shown and discussed in **FIGS. 5A-5D** as a sine wave and square wave, those skilled in the art will appreciate that other waveforms may also be modulated onto a carrier signal.

[0053] **FIG. 4** depicts a cross-sectional view of a second embodiment of a dual frequency bias plasma chamber system **400**. This second embodiment may also be used to practice the invention and is illustratively an inductively coupled plasma chamber reactor **400**, such as a DPS-DT reactor, available from Applied Materials Inc., of Santa Clara, Calif. For a detailed description of the exemplary inductively coupled reactor **400**, the reader is directed to U.S. Pat. Nos. 6,444,085, 6,454,898, 6,444,084, and 6,270,617, which are incorporated herein by reference in their entirety. In general, any etch chamber having a plasma source element and a wafer bias element, where the wafer bias element is capable of being coupled to a modulated bias power may be utilized. That is, those skilled in the art will appreciate that other forms of etch chambers may be used to practice the invention, including chambers with remote plasma sources, microwave plasma chambers, electron cyclotron resonance (ECR) plasma chambers, among others.

[0054] The reactor **400** comprises a process chamber **406** having a wafer support pedestal **420** within a conductive body (wall) **422**, and a controller **410**. The wall **422** is supplied with a dome-shaped dielectric ceiling **472**. Other modifications of the chamber **406** may have other types of ceilings, e.g., a flat ceiling. Typically, the wall **422** is coupled to an electrical ground. Above the ceiling **472** is disposed an inductive coil antenna **404**. The inductive coil antenna **404** is coupled to a plasma power source **462**, through a first matching network **461**. The inductive coil antenna **404** serves as a plasma generating element, and is disposed as a spiral shaped helicoid around the dome ceiling **472**. Alternatively, in instances where the invention is practiced in chamber **100** having a substantially flat ceiling **472**, a stack or other forms of antennas **404** may be provided over the ceiling **472**. The plasma power source **462** typically is capable of producing power between about 100 Watts and

about 7500 Watts, at a frequency of about 2 MHz to about 180 MHz, and in one embodiment, at a frequency of about 2 MHz to 13.56 MHz.

[0055] The support pedestal (biasing element) **421**, which is coupled, through a first matching network **451**, to a first biasing power source **450**, as well as a second matching network **455**, to a second biasing power source **454**. In one embodiment, the first and second biasing power supplies **150** and **154** are coupled to a chucking electrode (e.g., monopolar electrode), which is embedded in the support pedestal (chuck) and functions as the biasing element. Similar to the first embodiment shown in **FIG. 1**, the first biasing power supply **450** provides RF power in the range of about 10 Watts to 7500 Watts (W), and at a frequency in the range of about 100 KHz to 6 MHz. The second biasing power supply **454** provides RF power in the range of about 10 W to 7500 W, at a frequency in the range of about 10 MHz to 60 MHz relative the ground, and, for example, at a frequency of 13.56 MHz. As such, the signal from the first bias power supply **450** amplitude modulates the signal from the second bias power supply **454**. For example, a 13.56 MHz signal from the second bias power supply **154** is amplitude modulated with a 2 MHz signal from the first biasing power supply **150**, as discussed above with regard to method **300** of **FIG. 3** and illustrated by the waveforms depicted in **FIGS. 5A-5D**.

[0056] In operation, a semiconductor wafer **401** is placed on the pedestal **420** and process gases are supplied from a gas panel **460** through gas entry ports (nozzles) **474** to provide a gaseous mixture in the processing region **440**. The gaseous mixture is ignited into a plasma in the chamber **406** by applying power from the source **462** to the antenna **404**. The pressure within the interior of the chamber **406** is controlled using a throttle valve **427** and a vacuum pump **464**. The temperature of the chamber wall **422** is controlled using liquid-containing conduits (not shown) that run through the wall **422**.

[0057] The temperature of the wafer **401** is controlled by stabilizing a temperature of the support pedestal **420**. In one embodiment, helium gas from a source **448** is provided via a gas conduit **449** to channels formed by the back of the wafer **401** and grooves (not shown) on the pedestal surface. The helium gas is used to facilitate heat transfer between the pedestal **420** and the wafer **401**.

[0058] To facilitate control of the chamber as described above, the controller **410** may be one of any form of general-purpose computer processor that can be used in an industrial setting for controlling various chambers and sub-processors. The controller **410** comprises a central processing unit (CPU) **412**, a memory **414**, and support circuits **416** for the CPU **412**. The controller **410** facilitates control of the components of the DPS etch process chamber **400** in a similar manner as discussed for the controller **110** and chamber **106** of **FIG. 1**.

[0059] Accordingly, an apparatus for controlling a plasma in a chamber during wafer processing has been shown and discussed above. The apparatus comprises a biasing element disposed in the chamber and adapted to support a wafer, and a plasma generating element is disposed over the biasing element. A first power source is coupled to the plasma generating element, and a second power source is also coupled to the biasing element to provide a modulated signal to the biasing element.

[0060] It is noted that the teachings of the present invention have been shown and described in two exemplary etching chambers utilizing a source power supply **162** and **462** to control ion energy and ion bombardment on the wafers. However, the present invention is also applicable where no power (i.e., power (W) and frequency (Hz) both equal zero) is provided from a source power supply, such as in an eMAX chamber, which is available from Applied Materials Inc. of Santa Clara, Calif. In this instance, the chamber surface serves as an RF ground (anode) with respect to the biasing power supplies **150** and **154**, and one of the biasing power supplies may be utilized to serve as both bias and source power supplies.

[0061] Although various embodiments that incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

What is claimed is:

1. A method of processing a workpiece in a plasma reactor having electrode apparatus for coupling RF power to plasma in said reactor, said method comprising:

simultaneously applying RF power from three RF sources of three different RF frequencies to said electrode apparatus;

selecting respective power levels of said three RF sources to select respective characteristics of a plasma in said reactor.

2. The method of claim 1 wherein said electrode apparatus comprises a top electrode at a ceiling of the reactor and a bottom electrode at a wafer support of said reactor, and wherein the step of applying RF power comprises coupling first and second ones of said three RF sources to said bottom electrode.

3. The method of claim 2 wherein the step of applying RF power further comprises coupling a third one of said RF sources to said electrode apparatus.

4. The method of claim 3 wherein the step of coupling said third one of said RF sources to said electrode apparatus comprises coupling said third RF source to said top electrode.

5. The method of claim 1 wherein said respective characteristics comprise plasma ion density, plasma ion energy and wideness of energy band of said plasma ion energy.

6. The method of claim 1 wherein the frequencies of said first, second and third RF sources are VHF, HF and LF frequencies respectively.

7. The method of claim 6 wherein the step of selecting respective power levels comprises selecting the power levels of said first, second and third RF sources within respective predetermined ranges.

8. A plasma reactor for processing a workpiece, comprising:

a reactor chamber and a wafer support within said chamber;

electrode apparatus for coupling RF power to plasma in said reactor;

three RF sources of three different RF frequencies coupled to said electrode apparatus.

9. The reactor of claim 8 wherein said three RF sources are independently controllable.

10. The reactor of claim 8 wherein said electrode apparatus comprises a top electrode at a ceiling location overlying said wafer support and a bottom electrode at said wafer support of said reactor.

11. The reactor of claim 10 wherein said first and second RF sources are coupled to said bottom electrode.

12. The reactor of claim 11 wherein said third RF sources is coupled to said top electrode.

13. The reactor of claim 8 further comprising first, second and third impedance match elements connected between said first, second and third RF sources, respectively, and said electrode apparatus.

14. The method of claim 8 wherein the frequencies of said first, second and third RF sources are VHF, HF and LF frequencies respectively.

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