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(54) **POLARITY CONTROL FOR REMOTE PLASMA**

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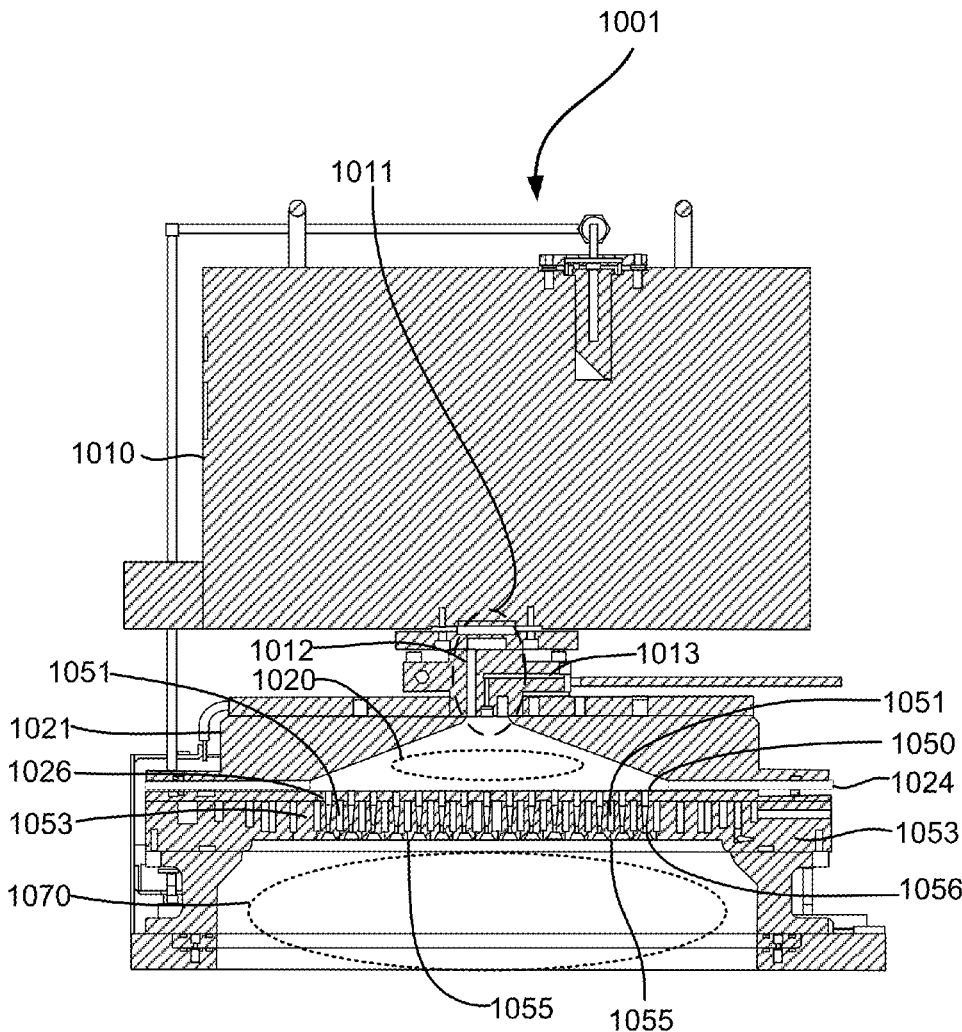
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(57) **ABSTRACT**  
Methods of controlling the polarity of capacitive plasma power applied to a remote plasma are described. Rather than applying a plasma power which involves both a positive and negative voltage swings equally, a capacitive plasma power is applied which favors either positive or negative voltage swings in order to select desirable process attributes. For example, the plasma power may be formed by applying a unipolar oscillating voltage between an electrode and a perforated plate. The unipolar oscillating voltage may have only positive or only negative voltages between the electrode and the perforated plate. The unipolar oscillating voltage may cross electrical ground in some portion of its oscillating voltage.

**Related U.S. Application Data**

(60) Provisional application No. 61/911,791, filed on Dec. 4, 2013.



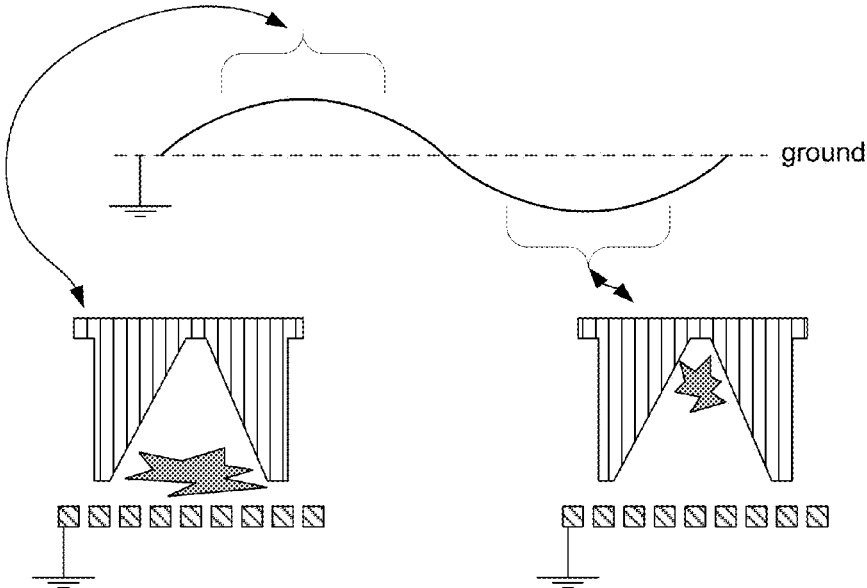


FIG. 1

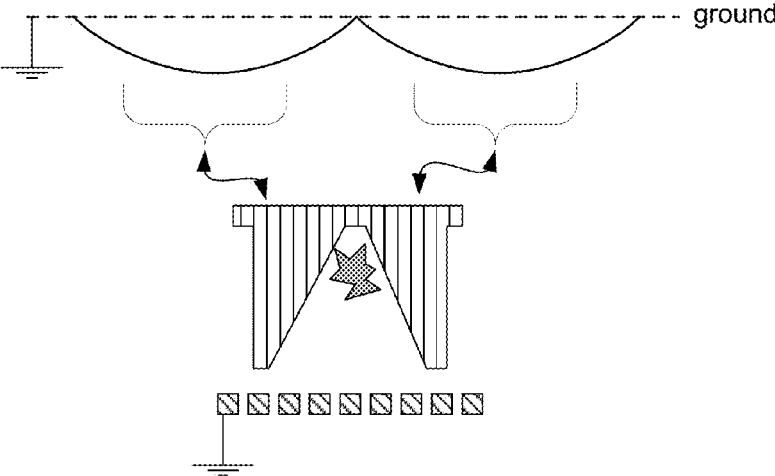
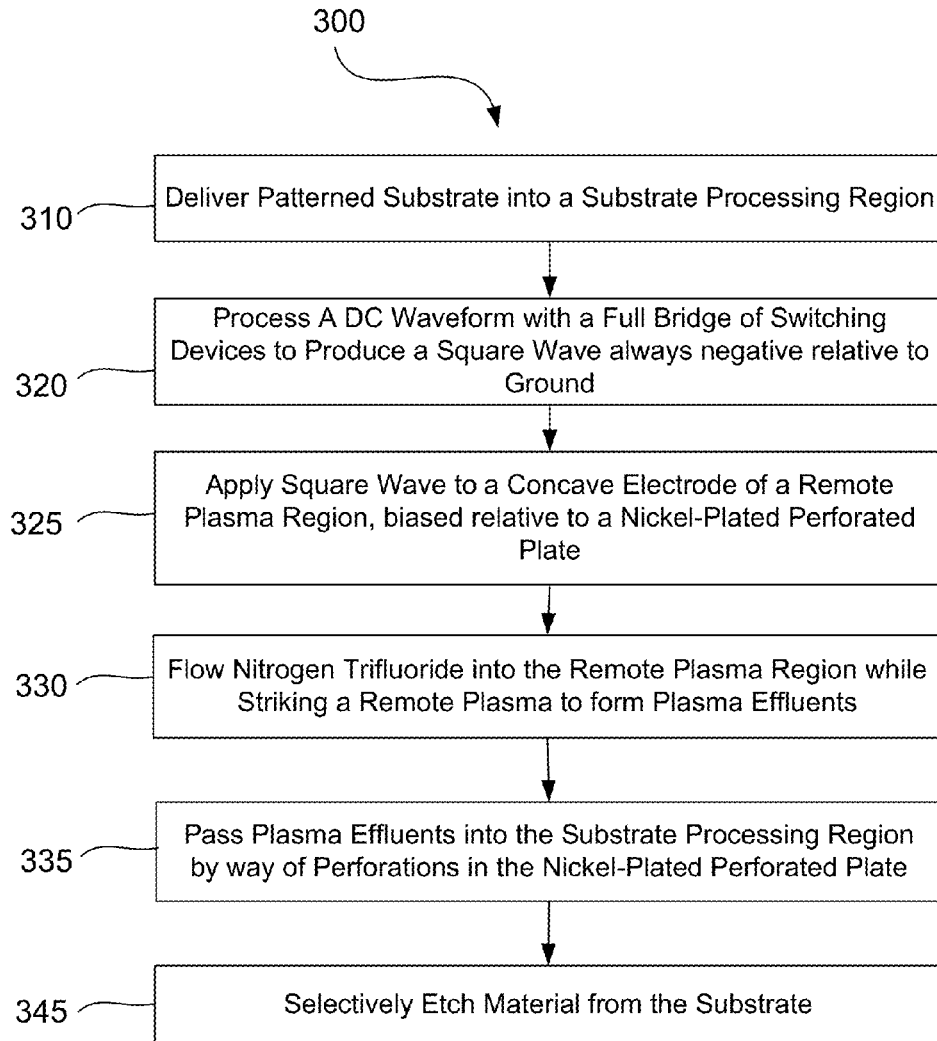


FIG. 2



**FIG. 3**

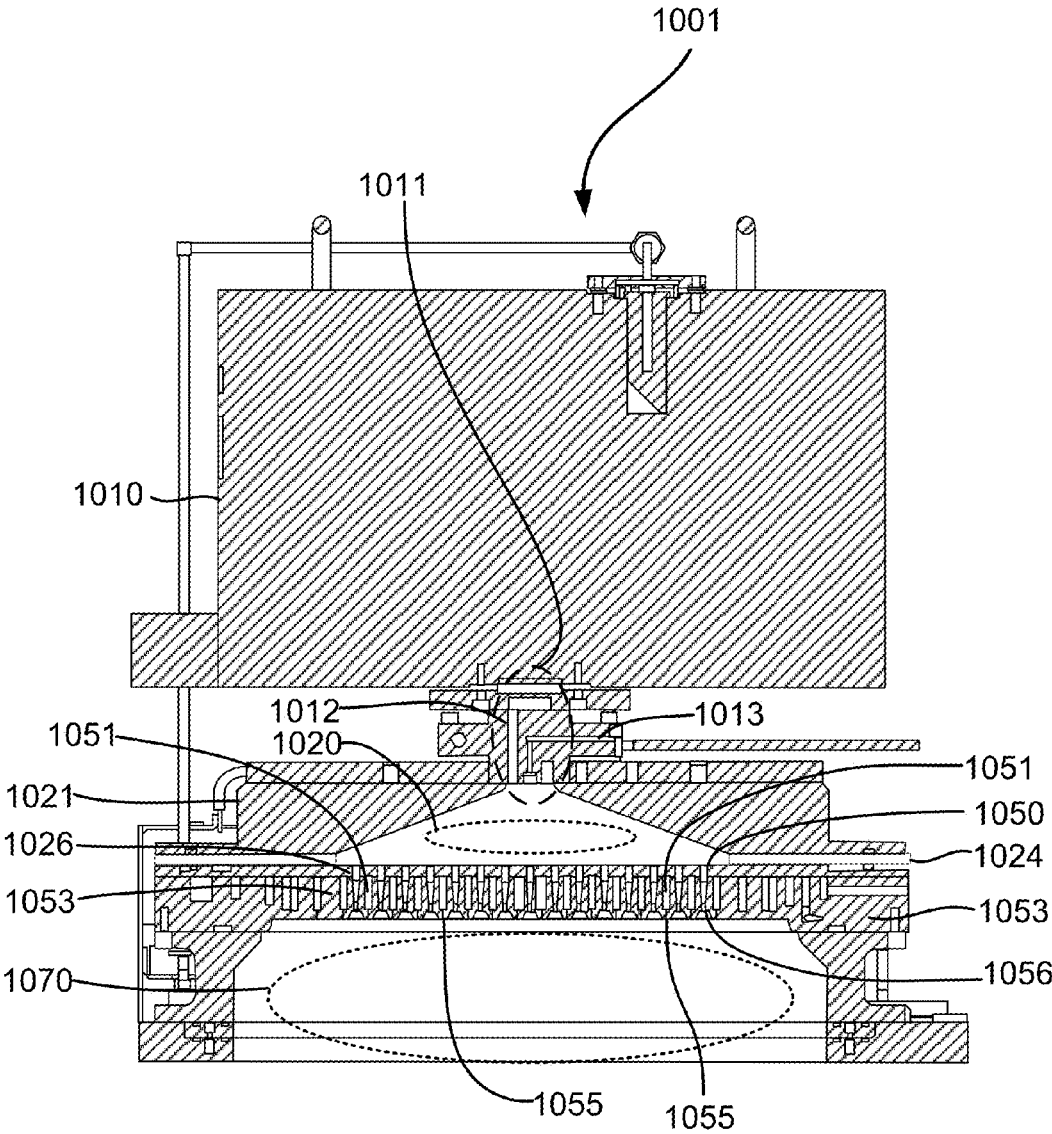
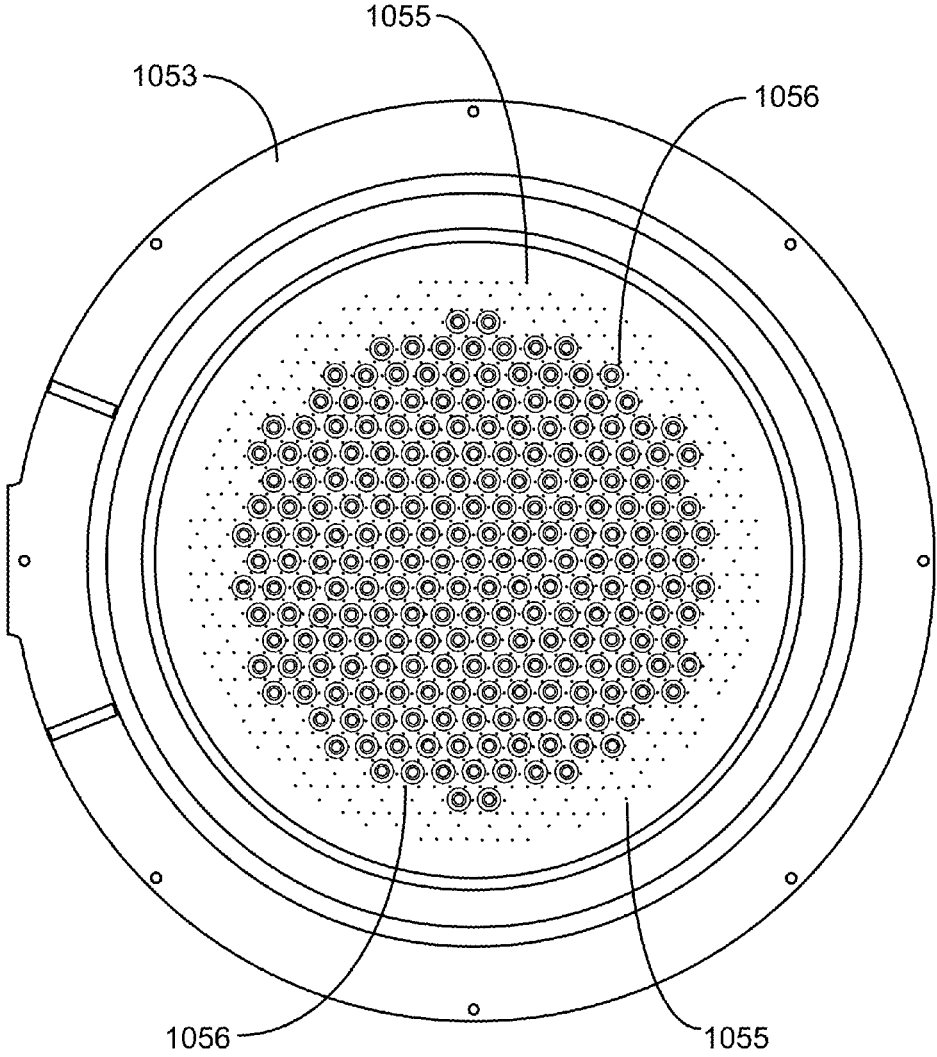
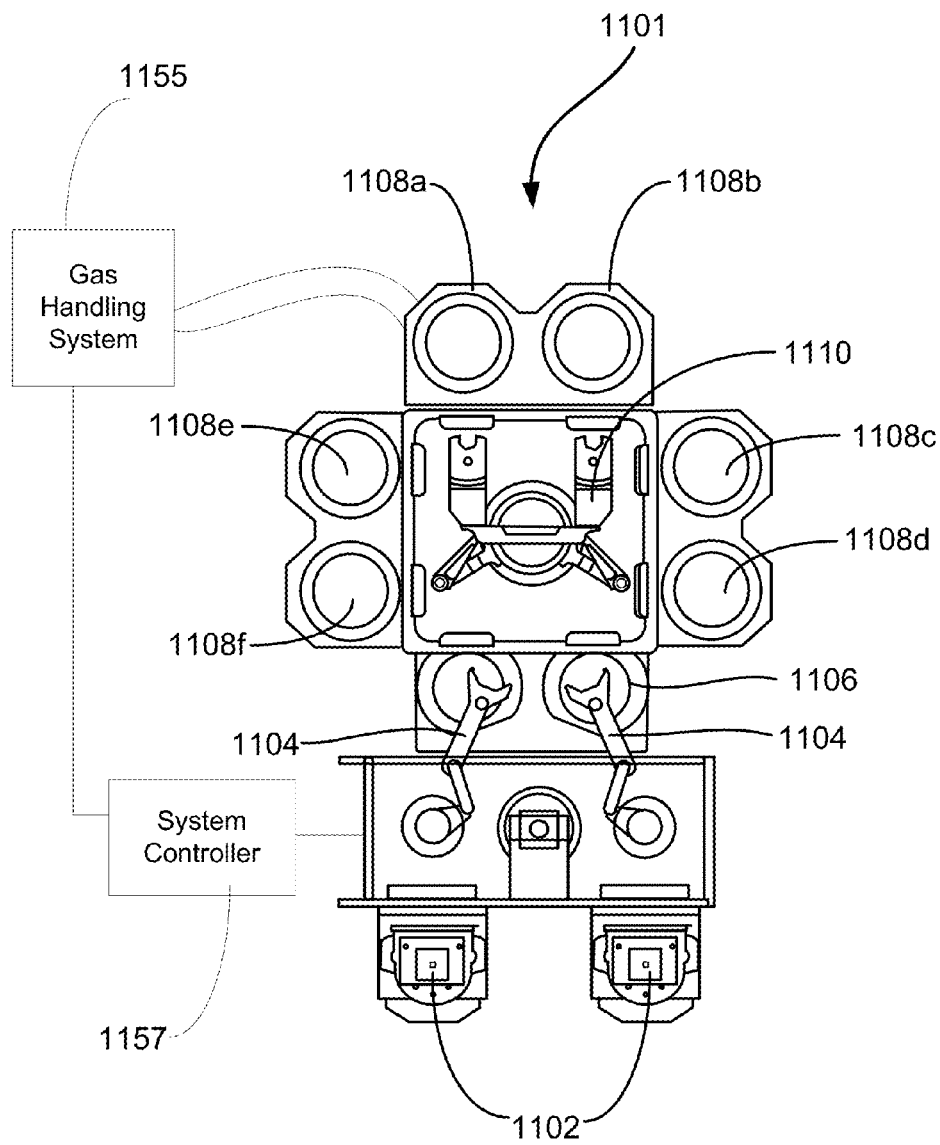


FIG. 4A



**FIG. 4B**



**FIG. 5**

## POLARITY CONTROL FOR REMOTE PLASMA

### CROSS-REFERENCES TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of U.S. Prov. Pat. App. No. 61/911,791 filed Dec. 4, 2013, and titled "POLARITY CONTROL FOR REMOTE PLASMA" by Cho et al., which is hereby incorporated herein in its entirety by reference for all purposes.

### FIELD

**[0002]** Embodiments of the invention relate to polarity control using a remote plasma.

### BACKGROUND

**[0003]** Integrated circuits are made possible by processes which produce intricately patterned material layers on substrate surfaces. Producing patterned material on a substrate requires controlled methods for removal of exposed material. Chemical etching is used for a variety of purposes including transferring a pattern in photoresist into underlying layers, thinning layers or thinning lateral dimensions of features already present on the surface. Often it is desirable to have an etch process which etches one material faster than another helping e.g. a pattern transfer process proceed. Such an etch process is said to be selective of the first material. As a result of the diversity of materials, circuits and processes, etch processes have been developed that selectively remove one or more of a broad range of materials. However, there are few options for selectively etching silicon using gas phase reactants.

**[0004]** Dry etch processes are often desirable for selectively removing material from semiconductor substrates. The desirability stems from the ability to gently remove material from miniature structures with minimal physical disturbance. Dry etch processes also allow the etch rate to be abruptly stopped by removing the gas phase reagents. Some dry-etch processes involve the exposure of a substrate to remote plasma by-products formed from one or more precursors. For example, remote plasma generation of nitrogen trifluoride in combination with ion suppression techniques enables silicon to be selectively removed from a patterned substrate when the plasma effluents are flowed into the substrate processing region.

**[0005]** Methods are needed to improve process control for remote plasma processes.

### SUMMARY

**[0006]** Methods of controlling the polarity of capacitive plasma power applied to a remote plasma are described. Rather than applying a plasma power which involves both a positive and negative voltage swings equally, a capacitive plasma power is applied which favors either positive or negative voltage swings in order to select desirable process attributes. For example, the plasma power may be formed by applying a unipolar oscillating voltage between an electrode and a perforated plate. The unipolar oscillating voltage may have only positive or only negative voltages between the electrode and the perforated plate. The unipolar oscillating voltage may be formed by offsetting an input oscillating voltage with a DC offset voltage, or it may be formed by rectifying an input oscillating voltage using a diode or diode

bridge or it may be formed from an input DC voltage processed using switching devices to form a unipolar square-wave voltage. The unipolar oscillating voltage may have mostly positive or mostly negative voltages between the electrode and the perforated plate. The remote plasma may be used to excite a fluorine-containing precursor whose effluents are passed into a substrate processing region to selectively etch a patterned substrate.

**[0007]** Embodiments of the invention include methods of processing a substrate. The methods include transferring the substrate into a substrate processing region of a substrate processing chamber. The methods further include applying a unipolar oscillating voltage between an electrode and a perforated plate. The unipolar oscillating voltage, on average, biases the perforated plate at a positive voltage relative to the electrode. The methods further include forming a remote plasma between the electrode and the perforated plate to form plasma effluents. The methods further include flowing the plasma effluents into the substrate processing region housing the substrate. The plasma effluents flow into the substrate processing region through perforations in the perforated plate. The methods further include reacting the plasma effluents with the substrate.

**[0008]** Embodiments of the invention include methods of etching a substrate. The methods include transferring the substrate into a substrate processing region of a substrate processing chamber. The methods further include applying a unipolar oscillating voltage between an electrode and a perforated plate. The unipolar oscillating voltage negatively biases the electrode relative to the perforated plate. The methods further include flowing a halogen-containing precursor into a remote plasma between the electrode and the perforated plate while forming a remote plasma to form plasma effluents. The methods further include flowing the plasma effluents into the substrate processing region housing the substrate. The plasma effluents flow into the substrate processing region through perforations in the perforated plate. The methods further include etching the substrate with the plasma effluents.

**[0009]** Embodiments of the invention include methods of etching a patterned substrate. The methods include transferring the patterned substrate into a substrate processing region of a substrate processing chamber. The methods further include sending a DC voltage through a full bridge of four switching devices to form a unipolar oscillating voltage. The methods further include applying the unipolar oscillating voltage between a concave electrode and a flat nickel-plated perforated plate. The unipolar oscillating voltage biases the concave electrode at a negative voltage relative to the flat nickel-plated perforated plate. The methods further include flowing a fluorine-containing precursor into a remote plasma between the concave electrode and the flat nickel-plated perforated plate while forming a remote plasma to form plasma effluents. The methods further include flowing the plasma effluents into the substrate processing region housing the patterned substrate. The plasma effluents flow into the substrate processing region through perforations in the perforated plate. The methods further include selectively etching the patterned substrate with the plasma effluents.

**[0010]** Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the disclosed embodiments. The features and advantages of the dis-

closed embodiments may be realized and attained by means of the instrumentalities, combinations, and methods described in the specification.

#### DESCRIPTION OF THE DRAWINGS

**[0011]** A further understanding of the nature and advantages of the disclosed embodiments may be realized by reference to the remaining portions of the specification and the drawings.

**[0012]** FIG. 1 is a graphic showing a bipolar oscillating voltage, a concave electrode, and resulting plasma location according to embodiments.

**[0013]** FIG. 2 is a graphic showing a unipolar oscillating voltage and resulting plasma according to embodiments.

**[0014]** FIG. 3 is a flow chart of a substrate processing sequence according to embodiments.

**[0015]** FIG. 4A shows a substrate processing chamber according to embodiments of the invention.

**[0016]** FIG. 4B shows a showerhead of a substrate processing chamber according to embodiments of the invention.

**[0017]** FIG. 5 shows a substrate processing system according to embodiments of the invention.

**[0018]** In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

#### DETAILED DESCRIPTION

**[0019]** Methods of controlling the polarity of capacitive plasma power applied to a remote plasma are described. Rather than applying a plasma power which involves both a positive and negative voltage swings equally, a capacitive plasma power is applied which favors either positive or negative voltage swings in order to select desirable process attributes. For example, the plasma power may be formed by applying a unipolar oscillating voltage between an electrode and a perforated plate. The unipolar oscillating voltage may have only positive or only negative voltages between the electrode and the perforated plate. The unipolar oscillating voltage may be formed by offsetting an input oscillating voltage with a DC offset voltage, or it may be formed by rectifying an input oscillating voltage using a diode or diode bridge or it may be formed from an input DC voltage processed using switching devices to form a unipolar square-wave voltage. A unipolar oscillating voltage may be generally positive or negative while having a much smaller amount of negative or positive voltages, respectively. In other words, a unipolar oscillating voltage may cross electrical ground in some portion of the oscillating voltage. The remote plasma may be used to excite a fluorine-containing precursor whose effluents are passed into a substrate processing region to selectively etch a patterned substrate.

**[0020]** Reference is now made to FIG. 1 which is a graphic showing a bipolar oscillating voltage used to drive a concave electrode and the plasma locations which have been found to occur during the positive and negative swings embodiments. A bipolar sinusoidal voltage is shown and is symmetric around electrical ground. The bipolar sinusoidal voltage rep-

resents a sinusoidally varying voltage (varying in time) applied to an electrode relative to a grounded perforated plate. The electrode is not planar and the perforated plate is planar according to embodiments. As shown, the plasma has been found to change positions within the remote plasma region between the non-planar electrode and the perforated plate. The bipolar sinusoidal voltage initially swings positive such that the non-planar electrode is positively biased relative to the grounded perforated plate. During this time, the plasma is located close to the perforated plate. When the sinusoidal voltage swings negative, the non-planar electrode is negatively biased relative to the grounded perforated plate and the plasma switches to a position farther away from the perforated plate. Other shapes of bipolar oscillating voltages may be used to drive the concave electrode and the locations of the two plasma excitations would be similar.

**[0021]** The non-planar electrode may be referred to as a concave electrode (or a hollow cathode) when the interior surface is cup-shaped as shown. A concave electrode forms a larger volume near the center of the remote plasma region. A perpendicular distance from the perforated plate to a concave electrode may be greater near the center of the perforated plate than a perpendicular distance from the perforated plate to the electrode near the edge. The remote plasma on the left of FIG. 1 may be referred to as "glow discharge mode" and the remote plasma on the right of FIG. 1 may be referred to as "hollow cathode mode." The hollow cathode mode has been found to be desirable in embodiments. The concave electrode is negatively biased during the hollow cathode mode which directs ions away from the perforated plate and may reduce sputtering effects. The perforated plate may be coated with nickel in embodiments. A substrate is disposed below the perforated plate during processing and substrates have been found to possess more micro-contamination (in the form of elevated particle count) in glow discharge mode relative to hollow cathode mode. The benefit may also arise from the location of the plasma relative to the perforated plate and may result from the presence of the nickel coating.

**[0022]** FIG. 2 is a graphic showing a unipolar oscillating voltage according to embodiments. A bipolar sinusoidal voltage is processed to switch the sign of the positive swing, in embodiments, so that the resulting unipolar oscillating voltage possesses two negative swings per period of the original bipolar sinusoidal voltage. The period of the unipolar oscillating voltage is half the period of the original bipolar sinusoidal voltage. The unipolar oscillating voltage is still a repetitive oscillating voltage but may not be referred to as a sinusoidal oscillating voltage anymore. The unipolar oscillating voltage is applied to the concave electrode and the plasma predominantly forms in the same portion of the remote plasma region during every peak of the unipolar oscillating voltage and not just half of the peaks. The bipolar sinusoidal voltage may be processed by passing the bipolar sinusoidal voltage through a diode bridge formed from any appropriate type of four diodes. High voltage bipolar sinusoidal voltages may be processed using IGBT (insulated gate bipolar transistor) diodes and low voltage bipolar sinusoidal voltages (less than 1-2 kV) may be processed using FET-style diodes. A full bridge rectifying circuit would eliminate the ability of the bipolar oscillating voltage to excite a plasma so only a portion of a rectification operation is performed on the bipolar sinusoidal voltage as shown in FIG. 2. Alternatively, the bipolar sinusoidal voltage may be processed with a more simplistic circuit (involving e.g. a single diode) to create a unipolar



oscillating voltage with one negative swing for each period of the original bipolar oscillating voltage. In this case, the unipolar oscillating voltage would possess the same period as the bipolar sinusoidal voltage. Alternatively, the unipolar oscillating voltage may be formed by passing a DC voltage through a full bridge formed from any appropriate type of four switching devices.

[0023] In order to better understand and appreciate the invention, reference is now made to FIG. 3 which is a flow chart of a substrate processing method 300 according to embodiments. A substrate (which may be patterned) is transferred into a substrate processing region in operation 310. A DC voltage may then be processed to form a "square wave" for the unipolar oscillating voltage (operation 320) of negative sign. Alternatively, a sinusoidal voltage may be processed using a diode bridge (operation 320) to form a unipolar oscillating voltage which may always be negative relative to the potential of a nickel-plated perforated plate. The nickel-plated perforated plate is connected to electrical ground in substrate processing sequence 300 but may be held at another potential in embodiments. The unipolar oscillating voltage is applied to a concave electrode relative to the nickel-plated perforated plate (operation 325).

[0024] Nitrogen trifluoride is flowed into a remote plasma region and a remote plasma power is applied (operation 330) to form plasma effluents. The remote plasma region is separated from the substrate processing region by the nickel-plated perforated plate. The plasma effluents are flowed into the substrate processing region (operation 335). Other sources of fluorine may be used to augment or replace the nitrogen trifluoride. In general, a fluorine-containing precursor may be flowed into the remote plasma region and the fluorine-containing precursor may include one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen trifluoride, perfluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride. The plasma effluents formed in the remote plasma region are then flowed into the substrate processing region (operation 335) through perforations in the nickel-plated perforated plate which separates the remote plasma region and the substrate processing region. One material on the patterned substrate is selectively etched relative to another (operation 345). The reactive chemical species and any process effluents are removed from the substrate processing region and then the substrate is removed from the substrate processing region.

[0025] The remote plasma region is located within a compartment within the substrate processing chamber between the electrode and the perforated plate. The remote plasma region may be fluidly coupled to the substrate processing region by way of perforations in perforated plate. The hardware just described (and elaborated on in the equipment section) may also be used in all processes discussed herein. The perforated plate may be the showerhead described herein or it may be the ion suppression element according to embodiments. The perforated plate may also describe the combination of an ion suppression element and a showerhead.

[0026] The selective etching operation 345 may remove one material faster than another. For example, silicon on the substrate may be selectively etched such that silicon is removed more rapidly than a variety of other materials. The etch selectivity (silicon:silicon oxide or silicon:silicon nitride) may also be greater than or about 70:1, greater than or about 100:1, greater than or about 150:1, greater than or about 200:1, greater than or about 250:1 or greater than or about

300:1 according to embodiments. Regions of exposed tungsten or titanium nitride may be present, in embodiments, on the patterned substrate and may be referred to as exposed metallic regions. The etch selectivity (silicon:exposed metallic region) may be greater than or about 100:1, greater than or about 150:1, greater than or about 200:1, greater than or about 250:1, greater than or about 500:1, greater than or about 1000:1, greater than or about 2000:1 or greater than or about 3000:1 according to embodiments. The flow rate ranges now given for fluorine-containing precursors apply to flowing operation 330 (as well as all flowing operations described herein). In embodiments, the fluorine-containing precursor (e.g.  $\text{NF}_3$ ) is supplied at a flow rate of between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm.

[0027] The method also includes applying energy to the fluorine-containing precursor in the remote plasma region to generate the plasma effluents in operation 330 (as well as all remote plasmas described herein). The plasma may be generated using low frequency excitations applied using capacitively-coupled power according to embodiments. The remote plasma source power may be between about 10 watts and about 3000 watts, between about 20 watts and about 2000 watts, between about 30 watts and about 1000 watts in embodiments. The low frequency excitation may be a driving voltage in the form of a square wave, triangle wave or sinusoidal voltage but may also be a variety of repetitive voltages (aka unipolar oscillating voltages according to embodiments). The unipolar oscillating voltage may have a unipolar oscillating frequency of less than or about 1,000 kHz, less than or about 500 kHz, less than or about 300 kHz or between 1 kHz and 200 kHz according to embodiments. The peak-to-peak amplitude of the unipolar oscillating voltage may be greater than 300 volts, greater than 500 volts or greater than 800 volts in embodiments.

[0028] Generally speaking, a unipolar oscillating voltage is applied between the non-planar electrode and the perforated plate. The differential voltage applied in this way will be referred to as the unipolar oscillating voltage. For example, the unipolar oscillating voltage may be applied to the non-planar electrode while the perforated plate is at electrical ground. The unipolar oscillating voltage may be applied to the perforated plate while the non-planar electrode is at electrical ground according to embodiments. In embodiments, neither the perforated plate nor the non-planar electrode is at ground but the unipolar oscillating voltage is still applied as a differential voltage between the perforated plate and the non-planar electrode.

[0029] The unipolar oscillating voltage may be formed using a variety of techniques. A DC input voltage may be chopped into a unipolar oscillating voltage which is a "square wave" aside from slew rate effects. An input voltage may be processed to create the unipolar oscillating voltage used to create the plasma. The unipolar oscillating voltage is applied between the non-planar electrode and the perforated plate. The input voltage may be processed using a diode or diode bridge, as described previously, to form the unipolar oscillating voltage. The input voltage may be a sinusoidally-varying function in time centered about the potential of the perforated plate or ground, in embodiments. The input voltage may be shifted with a DC offset voltage such that the unipolar oscillating voltage is no longer centered around the potential of the

perforated plate. Regardless of the processing technique used, the electrical potential of the non-planar electrode may be greater than the electrical potential of the perforated plate more than 85% of the time, more than 90% of the time, more than 95% of the time or all the time according to embodiments. Alternatively, the electrical potential of the non-planar electrode may be less than the electrical potential of the perforated plate more than 85% of the time, more than 90% of the time, more than 95% of the time or all the time according to embodiments. Alternatively, the electrical potential of the non-planar electrode may have a negative peak differential voltage whose magnitude exceeds its positive peak voltage of the perforated plate (with each peak measured from the potential of the perforated plate) by a multiplicative factor of 5, a multiplicative factor of 10 or a multiplicative factor of 20 in embodiments. Analogously, the electrical potential of the non-planar electrode may have a positive peak differential voltage whose magnitude exceeds its negative peak voltage of the perforated plate (with each peak measured from the potential of the perforated plate) by a multiplicative factor of 5, a multiplicative factor of 10 or a multiplicative factor of 20 according to embodiments.

**[0030]** In all embodiments described herein which use a remote plasma, the term “plasma-free” may be used to describe the substrate processing region during application of no or essentially no plasma power. A plasma-free substrate processing region may be used during substrate processing method **300** in embodiments.

**[0031]** The temperature of the substrate for all embodiments described herein may be greater than 0° C. during the etch process. The substrate temperature may be greater than or about -20° C. and less than or about 300° C. The pressure in the substrate processing region may be similar to the pressure in the remote plasma region during substrate processing method **300**. The pressure within the substrate processing region may be below or about 10 Torr, below or about 5 Torr, below or about 3 Torr, below or about 2 Torr, below or about 1 Torr or below or about 750 mTorr according to embodiments. In order to ensure adequate etch rate, the pressure may be above or about 0.05 Torr, above or about 0.1 Torr, above or about 0.2 Torr or above or about 0.4 Torr in embodiments. Any of the upper limits on pressure may be combined with lower limits according to embodiments.

**[0032]** In each remote plasmas described herein, the flows of the precursors into the remote plasma region may further include one or more relatively inert gases such as He, N<sub>2</sub>, Ar. The inert gas can be used to improve plasma stability, ease plasma initiation, and improve process uniformity. Argon is helpful, as an additive, to promote the formation of a stable plasma. Process uniformity is generally increased when helium is included. These additives are present in embodiments throughout this specification. Flow rates and ratios of the different gases may be used to control etch rates and etch selectivity.

**[0033]** The non-planar electrode may be a variety of shapes and may be a concave electrode in disclosed embodiments. A concave electrode may include a portion shaped like a cone, a surface of revolution formed using a parabola, a surface of revolution formed using a circle or a surface of revolution using any generatrix according to embodiments.

**[0034]** In embodiments, an ion suppressor as described in the exemplary equipment section may be used to provide radical and/or neutral species for selectively etching substrates. The ion suppressor may also be referred to as an ion

suppression element. In embodiments, for example, the ion suppressor is used to filter fluorine-containing plasma effluents to selectively etch silicon. The ion suppressor may be included in each exemplary process described herein. Using the plasma effluents, an etch rate selectivity of a selected material to a wide variety of materials may be achieved.

**[0035]** The ion suppressor may be used to provide a reactive gas having a higher concentration of radicals than ions. The ion suppressor functions to dramatically reduce or substantially eliminate ionically charged species traveling from the plasma generation region to the substrate. The electron temperature may be measured using a Langmuir probe in the substrate processing region during excitation of a plasma in the remote plasma region on the other side of the ion suppressor. In embodiments, the electron temperature may be less than 0.5 eV, less than 0.45 eV, less than 0.4 eV, or less than 0.35 eV. These extremely low values for the electron temperature are enabled by the presence of the showerhead and/or the ion suppressor positioned between the substrate processing region and the remote plasma region. Uncharged neutral and radical species may pass through the openings in the ion suppressor to react at the substrate. Because most of the charged particles of a plasma are filtered or removed by the ion suppressor, the substrate is not necessarily biased during the etch process. Such a process using radicals and other neutral species can reduce plasma damage compared to conventional plasma etch processes that include sputtering and bombardment. The ion suppressor helps control the concentration of ionic species in the reaction region at a level that assists the process. Embodiments of the present invention are also advantageous over conventional wet etch processes where surface tension of liquids can cause bending and peeling of small features.

**[0036]** FIG. 3 is a plot of silicon etch rates **300** without a preventative maintenance procedure and following a preventative maintenance procedure according to embodiments. The plot of silicon etch rates **300** includes etch rate measurements performed over a sequence of 900 wafers (an example of substrates). Data **310** are included showing changes to etch rate of silicon over time while processing a sequence of wafers without any treatment operation prior to processing the wafers. The etch rate can be shown drifting upward as, presumably, the interior surfaces bordering the substrate processing region evolve over time. Data **320** are also included which show a relatively stable silicon etch rate following treatment operation **125** (using a fluorine-containing precursor). Data **330** are also included which show a relatively stable silicon etch rate following treatment **225** (using a hydrogen-containing precursor). The data following fluorine treatment operation **125** and the data following hydrogen treatment operation **225** are both indicative of a stable silicon etch rate which are each desirable in a manufacturing environment. Note that the magnitude of the etch rate following each of the two preventative maintenance operations differ from one another, presumably because the surfaces are covered with different chemical species. The interior surfaces bordering the substrate processing region are coated after fluorine treatment operation **125** such that the etch rate is stable at a value similar to the first wafer processed in an untreated chamber (the left-most data point in untreated data **310**). The interior surfaces are coated after hydrogen treatment operation **225** such that the etch rate is stable at a higher silicon etch rate which roughly matches the asymptotic extension of the etch rates for untreated data **310** after a large number of wafers is

processed. The appropriate preventative maintenance procedure may be selected based on a variety of process characteristics such as magnitude of etch rate, particle performance and etch rate within-wafer uniformity.

[0037] Additional process parameters are disclosed in the course of describing an exemplary processing chamber and system.

#### Exemplary Processing System

[0038] Processing chambers that may implement embodiments of the present invention may be included within processing platforms such as the CENTURA® and PRODUCER® systems, available from Applied Materials, Inc. of Santa Clara, Calif.

[0039] FIG. 4A is a substrate processing chamber 1001 according to embodiments. A remote plasma system 1010 may process a fluorine-containing precursor which then travels through a gas inlet assembly 1011. Two distinct gas supply channels are visible within the gas inlet assembly 1011. A first channel 1012 carries a gas that passes through the remote plasma system 1010 (RPS), while a second channel 1013 bypasses the remote plasma system 1010. Either channel may be used for the fluorine-containing precursor in embodiments. On the other hand, the first channel 1012 may be used for the process gas and the second channel 1013 may be used for a treatment gas. The lid (or conductive top portion) 1021 and a perforated partition 1053 are shown with an insulating ring 1024 in between, which allows a unipolar oscillating voltage to be applied to the lid 1021 relative to perforated partition 1053. The unipolar oscillating voltage strikes a plasma in chamber plasma region 1020. The process gas may travel through first channel 1012 into chamber plasma region 1020 and may be excited by a plasma in chamber plasma region 1020 alone or in combination with remote plasma system 1010. If the process gas (the fluorine-containing precursor) flows through second channel 1013, then only the chamber plasma region 1020 is used for excitation. The combination of chamber plasma region 1020 and/or remote plasma system 1010 may be referred to as a remote plasma region herein. The perforated partition (also referred to as a showerhead) 1053 separates chamber plasma region 1020 from a substrate processing region 1070 beneath showerhead 1053. Showerhead 1053 allows a plasma present in chamber plasma region 1020 to avoid directly exciting gases in substrate processing region 1070, while still allowing excited species to travel from chamber plasma region 1020 into substrate processing region 1070.

[0040] Showerhead 1053 is positioned between chamber plasma region 1020 and substrate processing region 1070 and allows plasma effluents (excited derivatives of precursors or other gases) created within remote plasma system 1010 and/or chamber plasma region 1020 to pass through a plurality of through-holes 1056 that traverse the thickness of the plate. The showerhead 1053 also has one or more hollow volumes 1051 which can be filled with a precursor in the form of a vapor or gas (such as the fluorine-containing precursor) and pass through blind-holes 1055 into substrate processing region 1070 but not directly into chamber plasma region 1020. Showerhead 1053 is thicker than the length of the smallest diameter 1050 of the through-holes 1056 in embodiments. To maintain a significant concentration of excited species penetrating from chamber plasma region 1020 to substrate processing region 1070, the length 1026 of the smallest diameter 1050 of the through-holes may be restricted

by forming larger diameter portions of through-holes 1056 part way through the showerhead 1053. The length of the smallest diameter 1050 of the through-holes 1056 may be the same order of magnitude as the smallest diameter of the through-holes 1056 or less in embodiments. Showerhead 1053 may be referred to as a dual-channel showerhead, a dual-zone showerhead, a multi-channel showerhead or a multi-zone showerhead to convey the existence of through-holes and blind-holes for introducing precursors.

[0041] Showerhead 1053 may be configured to serve the purpose of an ion suppressor as shown in FIG. 4A. Alternatively, a separate processing chamber element may be included (not shown) which suppresses the ion concentration traveling into substrate processing region 1070. Lid 1021 and showerhead 1053 may function as a first electrode and second electrode, respectively, so that lid 1021 and showerhead 1053 may receive different electric voltages. In these configurations, unipolar oscillating electrical power may be applied to lid 1021, showerhead 1053, or both. For example, electrical power may be applied to lid 1021 while showerhead 1053 (and/or an ion suppressor) is grounded. The substrate processing system may include a unipolar oscillating voltage generator that provides electrical power to the lid 1021 or showerhead 1053 while the other is grounded. The voltage applied to lid 1021 may facilitate a uniform distribution of plasma (i.e., reduce localized plasma) within chamber plasma region 1020. To enable the formation of a plasma in chamber plasma region 1020, insulating ring 1024 may electrically insulate lid 1021 from showerhead 1053. Insulating ring 1024 may be made from a ceramic and may have a high breakdown voltage to avoid sparking. Portions of substrate processing chamber 1001 near the capacitively-coupled plasma components just described may further include a cooling unit (not shown) that includes one or more cooling fluid channels to cool surfaces exposed to the plasma with a circulating coolant (e.g., water).

[0042] In the embodiment shown, showerhead 1053 may distribute (via through-holes 1056) process gases which contain fluorine, hydrogen and/or plasma effluents of such process gases upon excitation by a plasma in chamber plasma region 1020. In embodiments, the process gas introduced into the remote plasma system 1010 and/or chamber plasma region 1020 may contain fluorine. The process gas may also include a carrier gas such as helium, argon, nitrogen (N<sub>2</sub>), etc. Plasma effluents may include ionized or neutral derivatives of the process gas and may also be referred to herein as radical-fluorine referring to the atomic constituent of the process gas introduced.

[0043] Through-holes 1056 are configured to suppress the migration of ionically-charged species out of the chamber plasma region 1020 while allowing uncharged neutral or radical species to pass through showerhead 1053 into substrate processing region 1070. These uncharged species may include highly reactive species that are transported with less-reactive carrier gas by through-holes 1056. As noted above, the migration of ionic species by through-holes 1056 may be reduced, and in some instances completely suppressed. Controlling the amount of ionic species passing through showerhead 1053 provides increased control over the gas mixture brought into contact with the underlying wafer substrate, which in turn increases control of the deposition and/or etch characteristics of the gas mixture. For example, adjustments in the ion concentration of the gas mixture can alter the etch selectivity (e.g., the silicon:silicon nitride etch rate ratio).

[0044] In embodiments, the number of through-holes **1056** may be between about 60 and about 2000. Through-holes **1056** may have a variety of shapes but are most easily made round. The smallest diameter **1050** of through-holes **1056** may be between about 0.5 mm and about 20 mm or between about 1 mm and about 6 mm in embodiments. There is also latitude in choosing the cross-sectional shape of through-holes, which may be made conical, cylindrical or combinations of the two shapes. The number of blind-holes **1055** used to introduce unexcited precursors into substrate processing region **1070** may be between about 100 and about 5000 or between about 500 and about 2000 in different embodiments. The diameter of the blind-holes **1055** may be between about 0.1 mm and about 2 mm.

[0045] Through-holes **1056** may be configured to control the passage of the plasma-activated gas (i.e., the ionic, radical, and/or neutral species) through showerhead **1053**. For example, the aspect ratio of the holes (i.e., the hole diameter to length) and/or the geometry of the holes may be controlled so that the flow of ionically-charged species in the activated gas passing through showerhead **1053** is reduced. Through-holes **1056** in showerhead **1053** may include a tapered portion that faces chamber plasma region **1020**, and a cylindrical portion that faces substrate processing region **1070**. The cylindrical portion may be proportioned and dimensioned to control the flow of ionic species passing into substrate processing region **1070**. An adjustable electrical bias may also be applied to showerhead **1053** as an additional means to control the flow of ionic species through showerhead **1053**.

[0046] Alternatively, through-holes **1056** may have a smaller inner diameter (ID) toward the top surface of showerhead **1053** and a larger ID toward the bottom surface. In addition, the bottom edge of through-holes **1056** may be chamfered to help evenly distribute the plasma effluents in substrate processing region **1070** as the plasma effluents exit the showerhead and promote even distribution of the plasma effluents and precursor gases. The smaller ID may be placed at a variety of locations along through-holes **1056** and still allow showerhead **1053** to reduce the ion density within substrate processing region **1070**. The reduction in ion density results from an increase in the number of collisions with walls prior to entry into substrate processing region **1070**. Each collision increases the probability that an ion is neutralized by the acquisition or loss of an electron from the wall. Generally speaking, the smaller ID of through-holes **1056** may be between about 0.2 mm and about 20 mm. In other embodiments, the smaller ID may be between about 1 mm and 6 mm or between about 0.2 mm and about 5 mm. Further, aspect ratios of the through-holes **1056** (i.e., the smaller ID to hole length) may be approximately 1 to 20. The smaller ID of the through-holes may be the minimum ID found along the length of the through-holes. The cross-sectional shape of through-holes **1056** may be generally cylindrical, conical, or any combination thereof.

[0047] FIG. 4B is a bottom view of a showerhead **1053** for use with a processing chamber according to embodiments. Showerhead **1053** corresponds with the showerhead shown in FIG. 4A. Through-holes **1056** are depicted with a larger inner-diameter (ID) on the bottom of showerhead **1053** and a smaller ID at the top. Blind-holes **1055** are distributed substantially evenly over the surface of the showerhead, even amongst the through-holes **1056** which helps to provide more even mixing than other embodiments described herein.

[0048] An exemplary patterned substrate may be supported by a pedestal (not shown) within substrate processing region **1070** when fluorine-containing plasma effluents arrive through through-holes **1056** in showerhead **1053**. Though substrate processing region **1070** may be equipped to support a plasma for other processes such as curing, no plasma is present during the etching of patterned substrate, in embodiments.

[0049] A plasma may be ignited either in chamber plasma region **1020** above showerhead **1053** or substrate processing region **1070** below showerhead **1053**. A plasma is present in chamber plasma region **1020** to produce the radical-fluorine from an inflow of the fluorine-containing precursor. A unipolar oscillating voltage (shifted or otherwise transformed to generally confine to one polarity) is applied between the conductive top portion (lid **1021**) of the processing chamber and showerhead **1053** to ignite a plasma in chamber plasma region **1020** during deposition. The unipolar oscillating voltage applied to lid **1021** is shifted such to not center about the potential of showerhead **1053**. A unipolar oscillating voltage power supply generates a unipolar oscillating frequency of less than or about 1,000 kHz, less than or about 500 kHz, less than or about 300 kHz or between 1 kHz and 200 kHz according to embodiments.

[0050] The top plasma may be left at low or no power when the bottom plasma in the substrate processing region **1070** is turned on to either cure a film or clean the interior surfaces bordering substrate processing region **1070**. A plasma in substrate processing region **1070** is ignited by applying the unipolar oscillating voltage between showerhead **1053** and the pedestal or bottom of the chamber. A cleaning gas may be introduced into substrate processing region **1070** while the plasma is present.

[0051] The pedestal may have a heat exchange channel through which a heat exchange fluid flows to control the temperature of the substrate. This configuration allows the substrate temperature to be cooled or heated to maintain relatively low temperatures (from room temperature through about 120° C.). The heat exchange fluid may comprise ethylene glycol and water. The wafer support platter of the pedestal (preferably aluminum, ceramic, or a combination thereof) may also be resistively heated to achieve relatively high temperatures (from about 120° C. through about 1100° C.) using an embedded single-loop embedded heater element configured to make two full turns in the form of parallel concentric circles. An outer portion of the heater element may run adjacent to a perimeter of the support platter, while an inner portion runs on the path of a concentric circle having a smaller radius. The wiring to the heater element passes through the stem of the pedestal.

[0052] The chamber plasma region and/or a region in a remote plasma system may be referred to as a remote plasma region. In embodiments, the radical precursors (e.g. radical-fluorine) are formed in the remote plasma region and travel into the substrate processing region where they may individually react with chamber walls or the substrate surface. Plasma power may essentially be applied only to the remote plasma region, in embodiments, to ensure that the radical-fluorine (which may also be referred to as plasma effluents) are not further excited in the substrate processing region.

[0053] In embodiments employing a chamber plasma region, the excited plasma effluents are generated in a section of the substrate processing region partitioned from a deposition region. The deposition region, also known herein as the

substrate processing region, is where the plasma effluents mix and react to etch the patterned substrate (e.g., a semiconductor wafer). The excited plasma effluents may also be accompanied by inert gases (in the exemplary case, argon). The substrate processing region may be described herein as “plasma-free” during etching of the substrate. “Plasma-free” does not necessarily mean the region is devoid of plasma. A relatively low concentration of ionized species and free electrons created within the remote plasma region do travel through pores (apertures) in the partition (showerhead/ion suppressor) due to the shapes and sizes of through-holes **1056**. In some embodiments, there is essentially no concentration of ionized species and free electrons within the substrate processing region. In embodiments, the electron temperature may be less than 0.5 eV, less than 0.45 eV, less than 0.4 eV, or less than 0.35 eV in substrate processing region **1070** during excitation of a remote plasma. The borders of the plasma in the chamber plasma region are hard to define and may encroach upon the substrate processing region through the apertures in the showerhead. In the case of an inductively-coupled plasma, a small amount of ionization may be effected within the substrate processing region directly. Furthermore, a low intensity plasma may be created in the substrate processing region without eliminating desirable features of the forming film. All causes for a plasma having much lower intensity ion density than the chamber plasma region (or a remote plasma region, for that matter) during the creation of the excited plasma effluents do not deviate from the scope of “plasma-free” as used herein.

**[0054]** The fluorine-containing precursor may be flowed into chamber plasma region **1020** at rates between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm in embodiments.

**[0055]** The flow rate of the fluorine-containing precursor into the chamber may account for 0.05% to about 20% by volume of the overall gas mixture; the remainder being carrier gases. The fluorine-containing precursor are flowed into the remote plasma region but the plasma effluents have the same volumetric flow ratio, in embodiments. A purge or carrier gas may be initiated into the remote plasma region before that of the fluorine-containing gas to stabilize the pressure within the remote plasma region.

**[0056]** Plasma power applied to the remote plasma region can be a variety of frequencies or a combination of multiple frequencies. In the exemplary processing system the plasma is provided by unipolar oscillating power delivered between lid **1021** and showerhead **1053**. The energy is applied using a capacitively-coupled plasma unit. The remote plasma source power may be between about 10 watts and about 3000 watts, between about 20 watts and about 2000 watts, between about 30 watts and about 1000 watts, or between about 40 watts and about 500 watts in embodiments.

**[0057]** Substrate processing region **1070** can be maintained at a variety of pressures during the flow of carrier gases and plasma effluents into substrate processing region **1070**. The pressure within the substrate processing region is below or about 50 Torr, below or about 30 Torr or below or about 20 Torr. The pressure may be above or about 0.1 Torr, above or about 0.2 Torr, above or about 0.5 Torr or above or about 1 Torr in embodiments. Lower limits on the pressure may be combined with upper limits on the pressure to obtain embodiments.

**[0058]** In one or more embodiments, the substrate processing chamber **1001** can be integrated into a variety of multi-processing platforms, including the Producer™ GT, Centura™ AP and Endura™ platforms available from Applied Materials, Inc. located in Santa Clara, Calif. Such a processing platform is capable of performing several processing operations without breaking vacuum. Processing chambers that may implement embodiments of the present invention may include dielectric etch chambers or a variety of chemical vapor deposition chambers, among other types of chambers.

**[0059]** Embodiments of the etching systems may be incorporated into larger fabrication systems for producing integrated circuit chips. FIG. 5 shows one such system **1101** of etching, deposition, baking and curing chambers according to embodiments. In the figure, a pair of FOUPs (front opening unified pods) **1102** supply substrate substrates (e.g., 300 mm diameter wafers) that are received by robotic arms **1104** and placed into a low pressure holding areas **1106** before being placed into one of the wafer processing chambers **1108a-f**. A second robotic arm **1110** may be used to transport the substrate wafers from the low pressure holding areas **1106** to the wafer processing chambers **1108a-f** and back. Each wafer processing chamber **1108a-f**, can be outfitted to perform a number of substrate processing operations including the dry etch processes described herein in addition to cyclical layer deposition (CLD), atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), etch, pre-clean, degas, orientation and other substrate processes.

**[0060]** The wafer processing chambers **1108a-f** may include one or more system components for depositing, annealing, curing and/or etching a dielectric film on the substrate wafer. In one configuration, two pairs of the processing chamber (e.g., **1108c-d** and **1108e-f**) may be used to deposit dielectric material on the substrate, and the third pair of processing chambers (e.g., **1108a-b**) may be used to etch the deposited dielectric. In another configuration, all three pairs of chambers (e.g., **1108a-f**) may be configured to etch a dielectric film on the substrate. Any one or more of the processes described may be carried out on chamber(s) separated from the fabrication system shown in different embodiments.

**[0061]** The substrate processing system is controlled by a system controller. In an exemplary embodiment, the system controller includes a hard disk drive, a floppy disk drive and a processor. The processor contains a single-board computer (SBC), analog and digital input/output boards, interface boards and stepper motor controller boards. Various parts of CVD system conform to the Versa Modular European (VME) standard which defines board, card cage, and connector dimensions and types. The VME standard also defines the bus structure as having a 16-bit data bus and a 24-bit address bus.

**[0062]** System controller **1157** is used to control motors, valves, flow controllers, power supplies and other functions required to carry out process recipes described herein. A gas handling system **1155** may also be controlled by system controller **1157** to introduce gases to one or all of the wafer processing chambers **1108a-f**. System controller **1157** may rely on feedback from optical sensors to determine and adjust the position of movable mechanical assemblies in gas handling system **1155** and/or in wafer processing chambers **1108a-f**. Mechanical assemblies may include the robot, throttle valves and susceptors which are moved by motors under the control of system controller **1157**.

**[0063]** In an exemplary embodiment, system controller **1157** includes a hard disk drive (memory), USB ports, a floppy disk drive and a processor. System controller **1157** includes analog and digital input/output boards, interface boards and stepper motor controller boards. Various parts of multi-chamber processing system **1101** which contains substrate processing chamber **1001** are controlled by system controller **1157**. The system controller executes system control software in the form of a computer program stored on computer-readable medium such as a hard disk, a floppy disk or a flash memory thumb drive. Other types of memory can also be used. The computer program includes sets of instructions that dictate the timing, mixture of gases, chamber pressure, chamber temperature, RF power levels, susceptor position, and other parameters of a particular process.

**[0064]** A process for etching, depositing or otherwise processing a film on a substrate or a process for cleaning chamber can be implemented using a computer program product that is executed by the controller. The computer program code can be written in any conventional computer readable programming language: for example, 68000 assembly language, C, C++, Pascal, Fortran or others. Suitable program code is entered into a single file, or multiple files, using a conventional text editor, and stored or embodied in a computer usable medium, such as a memory system of the computer. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of precompiled Microsoft Windows® library routines. To execute the linked, compiled object code the system user invokes the object code, causing the computer system to load the code in memory. The CPU then reads and executes the code to perform the tasks identified in the program.

**[0065]** The interface between a user and the controller may be via a touch-sensitive monitor and may also include a mouse and keyboard. In one embodiment two monitors are used, one mounted in the clean room wall for the operators and the other behind the wall for the service technicians. The two monitors may simultaneously display the same information, in which case only one is configured to accept input at a time. To select a particular screen or function, the operator touches a designated area on the display screen with a finger or the mouse. The touched area changes its highlighted color, or a new menu or screen is displayed, confirming the operator's selection.

**[0066]** As used herein "substrate" may be a support substrate with or without layers formed thereon. The patterned substrate may be an insulator or a semiconductor of a variety of doping concentrations and profiles and may, for example, be a semiconductor substrate of the type used in the manufacture of integrated circuits. Exposed "silicon" of the patterned substrate is predominantly Si but may include minority concentrations of other elemental constituents (e.g. nitrogen, oxygen, hydrogen, carbon). Exposed "silicon nitride" of the patterned substrate is predominantly Si<sub>3</sub>N<sub>4</sub> but may include minority concentrations of other elemental constituents (e.g. oxygen, hydrogen, carbon). Exposed "silicon oxide" of the patterned substrate is predominantly SiO<sub>2</sub> but may include minority concentrations of other elemental constituents (e.g. nitrogen, hydrogen, carbon). In some embodiments, silicon oxide films etched using the methods disclosed herein consist essentially of silicon and oxygen.

**[0067]** The term "precursor" is used to refer to any process gas which takes part in a reaction to either remove material

from or deposit material onto a surface. "Plasma effluents" describe gas exiting from the chamber plasma region and entering the substrate processing region. Plasma effluents are in an "excited state" wherein at least some of the gas molecules are in vibrationally-excited, dissociated and/or ionized states. A "radical precursor" is used to describe plasma effluents (a gas in an excited state which is exiting a plasma) which participate in a reaction to either remove material from or deposit material on a surface. "Radical-fluorine") are radical precursors which contain fluorine but may contain other elemental constituents. The phrase "inert gas" refers to any gas which does not form chemical bonds when etching or being incorporated into a film. Exemplary inert gases include noble gases but may include other gases so long as no chemical bonds are formed when (typically) trace amounts are trapped in a film.

**[0068]** The terms "gap" and "trench" are used throughout with no implication that the etched geometry has a large horizontal aspect ratio. Viewed from above the surface, trenches may appear circular, oval, polygonal, rectangular, or a variety of other shapes. A trench may be in the shape of a moat around an island of material. The term "via" is used to refer to a low aspect ratio trench (as viewed from above) which may or may not be filled with metal to form a vertical electrical connection. As used herein, a conformal etch process refers to a generally uniform removal of material on a surface in the same shape as the surface, i.e., the surface of the etched layer and the pre-etch surface are generally parallel. A person having ordinary skill in the art will recognize that the etched interface likely cannot be 100% conformal and thus the term "generally" allows for acceptable tolerances.

**[0069]** Having disclosed several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the disclosed embodiments. Additionally, a number of well known processes and elements have not been described to avoid unnecessarily obscuring the present invention. Accordingly, the above description should not be taken as limiting the scope of the invention.

**[0070]** Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between the upper and lower limits of that range is also specifically disclosed. Each smaller range between any stated value or intervening value in a stated range and any other stated or intervening value in that stated range is encompassed. The upper and lower limits of these smaller ranges may independently be included or excluded in the range, and each range where either, neither or both limits are included in the smaller ranges is also encompassed within the invention, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included.

**[0071]** As used herein and in the appended claims, the singular forms "a", "an", and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a process" includes a plurality of such processes and reference to "the dielectric material" includes reference to one or more dielectric materials and equivalents thereof known to those skilled in the art, and so forth.

**[0072]** Also, the words "comprise," "comprising," "include," "including," and "includes" when used in this specification and in the following claims are intended to

specify the presence of stated features, integers, components, or steps, but they do not preclude the presence or addition of one or more other features, integers, components, steps, acts, or groups.

1. A method of processing a substrate, the method comprising:

transferring the substrate into a substrate processing region of a substrate processing chamber;  
 applying a unipolar oscillating voltage between an electrode and a perforated plate, wherein the unipolar oscillating voltage, on average, biases the perforated plate at a positive voltage relative to the electrode;  
 forming a remote plasma between the electrode and the perforated plate to form plasma effluents;  
 flowing the plasma effluents into the substrate processing region housing the substrate, wherein the plasma effluents flow into the substrate processing region through perforations in the perforated plate; and  
 reacting the plasma effluents with the substrate.

2. The method of claim 1 wherein the unipolar oscillating voltage biases the electrode relative to the perforated plate at a positive potential throughout the operation of reacting the plasma effluents with the substrate.

3. The method of claim 1 wherein the perforated plate is grounded and the unipolar oscillating voltage biases the electrode at a negative voltage.

4. The method of claim 1 further comprising:

processing a DC voltage by passing the DC voltage through a full bridge formed from four switching devices to form the unipolar oscillating voltage.

5. The method of claim 1 further comprising:

processing a bipolar oscillating voltage by adding a DC offset voltage to the bipolar oscillating voltage to form the unipolar oscillating voltage.

6. The method of claim 1 further comprising:

processing a bipolar oscillating voltage with a diode to remove a positive portion of the bipolar oscillating voltage to form the unipolar oscillating voltage.

7. The method of claim 1 further comprising:

sending a bipolar oscillating voltage through a diode bridge to form the unipolar oscillating voltage.

8. The method of claim 1 wherein the electrode is cup-shaped such that a perpendicular distance from the perforated plate to the electrode is greater near the center of the perforated plate than a perpendicular distance from the perforated plate to the electrode near the edge.

9. The method of claim 1 wherein the electrode is nickel plated.

10. A method of etching a substrate, the method comprising:

transferring the substrate into a substrate processing region of a substrate processing chamber;

applying a unipolar oscillating voltage between an electrode and a perforated plate, wherein the unipolar oscillating voltage negatively biases the electrode relative to the perforated plate;

flowing a halogen-containing precursor into a remote plasma between the electrode and the perforated plate while forming a remote plasma to form plasma effluents;

flowing the plasma effluents into the substrate processing region housing the substrate, wherein the plasma effluents flow into the substrate processing region through perforations in the perforated plate; and

etching the substrate with the plasma effluents.

11. The method of claim 10 wherein the perforated plate is electrically grounded during the operation of applying the unipolar oscillating voltage to the electrode.

12. The method of claim 10 wherein the unipolar oscillating voltage biases the electrode at a negative potential, relative to the perforated plate, throughout the operation of reacting the plasma effluents with the substrate.

13. A method of etching a patterned substrate, the method comprising:

transferring the patterned substrate into a substrate processing region of a substrate processing chamber;

sending a DC voltage through a full bridge of four switching devices to form a unipolar oscillating voltage;

applying the unipolar oscillating voltage between a concave electrode and a flat nickel-plated perforated plate, wherein the unipolar oscillating voltage biases the concave electrode at a negative voltage relative to the flat nickel-plated perforated plate;

flowing a fluorine-containing precursor into a remote plasma between the concave electrode and the flat nickel-plated perforated plate while forming a remote plasma to form plasma effluents;

flowing the plasma effluents into the substrate processing region housing the patterned substrate, wherein the plasma effluents flow into the substrate processing region through perforations in the flat nickel-plated perforated plate; and

selectively etching the patterned substrate with the plasma effluents.

14. The method of claim 13 wherein the concave electrode comprises a portion shaped like a cone.

15. The method of claim 13 wherein the fluorine-containing precursor comprises one or more of atomic fluorine, diatomic fluorine, boron trifluoride, chlorine trifluoride, nitrogen, trifluoride, perfluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride.

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