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(54) **OPTICAL EMISSION SPECTROSCOPY (OES) FOR REMOTE PLASMA MONITORING**

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G01J 3/443	(2006.01)

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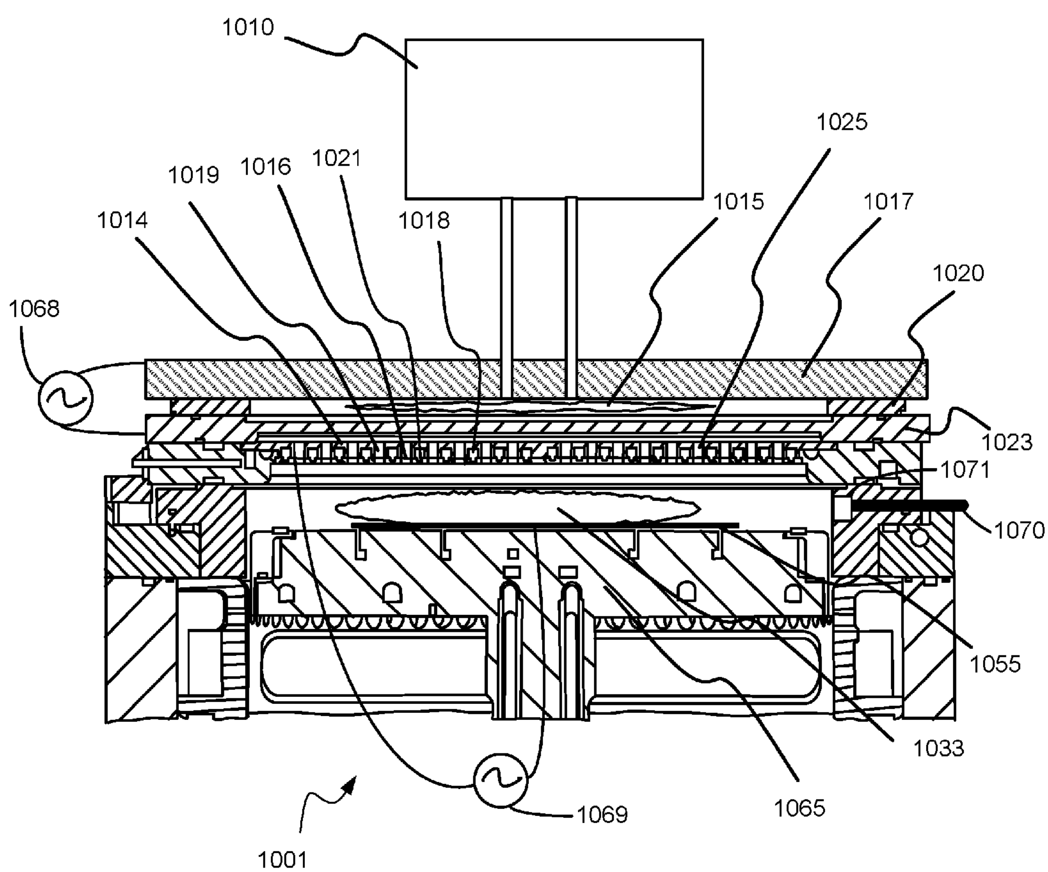
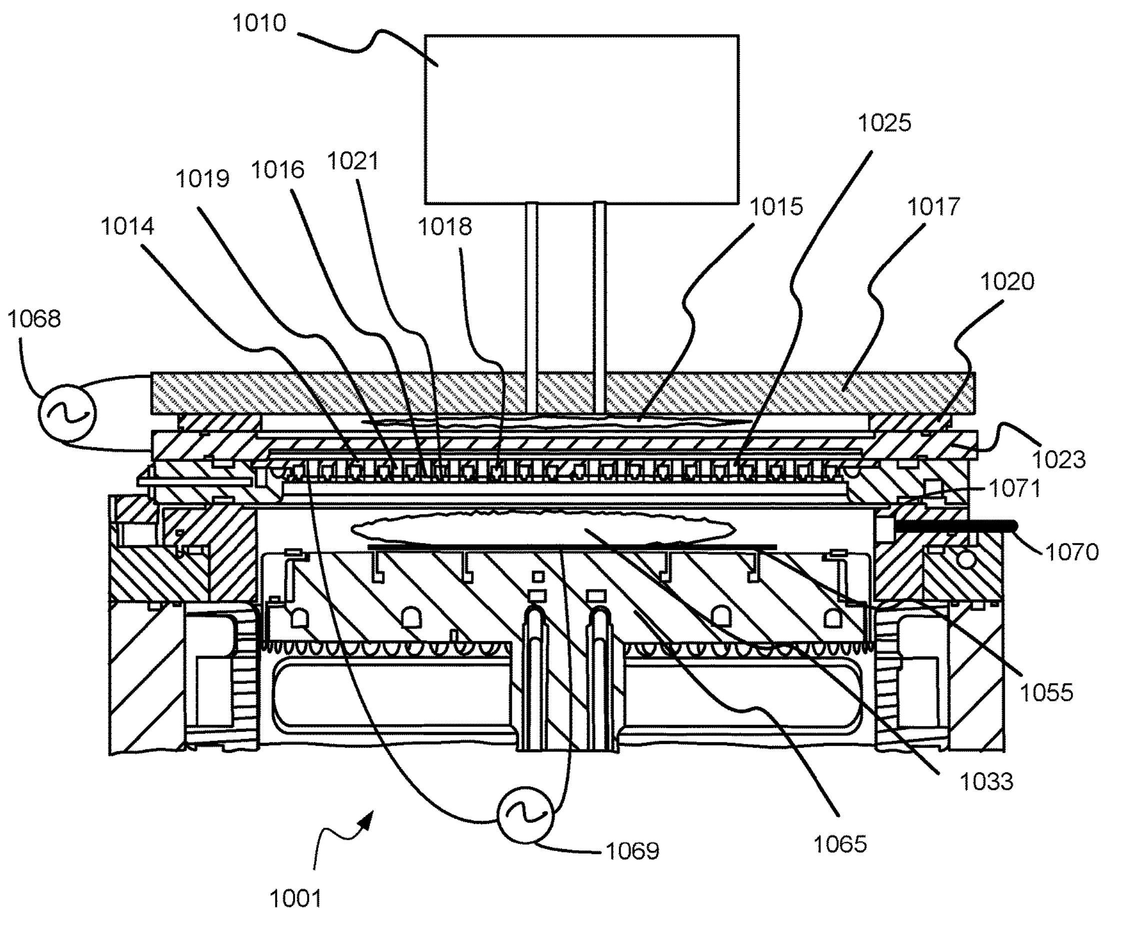
(57) **ABSTRACT**

Methods and systems for etching substrates using a remote plasma are described. Remotely excited etchants are formed in a remote plasma and flowed through a showerhead into a substrate processing region to etch the substrate. Optical emission spectra are acquired from the substrate processing region just above the substrate. The optical emission spectra may be used to determine an endpoint of the etch, determine the etch rate or otherwise characterize the etch process. A weak plasma may be present in the substrate processing region. The weak plasma may have much lower intensity than the remote plasma. In cases where no bias plasma is used above the substrate in an etch process, a weak plasma may be ignited near a viewport disposed near the side of the substrate processing region to characterize the etchants.




1010
1025
1019
1016
1021
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1023
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1055
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1065
1069
1001

FIG. 1

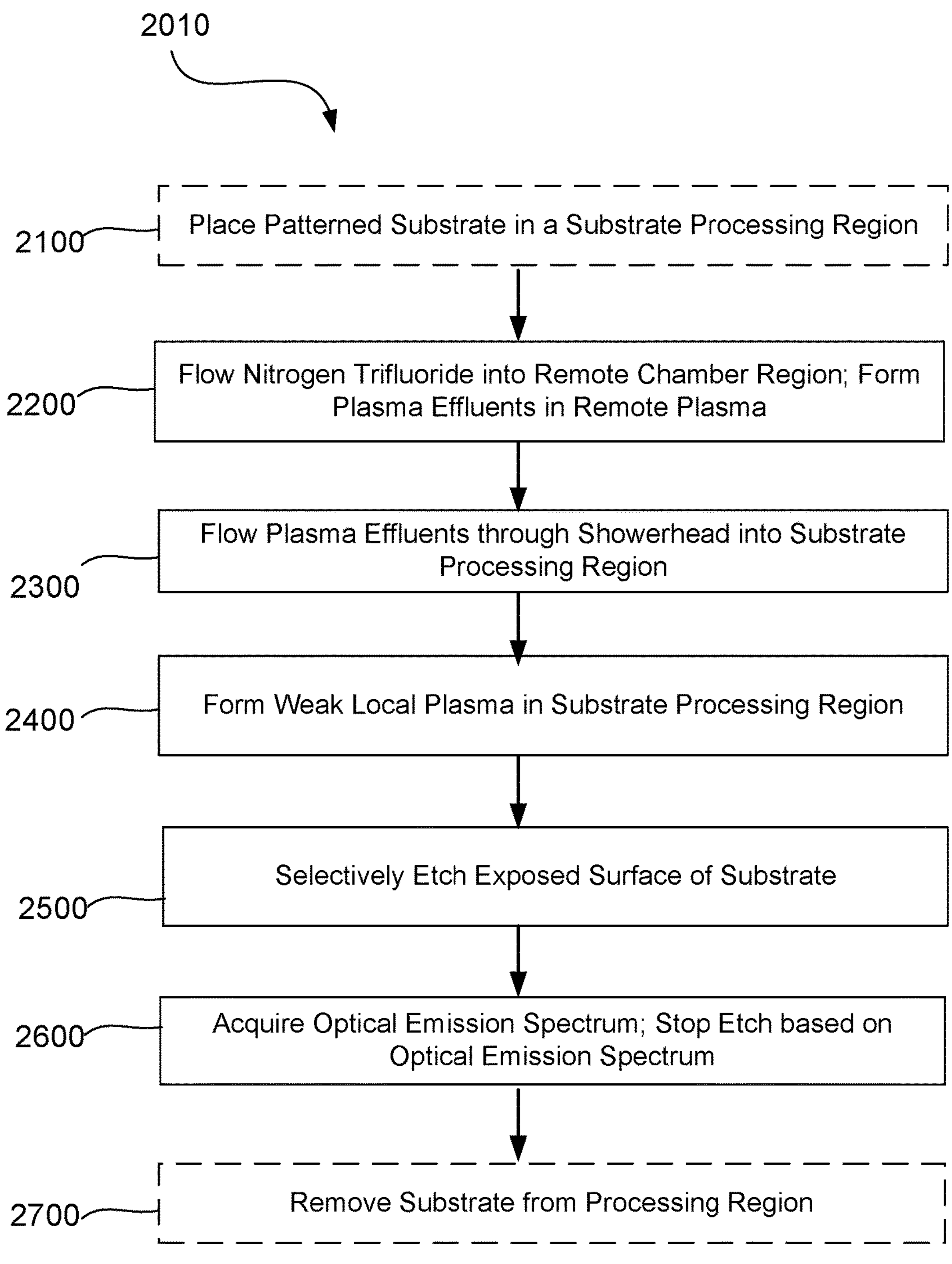
2010
2100
Place Patterned Substrate in a Substrate Processing Region
2200
Flow Nitrogen Trifluoride into Remote Chamber Region; Form Plasma Effluents in Remote Plasma
2300
Flow Plasma Effluents through Showerhead into Substrate Processing Region
2400
Form Weak Local Plasma in Substrate Processing Region
2500
Selectively Etch Exposed Surface of Substrate
2600
Acquire Optical Emission Spectrum; Stop Etch based on Optical Emission Spectrum
2700
Remove Substrate from Processing Region

FIG. 2

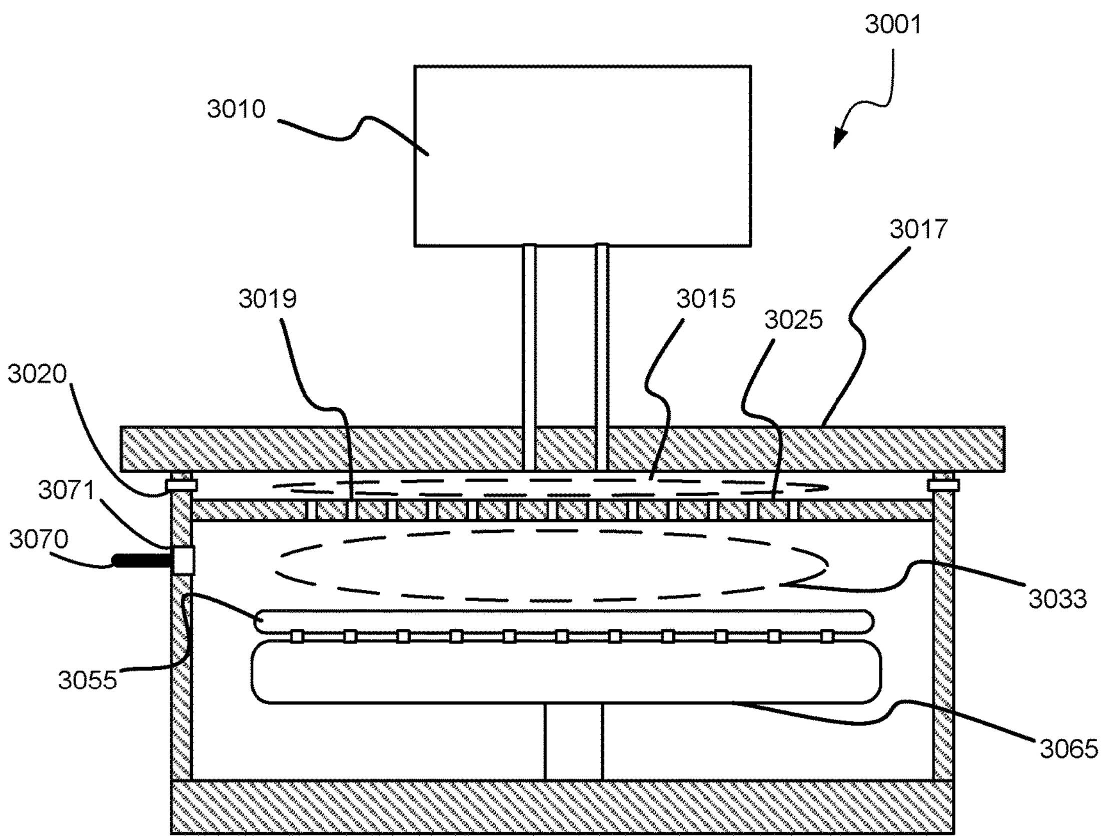

FIG. 3A

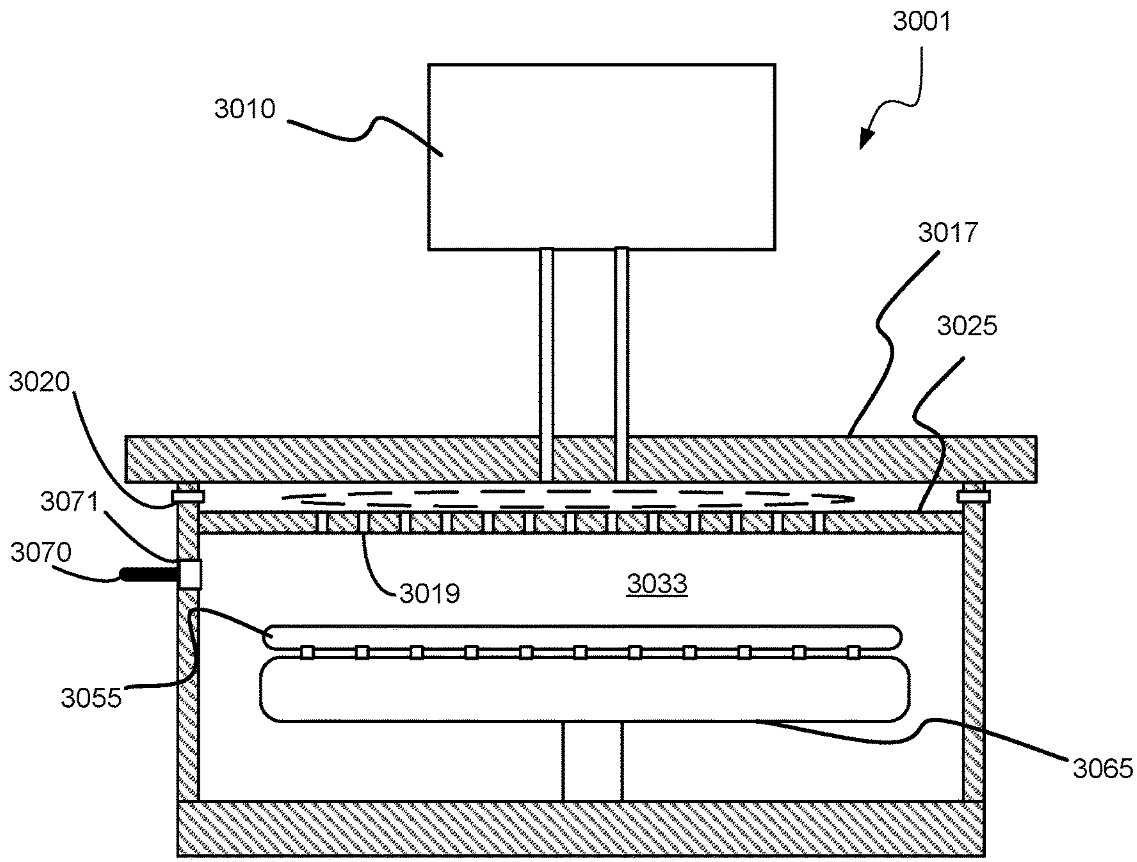

FIG. 3B

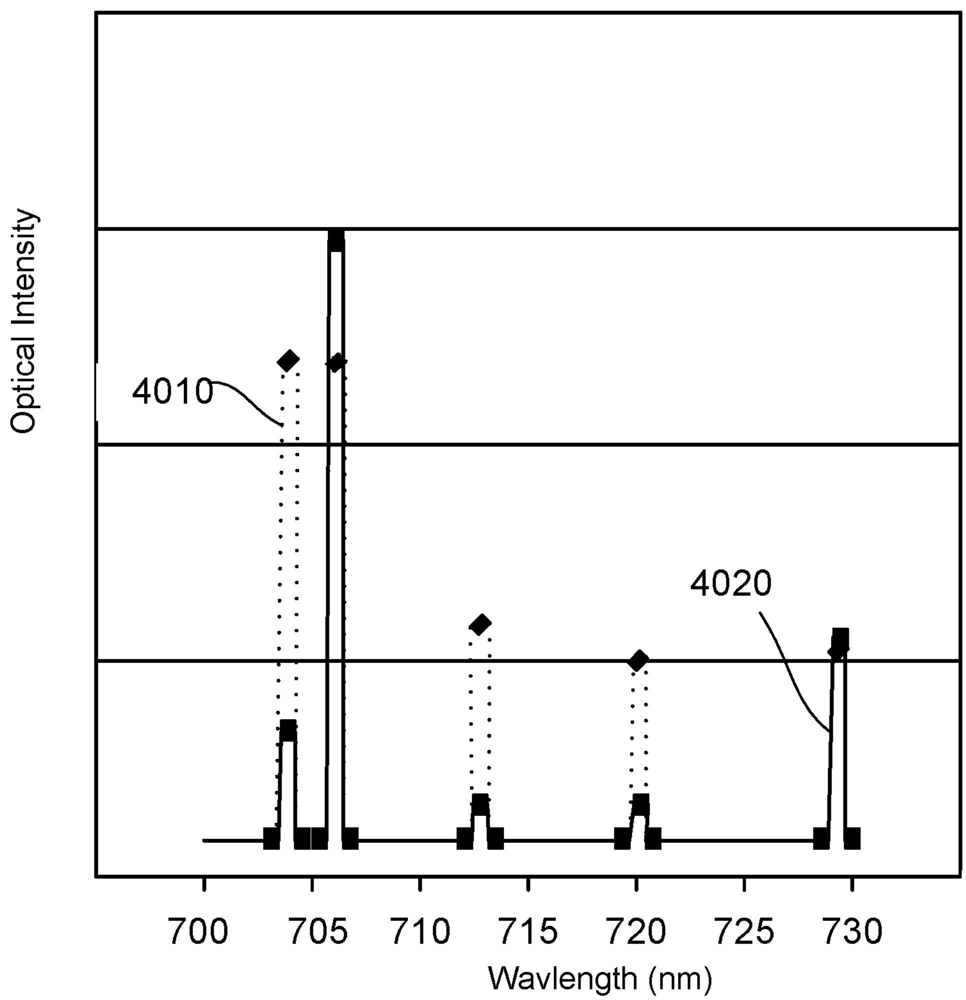
Optical Intensity
4010
4020
700
705
710
715
720
725
730
Wavlength (nm)

FIG. 4

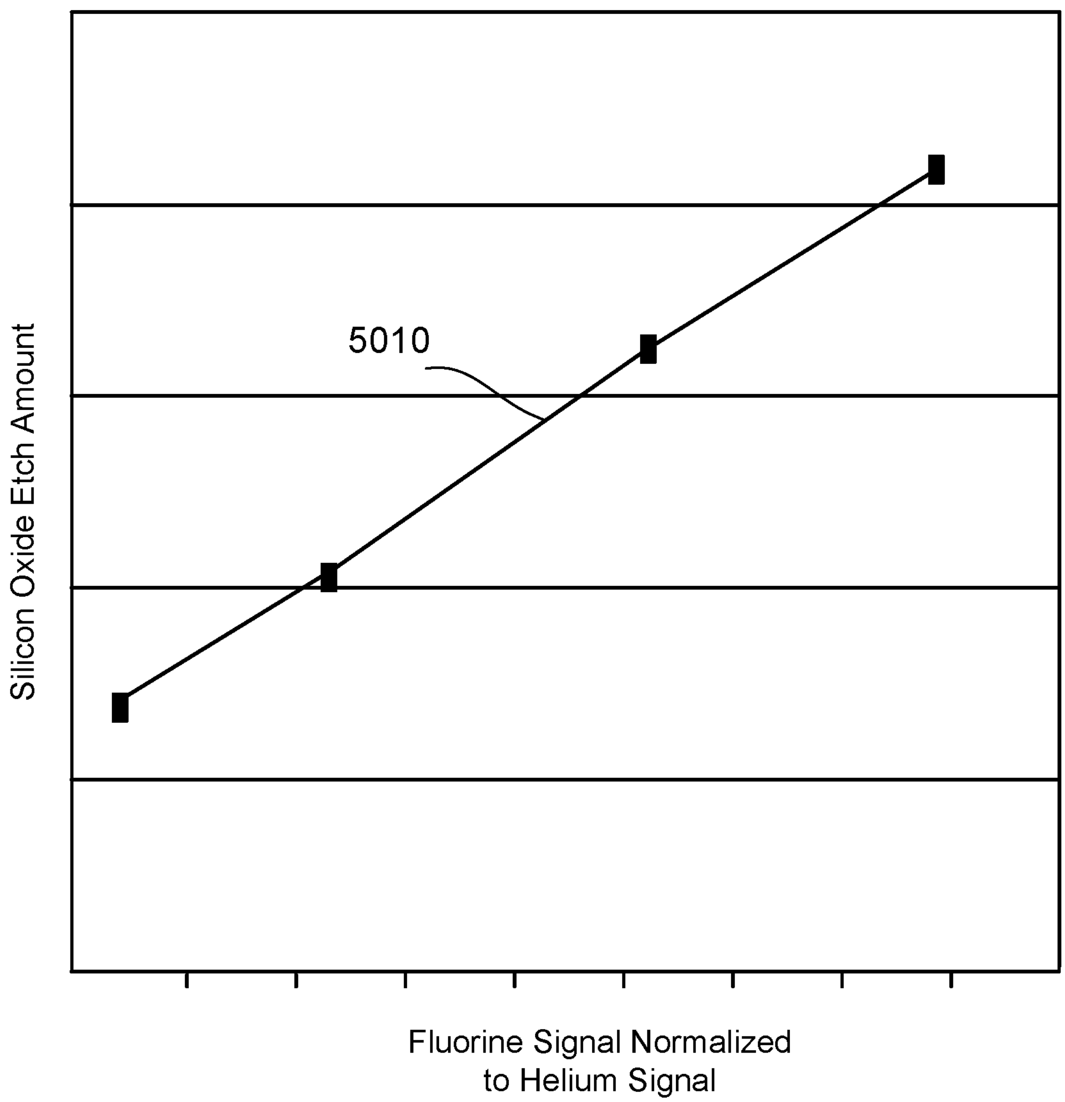
5010
Silicon Oxide Etch Amount
Fluorine Signal Normalized
to Helium Signal

FIG. 5

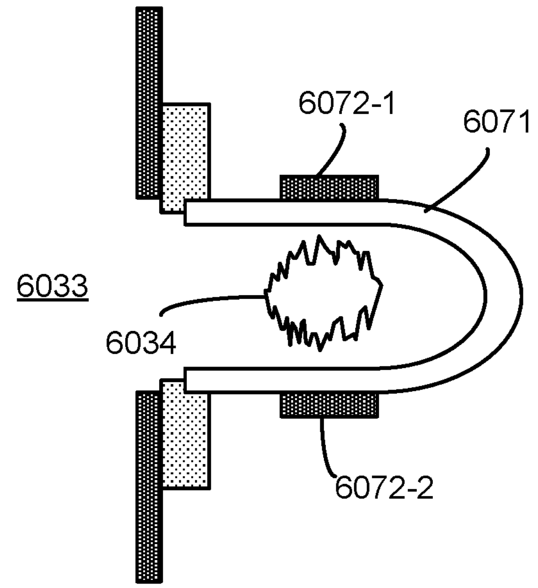
6072-1
6071
6033
6034
6072-2

FIG. 6A

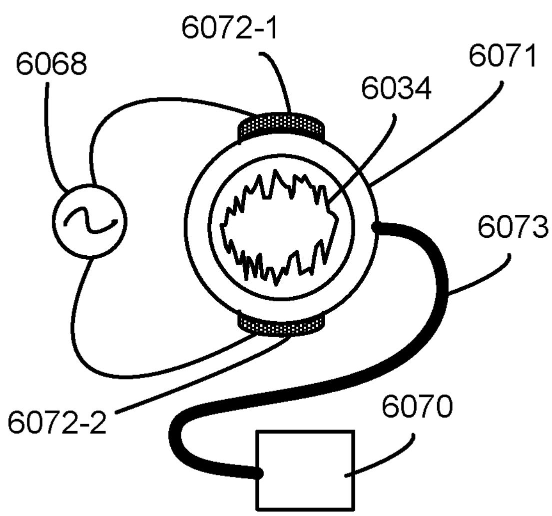
6072-1
6068
6034
6071
6073
6072-2
6070

FIG. 6B

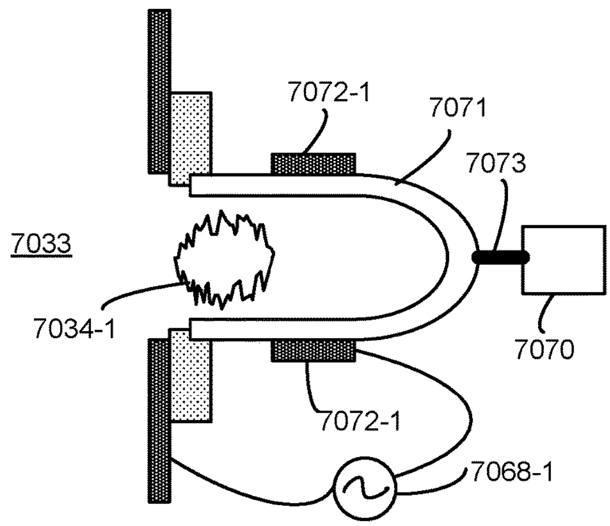

FIG. 7A

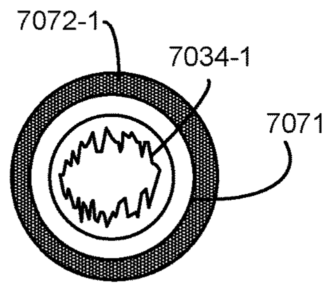

FIG. 7B

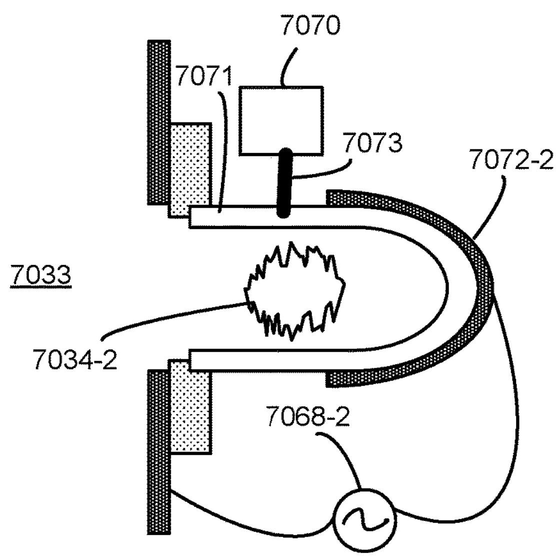

FIG. 7C

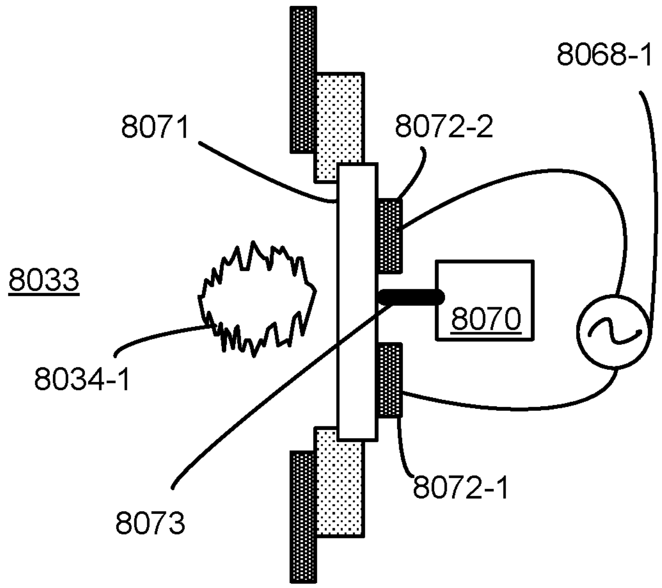
8068-1
8071
8072-2
8033
8070
8034-1
8073
8072-1

FIG. 8A

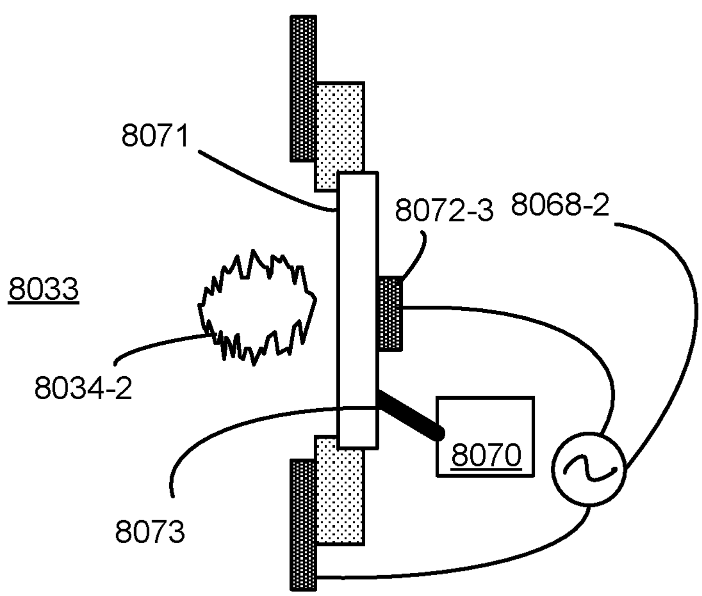
8071
8072-3
8068-2
8033
8034-2
8070
8073

FIG. 8B

OPTICAL EMISSION SPECTROSCOPY (OES) FOR REMOTE PLASMA MONITORING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional application of U.S. patent application Ser. No. 15/484,985 filed Apr. 11, 2017, the entire contents of which are hereby incorporated by reference in their entirety for all purposes.

FIELD

[0002] Embodiments disclosed herein relate to remote plasma etch processes.

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 photoresist pattern 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 relative to the second material. As a result of the diversity of materials, circuits and processes, etch processes have been developed with a selectivity towards a variety of materials.

[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. Remote excitation of etchants in a remote plasma system (instead of locally) may desirably increase selectivity.

[0005] Methods and systems are needed to monitor aspects of remote plasmas in-situ for a variety of purposes.

SUMMARY

[0006] Methods and systems for etching substrates using a remote plasma are described. Remotely excited etchants are formed in a remote plasma and flowed through a showerhead into a substrate processing region to etch the substrate. Optical emission spectra are acquired from the substrate processing region just above the substrate. The optical emission spectra may be used to determine an endpoint of the etch, determine the etch rate or otherwise characterize the etch process in-situ. A weak plasma may be present in the substrate processing region. The weak plasma may have lower intensity than the remote plasma. In cases where no bias plasma above the substrate is used in an etch process, a weak plasma may be ignited near a viewport disposed near the side of the substrate processing region to characterize the etchants.

[0007] Embodiments disclosed herein include methods of etching a substrate. The methods include placing the substrate in a substrate processing region of a substrate processing chamber. The methods further include flowing a fluorine-containing precursor into a remote plasma region separated from the substrate processing region by a showerhead. The methods further include forming a remote plasma having a remote plasma power in the remote plasma region. The methods further include producing plasma effluents from the fluorine-containing precursor in the remote plasma in the remote plasma region. The methods further include flowing the plasma effluents through the showerhead into the substrate processing region. The methods further include etching the substrate with the plasma effluents. The methods further include forming a local plasma having a local plasma power in the substrate processing region. The methods further include acquiring an optical emission spectrum through a viewport affixed to a side of the substrate processing chamber, the side forming a border of the substrate processing region. The optical emission spectrum represents intensity as a function of optical wavelength and the optical emission spectrum is acquired with an optical emission spectrometer.

[0008] The remote plasma power of the remote plasma may exceed the local plasma power of the local plasma by a factor of ten or more. The local plasma may be centered over the substrate. The local plasma may be positioned above the substrate and outside an edge of the substrate near the viewport. The local plasma may be formed using an electrode located on the outside of the viewport and the local plasma power may be applied between the electrode and the substrate processing chamber. The local plasma may be formed using a first electrode and a second electrode, each positioned on the outside of the viewport and the local plasma power may be applied between the first electrode and the second electrode.

[0009] Embodiments disclosed herein include substrate processing chambers The substrate processing chambers include a remote plasma region. The remote plasma region is configured to receive a fluorine-containing precursor and form a remote plasma from the fluorine-containing precursor. The substrate processing chambers further include a remote plasma power supply configured to apply a remote plasma power to the remote plasma region and configured to form the remote plasma. The substrate processing chambers further include a substrate processing region. The substrate processing chambers further include a showerhead positioned between the remote plasma region and the substrate processing region. The substrate processing region is fluidly coupled to the remote plasma region by through-holes in the showerhead. The substrate processing chambers further include a pedestal configured to support a substrate. The substrate processing chambers further include a flange attached to the substrate processing chamber. The flange forms a vacuum seal with the substrate processing chamber. The substrate processing chamber further includes a viewport attached to the flange forming a vacuum seal with the flange. The viewport is optically transmissive in a near infrared spectrum. The substrate processing chambers further include an optical emission spectrometer configured to receive optical radiation after the optical radiation passes through the viewport. The optical emission spectrometer is positioned on an exterior of the viewport and the optical radiation originates from inside the substrate processing region above the substrate.

[0010] The substrate processing chambers may further include a local plasma power supply configured to form a local plasma in the substrate processing region. The local plasma may have a local plasma power less than 10% of the remote plasma power. The substrate processing chambers may further include a fiber optic cable configured to guide the optical radiation from the viewport to the optical emission spectrometer. The substrate processing chambers may further include an electrode proximal to the viewport. The electrode may be positioned on the exterior of the viewport. The substrate processing chambers may further include a plasma power supply configured to apply a plasma power to the electrode. The substrate processing chambers may further include a second electrode configured to apply a plasma power to the electrode. The electrode may be electrically insulated from the second electrode.

[0011] Embodiments disclosed herein include optical emission spectrometer assemblies. The optical emission spectrometer assemblies include a flange configured to attach to a substrate processing chamber. The flange is configured to form a vacuum seal with the substrate processing chamber. The optical emission spectrometer assemblies further include a planar viewport attached to the flange forming a vacuum seal with the flange. The planar viewport is optically transmissive in a near infrared spectrum. The optical emission spectrometer assemblies further include an electrode proximal to the planar viewport. The electrode is disposed on an external side of the planar viewport. The optical emission spectrometer assemblies further include an optical emission spectrometer configured to receive optical radiation after the optical radiation passes through the planar viewport. The optical emission spectrometer is positioned on the external side of the planar viewport. The optical emission spectrometer assemblies further include a plasma power supply configured to apply a plasma power to the electrode.

[0012] The optical emission spectrometer assemblies may further include a fiber optic cable configured to guide infrared light from the planar viewport to the optical emission spectrometer. The plasma power supply may be configured to apply the plasma power between the electrode and the substrate processing chamber. The optical emission spectrometer assemblies may further include a second electrode proximal to the planar viewport. The electrode may be electrically insulated from the second electrode. The plasma power supply may be configured to apply the plasma power between the electrode and the second electrode.

[0013] 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 disclosed embodiments may be realized and attained by means of the instrumentalities, combinations, and methods described in the specification.

DESCRIPTION OF THE DRAWINGS

[0014] A further understanding of the nature and advantages of the embodiments may be realized by reference to the remaining portions of the specification and the drawings.

[0015] FIG. **1** shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

[0016] FIG. **2** is a flow chart of a remote plasma etch process according to embodiments.

[0017] FIG. **3**A shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

[0018] FIG. **3**B shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

[0019] FIG. **4** is an optical emission spectrum according to embodiments.

[0020] FIG. **5** is a plot of etch amount correlation with fluorine signal according to embodiments.

[0021] FIG. **6**A shows a cross-sectional side view of a weak plasma viewport according to embodiments.

[0022] FIG. **6**B shows a cross-sectional end view of a weak plasma viewport according to embodiments.

[0023] FIG. **7**A shows a cross-sectional side view of a weak plasma viewport according to embodiments.

[0024] FIG. **7**B shows a cross-sectional end view of a weak plasma viewport according to embodiments.

[0025] FIG. **7**C shows a cross-sectional side view of a weak plasma viewport according to embodiments.

[0026] FIG. **8**A shows a cross-sectional side view of a weak plasma viewport according to embodiments.

[0027] FIG. **8**B shows a cross-sectional side view of a weak plasma viewport according to embodiments.

[0028] 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

[0029] Methods and systems for etching substrates using a remote plasma are described. Remotely excited etchants are formed in a remote plasma and flowed through a showerhead into a substrate processing region to etch the substrate. Optical emission spectra are acquired from the substrate processing region just above the substrate. The optical emission spectra may be used to determine an endpoint of the etch, determine the etch rate or otherwise characterize the etch process in-situ. A weak plasma may be present in the substrate processing region. The weak plasma may have much lower intensity than the remote plasma. In cases where no bias plasma above the substrate is used in an etch process, a weak plasma may be ignited near a viewport disposed near the side of the substrate processing region to characterize the etchants.

[0030] In the past, gas phase etch processes have excited NF_3 in a local plasma inside substrate processing region. Optical emission spectroscopy was performed by flowing some of the reactants in the substrate processing region through tubing to a separate plasma used for the characterization and then disposing any chemical effluents through a vacuum pump. Recently, high selectivity gas-phase etch processes have been developed using a spatially-constrained remote plasma region separated from the substrate processing region by a showerhead (sometimes a dual-channel showerhead). Plasma effluents are formed in the remote plasma region and flow into the substrate processing region through the showerhead. The remote plasma effluents are optionally further excited in a bias plasma above the substrate.

[0031] The methods and systems described herein provide the benefit of characterizing remote plasma etch processes in the substrate processing region where there is more space than in the remote plasma region. The characterization of the plasma effluents occurs closer to the substrate, providing a more accurate determination of the etch process compared to the more circuitous sampling routes used previously.

[0032] FIG. **1** shows a schematic cross-sectional view of an exemplary substrate processing chamber. The schematic of the substrate processing chamber **1001** serves to introduce the optical emission spectrometer but also provide context for alternative configurations and details provided in subsequent descriptions. Later drawings will provide less detail compared to FIG. **1** but only for the sake of brevity. Any combination of features found in FIG. **1** may be present in any or all subsequent embodiments. The substrate processing chamber **1001** has a remote plasma region **1015** and a substrate processing region **1033** inside. The remote plasma region **1015** is partitioned from the substrate processing region **1033** by an ion suppressor **1023** and a showerhead **1025**.

[0033] A top plate **1017**, ion suppressor **1023**, showerhead **1025**, and a substrate support **1065** (also known as a pedestal), having a substrate **1055** disposed thereon, are shown and may each be included according to all embodiments described herein. The pedestal **1065** may have a heat exchange channel through which a heat exchange fluid flows to control the temperature of the substrate **1055**. This configuration may allow the substrate **1055** temperature to be cooled or heated to maintain relatively low temperatures, such as between −20° C. to 200° C. The pedestal **1065** may also be resistively heated to relatively high temperatures, such as between 100° C. and 1100° C., using an embedded heater element.

[0034] The etchant precursors flow from the etchant supply system **1010** through the holes in the top plate **1017** into the remote plasma region **1015**. The structural features may include the selection of dimensions and cross-sectional geometries of the apertures in the top plate **1017** to deactivate back-streaming plasma in cases where a plasma is generated in remote plasma region **1015**. The top plate **1017**, or a conductive top portion of the substrate processing chamber **1001**, and the showerhead **1025** are shown with an intervening insulating ring **1020**, which allows an AC potential to be applied to the top plate **1017** relative to the showerhead **1025** and/or the ion suppressor **1023**. The insulating ring **1020** may be positioned between the top plate **1017** and the showerhead **1025** and/or the ion suppressor **1023** enabling a capacitively-coupled plasma (CCP) to be formed in the remote plasma region **1015**. The remote plasma region **1015** houses the remote plasma.

[0035] The plurality of holes in the ion suppressor **1023** may be configured to control the passage of the activated gas, i.e., the ionic, radical, and/or neutral species, through the ion suppressor **1023**. For example, the aspect ratio of the holes, or the hole diameter to length, and/or the geometry of the holes may be selected so that the flow of ionically-charged species in the activated gas passing through the ion suppressor **1023** is reduced. The holes in the ion suppressor **1023** may include a tapered portion that faces the remote plasma region **1015**, and a cylindrical portion that faces the showerhead **1025**. The cylindrical portion may be shaped and dimensioned to control the flow of ionic species passing to and through the showerhead **1025**. An adjustable electrical bias may also be applied to the ion suppressor **1023** as an additional means to control the flow of ionic species through the suppressor. The ion suppressor **1023** may function to reduce or eliminate the amount of ionically charged species traveling from the plasma generation region to the substrate. Uncharged neutral and radical species may still pass through the openings in the ion suppressor to react with the substrate.

[0036] Remote plasma power can be of a variety of frequencies or a combination of multiple frequencies. The remote plasma may be provided by remote RF power delivered from the remote plasma power supply **1068** to the top plate **1017** relative to the ion suppressor **1023**, relative to the showerhead **1025**, or relative to both the ion suppressor **1023** and the showerhead **1025** (as shown). The remote RF power may be between 10 watts and 10,000 watts, between 10 watts and 5,000 watts, preferably between 25 watts and 2000 watts or more preferably between 50 watts and 1500 watts to increase the longevity of chamber components. The remote RF frequency applied in the exemplary processing system to the remote plasma region may be low RF frequencies less than 200 kHz, higher RF frequencies between 10 MHz and 15 MHz, or microwave frequencies greater than 1 GHz in embodiments. The plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the remote plasma region.

[0037] Plasma effluents derived from the etchant precursors in the remote plasma region **1015** may travel through apertures in the ion suppressor **1023**, and/or the showerhead **1025** and into the substrate processing region **1033** through through-holes or the first fluid channels **1019** of the showerhead in embodiments. Little or no plasma may be present in substrate processing region **1033** during the remote plasma etch process. The plasma effluents react with the substrate to etch material from the substrate.

[0038] The showerhead **1025** may be a dual channel showerhead (DCSH). The dual channel showerhead **1025** may provide for etching processes that allow for separation of etchants outside of the substrate processing region **1033** to provide limited interaction with chamber components and each other prior to being delivered into the substrate processing region **1033**. The showerhead **1025** may comprise an upper plate **1014** and a lower plate **1016**. The plates may be coupled with one another to define a volume **1018** between the plates. The plate configuration may provide the first fluid channels **1019** through the upper and lower plates, and the second fluid channels **1021** through the lower plate **1016**. The formed channels may be configured to provide fluid access from the volume **1018** through the lower plate **1016** via the second fluid channels **1021** alone, and the first fluid channels **1019** may be fluidly isolated from the volume **1018** between the plates and the second fluid channels **1021**. The volume **1018** may be fluidly accessible through a side of the showerhead **1025** and used to supply an unexcited precursor in embodiments.

[0039] Optionally, a bias plasma power may be present in the substrate processing region in embodiments. The bias plasma may be used to further excite plasma effluents already excited in the remote plasma. The bias plasma refers to a local plasma located just above the substrate. The term bias plasma is used since the plasma effluents may be ionized and/or accelerated towards the substrate to beneficially accelerate or provide incoming alignment to some etch processes. The bias plasma may be formed by applying bias plasma power from a bias plasma power supply **1069** to the substrate **1055**/pedestal **1065** relative to the ion suppressor **1023**, relative to the showerhead **1025**, or relative to both the ion suppressor **1023** and the showerhead **1025** (as shown). The bias RF plasma power may be lower than the remote RF power. The bias RF plasma power may be below 20%, below 15%, below 10% or below 5% of the remote RF plasma power. The bias RF plasma power may be between 1 watt and 1,000 watts, between 1 watt and 500 watts, or between 2 watts and 100 watts in embodiments. The bias RF plasma frequency applied in the exemplary processing system to the remote plasma region may be low RF plasma frequencies less than 200 kHz, higher RF plasma frequencies between 10 MHz and 15 MHz, or microwave frequencies greater than 1 GHz in embodiments. The bias RF plasma frequency may be different from the remote RF frequency to further improve the integrity of the optical emission spectra. The plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the substrate plasma region.

[0040] A viewport **1071** is disposed on the side of the substrate processing chamber **1001** and forms a border of the substrate processing region **1033**. The viewport **1071** transmits optical radiation and may be transmissive in the infrared portion of the optical spectrum. Viewports described herein may be transmissive between 650 nm and 800 nm, between 680 nm and 760 nm or between 700 nm and 740 nm in embodiments. An optical emission spectrometer (OES) is disposed outside the viewport **1071** and configured to receive optical radiation, preferably infrared radiation, originating from the bias plasma formed in the substrate processing region **1033**. In cases where there is no bias plasma, a weak plasma may be formed on the interior side of the viewport **1071** to facilitate the acquisition of the optical emission spectrum by the optical emission spectrometer. The characteristics of the weak plasma (power, frequency) may be the same as the bias power properties provided earlier, according to embodiments. For example, the weak RF plasma power may be below 20%, below 15%, below 10% or below 5% of the remote RF plasma power. The weak RF plasma power may be between 1 watt and 1,000 watts, between 1 watt and 500 watts, or between 2 watts and 100 watts in embodiments. The weak RF plasma frequency applied in the exemplary processing system to the remote plasma region may be low RF plasma frequencies less than 200 kHz, higher RF plasma frequencies between 10 MHz and 15 MHz, or microwave frequencies greater than 1 GHz in embodiments. The weak RF plasma frequency may be different from the remote RF frequency to further improve the integrity of the optical emission spectra. The weak plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the substrate plasma region.

[0041] To better understand and appreciate the embodiments disclosed herein, reference is now made to FIG. **2** which is a flow chart of a highly selective etch process **2010** according to embodiments. Prior to the first operation, the substrate is patterned and then placed within the substrate processing region in optional operation **2100**. A fluorine-containing precursor (e.g. NF_3) may be flowed into the remote plasma region in operation **2200**. A remote plasma is formed from the fluorine-containing precursor in the remote plasma region by applying a remote plasma power across the remote plasma region to form plasma effluents. The plasma effluents are flowed through a showerhead disposed between the remote plasma region and the substrate processing region in operation **2300**. The plasma effluents flow through the showerhead from the remote plasma region into the substrate processing region. A bias plasma is formed by applying a bias plasma power across the substrate processing region to further excite the plasma effluents in operation **2400**. The bias plasma power is less than the remote plasma power and the bias plasma may be referred to as a "weak" plasma in embodiments. Portions of a patterned substrate are selectively etched in operation **2500**. An optical emission spectrum is acquired through a viewport in the side of the substrate processing chamber (operation **2600**) and the etch is stopped based on the results. The viewport forms a border of the substrate processing region. Optionally, the patterned substrate is removed from the substrate processing region (operation **2700**).

[0042] FIG. **3**A shows a schematic cross-sectional view of an exemplary substrate processing chamber. Process and equipment parameters given earlier apply to all embodiments described herein. Similarly, process and equipment parameters given here and in subsequent discussions may be used for all other embodiments described herein. The substrate processing chamber **3001** has a remote plasma region **3015** and a substrate processing region **3033** inside. The remote plasma region **3015** is partitioned from the substrate processing region **3033** by a showerhead **3025** with through-holes **3019** configured to pass plasma effluents.

[0043] A top plate **3017**, showerhead **3025**, and a pedestal **3065** supporting a substrate **3055** are shown. A fluorine-containing precursor may flow from the etchant supply system **3010** into the remote plasma region **3015**. The top plate **3017** and the showerhead **3025** are electrically-separated conductors separated by insulating ring **3020**. An AC potential (the remote plasma power) is applied to the top plate **3017** relative to the showerhead **3025** to form the remote plasma. The remote plasma may be a capacitively-coupled plasma (CCP) in the remote plasma region **3015**. Plasma frequencies and plasma powers provided by a remote plasma power supply (not shown) were provided previously.

[0044] Plasma effluents derived from the fluorine precursors in the remote plasma region **3015** may travel through the through-holes **3019** in the showerhead **3025** and into the substrate processing region **3033**. A bias plasma power is applied by a bias plasma power supply (not shown) to the substrate processing region **3033**. The bias plasma further excites the plasma effluents. The bias plasma weakly ionizes and accelerates plasma effluents towards the substrate to beneficially accelerate or provide incoming alignment to the etch processes. The bias plasma may be formed by applying bias plasma power from a bias plasma power supply to the substrate **3055**/pedestal **3065** relative to the showerhead **3025**. The plasma effluents react with the substrate to etch material from the substrate.

[0045] Acquisition of optical emission spectra uses the recombination of electrons with ions to emit photons indicative of a presence of specific atomic species. In the embodiment represented in FIG. **3**A, the bias plasma is sufficient to supply the ionization needed to acquire an optical emission spectrum. To further enable the measurement, a viewport **3071** is disposed in the side of the substrate processing chamber **3001**. The optical emission spectrum is measured using an optical emission spectrometer on the outside of the viewport **3071**.

[0046] FIG. **3**B shows a schematic cross-sectional view of an exemplary substrate processing chamber. The substrate processing chamber **3001** has a remote plasma region **3015**

and a substrate processing region **3033** inside. The remote plasma region **3015** is partitioned from the substrate processing region **3033** by a showerhead **3025** with through-holes **3019** to pass plasma effluents. A top plate **3017**, showerhead **3025**, and a pedestal **3065** supporting a substrate **3055** are shown. A fluorine-containing precursor may flow from the etchant supply system **3010** into the remote plasma region **3015**. An AC potential (the remote plasma power) is applied to the top plate **3017** relative to the showerhead **3025** to form the remote plasma.

[0047] Plasma effluents derived from the fluorine precursors in the remote plasma region **3015** travel through the through-holes **3019** in the showerhead **3025** and into the substrate processing region **3033**. The plasma effluents react with the substrate to etch material from the substrate.

[0048] No bias plasma power is applied to the substrate processing region **3033** in embodiments. The substrate processing region **3033** may be referred to as plasma-free and may be devoid of plasma in embodiments. A weak plasma near the substrate processing region is used to obtain an optical emission spectrum. The weak plasma results in recombination of electrons with ions and concomitant emission of photons indicative of a presence of specific atomic species. Therefore a weak plasma is formed just on the inside of a viewport **3071** by a variety of techniques to be described herein. The viewport **3071** is disposed in the side of the substrate processing chamber **3001**. The optical emission spectrum is measured using an optical emission spectrometer on the outside of the viewport **3071**. The weak plasma is formed by applying weak plasma power from a weak plasma power supply to one or more electrode(s) (not shown) near the viewport **3071**. The weak RF plasma power may be lower than the remote RF power. A relatively low weak RF plasma power avoids swamping the remote plasma OES signal with characteristics of the weak local plasma. The weak RF plasma power may be below 10%, below 8%, below 5% or below 3% of the remote RF plasma power. The weak RF plasma power may be between 0.1 watts and 300 watts, between 0.2 watts and 100 watts, or between 0.5 watts and 20 watts in embodiments. The weak RF plasma frequency applied in the exemplary processing system to the remote plasma region may be low RF plasma frequencies less than 200 kHz, higher RF plasma frequencies between 10 MHz and 15 MHz, or microwave frequencies greater than 1 GHz in embodiments. The weak RF plasma frequency may be different from the remote RF frequency to further improve the integrity of the optical emission spectra. For example, the weak RF plasma frequency may be 60 kHz and the remote RF frequency may be 13 MHz. The plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the substrate plasma region.

[0049] The pressure in the substrate processing region and the remote plasma region during the etching operations may be between 0.01 Torr and 50 Torr, between 0.1 Torr and 15 Torr or between 0.5 Torr and 10 Torr in embodiments. The temperature of the patterned substrate during the etching operations may be between −20° C. and 450° C., between 0° C. and 350° C. or between 5° C. and 200° C. in embodiments.

[0050] Reference is now made to FIG. **4** which is plot of an optical emission spectra. An optical emission spectrum **4010** is depicted which represents a concurrent remote plasma and a weak local plasma. Another optical emission spectrum **4020** is depicted which represents only a weak local plasma. The peaks near 703.7 nm, 712.8 nm, and 720.2 nm correspond with fluorine atom concentration. The peaks near 706.5 nm and 728.1 nm correspond with helium atom concentration. Helium or another inert gas may be used to benefit the etch process but may also be useful to compare and normalize the fluorine peaks. Qualitatively, the fluorine measurements can be seen to become more pronounced when the remote plasma is in use. More generally, the fluorine measurements may be used to determine whether the fluorine concentration is changing, has reached a plateau, or has reached a predetermined setpoint during an etch process.

[0051] FIG. **5** is a plot of etch amount correlation with fluorine signal according to embodiments. The fluorine signal normalized to helium signal is shown on the x-axis whereas the etch amount corresponds to the y-axis. A plot of etch amount (proportion to etch rate) versus normalized fluorine signal **5010** is shown to be roughly linear with an offset. The linearity enables the normalized fluorine signal to be an in-situ indicator of the etch rate of a substrate without measuring the substrate directly.

[0052] FIGS. **6**A and **6**B show cross-sectional side views of a weak plasma viewport according to embodiments. FIG. **6**A shows a substrate processing region **6033** with a tubular viewport **6071** affixed to the side and forming a vacuum seal with the wall of the substrate processing chamber. A first electrode **6072-1** and a second electrode **6072-2** are affixed to the tubular viewport **6071** on opposite sides. All electrodes described herein may be copper adhesive tape or silver paste to facilitate attaching the electrodes to the various viewports according to embodiments. Other adhesive formats may also be used. Alternatively, the electrodes may simply be placed near the tubular viewport **6071** on opposite sides since mechanical contact between the viewport and the electrodes is not necessary to form the plasma. A weak plasma **6034** is formed on the inside of the tubular viewport **6071** by applying a weak RF plasma power from a weak RF plasma power supply (not shown) between the first electrode **6072-1** and the second electrode **6072-2**. FIG. **6**B shows an end view of the same configuration and includes a view of the weak plasma power supply **6068**. A fiber optic cable **6073** is configured to guide optical radiation from the weak plasma **6034** through the tubular viewport **6071** and into the optical emission spectrometer **6070**.

[0053] FIGS. **7**A, **7**B, and **7**C show cross-sectional side views of a weak plasma viewport according to embodiments. FIG. **7**A shows a substrate processing region **7033** with a tubular viewport **7071** affixed to the side and forming a vacuum seal with the wall of the substrate processing chamber. An electrode **7072-1** is affixed to the tubular viewport **7071** around the exterior of the tubular viewport **7071**. The electrode **7072-1** may be a piece of conducting adhesive tape (e.g. copper) or a layer of conductive paste (e.g. silver) to facilitate attaching the electrode **7072-1** to the tubular viewport **7071** according to embodiments. The electrode **7072-1** may simply be a conducting hoop looped loosely around the tubular viewport **7071** since forming the weak plasma does not rely on mechanical contact between the tubular viewport **7071** and the electrode **7072-1**. A weak plasma **7034-1** is formed on the inside of the tubular viewport **7071** by applying a weak RF plasma power from a weak RF plasma power supply **7068-1** between the electrode **7072-1** and the rest of the substrate processing chamber or the wall shown as a border of the substrate processing region **7033**. Also shown is a fiber optic cable **7073** configured to guide optical radiation from the weak plasma **7034** through the tubular viewport **7071** and into the optical emission spectrometer **7070**. FIG. 7B shows an end view of the same configuration and includes a view of the electrode **7072-1** which is shaped like a hoop. FIG. 7C shows a related configuration having an electrode **7072-2** over the end of the tubular viewport **7071** and the fiber optic cable **7073** is relocated to peer at the weak plasma **7034-2** from a different angle through an unobstructed portion of the tubular viewport **7071**. A weak RF plasma power supply **7068-2** provides the weak RF plasma power between the electrode **7072-2** and the wall of the substrate processing chamber.

[0054] FIGS. 8A and 8B show cross-sectional side views of a weak plasma viewport according to embodiments. FIG. 8A shows a substrate processing region **8033** with a planar viewport **8071** affixed to the side and forming a vacuum seal with the wall of the substrate processing chamber. A first electrode **8072-1** and a second electrode **8072-2** are affixed to the planar viewport **8071** without any direct electrical connection between them. The first electrode **8072-1** and the second electrode may be pieces of conducting adhesive tape (e.g. copper), a layer of conductive paste (e.g. silver) or electrodes placed near or adjacent to the planar viewport **8071**. The electrodes (**8072-1**, **8072-2**) do not need to be in mechanical contact with the planar viewport **8071**, in embodiments, to provide the capability of forming a weak plasma **8034-1**. The weak plasma **8034-1** is formed on the inside of the planar viewport **8071** by applying a weak RF plasma power from a weak RF plasma power supply **8068-1** between the first electrode **8072-1** and the second electrode **8072-2**. Also shown is a fiber optic cable **8073** configured to guide optical radiation from the weak plasma **8034-1** through the planar viewport **8071** and into the optical emission spectrometer **8070**. FIG. 8B shows a substrate processing region **8033** with a planar viewport **8071** affixed to the side and forming a vacuum seal with the wall of the substrate processing chamber. An electrode **8072-3** is affixed to the planar viewport **8071**. The first electrode **8072-1** may again be a piece of conducting adhesive tape, a layer of conductive paste, or an electrode placed very near or contacting the planar viewport **8071**. The weak plasma **8034-1** is formed on the inside of the planar viewport **8071** by applying a weak RF plasma power from a weak RF plasma power supply **8068-2** between the electrode **8072-3** and the rest of the substrate processing chamber or the wall shown as a border of the substrate processing region **8033**. Also shown is a fiber optic cable **8073** configured to guide optical radiation from the weak plasma **8034-2** through the planar viewport **8071** and into the optical emission spectrometer **8070**.

[0055] The tubular viewports described herein may be more prone to breakage since they stick out from the substrate processing chamber. The planar viewports provide the benefit of reducing the chance of accidentally breaking the viewport. The thickness of the planar viewports described herein affect the intensity of the weak plasmas inside the substrate processing chamber near the substrate. The thickness of the planar viewports may be between 1 mm and 15 mm, between 2 mm and 10 mm or preferably between 3 mm and 8 mm according to embodiments. The height and/or width of the planar viewports (as viewed from the axis of the thinnest dimension) may be between 20 mm and 100 mm or between 30 mm and 70 mm in embodiments. The fiber optic cable in all embodiments described herein may be positioned to the side of the substrate and just above the major plane of the substrate to preferentially sample the portion of the plasma effluents most likely to be participating in the etch process. The fiber optic cable may point horizontally (parallel to the major plane of the substrate) between 1 mm and 10 mm above the top surface of the substrate according to embodiments.

[0056] In embodiments, an ion suppressor (which may be the showerhead) may be used to provide radical and/or neutral species for gas-phase etching. The ion suppressor may also be referred to as an ion suppression element and may be positioned between the remote chamber region and the substrate processing region along with the showerhead. In embodiments, for example, the ion suppressor is used to filter etching plasma effluents en route from the remote plasma region(s) to the substrate processing region. The ion suppressor may be used to provide a reactive gas having a higher concentration of radicals than ions. Plasma effluents pass through the ion suppressor disposed between the remote plasma region and the substrate processing region. The ion suppressor functions to dramatically reduce or substantially eliminate ionic species traveling from the plasma generation region to the substrate. The ion suppressors described herein are simply one way to achieve a low electron temperature in the substrate processing region during the gas-phase etch processes described herein.

[0057] In embodiments, an electron beam is passed through the substrate processing region in a plane parallel to the substrate to reduce the electron temperature of the plasma effluents. A simpler showerhead may be used if an electron beam is applied in this manner. The electron beam may be passed as a laminar sheet disposed above the substrate in embodiments. The electron beam provides a source of neutralizing negative charge and provides a more active means for reducing the flow of positively charged ions towards the substrate and increasing the etch selectivity in embodiments. The flow of plasma effluents and various parameters governing the operation of the electron beam may be adjusted to lower the electron temperature measured in the substrate processing region.

[0058] The electron temperature may be measured using a Langmuir probe in the substrate processing region during excitation of a plasma in the remote plasma. In all plasma-free regions described herein (especially in the substrate processing region), 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 electron beam, showerhead and/or the ion suppressor. Uncharged neutral and radical species may pass through the electron beam and/or the openings in the ion suppressor to react at the substrate. Such a process using radicals and other neutral species can reduce plasma damage compared to conventional plasma etch processes that include sputtering and bombardment. Embodiments disclosed herein are also advantageous over conventional wet etch processes where surface tension of liquids can cause bending and peeling of small features.

[0059] The substrate processing region may be described herein as "plasma-free" during the etch processes described herein. "Plasma-free" does not necessarily mean the region is devoid of plasma. A weak plasma may be present to perform the optical emission spectroscopy measurement but the region directly above the substrate may be devoid of plasma since the weak plasma is positioned off to the side of the substrate processing region in embodiments. Ionized species and free electrons created within the plasma region may travel through pores (apertures) in the partition (showerhead) at exceedingly small concentrations. The borders of the plasma in the remote plasma region (e.g. the remote chamber region and/or the remote plasma region) may encroach to some small degree upon the substrate processing region through the apertures in the showerhead. Furthermore, a low intensity plasma may be created in the substrate processing region without eliminating desirable features of the etch processes described herein. All causes for a plasma having much lower intensity ion density than the remote plasma region during the creation of the excited plasma effluents do not deviate from the scope of "plasma-free" as used herein.

[0060] 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 oxide" of the patterned substrate is predominantly SiO_2 but may include concentrations of other elemental constituents such as, e.g., nitrogen, hydrogen and carbon. In some embodiments, silicon oxide portions etched using the methods disclosed herein consist essentially of silicon and oxygen. Exposed "silicon nitride" of the patterned substrate is predominantly Si_3N_4 but may include concentrations of other elemental constituents such as, e.g., oxygen, hydrogen and carbon. In some embodiments, silicon nitride portions described herein consist essentially of silicon and nitrogen. Generally speaking, a first exposed portion of a patterned substrate is etched faster than a second exposed portion. The first exposed portion may have an atomic stoichiometry which differs from the second exposed portion. In embodiments, the first exposed portion may contain an element which is not present in the second exposed portion. Similarly, the second exposed portion may contain an element which is not present in the first exposed portion according to embodiments.

[0061] The term "precursor" is used to refer to any chemical which takes part in a reaction to either remove material from or deposit material onto a surface. "Plasma effluents" describe gas exiting from the remote plasma region and entering the remote chamber region and/or 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 precursors" describe 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.

[0062] 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 embodiments. Accordingly, the above description should not be taken as limiting the scope of the claims.

[0063] 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 claims, 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.

[0064] 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.

[0065] 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 substrate processing chamber, the substrate processing chamber comprising:

- a remote plasma region, wherein the remote plasma region is configured to receive a fluorine-containing precursor and form a remote plasma from the fluorine-containing precursor;
- a remote plasma power supply configured to apply a remote plasma power to the remote plasma region and configured to form the remote plasma;
- a substrate processing region;
- a showerhead disposed between the remote plasma region and the substrate processing region, wherein the substrate processing region is fluidly coupled to the remote plasma region by through-holes in the showerhead;
- a pedestal configured to support a substrate;
- a flange attached to the substrate processing chamber, wherein the flange forms a vacuum seal with the substrate processing chamber;
- a viewport attached to the flange forming a vacuum seal with the flange, wherein the viewport is optically transmissive in a near infrared spectrum; and
- an optical emission spectrometer configured to receive optical radiation after the optical radiation passes through the viewport, wherein the optical emission spectrometer is disposed on an exterior of the viewport and the optical radiation originates from above the substrate.

2. The substrate processing chamber of claim **1** further comprising a local plasma power supply configured to form a local plasma in the substrate processing region, wherein the local plasma has a local plasma power less than 10% of the remote plasma power.

3. The substrate processing chamber of claim **1** further comprising a fiber optic cable configured to guide the optical radiation from the viewport to the optical emission spectrometer.

4. The substrate processing chamber of claim **1** further comprising an electrode proximal to the viewport, wherein the electrode is disposed on the exterior of the viewport.

5. The substrate processing chamber of claim **4** further comprising a plasma power supply configured to apply a plasma power to the electrode.

6. The substrate processing chamber of claim **4** further comprising a second electrode configured to apply a plasma power to the electrode, wherein the electrode is electrically insulated from the second electrode.

7. An optical emission spectrometer assembly, the optical emission spectrometer assembly comprising:

a flange configured to attach to a substrate processing chamber, wherein the flange is configured to form a vacuum seal with the substrate processing chamber;

a planar viewport attached to the flange forming a vacuum seal with the flange, wherein the planar viewport is optically transmissive in a near infrared spectrum;

an electrode proximal to the planar viewport, wherein the electrode is disposed on an external side of the planar viewport;

an optical emission spectrometer configured to receive optical radiation after the optical radiation passes through the planar viewport, wherein the optical emission spectrometer is disposed on the external side of the planar viewport; and

a plasma power supply configured to apply a plasma power to the electrode.

8. The optical emission spectrometer assembly of claim **7** further comprising a fiber optic cable configured to guide infrared light from the planar viewport to the optical emission spectrometer.

9. The optical emission spectrometer assembly of claim **7** wherein the plasma power supply is configured to apply the plasma power between the electrode and the substrate processing chamber.

10. The optical emission spectrometer assembly of claim **7** further comprising a second electrode proximal to the planar viewport, wherein the electrode is electrically insulated from the second electrode.

11. The optical emission spectrometer assembly of claim **10** wherein the plasma power supply is configured to apply the plasma power between the electrode and the second electrode.

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