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(54) **ANISOTROPIC GAP ETCH**

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(58) **Field of Classification Search**

None

See application file for complete search history.

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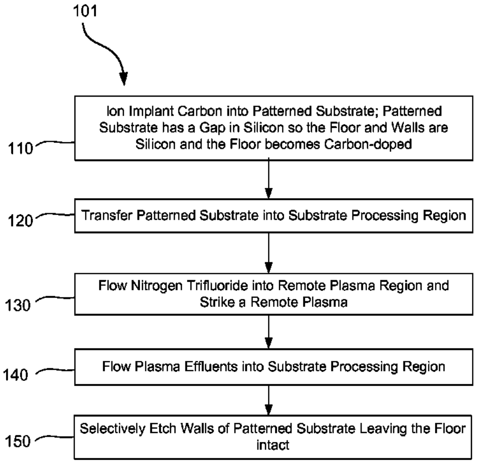
(57) **ABSTRACT**

A method of anisotropically dry-etching exposed substrate material on a patterned substrate is described. The patterned substrate has a gap formed in a single material made from, for example, a silicon-containing material or a metal-containing material. The method includes directionally ion-implanting the patterned structure to implant the bottom of the gap without implanting substantially the walls of the gap. Subsequently, a remote plasma is formed using a fluorine-containing precursor to etch the patterned substrate such that either (1) the walls are selectively etched relative to the floor of the gap, or (2) the floor is selectively etched relative to the walls of the gap. Without ion implantation, the etch operation would be isotropic owing to the remote nature of the plasma excitation during the etch process.

14 Claims, 8 Drawing Sheets



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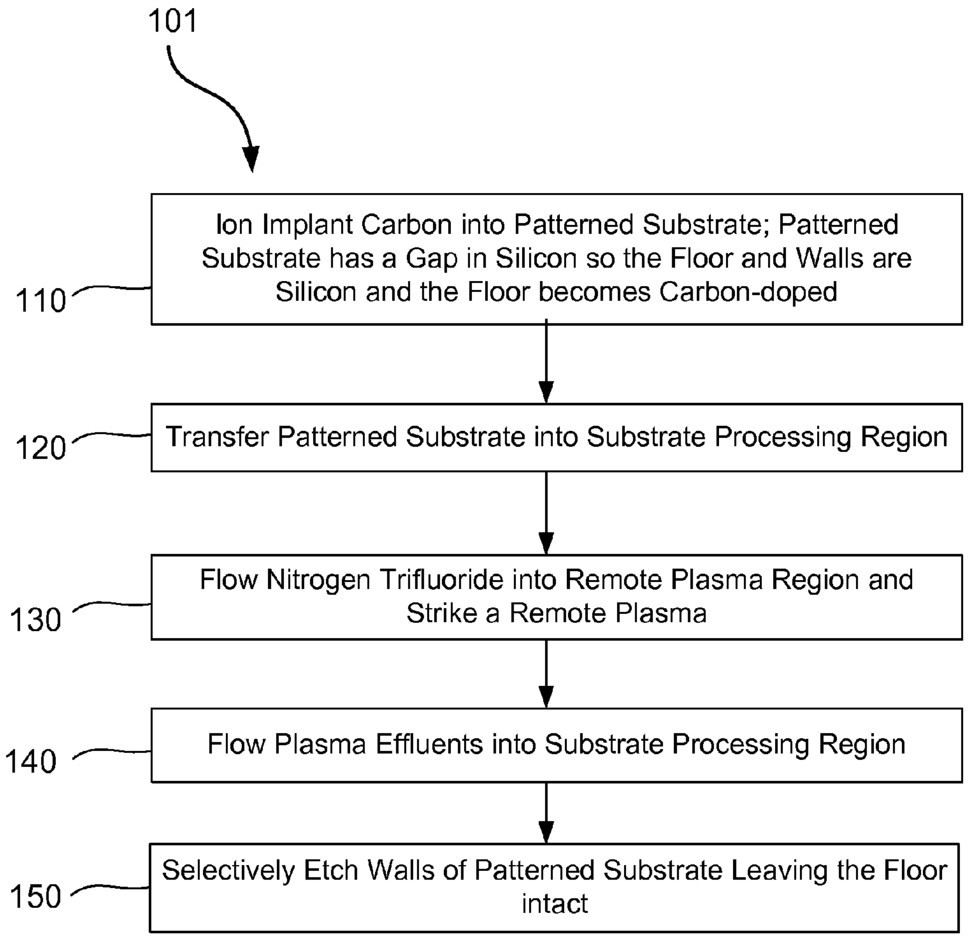
101
110
Ion Implant Carbon into Patterned Substrate; Patterned Substrate has a Gap in Silicon so the Floor and Walls are Silicon and the Floor becomes Carbon-doped
120
Transfer Patterned Substrate into Substrate Processing Region
130
Flow Nitrogen Trifluoride into Remote Plasma Region and Strike a Remote Plasma
140
Flow Plasma Effluents into Substrate Processing Region
150
Selectively Etch Walls of Patterned Substrate Leaving the Floor intact

FIG. 1

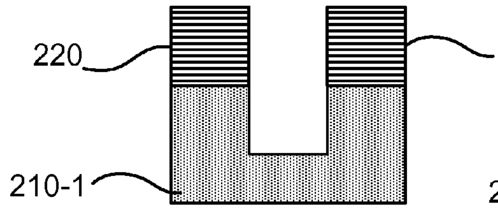

FIG. 2A

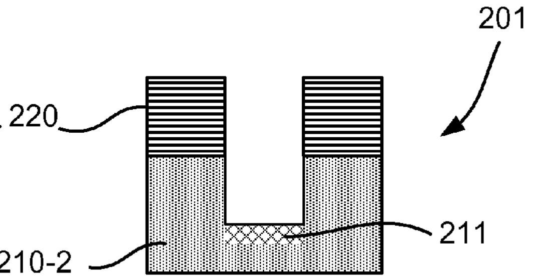

FIG. 2B

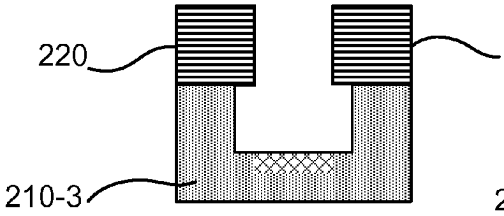

FIG. 2C

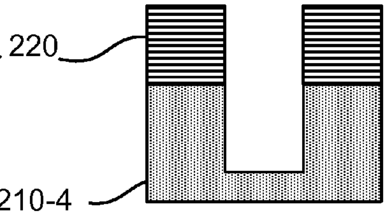

FIG. 2D

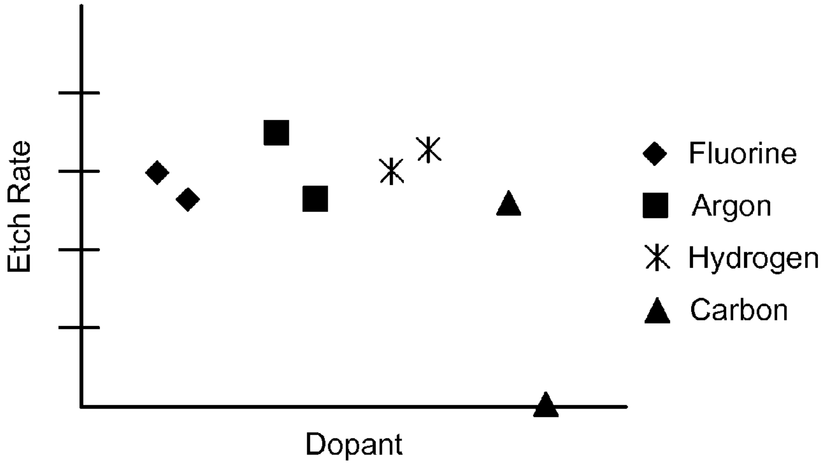

FIG. 3

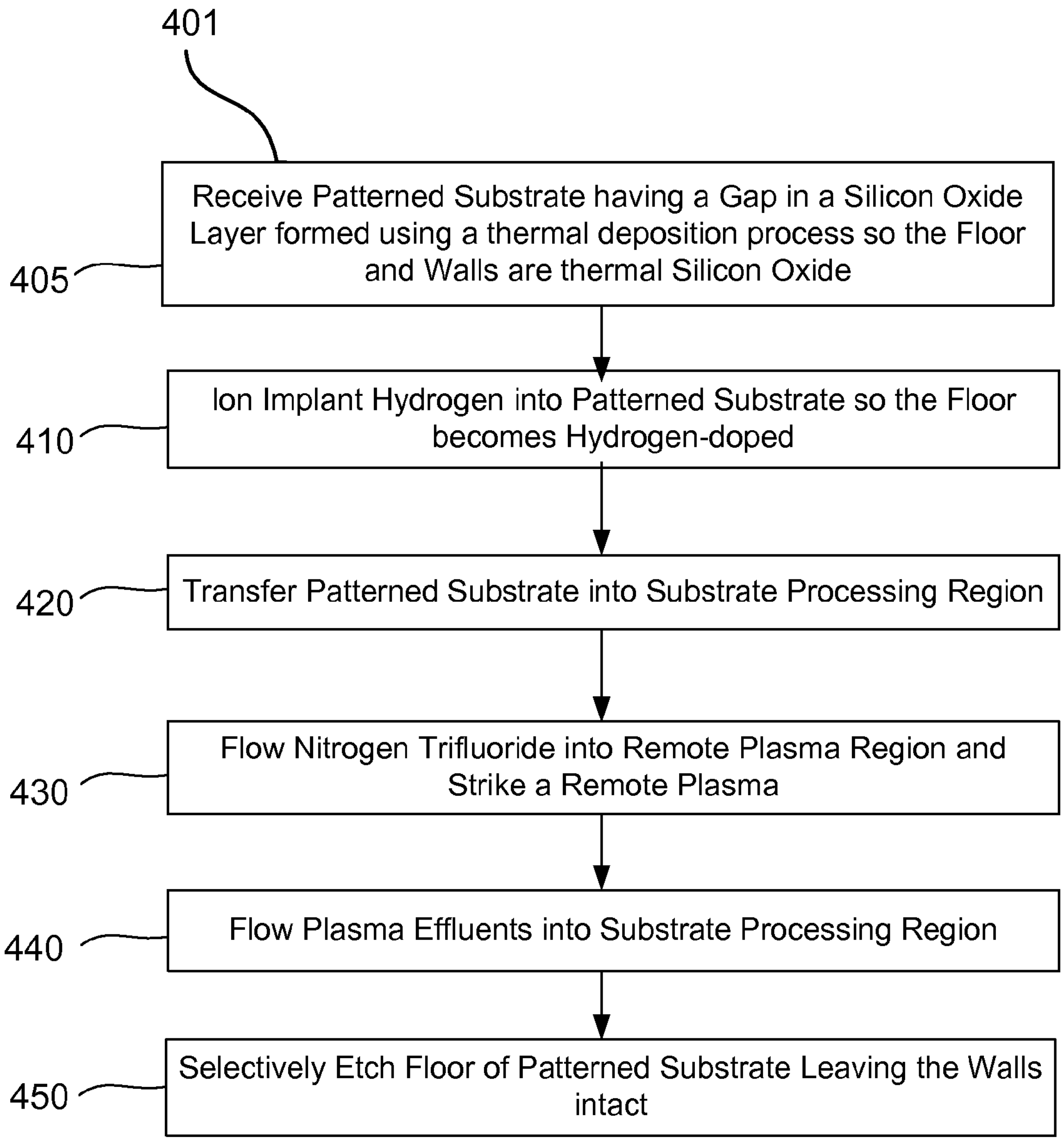
401
405
Receive Patterned Substrate having a Gap in a Silicon Oxide Layer formed using a thermal deposition process so the Floor and Walls are thermal Silicon Oxide
410
Ion Implant Hydrogen into Patterned Substrate so the Floor becomes Hydrogen-doped
420
Transfer Patterned Substrate into Substrate Processing Region
430
Flow Nitrogen Trifluoride into Remote Plasma Region and Strike a Remote Plasma
440
Flow Plasma Effluents into Substrate Processing Region
450
Selectively Etch Floor of Patterned Substrate Leaving the Walls intact

FIG. 4

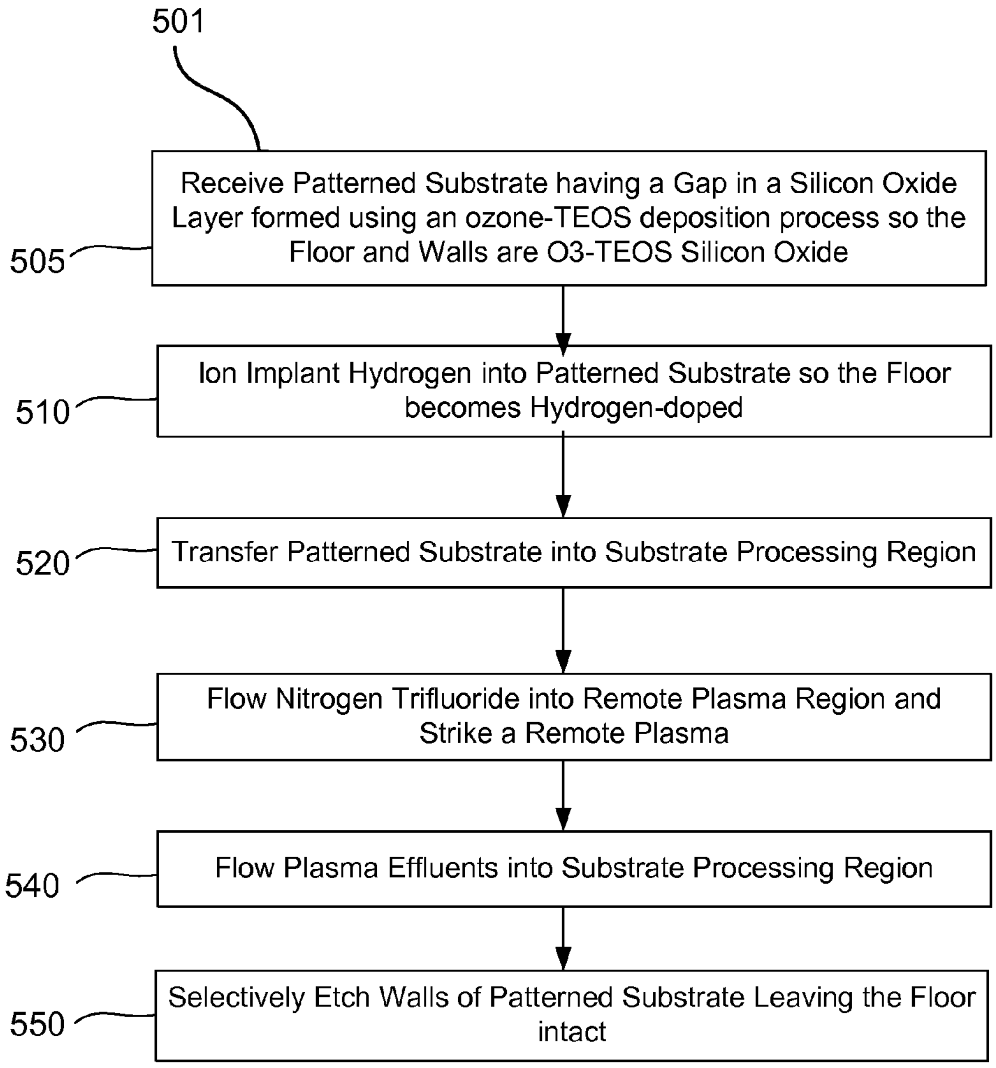
501
505
Receive Patterned Substrate having a Gap in a Silicon Oxide Layer formed using an ozone-TEOS deposition process so the Floor and Walls are O3-TEOS Silicon Oxide
510
Ion Implant Hydrogen into Patterned Substrate so the Floor becomes Hydrogen-doped
520
Transfer Patterned Substrate into Substrate Processing Region
530
Flow Nitrogen Trifluoride into Remote Plasma Region and Strike a Remote Plasma
540
Flow Plasma Effluents into Substrate Processing Region
550
Selectively Etch Walls of Patterned Substrate Leaving the Floor intact

FIG. 5

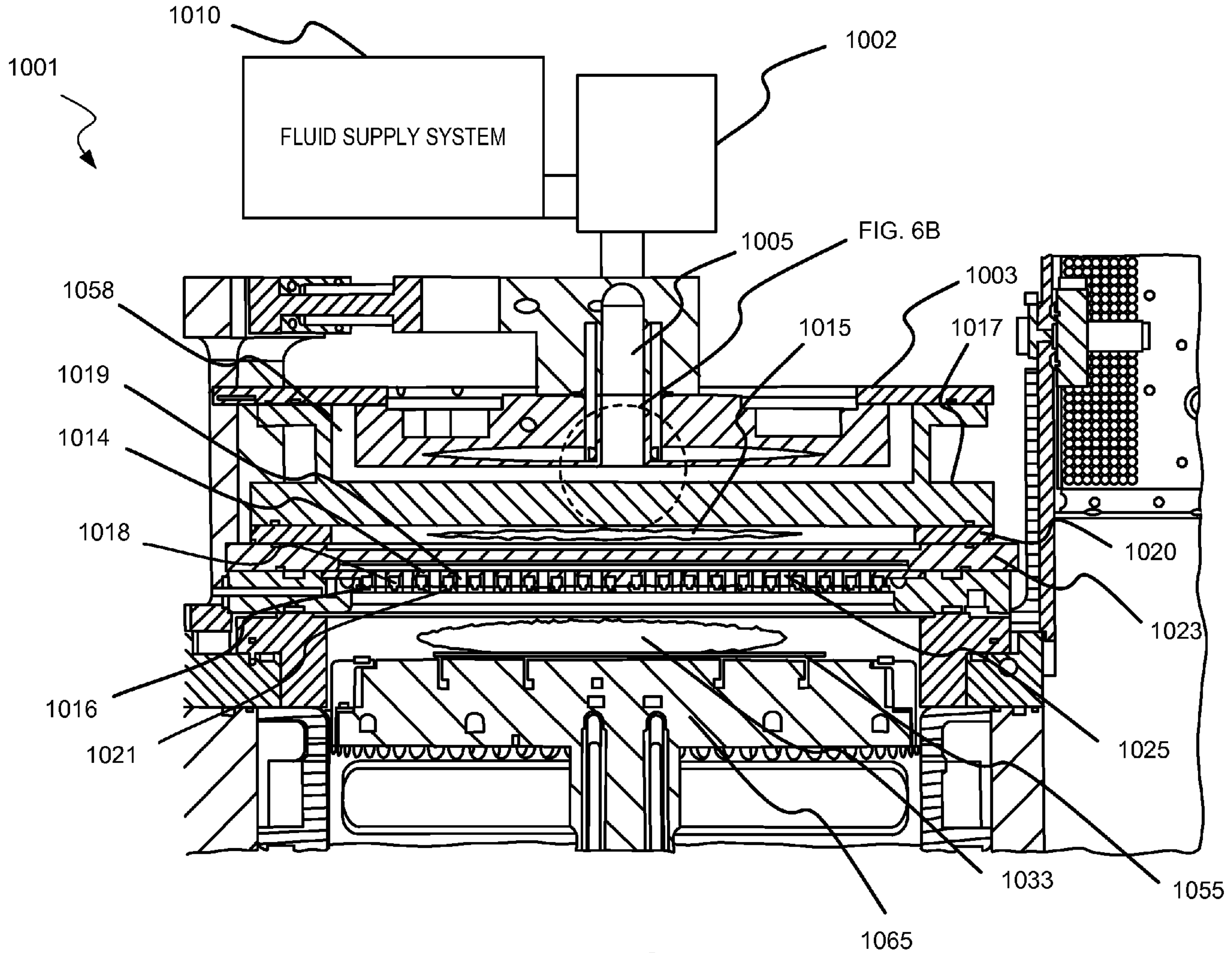
1001
1010
FLUID SUPPLY SYSTEM
1002
1005
FIG. 6B
1003
1058
1015
1017
1019
1014
1018
1020
1023
1016
1021
1025
1033
1055
1065

FIG. 6A

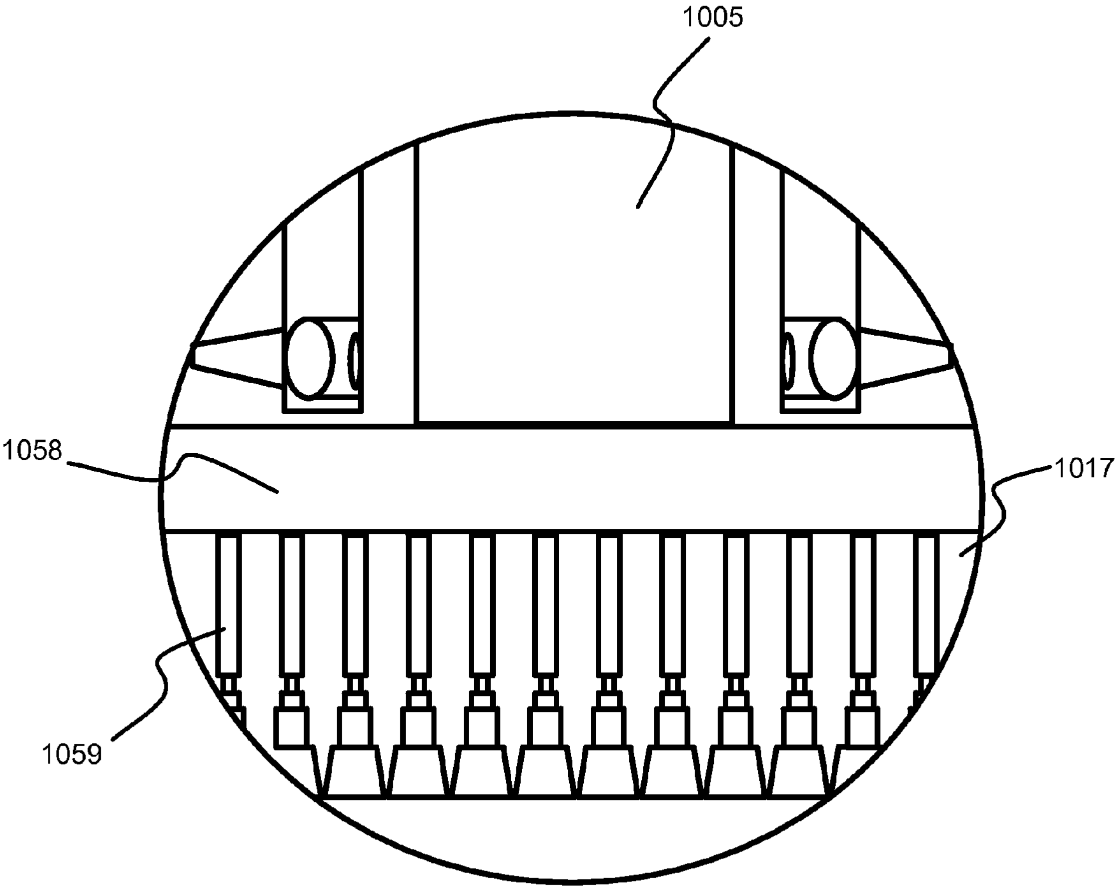

FIG. 6B

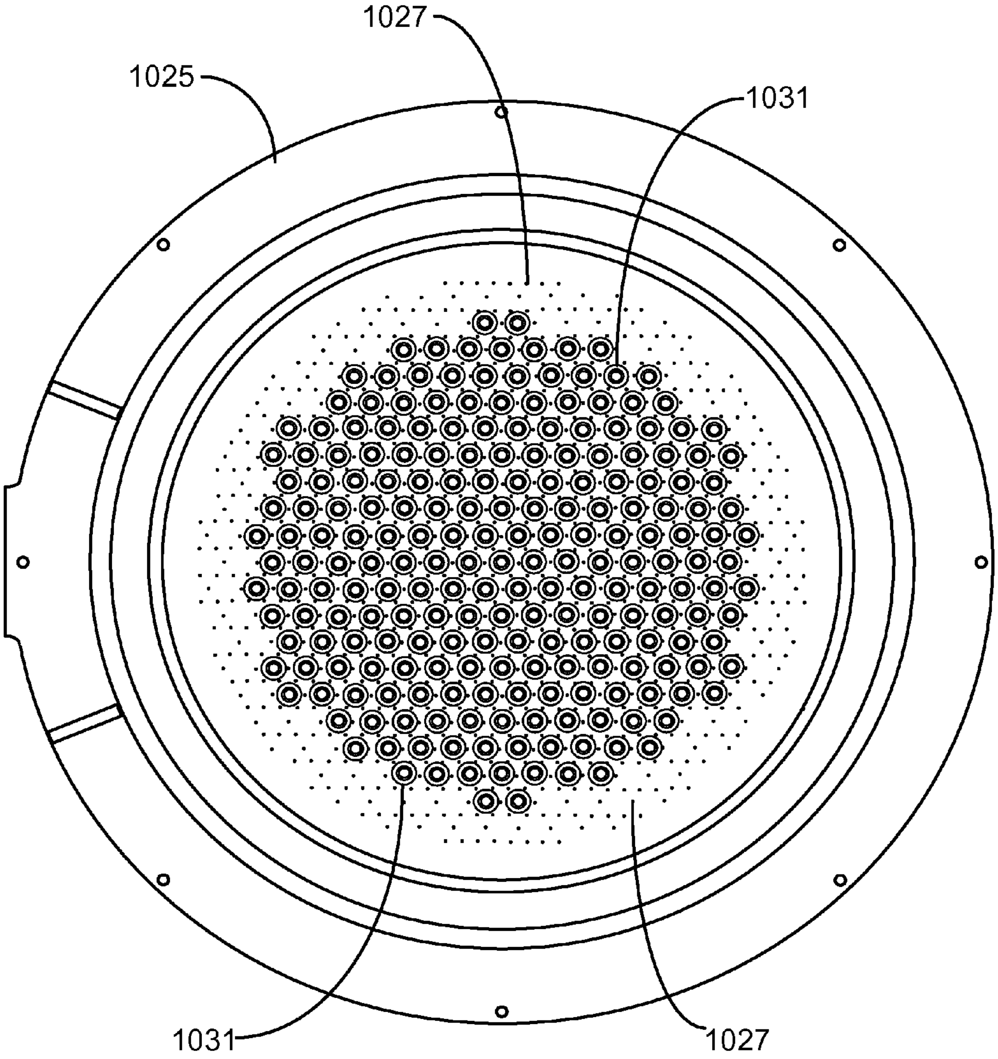

FIG. 6C

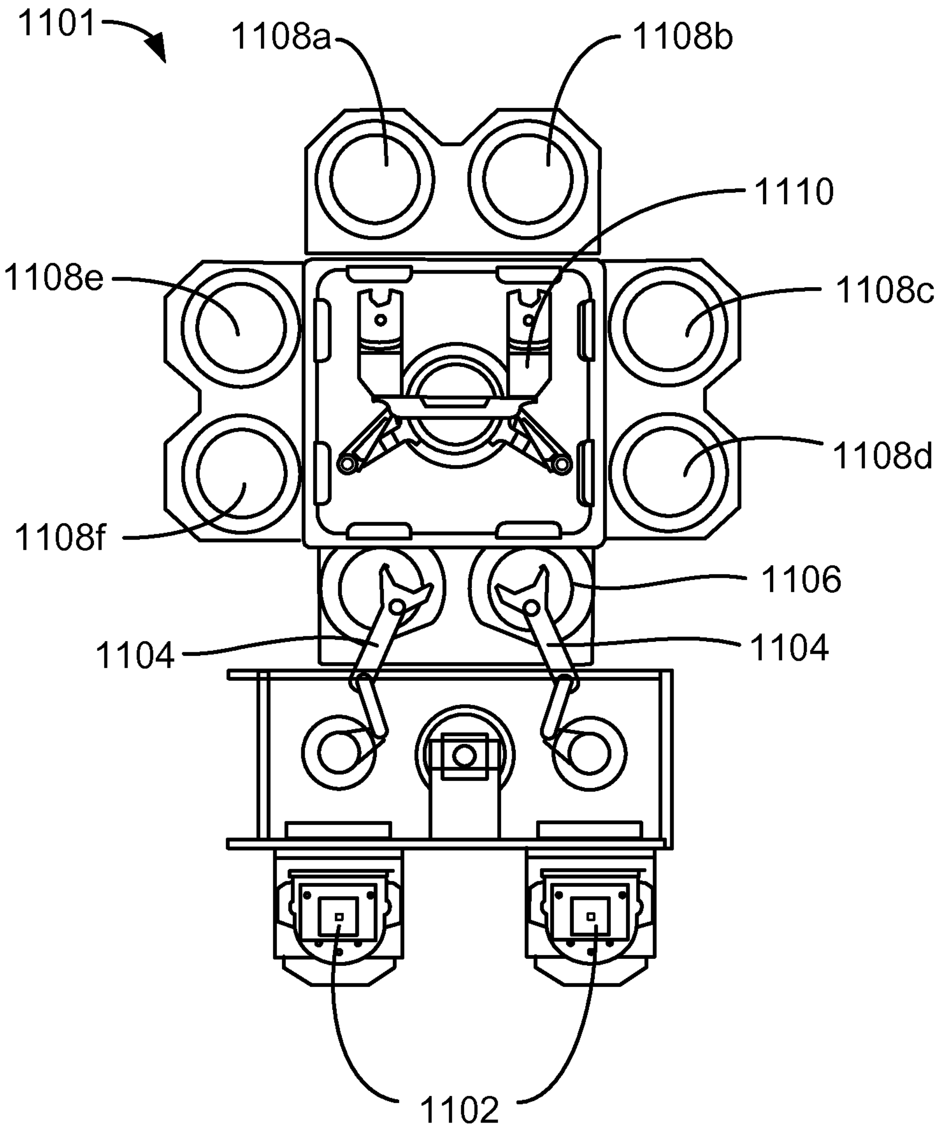
1101
1108a
1108b
1110
1108e
1108c
1108d
1108f
1106
1104
1104
1102

FIG. 7

ANISOTROPIC GAP ETCH

FIELD

The present invention relates to anisotropic etching of gaps.

BACKGROUND

Integrated circuits are made possible by processes which produce intricately patterned material layers on substrate surfaces. Producing patterned material on a substrate is enabled by 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 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.

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.

Methods are needed to broaden process flexibility for silicon-containing films and metal-containing films using dry etch processes.

BRIEF SUMMARY

A method of anisotropically dry-etching exposed substrate material on a patterned substrate is described. The patterned substrate has a gap formed in a single material made from, for example, a silicon-containing material or a metal-containing material. The method includes directionally ion-implanting the patterned structure to implant the bottom of the gap without implanting substantially the walls of the gap. Subsequently, a remote plasma is formed using a fluorine-containing precursor to etch the patterned substrate such that either (1) the walls are selectively etched relative to the floor of the gap, or (2) the floor is selectively etched relative to the walls of the gap. Without ion implantation, the etch operation would be isotropic owing to the remote nature of the plasma excitation during the etch process.

Embodiments of the invention include methods of etching a patterned substrate. The methods include ion implanting the patterned substrate. Ion implanting the patterned substrate includes ion implanting an exposed bottom portion of a gap in the patterned substrate with carbon. Both the exposed bottom portion and an exposed sidewall portion of the gap include silicon. The methods further include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The methods further include combining a fluorine-containing precursor with a hydrogen-containing precursor in a remote plasma region fluidly coupled to the substrate processing region by way of a showerhead while forming a remote plasma in the remote plasma region to produce plasma effluents. The methods further include anisotropically etching the patterned substrate such that the exposed sidewall portion etches at a greater etch rate than the exposed bottom portion.

The fluorine-containing precursor may be nitrogen trifluoride and the hydrogen-containing precursor may be molecular hydrogen (H_2). The exposed sidewall portion may etch more rapidly than the exposed bottom portion by a ratio of at least 25:1. The exposed bottom portion may be carbon-doped at a first concentration and the exposed sidewall portion may be carbon-doped at a second concentration which is less than the first concentration.

Embodiments of the invention include methods of etching a patterned substrate. The methods include ion implanting the patterned substrate. Ion implanting the patterned substrate includes ion implanting an exposed bottom portion of a gap in a silicon oxide layer on the patterned substrate. The exposed bottom portion and an exposed sidewall portion of the gap each include silicon oxide. The methods further include placing the patterned 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 fluidly coupled to the substrate processing region by way of a showerhead while forming a remote plasma in the remote plasma region to produce plasma effluents. The methods further include flowing a hydrogen-and-oxygen-containing precursor into the substrate processing region without first passing the hydrogen-and-oxygen-containing precursor through the remote plasma region. The hydrogen-and-oxygen-containing precursor includes an O—H bond. The methods further include combining the plasma effluents with the hydrogen-and-oxygen-containing precursor in the substrate processing region. The methods further include anisotropically etching the patterned substrate such that the exposed sidewall portion of the gap and the exposed bottom portion of silicon oxide etch at different etch rates from one another.

The operation of anisotropically etching the patterned substrate may etch the exposed sidewall portion more rapidly than the exposed bottom portion. The operation of anisotropically etching the patterned substrate may etch the exposed sidewall portion more slowly than the exposed bottom portion. The exposed sidewall portion may etch more rapidly than the exposed bottom portion by a ratio of at least 15:1.

Embodiments of the invention include methods of etching a patterned substrate. The methods include ion implanting the patterned substrate. Ion implanting the patterned substrate includes ion implanting an exposed bottom portion of a gap in a material layer on the patterned substrate. The exposed bottom portion of the gap comprises a material composition and an exposed sidewall portion of the gap comprises the same material composition. The methods further include anisotropically etching the patterned substrate such that the exposed sidewall portion and the exposed bottom portion etch at different etch rates from one another.

The operation of anisotropically etching the patterned substrate may etch the exposed sidewall portion more rapidly than the exposed bottom portion. The operation of anisotropically etching the patterned substrate may etch the exposed sidewall portion more slowly than the exposed bottom portion. The operation of ion implanting the patterned substrate may involves accelerating ions vertically into the gap on the patterned substrate. The operation of anisotropically etching the patterned substrate may be a dry-etch process. The operation of ion implanting the patterned substrate may be a local plasma process. The material layer may be a metal-containing layer or a silicon-containing layer.

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

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. **1** is a flow chart of a lateral anisotropic etch process according to embodiments.

FIGS. **2**A, **2**B, **2**C and **2**D show cross-sectional views of a device at various stages during an anisotropic etch process according to embodiments.

FIG. **3** shows a plot of etch rates during a lateral anisotropic etch process according to embodiments.

FIG. **4** is a flow chart of a vertical anisotropic etch process according to embodiments.

FIG. **5** is a flow chart of a lateral anisotropic etch process according to embodiments.

FIG. **6**A shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

FIG. **6**B shows a schematic cross-sectional view of a portion of a substrate processing chamber according to embodiments.

FIG. **6**C shows a bottom plan view of a showerhead according to embodiments.

FIG. **7** shows a top plan view of an exemplary substrate processing system according to embodiments.

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

A method of anisotropically dry-etching exposed substrate material on a patterned substrate is described. The patterned substrate has a gap formed in a single material made from, for example, a silicon-containing material or a metal-containing material. The method includes directionally ion-implanting the patterned structure to implant the bottom of the gap without implanting substantially the walls of the gap. Subsequently, a remote plasma is formed using a fluorine-containing precursor to etch the patterned substrate such that either (1) the walls are selectively etched relative to the floor of the gap, or (2) the floor is selectively etched relative to the walls of the gap. Without ion implantation, the etch operation would be isotropic owing to the remote nature of the plasma excitation during the etch process.

Embodiments of the present invention pertain to selectively removing material from a patterned substrate. The material may be silicon-containing such as silicon oxide, silicon nitride, polysilicon, silicon oxynitride, etc. in embodiments. The material may be metal-containing such as copper, aluminum, cobalt, tungsten, hafnium, copper oxide, aluminum oxide, cobalt oxide, tungsten oxide, hafnium oxide, etc. The patterned substrate has a gap in the material such that the floor (or bottom) and the walls (or sidewalls) are made of the same material. The patterned substrate is ion implanted to break the symmetry such that a remote plasma etch may then be used to anisotropically etch the patterned substrate. The anisotropic etches described herein may either remove sidewall material faster or bottom material faster depending on the nature of the material and the implant process. Before ion implantation, the portion of bottom material may be referred to herein as unimplanted material. After ion implantation, the portion of exposed material at the bottom of the gap will be referred to as implanted material. “Top”, “above” and “up” will be used herein to describe portions/directions perpendicularly distal from the substrate plane and further away from the center of mass of the substrate in the perpendicular direction. “Vertical” will be used to describe items aligned in the “up” direction towards the “top”. Other similar terms may be used whose meanings will now be clear.

In order to better understand and appreciate embodiments of the invention, reference is now made to FIG. **1** which is a flow chart of anisotropic etch process **101**. Cross-sectional views of a device **201** at stages throughout anisotropic etch process **101** are shown in FIGS. **2**A-**2**D. Device **201** comprises a gap in a polysilicon layer **210** of a patterned substrate and a mask **220**. Polysilicon layer **210-1** is unimplanted at the start of anisotropic etch process **101** and may be single crystalline or polycrystalline (in which case the term “polysilicon” has been used as a shorthand). FIG. **2**A shows device **201** before the start of anisotropic etch process **101**.

The patterned substrate is then placed in an ion implant chamber, which may be a beamline implant chamber or a biased plasma implant chamber. A biased plasma implant chamber is used in exemplary anisotropic etch process **101**. Methane is then flowed into the biased plasma implant chamber. The methane is excited in a capacitively-coupled plasma disposed next to the patterned substrate and the patterned substrate is bombarded with carbon (operation **110**). A DC voltage may be applied to assist in the acceleration of carbon toward the patterned substrate and to ion implant the floor of the gap in polysilicon layer **210-1** to create an ion implanted portion **211** of polysilicon layer **210-2** as shown in FIG. **2**B.

Generally speaking, a hydrocarbon may be used to augment or replace the methane of anisotropic etch process **101**. The hydrocarbon may be a hydrogen-and-carbon-containing precursor which may contain elements other than hydrogen and carbon in embodiments. The hydrogen-and-carbon-containing precursor may be halogen-free, chlorine-free and/or fluorine-free in embodiments. According to embodiments, the hydrogen-and-carbon-containing precursor may consist only of hydrogen and carbon. The hydrogen-and-carbon-containing precursor may be one of methane, ethane, propane or a higher order saturated alkane. The radical-hydrogen-carbon is the portion of the plasma effluents produced from the excitation of the hydrogen-and-carbon-containing precursor in the local plasma of the ion implant chamber. The radical-hydrogen-carbon may be halogen-free, chlorine-free or fluorine-free according to embodiments.

The patterned substrate is then placed in a substrate processing region in operation **120**. A flow of nitrogen trifluoride is then introduced into a remote plasma region (operation **130** of anisotropic etch process **101**) where the nitrogen trifluoride is excited in a remote plasma struck within the separate plasma region. The separate plasma region may be referred to as a remote plasma region herein and may be within a distinct module from the processing chamber or a compartment within the processing chamber separated from the substrate processing region by a permeable barrier. In general, a fluorine-containing precursor may be flowed into the remote plasma region and the fluorine-containing precursor comprises at least one precursor selected from the group consisting of atomic fluorine, diatomic fluorine, bromine trifluoride, chlorine trifluoride, nitrogen trifluoride, hydrogen fluoride, fluorinated hydrocarbons, sulfur hexafluoride and xenon difluoride. The remote plasma region may be devoid of hydrogen during operations **130-150** of anisotropic etch process **101**.

Continuing with embodiments of anisotropic etch process **101**, the plasma effluents formed in the remote plasma region are then flowed into the substrate processing region (operation **140**) and the patterned substrate is anisotropically etched (operation **150**). The plasma effluents may enter the substrate processing region through through-holes in a showerhead which separates the remote plasma region from the substrate processing region. Ion implanted polysilicon portion **211** of polysilicon layer **210-2** is implanted with carbon and etches more slowly than the sidewalls which have not been implanted to the same degree. FIG. **2**C shows the profile of device **201** following operation **150**. The reactive chemical species are removed from the substrate processing region and then the substrate is removed from the processing region.

Anisotropic etch process **101** includes applying energy to the hydrocarbon (e.g. methane) while in the biased plasma implant chamber to generate the ions used to implant the patterned substrate (operation **110**). The plasma characteristics and parameters presented here also apply to the examples presented later with reference to FIGS. **4** and **5**. The plasma may be generated using known techniques (e.g., radio frequency excitations, capacitively-coupled power, inductively coupled power, etc.). In the example, the energy is applied using a capacitively-coupled plasma unit. The local plasma power may be between about 10 watts and about 500 watts, between about 20 watts and about 400 watts, between about 30 watts and about 300 watts, or between about 50 watts and about 200 watts according to embodiments. Plasma power and operating pressure may be used to adjust the current and kinetic energy of impinging ions and may be used to adjust the dimensions of implanted polysilicon portion **211**.

A DC accelerating voltage may also be applied such that positive ions formed in the local plasma are further accelerated in the direction of the patterned substrate. In other words, the local plasma may be formed by applying a DC bias power such that the local plasma power comprises both an AC portion and a DC portion. The DC bias power supplies a DC accelerating voltage which may be greater than 400 volts, greater than 500 volts, greater than 600 volts, or greater than 700 volts in embodiments. The DC voltage may be less than 2000 volts, less than 1500 volts, less than 1300 volts or less than 1100 volts to preserve integrity of exposed delicate features. The pressure in the biased plasma implant chamber may be between about 0.5 mTorr and about 50 mTorr, between about 2 mTorr and about 200 mTorr or between about 5 mTorr and about 100 mTorr according to embodiments.

Anisotropic etch process **101** also includes applying energy to the fluorine-containing precursor while in the remote plasma region to generate the plasma effluents (operation **130**). As would be appreciated by one of ordinary skill in the art, the plasma may include a number of charged and neutral species including radicals and ions. The plasma may be generated using known techniques (e.g., radio frequency excitations, capacitively-coupled power, inductively coupled power, etc.). In the example, the energy is applied using a capacitively-coupled plasma unit. The remote plasma source power may be between about 10 watts and about 5000 watts, between about 100 watts and about 3000 watts, between about 250 watts and about 2000 watts, or between about 500 watts and about 1500 watts in embodiments. The pressure in the remote plasma region and/or the pressure in the substrate processing region may be between 0.01 Torr and 50 Torr or between 0.1 Torr and 5 Torr according to embodiments. The RF frequency applied for either the local or remote plasmas described herein may be low RF frequencies less than 200 kHz, high RF frequencies between 10 MHz and 15 MHz, or microwave frequencies greater than 1 GHz in embodiments.

FIG. **3** shows a plot of etch rate of polysilicon versus various dopant elements and concentrations. Each pair of data points correspond to fluorine, argon, hydrogen and carbon, from left to right in the plot. The left of each pair of data points corresponds with a dopant density of about one times ten to the sixteenth atoms per cubic centimeter. The right data point of each pair corresponds with a dopant density of about five times ten to the sixteenth atoms per cubic centimeter. Fluorine, argon and hydrogen are not effective at suppressing the etch rate. Carbon, on the other hand, causes no discernible difference in etch rate at lower concentrations but essentially halts the etch progress at the higher concentration. This data motivates the use of a hydrocarbon for the ion implantation precursor in the example of FIG. **1**.

As alluded to previously, the methods described herein may be applied to materials other than polysilicon. The material which undergoes anisotropic etching need only have the same exposed material on the bottom of a gap as on the sidewalls to benefit from the anisotropic etch processes presented herein. The ion implantation element(s) and other parameters may be adjusted based on the properties of the material. In embodiments, the material may comprise a metal element and/or silicon. A metal element is one which forms a conductor in a material which consists only of that particular metal element. The metal-containing material may further comprise oxygen, nitrogen, carbon or silicon according to embodiments.

In the case of silicon (e.g. polysilicon), a silicon oxide layer may be present on exposed portions. When silicon is exposed to atmosphere or most oxygen-containing precursors, a thin silicon oxide layer generally forms and is often referred to as a "native" oxide. The native oxide can be removed by local plasma processes, remote plasma processes which form sublimatable salts or chemical treatments carried out at atmospheric pressures. Regardless of the method used, the native oxide (if present) may or may not be removed before the operations of ion implanting and etching the exposed silicon. The ion implantation has been found, in embodiments, to remove (or enable the subsequent removal of) the thin native oxide in addition to ion implanting the exposed silicon portion. Finally, the terms "exposed silicon portion" and "exposed silicon" will be used herein regardless of whether a thin native oxide is present. Generally speaking, a native oxide may be present on any of the gap materials described herein. Metal-containing films often acquire a native oxide when exposed to atmosphere. An aluminum film, for example, will acquire a thin aluminum oxide coating when exposed to atmosphere. The phrase "exposed material" will be used despite the occasional presence of an oxide coating.

The methods presented herein exhibit high etch selectivity of sidewall material relative to bottom material or bottom material relative to sidewall material according to embodiments. An example of the latter will be presented during the next example which pertains to FIG. **4**. The etch selectivity of the sidewall material relative to the bottom material may be greater than 25:1, greater than 40:1 or greater than 50:1 according to embodiments. In material and ion implantation systems which display the inverted behavior, the etch selectivity of the bottom material relative to the sidewall material may be greater than 15:1, greater than 30:1 or greater than 40:1 according to embodiments.

Reference is now made to FIG. **4** which is a flow chart of anisotropic etch process **401**. In this example, device **201** comprises a gap in a silicon oxide layer **210** of a patterned substrate and a mask **220**. Identifier **210** will be reused and represent silicon oxide rather than polysilicon for anisotropic etch process **401**. Silicon oxide layer **210-1** is a dense thermally-grown silicon oxide and is unimplanted at the start of anisotropic etch process **401** and may be succinctly referred to as thermal silicon oxide. FIG. **2**A shows device **201** before the start of anisotropic etch process **401**. All process characteristics and parameters provided for anisotropic etch process **101** apply to anisotropic etch processes **401** and **501** unless alternative values and or characteristics are provided.

The patterned substrate is placed in an ion implant chamber in operation **405**. Hydrogen (H_2) is then flowed into the biased plasma implant chamber. The hydrogen is excited in a capacitively-coupled plasma disposed next to the patterned substrate and the patterned substrate is bombarded with hydrogen (operation **410**). A DC voltage may be applied to assist in the acceleration of hydrogen toward the patterned substrate and to ion implant the floor of the gap in thermal silicon oxide layer **210-1** to create an ion implanted portion **211** of thermal silicon oxide layer **210-2** as shown in FIG. **2**B.

Generally speaking, a hydrogen-containing precursor may be used to augment or replace the hydrogen (H_2) of anisotropic etch process **401**. The hydrogen-containing precursor may be carbon-free, halogen-free, chlorine-free and/or fluorine-free in embodiments. According to embodiments, the hydrogen-containing precursor may consist only of hydrogen. The radical-hydrogen is the portion of the plasma effluents produced from the excitation of the hydrogen-containing precursor in the local plasma of the ion implant chamber. The radical-hydrogen may be carbon-free, halogen-free, chlorine-free or fluorine-free according to embodiments.

The patterned substrate is then placed in a substrate processing region in operation **420**. A flow of nitrogen trifluoride (or another fluorine-containing precursor) is then introduced into a remote plasma region (operation **430** of anisotropic etch process **401**) where the nitrogen trifluoride is excited in a remote plasma struck within the remote plasma region. The remote plasma region may be devoid of hydrogen during operations **430-450** of anisotropic etch process **401**.

The plasma effluents formed in the remote plasma region are flowed into the substrate processing region (operation **440**) and the patterned substrate is anisotropically etched (operation **450**). The plasma effluents may enter the substrate processing region through through-holes in a showerhead which separates the remote plasma region from the substrate processing region. Ion implanted thermal silicon oxide portion **211** of thermal silicon oxide layer **210-2** is implanted with hydrogen and etches more rapidly than the sidewalls which have not been implanted to the same degree. FIG. **2**D shows the profile of device **201** following operation **450**. The inversion of the selectivity compared with FIG. **1** and FIG. **5** may arise because of the extremely high density of thermal silicon oxide. The etch rate has nowhere to go but up so the hydrogen implanted bottom portion etches more rapidly than the unimplanted sidewalls. The reactive chemical species are removed from the substrate processing region and then the substrate is removed from the processing region.

Reference is now made to FIG. **5** which is a flow chart of anisotropic etch process **501**. In this example, device **201** comprises a gap in a silicon oxide layer **210** of a patterned substrate and a mask **220**. Identifier **210** will again be used to represent silicon oxide for anisotropic etch process **501**. Silicon oxide layer **210-1** is a less dense CVD silicon oxide grown using ozone and tetraethylorthosilicate (TEOS) in a plasma-free reactor. CVD silicon oxide layer **210-1** is unimplanted at the start of anisotropic etch process **501** and may be succinctly referred to as CVD silicon oxide or O_3-TEOS silicon oxide. FIG. **2**A shows device **201** before the start of anisotropic etch process **501**.

The patterned substrate is placed in an ion implant chamber in operation **505**. Hydrogen (H_2) is then flowed into the biased plasma implant chamber. The hydrogen is excited in a capacitively-coupled plasma disposed next to the patterned substrate and the patterned substrate is bombarded with hydrogen (operation **510**). A DC voltage may be applied to assist in the acceleration of hydrogen toward the patterned substrate and to ion implant the floor of the gap in CVD silicon oxide layer **210-1** to create an ion implanted portion **211** of CVD silicon oxide layer **210-2** as shown in FIG. **2**B.

Generally speaking, a hydrogen-containing precursor may be used to augment or replace the hydrogen (H_2) of anisotropic etch process **501**. The hydrogen-containing precursor may be carbon-free, halogen-free, chlorine-free and/or fluorine-free in embodiments. According to embodiments, the hydrogen-containing precursor may consist only of hydrogen. The radical-hydrogen is the portion of the plasma effluents produced from the excitation of the hydrogen-containing precursor in the local plasma of the ion implant chamber. The radical-hydrogen may be carbon-free, halogen-free, chlorine-free or fluorine-free according to embodiments.

The patterned substrate is then placed in a substrate processing region in operation **520**. A flow of nitrogen trifluoride (or another fluorine-containing precursor) is then introduced into a remote plasma region (operation **530** of anisotropic etch process **501**) where the nitrogen trifluoride is excited in a remote plasma struck within the remote plasma region. The remote plasma region may be devoid of hydrogen during operations **530-550** of anisotropic etch process **501**.

The plasma effluents formed in the remote plasma region are flowed into the substrate processing region (operation

540) and the patterned substrate is anisotropically etched (operation **550**). The plasma effluents may enter the substrate processing region through through-holes in a showerhead which separates the remote plasma region from the substrate processing region. Ion implanted CVD silicon oxide portion **211** of CVD silicon oxide layer **210-2** is implanted with hydrogen and etches more slowly than the sidewalls which have not been implanted to the same degree. FIG. **2**C shows the profile of device **201** following operation **550**. Hydrogen implantation may be increasing the density of CVD silicon oxide which may be suppressing the etch rate of the bottom portion of the gap (ion implanted CVD silicon oxide portion **211**). The reactive chemical species are removed from the substrate processing region and then the substrate is removed from the processing region.

The rectangular cavern created by the exemplary etch processes **101**, **401** and **501** may provide a number of engineering benefits. Each allows the geometry of a trench to be customized to, perhaps, deposit a dissimilar material which applies a precise stress to optimize the performance of an device's active area. The methods described herein allow the physical dimensions of a gap to be selected to optimize a variety of performance characteristics. The anisotropic etch processes **401** depicted in FIG. **4** may be repeated in the form of ion implant-etch cycles. For example, implant-etch-implant-etch sequences and implant-etch-implant-etch-implant-etch sequences are possible. Breaking up the etch process into multiple implant-etch cycles allows anisotropic etch process **401** to remove the implanted portion of bottom gap material and then recreate a new implanted portion before removing the new implanted portion with the remote plasma etch operation. Operation **410** enables implantation of a certain depth of the gap material (thermal silicon oxide in the example). Etching at operation **450** beyond the implanted thermal silicon oxide portion will lower the effective etch rate of the combined process. Multiple cycles may be desirable to allow each cycle to avoid etching beyond the implanted silicon portion.

The flow of the fluorine-containing precursor may further include one or more relatively inert gases such as He, N_2, Ar. The inert gas can be used to improve plasma stability plasma strikability and/or 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 gases may be used to control etch rates and etch selectivity.

In embodiments, the fluorine-containing gas (e.g. NF_3) is supplied at a flow rate of between about 5 sccm (standard cubic centimeters per minute) and 400 sccm, He at a flow rate of between about 0 slm (standard liters per minute) and 3 slm, and N_2 at a flow rate of between about 0 slm and 3 slm. One of ordinary skill in the art would recognize that other gases and/or flows may be used depending on a number of factors including processing chamber configuration, substrate size, and/or geometry and layout of features being etched. The temperature of the substrate may be between about −20° C. and about 200° C. during both the ion implantation and the etching processes described herein.

The gaps in the patterned substrates etched according to the embodiments described herein may be a via or a trench. The via may be a low aspect ratio gap and may be, e.g., circular as viewed from above the patterned substrate laying flat. The trench may be a high aspect ratio gap with a length to width ratio of at least 10:1. A width of the via may be less than 50 nm, less than 40 nm, less than 30 nm or less than 20 nm according to embodiments. A depth of the via may be greater than 50 nm, greater than 60 nm, greater than 70 nm or greater than 80 nm in embodiments. The depth of the via may be increased by 10 nm while the width may be increased by less than 1 nm during the anisotropic etch processes described herein. Analogously, the width of the via may be increased by 10 nm while the depth may be increased by less than 1 nm during the anisotropic etch processes described herein according to embodiments. A width of the trench may be less than 70 nm, less than 50 nm, less than 40 nm or less than 30 nm in embodiments. A depth of the trench may be greater than 70 nm, greater than 80 nm, greater than 90 nm or greater than 100 nm according to embodiments. The depth of the trench may be increased by 10 nm while the width may be increased by less than 1 nm during the anisotropic etch processes described herein. Analogously, the width of the trench may be increased by 10 nm while the depth may be increased by less than 1 nm during the anisotropic etch processes described herein according to embodiments.

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. In embodiments, for example, the ion suppressor is used to filter etching plasma effluents en route from the remote plasma region 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.

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.

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 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 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 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. In point of contrast, the electron temperature during the anisotropic removal process may be greater than 0.5 eV, greater than 0.6 eV or greater than 0.7 eV according to embodiments.

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. 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 chamber 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 chamber plasma region during the creation of the excited plasma effluents do not deviate from the scope of "plasma-free" as used herein.

FIG. **3**A shows a cross-sectional view of an exemplary substrate processing chamber **1001** with a partitioned plasma generation region within the processing chamber. During film etching, a process gas may be flowed into chamber plasma region **1015** through a gas inlet assembly **1005**. A remote plasma system (RPS) **1002** may optionally be included in the system, and may process a first gas which then travels through gas inlet assembly **1005**. The process gas may be excited within RPS **1002** prior to entering chamber plasma region **1015**. Accordingly, the fluorine-containing precursor as discussed above, for example, may pass through RPS **1002** or bypass the RPS unit in embodiments.

A cooling plate **1003**, faceplate **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 embodiments. Pedestal **1065** may have a heat exchange channel through which a heat exchange fluid flows to control the temperature of the substrate. 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. Pedestal **1065** may also be resistively heated to relatively high temperatures, such as between 100° C. and 1100° C., using an embedded heater element.

Exemplary configurations may include having the gas inlet assembly **1005** open into a gas supply region **1058** partitioned from the chamber plasma region **1015** by faceplate **1017** so that the gases/species flow through the holes in the faceplate **1017** into the chamber plasma region **1015**. Structural and operational features may be selected to prevent significant backflow of plasma from the chamber plasma region **1015** back into the supply region **1058**, gas inlet assembly **1005**, and fluid supply system **1010**. The structural features may include the selection of dimensions and cross-sectional geometries of the apertures in faceplate **1017** to deactivate back-streaming plasma. The operational features may include maintaining a pressure difference between the gas supply region **1058** and chamber plasma region **1015** that maintains a unidirectional flow of plasma through the showerhead **1025**. The faceplate **1017**, or a conductive top portion of the chamber, and showerhead **1025** are shown with an insulating ring **1020** located between the features, which allows an AC potential to be applied to the faceplate **1017** relative to showerhead **1025** and/or ion suppressor **1023**. The insulating ring **1020** may be positioned between the faceplate **1017** and the showerhead **1025** and/or ion suppressor **1023** enabling a capacitively coupled plasma (CCP) to be formed in the chamber plasma region.

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 controlled 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 chamber 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 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 suppression element **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.

Plasma power can be of a variety of frequencies or a combination of multiple frequencies. In the exemplary processing system the plasma may be provided by RF power delivered to faceplate **1017** relative to ion suppressor **1023** and/or showerhead **1025**. The RF power may be between about 10 watts and about 5000 watts, between about 100 watts and about 2000 watts, between about 200 watts and about 1500 watts, or between about 200 watts and about 1000 watts in embodiments. The RF frequency applied in the exemplary processing system may be low RF frequencies less than 200 kHz, high 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.

A precursor, for example a fluorine-containing precursor and (optionally) a supplementary radical precursor, may be flowed into substrate processing region **1033** by embodiments of the showerhead described herein. Excited species derived from the process gas in chamber plasma region **1015** may travel through apertures in the ion suppressor **1023**, and/or showerhead **1025** and react with (optionally) a supplementary unexcited precursor flowing into substrate processing region **1033** from a separate portion of the showerhead. Alternatively, if all precursor species are being excited in chamber plasma region **1015**, no supplementary unexcited precursors may be flowed through the separate portion of the showerhead. Little or no plasma may be present in substrate processing region **1033** during the remote plasma etch process. Excited derivatives of the precursors may combine in the region above the substrate and/or on the substrate to etch structures or remove species from the substrate.

The supplementary radical precursor may be a hydrogen-containing precursor (e.g. hydrogen H_2) to improve the etch selectivity of silicon (e.g. polysilicon) according to embodiments. The radical-supplementary precursor may be referred to as radical-hydrogen in this case. The supplementary unexcited precursor may be an alcohol or moisture (H_2O) to improve the etch selectivity of silicon oxide in embodiments.

The processing gases may be excited in chamber plasma region **1015** and may be passed through the showerhead

1025 to substrate processing region **1033** in the excited state. While a plasma may be generated in substrate processing region **1033**, a plasma may alternatively not be generated in the processing region. In one example, the only excitation of the processing gas or precursors may be from exciting the processing gases in chamber plasma region **1015** to react with one another in substrate processing region **1033**. As previously discussed, this may be to protect the structures patterned on substrate **1055**.

FIG. **6**B shows a detailed view of the features affecting the processing gas distribution through faceplate **1017**. The gas distribution assemblies such as showerhead **1025** for use in the processing chamber section **1001** may be referred to as dual channel showerheads (DCSH) and are additionally detailed in the embodiments described in FIG. **6**A as well as FIG. **6**C herein. The dual channel showerhead may provide for etching processes that allow for separation of etchants outside of the processing region **1033** to provide limited interaction with chamber components and each other prior to being delivered into the processing region.

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 coupling of the plates may be so as to provide first fluid channels **1019** through the upper and lower plates, and 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 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 gas distribution assembly **1025**. Although the exemplary system of FIGS. **6**A-**6**C includes a dual-channel showerhead, it is understood that alternative distribution assemblies may be utilized that maintain first and second precursors fluidly isolated prior to substrate processing region **1033**. For example, a perforated plate and tubes underneath the plate may be utilized, although other configurations may operate with reduced efficiency or not provide as uniform processing as the dual-channel showerhead described.

In the embodiment shown, showerhead **1025** may distribute via first fluid channels **1019** process gases which contain plasma effluents upon excitation by a plasma in chamber plasma region **1015**. In embodiments, the process gas introduced into RPS **1002** and/or chamber plasma region **1015** may contain fluorine, e.g., NF_3. The process gas may also include a carrier gas such as helium, argon, nitrogen (N_2), etc. Plasma effluents may include ionized or neutral derivatives of the process gas and may also be referred to herein as a radical-fluorine precursor referring to the atomic constituent of the process gas introduced into substrate processing region **1033**.

FIG. **6**C is a bottom view of a showerhead **1025** for use with a processing chamber in embodiments. Showerhead **1025** corresponds with the showerhead shown in FIG. **6**A. Through-holes **1031**, which show a view of first fluid channels **1019**, may have a plurality of shapes and configurations to control and affect the flow of precursors through the showerhead **1025**. Small holes **1027**, which show a view of second fluid channels **1021**, may be distributed substantially evenly over the surface of the showerhead, even amongst the through-holes **1031**, which may help to provide more even mixing of the precursors as they exit the showerhead than other configurations.

The chamber plasma region **1015** or a region in an RPS may be referred to as a remote plasma region. In embodiments, the radical-fluorine precursor and the optional radical-supplementary precursor are created in the remote plasma region and travel into the substrate processing region to combine with an optional supplementary unexcited precursor. In embodiments, the optional supplementary unexcited precursor is excited only by the radical-fluorine and the optional radical-supplementary precursor. Plasma power may essentially be applied only to the remote plasma region in embodiments to ensure that the radical-fluorine and the optional radical-supplementary precursor provide the dominant excitation.

Embodiments of the dry etch systems may be incorporated into larger fabrication systems for producing integrated circuit chips. FIG. **7** shows one such processing system (mainframe) **1101** of deposition, etching, baking, and curing chambers in embodiments. In the figure, a pair of front opening unified pods (load lock chambers **1102**) supply substrates of a variety of sizes that are received by robotic arms **1104** and placed into a low pressure holding area **1106** before being placed into one of the substrate processing chambers **1108***a-f*. A second robotic arm **1110** may be used to transport the substrate wafers from the holding area **1106** to the substrate processing chambers **1108***a-f* and back. Each substrate processing chamber **1108***a-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.

Nitrogen trifluoride (or another fluorine-containing precursor) may be flowed into chamber plasma region **1020** at rates between about 1 sccm and about 400 sccm, between about 3 sccm and about 250 sccm or between about 5 sccm and about 100 sccm in embodiments. A supplementary radical precursor (optional) may be flowed into chamber plasma region **1020** at rates between about 10 sccm and about 400 sccm, between about 30 sccm and about 250 sccm or between about 50 sccm and about 150 sccm in embodiments. A supplementary unexcited precursor (optional) may be flowed into substrate processing region **1070** at rates between about 5 sccm and about 100 sccm, between about 10 sccm and about 50 sccm or between about 15 sccm and about 25 sccm according to embodiments. The flow rate ratio of the supplementary radical precursor to the fluorine-containing precursor may be greater than 4, greater than 6 or greater than 10 according to embodiments. The flow rate ratio of the supplementary radical precursor to the fluorine-containing precursor may be less than 40, less than 30 or less than 20 in embodiments. Upper limits may be combined with lower limits according to embodiments.

The showerhead may be referred to as a dual-channel showerhead as a result of the two distinct pathways into the substrate processing region. The radical-fluorine and any supplementary radical precursor may be flowed through the through-holes in the dual-zone showerhead and any unexcited precursor may pass through separate zones in the dual-zone showerhead. The separate zones may open into the substrate processing region but not into the remote plasma region as described above.

Combined flow rates of plasma effluents into the substrate processing region may account for 0.05% to about 20% by volume of the overall gas mixture; the remainder being carrier gases. The fluorine-containing precursor and any supplementary radical precursor flowed into the remote plasma region have the same volumetric flow ratio as the plasma effluents in embodiments. In the case of the fluorine-containing precursor, a purge or carrier gas may be first initiated into the remote plasma region before those of the fluorine-containing gas and the any supplementary radical precursor to stabilize the pressure within the remote plasma region.

In the preceding description, for the purposes of explanation, numerous details have been set forth to provide an understanding of various embodiments of the present invention. It will be apparent to one skilled in the art, however, that certain embodiments may be practiced without some of these details, or with additional details.

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 silicon but may include minority concentrations of other elemental constituents such as nitrogen, oxygen, hydrogen or carbon. Exposed "silicon" may consist of or consist essentially of silicon. Exposed "silicon nitride" of the patterned substrate is predominantly Si_3N_4 but may include minority concentrations of other elemental constituents such as oxygen, hydrogen and carbon. "Exposed silicon nitride" may consist essentially of or consist of silicon and nitrogen. Exposed "silicon oxide" of the patterned substrate is predominantly SiO_2 but may include minority concentrations of other elemental constituents such as nitrogen, hydrogen and carbon. In embodiments, silicon oxide films etched using the methods taught herein consist essentially of or consist of silicon and oxygen. Exposed "tungsten" of the patterned substrate is predominantly tungsten but may include minority concentration of other elemental constituents such as nitrogen, silicon, oxygen, hydrogen and carbon. In embodiments, tungsten films consist essentially of or consist of tungsten. Exposed "tungsten oxide" of the patterned substrate is predominantly tungsten and oxygen but may include minority concentration of other elemental constituents such as nitrogen, silicon, hydrogen and carbon. In embodiments, tungsten oxide films consist essentially of or consist of tungsten and oxygen. Tungsten oxide and tungsten are examples of metal-containing films as used herein. The definition of other metal-containing films such as "aluminum" and "aluminum oxide" follow analogous definitions and will now be understood from these representative examples.

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. "Radical-hydrogen" and other radical precursors follow analogous definitions and will now be understood from these representative examples. "Radical-oxygen-hydrogen" follows an analogous definition. 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.

The term "gap" is used throughout with no implication that the etched geometry has a large horizontal aspect ratio. Viewed from above the surface, gaps may appear circular, oval, polygonal, rectangular, or a variety of other shapes. A gap 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 gap (as viewed from above) which may or may not be filled with metal to form a vertical electrical connection. The term "trench" is used to refer to a high aspect ratio gap (as viewed from above) with an aspect ratio of at least 10:1 (length: width). 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.

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.

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.

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.

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.

The invention claimed is:

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

ion implanting the patterned substrate, wherein ion implanting the patterned substrate comprises ion implanting an exposed undoped bottom portion of a gap in the patterned substrate with carbon, wherein both the exposed undoped bottom portion and an exposed undoped sidewall portion of the gap comprise silicon, wherein the exposed undoped sidewall portion and the exposed undoped bottom portion are formed from a single material having the same stoichiometry prior to ion implantation, and wherein the ion implantation dopes the exposed undoped bottom portion to form an exposed doped bottom portion but the ion implantation does not dope the exposed undoped sidewall portion;

placing the patterned substrate in a substrate processing region of a substrate processing chamber;

combining a fluorine-containing precursor with a hydrogen-containing precursor in a remote plasma region fluidly coupled to the substrate processing region by way of a showerhead while forming a remote plasma in the remote plasma region to produce plasma effluents; and

anisotropically etching the patterned substrate such that the exposed undoped sidewall portion etches at a greater etch rate than the exposed doped bottom portion.

2. The method of claim **1** wherein the fluorine-containing precursor is nitrogen trifluoride and the hydrogen-containing precursor is molecular hydrogen (H_2).

3. The method of claim **1** wherein the exposed undoped sidewall portion etches more rapidly than the exposed doped bottom portion by a ratio of at least 25:1.

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

ion implanting the patterned substrate, wherein ion implanting the patterned substrate comprises ion implanting an exposed bottom portion of a gap in a silicon oxide layer on the patterned substrate, wherein the exposed bottom portion and an exposed sidewall portion of the gap each comprise silicon oxide;

placing the patterned substrate in a substrate processing region of a substrate processing chamber;

flowing a fluorine-containing precursor into a remote plasma region fluidly coupled to the substrate processing region by way of a showerhead while forming a remote plasma in the remote plasma region to produce plasma effluents;

flowing a hydrogen-and-oxygen-containing precursor into the substrate processing region without first passing the hydrogen-and-oxygen-containing precursor through the remote plasma region, wherein the hydrogen-and-oxygen-containing precursor comprises an O—H bond;

combining the plasma effluents with the hydrogen-and-oxygen-containing precursor in the substrate processing region; and

anisotropically etching the patterned substrate such that the exposed sidewall portion of the gap and the exposed bottom portion of silicon oxide etch at different etch rates from one another.

5. The method of claim **4** wherein the operation of anisotropically etching the patterned substrate etches the exposed sidewall portion more rapidly than the exposed bottom portion.

6. The method of claim **4** wherein the operation of anisotropically etching the patterned substrate etches the exposed sidewall portion more slowly than the exposed bottom portion.

7. The method of claim **6** wherein the exposed sidewall portion etches more rapidly than the exposed bottom portion by a ratio of at least 15:1.

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

forming a gap in a material layer on the patterned substrate, wherein forming the gap forms an exposed undoped bottom portion of the gap and an exposed undoped sidewall portion of the gap having the same material composition upon formation;

ion implanting the patterned substrate, wherein ion implanting the patterned substrate comprises ion implanting the exposed undoped bottom portion of the gap to form an exposed doped bottom portion of the gap; and

anisotropically etching the patterned substrate such that the exposed undoped sidewall portion and the exposed doped bottom portion etch at different etch rates from one another.

9. The method of claim **8** wherein the operation of anisotropically etching the patterned substrate etches the exposed undoped sidewall portion more rapidly than the exposed doped bottom portion.

10. The method of claim **8** wherein the operation of anisotropically etching the patterned substrate etches the exposed undoped sidewall portion more slowly than the exposed doped bottom portion.

11. The method of claim **8** wherein the operation of ion implanting the patterned substrate comprises accelerating ions vertically into the gap on the patterned substrate.

12. The method of claim **8** wherein the operation of anisotropically etching the patterned substrate is a dry-etch process.

13. The method of claim **8** wherein the operation of ion implanting the patterned substrate is a local plasma process.

14. The method of claim **8** wherein the material layer is a metal-containing layer or a silicon-containing layer.

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