



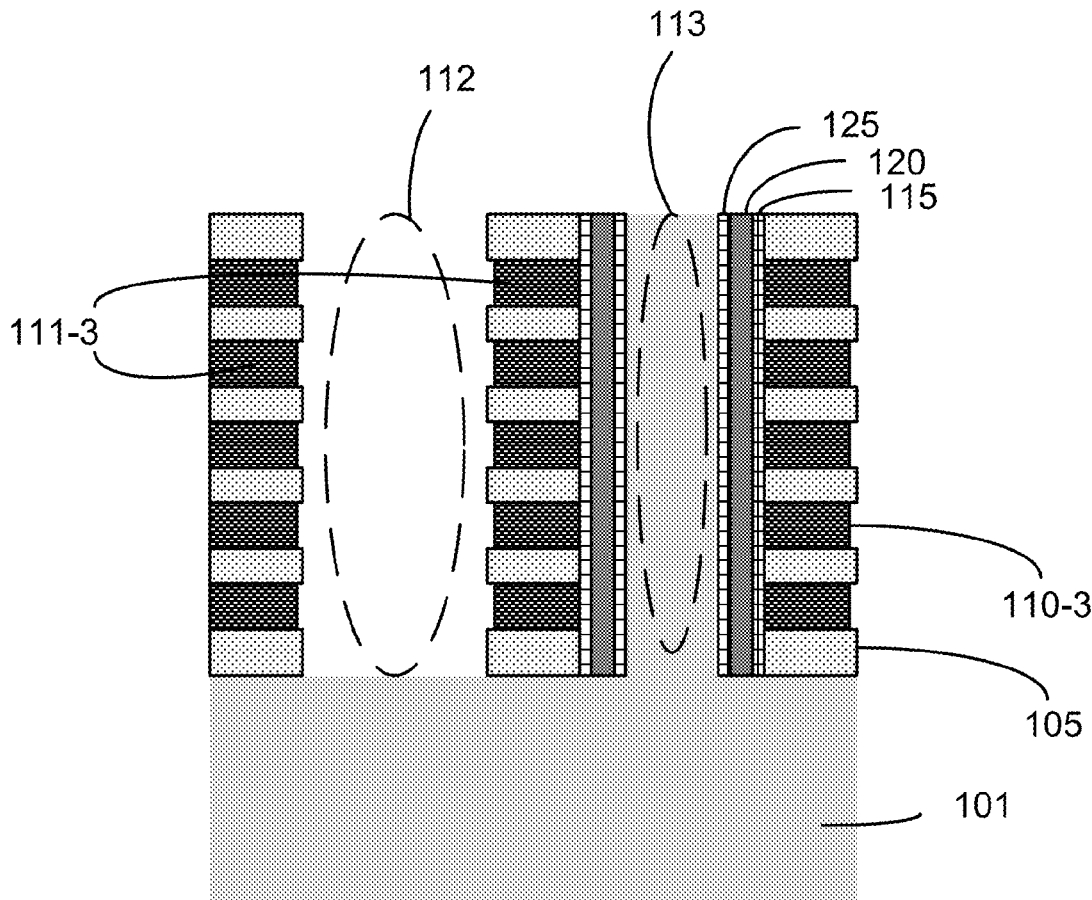
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(19) **United States**(12) **Patent Application Publication****Liu et al.**(10) **Pub. No.: US 2017/0110475 A1**(43) **Pub. Date: Apr. 20, 2017**(54) **HIGH ASPECT RATIO 3-D FLASH MEMORY DEVICE**(71) Applicant: **Applied Materials, Inc.**, Santa Clara, CA (US)(72) Inventors: **Jie Liu**, Sunnyvale, CA (US); **Xikun Wang**, Sunnyvale, CA (US); **Anchuan Wang**, San Jose, CA (US); **Nitin K. Ingle**, San Jose, CA (US)(73) Assignee: **Applied Materials, Inc.**, Santa Clara, CA (US)(21) Appl. No.: **15/393,105**(22) Filed: **Dec. 28, 2016****Related U.S. Application Data**

(62) Division of application No. 14/463,561, filed on Aug. 19, 2014, now Pat. No. 9,553,102.

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H01L 21/3213 (2006.01)**H01L 21/67** (2006.01)**H01L 27/11568** (2006.01)(52) **U.S. Cl.****CPC .. H01L 27/11582** (2013.01); **H01L 27/11568** (2013.01); **H01L 21/32136** (2013.01); **H01L 21/67225** (2013.01)(57) **ABSTRACT**

Methods of selectively etching tungsten from the surface of a patterned substrate are described. The etch electrically separates vertically arranged tungsten slabs from one another as needed, for example, in the manufacture of vertical flash memory devices. The tungsten etch may selectively remove tungsten relative to films such as silicon, polysilicon, silicon oxide, aluminum oxide, titanium nitride and silicon nitride. The methods include exposing electrically-shortened tungsten slabs to remotely-excited fluorine formed in a capacitively-excited chamber plasma region. The methods then include exposing the tungsten slabs to remotely-excited fluorine formed in an inductively-excited remote plasma system. A low electron temperature is maintained in the substrate processing region during each operation to achieve high etch selectivity.



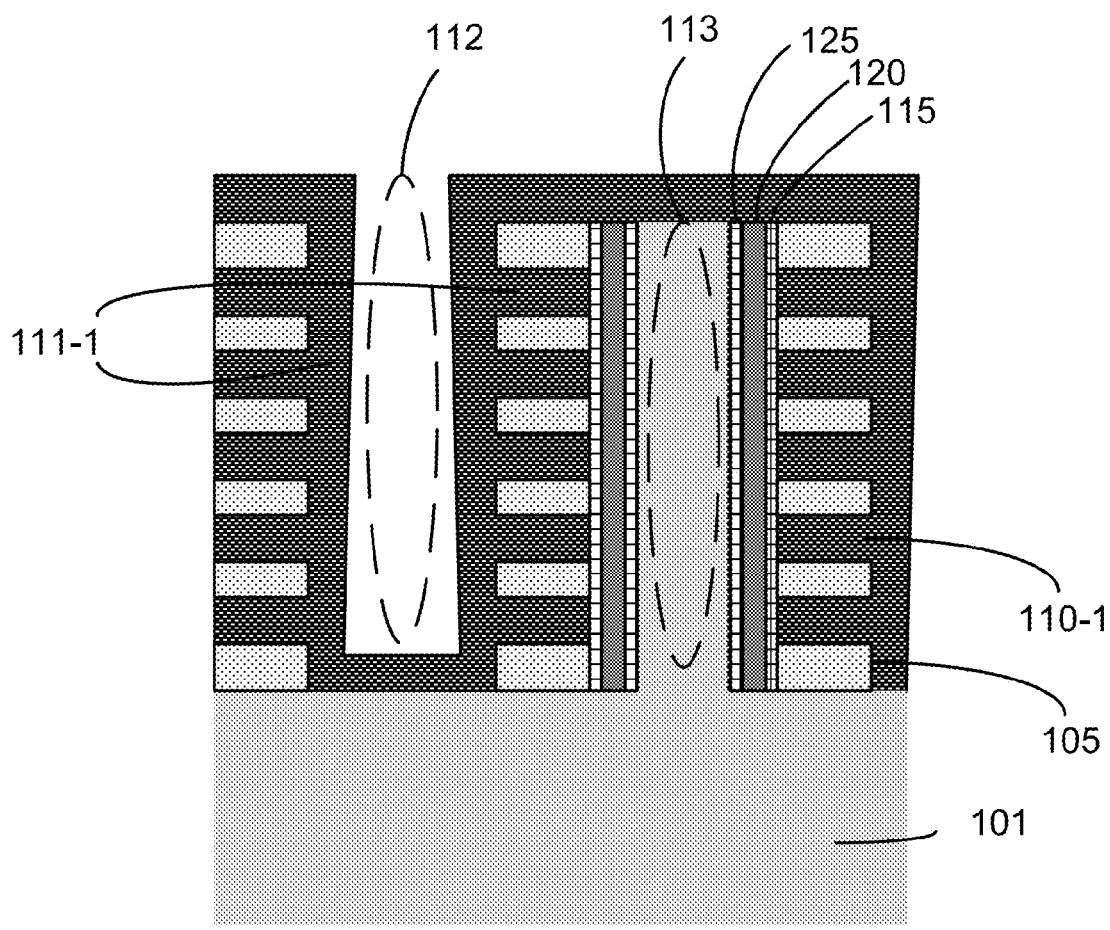


FIG. 1A

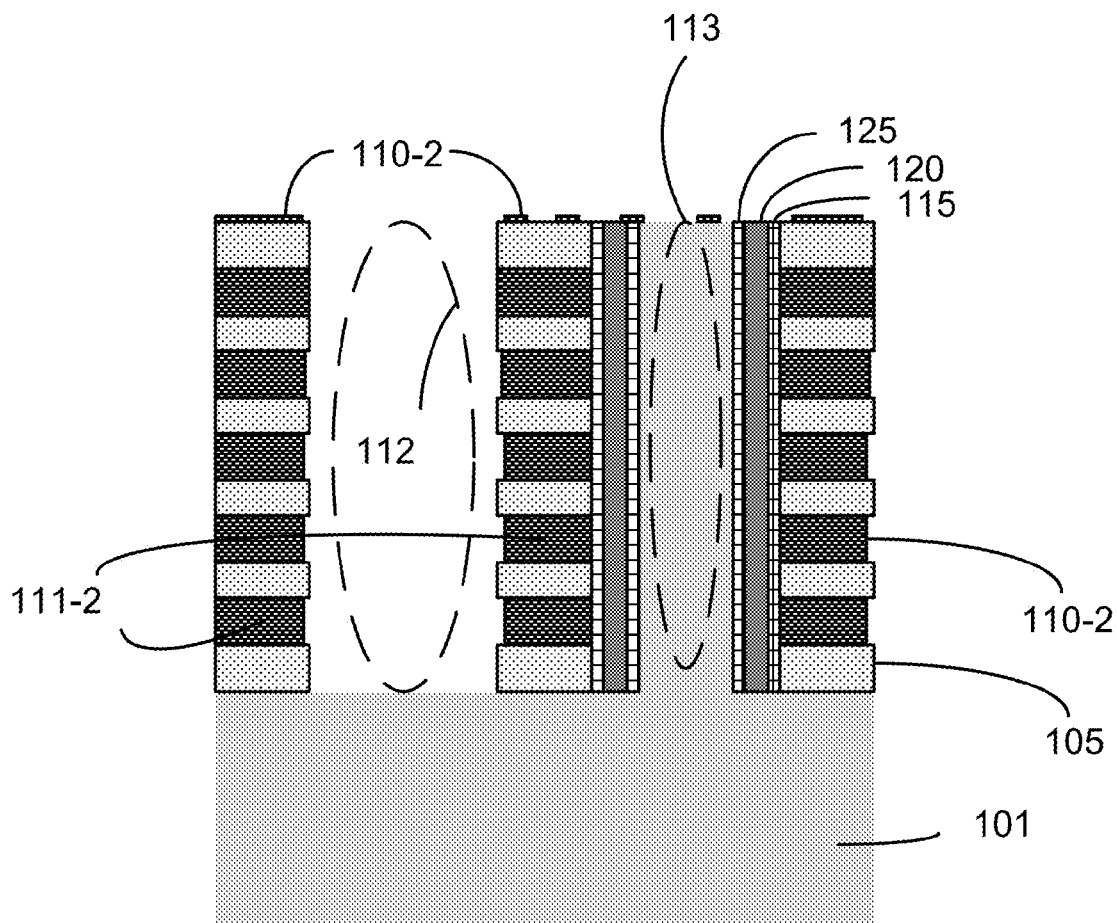


FIG. 1B

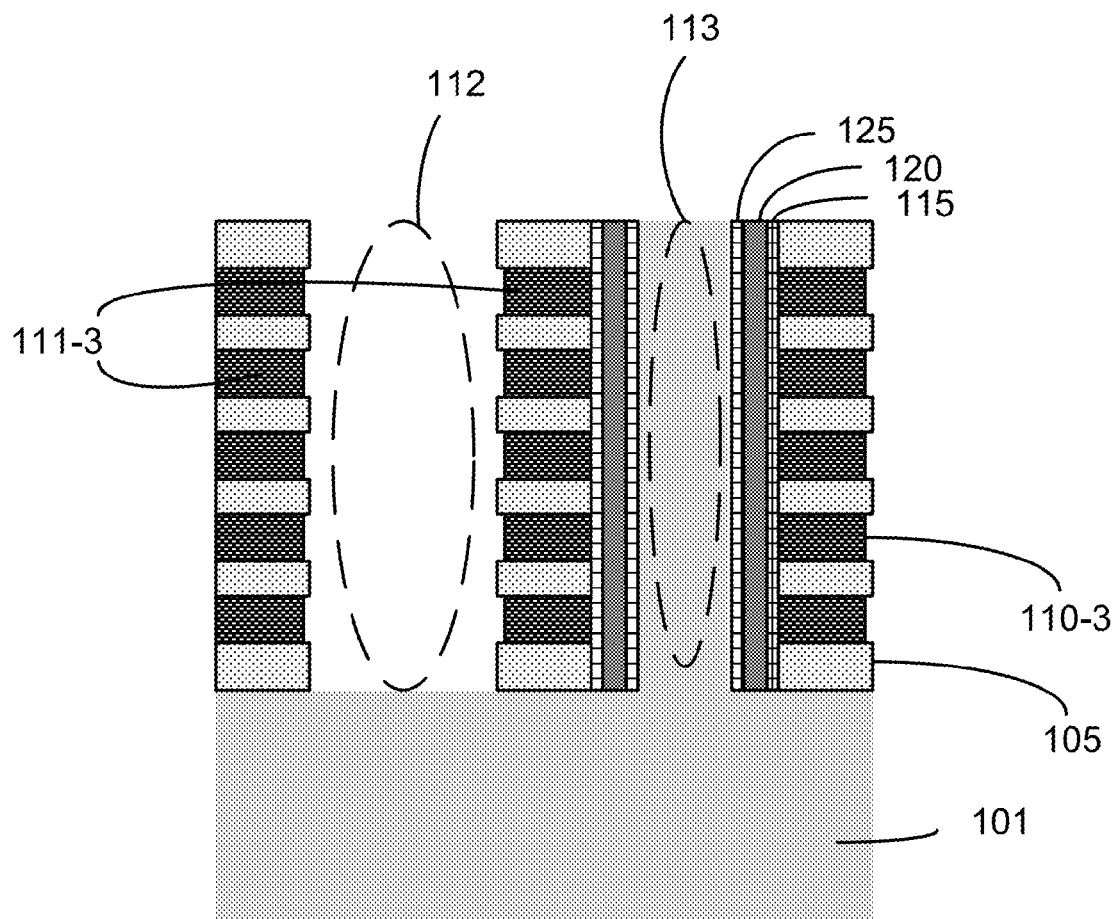


FIG. 1C

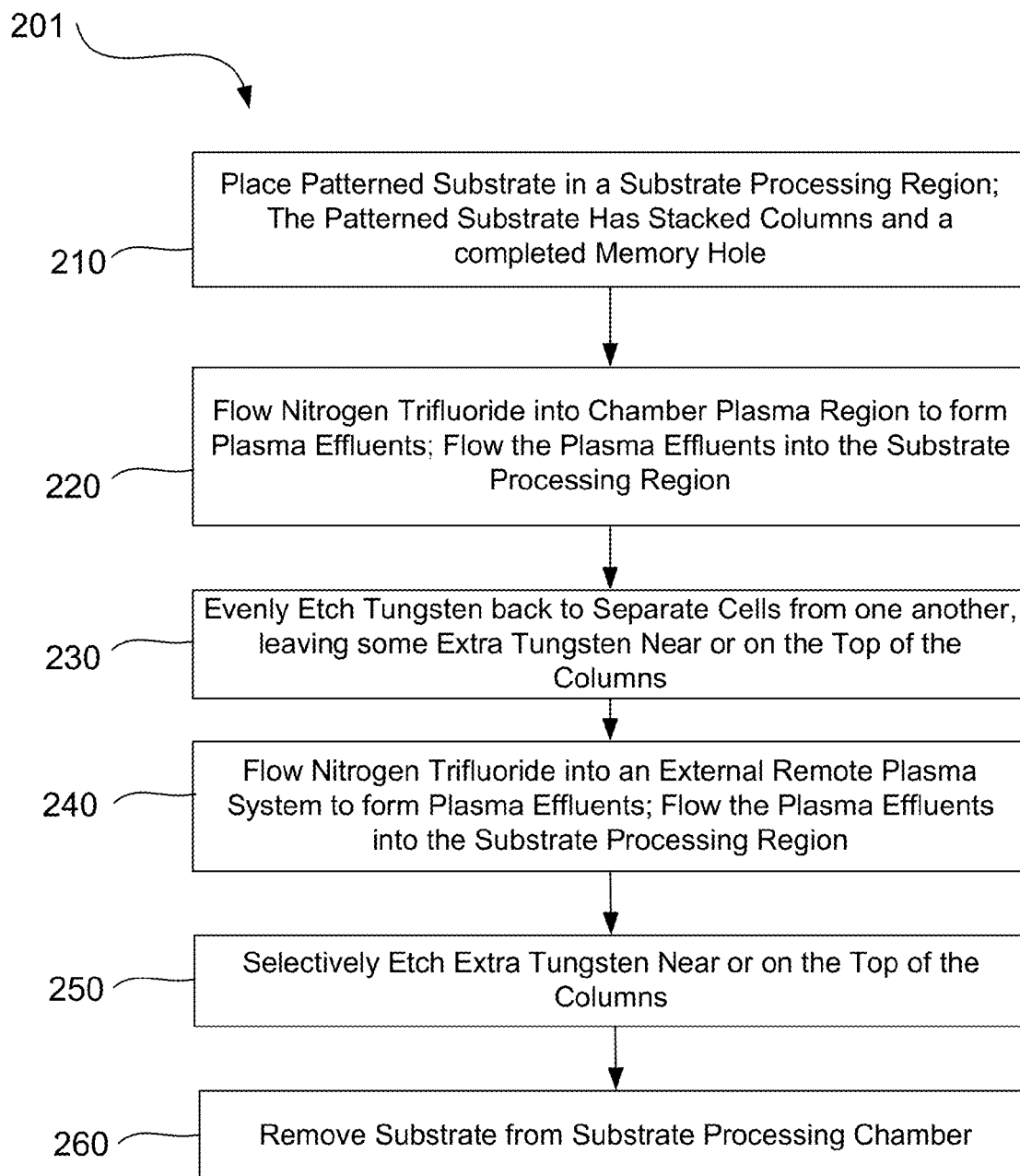
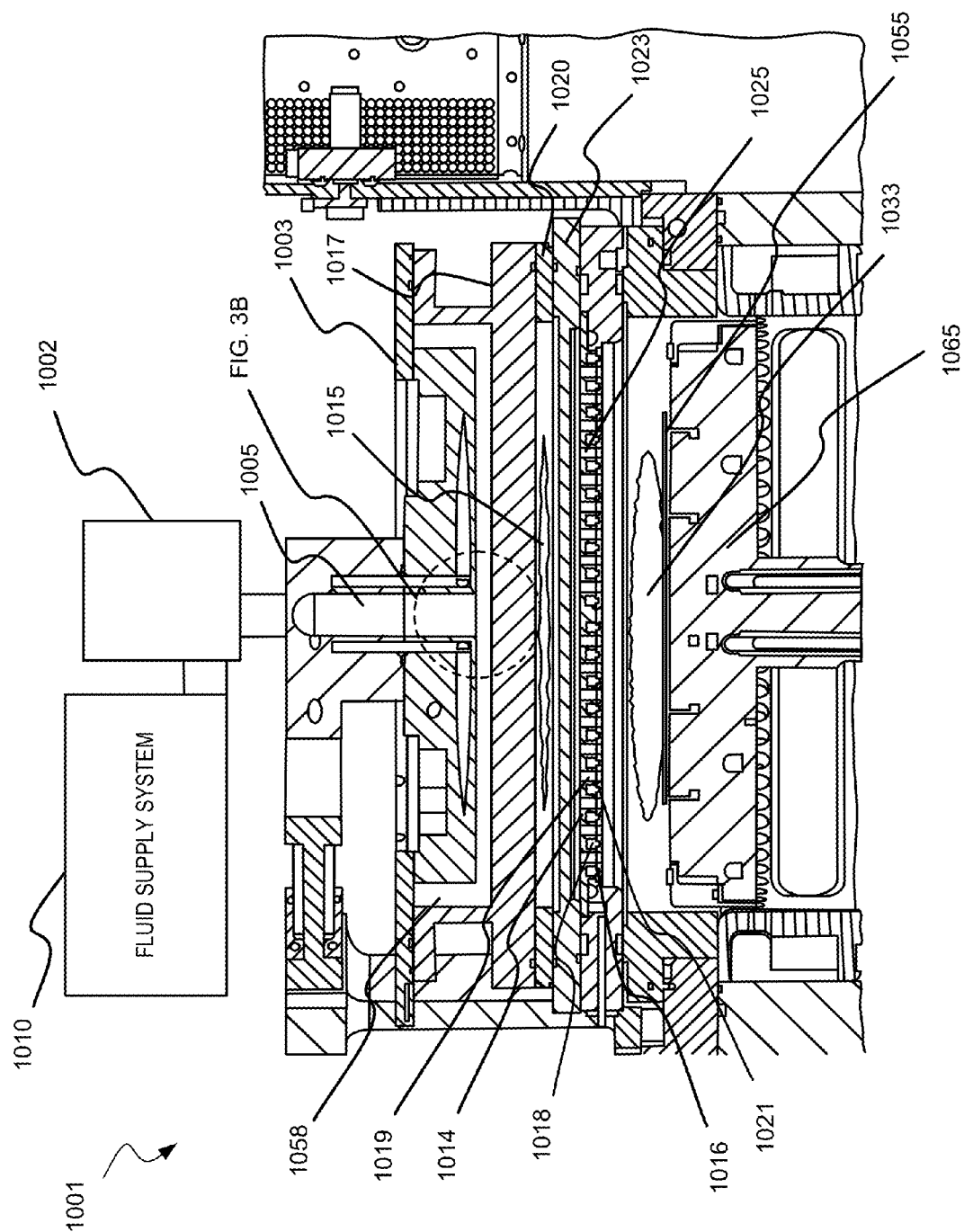


FIG. 2



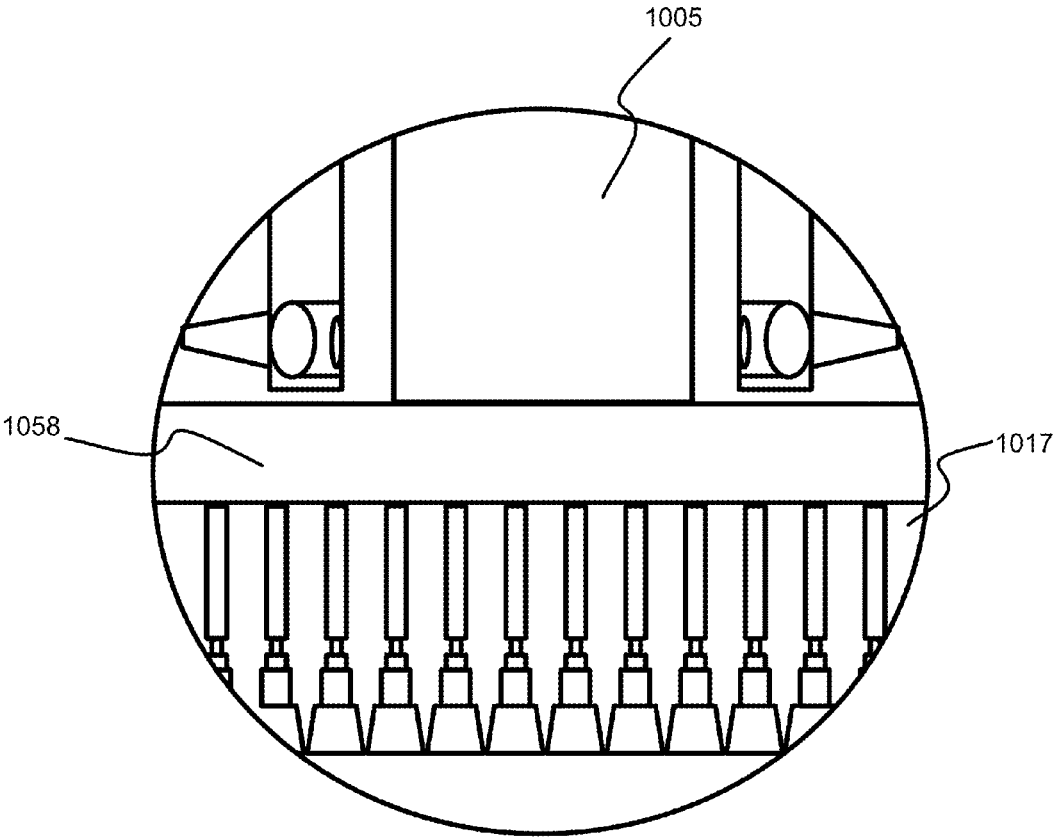


FIG. 3B

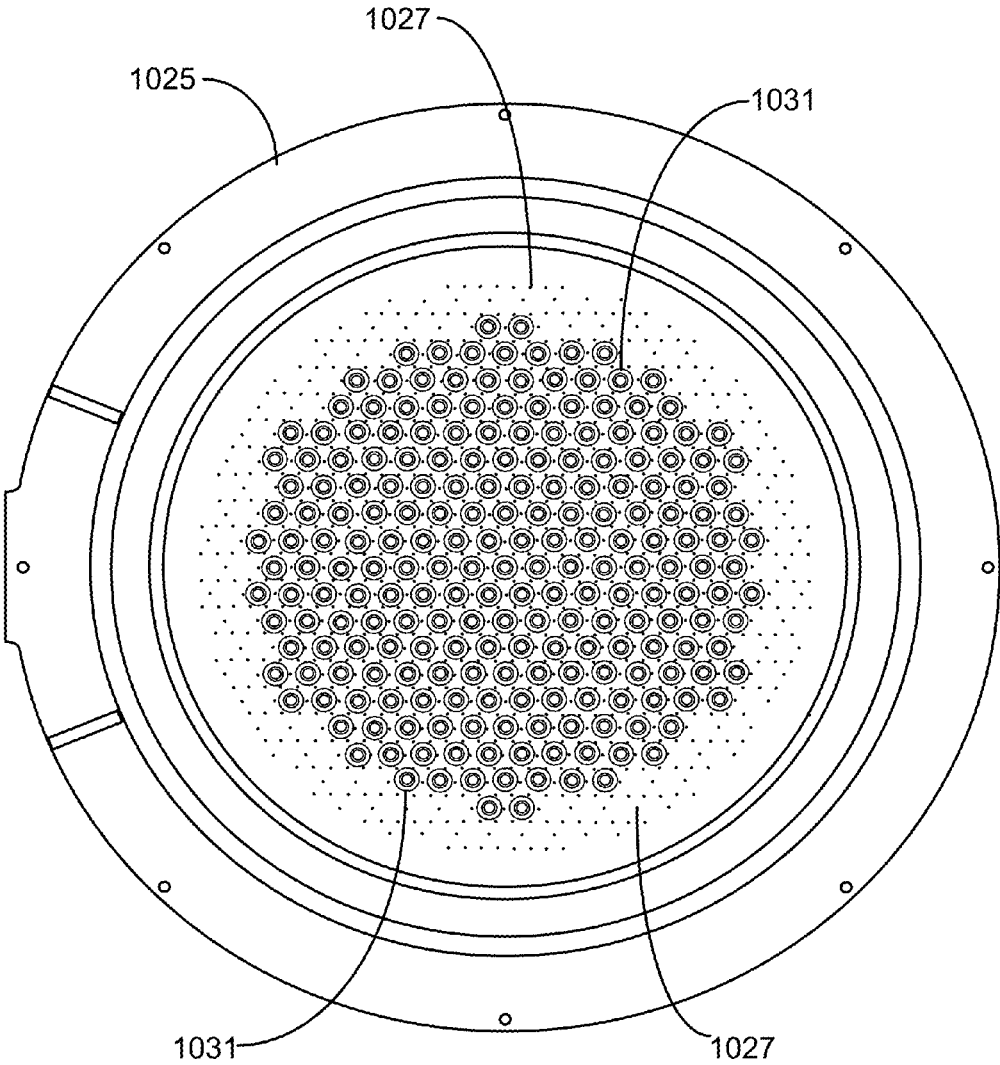


FIG. 3C

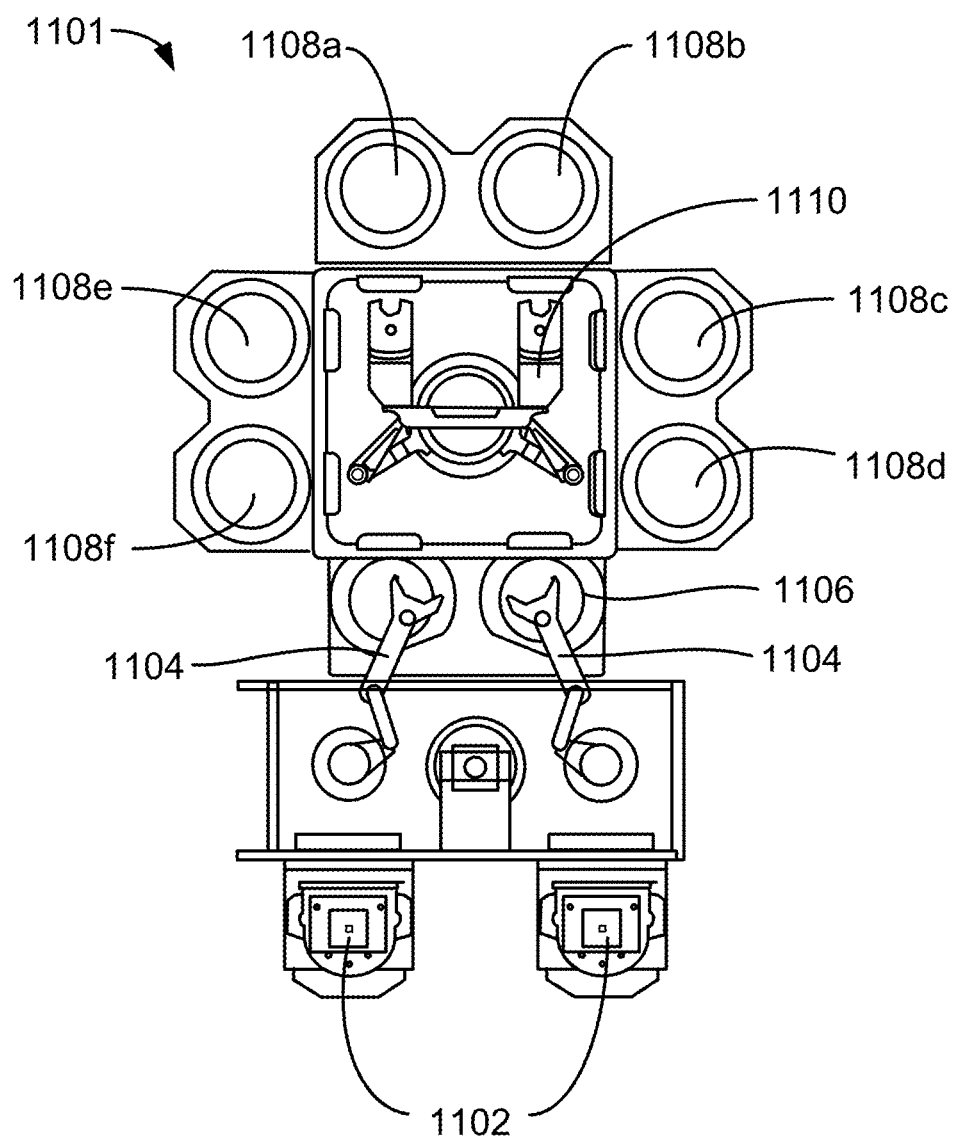


FIG. 4

HIGH ASPECT RATIO 3-D FLASH MEMORY DEVICE

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 14/463,561, filed Aug. 19, 2014, and titled "TUNGSTEN SEPARATION". The disclosure of Ser. No. 14/463,561 is hereby incorporated by reference in its entirety for all purposes.

FIELD

[0002] This invention relates to electrically separating a vertical stack of tungsten slabs.

BACKGROUND

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

[0004] Dry etch processes are increasingly 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 isotropically and selectively removed from a patterned substrate when the plasma effluents are flowed into the substrate processing region.

[0005] Methods are needed to broaden the utility of selective dry isotropic etch processes.

SUMMARY

[0006] Methods of selectively etching tungsten from the surface of a patterned substrate are described. The etch electrically separates vertically arranged tungsten slabs from one another as needed, for example, in the manufacture of vertical flash memory devices. The tungsten etch may selectively remove tungsten relative to films such as silicon, polysilicon, silicon oxide, aluminum oxide, titanium nitride and silicon nitride. The methods include exposing electrically-shortened tungsten slabs to remotely-excited fluorine formed in a capacitively-excited chamber plasma region. The methods then include exposing the tungsten slabs to remotely-excited fluorine formed in an inductively-excited remote plasma system. A low electron temperature is maintained in the substrate processing region during each operation to achieve high etch selectivity.

[0007] Embodiments include methods of etching a patterned substrate. The methods include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The patterned substrate includes electrically-shortened tungsten slabs arranged in at least one of two adjacent vertical columns. A trench is located between the two adjacent vertical columns. The methods further include flowing a first fluorine-containing precursor into a chamber plasma region within the substrate processing chamber and exciting the first fluorine-containing precursor in a first remote plasma in the chamber plasma region to produce first plasma effluents. The chamber plasma region is fluidly coupled with the substrate processing region through a showerhead and the first remote plasma is capacitively-coupled. The methods further include flowing the first plasma effluents into the substrate processing region through the showerhead and isotropically etching the electrically-shortened tungsten slabs. The methods further include flowing a second fluorine-containing precursor into a remote plasma system outside the substrate processing chamber and exciting the second fluorine-containing precursor in a second remote plasma in the remote plasma system to produce second plasma effluents. The second remote plasma is inductively-coupled. The methods further include flowing the second plasma effluents into the substrate processing region and anisotropically etching additional tungsten material.

[0008] Embodiments include methods of etching a patterned substrate. The methods include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The patterned substrate includes electrically-shortened tungsten slabs arranged in at least one of two adjacent vertical columns. A trench is located between the two adjacent vertical columns. The methods further include flowing a fluorine-containing precursor into a remote plasma system outside the substrate processing chamber and exciting the fluorine-containing precursor in an external remote plasma in the remote plasma system to produce intermediate plasma effluents. The methods further include flowing the intermediate plasma effluents into a chamber plasma region within the substrate processing chamber and exciting the intermediate plasma effluents in an internal remote plasma in the chamber plasma region to produce plasma effluents. The chamber plasma region is fluidly coupled with the substrate processing region through a showerhead. The methods further include flowing the first plasma effluents into the substrate processing region through the showerhead and selectively etching the electrically-shortened tungsten slabs. Selectively etching the electrically-shortened tungsten slabs electrically isolates the electrically-shortened tungsten slabs from one another to form electrically-isolated tungsten slabs.

[0009] Embodiments include 3-D flash memory devices. The 3-D flash memory devices include a plurality of electrically-isolated tungsten slabs arranged in two adjacent vertical columns. The plurality of electrically-isolated tungsten slabs include at least fifty tungsten slabs in each of the two adjacent vertical columns. The 3-D flash memory devices include a plurality of dielectric slabs interleaved with the plurality of electrically-isolated tungsten slabs. At least fifty of the plurality of electrically-isolated tungsten slabs are recessed between 1 nm and 7 nm laterally relative to the plurality of dielectric slabs.

[0010] A height of the two adjacent vertical columns may be greater than a gap between the two adjacent vertical columns by a factor of at least ten. The at least fifty of the plurality of electrically-isolated tungsten slabs may be recessed within 1 nm of an average recess of the at least fifty of the plurality of electrically-isolated tungsten slabs. Each of the at least fifty of the plurality of electrically-isolated tungsten slabs may be electrically-isolated from every other of the at least fifty of the plurality of electrically-isolated tungsten slabs. The plurality of electrically-shortened tungsten slabs may consist of tungsten and a barrier layer. A trench may be disposed between the two adjacent vertical columns. A depth of the trench may be greater than one micron. Each of the two adjacent vertical columns may include at least fifty tungsten slabs. The 3-D flash memory device may be formed by (1) initially forming a plurality of electrically-shortened tungsten slabs (2) isotropically etching the plurality of electrically-shortened tungsten slabs and (3) anisotropically etching additional tungsten material. The isotropically etching may leave a tungsten residue at the top of the two adjacent vertical columns, and the anisotropically etching may remove the tungsten residue from the top of the two adjacent vertical columns. Isotropically etching the plurality of electrically-shortened tungsten slabs in combination with anisotropically etching the additional tungsten material electrically may isolate the plurality of electrically-shortened tungsten slabs from one another to form the plurality of electrically-isolated tungsten slabs.

[0011] 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

[0012] 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.

[0013] FIGS. 1A, 1B and 1C are cross-sectional views of a patterned substrate during an tungsten etch process according to embodiments.

[0014] FIG. 2 is a flow chart of a tungsten etch process according to embodiments.

[0015] FIG. 3A shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

[0016] FIG. 3B shows a schematic cross-sectional view of a portion of a substrate processing chamber according to embodiments.

[0017] FIG. 3C shows a bottom view of a showerhead according to embodiments.

[0018] FIG. 4 shows a top view of an exemplary substrate processing system according to embodiments.

[0019] 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

[0020] Methods of selectively etching tungsten from the surface of a patterned substrate are described. The etch electrically separates vertically arranged tungsten slabs from one another as needed, for example, in the manufacture of vertical flash memory devices. The tungsten etch may selectively remove tungsten relative to films such as silicon, polysilicon, silicon oxide, aluminum oxide, titanium nitride and silicon nitride. The methods include exposing electrically-shortened tungsten slabs to remotely-excited fluorine formed in a capacitively-excited chamber plasma region. The methods then include exposing the tungsten slabs to remotely-excited fluorine formed in an inductively-excited remote plasma system. A low electron temperature is maintained in the substrate processing region during each operation to achieve high etch selectivity.

[0021] Vertical flash memory is referred to as 3-D flash memory and includes a plurality of electrically-isolated tungsten slabs arranged in at least one of two adjacent vertical columns. The number of slabs is increasing to increase the amount of storage per integrated circuit (IC). As the number of slabs is increased, the aspect ratio of a trench between two adjacent vertical columns is also increased. The tungsten is typically deposited by chemical vapor deposition (CVD) which results in a thicker layer of tungsten near the top of the two adjacent vertical columns compared with deep within the trench between the two adjacent vertical columns. The methods described herein were developed to compensate for this variability in tungsten film thickness while avoiding the use of a local plasma or a bias plasma power. No local plasma (e.g. no bias power) is applied to the substrate processing region during all etching operations described below. The etch selectivity is desirably increased by avoiding local plasma excitation (applying plasma power directly to the substrate processing region).

[0022] In order to better understand and appreciate embodiments of the invention, reference is now made to FIGS. 1A, 1B and 1C which are cross-sectional views of a 3-D flash memory cell during a method 201 (see FIG. 2) of forming the 3-D flash memory cells according to embodiments. In one example, a flash memory cell on patterned substrate 101 comprises alternatively stacked silicon oxide 105 and electrically-shortened tungsten slabs 111-1 in two adjacent columns. Tungsten 110-1 has recently been deposited into the stack, replacing sacrificial silicon nitride at the levels shown in FIG. 1A. FIG. 1A shows only five levels of tungsten to allow a more detailed discussion of the tungsten etch process 201. There may be fifty, more than fifty, more than seventy or more than ninety tungsten levels according to embodiments.

[0023] Tungsten deposited outside the stack shorts the tungsten levels together and becomes thicker near the top of FIG. 1A. Tungsten 110 may consist essentially of or consist of tungsten in embodiments. Tungsten 110 may consist of tungsten and a barrier layer in embodiments. The trench in which tungsten has been deposited may be called a “slit trench” 112 between the two adjacent columns to indicate that this trench has a much larger aspect ratio (longer into the page) than the memory hole 113 also shown in FIG. 1A. The aspect ratio (depth divided by width) of slit trench 112 may be greater than ten, fifteen or twenty according to embodiments. The depth is measured vertically and the width is measured horizontally in the plane of FIG. 1A. The sides of memory hole 113 are lined with a conformal ONO layer. The

ONO layer includes a silicon oxide layer **115** (often referred to as IPD or interpoly dielectric), a silicon nitride layer **120** (which serves as the charge trap layer) and a silicon oxide layer **125** (the gate dielectric). “Top” 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. The vertical memory hole **113** may be circular as viewed from above.

[0024] The conformal ONO layer may be used as an etch stop for the selective gas-phase tungsten etch and the structure of the conformal ONO layer will now be described. The tungsten barrier layer may also be used as an etch stop in embodiments. Silicon oxide layer **115** may be in contact with silicon nitride layer **120**, which may be in contact with silicon oxide layer **125** in embodiments. Silicon oxide layer **115** may contact stacked silicon oxide layers **105** and stacked tungsten layers **110** whereas silicon oxide layer **125** may contact silicon **101** (epitaxially grown) or a polysilicon layer in embodiments. Silicon oxide layer **115** may have a thickness less than or about 8 nm or less than 6 nm in embodiments. Silicon oxide layer **115** may comprise or consist of silicon and oxygen in embodiments. Silicon nitride **120** may have a thickness less than or about 8 nm or less than 6 nm in embodiments. Silicon nitride layer **120** may comprise or consist of silicon and nitrogen in embodiments. Silicon oxide layer **125** may have a thickness less than or about 8 nm or less than 6 nm in embodiments. Silicon oxide layer **125** may comprise or consist of silicon and oxygen in embodiments. The constrained geometries and thinness of the layers result in damage to the memory cell when liquid etchants are used, further motivating the gas-phase etching methods presented herein. Liquid etchants cannot be as completely removed and continue to etch. Liquid etchants may ultimately form and/or penetrate through pinholes and damage devices after manufacturing is complete.

[0025] Patterned substrate **101** as shown in FIG. 1A is delivered into a substrate processing chamber. Patterned substrate **101** is transferred into a first substrate processing region within a substrate processing chamber (operation **210**) to initiate method **201** of forming a flash memory cell. A flow of nitrogen trifluoride is then introduced into a chamber plasma region where the nitrogen trifluoride is excited in a first remote plasma struck within the chamber plasma region in operation **220**. The chamber plasma region is a remote plasma region in a compartment within the substrate processing chamber separated from the substrate processing region by an aperture or a showerhead. In general, a fluorine-containing precursor may be flowed into the chamber 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. Also in operation **220**, first plasma effluents formed in the chamber plasma region are flowed through the aperture or showerhead into the substrate processing region housing patterned substrate **101**.

[0026] According to embodiments, first plasma effluents may pass through a showerhead and/or ion suppressor to reduce the electron temperature (to reduce the ion concen-

tration) in the substrate processing region. Reduced electron temperatures as described subsequently herein have been found to increase the etch selectivity of tungsten compared to other exposed materials (e.g. silicon oxide or silicon nitride). Reduced electron temperatures apply to all tungsten etch operations described herein using either chamber plasma regions or remote plasma systems or the combination of the two in the integrated process described below. The low electron temperatures are described later in the specification (e.g. <0.5 eV). Operation **230** (and all etches described herein) may be referred to as a gas-phase etch to highlight the contrast with liquid etch processes. In operation **230**, tungsten **110-1** is selectively etched back to electrically separate electrically-shortened tungsten slabs **111-1** from one another to form intermediate electrically-isolated tungsten slabs **111-2**. The reactive chemical species are removed from the substrate processing region.

[0027] For the purposes of dimensions and other characterizations described herein, tungsten and tungsten slabs will be understood to include their barrier layers or other conformal layers useful for forming or using the tungsten or tungsten slabs. Exemplary tungsten barrier layers may include titanium, titanium nitride, tantalum or tantalum nitride in embodiments. The barrier layer may also provide etch stop functionality in the etch processes described herein.

[0028] In addition to the fluorine-containing precursor flowing into the remote plasma region, some additional precursors may be helpful to make the etch operation **230** selective of tungsten **110-1** of the electrically-shortened tungsten slabs **111-1**. An oxygen-containing precursor, e.g. molecular oxygen, may be flowed into the remote plasma region in combination or to combine with the fluorine-containing precursor in embodiments. Alternatively, or in combination, a hydrogen-containing precursor, e.g. molecular hydrogen, may be flowed into the remote plasma region in combination or to combine with the fluorine-containing precursor in embodiments. According to embodiments, the plasma effluents may pass through a showerhead and/or ion suppressor to reduce the electron temperature (to reduce the ion concentration) in the substrate processing region. Reduced electron temperatures as described subsequently herein have been found to increase the etch selectivity of tungsten **110-1** in the electrically-shortened tungsten slabs **111-1** compared to other exposed materials.

[0029] Alternatively, an unexcited precursor may be flowed directly into the second substrate processing region without first passing the unexcited precursor through any plasma prior to entering the second substrate processing region. The unexcited precursor may be excited only by the plasma effluents formed in the second remote plasma region. The unexcited precursor may be water or an alcohol (each of which contains an OH group) in embodiments. The unexcited precursor may also be N_xH_y (with x and y each greater than or equal to one), may be flowed directly into first substrate processing region without prior plasma excitation. For example, the unexcited precursor may be ammonia in embodiments. The presence of the unexcited precursor just described may increase low-quality silicon oxide selectivity for etch operation **250**. As before, the plasma effluents may pass through a showerhead and/or ion suppressor to reduce the electron temperature (to reduce the ion concentration) in the substrate processing region prior to combination with unexcited N_xH_y or OH group precursor. All the additives

just described may also be present in all operations described herein for etching tungsten (e.g. operation 220 and operation 240 described elsewhere).

[0030] Operation 220 may include applying energy to the fluorine-containing precursor while in the chamber plasma region to generate the plasma effluents. 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 or inductively coupled power). In an embodiment, the energy is applied using a capacitively-coupled plasma unit. The remote plasma source power may be between about 5 watts and about 5000 watts, between about 25 watts and about 1500 watts or between about 50 watts and about 1000 watts according to embodiments. The capacitively-coupled plasma unit may be disposed remote from a substrate processing region of the processing chamber. For example, the capacitively-coupled plasma unit and the plasma generation region may be separated from the substrate processing region by a showerhead. All process parameters (e.g. power above, temperature and pressure below) apply to all remote plasma embodiments herein unless otherwise indicated.

[0031] In operation 240, nitrogen trifluoride is introduced into a remote plasma system located outside the substrate processing chamber and a second remote plasma is struck to form second remote plasma effluents. Generally speaking, a fluorine-containing precursor may be used as described in operation 220. The second remote plasma effluents are flowed into the substrate processing region. Flowing the first plasma effluents into the substrate processing region occurs before flowing the second plasma effluents into the substrate processing region according to embodiments. In operation 250, second remote plasma effluents react with some extra tungsten preferentially present (leftover from operation 230) near the top of the columns. The leftover tungsten remains due to the isotropic nature of operation 230 and the higher initial thickness of tungsten near the top of the columns. The reactive chemical species and any process effluents are removed from the substrate processing region and then the substrate is removed from the substrate processing region (operation 260).

[0032] During operation 240, the second remote plasma in the remote plasma system may be generated using known techniques (e.g., radio frequency excitations, capacitively-coupled power, inductively coupled power). In an embodiment, the energy is applied using an inductively-coupled plasma unit. The second remote plasma power may be between 1000 watts and 15,000 watts, between 2,000 watts and 10,000 watts, between 3,000 watts and about 7,000 watts in embodiments. The first remote plasma power of operation 220 may be less than 15%, less than 12% or less than 10% of the second remote plasma power of operation 240 according to embodiments.

[0033] In all operations described herein, the fluorine-containing precursor (e.g. NF_3) is supplied at a flow rate of between about 5 sccm and about 500 sccm, between about 10 sccm and about 300 sccm, between about 25 sccm and about 200 sccm, between about 50 sccm and about 150 sccm or between about 75 sccm and about 125 sccm. The temperature of the patterned substrate may be between about -20°C . and about 200°C . during tungsten selective etches described herein. The patterned substrate temperature may

also be maintained at between 0°C . and about 60°C . or between about 15°C . and about 45°C . during all the gas-phase etching processes according to embodiments.

[0034] The process pressures described next apply to all the embodiments herein. The pressure within the substrate processing region is below 50 Torr, below 30 Torr, below 20 Torr, below 10 Torr or below 5 Torr. The pressure may be above 0.1 Torr, above 0.2 Torr, above 0.5 Torr or above 1 Torr in embodiments. In a preferred embodiment, the pressure while etching may be between 0.3 Torr and 10 Torr. However, any of the upper limits on temperature or pressure may be combined with lower limits to form additional embodiments.

[0035] An advantage of the processes described herein lies in the conformal rate of removal of tungsten from the substrate. The methods do not rely on any bias power (or at least do not rely on a high bias power) to accelerate etchants towards the substrate, which reduces the tendency of the etch processes to remove material on the tops and bottom of trenches before material on the sidewalls can be removed. As used herein, a conformal etch process refers to a generally uniform removal rate of material from a patterned surface regardless of the shape of the surface. The surface of the layer before and after the etch process are generally parallel. A person having ordinary skill in the art will recognize that the etch process likely cannot be 100% conformal and thus the term “generally” allows for acceptable tolerances.

[0036] Operation 230 may isotropically etch the electrically-shortened tungsten slabs 111-1 and may leave a tungsten residue at the top of the vertical columns in embodiments. Operation 230 may leave less of a recess near the top of the trench compared to the bottom according to embodiments. Operation 250 may then anisotropically etch additional tungsten material from near the top of the trench preferentially. For example, operation 250 may remove the tungsten residue from the top of the vertical columns or may increase the recess amount near the top of the trench to homogenize the recess amounts in embodiments. The electrically-isolated tungsten slabs 111-3 of the 3-D flash memory device formed using etch process 201 may each end up recessed within 1 nm of the average recess of the electrically-isolated tungsten slabs in embodiments. Operation 230 followed by operation 250 electrically isolates the electrically-shortened tungsten slabs 111-1 from one another to form electrically-isolated tungsten slabs 111-3 having more homogeneous recesses. Electrically-isolated tungsten slabs 111-3 may each be electrically-isolated from every other of the electrically-isolated tungsten slabs 111-3 according to embodiments.

[0037] According to embodiments, operations 230 and 250 may occur simultaneously. The patterned substrate may be placed in the substrate processing region of the substrate processing chamber. The patterned substrate includes electrically-shortened tungsten slabs 111-1 arranged in at least one of two adjacent vertical columns. Again, a trench is disposed between the two adjacent vertical columns as shown in FIG. 1A. A fluorine-containing precursor may then be flowed into the inductively-coupled remote plasma system outside the substrate processing chamber and excited an external remote plasma in the remote plasma system to produce intermediate plasma effluents. The intermediate plasma effluents may then be flowed into a chamber plasma region within the substrate processing chamber and excited in an internal remote plasma in the chamber plasma region to produce

plasma effluents. The chamber plasma region is fluidly coupled with the substrate processing region through a showerhead. The plasma effluents may be flowed into the substrate processing region through the showerhead and the electrically-shorted tungsten slabs **111-1** may be selectively etched. The electrically-shorted tungsten slabs **111-1** may be electrically isolated in the process to form electrically-isolated tungsten slabs **111-3** perhaps without passing through intermediate state **111-2**. External remote plasma may have all the same process parameter embodiments described earlier with reference to the second remote plasma. Similarly, internal remote plasma may have all the same process parameter embodiments described earlier with reference to the first remote plasma.

[0038] In each remote plasma described herein, the flows of the precursors into the remote plasma region may further include one or more relatively inert gases such as He, N₂, Ar. The inert gas can be used to improve plasma stability, ease plasma initiation, and improve process uniformity. Argon is helpful, as an additive, to promote the formation of a stable plasma. Process uniformity is generally increased when helium is included. These additives are present in embodiments throughout this specification. Flow rates and ratios of the different gases may be used to control etch rates and etch selectivity.

[0039] 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.

[0040] 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.

[0041] 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 embodiments described herein, 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.

[0042] 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 are hard to define and may encroach 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.

[0043] The etch selectivities during the tungsten etches described herein (tungsten:silicon oxide or tungsten:silicon nitride or tungsten:polysilicon and tungsten:titanium nitride (or another barrier material listed herein)) may be greater than or about 50:1, greater than or about 100:1, greater than or about 150:1 or greater than or about 250:1 according to embodiments.

[0044] FIG. 3A 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.

[0045] 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.

[0046] 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 first plasma region.

[0047] 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.

[0048] 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 about 200 kHz, high RF frequencies between about 10 MHz and about 15 MHz, or microwave frequencies greater than or about 1 GHz in embodiments. The plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the remote plasma region.

[0049] A precursor, for example a fluorine-containing 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 an additional 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 additional 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.

[0050] 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**.

[0051] FIG. 3B 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. 3A as well as FIG. 3C 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.

[0052] 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. 3A-3C 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 as described.

[0053] 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.

[0054] FIG. 3C 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. 3A. 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.

[0055] The chamber plasma region **1015** or a region in an RPS may be referred to as a remote plasma region. In embodiments, the radical precursor, e.g., a radical-fluorine precursor, is created in the remote plasma region and travels into the substrate processing region where it may or may not combine with additional precursors. In embodiments, the additional precursors are excited only by the radical-fluorine precursor. Plasma power may essentially be applied only to the remote plasma region in embodiments to ensure that the radical-fluorine precursor provides the dominant excitation.

[0056] Combined flow rates of precursors into the chamber may account for 0.05% to about 20% by volume of the overall gas mixture; the remainder being carrier gases. The fluorine-containing precursor may be flowed into the remote plasma region, but the plasma effluents may have the same volumetric flow ratio 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 the fluorine-containing gas to stabilize the pressure within the remote plasma region. Substrate processing region **1033** can be maintained at a variety of pressures during the flow of precursors, any carrier gases, and plasma effluents into substrate processing region **1033**. The pressure may be maintained between 0.1 mTorr and 100 Torr, between 1 Torr and 20 Torr or between 1 Torr and 5 Torr in embodiments.

[0057] Embodiments of the dry etch systems may be incorporated into larger fabrication systems for producing integrated circuit chips. FIG. 4 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 **1108a-f**. A second robotic arm **1110** may be used to transport the substrate wafers from the holding area **1106** to the substrate processing chambers **1108a-f** and back. Each substrate processing chamber **1108a-f**, can be outfitted to perform a number of substrate processing operations including the dry etch processes described herein in addition to cyclical layer deposition (CLD), atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), etch, pre-clean, degas, orientation, and other substrate processes.

[0058] The substrate processing chambers **1108a-f** may be configured for depositing, annealing, curing and/or etching a film on the substrate wafer. In one configuration, all three pairs of chambers, e.g., **1108a-f**, may be configured to etch a film on the substrate, for example, chambers **1108a-d** may be used to etch the gapfill silicon oxide to create space for the airgap while chambers **1108e-f** may be used to etch the polysilicon.

[0059] 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.

[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” or “polysilicon” of the patterned substrate is predominantly Si but may include minority concentrations of other elemental constituents such as nitrogen, oxygen, hydrogen and carbon. Exposed “silicon” or “polysilicon” may consist of or consist essentially of silicon. Exposed “silicon nitride” of the patterned substrate is predominantly silicon and nitrogen 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 SiO₂ 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.

[0061] Analogous definitions will be understood for “tungsten”, “titanium”, “titanium nitride”, “tantalum” and “tantalum nitride”.

[0062] The term “precursor” is used to refer to any process gas which takes part in a reaction to either remove material from or deposit material onto a surface. “Plasma effluents” describe gas exiting from the chamber plasma region and entering the substrate processing region. Plasma effluents are in an “excited state” wherein at least some of the gas molecules are in vibrationally-excited, dissociated and/or ionized states. A “radical precursor” is used to describe plasma effluents (a gas in an excited state which is exiting a plasma) which participate in a reaction to either remove material from or deposit material on a surface. “Radical-fluorine” are radical precursors which contain fluorine but may contain other elemental constituents. The phrase “inert gas” refers to any gas which does not form chemical bonds when etching or being incorporated into a film. Exemplary inert gases include noble gases but may include other gases so long as no chemical bonds are formed when (typically) trace amounts are trapped in a film.

[0063] The terms “gap” and “trench” are used throughout with no implication that the etched geometry has a large horizontal aspect ratio. Viewed from above the surface, trenches may appear circular, oval, polygonal, rectangular, or a variety of other shapes. A trench may be in the shape of a moat around an island of material. The term “via” is used to refer to a low aspect ratio trench (as viewed from above) which may or may not be filled with metal to form a vertical electrical connection. As used herein, an isotropic or 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.

[0064] 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.

[0065] 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.

[0066] 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.

[0067] 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 3-D flash memory device comprising:
 - a plurality of electrically-isolated tungsten slabs arranged in two adjacent vertical columns, wherein the plurality of electrically-isolated tungsten slabs comprise at least fifty tungsten slabs in the two adjacent vertical columns;
 - a plurality of dielectric slabs interleaved with the plurality of electrically-isolated tungsten slabs, wherein at least fifty of the plurality of electrically-isolated tungsten slabs are recessed between 1 nm and 7 nm laterally relative to the plurality of dielectric slabs.

2. The 3-D flash memory device of claim 1 wherein a height of the two adjacent vertical columns is greater than a gap between the two adjacent vertical columns by a factor of at least ten.

3. The 3-D flash memory device of claim 1 wherein the at least fifty of the plurality of electrically-isolated tungsten slabs are recessed within 1 nm of an average recess of the at least fifty of the plurality of electrically-isolated tungsten slabs.

4. The 3-D flash memory device of claim 1 wherein each of the at least fifty of the plurality of electrically-isolated tungsten slabs are electrically-isolated from every other of the at least fifty of the plurality of electrically-isolated tungsten slabs.

5. The 3-D flash memory device of claim 1 wherein the plurality of electrically-shortened tungsten slabs consist of tungsten and a barrier layer.

6. The 3-D flash memory device of claim 1 wherein a trench is disposed between the two adjacent vertical columns.

7. The 3-D flash memory device of claim 6 wherein a depth of the trench is greater than one micron.

8. The 3-D flash memory device of claim 1 wherein each of the two adjacent vertical columns comprise at least fifty tungsten slabs.

9. The 3-D flash memory device of claim 1 wherein the 3-D flash memory device is formed by:

- initially forming a plurality of electrically-shortened tungsten slabs,

- isotropically etching the plurality of electrically-shortened tungsten slabs, wherein the isotropically etching leaves a tungsten residue at the top of the two adjacent vertical columns, and

- anisotropically etching additional tungsten material, wherein the anisotropically etching removes the tungsten residue from the top of the two adjacent vertical columns.

10. The 3-D flash memory device of claim 9 wherein isotropically etching the plurality of electrically-shortened tungsten slabs in combination with anisotropically etching the additional tungsten material electrically isolates the plurality of electrically-shortened tungsten slabs from one another to form the plurality of electrically-isolated tungsten slabs.

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