CARBON GAPFILL GROWTH AND PATTERN LOADING CONTROL FOR VARIABLE CD/AR FEATURES

BACKGROUND

Field

[0001] Embodiments of the present disclosure generally relate to manufacture of semiconductor components and devices. More specifically, embodiments described herein provide methods for forming even carbon gapfill layers on a semiconductor surface in trenches of varying sizes and/or aspect ratios.

Description of the Related Art

[0002] In semiconductor processing, devices are being manufactured with continually decreasing feature dimensions. Often, features utilized to manufacture devices at these advanced technology nodes include high aspect ratio structures and it is often necessary to fill a gap between circuit elements/structures with a variety of materials. Examples where gapfill material layers are utilized include filling shallow trench isolation (STI), horizontal interconnects, vias between adjacent metal layers, inter-metal dielectric layers (ILD), pre-metal dielectrics (PMD), passivation layers, patterning applications, etc. As the width between the structures shrink, the gap between them often gets taller and narrower, making the gap more difficult to fill without the gapfill material being stuck on sidewalls and creating voids and weak seams. Furthermore, often times a single device or substrate will have multiple gaps of varying widths (e.g., critical dimensions (CD)) and/or aspect ratios that will need to be filled with the gapfill material.

[0003] Conventional chemical vapor deposition (CVD) techniques often experience an overgrowth of material at the top of the gap before it has been completely filled. This can create a void or seam in the gap where the depositing material has been prematurely cut off by the overgrowth; a problem sometimes referred to as bread-loafing. As device geometries shrink and thermal budgets are reduced, void-free and seam-free filling of high aspect ratio spaces becomes increasingly difficult due to limitations of existing deposition processes, especially for forming gapfill material layers to concurrently fill multiple gaps with different CDs and/or aspect ratios.

[0004] Accordingly, what is needed in the art are improved methods for forming gapfill material layers in trenches.

SUMMARY

[0005] Embodiments described herein generally relate to processes for forming gapfill material layers. More specifically, embodiments described herein relate to processes for forming carbon gapfill layers using dual frequency radio frequency during deposition.

[0006] In one embodiment, a method for forming a carbon gapfill layer is disclosed. The method includes positioning a substrate with a top surface and at least one feature on a substrate support in a processing volume of a process chamber, flowing a hydrocarbon precursor gas into the processing volume at a precursor flow rate for providing a deposition species, flowing an etchant gas into the processing volume for providing an etchant species, providing dual frequency radio frequency (RF) power to the processing volume to generate and maintain a RF plasma in the processing volume, where the dual frequency RF power includes applying a constant high frequency radio frequency (HFRF) power and a pulsing low frequency radio frequency (LFRF) power and forming a carbon gapfill layer in at least one feature by using the RF plasma to concurrently deposit the deposition species on the substrate and etch some of the deposition species deposited on the substrate with the etch species.

[0007] In another embodiment, a method for forming a carbon gapfill layer is disclosed. The method includes positioning a substrate having at least one feature on a substrate support in a processing volume of a process chamber, flowing a hydrocarbon precursor gas into the processing volume at a precursor flow rate for providing a deposition species, flowing an etchant gas into the processing volume at an etchant flow rate for providing an etch species, providing a dual frequency radio frequency (RF) power to the processing volume to generate and maintain a RF plasma in the processing volume where providing the dual frequency RF power includes applying a high frequency radio frequency (HFRF) power and a power loop of low frequency radio frequency (LFRF) power, forming a carbon gapfill layer in the at least one feature by using the RF plasma to concurrently deposit the deposition species on the substrate and etch some of the deposition species deposited on the substrate with

the etch species, flowing a hydrocarbon precursor gas into the processing volume at a precursor flow row rate for providing a hydrocarbon deposition species, flowing an etchant gas into the processing volume at an etchant flow rate for providing an etch species, and forming a carbon conformal layer on the carbon gapfill layer by using the RF plasma to concurrently deposit the deposition species on the substrate and etch some of the deposition species on the substrate with the etch species.

[0008] In another embodiment, a device is disclosed. The device includes a substrate with at least one feature on a top surface of the substrate, the at least one feature comprising a trench formed between a first structure and a second structure disposed on the top surface of the substrate, and a carbon gapfill layer disposed on the substrate and at least one feature. The carbon gapfill layer includes a lower portion and an upper portion, the lower portion is disposed in at least a portion of the trench of each of the at least one feature and the upper portion is disposed on the lower portion and on each of the first and second structures of at least one feature, where the lower portion of the carbon gapfill layer is formed from a coetaneous deposition and etch process using a dual frequency RF power, and the upper portion of the carbon gapfill layer is formed using a conformal deposition process.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments and are therefore not to be considered limiting of its scope, and may admit to other equally effective embodiments.

[0010] Figure 1 is a schematic cross-sectional view of a process chamber, according to certain embodiments.

[0011] Figure 2 is a schematic block diagram of a method for forming a carbon gapfill layer, according to certain embodiments.

[0012] Figures 3A-3C are partial schematic side cross-sectional views of a substrate during the method of FIG. 2, according to certain embodiments.

[0013] Figure 4A and Figure 4B is a partial schematic side cross-sectional views of a carbon gapfill lawyer formed on a substrate, according to certain embodiments;

[0014] Figure 5 is a schematic block diagram of a method for forming a carbon gapfill layer, according to certain embodiments.

[0015] Figures 6A-6C are partial schematic side cross-sectional views of a substrate during the method of FIG. 5, according to certain embodiments.

[0016] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0017] The following disclosure describes techniques for forming gapfill material layers in features, such as trenches formed on a substrate or a material layer disposed thereon. Certain details are set forth in the following description and figures to provide a thorough understanding of various embodiments of the disclosure. Other details describing well-known structures and systems often associated with chemical vapor deposition (CVD) processing are not set forth in the following disclosure to avoid unnecessarily obscuring the description of the various embodiments.

[0018] Many of the details, dimensions, angles and other features shown in the figures are merely illustrative of particular embodiments. Accordingly, other embodiments can have other details, components, dimensions, angles and features without departing from the spirit or scope of the present disclosure. In addition, further embodiments of the disclosure can be practiced without several of the details described below.

[0019] Embodiments described herein will be described below in reference to a CVD deposition process that can be carried out using any suitable thin film deposition

system. Examples of suitable systems include the CENTURA® systems which may use a DXZ® process chamber, PRECISION 5000® systems, PRODUCER® systems, PRODUCER® GTTM systems, PRODUCER® XP PrecisionTM systems, PRODUCER® SETM systems, Sym3® process chamber, and Mesa™ process chamber, all of which are commercially available from Applied Materials, Inc., of Santa Clara, California.

[0020] A "substrate" as used herein, refers to any substrate or material surface formed on a substrate upon which film processing is performed during a fabrication process. For example, a substrate surface on which processing can be performed include materials such as silicon, silicon oxide, strained silicon, silicon on insulator (SOI), carbon doped silicon oxides, amorphous silicon, doped silicon, germanium, gallium arsenide, glass, sapphire, and any other materials such as metals, metal nitrides, metal alloys, and other conductive materials, depending on the application. Substrates include, without limitation, semiconductor wafers. Substrates may be exposed to a pretreatment process to polish, etch, reduce, oxidize, hydroxylate, anneal, UV cure, e-beam cure and/or bake the substrate surface.

[0021] In addition to film processing directly on the surface of the substrate itself, in the present disclosure, any of the processing steps disclosed may also be performed on an intermediate layer formed on the substrate as disclosed in more detail below, and the term "substrate surface" is intended to include such intermediate layer as the context indicates. Thus, for example, where a film/layer or partial film/layer has been deposited onto a substrate surface, the exposed surface of the newly deposited film/layer becomes the substrate surface.

[0022] Carbon-based film deposition has been used to provide gapfill material layers during semiconductor processing through vapor deposition process techniques, such as CVD or plasma enhanced chemical vapor deposition (PECVD). Most vapor deposition methods, including CVD and PECVD, utilize a blanket deposition process that generally deposits more gapfill material towards the center of a high aspect ratio feature, such as a trench formed between two vertical structures. In some embodiments, the deposition in turn causes growth of the gapfill material to form a triangular peak in the trench. The triangular peak is due to a shadow effect from the

high vertical walls on opposite sides of the trench as the walls partially block ions from entering the trench. Additionally, without being bound by theory, it was observed that growth in wide CD features is generally higher compared to narrow CD features thereby creating more causes or opportunity for topography issues when filling completely. This phenomenon was observed with both high and low aspect features. The inconsistency or uneven growth of gap fill material in such features may lead to premature closing of the trench which can cause seams or voids in the formed gapfill material feature. These defects may affect the quality of the semiconductor device.

[0023] Conventional carbon gapfill material layer deposition techniques currently lack a technique for precise control over carbon deposition within trenches to allow for a pure bottom-up deposition approach. As such, when filling multiple adjacent trenches with varying CDs and/or aspect ratios, gapfill material layers formed by blanket deposition techniques in trenches of differing CD or aspect ratios generally will each vary in quality which in turn can affect subsequent processing operations needing to be performed and/or circuit performance of the resulting device. For example, since wider trenches are generally also deeper, a lack of a pure bottom-up deposition process leads to increased likelihood of voids and seams being formed in the deposited gapfill material layer.

[0024] Embodiments of the present disclosure provide techniques for performing a deposition with the use of dual frequency radio frequency (RF) to form a substantially even carbon gapfill layer in a trench between adjacent vertical structures. In some embodiments, the dual frequency RF power includes a high frequency RF (HFRF) power and a low frequency RF (LFRF) power. Specifically, in some embodiments, methods of the present disclosure include providing a constant HFRF power and pulsing a LFRF power on and off during deposition of a hydrocarbon deposition species for forming the carbon gapfill layer. In such embodiments, without being bound by theory, it was observed that the growth profile of the carbon gapfill layer in each of the trenches was more uniform when a dual frequency RF power regime was used than when only a constant HFRF power was used. The providing of the LFRF power in the methods of the present disclosure during deposition of the carbon gapfill layer in turn allows for a more even bottom-up growth approach.

[0025] FIG. 1 is a schematic cross sectional view of a process chamber 100 configured according to various embodiments of the present disclosure. By way of example, the embodiment of the process chamber 100 in FIG. 1 is described in terms of a PECVD system, but any other process chamber may fall within the scope of the embodiments, including other plasma deposition chambers or plasma etch chambers. The process chamber 100 includes a chamber body 102, a lid assembly 106, and a substrate support 105. The lid assembly 106 is disposed at an upper end of and is supported by the chamber body 102, and the substrate support 105 is at least partially disposed within the chamber body 102. The chamber body 102, lid assembly 106, and substrate support 105 together define an processing volume 146 within the process chamber 100 in which a substrate may be processed. The processing volume 146 may be accessed through a port 104 formed in the chamber body 102 that facilitates transfer of a substrate into and out of the processing volume 146 of the process chamber 100.

[0026] The lid assembly 106 includes a gas distributor 108, a modulation electrode 110, and insulators 112. The insulator 112, which may be a dielectric material such as a ceramic or metal oxide, for example aluminum oxide and/or aluminum nitride, contacts the modulation electrode 110 and separates the modulation electrode 110 electrically and thermally from the gas distributor 108 and from the chamber body 102. The gas distributor 108 (e.g., showerhead) has passages 114 therethrough for admitting process gas into the processing volume 146. A pair of insulators (e.g., annular insulators) are disposed between the gas distributor 108 and the modulation electrode 110. The modulation electrode 110 is annular and circumscribes the processing volume 146.

[0027] Process gases (e.g., one or more precursor and one or more inert carrier gas) may be provided through the conduit 120 from a gas source 122 to be introduced into the process chamber 100. The processing gas from the conduit 120 enters the processing volume 146 through the passages 114 in the gas distributor 108 such that the processing gas is uniformly distributed in the processing volume 146. In one embodiment, the passages 114 in the gas distributor 108 may be radially distributed and gas flow to each of the passages 114 may be separately controlled to further facilitate gas uniformity within the processing volume 146.

[0028] The processing gases can be evacuated from the processing volume 146 through an outlet 118 which may be located at any convenient location along the chamber body 102. In some embodiments, the outlet 118 may be associated with a vacuum pump (not shown) fluidly coupled to the processing volume 146. The vacuum pump may be part of the gas and pressure control system of the processing chamber 100.

[0029] In some embodiments, portions of the gas distributor 108 may be heated using a resistive heater (not shown) or thermal fluid disposed in a conduit (not shown) through a portion of the gas distributor 108 or otherwise in direct contact or thermal contact with the gas distributor 108. The conduit may be disposed through an edge portion of the gas distributor 108 to avoid disturbing the gas flow function of the gas distributor 108. Heating the edge portion of the gas distributor 108 may be useful to reduce the tendency of the edge portion of the gas distributor 108 to be a heat sink within the process chamber 100.

[0030] In some embodiments, the walls of the chamber body 102 may also be heated to similar effect. Heating the chamber surfaces exposed to the plasma also minimizes deposition, condensation, and/or reverse sublimation on the chamber surfaces, reducing the cleaning frequency of the chamber and increasing mean cycles per clean. Higher temperature surfaces also promote dense deposition that is less likely to produce particles that fall onto a substrate. Thermal control conduits with resistive heaters and/or thermal fluids (not shown) may be disposed through the chamber walls to achieve thermal control of the chamber walls. Temperature of all surfaces may be controlled by a controller.

[0031] In some embodiments, the gas distributor 108 may be coupled to a first RF power source 116A and a second RF power source 116B, such as a RF generator, as shown in FIG. 1. DC power, pulsed DC power, and pulsed RF power may alternatively be used. In other embodiments, the gas distributor 108 may be coupled to ground. Both RF power sources 116A, 116B are electrically connected to the gas distributor 108 and is configured to apply a RF potential to the gas distributor 108 to facilitate the generation of plasma in the processing volume 146. Each RF power source 116A, 116B may include a high frequency RF power source (“HFRF power source”) capable

of generating an RF power (e.g., at a frequency of about 13.56 MHz), and/or a low frequency RF power source ("LFRF power source") generating an RF power (e.g., at a frequency of about 300 kHz). The LFRF power source can provide both low frequency generation and fixed match elements. The HFRF power source can be designed for use with a fixed match and can regulate the power delivered to the load, eliminating concerns about forward and reflected power.

[0032] The modulation electrode 110 may be coupled to a tuning circuit 144 that controls an impedance of an electrical path from the modulation electrode 110 to an electrical ground. The tuning circuit 144 comprises an electronic sensor 148 and an electronic controller, which may be a variable capacitor 150 as shown that is controllable by the electronic sensor 148. The tuning circuit 144 may be an LLC circuit comprising one or more inductors 152. The electronic sensor 148 may be a voltage or current sensor, and may be coupled to the variable capacitor 150 to afford a degree of closed-loop control of plasma conditions inside the processing volume 146. In some embodiments, the tuning circuit 144 may be any circuit that features a variable or controllable impedance under the plasma conditions present in the processing volume 146 during processing

[0033] The substrate support 105 may be disposed within the process chamber 100. The substrate support 105 may support a substrate 126 during processing. A first electrode 160 and a second electrode 162 are disposed in and/or on the substrate support 105. Further, in some embodiments, a heater element (not shown) may be embedded in the substrate support 105. The heater element can be operable to controllably heat the substrate support 105 and the substrate 126 positioned thereon to a target temperature, such as to maintain the substrate 126 at a temperature in a range from about 200 degrees Celsius to about 700 degrees Celsius.

[0034] The substrate support 105 is coupled to a shaft 166 for support. The shaft 166 can provide a conduit from a gas source 122 and electrical and temperature monitoring leads (not shown) between the substrate support 105 and other components of the process chamber 100. In some examples, a purge gas may be provided from the gas source 122 to the backside of the substrate 126 through one or more purge gas inlets 169 connected to the substrate support 105. The purge gas

flowed toward the backside of the substrate 126 can help prevent particle contamination caused by deposition on the backside of the substrate 126. The purge gas may also be used as a form of temperature control to cool the backside of the substrate 126. Although not illustrated, the shaft 166 may be coupled to an actuator (not shown) which extends through a centrally-located opening formed in a bottom of the chamber body 102. The actuator may be flexibly sealed to the chamber body 102 by bellows (not shown) that prevent vacuum leakage from around the shaft 166. The actuator can allow the substrate support 105 to be moved vertically within the chamber body 102 between a process position and a lower, transfer position. The transfer position is slightly below the port 104 in the chamber body 102. In operation, the substrate support 105 may be elevated to a position in close proximity to the lid assembly 106 for processing.

[0035] The first electrode 160 may be embedded within the substrate support 105 or coupled to a surface of the substrate support 105. The first electrode 160 may be a plate, a perforated plate, a mesh, a wire screen, or any other distributed arrangement. The first electrode 160 may be a tuning electrode, and may be coupled to a tuning circuit 170. The tuning circuit 170 may have an electronic sensor 172 and an electronic controller, such as a variable capacitor 174 electrically connected between the first electrode 160 and an electrical ground. The electronic sensor 172 may be a voltage or current sensor, and may be coupled to the variable capacitor 174 to provide further control over plasma conditions in the processing volume 146.

[0036] The second electrode 162, which may be a bias electrode and/or an electrostatic chucking electrode, may be coupled to the substrate support 105. The second electrode 162 may be coupled to a bias power source 176 through an impedance matching circuit 178. The bias power source 176 may be DC power, pulsed DC power, RF power, pulsed RF power, or a combination thereof.

[0037] In operation, the substrate 126 is disposed on the substrate support 105, and process gases are flowed through the lid assembly 106 according to any desired flow plan. Electric power is coupled to the gas distributor to establish a plasma in the processing volume 146. The substrate 126 may be subjected to an electrical bias using the bias power source 176, if desired.

[0038] Upon energizing a plasma in the processing volume 146, a potential difference is established between the plasma and the modulation electrode 110. A potential difference is also established between the plasma and the first electrode 160. The variable capacitors 150 and 174 may then be used to adjust the impedances of the paths to an electrical ground represented by the tuning circuits 144 and 170. A set point may be delivered to the tuning circuit 144 and 170 to provide independent control of the plasma density uniformity from center to edge and deposition rate. The electronic sensors may adjust the variable capacitors to maximize deposition rate and minimize thickness non-uniformity independently. The components implemented to control temperature and uniformity of the plasma, among other, can permit deposition of a highly conformal layer on a substrate being processed, even within small gaps.

[0039] FIG. 2 depicts a process flow diagram of a method 200, for forming a carbon gapfill layer with a bottom-up approach in a feature formed on a substrate 302, in accordance with one or more embodiments of the present disclosure. FIG. 3A and FIG. 3B depict schematic cross-sectional views of a substrate structure illustrating the carbon gapfill layer formation sequence according to method 200. As used in this regard, the term “feature” means any intentional surface irregularity. The shape of the feature can be any suitable shape including, but not limited to, trenches cylindrical vias. Suitable examples of features include, but are not limited to trenches which two sidewalls and a bottom surface, and vias which have a generally cylindrical sidewall. Other examples of features include without limitation, lines, contact holes, through-holes or other feature definitions utilized in a semiconductor, solar, or other electronic devices, such as high ratio contact plugs. The features can have any suitable aspect ratio (ratio of the depth of the feature to the width of the feature).

[0040] Although the method 200 is described below with reference to forming a carbon gapfill layer in a trench between structures formed on a substrate, the method 200 may also be used to advantage in other device manufacturing applications. Further, it should also be understood that the operations depicted in FIG. 2 may be performed simultaneously and/or in a different order than the order depicted in FIG. 2.

[0041] The method 200 begins at operation 210 by positioning a substrate 302, into a processing volume of a process chamber, such as the processing volume 146 of the

process chamber 100 depicted in FIG. 1. The substrate 302 may be the substrate 126 depicted in FIG 1. As show in FIG. 3A and FIG. 3B, the substrate 302 includes at least one feature, such as a trench 304 formed between a pair of vertical structures 306 disposed on the substrate 302. The trench 304 includes a bottom surface 308 between sidewalls 310, and an opening between top surfaces 312 of each of the vertical structures 306. In some embodiments, the trench 304 may be a negative feature formed directly in the substrate 302. Although FIG. 3A and FIG. 3B show substrate 302 having a single trench 304 for illustrative purposes, those skilled in the art will understand that there can be more than one trench 304 each with the same or different CDs.

[0042] While the substrate 302 is illustrated as a single body, it is understood that the substrate 302 may contain one or more materials used in forming semiconductor devices such as metal contacts, trench isolations, gates, bitlines, or any other interconnect features. The substrate 302 may comprise one or more metal layers, one or more dielectric materials, semiconductor material, and combinations thereof utilized to fabricate semiconductor devices. For example, the substrate 302 may include an oxide material, a nitride material, a polysilicon material, or the like, depending upon application. The substrate 302 may be any substrate or material surface upon which film processing is performed. For example, the substrate 302 may be a material such as crystalline silicon, silicon oxide, silicon oxynitride, silicon nitride, strained silicon, silicon germanium, tungsten, titanium nitride, doped or undoped polysilicon, doped or undoped silicon wafers and patterned or non-patterned wafers, silicon on insulator (SOI), carbon doped silicon oxides, silicon nitrides, doped silicon, germanium, gallium arsenide, glass, sapphire, low-k dielectrics, and combinations thereof.

[0043] In an embodiment, the substrate, e.g., substrate 302, is transferred into the process chamber 100 and onto the substrate support 105 by any suitable means, such as by substrate transfer port (not shown). The substrate support 105 can be adjusted to a processing position by an actuator (not shown). In some embodiments, the position of the substrate support 105 and the substrate 302 in the processing volume 146 may be changed such that the substrate 302 may be moved towards the gas distributor 108 and the spacing between the bottom surface of the gas distributor 108

and a top surface of the substrate support 105 is between about 200 mils and about 1,000 mils.

[0044] At operation 220, a hydrocarbon precursor gas is flowed into the processing volume 146. In an embodiment, the hydrocarbon precursor gas may be flowed from the gas source 122 into the processing volume 146 through the gas distributor 108. During processing, the hydrocarbon precursor gas may be used to provide a deposition species for forming the carbon gapfill layer. In an embodiment, the hydrocarbon precursor gas includes a hydrocarbon compound having a general formula C_xH_y, where x has a range of between 1 and 20 and y has a range of between 1 and 20. Suitable carbon compounds include, for example, methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), butylenes (C_4H_8), cyclobutane (C_4H_8), and methylcyclopropane (C_4H_8). Suitable butylenes include, for example, 1-Butene, 2-Butene, and isobutylene. In certain embodiments, the hydrocarbon source can be a liquid or gas. In one embodiment, the hydrocarbon precursor gas includes acetylene (C_2H_2). In another embodiment, the hydrocarbon precursor gas includes propylene (C_3H_6). In another embodiment, the hydrocarbon precursor gas includes methane (CH_4). In one example, the hydrocarbon precursor gas is vapor at room temperature, which simplifies the hardware for material metering, control and delivery to the process chamber.

[0045] In some embodiments, the hydrocarbon precursor gas may further include a dilution gas. Suitable dilution gases such as helium (He), argon (Ar), or combinations thereof, may be added to the hydrocarbon precursor gas. Alternatively, dilution gases may not be used during the deposition.

[0046] At an operation 230, an etchant gas may be flowed into the process chamber 100. In certain embodiments, the etchant gas may be flowed from the gas source 122 into the processing volume 146 through the gas distributor 108. In some embodiments, the flow of the etchant gas may occur simultaneously to the flow of the hydrocarbon precursor gas. In an embodiment, the etchant gas includes hydrogen gas (H_2) for providing H* radicals to etch portions of the carbon gapfill layer 316 deposited during processing. In other embodiments, the etchant gas may be CO_2 or

NH_3 gas. In some embodiments, the flow rate of the etchant gas may range from about 2000 sccm to about 6000 sccm.

[0047] At operation 240, a dual frequency RF power is applied to the process chamber 100 to ignite and generate a RF plasma in the processing volume 146. The dual frequency RF may be provided by a first RF power source 116A and a second RF power source 116B (seen in FIG. 1) through a matching network 180A, 180B to facilitate generation of the RF plasma. The dual frequency RF power includes a HFRF power provided by a first RF power source 116A, and a LFRF is provided by a second RF power source 116B. The HFRF power provides for generating and maintaining a stable plasma in the processing volume 146. Operation 240 may include a HFRF pulsing method, a LFRF power looping method, or an RF pulsing method. In one or more embodiments, the HFRF pulsing method is used during operation 240. The HFRF pulsing method includes a duty cycle of about 5% to about 50% and a frequency from about 200hz to about 20000hz.

[0048] In one or more embodiments, the LFRF power looping method is used during operation 240. In the LFRF power looping method, the HFRF power is maintained during the deposition of a hydrocarbon deposition species 320 while the LFRF power is pulsed on and off (e.g., in a power loop) during the deposition of a hydrocarbon deposition species 320. In the LFRF power looping method, the HFRF power may be maintained during processing in a range between about 400 W and about 2000 W, such as between about 500W and about 650W, and at high frequency of about 13.56MHz, 27MHz, and/or 40MHz. The LFRF power applied in operation 240 during method 200 may be in a range between about 200W and about 800W, and at about 350KHz, 400kHz and/or 2MHz. In one or more embodiments, the LFRF power is power looped during operation 240 with about 0.2 to 1 second on and about 0.2 to 1 second off. In some embodiments, the LFRF power may have a duty cycle in a range from about 13% to about 50%. In some embodiments, the LFRF power may be pulsed or cycled 80 to 400 times during the deposition process. In an embodiment, the LFRF power may be pulsed or cycled between about 200 and about 300 times during the deposition process. More specifically, as non-limiting examples, the LFRF power may be pulsed at an interval of 0.2 seconds on and 0.2 seconds off, or pulsed at an interval of about 0.2 seconds on and 1.0 seconds off. The LFRF power looping

may occur manually or by a mechanical system. The dual frequency RF power may be varied to adjust the deposition rate of the carbon gapfill layer 316 in the trenches 304.

[0049] In one or more embodiments, an RF pulsing method is used during operation 240. During the RF pulsing method, the HFRF is constant while the LFRF is pulsed from the generator. The LFRF includes a duty cycle range from about 5% to about 50%. The LFRF includes a frequency of about 200hz to about 20000hz. In one or more embodiments, during the RF pulsing from the generator method, the HFRF and the LFRF are pulsed. For example, the LFRF and the HFRF both include a duty cycle range from about 5% to about 50% and a frequency range of about 200hz to about 20000hz. The pulsing may occur manually or by a mechanical system.

[0050] During operation 240, the chamber is maintained at a pressure range of about 1 torr to about 10 torr. The spacing between the the substrate support 105 and gas distributor 108 may be about 200 mils to about 1000 mils. For example, the spacing between the substrate support 105 and gas distributor 108 is about 300 mils to about 700 mils.

[0051] As seen in FIG. 4B, the pulsed LFRF power narrows a directionality 318. In comparison, as seen in FIG. 4A, when there is no pulsed LFRF power the directionality 318 of the hydrocarbon deposition species 320 is at a wider angle. The wider angle in FIG. 4A leads to formation of a triangle 326 of the hydrocarbon deposition species 320 when the carbon gapfill layer 316 is formed between the vertical structures 306. The uneven growth (e.g., the peak or triangle 326) between vertical structures 306 may lead to voids or seams in the carbon gapfill layer 316. Turning to FIG. 4B, the pulsing of the LFRF power improves the directionality 318 of the hydrocarbon deposition species 320 such that the angular distribution of hydrocarbon deposition species 320 is narrower which in turn provides for a more uniform deposition of the hydrocarbon deposition species 320 in all portions of the trench 304. The pulsing of the LFRF power effects the hydrocarbon deposition species 320 to fall more evenly and at a narrower angle when compared to the depositing of hydrocarbon deposition species 320 without the use of a pulsed LFRF power, as seen in Figure 4A. Without being bound by theory, the additional pulsed LFRF power brings more deposition ions

onto the trench 304, and at a narrower angle. The pulsed LFRF power leads to a more even or planar carbon gapfill layer 316 being formed between the vertical structures 306 over the substrate 302 because the deposition rate is better controlled. Controlling the dual frequency RF to provide a more uniform deposition rate is particularly important when concurrently depositing the hydrocarbon deposition species 320 into multiple trenches 304 with varying CDs and/or aspect ratios, which leads to a more even carbon gapfill layer 316.

[0052] In general, it was observed that the when depositing in multiple trenches with varying CDs and/or aspect ratios, the deposition rate in each of the respective trenches is dependent on the specific CD and/or aspect ratio. Generally, the deposition rate in a trench with a larger CD will be higher than a trench with a lower CD. Controlling the deposition rate with pulsing LFRF power allows for a more similar deposition rate in multiple trenches with varying CDs and/or aspect ratio resulting in a more uniform growth profile.

[0053] In some embodiments, the flow rate of the hydrocarbon precursor gas may range from about 100 sccm to about 400 sccm. In some embodiments, the flow rate of the dilution gas may individually range from about 0 sccm to about 5,000 sccm (e.g., from about 2,000 sccm to about 4,000 sccm).

[0054] At an optional operation 250, an inert gas, such as argon may be supplied with the hydrocarbon precursor gas into the process chamber 100. In some embodiments, the flow rate of the argon gas may range from about 0 sccm to about 5,000 sccm. In some embodiments, argon may optionally be used for additional control over the deposition rate of the carbon gapfill layer. For example, when the carbon gapfill layer is being formed in multiple trenches of varying CDs, the deposition rate in trenches may vary as a result of the different CDs. Accordingly, argon may therefore be used to increase the deposition rate and provide for a more uniform deposition rate when depositing in multiple trenches with non-uniform CDs. In some embodiments, the addition of argon may also further assist in increased etching of deposition on the top surface 312 of the vertical structures 306 to reduce or minimize top-hat formation.

[0055] At operation 260, a carbon gapfill layer 316 is formed in the trench 304 on the substrate 302 using the RF plasma generated in operation 240. In an embodiment, the plasma may be formed by capacitive means, and may be energized by coupling RF power into the processing gas mixture provided in operations 220-240. The plasma generated in operation 260, as seen in FIG. 3C, from the processing gases in the process chamber 100 is correspondingly used to simultaneously deposit and etch the carbon gapfill layer on the substrate 302. During processing, the disassociation of the hydrocarbon precursors in the plasma results in the deposition of deposition species 330 (e.g., hydrocarbon ions) on the substrate 302, including the bottom surface 308 of the trench 304 and on the top surfaces 312 of the vertical structures 306. The plasma generated from the processing gases simultaneously also causes disassociation of the etchant gas resulting in etching species 332 (e.g., hydrogen radicals) that etch portions of the carbon gapfill layer deposited on the sidewalls 310 and the top surface 312 of the vertical structures 306 near the opening of the trench 304. The etching by the hydrogen radicals minimizes deposition on top of the vertical structures 306 near the opening of the trench 304, thereby preventing formation of top-hats on the vertical structures 306. The etching by the hydrogen radicals also prevents deposition on the sidewalls 310 within the trench 304 thereby preventing bread-loafing from occurring.

[0056] During formation of the carbon gapfill layer 316, the process chamber 100, the substrate 302, or both may be maintained at a temperature between about 200 degrees Celsius and about 700 degrees Celsius (e.g., between about 400 degrees Celsius to about 600 degrees Celsius; or between about 500 degrees Celsius to about 700 degrees Celsius). The chamber pressure may range from about 1 Torr to about 10 Torr (e.g., between about 2 Torr and about 8 Torr; or between about 4 Torr and about 8 Torr). The distance between the substrate support 105 and gas distributor 108 (e.g., spacing in FIG. 1) may be set to between about 200 mils and about 600 mils, for example, about 500 mils.

[0057] For most applications, the plasma is maintained for a time period to form the carbon gapfill layer 316 in the trench 304. The process of operation 260 may be performed simultaneously, sequentially or may partially overlap with the processes of operations 220-250. In some embodiments, the flow of each of the processing gases

(e.g., the hydrocarbon precursor gas and the etchant gas) may be stopped when each of the trench 304 is sufficiently filled. In some embodiments, the process disclosed can also planarize the field surface after the trench 304 is filled, thereby reducing the need for, and possibly even avoid altogether, any subsequent chemical mechanic polishing (CMP) process to prepare and flatten the surface for forming of subsequent optical structures. In some embodiments, the flow of each of the processing gases may be stopped when the carbon gapfill layer 316 above the trench 304 is sufficiently planarized. Any excess process gases and by-products from the deposition of the season layer may then be removed from the processing volume by performing an optional purge/evacuation process.

[0058] FIG. 5 depicts a process flow diagram of a method 500 for forming a carbon gapfill layer in a feature formed on a substrate 302, in accordance with one or more embodiments of the present disclosure. FIGS. 6A-6C depict schematic cross-sectional views of a substrate structure illustrating the carbon gapfill layer formation sequence according to method 500. As used in this regard, the term “feature” means any intentional surface irregularity. The shape of the feature can be any suitable shape including, but not limited to, trenches cylindrical vias. Suitable examples of features include, but are not limited to trenches which two sidewalls and a bottom surface, and vias which have a generally cylindrical sidewall. Other examples of features include without limitation, lines, contact holes, through-holes or other feature definitions utilized in a semiconductor, solar, or other electronic devices, such as high ratio contact plugs. The features can have any suitable aspect ratio (ratio of the depth of the feature to the width of the feature).

[0059] Although the method 500 is described below with reference to forming a carbon gapfill layer in a trench between structures formed on a substrate, the method 500 may also be used to advantage in other device manufacturing applications. Further, it should also be understood that the operations depicted in FIG. 5 may be performed simultaneously and/or in a different order than the order depicted in FIG. 5.

[0060] The method 500 begins at operation 510 by positioning a substrate 302, into a processing volume of a process chamber, such as the processing volume 146 of the process chamber 100 depicted in FIG. 1. The substrate 302 may be the substrate 126

depicted in FIG 1. As shown in FIGS. 6A-6C, the substrate 302 includes at least one feature, such as a trench 304, formed between a pair of vertical structures 306 disposed on the substrate 302. As seen in FIG. 6A, the trench 304 includes a bottom surface 308 between sidewalls 310, and an opening between a top surface 312 of each of the vertical structures 306. In some embodiments, the trench 304 may be a negative feature formed directly in the substrate 302. Although FIGS. 6A-6C show substrate 302 having a single trench 304 for illustrative purposes, those skilled in the art will understand that there can be more than one trench 304 each with the same or different CDs.

[0061] At operation 520, a deposition process is performed to form a carbon gapfill layer 316 on the substrate 302 and at least one feature, such as a trench 304, disposed on the substrate 302. In certain embodiments, the carbon gapfill layer 316 is formed in operation 520 utilizing the method 200, describing a bottom-up gapfill process, as discussed above in operations 220-260. As seen in FIG. 6A, the carbon gapfill layer 316 formed sufficiently fills the trench 304. Operation 520 may be performed until the desired amount of a carbon gapfill layer 316 is deposited into the trench 304. The height of the carbon gapfill layer 316 is predetermined and the carbon gapfill layer 316 may fill 10% to 100% of the trench 304 after deposition. In one embodiment, the desired height of the carbon gapfill layer 316 may fill about 50% to about 100% of the trench 304 after deposition, such as about 50% fill of the trench 304, about 60% fill of the trench 304, about 70% fill of the trench 304, or about 95% fill of the trench 304. In other embodiments, the method 200, describing a bottom-up gapfill process, may be used to fill all features on a substrate 302 completely. During operation 520, top-hats 316A may form on the high aspect ratio structures.

[0062] At an optional operation 530, an etch process may be performed to etch a top-hats 316A formed on the high aspect ratio structures in operation 520. In some embodiments, the etch process in optional operation 530 includes flowing an etchant gas into the processing volume 146 and igniting the etchant gas to perform a plasma etch process. The etchant gas may be flowed from the gas source 122 into the processing volume 146 through the gas distributor 108. In an embodiment, the etchant gas includes hydrogen gas (H_2). In one embodiment, a highly directional etch is used,

which is ion based and conducted at low pressure. Optional operation 530, as seen in FIG. 6B is used to remove top-hats 316A that may form during operation 520.

[0063] At operation 540, a conformal deposition process is performed to form a conformal deposition layer 322 on the carbon gapfill layer 316 formed in the trench 304 on the substrate 302. At operation 540, forming the conformal deposition layer 322 may including flowing a conformal hydrocarbon precursor gas from the gas source 122 into the processing volume 146 through the gas distributor 108 and generating a plasma in the processing volume 146 to deposit the conformal deposition layer 322. In an embodiment, at operation 540, a radical based and low power conformal deposition may be used.

[0064] During processing of the substrate 302 in operation 540, the conformal hydrocarbon precursor gas may be used to provide a deposition species for forming the conformal deposition layer. In an embodiment, the conformal hydrocarbon precursor gas includes a hydrocarbon compound having a general formula C_xH_y, where x has a range of between 1 and 20 and y has a range of between 1 and 20. Suitable carbon compounds include, for example, methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), butylenes (C_4H_8), cyclobutane (C_4H_8), and methylcyclopropane (C_4H_8). Suitable butylenes include, for example, 1-Butene, 2-Butene, and isobutylene. The conformal hydrocarbon source can be any liquid or gas. In one embodiment, the conformal hydrocarbon precursor gas includes acetylene (C_2H_2). In another embodiment, the conformal hydrocarbon precursor gas includes propylene (C_3H_6). In one example, the conformal hydrocarbon precursor gas is vapor at room temperature, which simplifies the hardware for material metering, control and delivery to the process chamber.

[0065] Operation 540 may be used to form a planarized surface after the trench 304 is at least partially filled by a carbon gapfill layer 316 formed in operation 520, as seen in FIG. 6C. The conformal precursor gas in turn forms a planarized conformal deposition layer 322 on the carbon gapfill layer 316 and the vertical structures to provide for an even planarized surface over the substrate 302 after the trench 304 is filled. In some embodiments, this may occur after optional operation 530, where an etchant gas was used to remove the top-hats 312A. In some embodiments, the flow

of each of the processing gases may be stopped when the carbon gapfill layer 316 above the trench 304 is sufficiently planarized. Any excess process gases and by-products from the deposition of the season layer may then be removed from the processing volume by performing an optional purge/evacuation process. In an embodiment, the trench 304 formed between two vertical structures 306 is filled with a carbon gapfill layer 316 that further comprises a lower portion and an upper portion. The lower portion is formed in operation 520 of method 500. The upper portion is formed at operation 540 of method 500.

[0066] Operation 540 may reduce the need for, and possibly even avoid altogether, any subsequent chemical mechanic polishing (CMP) process to prepare and flatten the surface for forming of subsequent optical structures.

[0067] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method for forming a carbon gapfill layer, comprising:

positioning a substrate having a top surface with at least one feature disposed thereon on a substrate support in a processing volume of a process chamber;

flowing a hydrocarbon precursor gas into the processing volume at a precursor flow rate for providing a deposition species;

flowing an etchant gas into the processing volume at an etchant flow rate for providing an etch species;

providing a dual frequency radio frequency (RF) power to the processing volume to generate and maintain a RF plasma in the processing volume, wherein providing the dual frequency RF power comprises applying a constant high frequency radio frequency (HFRF) power and a pulsing low frequency radio frequency (LFRF) power; and

forming a carbon gapfill layer in the at least one feature by using the RF plasma to concurrently deposit the deposition species on the substrate and etch some of the deposition species deposited on the substrate with the etch species.

2. The method of claim 1, wherein the etch species is hydrogen (H_2), and wherein etching the substrate with the etch species comprises etching the deposition species formed on portions of at least one feature on the substrate.

3. The method of claim 1, further comprising flowing a diluent gas comprising helium (He) at a diluent flow rate for providing a diluent species.

4. The method of claim 1, wherein the at least one feature comprises a trench between adjacent vertical structures.

5. The method of claim 1, wherein the hydrocarbon precursor gas comprises acetylene (C_2H_2), propylene (C_3H_6), or methane (CH_4).

6. The method of claim 1, wherein the constant HFRF power is applied and maintained between about 500 W and about 650 W at about 27 MHz.

7. The method of claim 1, wherein the LFRF power is pulsed with a duty cycle of about 5% to about 50%.

8. The method of claim 1, wherein the LFRF power is pulsed at a frequency of about 200hz to about 20000hz.

9. The method of claim 8, wherein the LFRF power is pulsed manually or by a mechanical system.

10. The method of claim 1, wherein a temperature inside the processing volume is between about 300 degrees Celsius and about 600 degrees Celsius.

11. The method of claim 1, wherein a pressure inside the processing volume is between about 1 Torr and about 10 Torr.

12. The method of claim 1, wherein the at least one feature comprises a plurality of trenches with non-uniform CDs and/or aspect ratios.

13. A method of forming a carbon gapfill layer comprising:

positioning a substrate having at least one feature on a substrate support in a processing volume of a process chamber;

flowing a hydrocarbon precursor gas into the processing volume at a precursor flow rate for providing a deposition species;

flowing an etchant gas into the processing volume at an etchant flow rate for providing an etch species;

providing a dual frequency radio frequency (RF) power to the processing volume to generate and maintain a RF plasma in the processing volume, wherein providing the dual frequency RF power comprises applying a high frequency radio frequency (HFRF) power and a power loop of low frequency radio frequency (LFRF) power;

forming a carbon gapfill layer in the at least one feature by using the RF plasma to concurrently deposit the deposition species on the substrate and etch some of the deposition species deposited on the substrate with the etch species;

flowing a conformal hydrocarbon precursor gas into the processing volume at a precursor flow rate for providing a hydrocarbon deposition species; and

performing a conformal deposition process using a low RF power to form a conformal carbon layer on the carbon gapfill layer.

14. The method of claim 13, wherein the HFRF power is constantly applied at a frequency of 27MHz.

15. The method of claim 13, wherein the HFRF power is pulsed with a duty cycle of about 5% to about 50% and a frequency of about 200hz to about 20000hz.

16. The method of claim 13, wherein the hydrocarbon precursor gas comprises acetylene (C_2H_2), propylene (C_3H_6), or methane (CH_4).

17. The method of claim 13, further comprising flowing an etchant gas into the processing volume and generating a plasma to etch a top surface of the carbon gapfill layer formed in a trench and on adjacent vertical structures prior to performing the conformal deposition process.

18. The method of claim 13, wherein the power loop of the LFRF power is looped inside the processing volume during deposition of the carbon gapfill layer, wherein the LFRF is between about 300 W and about 800 W and at about 350 KHz, and wherein the LFRF is pulsed at about 0.2 to 1 second on and about 0.2 to 1 second off.

19. The method of claim 13, wherein the LFRF power is looped between about 200 times and about 430 times when forming the carbon gapfill layer.

20. A device comprising:

a substrate;

at least one feature on a top surface of the substrate, the at least one feature comprising a trench formed between a first structure and a second structure disposed on the top surface of the substrate; and

a carbon gapfill layer disposed on the substrate and the at least one feature, the carbon gapfill layer comprising a lower portion and an upper portion, the lower portion disposed in at least a portion of the trench of each of the at least one feature, and the upper portion disposed on the lower portion and on each of the first and second structures of the at least one feature;

wherein the lower portion of the carbon gapfill layer is formed from a coetaneous deposition and etch process using a dual frequency RF power, and the upper portion of the carbon gapfill layer is formed using a conformal deposition process.