VARIABLE FILM DOPANT CONCENTRATIONS FOR LATERAL ETCH RATE CONTROL IN REDUCED TEMPERATURE ETCHING

BACKGROUND

[0001] Electronic device fabrication processes can involve many steps of material deposition, patterning, and removal to form integrated circuits and/or memory structures on substrates. Various methods can be used to deposit and etch films of materials. As an example, chemical vapor deposition (CVD) involves reacting precursors to form a film on a substrate. As another example, dry etching can be used to etch features into one or more material layers on a substrate.

SUMMARY

[0002] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter. Furthermore, the claimed subject matter is not limited to implementations that solve any or all disadvantages noted in any part of this disclosure.

[0003] One example provides a method of performing cryoetching. The method comprises cooling a substrate in a processing chamber, while cooling the substrate, etching through a first film portion comprising a film material with a first dopant profile, and while cooling the substrate, etching at least partially through a second film portion comprising the film material with a second dopant profile different than the first dopant profile. The first dopant profile causes a different lateral etch rate of the film material than the second dopant profile.

[0004] In some such examples, the first dopant profile comprises a first concentration of an etch rate-modifying dopant, and the second dopant profile comprises a second concentration of the etch rate-modifying dopant.

[0005] Alternatively or additionally, in some such examples, the etch rate-modifying dopant comprises nitrogen, carbon, phosphorus, hydrogen, arsenic, or boron.

[0006] Alternatively or additionally, in some such examples, the first film portion comprising the first dopant profile is doped silicon oxide, and the second film portion comprising the second dopant profile is doped silicon oxide with one or more

of a different etch rate-modifying dopant or a different dopant concentration than the first film portion.

[0007] Alternatively or additionally, in some such examples, the method further comprises, before performing cryoetching, depositing on the substrate the second film portion comprising the film material with the second dopant profile, and depositing the first film portion comprising the film material with the first dopant profile.

[0008] Alternatively or additionally, in some such examples, depositing the second film portion and depositing the first film portion comprises depositing by plasma-enhanced chemical vapor deposition (PECVD).

[0009] Alternatively or additionally, in some such examples, depositing the second film portion and depositing the first film portion comprises depositing by thermal chemical vapor deposition (TCVD) or atomic layer deposition (ALD).

[0010] Alternatively or additionally, in some such examples, etching through the first film portion and etching the second film portion comprises etching a capacitor hole for a dynamic random access memory (DRAM) device.

[0011] Alternatively or additionally, in some such examples, etching through the first film portion and etching the second film portion comprises etching a channel hole or a contact hole for a three dimensional (3D) NAND memory device.

[0012] Alternatively or additionally, in some such examples, at least one of the first dopant profile and the second dopant profile comprises two or more different etch rate-modifying dopants.

[0013] Alternatively or additionally, in some such examples, etching through the first film portion comprises forming a first plasma using a first etchant gas mixture, and the etching through the second film portion comprises forming a second plasma using a second etchant gas mixture different from the first etchant gas mixture.

[0014] Another example provides a device. The device comprises a first layer of a film material comprising a first dopant profile. The device further comprises a second layer of the film material under the first layer of the film material, the second layer of the film material comprising a second dopant profile different from the first dopant profile. The second layer of the film material comprises a faster lateral etch rate than the first layer of silicon oxide. The device further comprises a feature extending through the first layer of the film material and extending at least partially through the second layer of the film material.

[0015] In some such examples, a critical dimension at an opening of the feature is within 10 % of a critical dimension at a bottom of the feature.

[0016] Alternatively or additionally, in some such examples, the first layer comprising the first dopant profile is doped silicon oxide, and the second layer comprising the second dopant profile is doped silicon oxide with one or more of a different etch rate-modifying dopant or a different dopant concentration than the first layer.

[0017] Alternatively or additionally, in some such examples, the device comprises a three dimensional (3D) NAND memory device, and the feature comprises one of a channel hole or a contact hole.

[0018] Alternatively or additionally, in some such examples, the device comprises a dynamic random access memory (DRAM) device, and the feature comprises a capacitor hole.

[0019] Another example provides a deposition tool. The deposition tool comprises a processing chamber. The deposition tool further comprises a substrate support disposed in the processing chamber. The deposition tool further comprises flow control hardware configured to control flow of a film precursor and one or more etch rate-modifying dopant precursors into the processing chamber. The deposition tool further comprises a controller configured to, in a first deposition step, operate the flow control hardware to cause introduction of the film precursor and the one or more etch rate-modifying dopant precursors into the processing chamber under conditions configured to form a first film portion on a substrate, the first film portion comprising a first dopant profile. The controller is further configured to, in a second deposition step, operate the flow control hardware to cause introduction of the film precursor and the one or more etch rate-modifying dopant precursors into the processing chamber under conditions configured to form a second film portion on the first film portion, the second film portion comprising a second dopant profile, the second film portion comprising a slower lateral etch rate than the first film portion.

[0020] In some such examples, the controller is configured to, in the first deposition step, operate the flow control hardware to cause flow of a first etch rate-modifying dopant precursor of the one or more etch rate-modifying dopant precursors, thereby forming the first film portion comprising a first etch rate-modifying dopant and, in the second deposition step, operate the flow control hardware to cause flow of a second etch rate-modifying dopant precursor of the one or more etch rate-modifying

dopant precursors, thereby forming the second film portion comprising a second etch rate-modifying dopant that is different from the first etch rate-modifying dopant.

[0021] Alternatively or additionally, in some such examples, the controller is configured to, in the first deposition step, operate the flow control hardware to cause flow of an etch rate-modifying dopant precursor at a first molar ratio to the film precursor, thereby forming the first film portion comprising an etch rate-modifying dopant at a first dopant concentration and, in the second deposition step, operate the flow control hardware to cause flow of the etch rate-modifying dopant precursor at a second molar ratio to the film precursor, thereby forming the second film portion comprising the etch rate-modifying dopant at a second dopant concentration different from the first dopant concentration.

[0022] Alternatively or additionally, in some such examples the one or more etch rate-modifying dopant precursors comprises one or more of a nitrogen-containing precursor, a phosphorus-containing precursor, a carbon-containing precursor, hydrogen, an arsenic-containing precursor, or a boron-containing precursor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] FIG. 1A shows a schematic depiction of an example hole formed in an undoped layer by a cryogenic etching process.

[0024] FIG. 1B illustrates an example hole formed by a cryogenic etching process through a layer comprising a plurality of different dopant profiles.

[0025] FIGS. 2A-2B show structures formed in an example process for performing cryoetching through layers having different dopant profiles.

[0026] FIGS. 3A-3B show a flow diagram of an example method for depositing and etching through a plurality of film portions comprising a respective plurality of different dopant profiles.

[0027] FIG. 4 shows a plot of critical dimension as a function of depth for a hole etched in a silicon oxide film doped with a relatively higher nitrogen dopant concentration and a hole etched in a silicon oxide film doped with a relatively lower nitrogen dopant concentration.

[0028] FIGS. 5A-5B schematically show examples of an undoped silicon oxide film and a nitrogen-doped silicon oxide film after performing cryoetching using the same etching chemistries and conditions.

[0029] FIGS. 6A-6B schematically show examples of an undoped silicon oxide film and a carbon-doped silicon oxide film after performing cryoetching using the same etching chemistries and conditions.

[0030] FIG. 7 schematically shows a schematic depiction of an example processing tool that can be used to deposit a silicon oxide film doped with an etch rate-modifying dopant for controlling a lateral etch rate in a cryoetching process.

[0031] FIG. 8 schematically shows an example etching tool configured to perform cryoetching processes.

[0032] FIG. 9 schematically shows a block diagram of an example computing system.

DETAILED DESCRIPTION

[0033] The term "aspect ratio" generally represents a ratio between a depth of a substrate feature such as a hole and an average width of the feature.

[0034] The term "critical dimension" generally represents a width of a feature, such as a diameter of a hole.

[0035] The term "dopant profile" generally represents a type of etch rate-modifying dopant or dopants in a film and/or a concentration of each etch rate-modifying dopant in the film.

[0036] The term "etch" and variants thereof generally represent a process in which a material is selectively removed from a substrate. An etch using gas phase etchants is referred to as a "dry etch". In some etching processes, a mask is used to protect some regions of a substrate surface from being etched.

[0037] The term "etch rate" generally represents a depth of an etch as a function of time, and is a measure of a speed of an etching process. The term "lateral etch rate" generally represents an etch rate in a direction parallel to a plane of a substrate surface. The term "vertical etch rate" generally represents an etch rate in a direction normal to a plane of a substrate surface.

[0038] The term "etch rate-modifying dopant" generally represents a dopant in a film that allows the film to be etched at a different rate compared to an undoped film. Examples of dopants for modifying the etch rate of silicon oxide films include nitrogen, phosphorus, carbon, boron, arsenic, and combinations of two or more thereof.

[0039] The term "etch rate-modifying dopant precursor" generally represents a material comprising an etch rate-modifying dopant that can react with a silicon-

containing precursor and an oxygen-containing gas to deposit a doped silicon oxide layer. Examples of etch rate-modifying dopant precursors include hydrogen, nitrogen-containing precursors, phosphorus-containing precursors, carbon-containing precursors, boron-containing precursors, and arsenic-containing precursors.

[0040] Examples of nitrogen-containing precursors include ammonia (NH_3) and amino silanes. Examples of amino silanes include bis(diethylamino)silane, di(isopropylamino)silane (DIPAS), bis(t-butylamino) silane (BTBAS), (di-sec-butylamino)silane, and tris(dimethylamino)silane (3DMAS).

[0041] Examples of phosphorus-containing precursors include phosphine (PH_3) and alkyl phosphines such as trimethylphosphine, triethylphosphine, and tributylphosphine.

[0042] An example of a suitable boron-containing precursor is diborane (B_2H_6).

[0043] Examples of carbon-containing precursors include carbon monoxide (CO), alkanes, alkenes, alkynes, cyclic hydrocarbons, aromatics, alcohols, diols, aldehydes, esters, ethers, ketones, alkyl amines, alkyl diamines, and organosilicon compounds. Examples of suitable alkanes (C_nH_{2n+2} in which n = 1 to 10) may include methane, ethane, propane, and butane. Examples of suitable alkenes (C_nH_{2n} in which n = 2 to 10, for an alkene with a single carbon-carbon double bond) may include ethene, propene, and butene. Examples of suitable alkynes (C_nH_{2n-2} in which n = 2 to 10, for an alkyne with a single carbon-carbon triple bond) may include acetylene, propyne, and butyne. Examples of suitable cyclic hydrocarbons may include cyclobutane, cyclopentane, and cyclohexane. Examples of suitable aromatics may include benzene, toluene, pyridine, and pyrimidine. Examples of suitable alcohols may include methanol, ethanol, and propanol. Examples of suitable diols may include ethylene glycol, propylene glycol, and hydroquinone. Examples of suitable aldehydes may include formaldehyde and acetaldehyde. Examples of suitable esters may include ethyl formate, methyl acetate, and ethyl acetate. Example of suitable ethers may include diethyl ether, methyl phenyl ether, and aromatic ethers such as furan. Examples of suitable ketones may include acetone and methyl ethyl ketone. Examples of suitable alkyl halides may include ethyl fluoride, isopropyl bromide, and t-butyl chloride. Examples of suitable alkyl amines may include methylamine, dimethylamine, trimethylamine, and piperidine. Examples of suitable alkyl diamines may include ethylenediamine and 1,3-diaminopropane. Examples of suitable organosilicon

compounds include methylsilane, dimethylsilane, trimethylsilane, and siloxanes such as dimethyldiethoxysilane.

[0044] An example of an arsenic-containing precursor is arsine (AsH_3).

[0045] The term "etchant" generally represents a chemical used in an etching process to chemically remove and/or facilitate chemical removal of material from a substrate. The term "etchant gas mixture" generally represents a mixture of one or more gases comprising at least one etchant. Example etchants for plasma etching of silicon oxide include fluorine-containing etchants, such as hydrogen fluoride (HF), sulfur tetrafluoride (SF_4), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), boron trifluoride (BF_3), silicon tetrafluoride (SiF_4), phosphorus trifluoride (PF_3), phosphorus pentafluoride (PF_5), tungsten hexafluoride (WF_6), molybdenum hexafluoride (MoF_6), fluorocarbons (C_xF_y) such as CF_4 and C_2F_6, and hydrofluorocarbons ($C_xF_yH_z$). In some examples, hydrogen (H_2) can be used as an etchant. In some examples, an oxygen-containing etchant can be used, such as oxygen (O_2), carbon monoxide (CO), or carbonyl sulfide (COS).

[0046] The term "feature" generally represents a region of a substrate where material has been removed (e.g., by etching) to form a recess in a substrate surface. Example features that can be formed by etching include holes.

[0047] The term "film" generally represents a layer of a material deposited on a substrate. A film portion is a portion of a thickness of a film. Different film portions of a film can have different dopant profiles, causing different etch rates.

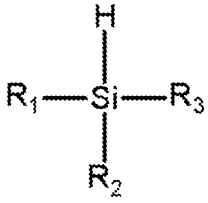
[0048] The term "oxygen-containing gas" generally represents a gas species containing oxygen available for reacting with an oxide-film precursor to form an oxide film. Examples of oxygen-containing gases comprise molecular oxygen (O_2), ozone (O_3), nitrogen oxides such as nitrous oxide (N_2O), hydrogen peroxide (H_2O_2), and water vapor (H_2O).

[0049] The term "processing chamber" generally represents an enclosure in which chemical and/or physical processes are performed on substrates. The pressure, temperature and atmospheric composition within a processing chamber may be controllable to perform chemical and/or physical processes.

[0050] The term "processing tool" generally represents a machine including a processing chamber and other hardware configured to enable processing to be carried out in the processing chamber.

[0051] The term "radiofrequency (RF) power source" generally represents a component of a processing tool configured to apply power to a pair of electrodes in a processing chamber to form a plasma between the electrodes.

[0052] The term "silicon-containing precursor" generally represents any material that can be introduced into a processing chamber in a gas phase to form a silicon oxide film on the substrate. Example silicon-containing precursors for forming silicon oxide films may comprise materials having the general structure:



where R_1, R_2 and R_3 may be the same or different substituents, and may include silanes, siloxy groups, amines, halides, hydrogen, or organic groups, such as alkylamines, alkoxy, alkyl, alkenyl, alkynyl and aromatic groups.

[0053] Example silicon-containing precursors include polysilanes (H_3Si-$(SiH_2)_n$-SiH_3), where n $\geq$1, such as silane, disilane, trisilane, tetrasilane, and trisilylamine.

[0054] In some examples, the silicon-containing precursor is an alkoxysilane. Alkoxysilanes that may be used include the following:

H_x-Si-$(OR)_y$, where x = 1-3, x+y = 4 and each R is a substituted or unsubstituted alkyl, alkenyl, alkynyl or aromatic group; and

$H_x(RO)_y$,-Si-Si-$(OR)_yH_x$, is a substituted or unsubstituted alkyl, alkenyl, alkynyl or aromatic group.

[0055] Examples of silicon-containing precursors include tetraethyl orthosilicate (TEOS), tetramethoxysilane (TMOS), methylsilane, trimethylsilane (3MS), ethylsilane, butasilanes, pentasilanes, octasilanes, heptasilane, hexasilane, cyclobutasilane, cycloheptasilane, cyclohexasilane, cyclooctasilane, cyclopentasilane, l,4-dioxa-2,3,5,6-tetrasilacyclohexane, diethoxymethylsilane (DEMS), diethoxysilane (DES), dimethoxymethylsilane, dimethoxysilane (DMOS), methyl-diethoxysilane (MDES), methyl-dimethoxysilane (MDMS), t-butoxydisilane, triethoxysilane (TES), and trimethoxysilane (TMS or TriMOS).

[0056] In some examples, the silicon-containing precursor may be a siloxane. Example siloxanes include octamethylcyclotetrasiloxane (OMCTS), octamethoxydodecasiloxane (OMODDS), tetramethylcyclotetrasiloxane (TMCTS), triethoxysiloxane (TRIES), and tetraoxymethylcyclotetrasiloxane (TOMCTS).

[0057] In some examples, the silicon-containing precursor may be an aminosilane, such as bis(diethylamino)silane, di(isopropylamino)silane (DIPAS), bis(t-butylamino) silane (BTBAS), (di-sec-butylamino)silane, and tris(dimethylamino)silane (3DMAS). Aminosilane precursors include the following: H_x-Si-$(NR)_y$, where x = 1-3, x+y = 4, and R is a substituted or unsubstituted alkyl, alkenyl, alkynyl or aromatic group or hydride group.

[0058] In some examples, a halogen-containing silane may be used such that the silane includes at least one hydrogen atom. Such a silane may have a chemical formula of SiX_aH_y where $y \geq 1$. For example, dichlorosilane (H_2SiCl_2) may be used in some examples.

[0059] The term "showerhead" generally represents a processing chemical outlet comprising a plurality of holes distributed across an area.

[0060] The term "substrate" generally represents any object on which a film can be deposited.

[0061] The term "substrate support" generally represents any structure for supporting a substrate in a processing chamber. Examples comprise chucks, pedestals, and showerhead pedestals used for backside deposition processes.

[0062] The term "3D memory structure" may generally refer to a structure formed at any point in a fabrication process for forming a memory device comprising a stacked architecture in which memory cells are layered vertically. Examples of 3D memory structures include structures formed in 3D NAND memory, 3D NOR, and 3D DRAM memory fabrication processes.

[0063] The term "3D NAND" is an acronym for three-dimensional NOT AND memory, and represents memory architecture based upon NOT AND logic gates.

[0064] The term "3D NOR" is an acronym for three-dimensional NOT OR memory, and represents memory architecture based upon NOT OR logic gates.

[0065] The term "DRAM" is an acronym for dynamic random access memory.

[0066] As mentioned above, fabrication of integrated circuits can involve many steps of material deposition, patterning and removal. Some fabrication processes

involve etching a hole into one or more previously-deposited material layers. For example, three-dimensional (3D) memory devices, such as 3D NAND and 3D NOR semiconductor devices, are built upon stacked pairs of materials, with the active device layer being one of the pairs and the other being a dielectric for electrical isolation. The stack of layers can be referred to as a "mold stack". The process of creating memory cells in the active device layers of the mold stack involves etching high aspect ratio holes through the mold stack. Similarly, high aspect ratio holes are etched into a dielectric layer adjacent to the mold stack for forming electrical contacts to the memory cells. The holes through the mold stack can be referred to as "channel holes". The holes through the adjacent dielectric layer can be referred to as "contact holes."

[0067] Other processes besides 3D memory device fabrication can involve etching high-aspect ratio holes into a substrate. Another example is the fabrication of planar dynamic random access memory (DRAM). Some DRAM devices include memory cells formed from a transistor and a capacitor. The capacitor can be cylindrical in shape. To form the cylindrical capacitors of the memory cells, high aspect ratio holes are etched into the underlying substrate. Then, the plates and dielectric layers of the capacitors are deposited within the cylindrical holes. High aspect ratio holes can be formed in many other integrated circuit manufacturing processes.

[0068] Dry etching processes can be used to etch high aspect ratio holes. Dry etching processes are etching processes that utilize gas phase etching chemistries. A plasma can be used to create reactive etching species from a precursor gas in a dry etching process. The plasma conditions and gas pressures used in an etching tool processing chamber can be controlled to perform a highly directional etch, where a rate of vertical etching (normal to a substrate surface) is much higher than a rate of lateral etching (parallel to a substrate surface).

[0069] In some dry etching processes, a material being exposed to the dry etch environment is actively cooled. Such an etching process is referred to as cryogenic etching, or cryoetching. The active cooling may result in the substrate having a temperature above, at, or below ambient temperatures in various processes. Cooling the exposed material removes heat from the substrate as chemical and physical reactions occur between the deposited material and the etchants. Keeping feature sidewalls cold during etching can enable ions in an etching process to move deeper into the gap. As more reactants are at the bottom of the gap, the etch rate can be enhanced. This can have a beneficial impact on relatively longer, deeper etches to keep the surrounding

material intact as the etch proceeds in time. As such, cryogenic etching tools can be used for etching high aspect ratio holes, such as in the applications described above.

[0070] However, etching such high aspect ratio holes can pose challenges. For example, cryoetching of a material, such as silicon oxide, can create a tapered hole profile. FIG. 1A shows a schematic depiction of an example hole 100 formed in a layer 102 by a cryogenic etching process. The term "CD" represents critical dimension, which is a diameter of the hole 100. CD1 represents the hole diameter at an opening of a hole. The opening of the hole 100 at CD1 can be immediately beneath a hardmask formed on a surface of the material through which the hole 100 is etched. The hardmask is not shown in FIG. 1A. CD2 represents the hole diameter at a bottom of the hole 100.

[0071] As can be seen, the hole 100 has a tapered profile with dissimilar diameters at the opening of the hole and the bottom of the hole where CD1 is greater than CD2. Such dissimilarities can create issues in integrated circuit fabrication and/or performance. As the depth and critical dimension of etched features continue to increase with advancements in integrated circuit design and manufacturing, controlling critical dimension as a function of depth is becoming more and more important.

[0072] Accordingly, examples are disclosed that relate to dopants in a material being etched to control a lateral etch rate of a cryoetching process. Briefly, two or more film portions are deposited on a substrate, each film portion comprising a different dopant profile. The term "dopant profile" can represent a type of etch rate-modifying dopant or combination of etch rate-modifying dopants in a film, and/or a concentration of each etch rate-modifying dopant in the film. Then, a cryoetching process forms a feature through the film portions. An etch rate-modifying dopant can be used to increase a lateral etch rate in a film portion closer to a hole bottom and/or reduce a lateral etch rate of a film portion closer to a hole opening. In various examples, a material comprising an etch rate-modifying dopant can have a lateral etch rate that is higher or lower than that of an undoped material. By controlling the lateral etch rate of different film portions, a feature can be etched with a reduced degree of tapering. Reducing a degree of taper of etched holes can provide various benefits for later processing steps. As one example, all surfaces within a hole would look identical from a wet removal perspective, ensuring consistent cleaning from top to bottom layers. Another example would be in simplification of the complicated dry etch process, as much time and engineering is spent optimizing etch hole critical dimensions.

[0073] By using a higher concentration of one or more etch rate-modifying dopants that can reduce a lateral etch rate in a film portion closer to a hole opening, and a lower concentration of the one or more etch rate-modifying dopants in a film portion closer to a hole bottom, a lateral etch rate within the hole closer to the hole opening can be reduced compared to a lateral etch rate closer to the hole bottom.

[0074] Likewise, by utilizing a higher concentration of one or more etch rate-modifying dopants that increase a lateral etch rate in a film region closer to a hole bottom, and a lower concentration of the one or more etch rate-modifying dopants that increase the lateral etch rate in a film region closer to a hole opening, a lateral etch rate within the hole closer to the hole bottom can be increased compared to a lateral etch rate within the hole closer to the hole opening. In this manner, etch rate-modifying dopant concentrations can be varied in a layer (or layers) through which a high aspect ratio hole will be formed by cryoetching to help achieve a more consistent hole diameter throughout a depth of the hole.

[0075] FIG. 1B illustrates an example hole 104 formed by a cryogenic etching process through a layer 106 comprising a plurality of different dopant profiles. More particularly, FIG. 1B illustrates hole 104 in which a bottom diameter (CD3) is similar to or a same diameter as a top diameter (CD1). Such a hole profile can be particularly beneficial when forming extremely narrow features. As one example, a hole for forming a capacitor in a DRAM device (e.g. a planar DRAM device) can have a CD of less than 20 nanometers. At such small diameters, even small variations in hole diameter as a function of depth can cause issues in later fabrication steps and/or device performance. It is noted that an overall hole diameter profile as a function of depth is particularly sensitive to the hole diameter close to an opening of the hole (e.g. immediately below a hardmask layer). As such, a mechanism for reducing lateral etching rates close to an opening of the hole can be of particular benefit.

[0076] Any suitable element or elements can be used as dopants in a film or a stack of films that will later be etched using a cryoetching process to form a hole. For example, nitrogen can be used as an etch rate-modifying dopant in silicon oxide. As explained in more detail below, doping silicon oxide with nitrogen can reduce a lateral etch rate of the silicon oxide in a cryoetching process compared to undoped silicon oxide. As such, a region of a silicon oxide film (or stack of films including silicon oxide films) closer to an opening of a hole can be doped with a relatively higher concentration of nitrogen, and a region closer to a hole bottom can be doped with a relatively lower

concentration of nitrogen, to help avoid a tapered hole profile. Doping can be performed, for example, by including a nitrogen-containing precursor in a gas mixture used for film deposition. An etch rate-modifying dopant concentration can be varied, for example, by varying a mole fraction of the nitrogen-containing precursor in the gas mixture. Example methods of depositing doped silicon oxide films are described in more detail below.

[0077] Other examples of etch rate-modifying dopants include carbon and phosphorus. Doping silicon oxide with phosphorus can increase a lateral etch rate of silicon oxide. Thus, a region of a silicon oxide film, or a stack of films including silicon oxide films, closer to an opening of a hole being etched can include a lower concentration of phosphorus than a region closer to a bottom of the hole being etched to help avoid a tapered hole profile. Doping a silicon oxide film with carbon can help reduce a lateral etch rate of silicon oxide. Doping a silicon oxide film with carbon also can help increase a resistance to higher ion energies during an etching process. Thus, a region of a silicon oxide film, or a stack of films including silicon oxide films, closer to an opening of a hole being etched can include a higher concentration of carbon than a region closer to a bottom of the hole being etched to help avoid a tapered hole profile. In some examples, two or more etch rate-modifying dopants can be used in a film portion. Further, dopants other than nitrogen, carbon, and phosphorus can be used as etch rate-modifying dopants in some examples. Other examples of etch rate-modifying dopants include boron and arsenic.

[0078] In further examples, hydrogen can be used as an etch rate-modifying dopant. Doping a film with hydrogen can lead to a lower film density compared to an undoped film. This can increase the vertical etch rate of the film. In some examples, a film doped with hydrogen can be formed using a hydrogen-containing precursor, such as molecular hydrogen (H_2), during PECVD. Additionally or alternatively, H doping can be achieved using H from precursor molecules. For example, when depositing silicon oxide using silane (SiH_4) precursor, a lower plasma power can be used during film deposition to preserve Si-H bonding in precursor molecules as the film is deposited. Use of a lower plasma power also can help preserve N-H bonding in films that utilize ammonia as a film precursor. Thus, plasma conditions also can be adjusted to increase to form an H-doped film.

[0079] FIGS. 2A-2B schematically show structures that are formed in an example process for controlling a diameter of a hole etched into a layer by varying a

dopant profile within the layer. FIG. 2A illustrates a film stack 200 in which each film portion in the stack has a different dopant profile. Film stack 200 comprises a first film portion 202 comprising a first dopant profile, a second film portion 204 comprising a second dopant profile, and a third film portion 206 comprising a third dopant profile. The term "dopant profile" can represent a type of etch rate-modifying dopant or combination of etch rate-modifying dopants in a film, as well as a concentration of each etch rate-modifying dopant in the film. In some examples, each film portion in the film stack 200 of Step 1 can represent a silicon oxide film. In the case of nitrogen as an etch rate-modifying dopant, as described above, to help avoid a tapered hole profile, first film portion 202 can have a higher concentration of nitrogen than second film portion 204. Similarly, second film portion 204 can have a higher concentration of nitrogen than third film portion 206. In the case of phosphorus as a dopant, to help avoid a tapered hole profile, first film portion 202 can have a lower concentration of phosphorus than second film portion 204. Similarly, second film portion 204 can have a lower concentration of phosphorus than third film portion 206. In the case of carbon as a dopant, to help avoid a tapered hole profile, first film portion 202 can have a higher concentration of carbon than second film portion 204. Similarly, second film portion 204 can have a higher concentration of carbon than third film portion 206. In yet other examples, mixtures of two or more dopants can be used to modify a lateral etching rate. While three film portions are shown in the example of FIG. 2A, in other examples, any other suitable number of film portions with different dopant profiles can be used. In yet further examples, a film may have a continuous dopant concentration gradient as a function of thickness, rather than having discrete layers with different dopant profiles.

[0080] The film portions of the film stack 200 of FIG. 2A can be deposited in any suitable manner. As one example, silicon oxide layers can be formed using plasma-enhanced chemical vapor deposition (PECVD), with silane as a silicon precursor and nitrous oxide as an oxidant. In such examples, the dopant source can be added directly to the silane/nitrous oxide gas mixture. As another example, the silicon oxide can be deposited using tetraethyl orthosilicate (TEOS) as a precursor, and oxygen as an oxidant. In such a process, the etch rate-modifying dopant can be introduced cyclically between silicon oxide deposition steps using a plasma with suitable energy to implant the etch rate-modifying dopant into the silicon oxide. In yet other examples, other deposition techniques, such as thermal CVD (which uses heat in the absence of a plasma for reaction energy), and atomic layer deposition (ALD), can be used to form a doped

silicon oxide layer. In further examples, any other suitable method or methods can be used to form doped film layers to control a lateral etching rate when etching a hole in a substrate.

[0081] FIGS. 3A-3B show an example method 300 for depositing film portions with different dopant profiles, and etching a hole through the film portions. At 302, method 300 comprises depositing a second film portion on a substrate, the second portion comprising a film material with a second dopant profile. In some examples, at 304, the method comprises depositing a third film portion comprising a third dopant profile on the substrate prior to depositing the second film portion at 302. In some examples, at 306, method 300 comprises depositing the film portions using PECVD. In other examples, at 308, method 300 comprises depositing the film portions using thermal CVD. In further examples, at 310, method 300 comprises depositing the film portions using ALD.

[0082] Continuing, at 312, method 300 further comprises depositing a first film portion on the second film portion, the first film portion comprising the film material with a first dopant profile different than the second dopant profile. The first dopant profile and second dopant profile can differ in any suitable manner such that the lateral etch rate of the first film portion is different than the lateral etch rate of the second film portion. For example, the first and second dopant profiles can have different dopant concentrations, different types of etch rate-modifying dopants, and/or a different combination of dopant species. In some examples, at 314, the first dopant profile comprises a first concentration of a dopant, and the second dopant profile comprises a second concentration of the dopant. Further, in some examples, at 316, the dopant comprises one of nitrogen, carbon, phosphorus, hydrogen, arsenic, or boron. In some examples, at 318, the first film portion comprises a film material doped with a first dopant species, and the second film portion comprises the film material doped with a second dopant species different from the first dopant species. In some examples, at 320, the film material comprises doped silicon oxide. In other examples, any suitable film material can be used.

[0083] Any suitable etch rate-modifying dopant precursor can be used for depositing the film portions. Examples of etch rate-modifying dopant precursors include hydrogen, nitrogen-containing precursors, phosphorus-containing precursors, carbon-containing precursors, boron-containing precursors, and arsenic-containing precursors. Examples of suitable nitrogen-containing precursors include ammonia

(NH_3), hydrazine, and aminosilanes. Examples of aminosilanes include bis(diethylamino)silane, di(isopropylamino)silane (DIPAS), bis(t-butylamino) silane (BTBAS), (di-sec-butylamino)silane, and tris(dimethylamino)silane (3DMAS). Examples of phosphorus-containing precursors include phosphine (PH_3) and alkyl phosphines such as trimethylphosphine, triethylphosphine, and tributylphosphine. An example of an arsenic-containing precursor is arsine (AsH_3). An example of a suitable boron-containing precursor is diborane (B_2H_6).

[0084] Suitable carbon-containing precursors can include a variety of carbon-containing molecules that are gas phase at processing temperatures. Examples of suitable carbon sources include alkanes, alkenes, alkynes, cyclic hydrocarbons, aromatics, alcohols, diols, aldehydes, esters, ethers, ketones, alkyl amines, alkyl diamines, and organosilicon compounds. Examples of suitable alkanes (C_nH_{2n+2} in which n = 1 to 10) can include methane, ethane, propane, and butane. Examples of suitable alkenes (C_nH_{2n} in which n = 2 to 10, for an alkene with a single carbon-carbon double bond) can include ethene, propene, and butene. Examples of suitable alkynes (C_nH_{2n-2} in which n = 2 to 10, for an alkyne with a single carbon-carbon triple bond) can include acetylene, propyne, and butyne. Examples of suitable cyclic hydrocarbons can include cyclobutane, cyclopentane, and cyclohexane. Examples of suitable aromatics can include benzene, toluene, pyridine, and pyrimidine. Examples of suitable alcohols can include methanol, ethanol, and propanol. Examples of suitable diols can include ethylene glycol, propylene glycol, and hydroquinone. Examples of suitable aldehydes can include formaldehyde and acetaldehyde. Examples of suitable esters can include ethyl formate, methyl acetate, and ethyl acetate. Examples of suitable ethers can include diethyl ether, methyl phenyl ether, and aromatic ethers such as furan. Examples of suitable ketones can include acetone and methyl ethyl ketone. Examples of suitable alkyl halides can include ethyl fluoride, isopropyl bromide, and t-butyl chloride. Examples of suitable alkyl amines can include methylamine, dimethylamine, trimethylamine, and piperidine. Examples of suitable alkyl diamines can include ethylenediamine and 1,3-diaminopropane. Examples of suitable organosilicon compounds include methylsilane, dimethylsilane, trimethylsilane, and siloxanes such as dimethyldiethoxysilane.

[0085] Continuing with method 300, at 321, in some examples the method comprises using first plasma conditions to deposit the first film portion, and using second plasma conditions to deposit the second film portion, the second plasma

conditions different than the first plasma conditions. As discussed above, this can help control H doping in a deposited film.

[0086] Continuing to FIG. 3B, method 300 further comprises cryoetching to form a feature through the deposited film portions. Method 300 further comprises, at 322, cooling the substrate. In some examples, at 324, method 300 comprises cooling the substrate to a temperature of -150 °C to 40 °C. Method 300 further comprises, at 326, while cooling the substrate, etching through the first film portion comprising the first dopant profile. In some examples, at 328, the etching at 326 comprises using an etchant gas mixture comprising one or more of HF, SF_4, SF_6, NF_3, BF_3, SiF_4, PF_3, PF_5, WF_6, MoF_6, a fluorocarbon, a hydrofluorocarbon, H_2, CO, COS, and O_2.

[0087] Continuing, method 300 further comprises, at 330, while cooling the substrate, etching at least partially through the second film portion comprising the second dopant profile. In some examples, at 332, such as where a third film portion has been deposited, method 300 comprises etching fully through the second film portion and at least partially through the third film portion comprising the third dopant profile.

[0088] Referring briefly back to FIG. 2B, this figure shows the film portions of FIG. 2A after using cryoetching to etch a feature 208 through first film portion 202, second film portion 204, and third film portion 206. In this example, the feature 208 is a channel hole of a 3D NAND memory structure. However, in other examples, other types of holes can be etched. In some examples, feature 208 comprises a contact hole of a 3D NAND memory structure. In further examples, feature 208 can be a capacitor hole of a DRAM device. Feature 208 can be filled at a later processing step. While the depicted feature 208 extends fully through first film portion 202, second film portion 204 and third film portion 206, in other examples, a feature may extent only partially through a deepest film portion etched to form the feature.

[0089] Any suitable processing conditions can be used for etching feature 208. As mentioned above, a reduced temperature etch can be performed where a substrate support is actively cooled during etching. In some examples, the substrate support is cooled to a temperature within a range of -150 °C to 40 °C, -70 °C to 20 °C, or -50 °C to 0 °C. Any suitable pressure can be used, such as a pressure within a range of 5 mTorr to 80 mTorr, 5 mTorr to 50 mTorr, or 10 mTorr to 50 mTorr. Further, any suitable plasma conditions can be used. Examples include radiofrequency power of 5 kW to 100 kW and frequencies of 400 kHz, 1 MHz, 2 MHz, 13.56 MHz, 27 MHz, 60 MHz, 90 MHz, 100 MHz, and 120 MHz. In some examples, a radiofrequency plasma can be

formed using a plurality of different frequencies and/or powers. For example, a plasma can comprise both a higher frequency radiofrequency energy component ("HF component") and a lower frequency radiofrequency energy component ("LF component"). Examples of LF radiofrequency energy include a frequency of 400 kHz and powers of 5 kW to 100 kW. Examples of HF radiofrequency energy include a frequency of 60 MHz and powers of 2 kW to 40 kW. In some examples, the plasma can be pulsed. Pulsing the plasma can comprise pulsing the radiofrequency energy between zero and a peak power. In other examples, the plasma can be pulsed between multiple different power levels.

[0090] Any suitable etchant gas mixture can be used. Example etchants for plasma etching of silicon oxide include fluorine-containing etchants, such as HF, SF_4, SF_6, NF_3, BF_3, SiF_4, PF_3, PF_5, WF_6, MoF_6, fluorocarbons, such as CF_4, C_2F_6, C_4F_6, C_3F_8, and C_4F_8, hydrofluorocarbons such as CH_2F_2, and mixtures of two or more thereof. Example etchants further include H_2, O_2, CO, and COS. In some examples, an inert gas is included in an etchant gas mixture. As shown schematically in FIG. 2, the use of the stack of film portions with different dopant profiles when cryoetching a hole can help to achieve a hole with less taper as a function of depth than cryoetching undoped silicon oxide. In some examples, a CD at the opening of a feature is within 10% of a CD at the bottom of the feature.

[0091] The use of different doping profiles to achieve less taper in an etched hole may be particularly useful for cryoetching compared to dry etching that does not utilize a reduced substrate temperature. Without wishing to be bound by theory, byproducts formed during dry etching of silicon oxide etch may tend to stick to the sidewalls of the hole, thereby behaving like a protective barrier against lateral etching. With lower temperatures, the sticking coefficient of the byproducts on the walls is higher. With the addition of N, salt-forming byproducts are more readily formed, thereby creating thicker protective layers. However, film portions with different dopant profiles also can be used in a non-cryogenic dry etching process.

[0092] Alternatively or additionally to varying a dopant profile in a film or a film stack to control lateral etching rates, lateral etching rates also may be controlled by controlling etching chemistry and/or etching conditions (e.g. pressure, plasma power, etc.) as a function of hole depth during etching. For example, an etchant gas mixture can be varied as a function of a hole depth of an etching process to control

lateral etching as a function of depth. Such changes of etching chemistry and/or conditions can be used in conjunction with a varying dopant profile.

[0093] Referring once more to FIG. 3B, in some examples, at 334, method 300 comprises using an etchant gas mixture that is different than the etchant gas mixture used at step 326. An etchant gas mixture can be varied based on the dopant profile of a film portion being etched. For example, carbon-containing etchant gases (such as fluorocarbons and hydrofluorocarbons listed above) can be effective for etching some silicon oxide films due to polymerizing etching chemistries. However, use of carbon-containing etchant gases can result in carbon deposition near the opening of a hole and/or on a hardmask. These issues can pose challenges at small CD, as carbon deposition near the hole opening can pinch off the hole and restrict flow of etchant gas into the hole. The use of carbon-containing etchant gases can be avoided when etching through a film portion comprising a relatively higher concentration of C dopant. This is because a sufficient etch rate can be achieved without relying on polymerizing etching chemistries of carbon-containing etchant gases. Thus, in examples where a film portion being etched has a relatively higher concentration of C dopant, the etchant gas mixture can be adjusted to utilize relatively lower proportion of carbon-containing etchant gas than an etchant gas mixture used for a different film portion comprising a lower concentration of C dopant. For example, the etchant gas mixture can instead include a relatively greater proportion of HF, NF_3, SF_4, SF_6, BF_3, SiF_4, PF_3, PF_5, WF_6, MoF_6, H_2, CO, COS, and/or O_2 compared to other etchant gas mixtures.

[0094] As another example, relatively higher ion energies can be used in etching for film regions with relatively higher carbon dopant concentrations, and relatively lower ion energies can be used for film regions with relatively lower carbon dopant concentrations. This is because relatively higher carbon dopant concentrations may provide more protection against damage from ions than relatively lower carbon dopant concentrations.

[0095] Method 300 can be performed as part of a fabrication process for a memory device, such as a 3D NAND memory device or a DRAM device. In some examples, at 336, method 300 comprises etching a capacitor hole for a DRAM device. In some examples, at 338, method 300 comprises etching a channel hole or a contact hole for a 3D NAND memory device. Such features can be filled during a later processing step.

[0096] FIG. 4 shows a plot of critical dimension as a function of depth for holes etched in a silicon oxide films with a relatively higher nitrogen dopant concentration and with a relatively lower nitrogen dopant concentration. The top of the graph represents a location immediately below a hard mask used to define the hole being etched. The etching conditions and chemistries were the same for the two films. As can be seen, the higher nitrogen doping results in a narrower critical dimension for the etching conditions used. Further, there is less variation in the critical dimension for the higher nitrogen dopant concentration than for the relatively lower nitrogen dopant concentration. This indicates that nitrogen doping concentrations can be used to help control critical dimensions of an etched hole.

[0097] FIGS. 5A-5B schematically show cross-sectional views illustrating an undoped silicon oxide film 500 (FIG. 5A) and a nitrogen-doped silicon oxide film 510 (FIG. 5B) after performing cryoetching using the same etching chemistries and conditions. Each film comprises a hardmask 502, 512 and a hole 504, 514 etched through the hardmask and the film. Due to lateral etching, the undoped silicon oxide film 500 is etched laterally below hardmask 502. As indicated at 506, this results in bowing. Due to bowing, a critical dimension at 506 is larger than the width of the hole through the hardmask 502. As illustrated in FIG. 5B, the nitrogen-doped silicon oxide film 510 exhibits less bowing, as indicated at 516. As such, hole 514 comprises a narrower critical dimension at 516 immediately below the hard mask 512 compared to the critical dimension at 506 of the undoped silicon oxide film 500. This again indicates that nitrogen doping concentrations can be used to help control critical dimensions of an etched hole. Nitrogen doping also can help reduce bowing.

[0098] FIGS. 6A-6B schematically show cross-sectional views illustrating an undoped silicon oxide film 600 (FIG. 6A) and a carbon-doped silicon oxide film 610 (FIG. 6B) after performing cryoetching using the same etching chemistries and conditions. The undoped silicon oxide film 600 comprises a hardmask 602 and a hole 604 etched through the hardmask 602 and the undoped silicon oxide film 600. Due to lateral etching, the undoped silicon oxide film 600 is etched laterally below hardmask 602. This results in bowing, as indicated at 606, where a critical dimension at 606 is larger than the width of the hole through the hardmask 602. As illustrated in FIG. 6B, the carbon-doped silicon oxide film 610 comprises a hardmask 612 and a hole 614 etched through the hardmask 612 and the carbon-doped silicon oxide film 610. The carbon-doped silicon oxide film 610 has a narrower critical dimension immediately

below the hard mask 612 (indicated at 616) compared to the undoped silicon oxide film 602. Here, the critical dimension at 616 is similar to the width of the hole 614. This indicates that carbon doping concentrations can be used to help control critical dimensions of an etched hole. Further, doping a film with carbon can help avoid and/or eliminate bowing.

[0099] FIG. 7 schematically shows a schematic depiction of an example processing tool 700 that can be used to deposit a silicon oxide film doped with an etch rate-modifying dopant for controlling a lateral etch rate. Processing tool 700 is configured as a plasma enhanced chemical vapor deposition (PECVD) tool. In other examples, any other suitable deposition tool can be used to deposit a silicon oxide material doped with an etch rate-modifying dopant. Examples can include atomic layer deposition (ALD) tools.

[00100] Processing tool 700 comprises a processing chamber 702 and a substrate support 704 within the processing chamber. Substrate support 704 is configured to support a substrate 706 disposed within processing chamber 702. In some examples, processing tool 700 comprises a substrate heater 708 disposed adjacent to substrate 706. In other examples, a heater can be omitted, or can be located elsewhere within processing chamber 702. Substrate support 704 can comprise a pedestal, a chuck, and/or any other suitable structure.

[00101] Processing tool 700 further comprises a showerhead 710, a gas inlet 712 connected to the showerhead 710, and flow control hardware 714. In other examples, processing tool can comprise a nozzle or other apparatus for introducing gas into processing chamber 702, as opposed to or in addition to a showerhead. Flow control hardware 714 is connected to a silicon-containing precursor source 716, a first etch rate-modifying dopant gas source 717, one or more optional additional etch rate-modifying dopant gas source(s) 718, an oxygen-containing gas source 719, and an inert gas source 720. Silicon-containing precursor source 716 can comprise any suitable silicon-containing precursor that, when reacted with the oxygen-containing gas, forms a silicon oxide film. One example silicon-containing precursor is silane. In some examples, one or more aminosilanes can be used. Suitable aminosilanes include di(isopropylamino)silane (DIPAS) and bis(t-butylamino)silane (BTBAS). Another example silicon-containing precursor is TEOS. Yet other example silicon-containing precursors include those mentioned above.

[00102] Oxygen-containing gas source 719 can comprise, for example, O_2, O_3, N_2O, H_2O_2, water vapor, or a mixture of two or more thereof.

[00103] First etch rate-modifying dopant gas source 717 can include any suitable gas for introducing an etch rate-modifying dopant into a silicon oxide film. Optional additional etch rate-modifying dopant gas source(s) 718 can comprise one or more other etch rate-modifying dopant precursor different from the first etch rate-modifying dopant precursor. In some examples, a processing tool can include additional etch rate-modifying dopant gas sources.

[00104] Examples of suitable etch rate-modifying dopant precursors include hydrogen, nitrogen-containing precursors, phosphorus-containing precursors, carbon-containing precursors, boron-containing precursors, and arsenic-containing precursors. For films that use two of more etch rate-modifying dopants, any suitable combination of etch rate-modifying dopants can be used. Examples of nitrogen-containing precursors include ammonia (NH_3), hydrazine, and aminosilanes. For example, an aminosilane can be used to provide both silicon and nitrogen to grow a nitrogen-doped silicon oxide film. Suitable aminosilanes include DIPAS and BTBAS. Examples of phosphorus-containing precursors include phosphine (PH_3) and alkyl phosphines such as trimethylphosphine, triethylphosphine, and tributylphosphine. One example of a boron-containing precursor is diborane (B_2H_6). Examples of carbon-containing precursors include carbon monoxide (CO), alkanes, alkenes, alkynes, cyclic hydrocarbons, aromatics, alcohols, aldehydes, esters, ethers, ketones, alkyl amines, alkyl diamines, and organosilicon precursors (e.g., methylsilane, dimethylsilane, trimethylsilane, and siloxanes). One example of an arsenic-containing precursor is arsine (AsH_3). In further examples, molecular hydrogen (H_2) can be used as a etch rate-modifying dopant precursor to form a film doped with hydrogen.

[00105] Inert gas source 720 can comprise any suitable inert gas or gases. Examples include one or more of helium, neon, argon, krypton, xenon, or nitrogen.

[00106] Flow control hardware 714 can be controlled to flow gas from the various gas sources into processing chamber 702 via gas inlet 712. Flow control hardware 714 can comprise one or more valves controllable to place a selected gas source in fluid connection with gas inlet 712.

[00107] Processing tool 700 further comprises an exhaust system 724. Exhaust system 724 is configured to receive gas outflowing from processing chamber 702. In some examples, exhaust system 724 is configured to actively remove gas from

processing chamber 702 and/or apply a partial vacuum. Exhaust system 724 can comprise any suitable hardware, including one or pumps.

[00108] Processing tool 700 further comprises a radiofrequency power source 728 that is electrically connected to substrate support 704. Radiofrequency power source 728 is configured to form a plasma comprising the oxygen-containing gas. Processing tool 700 also comprises a matching network 729 for impedance matching of the radiofrequency power source 728. The plasma also can comprise an inert diluent gas from inert gas source 720. Radiofrequency power source 728 can be configured for any suitable frequency (e.g., 400 kHz or 13.56 MHz as examples) and power (e.g., between 0 and 6500 watts). In some examples, radiofrequency power source 728 is configured to operate at a plurality of different frequencies and/or powers. Further, in some examples, a relatively lower power plasma can be used to deposit a film with a relatively higher concentration of hydrogen. Likewise, a relatively higher power plasma can be used to deposit a film with a relatively lower concentration of hydrogen. As such, the plasma power can be varied to control the dopant profile of films comprising hydrogen as an etch rate-modifying dopant.

[00109] Controller 730 is operatively coupled to substrate heater 708, flow control hardware 714, exhaust system 724, and radiofrequency power source 728. Controller 730 is configured to control various functions of processing tool 700, such as operating substrate heater 708 to heat to a desired temperature. Controller 730 is further configured to operate flow control hardware 714 to flow selected gases into processing chamber 702. Controller 730 is further configured to operate exhaust system 724. Controller 730 is further configured to operate radiofrequency power source 728 to form a plasma. Controller 730 can comprise any suitable computing system, examples of which are described below with reference to FIG. 9.

[00110] FIG. 8 schematically shows an example etching tool 800 configured to perform cryoetching processes. Etching tool 800 comprises a processing chamber 802 and a substrate support 804 within the processing chamber. Substrate support 804 is configured to support a substrate 806 disposed within processing chamber 802. Substrate support 804 can comprise a pedestal, a chuck, and/or any other suitable structure.

[00111] Etching tool 800 further comprises a gas inlet 812 and flow control hardware 814. Flow control hardware 814 is connected to an etchant gas source 816 and an inert gas source 820. Etchant gas source 816 can comprise any suitable etchant

chemical. Examples include fluorine-containing etchants, oxygen-containing etchants, and hydrogen. Suitable fluorine-containing etchants include HF, SF_4, SF_6, NF_3, BF_3, SiF_4, PF_3, PF_5, WF_6, MoF_6, fluorocarbons, such as CF_4, C_2F_6, C_4F_6, C_3F_8, and C_4F_8, and hydrofluorocarbons such as CH_2F_2. Suitable oxygen-containing etchants include CO, COS, and O_2. Inert gas source 820 can comprise any suitable inert gas, such as one or more of helium, neon, argon, krypton, xenon, or nitrogen.

[00112] Flow control hardware 814 is controllable to flow gas from etchant gas source 816 and inert gas source 820 into processing chamber 802 via gas inlet 812. Flow control hardware 814 comprises one or more valves controllable to place a selected gas source in fluid connection with gas inlet 812.

[00113] Etching tool 800 further comprises an exhaust system 824. Exhaust system 824 is configured to receive gas outflowing from processing chamber 802. In some examples, exhaust system 824 is configured to actively remove gas from processing chamber 802 and/or apply a partial vacuum. Examples of suitable pressures include pressures of 5 to 80 mTorr. Exhaust system 824 can comprise any suitable hardware, including one or pumps.

[00114] Etching tool 800 further comprises a radiofrequency power source 828 that is electrically connected to substrate support 804. Thus, substrate support 804 forms a first electrode. Etching tool 800 further comprises a second electrode 850. Radiofrequency power source 828 is configured to form a plasma comprising the etchant gas. Etching tool 800 can include a matching network 829 for impedance matching of the radiofrequency power source 828. The plasma also can comprise an inert diluent gas from inert gas source 820. Radiofrequency power source 828 can be configured for any suitable frequency and power. Examples include radiofrequency power of 5 kW to 100 kW and frequencies of 400 kHz, 1 MHz, 2 MHz, 13.56 MHz, 27 MHz, 60 MHz, 90 MHz, 100 MHz, and 120 MHz. In some examples, radiofrequency power source 828 is configured to operate at a plurality of different frequencies and/or powers. For example, radiofrequency power source 828 can be operated using both a higher frequency radiofrequency energy component and a lower frequency radiofrequency energy component. Examples of LF radiofrequency energy include a frequency of 400 kHz and powers of 5 kW to 100 kW. Examples of HF radiofrequency energy include frequency of 60 MHz and powers of 2 kW to 40 kW. In some examples, the plasma can be pulsed. Pulsing the plasma can comprise pulsing the radiofrequency

energy between zero and a peak power. In other examples, the plasma can be pulsed between multiple different power levels.

[00115] Etching tool 800 further comprises a chiller 852 configured to circulate a coolant through substrate support 804 to cool a substrate for a reduced temperature etching process. Any suitable temperature can be used. In some examples, chiller 852 is configured to cool to a temperature of -150 ºC to +40 ºC.

[00116] Controller 830 is operatively coupled to flow control hardware 814, exhaust system 824, radiofrequency power source 828, and chiller 852. Controller 830 is configured to control various functions of etching tool 800, such as operating substrate chiller 852 to cool a substrate to a desired temperature. Controller 830 is further configured to operate flow control hardware 814 to flow selected gases into processing chamber 802. Controller 830 is further configured to operate exhaust system 824. Controller 830 is further configured to operate radiofrequency power source 828 to form a plasma.

[00117] FIG. 9 schematically shows a block diagram of an example computing system. Computing system 900 is shown in simplified form. Computing system 900 can take the form of one or more personal computers, workstations, computers integrated with substrate processing tools, and/or network accessible server computers.

[00118] Computing system 900 includes a logic machine 902 and a storage machine 904. Computing system 900 can optionally include a display subsystem 906, input subsystem 908, communication subsystem 910, and/or other components not shown in FIG. 9. Controller 730 and controller 830 are examples of computing system 900.

[00119] Logic machine 902 includes one or more physical devices configured to execute instructions. For example, the logic machine can be configured to execute instructions that are part of one or more applications, services, programs, routines, libraries, objects, components, data structures, or other logical constructs. Such instructions can be implemented to perform a task, implement a data type, transform the state of one or more components, achieve a technical effect, or otherwise arrive at a desired result.

[00120] The logic machine can include one or more processors configured to execute software instructions. Additionally or alternatively, the logic machine can include one or more hardware or firmware logic machines configured to execute hardware or firmware instructions. Processors of the logic machine can be single-core

or multi-core, and the instructions executed thereon can be configured for sequential, parallel, and/or distributed processing. Individual components of the logic machine optionally can be distributed among two or more separate devices, which can be remotely located and/or configured for coordinated processing. Aspects of the logic machine can be virtualized and executed by remotely accessible, networked computing devices configured in a cloud-computing configuration.

[00121] Storage machine 904 includes one or more physical devices configured to hold instructions 912 executable by the logic machine to implement the methods and processes described herein. When such methods and processes are implemented, the state of storage machine 904 can be transformed—e.g., to hold different data.

[00122] Storage machine 904 can include removable and/or built-in devices. Storage machine 904 can include optical memory (e.g., CD, DVD, HD-DVD, Blu-Ray Disc, etc.), semiconductor memory (e.g., RAM, EPROM, EEPROM, etc.), and/or magnetic memory (e.g., hard-disk drive, floppy-disk drive, tape drive, MRAM, etc.), among others. Storage machine 904 can include volatile, nonvolatile, dynamic, static, read/write, read-only, random-access, sequential-access, location-addressable, file-addressable, and/or content-addressable devices.

[00123] It will be appreciated that storage machine 904 includes one or more physical devices. However, aspects of the instructions described herein alternatively can be propagated by a communication medium (e.g., an electromagnetic signal, an optical signal, etc.) that is not held by a physical device for a finite duration.

[00124] Aspects of logic machine 902 and storage machine 904 can be integrated together into one or more hardware-logic components. Such hardware-logic components can include field-programmable gate arrays (FPGAs), program- and application-specific integrated circuits (PASIC / ASICs), program- and application-specific standard products (PSSP / ASSPs), system-on-a-chip (SOC), and complex programmable logic devices (CPLDs), for example.

[00125] When included, display subsystem 906 can be used to present a visual representation of data held by storage machine 904. This visual representation can take the form of a graphical user interface (GUI). As the herein described methods and processes change the data held by the storage machine, and thus transform the state of the storage machine, the state of display subsystem 906 can likewise be transformed to visually represent changes in the underlying data. Display subsystem 906 can include one or more display devices utilizing virtually any type of technology. Such display

devices can be combined with logic machine 902 and/or storage machine 904 in a shared enclosure, or such display devices can be peripheral display devices.

[00126] When included, input subsystem 908 can comprise or interface with one or more user-input devices such as a keyboard, mouse, or touch screen. In some examples, the input subsystem can comprise or interface with selected natural user input (NUI) componentry. Such componentry can be integrated or peripheral, and the transduction and/or processing of input actions can be handled on- or off-board. Example NUI componentry can include a microphone for speech and/or voice recognition, and an infrared, color, stereoscopic, and/or depth camera for machine vision and/or gesture recognition.

[00127] When included, communication subsystem 910 can be configured to communicatively couple computing system 900 with one or more other computing devices. Communication subsystem 910 can include wired and/or wireless communication devices compatible with one or more different communication protocols. As non-limiting examples, the communication subsystem can be configured for communication via a wireless telephone network, or a wired or wireless local- or wide-area network. In some examples, the communication subsystem can allow computing system 900 to send and/or receive messages to and/or from other devices via a network such as the Internet.

[00128] It will be understood that the configurations and/or approaches described herein are exemplary in nature, and that these specific examples are not to be considered in a limiting sense, because numerous variations are possible. The specific routines or methods described herein can represent one or more of any number of processing strategies. As such, various acts illustrated and/or described can be performed in the sequence illustrated and/or described, in other sequences, in parallel, or omitted. Likewise, the order of the above-described processes can be changed.

[00129] The subject matter of the present disclosure includes all novel and non-obvious combinations and sub-combinations of the various processes, systems and configurations, and other features, functions, acts, and/or properties disclosed herein, as well as any and all equivalents thereof.

CLAIMS:

1. A method of performing cryoetching, comprising:

cooling a substrate in a processing chamber;

while cooling the substrate, etching through a first film portion comprising a film material with a first dopant profile; and

while cooling the substrate, etching at least partially through a second film portion comprising the film material with a second dopant profile different than the first dopant profile, wherein the first dopant profile causes a different lateral etch rate of the film material than the second dopant profile.

2. The method of claim 1, wherein the first dopant profile comprises a first concentration of an etch rate-modifying dopant, and wherein the second dopant profile comprises a second concentration of the etch rate-modifying dopant.

3. The method of claim 2, wherein the etch rate-modifying dopant comprises nitrogen, carbon, phosphorus, hydrogen, arsenic, or boron.

4. The method of claim 1, wherein the first film portion comprising the first dopant profile is doped silicon oxide, and wherein the second film portion comprising the second dopant profile is doped silicon oxide with one or more of a different etch rate-modifying dopant or a different dopant concentration than the first film portion.

5. The method of claim 1, further comprising, before performing cryoetching, depositing on the substrate the second film portion comprising the film material with the second dopant profile, and depositing the first film portion comprising the film material with the first dopant profile.

6. The method of claim 5, wherein depositing the second film portion and depositing the first film portion comprises depositing by plasma-enhanced chemical vapor deposition (PECVD).

7. The method of claim 5, wherein depositing the second film portion and depositing the first film portion comprises depositing by thermal chemical vapor deposition (TCVD) or atomic layer deposition (ALD).

8. The method of claim 1, wherein etching through the first film portion and etching the second film portion comprises etching a capacitor hole for a dynamic random access memory (DRAM) device.

9. The method of claim 1 wherein the method comprises etching a channel hole or a contact hole for a three dimensional (3D) NAND memory device.

10. The method of claim 1, wherein at least one of the first dopant profile and the second dopant profile comprises two or more different etch rate-modifying dopants.

11. The method of claim 1, wherein the etching through the first film portion comprises forming a first plasma using a first etchant gas mixture, and the etching through the second film portion comprises forming a second plasma using a second etchant gas mixture different from the first etchant gas mixture.

12. A device, comprising:

a first layer of a film material comprising a first dopant profile;

a second layer of the film material under the first layer of the film material, the second layer of the film material comprising a second dopant profile different from the first dopant profile, the second layer of the film material comprising a faster lateral etch rate than the first layer of silicon oxide; and

a feature extending through the first layer of the film material and at least partially through the second layer of the film material.

13. The device of claim 12, wherein a critical dimension at an opening of the feature is within 10 % of a critical dimension at a bottom of the feature.

14. The device of claim 12, wherein the first layer comprising the first dopant profile is doped silicon oxide, and wherein the second layer comprising the second dopant profile is doped silicon oxide with one or more of a different etch rate-modifying dopant or a different dopant concentration than the first layer.

15. The device of claim 12, wherein the device comprises a three dimensional (3D) NAND memory structure, and the feature comprises one of a channel hole or a contact hole.

16. The device of claim 12, wherein the device comprises a dynamic random access memory (DRAM) device, and the feature comprises a capacitor hole.

17. A deposition tool, comprising:

a processing chamber;

a substrate support disposed in the processing chamber;

flow control hardware configured to control flow of a film precursor and one or more etch rate-modifying dopant precursors into the processing chamber; and

a controller configured to:

in a first deposition step, operate the flow control hardware to cause introduction of the film precursor and the one or more etch rate-modifying dopant precursors into the processing chamber under conditions configured to convert the film precursor into a first film portion on a substrate, the first film portion comprising a first dopant profile, and

in a second deposition step, operate the flow control hardware to cause introduction of the film precursor and the one or more etch rate-modifying dopant precursors into the processing chamber under conditions configured to convert the film precursor into a second film portion on the substrate, the second film portion deposited on the first film portion, the second film portion comprising a second dopant profile, the second film portion comprising a slower lateral etch rate than the first film portion.

18. The deposition tool of claim 17, wherein the controller is configured to:

in the first deposition step, operate the flow control hardware to cause flow of a first etch rate-modifying dopant precursor of the one or more etch rate-modifying dopant precursors, thereby forming the first film portion comprising a first etch rate-modifying dopant, and

in the second deposition step, operate the flow control hardware to cause flow of a second etch rate-modifying dopant precursor of the one or more etch rate-modifying dopant precursors, thereby forming the second film portion comprising a

second etch rate-modifying dopant that is different from the first etch rate-modifying dopant.

19. The deposition tool of claim 17, wherein the controller is configured to:

in the first deposition step, operate the flow control hardware to cause flow of an etch rate-modifying dopant precursor at a first molar ratio to the film precursor, thereby forming the first film portion comprising an etch rate-modifying dopant at a first dopant concentration, and

in the second deposition step, operate the flow control hardware to cause flow of the etch rate-modifying dopant precursor at a second molar ratio to the film precursor, thereby forming the second film portion comprising the etch rate-modifying dopant at a second dopant concentration different from the first dopant concentration.

20. The deposition tool of claim 17, wherein the one or more etch rate-modifying dopant precursors comprise one or more of a nitrogen-containing precursor, a phosphorus-containing precursor, a carbon-containing precursor, hydrogen, an arsenic-containing precursor, or a boron-containing precursor.