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### Method of making a three-dimensional memory device using composite hard masks for formation of deep via openings

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#### Abstract

A method of forming a structure includes forming an alternating stack of first material layers and second material layers over a substrate, forming a first etch mask material layer, forming a first cladding liner, and forming a via opening through the alternating stack by performing an anisotropic etch process that employs a combination of at least the first cladding liner and the first etch mask material layer as a composite etch mask structure.

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## **Background/Summary**

RELATED APPLICATIONS (1) This application is a continuation-in-part (CIP) application of U.S. application Ser. No. 17/657,521 filed on Mar. 31, 2022, which is a CIP application of U.S. application Ser. No. 17/590,278 filed on Feb. 1, 2022, which is a CIP application of U.S. application Ser. No. 17/508,036 filed on Oct. 22, 2021, which is a CIP application of Ser. No. 17/494,114 filed on Oct. 5, 2021, which is a CIP application of U.S. application Ser. No. 17/355,955 filed on Jun. 23, 2021, which is a CIP application of U.S. application Ser. No. 17/136,471 filed on Dec. 29, 2020, the entire contents of which are incorporated herein by reference.

### **FIELD**

(1) The present disclosure relates generally to the field of semiconductor devices, and particularly to a method of making a three-dimensional memory device using composite hard masks for formation of deep via openings.

### **BACKGROUND**

(2) Three-dimensional vertical NAND strings having one bit per cell are disclosed in an article by T. Endoh et al., titled "Novel Ultra High Density Memory With A Stacked-Surrounding Gate Transistor (S-SGT) Structured Cell", IEDM Proc. (2001) 33-36.

### **SUMMARY**

(3) According to an aspect of the present disclosure, a method of forming a structure comprises forming an alternating stack of first material layers and second material layers over a substrate; forming a first etch mask material layer comprising a first etch mask material over the alternating stack; forming a first cladding liner comprising a first cladding material on a top surface of the first etch material layer and on a sidewall of the first etch mask material layer; and forming a via opening through the alternating stack by performing an anisotropic etch process that employs a combination of at least the first cladding liner and the first etch mask material layer. The anisotropic etch process comprises a first anisotropic etch step that etches materials of the alternating stack selective to the first etch mask material and the first cladding material. The first anisotropic etch step collaterally removes a horizontally-extending portion of the first cladding liner and collaterally vertically recesses the first etch mask material layer such that a vertically-extending portion of the first cladding liner protrudes above a top surface of a remaining portion of the first etch mask material layer during the first anisotropic etch step. The top surface of the remaining portion of the first etch mask material layer has a concave vertical cross-sectional profile which functions as an ion trap during the first anisotropic etch step.

(4) According to an aspect of the present disclosure, a method of forming a structure includes

forming an alternating stack of first material layers and second material layers over a substrate, forming a mask layer over the alternating stack, forming a cavity in the mask layer, forming a first cladding liner on a sidewall of the cavity in the mask layer, and forming a via opening the alternating stack by performing an anisotropic etch process that transfers a pattern of the cavity in the mask layer through the alternating stack using a combination of the first cladding liner and the mask layer as an etch mask.

(5) According to an aspect of the present disclosure, a method of forming a semiconductor structure comprises forming an alternating stack of first material layers and second material layers over a substrate; forming a composite hard mask layer over the alternating stack, wherein the composite hard mask layer comprises a layer stack including a lower patterning film, a first cladding material layer overlying the lower patterning film, and an upper patterning film overlying the first cladding material layer; forming a patterned photoresist layer including openings therethrough over the composite hard mask layer; forming openings in the hard mask layer by performing a hard-mask-open anisotropic etch process that transfers a pattern of the openings in the photoresist layer through the hard mask layer; and forming via openings through the alternating stack by performing an anisotropic etch process that transfers a pattern of the openings in the composite hard mask layer through the alternating stack. The upper patterning film functions as an etch mask at least during an initial phase of the anisotropic etch process and the first cladding material layer functions as an etch mask at least during a subsequent phase of the anisotropic etch process, and the first cladding material layer has higher etch resistance than the upper patterning film and the lower patterning film during the anisotropic etch process.

(6) According to an aspect of the present disclosure, a method of forming a semiconductor structure is provided, which comprises: forming a source-level semiconductor layer over a substrate; forming an alternating stack of first material layers and second material layers over the source-level semiconductor layer; forming a hard mask layer over the alternating stack; forming cavities in the hard mask layer; forming via openings through the alternating stack by performing an anisotropic etch process that transfers a pattern of the cavities in the hard mask layer through the alternating stack; forming a cladding liner on sidewalls of the cavities in the hard mask layer and on a top surface of the hard mask layer; and vertically extending the via openings at least through the source-level semiconductor layer by performing a second anisotropic etch process employing a combination of the cladding liner and the hard mask layer as an etch mask.

(7) According to an aspect of the present disclosure, a method of forming a semiconductor structure comprises forming an alternating stack of first material layers and second material layers over a substrate, forming a hard mask layer over the alternating stack, applying and patterning a photoresist layer over the hard mask layer, wherein openings are formed in the photoresist layer, forming cavities in the hard mask layer, forming a cladding liner on sidewalls of the cavities in the hard mask layer, and forming via openings the alternating stack by performing an anisotropic etch process that transfers a pattern of the cavities in the hard mask layer through each layer within the alternating stack employing a combination of the cladding liner and the hard mask layer as an etch mask.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. 1 is a schematic vertical cross-sectional view of a first exemplary structure after formation of at least one peripheral device, a semiconductor material layer, and a gate dielectric layer according to the first embodiment of the present disclosure.

(2) FIG. 2 is a schematic vertical cross-sectional view of the first exemplary structure after formation of an alternating stack of insulating layers and sacrificial material layers according to the

first embodiment of the present disclosure.

(3) FIG. 3 is a schematic vertical cross-sectional view of the first exemplary structure after formation of stepped terraces and a retro-stepped dielectric material portion according to the first embodiment of the present disclosure.

(4) FIG. 4A is a schematic vertical cross-sectional view of the first exemplary structure after formation of memory openings and support openings according to the first embodiment of the present disclosure.

(5) FIG. 4B is a top-down view of the first exemplary structure of FIG. 4A. The vertical plane A-A' is the plane of the cross-section for FIG. 4A.

(6) FIGS. 5A-5D are sequential vertical cross-sectional views of a region of a first configuration of the first exemplary structure during formation of the memory openings according to the first embodiment of the present disclosure.

(7) FIGS. 6A-6D are sequential vertical cross-sectional views of a region of a second configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(8) FIGS. 7A-7C are sequential vertical cross-sectional views of a region of a third configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(9) FIGS. 8A-8C are sequential vertical cross-sectional views of a region of a fourth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(10) FIGS. 9A-9D are sequential vertical cross-sectional views of a region of a fifth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(11) FIGS. 10A-10D are sequential vertical cross-sectional views of a region of a sixth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(12) FIGS. 11A-11H are sequential schematic vertical cross-sectional views of a memory opening within the first exemplary structure during formation of a memory stack structure, an optional dielectric core, and a drain region therein according to the first embodiment of the present disclosure.

(13) FIG. 12 is a schematic vertical cross-sectional view of the first exemplary structure after formation of memory stack structures and support pillar structures according to the first embodiment of the present disclosure.

(14) FIG. 13A is a schematic vertical cross-sectional view of the first exemplary structure after formation of backside trenches and source regions according to the first embodiment of the present disclosure.

(15) FIG. 13B is a partial see-through top-down view of the first exemplary structure of FIG. 13A. The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 13A.

(16) FIG. 14 is a schematic vertical cross-sectional view of the first exemplary structure after formation of backside recesses according to the first embodiment of the present disclosure.

(17) FIGS. 15A-15D are sequential vertical cross-sectional views of a region of the first exemplary structure during formation of electrically conductive layers according to the first embodiment of the present disclosure.

(18) FIG. 16 is a schematic vertical cross-sectional view of the first exemplary structure at the processing step of FIG. 15D.

(19) FIG. 17A is a schematic vertical cross-sectional view of the first exemplary structure after removal of conductive materials from within the backside trenches according to the first embodiment of the present disclosure.

(20) FIG. 17B is a partial see-through top-down view of the first exemplary structure of FIG. 17A.

The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 17A.

(21) FIG. 18A is a schematic vertical cross-sectional view of the first exemplary structure after formation of insulating spacers and backside contact via structures according to the first embodiment of the present disclosure.

(22) FIG. 18B is a partial see-through top-down view of the first exemplary structure of FIG. 18A. The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 18A.

(23) FIG. 19A is a schematic vertical cross-sectional view of the first exemplary structure after formation of additional contact via structures according to the first embodiment of the present disclosure.

(24) FIG. 19B is a top-down view of the first exemplary structure of FIG. 19A. The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 19A.

(25) FIG. 20A is a vertical cross-sectional view of a second exemplary structure after formation of semiconductor devices, lower level dielectric layers, lower metal interconnect structures, and in-process source level material layers on a semiconductor substrate according to the second embodiment of the present disclosure.

(26) FIG. 20B is a top-down view of the second exemplary structure of FIG. 20A. The hinged vertical plane A-A' is the plane of the vertical cross-sectional view of FIG. 20A.

(27) FIG. 20C is a magnified view of the in-process source level material layers along the vertical plane C-C' of FIG. 20B.

(28) FIG. 21 is a vertical cross-sectional view of the second exemplary structure after formation of a first-tier alternating stack of first insulating layers and first spacer material layers according to the second embodiment of the present disclosure.

(29) FIG. 22 is a vertical cross-sectional view of the second exemplary structure after patterning a first-tier staircase region, a first retro-stepped dielectric material portion, and an inter-tier dielectric layer according to the second embodiment of the present disclosure.

(30) FIG. 23A is a vertical cross-sectional view of the second exemplary structure after application of a patterning film and a photoresist layer, patterning of the photoresist layer, and transfer of a pattern of openings in the photoresist layer through the patterning film according to the second embodiment of the present disclosure.

(31) FIG. 23B is a top-down view of the first exemplary structure of FIG. 23A. The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 23A.

(32) FIG. 23C is vertical cross-sectional view of a region of the second exemplary structure along the vertical plane C-C' of FIG. 23B.

(33) FIG. 24A is a vertical cross-sectional view of the second exemplary structure after a first anisotropic etch process that transfers a pattern of openings in the patterning film through the first alternating stack according to the second embodiment of the present disclosure.

(34) FIG. 24B is a top-down view of the first exemplary structure of FIG. 24A. The vertical plane A-A' is the plane of the schematic vertical cross-sectional view of FIG. 24A.

(35) FIG. 24C is vertical cross-sectional view of a region of the second exemplary structure along the vertical plane C-C' of FIG. 24B.

(36) FIGS. 25A-25C are sequential vertical cross-sectional views of a memory opening in a first configuration of the second exemplary structure during the processing steps for formation of a cladding liner, a second anisotropic etch process, and removal of the cladding liner and the patterning film according to the second embodiment of the present disclosure.

(37) FIG. 25D is an alternative embodiment of the first configuration of a memory opening in the first configuration of the second exemplary structure.

(38) FIGS. 26A-26C are sequential vertical cross-sectional views of a memory opening in a second configuration of the second exemplary structure during the processing steps for formation of a cladding liner, a second anisotropic etch process, and removal of the cladding liner and the patterning film according to the second embodiment of the present disclosure.

(39) FIG. 26D is an alternative embodiment of the second configuration of a memory opening in the second configuration of the second exemplary structure.

(40) FIGS. 27A-27C are sequential vertical cross-sectional views of a memory opening in a third configuration of the second exemplary structure during the processing steps for formation of a cladding liner, a second anisotropic etch process, and removal of the cladding liner and the patterning film according to the second embodiment of the present disclosure.

(41) FIG. 27D is an alternative embodiment of the third configuration of a memory opening in the third configuration of the second exemplary structure.

(42) FIG. 28A is a vertical cross-sectional view of the second exemplary structure after formation of first-tier memory openings and first-tier support openings according to the second embodiment of the present disclosure.

(43) FIG. 28B is a horizontal cross-sectional view of the second exemplary structure of FIG. 28A. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. 28A.

(44) FIG. 29 is a vertical cross-sectional view of the second exemplary structure after formation of various sacrificial fill structures according to the second embodiment of the present disclosure.

(45) FIG. 30 is a vertical cross-sectional view of the second exemplary structure after formation of a second-tier alternating stack of second insulating layers and second spacer material layers, second stepped surfaces, and a second retro-stepped dielectric material portion according to the second embodiment of the present disclosure.

(46) FIG. 31A is a vertical cross-sectional view of the second exemplary structure after formation of second-tier memory openings and second-tier support openings according to the second embodiment of the present disclosure.

(47) FIG. 31B is a horizontal cross-sectional view of the second exemplary structure along the horizontal plane B-B' of FIG. 31A. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. 31A.

(48) FIG. 32 is a vertical cross-sectional view of the second exemplary structure after formation of inter-tier memory openings and inter-tier support openings according to the second embodiment of the present disclosure.

(49) FIGS. 33A-33D illustrate sequential vertical cross-sectional views of a memory opening during formation of a memory opening fill structure according to the second embodiment of the present disclosure.

(50) FIG. 34 is a vertical cross-sectional view of the second exemplary structure after formation of memory opening fill structures and support pillar structures according to the second embodiment of the present disclosure.

(51) FIG. 35A is a vertical cross-sectional view of the second exemplary structure after formation of pillar cavities according to the second embodiment of the present disclosure.

(52) FIG. 35B is a horizontal cross-sectional view of the second exemplary structure along the horizontal plane B-B' of FIG. 35A. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. 35A.

(53) FIG. 36 is a vertical cross-sectional view of the second exemplary structure after formation of dielectric pillar structures according to the second embodiment of the present disclosure.

(54) FIG. 37A is a vertical cross-sectional view of the second exemplary structure after formation of a first contact-level dielectric layer and backside trenches according to the second embodiment of the present disclosure.

(55) FIG. 37B is a horizontal cross-sectional view of the second exemplary structure along the horizontal plane B-B' of FIG. 37A. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. 37A.

(56) FIG. 38 is a vertical cross-sectional view of the second exemplary structure after formation of backside trench spacers according to the second embodiment of the present disclosure.



(57) FIGS. **39A-39E** illustrate sequential vertical cross-sectional views of memory opening fill structures and a backside trench during formation of source-level material layers according to the second embodiment of the present disclosure.

(58) FIG. **40** is a vertical cross-sectional view of the second exemplary structure after formation of source-level material layers according to the second embodiment of the present disclosure.

(59) FIG. **41** is a vertical cross-sectional view of the second exemplary structure after formation of backside recesses according to the second embodiment of the present disclosure.

(60) FIG. **42A** is a vertical cross-sectional view of the second exemplary structure after formation of electrically conductive layers according to the second embodiment of the present disclosure.

(61) FIG. **42B** is a horizontal cross-sectional view of the second exemplary structure along the horizontal plane B-B' of FIG. **42A**. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **42A**.

(62) FIG. **43A** is a vertical cross-sectional view of the second exemplary structure after formation of backside trench fill structures in the backside trenches according to the second embodiment of the present disclosure.

(63) FIG. **43B** is a horizontal cross-sectional view of the second exemplary structure along the horizontal plane B-B' of FIG. **43A**. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **43A**.

(64) FIG. **43C** is a vertical cross-sectional view of the second exemplary structure along the vertical plane C-C' of FIG. **43B**.

(65) FIG. **44A** is a vertical cross-sectional view of the second exemplary structure after formation of a second contact-level dielectric layer and various contact via structures according to the second embodiment of the present disclosure.

(66) FIG. **44B** is a horizontal cross-sectional view of the second exemplary structure along the vertical plane B-B' of FIG. **44A**. The hinged vertical plane A-A' corresponds to the plane of the vertical cross-sectional view of FIG. **44A**.

(67) FIG. **45** is a vertical cross-sectional view of the second exemplary structure after formation of through-memory-level via structures and upper metal line structures according to the second embodiment of the present disclosure.

(68) FIGS. **46A-46D** are sequential vertical cross-sectional views of a memory opening in a first configuration of a third exemplary structure during the processing steps for patterning a patterning film, formation of a cladding liner, and an anisotropic etch process according to a third embodiment of the present disclosure.

(69) FIG. **47** is a vertical cross-sectional view of a region of the first configuration of the third exemplary structure after formation of memory openings according to the third embodiment of the present disclosure.

(70) FIGS. **48A** and **48B** are sequential vertical cross-sectional views of a memory opening in a second configuration of the third exemplary structure during an anisotropic etch process according to a third embodiment of the present disclosure.

(71) FIG. **49** is a vertical cross-sectional view of a region of the second configuration of the third exemplary structure after formation of memory openings according to the third embodiment of the present disclosure.

(72) FIGS. **50A-50G** are sequential vertical cross-sectional views of a region of a memory opening in a third configuration of the third exemplary structure during formation of the memory opening according to the third embodiment of the present disclosure.

(73) FIGS. **51A-51E** are sequential vertical cross-sectional views of a region of a memory opening in a fourth configuration of the third exemplary structure during formation of the memory opening according to the third embodiment of the present disclosure.

(74) FIGS. **52A-52C** are sequential vertical cross-sectional views of a region of a memory opening in a fifth configuration of the third exemplary structure during formation of the memory opening

according to the third embodiment of the present disclosure.

(75) FIGS. 53A-53G are sequential vertical cross-sectional view of a region of a memory opening in a first configuration of a fourth exemplary structure during formation of the memory opening according to a fourth embodiment of the present disclosure.

(76) FIG. 53H is a vertical cross-sectional view of a region of a memory opening in an alternative first configuration of the fourth exemplary structure according to the fourth embodiment of the present disclosure.

(77) FIGS. 54A-54G are sequential vertical cross-sectional view of a region of a memory opening in a second configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(78) FIG. 55A-55C are vertical cross-sectional views of a region of a memory opening in alternative embodiments of the second configuration of the fourth exemplary structure after application and patterning of a photoresist layer according to the fourth embodiment of the present disclosure.

(79) FIGS. 56A-56H are sequential vertical cross-sectional views of a region of a memory opening in a third configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(80) FIGS. 57A-57H are sequential vertical cross-sectional views of a region of a memory opening in a fourth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(81) FIGS. 58A-58H are sequential vertical cross-sectional views of a region of a memory opening in a fifth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(82) FIGS. 59A-59H are sequential vertical cross-sectional views of a region of a memory opening in a sixth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(83) FIGS. 60A-60H are sequential vertical cross-sectional views of a region of a memory opening in a seventh configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(84) FIGS. 61A-61M are sequential vertical cross-sectional views of a region of a memory opening in an eighth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(85) FIGS. 62A-62G are sequential vertical cross-sectional views of a region of a memory opening in a ninth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(86) FIGS. 63A-63N are sequential vertical cross-sectional views of a region of a memory opening in a fifth exemplary structure during formation of etch stop structures according to a fifth embodiment of the present disclosure. FIGS. 63O and 63P are vertical cross-sectional views of a region of a memory opening in two alternative configurations of the fifth exemplary structure according to alternative configurations of the fifth embodiment of the present disclosure.

(87) FIGS. 64A-64E are sequential vertical cross-sectional view of a region of a memory opening in the fifth exemplary structure during an anisotropic etch process that forms memory openings according to the fifth embodiment of the present disclosure.

#### DETAILED DESCRIPTION

(88) As discussed above, the present disclosure is directed to methods of making a three-dimensional memory device using composite hard masks for formation of deep via openings, the various aspects of which are described below. The embodiments of the disclosure can be employed to form various structures including a multilevel memory structure, non-limiting examples of which include semiconductor devices such as three-dimensional memory array devices comprising a plurality of NAND memory strings.

(89) The drawings are not drawn to scale. Multiple instances of an element may be duplicated where a single instance of the element is illustrated, unless absence of duplication of elements is expressly described or clearly indicated otherwise. Ordinals such as “first,” “second,” and “third” are employed merely to identify similar elements, and different ordinals may be employed across the specification and the claims of the instant disclosure. The term “at least one” element refers to all possibilities including the possibility of a single element and the possibility of multiple elements.

(90) The same reference numerals refer to the same element or similar element. Unless otherwise indicated, elements having the same reference numerals are presumed to have the same composition and the same function. Unless otherwise indicated, a “contact” between elements refers to a direct contact between elements that provides an edge or a surface shared by the elements. If two or more elements are not in direct contact with each other or from each other, the two elements are “disjoined from” each other or “disjoined among” one another. As used herein, a first element located “on” a second element can be located on the exterior side of a surface of the second element or on the interior side of the second element. As used herein, a first element is located “directly on” a second element if there exist a physical contact between a surface of the first element and a surface of the second element. As used herein, a first element is “electrically connected to” a second element if there exists a conductive path consisting of at least one conductive material between the first element and the second element. As used herein, a “prototype” structure or an “in-process” structure refers to a transient structure that is subsequently modified in the shape or composition of at least one component therein.

(91) As used herein, a “layer” refers to a material portion including a region having a thickness. A layer may extend over the entirety of an underlying or overlying structure, or may have an extent less than the extent of an underlying or overlying structure. Further, a layer may be a region of a homogeneous or inhomogeneous continuous structure that has a thickness less than the thickness of the continuous structure. For example, a layer may be located between any pair of horizontal planes between, or at, a top surface and a bottom surface of the continuous structure. A layer may extend horizontally, vertically, and/or along a tapered surface. A substrate may be a layer, may include one or more layers therein, or may have one or more layer thereupon, thereabove, and/or therebelow.

(92) Generally, a semiconductor die, or a semiconductor package, can include a memory chip. Each semiconductor package contains one or more dies (for example one, two, or four). The die is the smallest unit that can independently execute commands or report status. Each die contains one or more planes (typically one or two). Identical, concurrent operations can take place on each plane, although with some restrictions. Each plane contains a number of blocks, which are the smallest unit that can be erased by in a single erase operation. Each block contains a number of pages, which are the smallest unit that can be programmed, i.e., a smallest unit on which a read operation can be performed.

(93) Referring to FIG. 1, a first exemplary structure according to a first embodiment of the present disclosure is illustrated, which can be employed, for example, to fabricate a device structure containing vertical NAND memory devices. The first exemplary structure includes a substrate (9, 10), which can be a semiconductor substrate. The substrate can include a substrate semiconductor layer 9 and an optional semiconductor material layer 10. The substrate semiconductor layer 9 may be a semiconductor wafer or a semiconductor material layer, and can include at least one elemental semiconductor material (e.g., single crystal silicon wafer or layer), at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, or other semiconductor materials known in the art.

(94) The substrate can have a major surface 7, which can be, for example, a topmost surface of the substrate semiconductor layer 9. The major surface 7 can be a semiconductor surface. In one embodiment, the major surface 7 can be a single crystalline semiconductor surface, such as a single crystalline semiconductor surface.

(95) As used herein, a “semiconducting material” refers to a material having electrical conductivity in the range from  $1.0 \times 10^{-6}$  S/cm to  $1.0 \times 10^{+5}$  S/cm. As used herein, a “semiconductor material” refers to a material having electrical conductivity in the range from  $1.0 \times 10^{-6}$  S/cm to  $1.0 \times 10^{+5}$  S/cm in the absence of electrical dopants therein, and is capable of producing a doped material having electrical conductivity in a range from 1.0 S/cm to  $1.0 \times 10^{+5}$  S/cm upon suitable doping with an electrical dopant. As used herein, an “electrical dopant” refers to a p-type dopant that adds a hole to a valence band within a band structure, or an n-type dopant that adds an electron to a conduction band within a band structure. As used herein, a “conductive material” refers to a material having electrical conductivity greater than  $1.0 \times 10^{+5}$  S/cm. As used herein, an “insulator material” or a “dielectric material” refers to a material having electrical conductivity less than  $1.0 \times 10^{-6}$  S/cm. As used herein, a “heavily doped semiconductor material” refers to a semiconductor material that is doped with electrical dopant at a sufficiently high atomic concentration to become a conductive material either as formed as a crystalline material or if converted into a crystalline material through an anneal process (for example, from an initial amorphous state), i.e., to have electrical conductivity greater than  $1.0 \times 10^{+5}$  S/cm. A “doped semiconductor material” may be a heavily doped semiconductor material, or may be a semiconductor material that includes electrical dopants (i.e., p-type dopants and/or n-type dopants) at a concentration that provides electrical conductivity in the range from  $1.0 \times 10^{-6}$  S/cm to  $1.0 \times 10^{+5}$  S/cm. An “intrinsic semiconductor material” refers to a semiconductor material that is not doped with electrical dopants. Thus, a semiconductor material may be semiconducting or conductive, and may be an intrinsic semiconductor material or a doped semiconductor material. A doped semiconductor material can be semiconducting or conductive depending on the atomic concentration of electrical dopants therein. As used herein, a “metallic material” refers to a conductive material including at least one metallic element therein. All measurements for electrical conductivities are made at the standard condition.

(96) At least one semiconductor device **700** for a peripheral circuitry can be formed on a portion of the substrate semiconductor layer **9**. The at least one semiconductor device can include, for example, field effect transistors. For example, at least one shallow trench isolation structure **720** can be formed by etching portions of the substrate semiconductor layer **9** and depositing a dielectric material therein. A gate dielectric layer, at least one gate conductor layer, and a gate cap dielectric layer can be formed over the substrate semiconductor layer **9**, and can be subsequently patterned to form at least one gate structure (**750**, **752**, **754**, **758**), each of which can include a gate dielectric **750**, a gate electrode (**752**, **754**), and a gate cap dielectric **758**. The gate electrode (**752**, **754**) may include a stack of a first gate electrode portion **752** and a second gate electrode portion **754**. At least one gate spacer **756** can be formed around the at least one gate structure (**750**, **752**, **754**, **758**) by depositing and anisotropically etching a dielectric liner. Active regions **730** can be formed in upper portions of the substrate semiconductor layer **9**, for example, by introducing electrical dopants employing the at least one gate structure (**750**, **752**, **754**, **758**) as masking structures. Additional masks may be employed as needed. The active region **730** can include source regions and drain regions of field effect transistors. A first dielectric liner **761** and a second dielectric liner **762** can be optionally formed. Each of the first and second dielectric liners (**761**, **762**) can comprise a silicon oxide layer, a silicon nitride layer, and/or a dielectric metal oxide layer. As used herein, silicon oxide includes silicon dioxide as well as non-stoichiometric silicon oxides having more or less than two oxygen atoms for each silicon atoms. Silicon dioxide is preferred. In an illustrative example, the first dielectric liner **761** can be a silicon oxide layer, and the second dielectric liner **762** can be a silicon nitride layer. The at least one semiconductor device for the peripheral circuitry can contain a driver circuit for memory devices to be subsequently formed, which can include at least one NAND device.

(97) A dielectric material such as silicon oxide can be deposited over the at least one semiconductor device, and can be subsequently planarized to form a planarization dielectric layer **770**. In one

embodiment the planarized top surface of the planarization dielectric layer **770** can be coplanar with a top surface of the dielectric liners (**761**, **762**). Subsequently, the planarization dielectric layer **770** and the dielectric liners (**761**, **762**) can be removed from an area to physically expose a top surface of the substrate semiconductor layer **9**. As used herein, a surface is “physically exposed” if the surface is in physical contact with vacuum, or a gas phase material (such as air).

(98) The optional semiconductor material layer **10**, if present, can be formed on the top surface of the substrate semiconductor layer **9** prior to, or after, formation of the at least one semiconductor device **700** by deposition of a single crystalline semiconductor material, for example, by selective epitaxy. The deposited semiconductor material can be the same as, or can be different from, the semiconductor material of the substrate semiconductor layer **9**. The deposited semiconductor material can be any material that can be employed for the substrate semiconductor layer **9** as described above. The single crystalline semiconductor material of the semiconductor material layer **10** can be in epitaxial alignment with the single crystalline structure of the substrate semiconductor layer **9**. Portions of the deposited semiconductor material located above the top surface of the planarization dielectric layer **170** can be removed, for example, by chemical mechanical planarization (CMP). In this case, the semiconductor material layer **10** can have a top surface that is coplanar with the top surface of the planarization dielectric layer **770**. The region (i.e., area) of the at least one semiconductor device **700** is herein referred to as a peripheral device region **200**. The region in which a memory array is subsequently formed is herein referred to as a memory array region **100**. A contact region **300** for subsequently forming stepped terraces of electrically conductive layers can be provided between the memory array region **100** and the peripheral device region **200**.

(99) In one alternative embodiment, the peripheral device region **200** containing the at least one semiconductor device **700** for a peripheral circuitry may be located under the memory array region **100** in a CMOS under array configuration. In another alternative embodiment, the peripheral device region **200** may be located on a separate substrate which is subsequently bonded to the memory array region **100**.

(100) Referring to FIG. 2, a stack of an alternating plurality of first material layers (which can be insulating layers **32**) and second material layers (which can be sacrificial material layer **42**) is formed over the top surface of the substrate (**9**, **10**). As used herein, a “material layer” refers to a layer including a material throughout the entirety thereof. As used herein, an alternating plurality of first elements and second elements refers to a structure in which instances of the first elements and instances of the second elements alternate. Each instance of the first elements that is not an end element of the alternating plurality is adjoined by two instances of the second elements on both sides, and each instance of the second elements that is not an end element of the alternating plurality is adjoined by two instances of the first elements on both ends. The first elements may have the same thickness thereamongst, or may have different thicknesses. The second elements may have the same thickness thereamongst, or may have different thicknesses. The alternating plurality of first material layers and second material layers may begin with an instance of the first material layers or with an instance of the second material layers, and may end with an instance of the first material layers or with an instance of the second material layers. In one embodiment, an instance of the first elements and an instance of the second elements may form a unit that is repeated with periodicity within the alternating plurality.

(101) Each first material layer includes a first material, and each second material layer includes a second material that is different from the first material. In one embodiment, each first material layer can be an insulating layer **32**, and each second material layer can be a sacrificial material layer. In this case, the stack can include an alternating plurality of insulating layers **32** and sacrificial material layers **42**, and constitutes a prototype stack of alternating layers comprising insulating layers **32** and sacrificial material layers **42**.

(102) The stack of the alternating plurality is herein referred to as an alternating stack (**32**, **42**). In

one embodiment, the alternating stack (32, 42) can include insulating layers 32 composed of the first material, and sacrificial material layers 42 composed of a second material different from that of insulating layers 32. The first material of the insulating layers 32 can be at least one insulating material. As such, each insulating layer 32 can be an insulating material layer. Insulating materials that can be employed for the insulating layers 32 include, but are not limited to, silicon oxide (including doped or undoped silicate glass), silicon nitride, silicon oxynitride, organosilicate glass (OSG), spin-on dielectric materials, dielectric metal oxides that are commonly known as high dielectric constant (high-k) dielectric oxides (e.g., aluminum oxide, hafnium oxide, etc.) and silicates thereof, dielectric metal oxynitrides and silicates thereof, and organic insulating materials. In one embodiment, the first material of the insulating layers 32 can be silicon oxide.

(103) The second material of the sacrificial material layers 42 is a sacrificial material that can be removed selective to the first material of the insulating layers 32. As used herein, a removal of a first material is “selective to” a second material if the removal process removes the first material at a rate that is at least twice the rate of removal of the second material. The ratio of the rate of removal of the first material to the rate of removal of the second material is herein referred to as a “selectivity” of the removal process for the first material with respect to the second material.

(104) The sacrificial material layers 42 may comprise an insulating material, a semiconductor material, or a conductive material. The second material of the sacrificial material layers 42 can be subsequently replaced with electrically conductive electrodes which can function, for example, as control gate electrodes of a vertical NAND device. Non-limiting examples of the second material include silicon nitride, an amorphous semiconductor material (such as amorphous silicon), and a polycrystalline semiconductor material (such as polysilicon). In one embodiment, the sacrificial material layers 42 can be spacer material layers that comprise silicon nitride or a semiconductor material including at least one of silicon and germanium.

(105) In one embodiment, the insulating layers 32 can include silicon oxide, and sacrificial material layers can include silicon nitride sacrificial material layers. The first material of the insulating layers 32 can be deposited, for example, by chemical vapor deposition (CVD). For example, if silicon oxide is employed for the insulating layers 32, tetraethyl orthosilicate (TEOS) can be employed as the precursor material for the CVD process. The second material of the sacrificial material layers 42 can be formed, for example, CVD or atomic layer deposition (ALD).

(106) The sacrificial material layers 42 can be suitably patterned so that conductive material portions to be subsequently formed by replacement of the sacrificial material layers 42 can function as electrically conductive electrodes, such as the control gate electrodes of the monolithic three-dimensional NAND string memory devices to be subsequently formed. The sacrificial material layers 42 may comprise a portion having a strip shape extending substantially parallel to the major surface 7 of the substrate.

(107) The thicknesses of the insulating layers 32 and the sacrificial material layers 42 can be in a range from 20 nm to 50 nm, although lesser and greater thicknesses can be employed for each insulating layer 32 and for each sacrificial material layer 42. The number of repetitions of the pairs of an insulating layer 32 and a sacrificial material layer (e.g., a control gate electrode or a sacrificial material layer) 42 can be in a range from 2 to 1,024, and typically from 8 to 256, although a greater number of repetitions can also be employed. The top and bottom gate electrodes in the stack may function as the select gate electrodes. In one embodiment, each sacrificial material layer 42 in the alternating stack (32, 42) can have a uniform thickness that is substantially invariant within each respective sacrificial material layer 42.

(108) While the present disclosure is described employing an embodiment in which the spacer material layers are sacrificial material layers 42 that are subsequently replaced with electrically conductive layers, embodiments are expressly contemplated herein in which the sacrificial material layers are formed as electrically conductive layers. In this case, steps for replacing the spacer material layers with electrically conductive layers can be omitted.

(109) Optionally, an insulating cap layer **70** can be formed over the alternating stack (**32, 42**). The insulating cap layer **70** includes a dielectric material that is different from the material of the sacrificial material layers **42**. In one embodiment, the insulating cap layer **70** can include a dielectric material that can be employed for the insulating layers **32** as described above. The insulating cap layer **70** can have a greater thickness than each of the insulating layers **32**. The insulating cap layer **70** can be deposited, for example, by chemical vapor deposition. In one embodiment, the insulating cap layer **70** can be a silicon oxide layer.

(110) Referring to FIG. 3, stepped surfaces are formed at a peripheral region of the alternating stack (**32, 42**), which is herein referred to as a terrace region. As used herein, “stepped surfaces” refer to a set of surfaces that include at least two horizontal surfaces and at least two vertical surfaces such that each horizontal surface is adjoined to a first vertical surface that extends upward from a first edge of the horizontal surface, and is adjoined to a second vertical surface that extends downward from a second edge of the horizontal surface. A stepped cavity is formed within the volume from which portions of the alternating stack (**32, 42**) are removed through formation of the stepped surfaces. A “stepped cavity” refers to a cavity having stepped surfaces.

(111) The terrace region is formed in the contact region **300**, which is located between the memory array region **100** and the peripheral device region **200** containing the at least one semiconductor device for the peripheral circuitry. The stepped cavity can have various stepped surfaces such that the horizontal cross-sectional shape of the stepped cavity changes in steps as a function of the vertical distance from the top surface of the substrate (**9, 10**). In one embodiment, the stepped cavity can be formed by repetitively performing a set of processing steps. The set of processing steps can include, for example, an etch process of a first type that vertically increases the depth of a cavity by one or more levels, and an etch process of a second type that laterally expands the area to be vertically etched in a subsequent etch process of the first type. As used herein, a “level” of a structure including alternating plurality is defined as the relative position of a pair of a first material layer and a second material layer within the structure.

(112) Each sacrificial material layer **42** other than a topmost sacrificial material layer **42** within the alternating stack (**32, 42**) laterally extends farther than any overlying sacrificial material layer **42** within the alternating stack (**32, 42**) in the terrace region. The terrace region includes stepped surfaces of the alternating stack (**32, 42**) that continuously extend from a bottommost layer within the alternating stack (**32, 42**) to a topmost layer within the alternating stack (**32, 42**).

(113) Each vertical step of the stepped surfaces can have the height of one or more pairs of an insulating layer **32** and a sacrificial material layer. In one embodiment, each vertical step can have the height of a single pair of an insulating layer **32** and a sacrificial material layer **42**. In another embodiment, multiple “columns” of staircases can be formed along a first horizontal direction **hd1** such that each vertical step has the height of a plurality of pairs of an insulating layer **32** and a sacrificial material layer **42**, and the number of columns can be at least the number of the plurality of pairs. Each column of staircase can be vertically offset from each other such that each of the sacrificial material layers **42** has a physically exposed top surface in a respective column of staircases. In the illustrative example, two columns of staircases are formed for each block of memory stack structures to be subsequently formed such that one column of staircases provide physically exposed top surfaces for odd-numbered sacrificial material layers **42** (as counted from the bottom) and another column of staircases provide physically exposed top surfaces for even-numbered sacrificial material layers (as counted from the bottom). Configurations employing three, four, or more columns of staircases with a respective set of vertical offsets among the physically exposed surfaces of the sacrificial material layers **42** may also be employed. Each sacrificial material layer **42** has a greater lateral extent, at least along one direction, than any overlying sacrificial material layers **42** such that each physically exposed surface of any sacrificial material layer **42** does not have an overhang. In one embodiment, the vertical steps within each column of staircases may be arranged along the first horizontal direction **hd1**, and the columns of staircases

may be arranged along a second horizontal direction hd2 that is perpendicular to the first horizontal direction hd1. In one embodiment, the first horizontal direction hd1 may be perpendicular to the boundary between the memory array region **100** and the contact region **300**.

(114) A retro-stepped dielectric material portion **65** (i.e., an insulating fill material portion) can be formed in the stepped cavity by deposition of a dielectric material therein. For example, a dielectric material such as silicon oxide can be deposited in the stepped cavity. Excess portions of the deposited dielectric material can be removed from above the top surface of the insulating cap layer **70**, for example, by chemical mechanical planarization (CMP). The remaining portion of the deposited dielectric material filling the stepped cavity constitutes the retro-stepped dielectric material portion **65**. As used herein, a “retro-stepped” element refers to an element that has stepped surfaces and a horizontal cross-sectional area that increases monotonically as a function of a vertical distance from a top surface of a substrate on which the element is present. If silicon oxide is employed for the retro-stepped dielectric material portion **65**, the silicon oxide of the retro-stepped dielectric material portion **65** may, or may not, be doped with dopants such as B, P, and/or F.

(115) Optionally, drain-select-level isolation structures **72** can be formed through the insulating cap layer **70** and a subset of the sacrificial material layers **42** located at drain-select-levels. The drain-select-level isolation structures **72** can be formed, for example, by forming drain-select-level isolation trenches and filling the drain-select-level isolation trenches with a dielectric material such as silicon oxide. Excess portions of the dielectric material can be removed from above the top surface of the insulating cap layer **70**.

(116) Referring to FIGS. **4A** and **4B**, a lithographic material stack (not shown) including at least a photoresist layer can be formed over the insulating cap layer **70** and the retro-stepped dielectric material portion **65**, and can be lithographically patterned to form openings therein. The openings include a first set of openings formed over the memory array region **100** and a second set of openings formed over the contact region **300**. The pattern in the lithographic material stack can be transferred through the insulating cap layer **70** or the retro-stepped dielectric material portion **65**, and through the alternating stack (**32**, **42**) by at least one anisotropic etch that employs the patterned lithographic material stack as an etch mask. Portions of the alternating stack (**32**, **42**) underlying the openings in the patterned lithographic material stack are etched to form memory openings **49** and support openings **19**. As used herein, a “memory opening” refers to a structure in which memory elements, such as a memory stack structure, is subsequently formed. As used herein, a “support opening” refers to a structure in which a support structure (such as a support pillar structure) that mechanically supports other elements is subsequently formed. The memory openings **49** are formed through the insulating cap layer **70** and the entirety of the alternating stack (**32**, **42**) in the memory array region **100**. The support openings **19** are formed through the retro-stepped dielectric material portion **65** and the portion of the alternating stack (**32**, **42**) that underlie the stepped surfaces in the contact region **300**.

(117) The memory openings **49** extend through the entirety of the alternating stack (**32**, **42**). The support openings **19** extend through a subset of layers within the alternating stack (**32**, **42**). The chemistry of the anisotropic etch process employed to etch through the materials of the alternating stack (**32**, **42**) can alternate to optimize etching of the first and second materials in the alternating stack (**32**, **42**). The anisotropic etch can be, for example, a series of reactive ion etches. The sidewalls of the memory openings **49** and the support openings **19** can be substantially vertical, or can be tapered. The patterned lithographic material stack can be subsequently removed, for example, by ashing.

(118) The memory openings **49** and the support openings **19** can extend from the top surface of the alternating stack (**32**, **42**) to at least the horizontal plane including the topmost surface of the semiconductor material layer **10**. In one embodiment, an overetch into the semiconductor material layer **10** may be optionally performed after the top surface of the semiconductor material layer **10**



is physically exposed at a bottom of each memory opening **49** and each support opening **19**. The overetch may be performed prior to, or after, removal of the lithographic material stack. In other words, the recessed surfaces of the semiconductor material layer **10** may be vertically offset from the un-recessed top surfaces of the semiconductor material layer **10** by a recess depth. The recess depth can be, for example, in a range from 1 nm to 50 nm, although lesser and greater recess depths can also be employed. The overetch is optional, and may be omitted. If the overetch is not performed, the bottom surfaces of the memory openings **49** and the support openings **19** can be coplanar with the topmost surface of the semiconductor material layer **10**.

(119) Each of the memory openings **49** and the support openings **19** may include a sidewall (or a plurality of sidewalls) that extends substantially perpendicular to the topmost surface of the substrate. A two-dimensional array of memory openings **49** can be formed in the memory array region **100**. A two-dimensional array of support openings **19** can be formed in the contact region **300**. The substrate semiconductor layer **9** and the semiconductor material layer **10** collectively constitutes a substrate (**9, 10**), which can be a semiconductor substrate. Alternatively, the semiconductor material layer **10** may be omitted, and the memory openings **49** and the support openings **19** can be extend to a top surface of the substrate semiconductor layer **9**.

(120) FIGS. 5A-5D are sequential vertical cross-sectional views of a region of a first configuration of the first exemplary structure during formation of the memory openings **49** according to a first embodiment of the present disclosure. In other words, the processing steps of FIGS. 5A-5D can be employed on the first exemplary structure of FIG. 3 to form the first exemplary structure of FIGS. 4A and 4B.

(121) Referring to FIG. 5A, a hard mask layer **22** can be formed over the alternating stack (**32, 42**) of the first exemplary structure of FIG. 3. Preferably, the hard mask layer **22** comprises a carbon-based hard mask layer which comprises at least 60% of carbon in atomic concentration. For example, the carbon-based hard mask layer **22** may include amorphous carbon, diamond-like carbon, boron-doped carbon, or a commercially available carbon-based mask material, such as Advanced Patterning Film™ provided by Applied Materials, Inc.™ In one embodiment, the carbon-based hard mask layer **22** may include at least 10% of hydrogen in atomic concentration. In one embodiment, the total atomic percentage of carbon atoms and hydrogen atoms in the carbon-based hard mask layer **22** may be at least 80%, such as at least 90%, for example 80 to 100%. The carbon-based hard mask layer **22** may be deposited by a conformal or non-conformal deposition process. The thickness of the carbon-based hard mask layer **22** may be in a range from 1 micron to 10 microns, such as 2 microns to 5 microns although lesser and greater thicknesses may also be employed.

(122) A photoresist layer **27** can be applied over the carbon-based hard mask layer **22**, and can be lithographically patterned to form openings in a pattern that is the same as the pattern of the memory openings **49** and the support openings **19** illustrated in FIGS. 4A and 4B. The pattern in the photoresist layer **27** can be transferred through the carbon-based hard mask layer **22** by performing a first anisotropic etch process. Cavities **21** can be formed in the carbon-based hard mask layer **22** by the first anisotropic etch process, which transfers the pattern of the openings in the photoresist layer **27** through the carbon-based hard mask layer **22**. In one embodiment, the vertical cross-sectional profile of each cavity **21** through the carbon-based hard mask layer **22** may be tapered at an upper portion and may include a bulge at a lower portion. A bottom portion of a cavity **21** may vertically extend into one or more topmost layers of the alternating stack (**32, 42**).

(123) Referring to FIG. 5B, a second anisotropic etch process, such as a reactive ion etch (RIE) process, may be performed to transfer the pattern of the cavities **21** in the carbon-based hard mask layer **22** into an upper portion of the alternating stack (**32, 42**), i.e., into a subset of the insulating layers **32** and the sacrificial material layers **42** that are located within the upper portion of the alternating stack (**32, 42**). The chemistry of the second anisotropic etch process can be selected such that the second anisotropic etch process etches the materials of the insulating layers **32** and the

sacrificial material layers **42** selective to the material of the carbon-based hard mask layer **22**. The photoresist layer **27** may be consumed during the second anisotropic etch process, or may be removed prior to or after the second anisotropic etch process. Via openings (**49, 19**), which include memory openings **49** and the support openings **19**, can be formed through the alternating stack (**32, 42**). The number of layers within the alternating stack (**32, 42**) through which the memory openings **49** vertically extend at the end of the second anisotropic etch process may be in a range from 20% to 80%, such as from 40% to 60%, of the total number of the layers within the alternating stack (**32, 42**). Generally, the via openings (**49, 19**) can be formed through the upper portion of the alternating stack (**32, 42**) by performing the second anisotropic etch process, which transfers the pattern of the cavities **21** in the carbon-based hard mask layer **22** through an upper subset of layers of the alternating stack (**32, 42**). In one embodiment, the via openings (**49, 19**) as formed by the second anisotropic etch process may have tapered sidewalls.

(124) Referring to FIG. 5C, a cladding liner **26** including a cladding material can be deposited on sidewalls of the cavities **21** in the carbon-based hard mask layer **22**. In one embodiment, the cladding liner **26** may be deposited by a selective deposition process that grows the cladding material (i.e., the material of the cladding liner **26**) from physically exposed surfaces of the carbon-based hard mask layer **22** without growth of the cladding material from physically exposed surfaces of the alternating stack (**32, 42**). In this case, the cladding material may be any material that allows selective deposition on the material of the carbon-based hard mask layer **22** without growth from surfaces of the alternating stack (**32, 42**). Thus, the cladding liner **26** is deposited conformally on the physically exposed surfaces of the carbon-based hard mask layer **22**, and is not deposited on the physically exposed surfaces of the alternating stack (**32, 42**).

(125) In one embodiment, the cladding liner **26** comprises, and/or consists essentially of, an inorganic material selected from amorphous carbon, diamond-like carbon, amorphous silicon, polycrystalline silicon, silicon carbide, or boron nitride. For example, silicon carbide may be selectively formed on the carbon-based hard mask layer **22** by selectively depositing a silicon layer (e.g., crystalline silicon layer) on the carbon-based hard mask layer **22**, followed by annealing the silicon layer at a sufficiently high temperature (e.g., at 600 degrees Celsius or higher, such as 600 to 800 degrees Celsius) to react the silicon layer with the carbon-based hard mask layer **22** to selectively form a conformal silicon carbide cladding liner **26** on the carbon-based hard mask layer **22**. In another embodiment, the cladding liner **26** comprises, and/or consists essentially of, a metallic (i.e., electrically conductive metal or metal alloy) material that can be selectively deposited on surfaces of the carbon-based hard mask layer **22**. Metallic materials that can be selectively deposited on surfaces of the carbon-based hard mask layer **22** include, but are not limited to, TiN, Ru, Co or Mo. For example, Ru can be selectively deposited by ALD on the carbon-based hard mask layer **22**. In another embodiment, the cladding liner **26** comprises, and/or consists essentially of, silicon oxide. The cladding liner **26** may be deposited by a conformal selective deposition process such as a chemical vapor deposition (CVD) process and/or an atomic layer deposition (ALD) process. The thickness of the cladding liner **26** may be in a range from 1 nm to 40 nm, such as from 2 nm to 20 nm, although lesser and greater thicknesses may also be employed.

(126) Referring to FIG. 5D, a third anisotropic etch process, such as an RIE process, can be performed to transfer the pattern of the cavities **21** (as reduced in volume due to the presence of the cladding liner **26**) through a lower portion of the alternating stack (**32, 42**), i.e., into a subset of the insulating layers **32** and the sacrificial material layers **42** that are located within the lower portion of the alternating stack (**32, 42**). The chemistry of the third anisotropic etch process can be selected such that the third anisotropic etch process etches the materials of the insulating layers **32** and the sacrificial material layers **42** selective to the materials of the cladding liner **26** and the carbon-based hard mask layer **22**. The cladding liner **26** may be partially or fully consumed during the third anisotropic etch process. The third anisotropic etch process vertically extends the via openings (**49, 19**) through the lower portion of the alternating stack (**32, 42**). Generally, the via openings (**49, 19**)

can be vertically extended through all layers within the alternating stack (32, 42) by performing the third anisotropic etch process, which employs a combination of the cladding liner 26 and the carbon-based hard mask layer 22 as an etch mask. Thus, the via openings (49, 19) vertically extend through each layer within the alternating stack (32, 42) after the third anisotropic etch process. (127) The via openings (49, 19) as formed by the third anisotropic etch process may have tapered sidewalls. The cladding liner 26 reduces the taper angle of the sidewalls of the via openings (49, 19) compared to an alternative etch scheme that does not employ the cladding liner 26. For example, the taper angle (as measured between a vertical direction and a sidewall of the via openings (49, 19)) can be in a range from 0.01 degree to 3 degrees, such as from 0.1 degree to 1.5 degrees, although lesser and greater taper angles may also be employed. In other words, the cladding liner 26 prevents or decreases a change in the mask profile during the latter part of a relatively long RIE of the deep, high aspect ratio via openings, which decreases the undesirable change in the via opening profile during the etching such via openings. The cladding liner 26 and the carbon-based hard mask layer 22 can be subsequently removed, for example, by ashing or selective etching.

(128) FIGS. 6A-6D are sequential vertical cross-sectional views of a region of a second configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(129) Referring to FIG. 6A, the second configuration of the first exemplary structure at the processing steps of FIG. 6A can be the same as the first configuration of the first exemplary structure at the processing step of FIG. 5A.

(130) Referring to FIG. 6B, the processing steps of FIG. 5B can be performed. Thus, the second configuration of the first exemplary structure at the processing steps of FIG. 6B can be the same as the first configuration of the first exemplary structure at the processing step of FIG. 5B.

(131) Referring to FIG. 6C, a cladding liner 26 including a cladding material can be deposited on sidewalls of the cavities 21 in the carbon-based hard mask layer 22. In one embodiment, the cladding liner 26 may be deposited by a selective but non-conformal deposition process that deposits a cladding material (i.e., the material of the cladding liner 26) anisotropically by directionally depositing the cladding material. The cladding material can be deposited with a variable thickness that decreases with a vertical distance from a horizontal plane including a top surface of the carbon-based hard mask layer 22. In this case, the cladding material may be any material that may be deposited anisotropically and provides etch resistance to the etch chemistry of a third anisotropic etch process to be subsequently employed. Thus, the cladding liner 26 is deposited on the physically exposed sidewalls of the carbon-based hard mask layer 22 with a variable thickness that decreases with a downward distance from a horizontal plane including the top surface of the carbon-based hard mask layer 22. The cladding liner 26 is not deposited on sidewalls of the via openings (49, 19).

(132) In one embodiment, the cladding liner 26 comprises, and/or consists essentially of, an inorganic material selected from amorphous carbon, diamond-like carbon, amorphous silicon, polycrystalline silicon, or boron nitride. In another embodiment, the cladding liner 26 comprises, and/or consists essentially of, a metallic material. Metallic materials that can be employed for the cladding liner 26 include, but are not limited to, TiN, Ru, Co or Mo. In one embodiment, the cladding liner 26 comprises, and/or consists essentially of, silicon oxide. The cladding liner 26 may be deposited by a nonconformal deposition process such as ALD, physical vapor deposition, atmospheric chemical vapor deposition (A-CVD) or a plasma-enhanced chemical vapor deposition process. For example, silicon oxide or carbon may be deposited non-conformally by ALD or A-CVD by controlling the flow of precursors, deposition time and number of cycles. The maximum thickness of the cladding liner 26 over the top surface of the carbon-based hard mask layer 22 may be in a range from 2 nm to 40 nm, such as from 4 nm to 20 nm, although lesser and greater thicknesses may also be employed.

(133) Referring to FIG. 6D, a third anisotropic etch process, such as a RIE process, can be performed to transfer the pattern of the cavities **21** (as reduced in volume due to the presence of the cladding liner **26**) through a lower portion of the alternating stack (**32, 42**), i.e., into a subset of the insulating layers **32** and the sacrificial material layers **42** that are located within the lower portion of the alternating stack (**32, 42**). The chemistry of the third anisotropic etch process can be selected such that the third anisotropic etch process etches the materials of the insulating layers **32** and the sacrificial material layers **42** selective to the materials of the cladding liner **26** and the carbon-based hard mask layer **22**. The cladding liner **26** may be partially or fully consumed during the third anisotropic etch process. The third anisotropic etch process vertically extends the via openings (**49, 19**) through the lower portion of the alternating stack (**32, 42**). Generally, the via openings (**49, 19**) can be vertically extended through all layers within the alternating stack (**32, 42**) by performing the third anisotropic etch process, which employs a combination of the cladding liner **26** and the carbon-based hard mask layer **22** as an etch mask. Thus, the via openings (**49, 19**) vertically extend through each layer within the alternating stack (**32, 42**) after the third anisotropic etch process.

(134) The via openings (**49, 19**) formed by the third anisotropic etch process may have tapered sidewalls. The cladding liner **26** reduces the taper angle of the sidewalls of the via openings (**49, 19**) compared to an alternative etch scheme that does not employ the cladding liner **26**. For example, the taper angle (as measured between a vertical direction and a sidewall of the via openings (**49, 19**)) can be in a range from 0.01 degree to 3 degrees, such as from 0.1 degree to 1.5 degrees, although lesser and greater taper angles may also be employed. The thicker upper portion of the cladding liner **26** protects the upper part of the carbon-based hard mask layer **22** and controls the critical dimension bow. The gradual reduction of thickness of the lower portion of the cladding liner **26** allows for bottom critical dimension expansion. The cladding liner **26** and the carbon-based hard mask layer **22** can be subsequently removed, for example, by ashing.

(135) FIGS. 7A-7C are sequential vertical cross-sectional views of a region of a third configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(136) Referring to FIG. 7A, a vertical stack including a first hard mask layer **122** comprising, and/or consisting essentially of, a doped carbon-based material and a second hard mask layer **28** having a different material composition than the first hard mask layer **122** over the alternating stack (**32, 42**). In one embodiment, the first hard mask layer **122** can include boron doped carbon hard mask material, such as Saphira™ hard mask material available from Applied Materials, Inc. In one embodiment, the first hard mask layer **122** may be a carbon-based hard mask layer containing 1 to 40 weight percent boron and having a homogenous material composition throughout (i.e., having a uniform boron doping as a function of thickness). The thickness of the first hard mask layer **122** may be in a range from 1 micron to 7 microns, such as from 2 microns to 4 microns, although lesser and greater thicknesses may also be employed.

(137) The second hard mask layer **28** is an additional hard mask layer that is formed over the first hard mask layer **122**. The second hard mask layer **28** comprises, and/or consists essentially of, a material selected from amorphous silicon, polysilicon, undoped amorphous or diamond-like carbon, a doped amorphous or diamond-like carbon material. For example, the second hard mask layer **28** may comprise the above described undoped APF which is not doped with boron. Generally, the second hard mask layer **28** may have a different material composition than the first hard mask layer **122**. The thickness of the second hard mask layer **28** may be in a range from 100 nm to 2 microns, such as from 500 nm to 1 micron, although lesser and greater thicknesses may also be employed.

(138) A photoresist layer **27** can be applied over the vertical stack of the first hard mask layer **122** and the second hard mask layer **28**, and can be lithographically patterned to form openings in a pattern that is the same as the pattern of the memory openings **49** and the support openings **19** illustrated in FIGS. 4A and 4B. The pattern in the photoresist layer **27** can be transferred through

the vertical stack of the first hard mask layer **122** and the second hard mask layer **28** by performing a first anisotropic etch process. Cavities **21** can be formed in the vertical stack of the first hard mask layer **122** and the second hard mask layer **28** by the first anisotropic etch process, which transfers the pattern of the openings in the photoresist layer **27** through the vertical stack of the first hard mask layer **122** and the second hard mask layer **28**. In one embodiment, the vertical cross-sectional profile of each cavity **21** may be tapered within the second hard mask layer **28** and may include a bulge within the first hard mask layer **122** due to various effects of the first anisotropic etch process such as accumulation etch residues, shadowing by overlying material portions, and differential etch rates between the materials of the first hard mask layer **122** and the second hard mask layer **28**. The first hard mask layer **124** may have a higher etch resistance than the second hard mask layer **28** during the second and third anisotropic etch processes described below. A bottom portion of a cavity **21** may vertically extend into one or more topmost layers of the alternating stack (**32**, **42**).

(139) Referring to FIG. 7B, a second anisotropic etch process, such as a RIE process, may be performed to transfer the pattern of the cavities **21** in the vertical stack of the first hard mask layer **122** and the second hard mask layer **28** into an upper portion of the alternating stack (**32**, **42**), i.e., into a subset of the insulating layers **32** and the sacrificial material layers **42** that are located within the upper portion of the alternating stack (**32**, **42**). The chemistry of the second anisotropic etch process can be selected such that the second anisotropic etch process etches the materials of the insulating layers **32** and the sacrificial material layers **42** selective to the material of the second hard mask layer **28**. The photoresist layer **27** may be consumed during or prior to the second anisotropic etch process. The second hard mask layer **28** can be partially consumed during the second anisotropic etch process. During the second anisotropic etch process, the critical dimension of the upper portion of the first hard mask layer **122** does not significantly change, while the critical dimension of the lower portion of the first hard mask layer **122** continues to expand. Via openings (**49**, **19**), which include memory openings **49** and the support openings **19**, can be formed through the alternating stack (**32**, **42**). The number of layers within the alternating stack (**32**, **42**) through which the memory openings **49** vertically extend at the end of the second anisotropic etch process may be in a range from 20% to 80%, such as from 40% to 60%, of the total number of the layers within the alternating stack (**32**, **42**). Generally, the via openings (**49**, **19**) can be formed through the upper portion of the alternating stack (**32**, **42**) by performing the second anisotropic etch process, which transfers the pattern of the cavities **21** through an upper subset of layers of the alternating stack (**32**, **42**). In one embodiment, the via openings (**49**, **19**) as formed by the second anisotropic etch process may have tapered sidewalls. In one embodiment, the bowing within the first hard mask layer **122** can be self-limiting due to the tapered profile of the sidewalls of the via openings (**49**, **19**) at the level of the second hard mask layer **28**.

(140) Referring to FIG. 7C, a third anisotropic etch process, such as a RIE process, can be performed to transfer the pattern of the cavities **21** through a lower portion of the alternating stack (**32**, **42**), i.e., into a subset of the insulating layers **32** and the sacrificial material layers **42** that are located within the lower portion of the alternating stack (**32**, **42**). The chemistry of the third anisotropic etch process can be selected such that the third anisotropic etch process etches the materials of the insulating layers **32** and the sacrificial material layers **42** selective to the materials of the first hard mask layer **122**, which is a carbon-based hard mask layer. In one embodiment, the second hard mask layer **28** may be entirely consumed during the third anisotropic etch process. During the third anisotropic etch process, the critical dimension of the upper portion of the first hard mask layer **122** has a minimal change, while the critical dimension of the lower portion of the first hard mask layer **122** continues to expand. Likewise, the bow critical dimension of the first hard mask layer **122** has a minimal change. The third anisotropic etch process vertically extends the via openings (**49**, **19**) through the lower portion of the alternating stack (**32**, **42**). Thus, the via openings (**49**, **19**) vertically extend through each layer within the alternating stack (**32**, **42**) after the

third anisotropic etch process.

(141) The via openings (49, 19) as formed by the third anisotropic etch process may have tapered sidewalls. The bow profile of each sidewalls of the cavities 21 in the first hard mask layer 122 can remain substantially invariant throughout the third anisotropic etch process due to the etch resistance of the doped carbon hard mask material within the first hard mask layer 122 during the third anisotropic etch process. For example, the taper angle (as measured between a vertical direction and a sidewall of the via openings (49, 19)) can be in a range from 0.01 degree to 3 degrees, such as from 0.1 degree to 1.5 degrees, although lesser and greater taper angles may also be employed. The first hard mask layer 122 can be subsequently removed, for example, by ashing.

(142) FIGS. 8A-8C are sequential vertical cross-sectional views of a region of a fourth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(143) Referring to FIG. 8A, a vertical stack including a first hard mask layer 124 comprising and/or consisting essentially of doped a carbon-based material and a second hard mask layer 28 having a different material composition than the first hard mask layer 124 over the alternating stack (32, 42). In one embodiment, the first hard mask layer 124 may comprise a boron doped carbon-based hard mask material having a boron dopant composition gradient along a vertical direction. In one embodiment, the first hard mask layer 124 may include a boron dopant at a variable dopant concentration that increases monotonically with a vertical distance from the substrate (9, 10). In one embodiment, the increasing dopant concentration within the first hard mask layer 124 may increase the etch resistance of the carbon-based hard mask material, and the dopant concentration gradient controls the etching selectivity. The first hard mask layer 124 may include 1 to 40 weight percent boron. The thickness of the first hard mask layer 124 may be the same as that of the first hard mask layer 122 described above. The second hard mask layer 28 may have the same material composition and the same thickness range as described above. The first hard mask layer 124 may have a higher etch resistance than the second hard mask layer 28 during the second and third anisotropic etch processes described below.

(144) Referring to FIG. 8B, a second anisotropic etch process, such as a RIE process, may be performed to transfer the pattern of the cavities 21 in the vertical stack of the first hard mask layer 124 and the second hard mask layer 28 into an upper portion of the alternating stack (32, 42), i.e., into a subset of the insulating layers 32 and the sacrificial material layers 42 that are located within the upper portion of the alternating stack (32, 42). The second anisotropic etch process of FIG. 8B may be the same as in the processing steps of FIG. 7B. The second hard mask layer 28 can be partially consumed during the second anisotropic etch process. Via openings (49, 19), which include memory openings 49 and the support openings 19, can be formed through the alternating stack (32, 42). In one embodiment, the via openings (49, 19) as formed by the second anisotropic etch process may have tapered sidewalls. In one embodiment, the vertical cross-sectional profile of each cavity 21 at an upper portion of the first hard mask layer 124 can remain relatively narrow due to higher etch resistance of the higher boron concentration in the upper portion of the first hard mask layer 124. In contrast, the bottom portion of each cavity 21 may be widened due to a lower etch resistance of the lower boron concentration in the lower portion of the first hard mask layer 124.

(145) Referring to FIG. 8C, a third anisotropic etch process, such as an RIE process can be performed to transfer the pattern of the cavities 21 through a lower portion of the alternating stack (32, 42), i.e., into a subset of the insulating layers 32 and the sacrificial material layers 42 that are located within the lower portion of the alternating stack (32, 42). The chemistry of the third anisotropic etch process can be selected such that the third anisotropic etch process etches the materials of the insulating layers 32 and the sacrificial material layers 42 selective to the materials of the first hard mask layer 124, which is a carbon-based hard mask layer. In one embodiment, the second hard mask layer 28 may be entirely consumed during the third anisotropic etch process. The

third anisotropic etch process vertically extends the via openings (49, 19) through the lower portion of the alternating stack (32, 42). Thus, the via openings (49, 19) vertically extend through each layer within the alternating stack (32, 42) after the third anisotropic etch process.

(146) Therefore, during the second and third anisotropic etch processes, the critical dimension of the upper portion of the first hard mask layer 124 has a minimal change, while the critical dimension of the lower portion of the first hard mask layer 124 continues to expand. Likewise, the bow critical dimension of the first hard mask layer 124 has a minimal change. This reduces or prevents excessive bowing of the via openings (49, 19) within the alternating stack (49, 19).

Therefore, the via openings (49, 19) as formed by the third anisotropic etch process may have tapered sidewalls. The bow profile of each sidewalls of the cavities 21 in the first hard mask layer 124 can remain substantially invariant throughout the third anisotropic etch process due to the etch resistance of the carbon-based hard mask material within the first hard mask layer 124 during the third anisotropic etch process. For example, the taper angle (as measured between a vertical direction and a sidewall of the via openings (49, 19)) can be in a range from 0.01 degree to 3 degrees, such as from 0.1 degree to 1.5 degrees, although lesser and greater taper angles may also be employed. The first hard mask layer 124 can be subsequently removed, for example, by ashing.

(147) FIGS. 9A-9D are sequential vertical cross-sectional views of a region of a fifth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(148) Referring to FIG. 9A, the fifth configuration of the first exemplary structure at the processing steps of FIG. 9A can be the same as the third configuration of the first exemplary structure at the processing step of FIG. 7A.

(149) Referring to FIG. 9B, the processing steps of FIG. 7B can be performed. Thus, the fifth configuration of the first exemplary structure at the processing steps of FIG. 9B can be the same as the third configuration of the first exemplary structure at the processing step of FIG. 7B.

(150) Referring to FIG. 9C, a cladding liner 26 including a cladding material can be deposited on sidewalls of the first hard mask layer 122 around the cavities 21. In one embodiment, the cladding liner 26 may be deposited by a selective deposition process that grows the cladding material (i.e., the material of the cladding liner 26) from physically exposed surfaces of the first hard mask layer 122 without growth of the cladding material from physically exposed surfaces of the alternating stack (32, 42) or from physically exposed surfaces of the second hard mask layer 28. In this case, the cladding material may be any material that allows selective deposition on the boron doped carbon-based material of the first hard mask layer 122 without growth from surfaces of the alternating stack (32, 42) or from surfaces of the second hard mask layer 28. Thus, the cladding liner 26 is deposited on the physically exposed surfaces of the first hard mask layer 122, and is not deposited on the physically exposed surfaces of the alternating stack (32, 42) or the second hard mask layer 28.

(151) In one embodiment, the cladding liner 26 comprises, and/or consists essentially of, an inorganic material selected from amorphous carbon, diamond-like carbon, amorphous silicon, polycrystalline silicon, or boron nitride. In another embodiment, the cladding liner 26 comprises, and/or consists essentially of, a metallic material that can be selectively deposited on surfaces of the carbon-based hard mask layer 22. Metallic materials that can be selectively deposited on surfaces of the carbon-based hard mask layer 22 include, but are not limited to tungsten. For example, low fluorine tungsten ALD deposition may be used to selectively deposit tungsten on boron doped first hard mask layer 122 rather than on undoped carbon second hard mask layer 28. In one embodiment, the cladding liner 26 comprises, and/or consists essentially of, silicon oxide. The cladding liner 26 may be deposited by a conformal selective deposition process such as a chemical vapor deposition (CVD) process and/or an atomic layer deposition (ALD) process. The thickness of the cladding liner 26 may be in a range from 1 nm to 40 nm, such as from 2 nm to 20 nm, although lesser and greater thicknesses may also be employed.

(152) Referring to FIG. 9D, a third anisotropic etch process, such as an RIE process, can be performed to transfer the pattern of the cavities 21 (as reduced in volume due to the presence of the cladding liner 26) through a lower portion of the alternating stack (32, 42), i.e., into a subset of the insulating layers 32 and the sacrificial material layers 42 that are located within the lower portion of the alternating stack (32, 42). The chemistry of the third anisotropic etch process can be selected such that the third anisotropic etch process etches the materials of the insulating layers 32 and the sacrificial material layers 42 selective to the materials of the cladding liner 26 and the first hard mask layer 122. The cladding liner 26 may be partially or fully consumed during the third anisotropic etch process. The third anisotropic etch process vertically extends the via openings (49, 19) through the lower portion of the alternating stack (32, 42). Generally, the via openings (49, 19) can be vertically extended through all layers within the alternating stack (32, 42) by performing the third anisotropic etch process, which employs a combination of the cladding liner 26 and the first hard mask layer 122 as an etch mask. Thus, the via openings (49, 19) vertically extend through each layer within the alternating stack (32, 42) after the third anisotropic etch process.

(153) The via openings (49, 19) as formed by the third anisotropic etch process may have tapered sidewalls. The cladding liner 26 reduces the taper angle of the sidewalls of the via openings (49, 19) compared to an alternative etch scheme that does not employ the cladding liner 26. For example, the taper angle (as measured between a vertical direction and a sidewall of the via openings (49, 19)) can be in a range from 0.01 degree to 3 degrees, such as from 0.1 degree to 1.5 degrees, although lesser and greater taper angles may also be employed. The cladding liner 26 and the first hard mask layer 122 can be subsequently removed, for example, by ashing.

(154) FIGS. 10A-10D are sequential vertical cross-sectional views of a region of a sixth configuration of the first exemplary structure during formation of the memory openings according to an embodiment of the present disclosure.

(155) Referring to FIG. 10A, the sixth configuration of the first exemplary structure at the processing steps of FIG. 10A can be the same as the fourth configuration of the first exemplary structure at the processing step of FIG. 8A.

(156) Referring to FIG. 10B, the processing steps of FIG. 8B can be performed. Thus, the sixth configuration of the first exemplary structure at the processing steps of FIG. 10B can be the same as the fourth configuration of the first exemplary structure at the processing step of FIG. 8B.

(157) Referring to FIG. 10C, the processing steps of FIG. 9C can be performed. Thus, the sixth configuration of the first exemplary structure at the processing steps of FIG. 10C can be the same as the fifth configuration of the first exemplary structure at the processing step of FIG. 9C. In other words, the cladding liner 26 may be deposited by a selective deposition process that deposits a cladding material (i.e., the material of the cladding liner 26) on upper portions of the sidewalls of the first hard mask layer 124 which comprises a boron doped carbon-based material.

(158) Referring to FIG. 10D, the processing steps of FIG. 10D can be performed. Thus, the sixth configuration of the first exemplary structure at the processing steps of FIG. 10D can be the same as the sixth configuration of the first exemplary structure at the processing step of FIG. 9D.

(159) Any of the processing sequences illustrated in FIGS. 5A-D, 6A-6D, 7A-7C, 8A-8C, 9A-9D, and 10A-10D may be employed to form the first exemplary structure illustrated in FIGS. 4A and 4B. Subsequently, a series of processing steps can be performed to form a memory opening fill structure in each memory opening and to form a support pillar structure in each support opening. FIGS. 11A-11H are sequential schematic vertical cross-sectional views of a memory opening within the first exemplary structure during formation of a memory stack structure, an optional dielectric core, and a drain region therein according to an embodiment of the present disclosure.

(160) Referring to FIG. 11A, a memory opening 49 in the exemplary device structure of FIGS. 4A and 4B is illustrated. The memory opening 49 extends through the insulating cap layer 70, the alternating stack (32, 42), and optionally into an upper portion of the semiconductor material layer 10. At this processing step, each support opening 19 can extend through the retro-stepped dielectric



material portion **65**, a subset of layers in the alternating stack (**32**, **42**), and optionally through the upper portion of the semiconductor material layer **10**. The recess depth of the bottom surface of each memory opening with respect to the top surface of the semiconductor material layer **10** can be in a range from 0 nm to 30 nm, although greater recess depths can also be employed. Optionally, the sacrificial material layers **42** can be laterally recessed partially to form lateral recesses (not shown), for example, by an isotropic etch.

(161) Referring to FIG. **11B**, an optional pedestal channel portion (e.g., an epitaxial pedestal) **11** can be formed at the bottom portion of each memory opening **49** and each support openings **19**, for example, by selective epitaxy. Each pedestal channel portion **11** comprises a single crystalline semiconductor material in epitaxial alignment with the single crystalline semiconductor material of the semiconductor material layer **10**. In one embodiment, the pedestal channel portion **11** can be doped with electrical dopants of the same conductivity type as the semiconductor material layer **10**. In one embodiment, the top surface of each pedestal channel portion **11** can be formed above a horizontal plane including the top surface of a sacrificial material layer **42**. In this case, at least one source select gate electrode can be subsequently formed by replacing each sacrificial material layer **42** located below the horizontal plane including the top surfaces of the pedestal channel portions **11** with a respective conductive material layer. The pedestal channel portion **11** can be a portion of a transistor channel that extends between a source region to be subsequently formed in the substrate (**9**, **10**) and a drain region to be subsequently formed in an upper portion of the memory opening **49**. A memory cavity **49'** is present in the unfilled portion of the memory opening **49** above the pedestal channel portion **11**. In one embodiment, the pedestal channel portion **11** can comprise single crystalline silicon. In one embodiment, the pedestal channel portion **11** can have a doping of the first conductivity type, which is the same as the conductivity type of the semiconductor material layer **10** that the pedestal channel portion contacts. If a semiconductor material layer **10** is not present, the pedestal channel portion **11** can be formed directly on the substrate semiconductor layer **9**, which can have a doping of the first conductivity type.

(162) Referring to FIG. **11C**, a stack of layers including a blocking dielectric layer **52**, a memory material layer **54**, a tunneling dielectric layer **56**, and an optional sacrificial cover material layer **601** can be sequentially deposited in the memory openings **49**.

(163) The blocking dielectric layer **52** can include a single dielectric material layer or a stack of a plurality of dielectric material layers. In one embodiment, the blocking dielectric layer can include a dielectric metal oxide layer consisting essentially of a dielectric metal oxide. As used herein, a dielectric metal oxide refers to a dielectric material that includes at least one metallic element and at least oxygen. The dielectric metal oxide may consist essentially of the at least one metallic element and oxygen, or may consist essentially of the at least one metallic element, oxygen, and at least one non-metallic element such as nitrogen. In one embodiment, the blocking dielectric layer **52** can include a dielectric metal oxide having a dielectric constant greater than 7.9, i.e., having a dielectric constant greater than the dielectric constant of silicon nitride.

(164) Non-limiting examples of dielectric metal oxides include aluminum oxide (Al.sub.2O.sub.3), hafnium oxide (HfO.sub.2), lanthanum oxide (LaO.sub.2), yttrium oxide (Y.sub.2O.sub.3), tantalum oxide (Ta.sub.2O.sub.5), silicates thereof, nitrogen-doped compounds thereof, alloys thereof, and stacks thereof. The dielectric metal oxide layer can be deposited, for example, by chemical vapor deposition (CVD), atomic layer deposition (ALD), pulsed laser deposition (PLD), liquid source misted chemical deposition, or a combination thereof. The thickness of the dielectric metal oxide layer can be in a range from 1 nm to 20 nm, although lesser and greater thicknesses can also be employed. The dielectric metal oxide layer can subsequently function as a dielectric material portion that blocks leakage of stored electrical charges to control gate electrodes. In one embodiment, the blocking dielectric layer **52** includes aluminum oxide. In one embodiment, the blocking dielectric layer **52** can include multiple dielectric metal oxide layers having different material compositions.

(165) Alternatively or additionally, the blocking dielectric layer 52 can include a dielectric semiconductor compound such as silicon oxide, silicon oxynitride, silicon nitride, or a combination thereof. In one embodiment, the blocking dielectric layer 52 can include silicon oxide. In this case, the dielectric semiconductor compound of the blocking dielectric layer 52 can be formed by a conformal deposition method such as low pressure chemical vapor deposition, atomic layer deposition, or a combination thereof. The thickness of the dielectric semiconductor compound can be in a range from 1 nm to 20 nm, although lesser and greater thicknesses can also be employed. Alternatively, the blocking dielectric layer 52 can be omitted, and a backside blocking dielectric layer can be formed after formation of backside recesses on surfaces of memory films to be subsequently formed.

(166) Subsequently, the memory material layer 54 can be formed. In one embodiment, the memory material layer 54 can be a continuous layer or patterned discrete portions of a charge trapping material including a dielectric charge trapping material, which can be, for example, silicon nitride. Alternatively, the memory material layer 54 can include a continuous layer or patterned discrete portions of a conductive material such as doped polysilicon or a metallic material that is patterned into multiple electrically isolated portions (e.g., floating gates), for example, by being formed within lateral recesses into sacrificial material layers 42. In one embodiment, the memory material layer 54 includes a silicon nitride layer. In one embodiment, the sacrificial material layers 42 and the insulating layers 32 can have vertically coincident sidewalls, and the memory material layer 54 can be formed as a single continuous layer.

(167) In another embodiment, the sacrificial material layers 42 can be laterally recessed with respect to the sidewalls of the insulating layers 32, and a combination of a deposition process and an anisotropic etch process can be employed to form the memory material layer 54 as a plurality of memory material portions that are vertically spaced apart. While the present disclosure is described employing an embodiment in which the memory material layer 54 is a single continuous layer, embodiments are expressly contemplated herein in which the memory material layer 54 is replaced with a plurality of memory material portions (which can be charge trapping material portions or electrically isolated conductive material portions) that are vertically spaced apart.

(168) In one embodiment, each vertical stack of memory elements comprises a vertical stack of charge storage material portions that retain electrical charges therein upon programming, or a vertical stack of ferroelectric memory elements that retains electrical polarization therein upon programming. In case the vertical stack of ferroelectric memory elements is used, the memory material layer 54 may comprise a continuous ferroelectric material layer or a plurality of discrete, vertically separated ferroelectric material portions. The ferroelectric material may comprise orthorhombic phase hafnium oxide doped with silicon, aluminum or zirconium for example.

(169) The memory material layer 54 can be formed as a single memory material layer of homogeneous composition, or can include a stack of multiple memory material layers. The multiple memory material layers, if employed, can comprise a plurality of spaced-apart floating gate material layers that contain conductive materials (e.g., metal such as tungsten, molybdenum, tantalum, titanium, platinum, ruthenium, and alloys thereof, or a metal silicide such as tungsten silicide, molybdenum silicide, tantalum silicide, titanium silicide, nickel silicide, cobalt silicide, or a combination thereof) and/or semiconductor materials (e.g., polycrystalline or amorphous semiconductor material including at least one elemental semiconductor element or at least one compound semiconductor material). Alternatively or additionally, the memory material layer 54 may comprise an insulating charge trapping material, such as one or more silicon nitride segments. Alternatively, the memory material layer 54 may comprise conductive nanoparticles such as metal nanoparticles, which can be, for example, ruthenium nanoparticles. The memory material layer 54 can be formed, for example, by chemical vapor deposition (CVD), atomic layer deposition (ALD), physical vapor deposition (PVD), or any suitable deposition technique for storing electrical charges therein. The thickness of the memory material layer 54 can be in a range from 2 nm to 20 nm,

although lesser and greater thicknesses can also be employed.

(170) The tunneling dielectric layer **56** includes a dielectric material through which charge tunneling can be performed under suitable electrical bias conditions. The charge tunneling may be performed through hot-carrier injection or by Fowler-Nordheim tunneling induced charge transfer depending on the mode of operation of the monolithic three-dimensional NAND string memory device to be formed. The tunneling dielectric layer **56** can include silicon oxide, silicon nitride, silicon oxynitride, dielectric metal oxides (such as aluminum oxide and hafnium oxide), dielectric metal oxynitride, dielectric metal silicates, alloys thereof, and/or combinations thereof. In one embodiment, the tunneling dielectric layer **56** can include a stack of a first silicon oxide layer, a silicon oxynitride layer, and a second silicon oxide layer, which is commonly known as an ONO stack. In one embodiment, the tunneling dielectric layer **56** can include a silicon oxide layer that is substantially free of carbon or a silicon oxynitride layer that is substantially free of carbon. The thickness of the tunneling dielectric layer **56** can be in a range from 2 nm to 20 nm, although lesser and greater thicknesses can also be employed.

(171) The optional sacrificial cover material layer **601** includes a sacrificial material that can be subsequently removed selective to the material of the tunneling dielectric layer **56**. In one embodiment, the sacrificial cover material layer **601** can include a semiconductor material such as amorphous silicon, or may include a carbon-based material such as amorphous carbon or diamond-like carbon (DLC). The sacrificial cover material layer **601** can be formed by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD). The thickness of the sacrificial cover material layer **601** can be in a range from 2 nm to 10 nm, although lesser and greater thicknesses can also be employed. A memory cavity **49'** is formed in the volume of each memory opening **49** that is not filled with the deposited material layers (**52**, **54**, **56**, **601**).

(172) Referring to FIG. **11D**, the optional sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, the blocking dielectric layer **52** are sequentially anisotropically etched employing at least one anisotropic etch process. The portions of the sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, and the blocking dielectric layer **52** located above the top surface of the insulating cap layer **70** can be removed by the at least one anisotropic etch process. Further, the horizontal portions of the sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, and the blocking dielectric layer **52** at a bottom of each memory cavity **49'** can be removed to form openings in remaining portions thereof. Each of the sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, and the blocking dielectric layer **52** can be etched by a respective anisotropic etch process employing a respective etch chemistry, which may, or may not, be the same for the various material layers.

(173) Each remaining portion of the sacrificial cover material layer **601** can have a tubular configuration. The memory material layer **54** can comprise a charge trapping material, a floating gate material or a ferroelectric material. In one embodiment, each memory material layer **54** can include a vertical stack of charge storage regions that store electrical charges upon programming. In one embodiment, the memory material layer **54** can be a memory material layer in which each portion adjacent to the sacrificial material layers **42** constitutes a charge storage region.

(174) A surface of the pedestal channel portion **11** (or a surface of the semiconductor material layer **10** in case the pedestal channel portions **11** are not employed) can be physically exposed underneath the opening through the sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, and the blocking dielectric layer **52**. Optionally, the physically exposed semiconductor surface at the bottom of each memory cavity **49'** can be vertically recessed so that the recessed semiconductor surface underneath the memory cavity **49'** is vertically offset from the topmost surface of the pedestal channel portion **11** (or of the semiconductor material layer **10** in case pedestal channel portions **11** are not employed) by a recess distance. A tunneling dielectric layer **56** is located over the memory material layer **54**. A set of a

blocking dielectric layer **52**, a memory material layer **54**, and a tunneling dielectric layer **56** in a memory opening **49** constitutes a memory film **50**, which includes a plurality of charge storage regions (as embodied as the memory material layer **54**) that are insulated from surrounding materials by the blocking dielectric layer **52** and the tunneling dielectric layer **56**. In one embodiment, the sacrificial cover material layer **601**, the tunneling dielectric layer **56**, the memory material layer **54**, and the blocking dielectric layer **52** can have vertically coincident sidewalls. The sacrificial cover material layer **601** can be subsequently removed selective to the material of the tunneling dielectric layer **56**. In case the sacrificial cover material layer **601** includes a semiconductor material, a wet etch process employing hot trimethyl-2 hydroxyethyl ammonium hydroxide ("hot TMY") or tetramethyl ammonium hydroxide (TMAH) can be performed to remove the sacrificial cover material layer **601**. Alternatively, the sacrificial cover material layer **601** may be retained in the final device if it comprises a semiconductor material.

(175) Referring to FIG. **11E**, a semiconductor channel layer **60L** can be deposited directly on the semiconductor surface of the pedestal channel portion **11** or the semiconductor material layer **10** if the pedestal channel portion **11** is omitted, and directly on the tunneling dielectric layer **56**. The semiconductor channel layer **60L** includes a semiconductor material such as at least one elemental semiconductor material, at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, or other semiconductor materials known in the art. In one embodiment, the semiconductor channel layer **60L** includes amorphous silicon or polysilicon. The semiconductor channel layer **60L** can have a doping of a first conductivity type, which is the same as the conductivity type of the semiconductor material layer **10** and the pedestal channel portions **11**. The semiconductor channel layer **60L** can be formed by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD). The thickness of the semiconductor channel layer **60L** can be in a range from 2 nm to 10 nm, although lesser and greater thicknesses can also be employed. The semiconductor channel layer **60L** may partially fill the memory cavity **49'** in each memory opening, or may fully fill the cavity in each memory opening.

(176) Referring to FIG. **11F**, in case the memory cavity **49'** in each memory opening is not completely filled by the semiconductor channel layer **60L**, a dielectric core layer **62L** can be deposited in the memory cavity **49'** to fill any remaining portion of the memory cavity **49'** within each memory opening. The dielectric core layer **62L** includes a dielectric material such as silicon oxide or organosilicate glass. The dielectric core layer **62L** can be deposited by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD), or by a self-planarizing deposition process such as spin coating.

(177) Referring to FIG. **11G**, the horizontal portion of the dielectric core layer **62L** can be removed, for example, by a recess etch process such that each remaining portions of the dielectric core layer **62L** is located within a respective memory opening **49** and has a respective top surface below the horizontal plane including the top surface of the insulating cap layer **70**. Each remaining portion of the dielectric core layer **62L** constitutes a dielectric core **62**.

(178) Referring to FIG. **11H**, a doped semiconductor material having a doping of a second conductivity type can be deposited within each recessed region above the dielectric cores **62**. The deposited semiconductor material can have a doping of a second conductivity type that is the opposite of the first conductivity type. For example, if the first conductivity type is p-type, the second conductivity type is n-type, and vice versa. The dopant concentration in the deposited semiconductor material can be in a range from  $5.0 \times 10^{19} \text{ cm}^{-3}$  to  $2.0 \times 10^{21} \text{ cm}^{-3}$ , although lesser and greater dopant concentrations can also be employed. The doped semiconductor material can be, for example, doped polysilicon.

(179) Excess portions of the deposited semiconductor material having a doping of the second conductivity type and a horizontal portion of the semiconductor channel layer **60L** can be removed from above the horizontal plane including the top surface of the insulating cap layer **70**, for

example, by chemical mechanical planarization (CMP) or a recess etch process. Each remaining portion of the doped semiconductor material having a doping of the second conductivity type constitutes a drain region **63**. Each remaining portion of the semiconductor channel layer **60L** (which has a doping of the first conductivity type) constitutes a vertical semiconductor channel **60**. (180) A tunneling dielectric layer **56** is surrounded by a memory material layer **54**, and laterally surrounds a portion of the vertical semiconductor channel **60**. Each adjoining set of a blocking dielectric layer **52**, a memory material layer **54**, and a tunneling dielectric layer **56** collectively constitute a memory film **50**, which can store electrical charges or ferroelectric polarization with a macroscopic retention time. In some embodiments, a blocking dielectric layer **52** may not be present in the memory film **50** at this step, and a blocking dielectric layer may be subsequently formed after formation of backside recesses. Furthermore, if the ferroelectric memory material layer **54** is used, then the tunneling dielectric layer **56** may be omitted. As used herein, a macroscopic retention time refers to a retention time suitable for operation of a memory device as a permanent memory device such as a retention time in excess of 24 hours.

(181) Each combination of a memory film **50** and a vertical semiconductor channel **60** within a memory opening **49** constitutes a memory stack structure **55**. The memory stack structure **55** is a combination of a semiconductor channel, a tunneling dielectric layer, a plurality of memory elements as embodied as portions of the memory material layer **54**, and an optional blocking dielectric layer **52**. Each combination of a pedestal channel portion **11** (if present), a memory stack structure **55**, a dielectric core **62**, and a drain region **63** within a memory opening **49** is herein referred to as a memory opening fill structure **58**. Each combination of a pedestal channel portion **11** (if present), a memory film **50**, a vertical semiconductor channel **60**, a dielectric core **62**, and a drain region **63** within each support opening **19** fills the respective support openings **19**, and constitutes a support pillar structure.

(182) Referring to FIG. **12**, the first exemplary structure is illustrated after formation of memory opening fill structures **58** and support pillar structure **20** within the memory openings **49** and the support openings **19**, respectively. An instance of a memory opening fill structure **58** can be formed within each memory opening **49** of the structure of FIGS. **4A** and **4B**. An instance of the support pillar structure **20** can be formed within each support opening **19** of the structure of FIGS. **4A** and **4B**.

(183) Each memory stack structure **55** includes a vertical semiconductor channel **60** and a memory film **50**. The memory film **50** may comprise a tunneling dielectric layer **56** laterally surrounding the vertical semiconductor channel **60** and a vertical stack of charge storage regions or ferroelectric regions (e.g., comprising portions of the memory material layer **54**) laterally surrounding the tunneling dielectric layer **56** (if present in combination with the charge storage regions) and an optional blocking dielectric layer **52**. While the present disclosure is described employing the illustrated configuration for the memory stack structure, the methods of the present disclosure can be applied to alternative memory stack structures including different layer stacks or structures for the memory film **50** and/or for the vertical semiconductor channel **60**.

(184) Referring to FIGS. **13A** and **13B**, a contact-level dielectric layer **73** can be formed over the alternating stack (**32**, **42**) of insulating layer **32** and sacrificial material layers **42**, and over the memory stack structures **55** and the support pillar structures **20**. The contact-level dielectric layer **73** includes a dielectric material that is different from the dielectric material of the sacrificial material layers **42**. For example, the contact-level dielectric layer **73** can include silicon oxide. The contact-level dielectric layer **73** can have a thickness in a range from 50 nm to 500 nm, although lesser and greater thicknesses can also be employed.

(185) A photoresist layer (not shown) can be applied over the contact-level dielectric layer **73**, and is lithographically patterned to form openings in areas between clusters of memory stack structures **55**. The pattern in the photoresist layer can be transferred through the contact-level dielectric layer **73**, the alternating stack (**32**, **42**) and/or the retro-stepped dielectric material portion **65** employing

an anisotropic etch to form backside trenches **79**, which vertically extend from the top surface of the contact-level dielectric layer **73** at least to the top surface of the substrate (**9**, **10**), and laterally extend through the memory array region **100** and the contact region **300**.

(186) In one embodiment, the backside trenches **79** can laterally extend along a first horizontal direction **hd1** and can be laterally spaced apart from each other along a second horizontal direction **hd2** that is perpendicular to the first horizontal direction **hd1**. The memory stack structures **55** can be arranged in rows that extend along the first horizontal direction **hd1**. The drain-select-level isolation structures **72** can laterally extend along the first horizontal direction **hd1**. Each backside trench **79** can have a uniform width that is invariant along the lengthwise direction (i.e., along the first horizontal direction **hd1**). Each drain-select-level isolation structure **72** can have a uniform vertical cross-sectional profile along vertical planes that are perpendicular to the first horizontal direction **hd1** that is invariant with translation along the first horizontal direction **hd1**. Multiple rows of memory stack structures **55** can be located between a neighboring pair of a backside trench **79** and a drain-select-level isolation structure **72**, or between a neighboring pair of drain-select-level isolation structures **72**. In one embodiment, the backside trenches **79** can include a source contact opening in which a source contact via structure can be subsequently formed. The photoresist layer can be removed, for example, by ashing. Generally, backside trenches **79** laterally extending along the first horizontal direction **hd1** can be formed through the contact-level dielectric layer **73** and the alternating stack (**32**, **42**). The alternating stack (**32**, **42**) as formed at the processing steps of FIG. **3** is divided into multiple alternating stacks (**32**, **42**) that are laterally spaced apart along the second horizontal direction **hd2** by the backside trenches **79**. Layer stacks (**32**, **42**, **70**, **73**) are formed, each of which includes a respective patterned portion of the contact-level dielectric layer **73** and a respective patterned portion of the alternating stack (**32**, **42**) as formed at the processing steps of FIG. **3** and laterally spaced from each other by the backside trenches **79**.

(187) Dopants of the second conductivity type can be implanted into physically exposed surface portions of the substrate (**9**, **10**) (which may be surface portions of the semiconductor material layer **10**) that are located at the bottom of the backside trenches by an ion implantation process. A source region **61** can be formed at a surface portion of the semiconductor material layer **10** under each backside trench **79**. Each source region **61** is formed in a surface portion of the substrate (**9**, **10**) that underlies a respective backside trench **79**. Due to the straggle of the implanted dopant atoms during the implantation process and lateral diffusion of the implanted dopant atoms during a subsequent activation anneal process, each source region **61** can have a lateral extent greater than the lateral extent of the lateral extent of the overlying backside trench **79**.

(188) An upper portion of the semiconductor material layer **10** that extends between the source region **61** and the plurality of pedestal channel portions **11** constitutes a horizontal semiconductor channel **59** for a plurality of field effect transistors. The horizontal semiconductor channel **59** is connected to multiple vertical semiconductor channels **60** through respective pedestal channel portions **11**. Each horizontal semiconductor channel **59** contacts a source region **61** and a plurality of pedestal channel portions **11**.

(189) Referring to FIGS. **14** and **15A**, an etchant that selectively etches the second material of the sacrificial material layers **42** with respect to the first material of the insulating layers **32** can be introduced into the backside cavities **79'**, for example, employing an etch process. Backside recesses **43** are formed in volumes from which the sacrificial material layers **42** are removed. The removal of the second material of the sacrificial material layers **42** can be selective to the first material of the insulating layers **32**, the material of the retro-stepped dielectric material portion **65**, the semiconductor material of the semiconductor material layer **10**, and the material of the outermost layer of the memory films **50**. In one embodiment, the sacrificial material layers **42** can include silicon nitride, and the materials of the insulating layers **32** and the retro-stepped dielectric material portion **65** can be selected from silicon oxide and dielectric metal oxides.

(190) The etch process that removes the second material selective to the first material and the outermost layer of the memory films **50** can be a wet etch process employing a wet etch solution, or can be a gas phase (dry) etch process in which the etchant is introduced in a vapor phase into the backside trenches **79**. For example, if the sacrificial material layers **42** include silicon nitride, the etch process can be a wet etch process in which the first exemplary structure is immersed within a wet etch tank including phosphoric acid, which etches silicon nitride selective to silicon oxide, silicon, and various other materials employed in the art. The support pillar structure **20**, the retro-stepped dielectric material portion **65**, and the memory stack structures **55** provide structural support while the backside recesses **43** are present within volumes previously occupied by the sacrificial material layers **42**.

(191) Each backside recess **43** can be a laterally extending cavity having a lateral dimension that is greater than the vertical extent of the cavity. In other words, the lateral dimension of each backside recess **43** can be greater than the height of the backside recess **43**. A plurality of backside recesses **43** can be formed in the volumes from which the second material of the sacrificial material layers **42** is removed. The memory openings in which the memory stack structures **55** are formed are herein referred to as front side openings or front side cavities in contrast with the backside recesses **43**. In one embodiment, the memory array region **100** comprises an array of monolithic three-dimensional NAND strings having a plurality of device levels disposed above the substrate (**9**, **10**). In this case, each backside recess **43** can define a space for receiving a respective word line of the array of monolithic three-dimensional NAND strings.

(192) Each of the plurality of backside recesses **43** can extend substantially parallel to the top surface of the substrate (**9**, **10**). A backside recess **43** can be vertically bounded by a top surface of an underlying insulating layer **32** and a bottom surface of an overlying insulating layer **32**. In one embodiment, each backside recess **43** can have a uniform height throughout. Generally, the backside recesses **43** can be formed by removing the sacrificial material layers **42** (which are patterned portions of the sacrificial material layers as formed at the processing steps of FIG. 3) selective to the insulating layers **32** (which are patterned portions of the insulating layers **32** as formed at the processing steps of FIG. 3).

(193) Physically exposed surface portions of the optional pedestal channel portions **11** and the semiconductor material layer **10** can be converted into dielectric material portions by thermal conversion and/or plasma conversion of the semiconductor materials into dielectric materials. For example, thermal conversion and/or plasma conversion can be employed to convert a surface portion of each pedestal channel portion **11** into a tubular dielectric spacer **116**, and to convert each physically exposed surface portion of the semiconductor material layer **10** into a planar dielectric portion **616**. In one embodiment, each tubular dielectric spacer **116** can be topologically homeomorphic to a torus, i.e., generally ring-shaped. As used herein, an element is topologically homeomorphic to a torus if the shape of the element can be continuously stretched without destroying a hole or forming a new hole into the shape of a torus. The tubular dielectric spacers **116** include a dielectric material that includes the same semiconductor element as the pedestal channel portions **11** and additionally includes at least one non-metallic element such as oxygen and/or nitrogen such that the material of the tubular dielectric spacers **116** is a dielectric material. In one embodiment, the tubular dielectric spacers **116** can include a dielectric oxide, a dielectric nitride, or a dielectric oxynitride of the semiconductor material of the pedestal channel portions **11**. Likewise, each planar dielectric portion **616** includes a dielectric material that includes the same semiconductor element as the semiconductor material layer and additionally includes at least one non-metallic element such as oxygen and/or nitrogen such that the material of the planar dielectric portions **616** is a dielectric material. In one embodiment, the planar dielectric portions **616** can include a dielectric oxide, a dielectric nitride, or a dielectric oxynitride of the semiconductor material of the semiconductor material layer **10**.

(194) Referring to FIG. 15B, a backside blocking dielectric layer **44** can be optionally formed. The

backside blocking dielectric layer **44**, if present, comprises a dielectric material that functions as a control gate dielectric for the control gates to be subsequently formed in the backside recesses **43**. In case the blocking dielectric layer **52** is present within each memory opening, the backside blocking dielectric layer **44** is optional. In case the blocking dielectric layer **52** is omitted, the backside blocking dielectric layer **44** is present.

(195) The backside blocking dielectric layer **44** can be formed in the backside recesses **43** and on a sidewall of the backside trench **79**. The backside blocking dielectric layer **44** can be formed directly on horizontal surfaces of the insulating layers **32** and sidewalls of the memory stack structures **55** within the backside recesses **43**. If the backside blocking dielectric layer **44** is formed, formation of the tubular dielectric spacers **116** and the planar dielectric portion **616** prior to formation of the backside blocking dielectric layer **44** is optional. In one embodiment, the backside blocking dielectric layer **44** can be formed by a conformal deposition process such as atomic layer deposition (ALD). The backside blocking dielectric layer **44** can consist essentially of aluminum oxide. The thickness of the backside blocking dielectric layer **44** can be in a range from 1 nm to 15 nm, such as 2 to 6 nm, although lesser and greater thicknesses can also be employed.

(196) The dielectric material of the backside blocking dielectric layer **44** can be a dielectric metal oxide such as aluminum oxide, a dielectric oxide of at least one transition metal element, a dielectric oxide of at least one Lanthanide element, a dielectric oxide of a combination of aluminum, at least one transition metal element, and/or at least one Lanthanide element.

Alternatively or additionally, the backside blocking dielectric layer **44** can include a silicon oxide layer. The backside blocking dielectric layer **44** can be deposited by a conformal deposition method such as chemical vapor deposition or atomic layer deposition. The backside blocking dielectric layer **44** is formed on the sidewalls of the backside trenches **79**, horizontal surfaces and sidewalls of the insulating layers **32**, the portions of the sidewall surfaces of the memory stack structures **55** that are physically exposed to the backside recesses **43**, and a top surface of the planar dielectric portion **616**. A backside cavity **79'** is present within the portion of each backside trench **79** that is not filled with the backside blocking dielectric layer **44**.

(197) Referring to FIG. **15C**, at least one conductive material can be deposited in the backside recesses **43** by providing at least one reactant gas into the backside recesses **43** through the backside trenches **79**. A metallic barrier layer **46A** can be deposited in the backside recesses **43**. The metallic barrier layer **46A** includes an electrically conductive metallic material that can function as a diffusion barrier layer and/or adhesion promotion layer for a metallic fill material to be subsequently deposited. The metallic barrier layer **46A** can include a conductive metallic nitride material such as TiN, TaN, WN, or a stack thereof, or can include a conductive metallic carbide material such as TiC, TaC, WC, or a stack thereof. In one embodiment, the metallic barrier layer **46A** can be deposited by a conformal deposition process such as chemical vapor deposition (CVD) or atomic layer deposition (ALD). The thickness of the metallic barrier layer **46A** can be in a range from 2 nm to 8 nm, such as from 3 nm to 6 nm, although lesser and greater thicknesses can also be employed. In one embodiment, the metallic barrier layer **46A** can consist essentially of a conductive metal nitride such as TiN.

(198) Referring to FIGS. **15D** and **16**, a metal fill material is deposited in the plurality of backside recesses **43**, on the sidewalls of the at least one the backside trench **79**, and over the top surface of the contact-level dielectric layer **73** to form a metallic fill material layer **46B**. The metallic fill material can be deposited by a conformal deposition method, which can be, for example, chemical vapor deposition (CVD), atomic layer deposition (ALD), electroless plating, electroplating, or a combination thereof. In one embodiment, the metallic fill material layer **46B** can consist essentially of at least one elemental metal. The at least one elemental metal of the metallic fill material layer **46B** can be selected, for example, from tungsten, cobalt, ruthenium, titanium, and tantalum. In one embodiment, the metallic fill material layer **46B** can consist essentially of a single elemental metal. In one embodiment, the metallic fill material layer **46B** can be deposited employing a fluorine-



containing precursor gas such as WF.sub.6. In one embodiment, the metallic fill material layer **46B** can be a tungsten layer including a residual level of fluorine atoms as impurities. The metallic fill material layer **46B** is spaced from the insulating layers **32** and the memory stack structures **55** by the metallic barrier layer **46A**, which is a metallic barrier layer that blocks diffusion of fluorine atoms therethrough.

(199) A plurality of electrically conductive layers **46** can be formed in the plurality of backside recesses **43**, and a continuous metallic material layer **46L** can be formed on the sidewalls of each backside trench **79** and over the contact-level dielectric layer **73**. Each electrically conductive layer **46** includes a portion of the metallic barrier layer **46A** and a portion of the metallic fill material layer **46B** that are located between a vertically neighboring pair of dielectric material layers such as a pair of insulating layers **32**. The continuous metallic material layer **46L** includes a continuous portion of the metallic barrier layer **46A** and a continuous portion of the metallic fill material layer **46B** that are located in the backside trenches **79** or above the contact-level dielectric layer **73**.

(200) Each sacrificial material layer **42** can be replaced with an electrically conductive layer **46**. A backside cavity **79'** is present in the portion of each backside trench **79** that is not filled with the backside blocking dielectric layer **44** and the continuous metallic material layer **46L**. A tubular dielectric spacer **116** laterally surrounds a pedestal channel portion **11**. A bottommost electrically conductive layer **46** laterally surrounds each tubular dielectric spacer **116** upon formation of the electrically conductive layers **46**.

(201) Referring to FIGS. **17A** and **17B**, the deposited metallic material of the continuous electrically conductive material layer **46L** is etched back from the sidewalls of each backside trench **79** and from above the contact-level dielectric layer **73** by performing an isotropic etch process that etches the at least one conductive material of the continuous electrically conductive material layer **46L**. Each remaining portion of the deposited metallic material in the backside recesses **43** constitutes an electrically conductive layer **46**. Each electrically conductive layer **46** can be a conductive line structure. Thus, the sacrificial material layers **42** are replaced with the electrically conductive layers **46**.

(202) Each electrically conductive layer **46** can function as a combination of a plurality of control gate electrodes located at a same level and a word line electrically interconnecting, i.e., electrically shorting, the plurality of control gate electrodes located at the same level. The plurality of control gate electrodes within each electrically conductive layer **46** are the control gate electrodes for the vertical memory devices including the memory stack structures **55**. In other words, each electrically conductive layer **46** can be a word line that functions as a common control gate electrode for the plurality of vertical memory devices.

(203) In one embodiment, the removal of the continuous electrically conductive material layer **46L** can be selective to the material of the backside blocking dielectric layer **44**. In this case, a horizontal portion of the backside blocking dielectric layer **44** can be present at the bottom of each backside trench **79**. In another embodiment, the removal of the continuous electrically conductive material layer **46L** may not be selective to the material of the backside blocking dielectric layer **44** or, the backside blocking dielectric layer **44** may not be employed. The planar dielectric portions **616** can be removed during removal of the continuous electrically conductive material layer **46L**. A backside cavity is present within each backside trench **79**. Each backside cavity continuous extends along the first horizontal direction **hd1**.

(204) Referring to FIGS. **18A** and **18B**, an insulating material layer can be formed in the backside trenches **79** and over the contact-level dielectric layer **73** by a conformal deposition process. Exemplary conformal deposition processes include, but are not limited to, chemical vapor deposition and atomic layer deposition. The insulating material layer includes an insulating material such as silicon oxide, silicon nitride, a dielectric metal oxide, an organosilicate glass, or a combination thereof. In one embodiment, the insulating material layer can include silicon oxide. The insulating material layer can be formed, for example, by low pressure chemical vapor

deposition (LPCVD) or atomic layer deposition (ALD). The thickness of the insulating material layer can be in a range from 1.5 nm to 60 nm, although lesser and greater thicknesses can also be employed.

(205) If a backside blocking dielectric layer **44** is present, the insulating material layer can be formed directly on surfaces of the backside blocking dielectric layer **44** and directly on the sidewalls of the electrically conductive layers **46**. If a backside blocking dielectric layer **44** is not employed, the insulating material layer can be formed directly on sidewalls of the insulating layers **32** and directly on sidewalls of the electrically conductive layers **46**.

(206) An anisotropic etch is performed to remove horizontal portions of the insulating material layer from above the contact-level dielectric layer **73** and at the bottom of each backside trench **79**. Each remaining portion of the insulating material layer constitutes an insulating spacer **74**. A backside cavity is present within a volume surrounded by each insulating spacer **74**.

(207) A top surface of a source region **61** can be physically exposed at the bottom of each backside trench **79**. A bottommost electrically conductive layer **46** provided upon formation of the electrically conductive layers **46** within the alternating stack (**32**, **46**) can comprise a select gate electrode for the field effect transistors. Each source region **61** is formed in an upper portion of the substrate (**9**, **10**). Semiconductor channels (**59**, **11**, **60**) extend between each source region **61** and a respective set of drain regions **63**. The semiconductor channels (**59**, **11**, **60**) include the vertical semiconductor channels **60** of the memory stack structures **55**.

(208) A backside contact via structure **76** can be formed within each backside cavity. Each contact via structure **76** can fill a respective cavity. The contact via structures **76** can be formed by depositing at least one conductive material in the remaining unfilled volume (i.e., the backside cavity) of the backside trench **79**. For example, the at least one conductive material can include a conductive liner **76A** and a conductive fill material portion **76B**. The conductive liner **76A** can include a conductive metallic liner such as TiN, TaN, WN, TiC, TaC, WC, an alloy thereof, or a stack thereof. The thickness of the conductive liner **76A** can be in a range from 3 nm to 30 nm, although lesser and greater thicknesses can also be employed. The conductive fill material portion **76B** can include a metal or a metallic alloy. For example, the conductive fill material portion **76B** can include W, Cu, Al, Co, Ru, Ni, an alloy thereof, or a stack thereof.

(209) The at least one conductive material can be planarized employing the contact-level dielectric layer **73** overlying the alternating stack (**32**, **46**) as a stopping layer. If chemical mechanical planarization (CMP) process is employed, the contact-level dielectric layer **73** can be employed as a CMP stopping layer. Each remaining continuous portion of the at least one conductive material in the backside trenches **79** constitutes a backside contact via structure **76**. Each backside contact via structure **76** extends through the alternating stacks (**32**, **46**), and contacts a top surface of a respective source region **61**. If a backside blocking dielectric layer **44** is employed, each backside contact via structure **76** can contact a sidewall of the backside blocking dielectric layer **44**.

(210) Generally, a backside contact via structure **76** can be formed within each of the backside trenches **79** after formation of the insulating spacers **74** by depositing and planarizing at least one conductive material in volumes of the backside trenches **79** that are not filled with the insulating spacers **74**.

(211) Alternatively, the above described insulating material layer can be formed in the backside trenches **79** to completely fill the entire volume of a backside trench **79** and may consist essentially of at least one dielectric material. In this alternative embodiment, the source region **61** and the backside trench via structure **76** may be omitted, and a horizontal source line (e.g., direct strap contact) may contact a side of the lower portion of the semiconductor channel **60**.

(212) Referring to FIGS. **19A** and **19B**, additional contact via structures (**88**, **86**, **8P**) can be formed through the contact-level dielectric layer **73**, and optionally through the retro-stepped dielectric material portion **65**. For example, drain contact via structures **88** can be formed through the contact-level dielectric layer **73** on each drain region **63**. Word line contact via structures **86** can be

formed on the electrically conductive layers **46** through the contact-level dielectric layer **73**, and through the retro-stepped dielectric material portion **65**. Peripheral device contact via structures **8P** can be formed through the retro-stepped dielectric material portion **65** directly on respective nodes of the peripheral devices.

(213) Referring to FIGS. **20A-20C**, a second exemplary structure according to the second embodiment of the present disclosure is illustrated. FIG. **20C** is a magnified view of an in-process source-level material layers **110'** illustrated in FIGS. **20A** and **20B**. The second exemplary structure includes a substrate **8** and semiconductor devices **710** formed thereupon. The substrate **8** includes a substrate semiconductor layer **9** at least at an upper portion thereof. Shallow trench isolation structures **720** may be formed in an upper portion of the substrate semiconductor layer **9** to provide electrical isolation from other semiconductor devices. The semiconductor devices **710** may include, for example, field effect transistors including respective transistor active regions **742** (i.e., source regions and drain regions), channel regions **746**, and gate structures **750**. The field effect transistors may be arranged in a CMOS configuration. Each gate structure **750** may include, for example, a gate dielectric **752**, a gate electrode **754**, a dielectric gate spacer **756** and a gate cap dielectric **758**. The semiconductor devices **710** may include any semiconductor circuitry to support operation of a memory structure to be subsequently formed, which is typically referred to as a driver circuitry, which is also known as peripheral circuitry. As used herein, a peripheral circuitry refers to any, each, or all, of word line decoder circuitry, word line switching circuitry, bit line decoder circuitry, bit line sensing and/or switching circuitry, power supply/distribution circuitry, data buffer and/or latch, or any other semiconductor circuitry that may be implemented outside a memory array structure for a memory device. For example, the semiconductor devices may include word line switching devices for electrically biasing word lines of three-dimensional memory structures to be subsequently formed.

(214) Dielectric material layers are formed over the semiconductor devices, which are herein referred to as lower-level dielectric material layers **760**. The lower-level dielectric material layers **760** may include, for example, a dielectric liner **762** (such as a silicon nitride liner that blocks diffusion of mobile ions and/or apply appropriate stress to underlying structures), first dielectric material layers **764** that overlie the dielectric liner **762**, a silicon nitride layer (e.g., hydrogen diffusion barrier) **766** that overlies the first dielectric material layers **764**, and at least one second dielectric layer **768**.

(215) The dielectric layer stack including the lower-level dielectric material layers **760** functions as a matrix for lower-level metal interconnect structures **780** that provide electrical wiring to and from the various nodes of the semiconductor devices and landing pads for through-memory-level contact via structures to be subsequently formed. The lower-level metal interconnect structures **780** are formed within the dielectric layer stack of the lower-level dielectric material layers **760**, and comprise a lower-level metal line structure located under and optionally contacting a bottom surface of the silicon nitride layer **766**.

(216) For example, the lower-level metal interconnect structures **780** may be formed within the first dielectric material layers **764**. The first dielectric material layers **764** may be a plurality of dielectric material layers in which various elements of the lower-level metal interconnect structures **780** are sequentially formed. Each dielectric material layer selected from the first dielectric material layers **764** may include any of doped silicate glass, undoped silicate glass, organosilicate glass, silicon nitride, silicon oxynitride, and dielectric metal oxides (such as aluminum oxide). In one embodiment, the first dielectric material layers **764** may comprise, or consist essentially of, dielectric material layers having dielectric constants that do not exceed the dielectric constant of undoped silicate glass (silicon oxide) of 3.9. The lower-level metal interconnect structures **780** may include various device contact via structures **782** (e.g., source and drain electrodes which contact the respective source and drain nodes of the device or gate electrode contacts), intermediate lower-level metal line structures **784**, lower-level metal via structures **786**, and landing-pad-level metal

line structures **788** that are configured to function as landing pads for through-memory-level contact via structures to be subsequently formed.

(217) The landing-pad-level metal line structures **788** may be formed within a topmost dielectric material layer of the first dielectric material layers **764** (which may be a plurality of dielectric material layers). Each of the lower-level metal interconnect structures **780** may include a metallic nitride liner and a metal fill structure. Top surfaces of the landing-pad-level metal line structures **788** and the topmost surface of the first dielectric material layers **764** may be planarized by a planarization process, such as chemical mechanical planarization. The silicon nitride layer **766** may be formed directly on the top surfaces of the landing-pad-level metal line structures **788** and the topmost surface of the first dielectric material layers **764**.

(218) The at least one second dielectric material layer **768** may include a single dielectric material layer or a plurality of dielectric material layers. Each dielectric material layer selected from the at least one second dielectric material layer **768** may include any of doped silicate glass, undoped silicate glass, and organosilicate glass. In one embodiment, the at least one first second material layer **768** may comprise, or consist essentially of, dielectric material layers having dielectric constants that do not exceed the dielectric constant of undoped silicate glass (silicon oxide) of 3.9.

(219) An optional layer of a metallic material and one or more layers of semiconductor and insulating material may be deposited over, or within patterned recesses of, the at least one second dielectric material layer **768**, and are lithographically patterned to provide an optional conductive plate layer **6** and in-process source-level material layers **110'**. The optional conductive plate layer **6**, if present, provides a high conductivity conduction path for electrical current that flows into, or out of, the in-process source-level material layers **110'**. The optional conductive plate layer **6** includes a conductive material such as a metal, metal silicide, or a heavily doped semiconductor material. The optional conductive plate layer **6**, for example, may include a tungsten layer having a thickness in a range from 3 nm to 100 nm, although lesser and greater thicknesses may also be used. A metal nitride layer (not shown) may be provided as a diffusion barrier layer on top of the conductive plate layer **6**. The conductive plate layer **6** may function as a special source line in the completed device. In addition, the conductive plate layer **6** may comprise an etch stop layer and may comprise any suitable conductive, semiconductor or insulating layer. The optional conductive plate layer **6** may include a metallic compound material such as a conductive metallic nitride (e.g., TiN) or silicide (e.g. tungsten or titanium silicide) and/or a metal (e.g., W). The thickness of the optional conductive plate layer **6** may be in a range from 5 nm to 100 nm, although lesser and greater thicknesses may also be used.

(220) The in-process source-level material layers **110'** may include various layers that are subsequently modified to form source-level material layers. The source-level material layers, upon formation, include a source contact layer that functions as a common source region for vertical field effect transistors of a three-dimensional memory device. In one embodiment, the in-process source-level material layers **110'** may include, from bottom to top, a lower source-level semiconductor layer **112**, a lower sacrificial liner **103**, a source-level sacrificial layer **104**, an upper sacrificial liner **105**, and an upper source-level semiconductor layer **118**.

(221) The lower source-level semiconductor layer **112** and the upper source-level semiconductor layer **118** may include a doped semiconductor material, such as doped polysilicon or doped amorphous silicon. The conductivity type of the lower source-level semiconductor layer **112** and the upper source-level semiconductor layer **118** may be the opposite of the conductivity of vertical semiconductor channels to be subsequently formed. For example, if the vertical semiconductor channels to be subsequently formed have a doping of a first conductivity type, the lower source-level semiconductor layer **112** and the upper source-level semiconductor layer **118** have a doping of a second conductivity type that is the opposite of the first conductivity type. The thickness of each of the lower source-level semiconductor layer **112** and the upper source-level semiconductor layer **118** may be in a range from 10 nm to 300 nm, such as from 20 nm to 150 nm, although lesser and

greater thicknesses may also be used.

(222) The source-level sacrificial layer **104** includes a sacrificial material that may be removed selective to the lower sacrificial liner **103** and the upper sacrificial liner **105**. In one embodiment, the source-level sacrificial layer **104** may include a dielectric material, such as silicon nitride. Alternatively, the source-level sacrificial layer **104** may include a semiconductor material such as undoped amorphous silicon or a silicon-germanium alloy with an atomic concentration of germanium greater than 20%. The thickness of the source-level sacrificial layer **104** may be in a range from 30 nm to 400 nm, such as from 60 nm to 200 nm, although lesser and greater thicknesses may also be used.

(223) The lower sacrificial liner **103** and the upper sacrificial liner **105** include materials that may function as an etch stop material during removal of the source-level sacrificial layer **104**. For example, the lower sacrificial liner **103** and the upper sacrificial liner **105** may include silicon oxide and/or a dielectric metal oxide. In one embodiment, each of the lower sacrificial liner **103** and the upper sacrificial liner **105** may include a silicon oxide layer having a thickness in a range from 2 nm to 30 nm, although lesser and greater thicknesses may also be used.

(224) The in-process source-level material layers **110'** may be formed directly above a subset of the semiconductor devices on the substrate **8** (e.g., silicon wafer). As used herein, a first element is located "directly above" a second element if the first element is located above a horizontal plane including a topmost surface of the second element and an area of the first element and an area of the second element has an areal overlap in a plan view (i.e., along a vertical plane or direction perpendicular to the top surface of the substrate **8**).

(225) The optional conductive plate layer **6** and the in-process source-level material layers **110'** may be patterned to provide openings in areas in which through-memory-level contact via structures and through-dielectric contact via structures are to be subsequently formed. Patterned portions of the stack of the conductive plate layer **6** and the in-process source-level material layers **110'** are present in each memory array region **100** in which three-dimensional memory stack structures are to be subsequently formed.

(226) The optional conductive plate layer **6** and the in-process source-level material layers **110'** may be patterned such that an opening extends over a contact region **300** in which contact via structures contacting word line electrically conductive layers are to be subsequently formed. In one embodiment, the contact region **300** may be laterally spaced from the memory array region **100** along a first horizontal direction (e.g., word line direction) **hd1**. A horizontal direction that is perpendicular to the first horizontal direction **hd1** is herein referred to as a second horizontal direction (e.g., bit line direction) **hd2**. In one embodiment, additional openings in the optional conductive plate layer **6** and the in-process source-level material layers **110'** may be formed within the area of a memory array region **100**, in which a three-dimensional memory array including memory stack structures is to be subsequently formed. A peripheral device region **400** that is subsequently filled with a field dielectric material portion may be provided adjacent to the contact region **300**.

(227) The region of the semiconductor devices **710** and the combination of the lower-level dielectric material layers **760** and the lower-level metal interconnect structures **780** is herein referred to an underlying peripheral device region **700**, which is located underneath a memory-level assembly to be subsequently formed and includes peripheral devices for the memory-level assembly. The lower-level metal interconnect structures **780** are formed in the lower-level dielectric material layers **760**.

(228) The lower-level metal interconnect structures **780** may be electrically connected to active nodes (e.g., transistor active regions **742** or gate electrodes **754**) of the semiconductor devices **710** (e.g., CMOS devices), and are located at the level of the lower-level dielectric material layers **760**. Through-memory-level contact via structures may be subsequently formed directly on the lower-level metal interconnect structures **780** to provide electrical connection to memory devices to be

subsequently formed. In one embodiment, the pattern of the lower-level metal interconnect structures **780** may be selected such that the landing-pad-level metal line structures **788** (which are a subset of the lower-level metal interconnect structures **780** located at the topmost portion of the lower-level metal interconnect structures **780**) may provide landing pad structures for the through-memory-level contact via structures to be subsequently formed.

(229) Referring to FIG. **21**, an alternating stack of first material layers and second material layers is subsequently formed. Each first material layer may include a first material, and each second material layer may include a second material that is different from the first material. In case at least another alternating stack of material layers is subsequently formed over the alternating stack of the first material layers and the second material layers, the alternating stack is herein referred to as a first-tier alternating stack. The level of the first-tier alternating stack is herein referred to as a first-tier level, and the level of the alternating stack to be subsequently formed immediately above the first-tier level is herein referred to as a second-tier level, etc.

(230) The first-tier alternating stack may include first insulating layers **132** as the first material layers, and first spacer material layers as the second material layers. In one embodiment, the first spacer material layers may be sacrificial material layers that are subsequently replaced with electrically conductive layers. In another embodiment, the first spacer material layers may be electrically conductive layers that are not subsequently replaced with other layers. While the present disclosure is described using embodiments in which sacrificial material layers are replaced with electrically conductive layers, embodiments in which the spacer material layers are formed as electrically conductive layers (thereby obviating the need to perform replacement processes) are expressly contemplated herein.

(231) In one embodiment, the first material layers and the second material layers may be first insulating layers **132** and first sacrificial material layers **142**, respectively. In one embodiment, each first insulating layer **132** may include a first insulating material, and each first sacrificial material layer **142** may include a first sacrificial material. An alternating plurality of first insulating layers **132** and first sacrificial material layers **142** is formed over the in-process source-level material layers **110'**. As used herein, a “sacrificial material” refers to a material that is removed during a subsequent processing step.

(232) As used herein, an alternating stack of first elements and second elements refers to a structure in which instances of the first elements and instances of the second elements alternate. Each instance of the first elements that is not an end element of the alternating plurality is adjoined by two instances of the second elements on both sides, and each instance of the second elements that is not an end element of the alternating plurality is adjoined by two instances of the first elements on both ends. The first elements may have the same thickness throughout, or may have different thicknesses. The second elements may have the same thickness throughout, or may have different thicknesses. The alternating plurality of first material layers and second material layers may begin with an instance of the first material layers or with an instance of the second material layers, and may end with an instance of the first material layers or with an instance of the second material layers. In one embodiment, an instance of the first elements and an instance of the second elements may form a unit that is repeated with periodicity within the alternating plurality.

(233) The first-tier alternating stack (**132**, **142**) may include first insulating layers **132** composed of the first material, and first sacrificial material layers **142** composed of the second material, which is different from the first material. The first material of the first insulating layers **132** may be at least one insulating material. Insulating materials that may be used for the first insulating layers **132** include, but are not limited to silicon oxide (including doped or undoped silicate glass), silicon nitride, silicon oxynitride, organosilicate glass (OSG), spin-on dielectric materials, dielectric metal oxides that are commonly known as high dielectric constant (high-k) dielectric oxides (e.g., aluminum oxide, hafnium oxide, etc.) and silicates thereof, dielectric metal oxynitrides and silicates thereof, and organic insulating materials. In one embodiment, the first material of the first

insulating layers **132** may be silicon oxide.

(234) The second material of the first sacrificial material layers **142** is a sacrificial material that may be removed selective to the first material of the first insulating layers **132**. As used herein, a removal of a first material is “selective to” a second material if the removal process removes the first material at a rate that is at least twice the rate of removal of the second material. The ratio of the rate of removal of the first material to the rate of removal of the second material is herein referred to as a “selectivity” of the removal process for the first material with respect to the second material.

(235) The first sacrificial material layers **142** may comprise an insulating material, a semiconductor material, or a conductive material. The second material of the first sacrificial material layers **142** may be subsequently replaced with electrically conductive electrodes which may function, for example, as control gate electrodes of a vertical NAND device. In one embodiment, the first sacrificial material layers **142** may be material layers that comprise silicon nitride.

(236) In one embodiment, the first insulating layers **132** may include silicon oxide, and sacrificial material layers may include silicon nitride sacrificial material layers. The first material of the first insulating layers **132** may be deposited, for example, by chemical vapor deposition (CVD). For example, if silicon oxide is used for the first insulating layers **132**, tetraethylorthosilicate (TEOS) may be used as the precursor material for the CVD process. The second material of the first sacrificial material layers **142** may be formed, for example, CVD or atomic layer deposition (ALD).

(237) The thicknesses of the first insulating layers **132** and the first sacrificial material layers **142** may be in a range from 20 nm to 50 nm, although lesser and greater thicknesses may be used for each first insulating layer **132** and for each first sacrificial material layer **142**. The number of repetitions of the pairs of a first insulating layer **132** and a first sacrificial material layer **142** may be in a range from 2 to 1,024, and typically from 8 to 256, although a greater number of repetitions may also be used. In one embodiment, each first sacrificial material layer **142** in the first-tier alternating stack (**132**, **142**) may have a uniform thickness that is substantially invariant within each respective first sacrificial material layer **142**. Generally, an alternating stack of first material layers (such as the first insulating layers **132**) and second material layers (such as the first sacrificial material layers **142**) may be formed over a semiconductor material layer (such as the upper source-level semiconductor layer **118**).

(238) A first insulating cap layer **170** is subsequently formed over the first alternating stack (**132**, **142**). The first insulating cap layer **170** includes a dielectric material, which may be any dielectric material that may be used for the first insulating layers **132**. In one embodiment, the first insulating cap layer **170** includes the same dielectric material as the first insulating layers **132**. The thickness of the first insulating cap layer **170** may be in a range from 20 nm to 300 nm, although lesser and greater thicknesses may also be used.

(239) Referring to FIG. 22, the first insulating cap layer **170** and the first-tier alternating stack (**132**, **142**) may be patterned to form first stepped surfaces in the contact region **300**. The contact region **300** may include a respective first stepped area in which the first stepped surfaces are formed, and a second stepped area in which additional stepped surfaces are to be subsequently formed in a second-tier structure (to be subsequently formed over a first-tier structure) and/or additional tier structures. The first stepped surfaces may be formed, for example, by forming a mask layer (not shown) with an opening therein, etching a cavity within the levels of the first insulating cap layer **170**, and iteratively expanding the etched area and vertically recessing the cavity by etching each pair of a first insulating layer **132** and a first sacrificial material layer **142** located directly underneath the bottom surface of the etched cavity within the etched area. In one embodiment, top surfaces of the first sacrificial material layers **142** may be physically exposed at the first stepped surfaces. The cavity overlying the first stepped surfaces is herein referred to as a first stepped cavity.

(240) A dielectric fill material (such as undoped silicate glass or doped silicate glass) may be deposited to fill the first stepped cavity. Excess portions of the dielectric fill material may be removed from above the horizontal plane including the top surface of the first insulating cap layer **170**. A remaining portion of the dielectric fill material that fills the region overlying the first stepped surfaces constitute a first retro-stepped dielectric material portion **165**. As used herein, a “retro-stepped” element refers to an element that has stepped surfaces and a horizontal cross-sectional area that increases monotonically as a function of a vertical distance from a top surface of a substrate on which the element is present. The first-tier alternating stack (**132**, **142**) and the first retro-stepped dielectric material portion **165** collectively constitute a first-tier structure, which is an in-process structure that is subsequently modified.

(241) An inter-tier dielectric layer **180** may be optionally deposited over the first-tier structure (**132**, **142**, **170**, **165**). The inter-tier dielectric layer **180** includes a dielectric material such as silicon oxide. In one embodiment, the inter-tier dielectric layer **180** may include a doped silicate glass having a greater etch rate than the material of the first insulating layers **132** (which may include an undoped silicate glass). For example, the inter-tier dielectric layer **180** may include borosilicate glass, phosphosilicate glass, or borophosphosilicate glass. The thickness of the inter-tier dielectric layer **180** may be in a range from 30 nm to 300 nm, although lesser and greater thicknesses may also be used.

(242) Referring to FIGS. **23A-23C**, a patterning film **331** can be deposited over the top surface of the inter-tier dielectric layer **180**. The patterning film **331** comprises a material that provides high etch selectivity during a subsequent anisotropic etch process to be employed to form via openings through the first-tier alternating stack (**132**, **142**). In one embodiment, the patterning film **331** comprises amorphous carbon or diamond-like carbon at an atomic percentage in a range from 80% to 100%. In one embodiment, the patterning film **331** may comprise an inorganic carbon-based material that can be subsequently employed as a hard mask material. In one embodiment, the patterning film **331** may have a homogeneous material composition throughout. In one embodiment, the patterning film **331** may comprise a commercially-available carbon-based patterning film such as Advanced Patterning Film™ from Applied Materials, Inc™, a commercially-available boron-doped carbon-based patterning film such as Saphira™ from Applied Materials, Inc™, or a tungsten boron carbide material. The patterning film **331** may be deposited by a conformal or nonconformal deposition process. For example, the patterning film **331** may be deposited by a chemical vapor deposition process. The thickness of the patterning film **331** may be in a range from 200 nm to 1,000 nm, such as from 300 nm to 600 nm, although lesser and greater thicknesses may also be employed.

(243) A photoresist layer **337** can be applied over the patterning film **331**, and can be lithographically patterned to form openings therein. The pattern of the openings in the photoresist layer **337** include arrays of openings that are formed in the memory array region **100** and arrays of openings that are formed in the contact region **300**. The pattern of the openings in the photoresist layer **337** that are formed in the memory array region **100** is a pattern for subsequently forming via openings through the first-tier alternating stack (**132**, **142**), which are herein referred to as first-tier memory openings. The pattern of the openings in the photoresist layer **337** that are formed in the contact region **300** is a pattern for subsequently forming via openings through the first retro-stepped dielectric material portion **165** and the first-tier alternating stack (**132**, **142**), which are herein referred to as first-tier support openings. In one embodiment, the openings in the photoresist layer **337** may have circular horizontal cross-sectional shapes or elliptical horizontal cross-sectional shapes. The maximum lateral dimension (such as a diameter) of each opening in the photoresist layer **337** may be in a range from 30 nm to 600 nm, such as from 60 nm to 300 nm, although lesser and greater maximum lateral dimensions may also be employed.

(244) An anisotropic etch process may be performed to transfer the pattern in the photoresist layer **337** through the patterning film **331**. For example, a reactive ion etch may be performed to transfer



the pattern of the openings in the photoresist layer **337** through the patterning film **331**. A top surface of the inter-tier dielectric layer **180** may be physically exposed at the bottom of each opening through the patterning film **331**. Generally, the sidewalls of the openings through the patterning film **331** may be vertical or substantially vertical.

(245) Referring to FIGS. **24A-24C**, a first anisotropic etch process may be performed to transfer the pattern of the openings in the patterning film **331** through the first-tier alternating stack (**132**, **142**). The chemistry of the first anisotropic etch process can be selected such that the materials of the first-tier alternating stack (**132**, **142**) and the first retro-stepped dielectric material portion **165** are etched selective to the material of the upper source-level semiconductor layer **118**. For example, if the first insulating layers **132** comprise silicon oxide, the first sacrificial material layers **142** comprise silicon nitride, and the first retro-stepped dielectric material portion **165** comprise silicon oxide, the first anisotropic etch process may have an etch chemistry employing a mixture of CF.sub.4, O.sub.2, optionally Ar, and optionally C.sub.4F.sub.8 and/or CF.sub.2Br.sub.2. The pattern of the openings can be transferred through the first-tier alternating stack (**132**, **142**) by the first anisotropic etch process.

(246) In one embodiment, the materials of the first-tier alternating stack (**132**, **142**) are etched concurrently with the material of the first retro-stepped dielectric material portion **165** during the first anisotropic etch process. The chemistry of the initial etch step may alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**) while providing a comparable average etch rate to the material of the first retro-stepped dielectric material portion **165**. The sidewalls of the various first-tier openings (**149**, **129**) may be substantially vertical, or may be tapered.

(247) Via openings are formed through the first-tier alternating stack (**132**, **142**) underneath each opening in the patterning film **331**. The photoresist layer **337** may be consumed during the first anisotropic etch process. Alternatively, the photoresist layer **337** may be removed prior to or after the first anisotropic etch process. In one embodiment, the etch chemistry of the first anisotropic etch process may be selective to the semiconductor material of the upper source-level semiconductor layer **118**. Alternatively, the first anisotropic etch process may be timed such that the via openings do not extend into the upper source-level semiconductor layer **118** by more than a predefined recess depth, which may be in a range from 1% to 50%, such as from 2% to 20%, of the thickness of the upper source-level semiconductor layer **118**.

(248) The via openings formed through the first-tier alternating stack (**132**, **142**) and the first retro-stepped dielectric material portion **165** are herein referred to first-tier openings (**149**, **129**), which comprise first-tier memory openings **149** and first-tier support openings **129**. The first-tier memory openings **149** are openings that are formed in the memory array region **100** through each layer within the first alternating stack (**132**, **142**) and are subsequently used to form memory stack structures therein. The first-tier memory openings **149** may be formed in clusters of first-tier memory openings **149** that are laterally spaced apart along the second horizontal direction **hd2**. Each cluster of first-tier memory openings **149** may be formed as a two-dimensional array of first-tier memory openings **149**.

(249) The first-tier support openings **129** are openings that are formed in the contact region **300**, and are subsequently employed to form support pillar structures. A subset of the first-tier support openings **129** that is formed through the first retro-stepped dielectric material portion **165** may be formed through a respective horizontal surface of the first stepped surfaces.

(250) The first anisotropic etch process transfers the pattern of the openings in the patterning film **331** through each layer in the alternating stack (**132**, **142**). Generally, the via openings (**149**, **129**) can vertically extend through the alternating stack (**132**, **142**) at least to a top surface of the upper source-level semiconductor layer **118** by the first anisotropic etch process.

(251) FIGS. **25A-25C** are sequential vertical cross-sectional views of a memory opening **149** in a first configuration of the second exemplary structure during the processing steps for formation of a

cladding liner **335**, a second anisotropic etch process, and removal of the cladding liner **335** and the patterning film **331** according to the second embodiment of the present disclosure.

(252) Referring to FIG. **25A**, a cladding liner **335** can be formed on a top surface of the patterning film **331** and sidewalls of the openings in the patterning film **331** by anisotropically depositing a cladding material. According to an embodiment of the present disclosure, the cladding liner **335** consists essentially of an electrically conductive (e.g., metallic) material.

(253) In one embodiment, the cladding liner **335** may be formed by anisotropic (e.g., non-conformal) deposition of a metallic material over the patterning film **331** after the first anisotropic etch process. While the cladding layer **335** shown in FIG. **25A** is formed after formation of via openings (**149**, **129**), in an alternative embodiment, the cladding layer **335** may be formed on top surface of the patterning film **331** and sidewalls of the openings in the patterning film **331** after removal of the photoresist layer **337** and before etching of the via openings (**149**, **129**).

(254) In one embodiment, the cladding liner **335** may be deposited by a physical vapor deposition process, such as sputtering, or by a non-conformal atomic layer deposition (ALD) in which a metallic material is deposited anisotropically with directionality such that the metallic material is deposited with a lesser thickness in recessed surfaces that underlie the horizontal plane including the top surface of the patterning film **331**. In this case, the thickness of the metallic material of the cladding liner **335** can rapidly decrease with a recess depth as measured from the horizontal plane including the top surface of the patterning film **331**. In one embodiment, the aspect ratio of the openings in the patterning film **331** may be at least 1.5, and may be in a range from 2 to 10, such as from 2.5 to 6. The lateral thickness of the portions of the cladding liner **335** located on sidewalls of the patterning film **331** decreases with a vertical distance from a horizontal plane including the top surface of the patterning film **331**. In one embodiment, the aspect ratio of the openings in the patterning film **331** and the directionality of the anisotropic deposition process that deposits the cladding liner **335** can be selected such that the lateral thickness of the cladding liner **335** becomes zero above a horizontal plane including a bottom surface of the patterning film **331**. In this case, a bottommost portion of a sidewall of the patterning film **331** may be physically exposed around an opening through the patterning film **331**.

(255) In one embodiment, the cladding liner **335** may consist essentially of a metal or metal nitride, such as at least one material selected from Ru, Co, Mo, W, TaN, TiN, or WN. The thickness of the horizontally-extending portion of the cladding liner **335** that overlies the patterning film **331** may be in a range from 5 nm to 100 nm, such as from 10 nm to 30 nm, although lesser and greater thicknesses may also be employed.

(256) In one embodiment, the cladding liner **335** comprises a horizontally-extending portion that overlies the top surface of the patterning film **331** and a plurality of vertically-extending tubular portions having a respective upper edge that is adjoined to the horizontally-extending portion. The plurality of vertically-extending tubular portions of the cladding liner **335** can be located on sidewalls of the openings in the patterning film **331**, and each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a variable lateral width that increases with a vertical distance from the upper source-level semiconductor layer **118**. In this case, each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a variable lateral thickness that decreases with a vertical distance downward from the horizontal plane including the top surface of the patterning film **331**. In one embodiment, each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a respective bottom edge that is located on a respective sidewall of the patterning film **331**.

(257) In one embodiment, the cladding liner **335** does not contact any sidewall of the first-tier alternating stack (**132**, **142**). In one embodiment, the cladding liner **335** does not contact any sidewall of the insulating cap layer **170** or the inter-tier dielectric layer **180**. In one embodiment, the entirety of the cladding liner **335** may be located above a horizontal plane HP including the bottom surface of the patterning film **331**.

(258) Referring to FIG. 25B, a second anisotropic etch process can be performed to etch through the semiconductor material layer that underlies the first-tier alternating stack (132, 142) (i.e., the upper source-level semiconductor layer 118), at least one dielectric material layer underlying the semiconductor material layer (such as a combination of the upper sacrificial liner 105, the source-level sacrificial layer 104, and the lower sacrificial liner 103), and an upper portion of an additional semiconductor layer that underlies the at least one dielectric material layer (such as the lower source-level semiconductor layer 112). In one embodiment, the second anisotropic etch process may comprise a first reactive ion etch process step having an etch chemistry employing  $\text{HBr/He/Cl.sub.2/O.sub.2}$  or an etch chemistry employing  $\text{SF.sub.6/O.sub.2/C.sub.4F.sub.8}$  and etches through the upper source-level semiconductor layer 118, a second reactive ion etch process step that employs a combination of  $\text{CHF.sub.3}$ ,  $\text{CF.sub.4}$ ,  $\text{O.sub.2}$ , and/or  $\text{CO.sub.2}$  and etches through the upper sacrificial liner 105, the source-level sacrificial layer 104, and the lower sacrificial liner 103, and a third reactive ion etch process step having an etch chemistry employing  $\text{HBr/He/Cl.sub.2/O.sub.2}$  or an etch chemistry employing  $\text{SF.sub.6/O.sub.2/C.sub.4F.sub.8}$  and etches through an upper portion of the lower source-level semiconductor layer 112. Each of the first reactive ion etch process step and the third reactive ion etch process step may comprise an overetch step employing  $\text{CH.sub.4/O.sub.2}$  etch chemistry.

(259) The via openings (149, 129) are vertically extended through the semiconductor material layer (such as the upper source-level semiconductor layer 118) at least to a bottom surface of the semiconductor material layer (such as the upper source-level semiconductor layer 118) by performing the second anisotropic etch process employing the cladding liner 335 as an etch mask. In one embodiment, the via openings (149, 129) are vertically extended through the at least one dielectric material layer underlying the semiconductor material layer (such as a combination of the upper sacrificial liner 105, the source-level sacrificial layer 104, and the lower sacrificial liner 103), and into an upper portion of the additional semiconductor layer that underlies the at least one dielectric material layer (such as the lower source-level semiconductor layer 112).

(260) Without wishing to be bound by a particular theory, it is believed that bowing in a vertical cross-sectional etch profile is caused by scattering of ions from tapered or faceted surfaces of an etch mask layer during an anisotropic etch process. The bowing in a vertical cross-sectional etch profile increase with an increase in the flux of scattered ions until a necking region is formed in an etch mask upon sufficient development of bowing in an upper portion of an etched material layer that underlies the etch mask. The net deposition rate of a polymer material on sidewalls of a via opening is defined by the bowing profile in the etched material layer and in the necking profile in the etch mask layer.

(261) The sputter rate of a hard mask material generally depends on the angle of an incident ion that causes sputtering of the hard mask material, and is typically at a maximum at a non-vertical direction. Typically, the maximum in the sputter rate occurs when the angle of incidence (as measured from the vertical direction) is in a range from 30 degrees to 60 degrees. A delta sputter rate is defined as the difference between the maximum sputter rate (generated when the angle of incidence is, for example, in a range from 30 degrees to 60 degrees) and the minimum sputter rate (which may occur, for example, wherein the angle of incidence is zero). For carbon-based hard mask materials, the ratio of the delta sputter rate to the minimum sputter rate can be much large because the sputter rate varies significantly based on ion impact angle. For example, the ratio of the delta sputter rate to the minimum sputter rate may be greater than 1 or about 1.

(262) According to an embodiment of the present disclosure, the metallic material of the cladding liner 335 decreases the ratio of the delta sputter rate to the minimum sputter rate to a number below 1, such as a number between 0.1 and 0.5. Generally, a metallic material including a metal having a high atomic mass (such as W or Ru) is preferred for the material of the cladding liner 335. A low number for the ratio of the delta sputter rate to the minimum sputter rate allows minimizing the deformation of an etch mask pattern and facilitates retaining the original shape of an etch mask

irrespective of the distribution in the ion impact angle during an anisotropic etch process.

(263) According to an aspect of the present disclosure, use of the cladding liner **335** prevents or reduces distortion of the patterning film **331**, and prevents or reduces development of bowing in the vertical cross-sectional profile of the via openings (**149**, **129**) at the processing steps of FIG. **25B**. The metallic material of the cladding liner **135** can provide high selectivity during the second anisotropic etch process that vertically extends the via openings (**149**, **129**).

(264) In another example, the cladding liner **335** may include tungsten. Generally, tungsten can be etched effectively employing a fluorine-containing etch chemistry which can generate a high volatility etch byproduct including a compound of tungsten and fluorine. It is known that the etch rate of tungsten in an etch chemistry employing SF<sub>6</sub> and NF<sub>3</sub> is almost independent of the bias voltage variation. This indicates that the mechanism for etching tungsten is chemical for fluorine-based etch chemistries. Thus, an etch chemistry for the semiconductor materials of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** and an etch chemistry for the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103** can provide high selectivity to tungsten by avoiding high fluorine content in the etch chemistry.

(265) It should be noted that the case of CF<sub>4</sub> as an etchant uses a different etch mechanism since there is a competition between fluorocarbon deposition and tungsten etching by free fluorine radicals. Thus, the second anisotropic etch process may employ a CF<sub>4</sub>/Cl<sub>2</sub> etch chemistry to effectively etch the materials of the in-process source-level material layers **110'** with high selectivity to tungsten in the cladding liner **335**. Also, use of O<sub>2</sub> during the second anisotropic etch process can lower the etch rate of tungsten.

(266) While the examples of Ru or W as the material of the cladding liner **335** are discussed above, other metallic materials such as Co, Mo, TaN, TiN or WN may also be employed for the cladding liner **335** such that the second anisotropic etch process has high selectivity with respect to the metallic material of the cladding liner **335**.

(267) Referring to FIG. **25C**, the patterning film **331** can be removed, for example, by ashing or lift-off. The cladding liner **335** located on the patterning film **331** is also lifted off during the lift-off or ashing process. Subsequently, a suitable clean process may be used to remove any residual metallic material, any residual carbon-based material, and/or any residual polymer material from sidewalls of the via openings (**149**, **129**) and from above the inter-tier dielectric layer **180**.

(268) FIG. **25D** is an alternative embodiment of the first configuration of a memory opening in the first configuration of the second exemplary structure. FIG. **25D** illustrates a configuration in which the via openings (**149**, **129**) are formed with a greater width at levels of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** than at the levels of the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103** due to the propensity of the second anisotropic etch process to provide more ancillary lateral etching of the semiconductor materials of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** than the materials of the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103**.

(269) FIGS. **26A-26C** are sequential vertical cross-sectional views of a memory opening in a second configuration of the second exemplary structure during the processing steps for formation of a cladding liner **335**, a second anisotropic etch process, and removal of the cladding liner **335** and the patterning film **331** according to the second embodiment of the present disclosure.

(270) Referring to FIG. **26A**, the second configuration of the second exemplary structure is illustrated, which can be derived from the first configuration of the second exemplary structure illustrated in FIG. **25A** by forming the cladding liner **335** employing a selective metallic material deposition process instead of the anisotropic deposition process. The selective metallic material deposition process grows a metallic material from physically exposed surfaces of patterning film **331** while suppressing growth of the metallic material from surfaces of the first-tier alternating

stack (132, 132) and from surfaces of the underlying semiconductor material layer (such as the upper source-level semiconductor layer 118).

(271) In one embodiment, the selective metallic material deposition process comprises an atomic layer deposition (ALD) process or a chemical vapor deposition (CVD) process. The deposition chemistry of the selective material deposition process can be selected such that a metallic precursor gas employed for the selective material deposition process decomposes and nucleates on physically exposed surfaces of the patterning film 331 at a significantly higher nucleation rate than a nucleation rate on physically exposed surfaces of the first-tier alternating stack (132, 142) and the upper source-level semiconductor layer 118. An etchant gas, such as NF.sub.3, CF.sub.4, Cl.sub.2, or HCl can be flowed into a process chamber simultaneously with, or alternately with, the flow of the metallic precursor gas to provide an etch rate that is greater than the nucleation rate of the metallic material on the physically exposed surfaces of the first-tier alternating stack (132, 142) and the upper source-level semiconductor layer 118, and is less than the nucleation rate of the metallic material on the physically exposed surfaces of the patterning film 331. Thus, the metallic material can be deposited only on the physically exposed surfaces of the patterning film 331 while growth of the metallic material from the physically exposed surfaces of the first-tier alternating stack (132, 142) and the upper source-level semiconductor layer 118 is suppressed.

(272) In one embodiment, the patterning film 331 comprises amorphous carbon or diamond-like carbon at an atomic percentage in a range from 80% to 100%. In one embodiment, the patterning film 331 may be doped with at least one dopant species to enhance the nucleation rate of the metallic material of the cladding liner 335 during selective deposition of the cladding liner 335. In one embodiment, the patterning film 331 may comprise at least dopant species at an atomic concentration in a range from 0.2% to 20%, the at least one dopant species being selected from boron and tungsten.

(273) In one embodiment, the cladding liner 335 comprises a plurality of vertically-extending tubular portions located on sidewalls of the openings in the patterning film 331, and each of the plurality of vertically-extending tubular portions of the cladding liner 335 has a uniform lateral thickness that is invariant under translation along a vertical direction. In one embodiment, the cladding liner 335 comprises a horizontally-extending portion that overlies the patterning film 331 and having a same vertical thickness and the uniform lateral thickness. In one embodiment, the cladding liner 335 may have a uniform thickness throughout.

(274) In one embodiment, the cladding liner 335 does not contact any sidewall of the first-tier alternating stack (132, 142). In one embodiment, the cladding liner 335 does not contact any sidewall of the insulating cap layer 170. In one embodiment, the entirety of the cladding liner 335 may be located above a horizontal plane HP located at a bottom surface of the patterning film 331.

(275) Generally, the cladding liner 335 in the second configuration of the second exemplary structure may include any metallic material that can be deposited by a selective deposition process. In one embodiment, the cladding liner 335 may consist essentially of at least one material selected from Ru, Co, W or Mo. The thickness of the cladding liner 335 may be in a range from 5 nm to 100 nm, such as from 10 nm to 30 nm, although lesser and greater thicknesses may also be employed.

(276) Referring to FIG. 26B, a second anisotropic etch can be performed in the same manner as in the processing steps of FIG. 25B.

(277) Referring to FIG. 26C, the cladding liner 335 and the patterning film 331 may be removed in the same manner as in the processing steps of FIG. 25C.

(278) FIG. 26D is an alternative embodiment of the second configuration of a memory opening in the second configuration of the second exemplary structure. FIG. 26D illustrates a configuration in which the via openings (149, 129) are formed with a greater width at levels of the upper source-level semiconductor layer 118 and the lower source-level semiconductor layer 112 than at the levels of the upper sacrificial liner 105, the source-level sacrificial layer 104, and the lower sacrificial liner 103 due to the propensity of the second anisotropic etch process to provide more ancillary

lateral etching of the semiconductor materials of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** than the materials of the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103**.

(279) FIGS. **27A-27C** are sequential vertical cross-sectional views of a memory opening in a third configuration of the second exemplary structure during the processing steps for formation of a cladding liner **335**, a second anisotropic etch process, and removal of the cladding liner **335** and the patterning film **331** according to the second embodiment of the present disclosure.

(280) In the third configuration of the second exemplary structure, the patterning film **331** can be formed as a vertical stack of a lower patterning film layer **331A** that comprises carbon atoms at an atomic percentage in a range from 99% to 100%, and an upper patterning film layer **331B** that comprises carbon an atomic percentage in a range from 80% to 99.8% and at least dopant species at an atomic concentration in a range from 0.2% to 20%. The at least one dopant species may be selected from boron and/or tungsten. In an illustrative example, the thickness of the lower patterning film layer **331A** may be in a range from 60 nm to 400 nm, such as from 100 nm to 200 nm, although lesser and greater thicknesses may also be employed. The thickness of the upper patterning film layer **331B** may be in a range from 120 nm to 600 nm, such as from 200 nm to 400 nm, although lesser and greater thicknesses may also be employed.

(281) In the third configuration of the second exemplary structure, the cladding liner **335** can be formed by a selective deposition process that grows a cladding material, such as tungsten, from physically exposed surfaces of the upper patterning film layer **331B** while suppressing growth of the cladding material from surfaces of the lower patterning film layer **331A**, the first-tier alternating stack (**132**, **142**), and the upper source-level semiconductor layer **118**. The dopant species in the upper patterning film layer **331B** increases the nucleation rate of the metallic material that is deposited on the physically exposed surfaces of the upper patterning film layer **331B** relative to the nucleation rate of the metallic material on the lower patterning film layer **331A** during the selective deposition process.

(282) In one embodiment, the cladding liner **335** may comprise tungsten and may have a uniform thickness that is less than a thickness of the lower patterning film layer **331A**. The thickness of the cladding liner **335** may be in a range from 5 nm to 100 nm, such as from 10 nm to 30 nm, although lesser and greater thicknesses may also be employed.

(283) In one embodiment, the cladding liner **335** does not contact any sidewall of the first-tier alternating stack (**132**, **142**). In one embodiment, the cladding liner **335** does not contact any sidewall of the insulating cap layer **170** or the inter-tier dielectric layer **180**. In one embodiment, the entirety of the cladding liner **335** may be located above a horizontal plane HP located at the bottom surface of the patterning film **331**, i.e., the horizontal plane including the bottom surface of the lower patterning film layer **331A**.

(284) Referring to FIG. **27B**, a second anisotropic etch can be performed in the same manner as in the processing steps of FIG. **25B**.

(285) Referring to FIG. **27C**, an ashing or lift-off process can be performed to remove the lower patterning film layer **331A** after the second anisotropic etch process. The upper patterning film layer **331B** and the cladding liner **335** can be removed at this time.

(286) FIG. **27D** is an alternative embodiment of the third configuration of a memory opening in the third configuration of the second exemplary structure. FIG. **27D** illustrates a configuration in which the via openings (**149**, **129**) are formed with a greater width at levels of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** than at the levels of the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103** due to the propensity of the second anisotropic etch process to provide more ancillary lateral etching of the semiconductor materials of the upper source-level semiconductor layer **118** and the lower source-level semiconductor layer **112** than the materials of the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103**.

(287) Referring to FIGS. 28A and 28B, the portions of the first-tier memory openings **149** and the first-tier support openings **129** at the level of the inter-tier dielectric layer **180** may be optionally laterally expanded by an isotropic etch. In this case, the inter-tier dielectric layer **180** may comprise a dielectric material (such as borosilicate glass) having a greater etch rate than the first insulating layers **132** (that may include undoped silicate glass) in dilute hydrofluoric acid. An isotropic etch (such as a wet etch using HF) may be used to expand the lateral dimensions of the first-tier memory openings **149** at the level of the inter-tier dielectric layer **180**. The portions of the first-tier memory openings **149** located at the level of the inter-tier dielectric layer **180** may be optionally widened to provide a larger landing pad for second-tier memory openings to be subsequently formed through a second-tier alternating stack (to be subsequently formed prior to formation of the second-tier memory openings).

(288) Referring to FIG. 29, sacrificial first-tier opening fill portions (**148**, **128**) may be formed in the various first-tier openings (**149**, **129**). For example, a sacrificial first-tier fill material is deposited concurrently deposited in each of the first-tier openings (**149**, **129**). The sacrificial first-tier fill material includes a material that may be subsequently removed selective to the materials of the first insulating layers **132** and the first sacrificial material layers **142**.

(289) In one embodiment, the sacrificial first-tier fill material may include a semiconductor material such as silicon (e.g., a-Si or polysilicon), a silicon-germanium alloy, germanium, a III-V compound semiconductor material, or a combination thereof. Optionally, a thin etch stop liner (such as a silicon oxide layer or a silicon nitride layer having a thickness in a range from 1 nm to 3 nm) may be used prior to depositing the sacrificial first-tier fill material. The sacrificial first-tier fill material may be formed by a non-conformal deposition or a conformal deposition method.

(290) In another embodiment, the sacrificial first-tier fill material may include a silicon oxide material having a higher etch rate than the materials of the first insulating layers **132**, the first insulating cap layer **170**, and the inter-tier dielectric layer **180**. For example, the sacrificial first-tier fill material may include borosilicate glass or porous or non-porous organosilicate glass having an etch rate that is at least 100 times higher than the etch rate of densified TEOS oxide (i.e., a silicon oxide material formed by decomposition of tetraethylorthosilicate glass in a chemical vapor deposition process and subsequently densified in an anneal process) in a 100:1 dilute hydrofluoric acid. In this case, a thin etch stop liner (such as a silicon nitride layer having a thickness in a range from 1 nm to 3 nm) may be used prior to depositing the sacrificial first-tier fill material. The sacrificial first-tier fill material may be formed by a non-conformal deposition or a conformal deposition method.

(291) In yet another embodiment, the sacrificial first-tier fill material may include amorphous silicon or a carbon-containing material (such as amorphous carbon or diamond-like carbon) that may be subsequently removed by ashing, or a silicon-based polymer that may be subsequently removed selective to the materials of the first alternating stack (**132**, **142**).

(292) Portions of the deposited sacrificial material may be removed from above the topmost layer of the first-tier alternating stack (**132**, **142**), such as from above the inter-tier dielectric layer **180**. For example, the sacrificial first-tier fill material may be recessed to a top surface of the inter-tier dielectric layer **180** using a planarization process. The planarization process may include a recess etch, chemical mechanical planarization (CMP), or a combination thereof. The top surface of the inter-tier dielectric layer **180** may be used as an etch stop layer or a planarization stop layer.

(293) Remaining portions of the sacrificial first-tier fill material comprise sacrificial first-tier opening fill portions (**148**, **128**). Specifically, each remaining portion of the sacrificial material in a first-tier memory opening **149** constitutes a sacrificial first-tier memory opening fill portion **148**. Each remaining portion of the sacrificial material in a first-tier support opening **129** constitutes a sacrificial first-tier support opening fill portion **128**. The various sacrificial first-tier opening fill portions (**148**, **128**) are concurrently formed, i.e., during a same set of processes including the deposition process that deposits the sacrificial first-tier fill material and the planarization process

that removes the first-tier deposition process from above the first alternating stack (132, 142) (such as from above the top surface of the inter-tier dielectric layer 180). The top surfaces of the sacrificial first-tier opening fill portions (148, 128) may be coplanar with the top surface of the inter-tier dielectric layer 180. Each of the sacrificial first-tier opening fill portions (148, 128) may, or may not, include cavities therein.

(294) Referring to FIG. 30, a second-tier structure may be formed over the first-tier structure (132, 142, 170, 148). The second-tier structure may include an additional alternating stack of insulating layers and spacer material layers, which may be sacrificial material layers. For example, a second alternating stack (232, 242) of material layers may be subsequently formed on the top surface of the first alternating stack (132, 142). The second alternating stack (232, 242) includes an alternating plurality of third material layers and fourth material layers. Each third material layer may include a third material, and each fourth material layer may include a fourth material that is different from the third material. In one embodiment, the third material may be the same as the first material of the first insulating layer 132, and the fourth material may be the same as the second material of the first sacrificial material layers 142.

(295) In one embodiment, the third material layers may be second insulating layers 232 and the fourth material layers may be second spacer material layers that provide vertical spacing between each vertically neighboring pair of the second insulating layers 232. In one embodiment, the third material layers and the fourth material layers may be second insulating layers 232 and second sacrificial material layers 242, respectively. The third material of the second insulating layers 232 may be at least one insulating material. The fourth material of the second sacrificial material layers 242 may be a sacrificial material that may be removed selective to the third material of the second insulating layers 232. The second sacrificial material layers 242 may comprise an insulating material, a semiconductor material, or a conductive material. The fourth material of the second sacrificial material layers 242 may be subsequently replaced with electrically conductive electrodes which may function, for example, as control gate electrodes of a vertical NAND device.

(296) In one embodiment, each second insulating layer 232 may include a second insulating material, and each second sacrificial material layer 242 may include a second sacrificial material. In this case, the second alternating stack (232, 242) may include an alternating plurality of second insulating layers 232 and second sacrificial material layers 242. The third material of the second insulating layers 232 may be deposited, for example, by chemical vapor deposition (CVD). The fourth material of the second sacrificial material layers 242 may be formed, for example, CVD or atomic layer deposition (ALD).

(297) The third material of the second insulating layers 232 may be at least one insulating material. Insulating materials that may be used for the second insulating layers 232 may be any material that may be used for the first insulating layers 132. The fourth material of the second sacrificial material layers 242 is a sacrificial material that may be removed selective to the third material of the second insulating layers 232. Sacrificial materials that may be used for the second sacrificial material layers 242 may be any material that may be used for the first sacrificial material layers 142. In one embodiment, the second insulating material may be the same as the first insulating material, and the second sacrificial material may be the same as the first sacrificial material.

(298) The thicknesses of the second insulating layers 232 and the second sacrificial material layers 242 may be in a range from 20 nm to 50 nm, although lesser and greater thicknesses may be used for each second insulating layer 232 and for each second sacrificial material layer 242. The number of repetitions of the pairs of a second insulating layer 232 and a second sacrificial material layer 242 may be in a range from 2 to 1,024, and typically from 8 to 256, although a greater number of repetitions may also be used. In one embodiment, each second sacrificial material layer 242 in the second alternating stack (232, 242) may have a uniform thickness that is substantially invariant within each respective second sacrificial material layer 242.

(299) Second stepped surfaces in the second stepped area may be formed in the contact region 300



using a same set of processing steps as the processing steps used to form the first stepped surfaces in the first stepped area with suitable adjustment to the pattern of at least one masking layer. A second retro-stepped dielectric material portion **265** may be formed over the second stepped surfaces in the contact region **300**.

(300) A second insulating cap layer **270** may be subsequently formed over the second alternating stack (**232, 242**). The second insulating cap layer **270** includes a dielectric material that is different from the material of the second sacrificial material layers **242**. In one embodiment, the second insulating cap layer **270** may include silicon oxide. In one embodiment, the first and second sacrificial material layers (**142, 242**) may comprise silicon nitride.

(301) Generally speaking, at least one alternating stack of insulating layers (**132, 232**) and spacer material layers (such as sacrificial material layers (**142, 242**)) may be formed over the in-process source-level material layers **110'**, and at least one retro-stepped dielectric material portion (**165, 265**) may be formed over the staircase regions on the at least one alternating stack (**132, 142, 232, 242**).

(302) Optionally, drain-select-level isolation structures **72** may be formed through a subset of layers in an upper portion of the second-tier alternating stack (**232, 242**). The second sacrificial material layers **242** that are cut by the drain-select-level isolation structures **72** correspond to the levels in which drain-select-level electrically conductive layers are subsequently formed. The drain-select-level isolation structures **72** include a dielectric material such as silicon oxide. The drain-select-level isolation structures **72** may laterally extend along a first horizontal direction **hd1**, and may be laterally spaced apart along a second horizontal direction **hd2** that is perpendicular to the first horizontal direction **hd1**. The combination of the second alternating stack (**232, 242**), the second retro-stepped dielectric material portion **265**, the second insulating cap layer **270**, and the optional drain-select-level isolation structures **72** collectively constitute a second-tier structure (**232, 242, 265, 270, 72**).

(303) Referring to FIGS. **31A** and **31B**, various second-tier openings (**249, 229**) may be formed through the second-tier structure (**232, 242, 265, 270, 72**). A photoresist layer (not shown) may be applied over the second insulating cap layer **270**, and may be lithographically patterned to form various openings therethrough. The pattern of the openings may be the same as the pattern of the various first-tier openings (**149, 129**), which is the same as the sacrificial first-tier opening fill portions (**148, 128**). Thus, the lithographic mask used to pattern the first-tier openings (**149, 129**) may be used to pattern the photoresist layer.

(304) The pattern of openings in the photoresist layer may be transferred through the second-tier structure (**232, 242, 265, 270, 72**) by a second anisotropic etch process to form various second-tier openings (**249, 229**) concurrently, i.e., during the second anisotropic etch process. The various second-tier openings (**249, 229**) may include second-tier memory openings **249** and second-tier support openings **229**.

(305) The second-tier memory openings **249** are formed directly on a top surface of a respective one of the sacrificial first-tier memory opening fill portions **148**. The second-tier support openings **229** are formed directly on a top surface of a respective one of the sacrificial first-tier support opening fill portions **128**. Further, each second-tier support openings **229** may be formed through a horizontal surface within the second stepped surfaces, which include the interfacial surfaces between the second alternating stack (**232, 242**) and the second retro-stepped dielectric material portion **265**. Locations of steps **S** in the first-tier alternating stack (**132, 142**) and the second-tier alternating stack (**232, 242**) are illustrated as dotted lines in FIG. **31B**.

(306) The second anisotropic etch process may include an etch step in which the materials of the second-tier alternating stack (**232, 242**) are etched concurrently with the material of the second retro-stepped dielectric material portion **265**. The chemistry of the etch step may alternate to optimize etching of the materials in the second-tier alternating stack (**232, 242**) while providing a comparable average etch rate to the material of the second retro-stepped dielectric material portion

265. The second anisotropic etch process may use, for example, a series of reactive ion etch processes or a single reaction etch process (e.g., CF.sub.4/O.sub.2/Ar etch). The sidewalls of the various second-tier openings (249, 229) may be substantially vertical, or may be tapered. A bottom periphery of each second-tier opening (249, 229) may be laterally offset, and/or may be located entirely within, a periphery of a top surface of an underlying sacrificial first-tier opening fill portion (148, 128). The photoresist layer may be subsequently removed, for example, by ashing.

(307) Referring to FIG. 32, the sacrificial first-tier fill material of the sacrificial first-tier opening fill portions (148, 128) may be removed using an etch process that etches the sacrificial first-tier fill material selective to the materials of the first and second insulating layers (132, 232), the first and second sacrificial material layers (142, 242), the first and second insulating cap layers (170, 270), and the inter-tier dielectric layer 180. A memory opening 49, which is also referred to as an inter-tier memory opening 49, is formed in each combination of a second-tier memory openings 249 and a volume from which a sacrificial first-tier memory opening fill portion 148 is removed. A support opening 19, which is also referred to as an inter-tier support opening 19, is formed in each combination of a second-tier support openings 229 and a volume from which a sacrificial first-tier support opening fill portion 128 is removed.

(308) FIGS. 33A-33D provide sequential cross-sectional views of a memory opening 49 during formation of a memory opening fill structure. The same structural change occurs in each of the memory openings 49 and the support openings 19.

(309) Referring to FIG. 33A, a memory opening 49 in the first exemplary device structure of FIG. 32 is illustrated. The memory opening 49 extends through the first-tier structure and the second-tier structure.

(310) Referring to FIG. 33B, a stack of layers including a blocking dielectric layer 52, a charge storage layer 54, a tunneling dielectric layer 56, and a semiconductor channel material layer 60L may be sequentially deposited in the memory openings 49. The blocking dielectric layer 52 may include a single dielectric material layer or a stack of a plurality of dielectric material layers. In one embodiment, the blocking dielectric layer may include a dielectric metal oxide layer consisting essentially of a dielectric metal oxide. As used herein, a dielectric metal oxide refers to a dielectric material that includes at least one metallic element and at least oxygen. The dielectric metal oxide may consist essentially of the at least one metallic element and oxygen, or may consist essentially of the at least one metallic element, oxygen, and at least one non-metallic element such as nitrogen. In one embodiment, the blocking dielectric layer 52 may include a dielectric metal oxide having a dielectric constant greater than 7.9, i.e., having a dielectric constant greater than the dielectric constant of silicon nitride. The thickness of the dielectric metal oxide layer may be in a range from 1 nm to 20 nm, although lesser and greater thicknesses may also be used. The dielectric metal oxide layer may subsequently function as a dielectric material portion that blocks leakage of stored electrical charges to control gate electrodes. In one embodiment, the blocking dielectric layer 52 includes aluminum oxide. Alternatively or additionally, the blocking dielectric layer 52 may include a dielectric semiconductor compound such as silicon oxide, silicon oxynitride, silicon nitride, or a combination thereof.

(311) Subsequently, the charge storage layer 54 may be formed. In one embodiment, the charge storage layer 54 may be a continuous layer or patterned discrete portions of a charge trapping material including a dielectric charge trapping material, which may be, for example, silicon nitride. Alternatively, the charge storage layer 54 may include a continuous layer or patterned discrete portions of a conductive material such as doped polysilicon or a metallic material that is patterned into multiple electrically isolated portions (e.g., floating gates), for example, by being formed within lateral recesses into sacrificial material layers (142, 242). In one embodiment, the charge storage layer 54 includes a silicon nitride layer. In one embodiment, the sacrificial material layers (142, 242) and the insulating layers (132, 232) may have vertically coincident sidewalls, and the charge storage layer 54 may be formed as a single continuous layer. Alternatively, the sacrificial

material layers (142, 242) may be laterally recessed with respect to the sidewalls of the insulating layers (132, 232), and a combination of a deposition process and an anisotropic etch process may be used to form the charge storage layer 54 as a plurality of memory material portions that are vertically spaced apart. The thickness of the charge storage layer 54 may be in a range from 2 nm to 20 nm, although lesser and greater thicknesses may also be used.

(312) The tunneling dielectric layer 56 includes a dielectric material through which charge tunneling may be performed under suitable electrical bias conditions. The charge tunneling may be performed through hot-carrier injection or by Fowler-Nordheim tunneling induced charge transfer depending on the mode of operation of the three-dimensional NAND string memory device to be formed. The tunneling dielectric layer 56 may include silicon oxide, silicon nitride, silicon oxynitride, dielectric metal oxides (such as aluminum oxide and hafnium oxide), dielectric metal oxynitride, dielectric metal silicates, alloys thereof, and/or combinations thereof. In one embodiment, the tunneling dielectric layer 56 may include a stack of a first silicon oxide layer, a silicon oxynitride layer, and a second silicon oxide layer, which is commonly known as an ONO stack. In one embodiment, the tunneling dielectric layer 56 may include a silicon oxide layer that is substantially free of carbon or a silicon oxynitride layer that is substantially free of carbon. The thickness of the tunneling dielectric layer 56 may be in a range from 2 nm to 20 nm, although lesser and greater thicknesses may also be used. The stack of the blocking dielectric layer 52, the charge storage layer 54, and the tunneling dielectric layer 56 constitutes a memory film 50 that stores memory bits.

(313) The semiconductor channel material layer 60L includes a p-doped semiconductor material such as at least one elemental semiconductor material, at least one III-V compound semiconductor material, at least one II-VI compound semiconductor material, at least one organic semiconductor material, or other semiconductor materials known in the art. In one embodiment, the semiconductor channel material layer 60L may have a uniform doping. In one embodiment, the semiconductor channel material layer 60L has a p-type doping in which p-type dopants (such as boron atoms) are present at an atomic concentration in a range from  $1.0 \times 10^{12}/\text{cm}^3$  to  $1.0 \times 10^{18}/\text{cm}^3$ , such as from  $1.0 \times 10^{14}/\text{cm}^3$  to  $1.0 \times 10^{17}/\text{cm}^3$ . In one embodiment, the semiconductor channel material layer 60L includes, and/or consists essentially of, boron-doped amorphous silicon or boron-doped polysilicon. In another embodiment, the semiconductor channel material layer 60L has an n-type doping in which n-type dopants (such as phosphorus atoms or arsenic atoms) are present at an atomic concentration in a range from  $1.0 \times 10^{12}/\text{cm}^3$  to  $1.0 \times 10^{18}/\text{cm}^3$ , such as from  $1.0 \times 10^{14}/\text{cm}^3$  to  $1.0 \times 10^{17}/\text{cm}^3$ . The semiconductor channel material layer 60L may be formed by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD). The thickness of the semiconductor channel material layer 60L may be in a range from 2 nm to 10 nm, although lesser and greater thicknesses may also be used. A cavity 49' is formed in the volume of each memory opening 49 that is not filled with the deposited material layers (52, 54, 56, 60L).

(314) Referring to FIG. 33C, in case the cavity 49' in each memory opening is not completely filled by the semiconductor channel material layer 60L, a dielectric core layer may be deposited in the cavity 49' to fill any remaining portion of the cavity 49' within each memory opening. The dielectric core layer includes a dielectric material such as silicon oxide or organosilicate glass. The dielectric core layer may be deposited by a conformal deposition method such as low pressure chemical vapor deposition (LPCVD), or by a self-planarizing deposition process such as spin coating. The horizontal portion of the dielectric core layer overlying the second insulating cap layer 270 may be removed, for example, by a recess etch. The recess etch continues until top surfaces of the remaining portions of the dielectric core layer are recessed to a height between the top surface of the second insulating cap layer 270 and the bottom surface of the second insulating cap layer 270. Each remaining portion of the dielectric core layer constitutes a dielectric core 62.

(315) Referring to FIG. 33D, a doped semiconductor material having a doping of a second

conductivity type may be deposited in cavities overlying the dielectric cores **62**. The second conductivity type is the opposite of the first conductivity type. For example, if the first conductivity type is p-type, the second conductivity type is n-type, and vice versa. Portions of the deposited doped semiconductor material, the semiconductor channel material layer **60L**, the tunneling dielectric layer **56**, the charge storage layer **54**, and the blocking dielectric layer **52** that overlie the horizontal plane including the top surface of the second insulating cap layer **270** may be removed by a planarization process such as a chemical mechanical planarization (CMP) process.

(316) Each remaining portion of the doped semiconductor material of the second conductivity type constitutes a drain region **63**. The dopant concentration in the drain regions **63** may be in a range from  $5.0 \times 10^{18} \text{ cm}^{-3}$  to  $2.0 \times 10^{21} \text{ cm}^{-3}$ , although lesser and greater dopant concentrations may also be used. The doped semiconductor material may be, for example, doped polysilicon.

(317) Each remaining portion of the semiconductor channel material layer **60L** constitutes a vertical semiconductor channel **60** through which electrical current may flow when a vertical NAND device including the vertical semiconductor channel **60** is turned on. A tunneling dielectric layer **56** is surrounded by a charge storage layer **54**, and laterally surrounds a vertical semiconductor channel **60**. Each adjoining set of a blocking dielectric layer **52**, a charge storage layer **54**, and a tunneling dielectric layer **56** collectively constitute a memory film **50**, which may store electrical charges with a macroscopic retention time. In some embodiments, a blocking dielectric layer **52** may not be present in the memory film **50** at this step, and a blocking dielectric layer may be subsequently formed after formation of backside recesses. As used herein, a macroscopic retention time refers to a retention time suitable for operation of a memory device as a permanent memory device such as a retention time in excess of 24 hours.

(318) Each combination of a memory film **50** and a vertical semiconductor channel **60** (which is a vertical semiconductor channel) within a memory opening **49** constitutes a memory stack structure **55**. The memory stack structure **55** is a combination of a vertical semiconductor channel **60**, a tunneling dielectric layer **56**, a plurality of memory elements comprising portions of the charge storage layer **54**, and an optional blocking dielectric layer **52**. Each combination of a memory stack structure **55**, a dielectric core **62**, and a drain region **63** within a memory opening **49** constitutes a memory opening fill structure **58**. The in-process source-level material layers **110'**, the first-tier structure (**132**, **142**, **170**, **165**), the second-tier structure (**232**, **242**, **270**, **265**, **72**), the inter-tier dielectric layer **180**, and the memory opening fill structures **58** collectively constitute a memory-level assembly.

(319) Referring to FIG. **34**, the second exemplary structure is illustrated after formation of the memory opening fill structures **58**. Support pillar structures **20** are formed in the support openings **19** concurrently with formation of the memory opening fill structures **58**. Each support pillar structure **20** may have a same set of components as a memory opening fill structure **58**.

(320) Referring to FIGS. **35A** and **35B**, a first contact-level dielectric layer **280** may be formed over the second-tier structure (**232**, **242**, **270**, **265**, **72**). The first contact-level dielectric layer **280** includes a dielectric material such as silicon oxide, and may be formed by a conformal or non-conformal deposition process. For example, the first contact-level dielectric layer **280** may include undoped silicate glass and may have a thickness in a range from 100 nm to 600 nm, although lesser and greater thicknesses may also be used.

(321) A photoresist layer (not shown) may be applied over the first contact-level dielectric layer **280**, and may be lithographically patterned to form discrete openings within the area of the memory array region **100** in which memory opening fill structures **58** are not present. An anisotropic etch may be performed to form vertical interconnection region cavities **585** having substantially vertical sidewalls that extend through the first contact-level dielectric layer **280**, the second-tier structure (**232**, **242**, **270**, **265**, **72**), and the first-tier structure (**132**, **142**, **170**, **165**) may be formed underneath the openings in the photoresist layer. A top surface of a lower-level metal interconnect structure **780**

may be physically exposed at the bottom of each vertical interconnection region cavity **585**. The photoresist layer may be removed, for example, by ashing.

(322) Referring to FIG. **36**, a dielectric material such as silicon oxide may be deposited in the vertical interconnection region cavities **585** by a conformal deposition process (such as low pressure chemical vapor deposition) or a self-planarizing deposition process (such as spin coating). Excess portions of the deposited dielectric material may be removed from above the top surface of the first contact-level dielectric layer **280** by a planarization process. Remaining portions of the dielectric material in the vertical interconnection region cavities **585** constitute interconnection region dielectric fill material portions **584**.

(323) Referring to FIGS. **37A** and **37B**, a photoresist layer may be applied over the first contact-level dielectric layer **280** and may be lithographically patterned to form elongated openings that extend along the first horizontal direction **hd1** between clusters of memory opening fill structures **58**. Backside trenches **79** may be formed by transferring the pattern in the photoresist layer (not shown) through the first contact-level dielectric layer **280**, the second-tier structure (**232**, **242**, **270**, **265**, **72**), and the first-tier structure (**132**, **142**, **170**, **165**), and into the in-process source-level material layers **110'**. Portions of the first contact-level dielectric layer **280**, the second-tier structure (**232**, **242**, **270**, **265**, **72**), the first-tier structure (**132**, **142**, **170**, **165**), and the in-process source-level material layers **110'** that underlie the openings in the photoresist layer may be removed to form the backside trenches **79**. In one embodiment, the backside trenches **79** may be formed between clusters of memory stack structures **55**. The clusters of the memory stack structures **55** may be laterally spaced apart along the second horizontal direction **hd2** by the backside trenches **79**.

(324) Referring to FIGS. **38** and **39A**, a backside trench spacer **77** may be formed on sidewalls of each backside trench **79**. For example, a conformal spacer material layer may be deposited in the backside trenches **79** and over the first contact-level dielectric layer **280**, and may be anisotropically etched to form the backside trench spacers **77**. The backside trench spacers **77** include a material that is different from the material of the source-level sacrificial layer **104**. For example, the backside trench spacers **77** may include silicon nitride.

(325) Referring to FIG. **39B**, an etchant that etches the material of the source-level sacrificial layer **104** selective to the materials of the first alternating stack (**132**, **142**), the second alternating stack (**232**, **242**), the first and second insulating cap layers (**170**, **270**), the first contact-level dielectric layer **280**, the upper sacrificial liner **105**, and the lower sacrificial liner **103** may be introduced into the backside trenches in an isotropic etch process. For example, if the source-level sacrificial layer **104** includes silicon nitride, and the upper and lower sacrificial liners (**105**, **103**) include silicon oxide, a wet etch process using phosphoric acid may be used to remove the source-level sacrificial layer **104** selective to the backside trench spacers **77** and the upper and lower sacrificial liners (**105**, **103**). A source cavity **109** is formed in the volume from which the source-level sacrificial layer **104** is removed. Each of the memory opening fill structures **58** is physically exposed to the source cavity **109**. Specifically, each of the memory opening fill structures **58** includes a sidewall and that are physically exposed to the source cavity **109**.

(326) Referring to FIG. **39C**, a sequence of isotropic etchants, such as wet etchants, may be applied to the physically exposed portions of the memory films **50** to sequentially etch the various component layers of the memory films **50** from outside to inside, and to physically expose cylindrical surfaces of the vertical semiconductor channels **60** at the level of the source cavity **109**. The upper and lower sacrificial liners (**105**, **103**) may be collaterally etched during removal of the portions of the memory films **50** located at the level of the source cavity **109**. The source cavity **109** may be expanded in volume by removal of the portions of the memory films **50** at the level of the source cavity **109** and the upper and lower sacrificial liners (**105**, **103**). A top surface of the lower source-level semiconductor layer **112** and a bottom surface of the upper source-level semiconductor layer **118** may be physically exposed to the source cavity **109**. The source cavity

**109** is formed by isotropically etching the source-level sacrificial layer **104** and a bottom portion of each of the memory films **50** selective to at least one source-level semiconductor layer (such as the lower source-level semiconductor layer **112** and the upper source-level semiconductor layer **118**) and the vertical semiconductor channels **60**.

(327) Referring to FIG. **39D**, a semiconductor material having a doping of the second conductivity type may be deposited on the physically exposed semiconductor surfaces around the source cavity **109**. The physically exposed semiconductor surfaces include bottom portions of outer sidewalls of the vertical semiconductor channels **60** and a horizontal surface of the at least one source-level semiconductor layer (such as a bottom surface of the upper source-level semiconductor layer **118** and/or a top surface of the lower source-level semiconductor layer **112**). For example, the physically exposed semiconductor surfaces may include the bottom portions of outer sidewalls of the vertical semiconductor channels **60**, the top horizontal surface of the lower source-level semiconductor layer **112**, and the bottom surface of the upper source-level semiconductor layer **118**.

(328) In one embodiment, the doped semiconductor material of the second conductivity type may be deposited on the physically exposed semiconductor surfaces around the source cavity **109** by a selective semiconductor deposition process. A semiconductor precursor gas, an etchant, and a dopant gas may be flowed concurrently into a process chamber including the second exemplary structure during the selective semiconductor deposition process. For example, the semiconductor precursor gas may include silane, disilane, or dichlorosilane, the etchant gas may include gaseous hydrogen chloride, and the dopant gas may include a hydride of a dopant atom such as phosphine, arsine, stibine, or diborane. In this case, the selective semiconductor deposition process grows a doped semiconductor material having a doping of the second conductivity type from physically exposed semiconductor surfaces around the source cavity **109**. The deposited doped semiconductor material forms a source contact layer **114**, which may contact sidewalls of the vertical semiconductor channels **60**. The atomic concentration of the dopants of the second conductivity type in the deposited semiconductor material may be in a range from  $1.0 \times 10^{20}/\text{cm}^3$  to  $2.0 \times 10^{21}/\text{cm}^3$ , such as from  $2.0 \times 10^{20}/\text{cm}^3$  to  $8.0 \times 10^{20}/\text{cm}^3$ . The source contact layer **114** as initially formed may consist essentially of semiconductor atoms and dopant atoms of the second conductivity type. Alternatively, at least one non-selective doped semiconductor material deposition process may be used to form the source contact layer **114**. Optionally, one or more etch back processes may be used in combination with a plurality of selective or non-selective deposition processes to provide a seamless and/or voidless source contact layer **114**.

(329) The duration of the selective semiconductor deposition process may be selected such that the source cavity **109** is filled with the source contact layer **114**, and the source contact layer **114** contacts bottom end portions of inner sidewalls of the backside trench spacers **77**. In one embodiment, the source contact layer **114** may be formed by selectively depositing a doped semiconductor material having a doping of the second conductivity type from semiconductor surfaces around the source cavity **109**. In one embodiment, the doped semiconductor material may include doped polysilicon. Thus, the source-level sacrificial layer **104** may be replaced with the source contact layer **114**.

(330) The layer stack including the lower source-level semiconductor layer **112**, the source contact layer **114**, and the upper source-level semiconductor layer **118** constitutes a buried source layer (**112**, **114**, **118**). The buried source layer (**112**, **114**, **118**) is also referred to as source-level material layers **110**, which replaces the in-process source-level material layers **110'**.

(331) Referring to FIGS. **39E** and **40**, the backside trench spacers **77** may be removed selective to the insulating layers (**132**, **232**), the first and second insulating cap layers (**170**, **270**), the first contact-level dielectric layer **280**, and the source contact layer **114** using an isotropic etch process. For example, if the backside trench spacers **77** include silicon nitride, a wet etch process using hot

phosphoric acid may be performed to remove the backside trench spacers 77. In one embodiment, the isotropic etch process that removes the backside trench spacers 77 may be combined with a subsequent isotropic etch process that etches the sacrificial material layers (142, 242) selective to the insulating layers (132, 232), the first and second insulating cap layers (170, 270), the first contact-level dielectric layer 280, and the source contact layer 114.

(332) An oxidation process may be performed to convert physically exposed surface portions of semiconductor materials into dielectric semiconductor oxide portions. For example, surfaces portions of the source contact layer 114 and the upper source-level semiconductor layer 118 may be converted into dielectric semiconductor oxide plates 123.

(333) Referring to FIG. 41, the sacrificial material layers (142, 242) are removed selective to the insulating layers (132, 232), the first and second insulating cap layers (170, 270), the first contact-level dielectric layer 280, and the source contact layer 114, and the dielectric semiconductor oxide plates 123. For example, an etchant that selectively etches the materials of the sacrificial material layers (142, 242) with respect to the materials of the insulating layers (132, 232), the first and second insulating cap layers (170, 270), the retro-stepped dielectric material portions (165, 265), and the material of the outermost layer of the memory films 50 may be introduced into the backside trenches 79, for example, using an isotropic etch process. For example, the sacrificial material layers (142, 242) may include silicon nitride, the materials of the insulating layers (132, 232), the first and second insulating cap layers (170, 270), the retro-stepped dielectric material portions (165, 265), and the outermost layer of the memory films 50 may include silicon oxide materials.

(334) The isotropic etch process may be a wet etch process using a wet etch solution, or may be a gas phase (dry) etch process in which the etchant is introduced in a vapor phase into the backside trench 79. For example, if the sacrificial material layers (142, 242) include silicon nitride, the etch process may be a wet etch process in which the second exemplary structure is immersed within a wet etch tank including phosphoric acid, which etches silicon nitride selective to silicon oxide, silicon, and various other materials used in the art.

(335) Backside recesses (143, 243) are formed in volumes from which the sacrificial material layers (142, 242) are removed. The backside recesses (143, 243) include first backside recesses 143 that are formed in volumes from which the first sacrificial material layers 142 are removed and second backside recesses 243 that are formed in volumes from which the second sacrificial material layers 242 are removed. Each of the backside recesses (143, 243) may be a laterally extending cavity having a lateral dimension that is greater than the vertical extent of the cavity. In other words, the lateral dimension of each of the backside recesses (143, 243) may be greater than the height of the respective backside recess (143, 243). A plurality of backside recesses (143, 243) may be formed in the volumes from which the material of the sacrificial material layers (142, 242) is removed. Each of the backside recesses (143, 243) may extend substantially parallel to the top surface of the substrate semiconductor layer 9. A backside recess (143, 243) may be vertically bounded by a top surface of an underlying insulating layer (132, 232) and a bottom surface of an overlying insulating layer (132, 232). In one embodiment, each of the backside recesses (143, 243) may have a uniform height throughout.

(336) Referring to FIGS. 42A and 42B, a backside blocking dielectric layer (not shown) may be optionally deposited in the backside recesses (143, 243) and the backside trenches 79 and over the first contact-level dielectric layer 280. The backside blocking dielectric layer includes a dielectric material such as a dielectric metal oxide, silicon oxide, or a combination thereof. For example, the backside blocking dielectric layer may include aluminum oxide. The backside blocking dielectric layer may be formed by a conformal deposition process such as atomic layer deposition or chemical vapor deposition. The thickness of the backside blocking dielectric layer may be in a range from 1 nm to 20 nm, such as from 2 nm to 10 nm, although lesser and greater thicknesses may also be used.

(337) At least one conductive material may be deposited in the plurality of backside recesses (143,

**243**), on the sidewalls of the backside trenches **79**, and over the first contact-level dielectric layer **280**. The at least one conductive material may be deposited by a conformal deposition method, which may be, for example, chemical vapor deposition (CVD), atomic layer deposition (ALD), electroless plating, electroplating, or a combination thereof. The at least one conductive material may include an elemental metal, an intermetallic alloy of at least two elemental metals, a conductive nitride of at least one elemental metal, a conductive metal oxide, a conductive doped semiconductor material, a conductive metal-semiconductor alloy such as a metal silicide, alloys thereof, and combinations or stacks thereof.

(338) In one embodiment, the at least one conductive material may include at least one metallic material, i.e., an electrically conductive material that includes at least one metallic element. Non-limiting exemplary metallic materials that may be deposited in the backside recesses (**143**, **243**) include tungsten, tungsten nitride, titanium, titanium nitride, tantalum, tantalum nitride, cobalt, and ruthenium. For example, the at least one conductive material may include a conductive metallic nitride liner that includes a conductive metallic nitride material such as TiN, TaN, WN, or a combination thereof, and a conductive fill material such as W, Co, Ru, Mo, Cu, or combinations thereof. In one embodiment, the at least one conductive material for filling the backside recesses (**143**, **243**) may be a combination of titanium nitride layer and a tungsten fill material.

(339) Electrically conductive layers (**146**, **246**) may be formed in the backside recesses (**143**, **243**) by deposition of the at least one conductive material. A plurality of first electrically conductive layers **146** may be formed in the plurality of first backside recesses **143**, a plurality of second electrically conductive layers **246** may be formed in the plurality of second backside recesses **243**, and a continuous metallic material layer (not shown) may be formed on the sidewalls of each backside trench **79** and over the first contact-level dielectric layer **280**. Each of the first electrically conductive layers **146** and the second electrically conductive layers **246** may include a respective conductive metallic nitride liner and a respective conductive fill material. Thus, the first and second sacrificial material layers (**142**, **242**) may be replaced with the first and second electrically conductive layers (**146**, **246**), respectively. Specifically, each first sacrificial material layer **142** may be replaced with an optional portion of the backside blocking dielectric layer and a first electrically conductive layer **146**, and each second sacrificial material layer **242** may be replaced with an optional portion of the backside blocking dielectric layer and a second electrically conductive layer **246**. A backside cavity is present in the portion of each backside trench **79** that is not filled with the continuous metallic material layer.

(340) Residual conductive material may be removed from inside the backside trenches **79**. Specifically, the deposited metallic material of the continuous metallic material layer may be etched back from the sidewalls of each backside trench **79** and from above the first contact-level dielectric layer **280**, for example, by an anisotropic or isotropic etch. Each remaining portion of the deposited metallic material in the first backside recesses constitutes a first electrically conductive layer **146**. Each remaining portion of the deposited metallic material in the second backside recesses constitutes a second electrically conductive layer **246**. Sidewalls of the first electrically conductive material layers **146** and the second electrically conductive layers may be physically exposed to a respective backside trench **79**. The backside trenches may have a pair of curved sidewalls having a non-periodic width variation along the first horizontal direction **hd1** and a non-linear width variation along the vertical direction.

(341) Each electrically conductive layer (**146**, **246**) may be a conductive sheet including openings therein. A first subset of the openings through each electrically conductive layer (**146**, **246**) may be filled with memory opening fill structures **58**. A second subset of the openings through each electrically conductive layer (**146**, **246**) may be filled with the support pillar structures **20**. Each electrically conductive layer (**146**, **246**) may have a lesser area than any underlying electrically conductive layer (**146**, **246**) because of the first and second stepped surfaces. Each electrically conductive layer (**146**, **246**) may have a greater area than any overlying electrically conductive



layer (**146, 246**) because of the first and second stepped surfaces.

(342) In some embodiment, drain-select-level isolation structures **72** may be provided at topmost levels of the second electrically conductive layers **246**. A subset of the second electrically conductive layers **246** located at the levels of the drain-select-level isolation structures **72** constitutes drain select gate electrodes. A subset of the electrically conductive layer (**146, 246**) located underneath the drain select gate electrodes may function as combinations of a control gate and a word line located at the same level. The control gate electrodes within each electrically conductive layer (**146, 246**) are the control gate electrodes for a vertical memory device including the memory stack structure **55**.

(343) Each of the memory stack structures **55** comprises a vertical stack of memory elements located at each level of the electrically conductive layers (**146, 246**). A subset of the electrically conductive layers (**146, 246**) may comprise word lines for the memory elements. The semiconductor devices in the underlying peripheral device region **700** may comprise word line switch devices configured to control a bias voltage to respective word lines. The memory-level assembly is located over the substrate semiconductor layer **9**. The memory-level assembly includes at least one alternating stack (**132, 146, 232, 246**) and memory stack structures **55** vertically extending through the at least one alternating stack (**132, 146, 232, 246**).

(344) Referring to FIGS. **43A-43C**, a dielectric material layer may be conformally deposited in the backside trenches **79** and over the first contact-level dielectric layer **280** by a conformal deposition process. The dielectric material layer may include, for example, silicon oxide. The dielectric material may be planarized by CMP or etch back to form dielectric wall structures **176** in the respective backside trenches **79**.

(345) Referring to FIGS. **44A** and **44B**, a second contact-level dielectric layer **282** may be formed over the first contact-level dielectric layer **280**. The second contact-level dielectric layer **282** includes a dielectric material such as silicon oxide, and may have a thickness in a range from 100 nm to 600 nm, although lesser and greater thicknesses may also be used.

(346) A photoresist layer (not shown) may be applied over the second contact-level dielectric layer **282**, and may be lithographically patterned to form various contact via openings. For example, openings for forming drain contact via structures may be formed in the memory array region **100**, and openings for forming staircase region contact via structures may be formed in the contact region **300**. An anisotropic etch process is performed to transfer the pattern in the photoresist layer through the second and first contact-level dielectric layers (**282, 280**) and underlying dielectric material portions. The drain regions **63** and the electrically conductive layers (**146, 246**) may be used as etch stop structures. Drain contact via cavities may be formed over each drain region **63**, and staircase-region contact via cavities may be formed over each electrically conductive layer (**146, 246**) at the stepped surfaces underlying the first and second retro-stepped dielectric material portions (**165, 265**). The photoresist layer may be subsequently removed, for example, by ashing.

(347) Drain contact via structures **88** are formed in the drain contact via cavities and on a top surface of a respective one of the drain regions **63**. Staircase-region contact via structures **86** are formed in the staircase-region contact via cavities and on a top surface of a respective one of the electrically conductive layers (**146, 246**). The staircase-region contact via structures **86** may include drain select level contact via structures that contact a subset of the second electrically conductive layers **246** that function as drain select level gate electrodes. Further, the staircase-region contact via structures **86** may include word line contact via structures that contact electrically conductive layers (**146, 246**) that underlie the drain select level gate electrodes and function as word lines for the memory stack structures **55**.

(348) Referring to FIG. **45**, peripheral-region via cavities may be formed through the second and first contact-level dielectric layers (**282, 280**), the second and first retro-stepped dielectric material portions (**265, 165**), and the drain-side dielectric layers **768** to top surfaces of a first subset of the lower-level metal interconnect structure **780** in the peripheral device region **400**. Through-memory-

region via cavities may be formed through the interconnection region dielectric fill material portions **584** and the drain-side dielectric layers **768** to top surfaces of a second subset of the lower-level metal interconnect structure **780**. At least one conductive material may be deposited in the peripheral-region via cavities and in the through-memory-region via cavities. Excess portions of the at least one conductive material may be removed from above the horizontal plane including the top surface of the second contact-level dielectric layer **282**. Each remaining portion of the at least one conductive material in a peripheral-region via cavity constitutes a peripheral-region contact via structure **488**. Each remaining portion of the at least one conductive material in a through-memory-region via cavity constitutes a through-memory-region via structure **588**.

(349) At least one additional dielectric layer may be formed over the contact-level dielectric layers (**280**, **282**), and additional metal interconnect structures (herein referred to as upper-level metal interconnect structures) may be formed in the at least one additional dielectric layer. For example, the at least one additional dielectric layer may include a line-level dielectric layer **290** that is formed over the contact-level dielectric layers (**280**, **282**). The upper-level metal interconnect structures may include bit lines **98** contacting a respective one of the drain contact via structures **88**, and interconnection line structures **96** contacting, and/or electrically connected to, at least one of the staircase-region contact via structures **86** and/or the peripheral-region contact via structures **488** and/or the through-memory-region via structures **588**. The word line contact via structures (which are provided as a subset of the staircase-region contact via structures **86**) may be electrically connected to the word line driver circuit through a subset of the lower-level metal interconnect structures **780** and through a subset of the peripheral-region contact via structures **488**.

(350) The various embodiments of the present disclosure can be employed to provide a straight etch profile for first-tier memory openings **149** and first-tier support openings **129** while reducing or eliminating bowing at an upper portion of the first-tier memory openings **149** and first-tier support openings **129**.

(351) FIGS. **46A-46D** are sequential vertical cross-sectional views of a memory opening in a first configuration of a third exemplary structure during the processing steps for patterning a hard mask layer, formation of a cladding liner, and an anisotropic etch process according to a third embodiment of the present disclosure.

(352) Referring to FIG. **46A**, the third exemplary structure according to the third embodiment of the present disclosure can be the same as the second exemplary structure of FIGS. **23A-23C**. Generally, an alternating stack of first material layers and second material layers (such as the first insulating layers **132** and the first sacrificial material layers **142**) can be formed over a substrate **8**, and a hard mask layer can be formed over the alternating stack. For example, the hard mask layer comprises, and/or consists essentially of, a carbon-based patterning film **331** hard mask layer comprising at least 60% of carbon in atomic concentration. Alternatively, other hard mask materials described above may be used to form the hard mask layer. A photoresist layer **337** can be applied and patterned over the patterning film **331** in the same manner as in the processing steps of FIGS. **23A-23C**. Openings are formed in the photoresist layer **337** by lithographic exposure and development, and cavities (i.e., openings) **332** can be formed in the patterning film **331** by performing a first anisotropic etch process that transfers the pattern of the openings in the photoresist layer **337** through the patterning film **331**. The photoresist layer **337** can be subsequently removed, for example, by ashing or by dissolution in an organic solvent.

(353) Referring to FIG. **46B**, a cladding liner **335** can be formed on a top surface of the patterning film **331** and sidewalls of the cavities **332** in the patterning film **331** by anisotropically depositing a cladding material. According to an embodiment of the present disclosure, the cladding liner **335** consists essentially of an electrically conductive (e.g., metallic) material, such as tungsten, ruthenium, cobalt, molybdenum, titanium nitride, etc. In this third embodiment, the cladding liner **335** is formed after patterning the patterning film **331** but prior to forming the openings **149** in the alternating stack (**132**, **142**).

(354) In one embodiment, the cladding liner **335** may be formed by anisotropic (e.g., non-conformal) deposition of a metallic material over the patterning film **331** after the first anisotropic etch process. The cladding layer **335** may be formed on top surface of the patterning film **331** and sidewalls of the cavities **332** in the patterning film **331** while a top surface of the inter-tier dielectric layer **180** is physically exposed at the bottom of each cavity **332** in the patterning film **331**. Generally, the cladding liner **335** can be formed on sidewalls of the cavities **332** in the patterning film **331** and on the top surface of the patterning film **331**.

(355) In another embodiment, the cladding liner **335** can be deposited by a selective deposition process that grows the material of the cladding liner **335** from physically exposed surfaces of the patterning film **331** without growth of the material of the cladding liner from physically exposed surfaces of a dielectric material layer (such as the inter-tier dielectric layer **180**) underlying the cavities in the patterning film **331**. The selective deposition process grows the cladding material (i.e., the material of the cladding liner **335**) from physically exposed surfaces of the patterning film **331** without growth of the cladding material from physically exposed surfaces of the inter-tier dielectric layer **180**. In this case, the cladding material may be any material that allows selective deposition on the material of the patterning film **331** without growth from surfaces of the inter-tier dielectric layer **180**. Thus, the cladding liner **335** is deposited conformally on the physically exposed surfaces of the patterning film **331**, and is not deposited on the physically exposed surfaces of the inter-tier dielectric layer **180**.

(356) In one embodiment, the cladding liner **335** comprises, and/or consists essentially of, an inorganic material selected from amorphous carbon, diamond-like carbon, amorphous silicon, polycrystalline silicon, silicon carbide, or boron nitride. For example, silicon carbide may be selectively formed on the patterning film **331** by selectively depositing a silicon layer (e.g., crystalline silicon layer) on the patterning film **331**, followed by annealing the silicon layer at a sufficiently high temperature (e.g., at 600 degrees Celsius or higher, such as 600 to 800 degrees Celsius) to react the silicon layer with the patterning film **331** to selectively form a conformal silicon carbide cladding liner **335** on the patterning film **331**. In another embodiment, the cladding liner **335** comprises, and/or consists essentially of, a metallic (i.e., electrically conductive metal or metal alloy) material that can be selectively deposited on surfaces of the patterning film **331**. Metallic materials that can be selectively deposited on surfaces of the patterning film **331** include, but are not limited to, TiN, Ru, Co or Mo. For example, Ru can be selectively deposited by ALD on the patterning film **331**. In another embodiment, the cladding liner **335** comprises, and/or consists essentially of, silicon oxide. The cladding liner **335** may be deposited by a conformal selective deposition process such as a chemical vapor deposition (CVD) process and/or an atomic layer deposition (ALD) process. The thickness of the portion of the cladding liner **335** overlying the top surface of the patterning film **331** may be in a range from 1 nm to 40 nm, such as from 2 nm to 20 nm, although lesser and greater thicknesses may also be employed.

(357) In another embodiment, the cladding liner **335** may be deposited by a non-conformal deposition process that deposits the material of the cladding liner **335** anisotropically with a variable thickness that decreases with a vertical distance from a horizontal plane including the top surface of the patterning film **331**. In one embodiment, the cladding liner **335** may be deposited by a physical vapor deposition process, such as sputtering, or by a non-conformal atomic layer deposition (ALD) in which a metallic material is deposited anisotropically with directionality such that the metallic material is deposited with a lesser thickness in recessed surfaces that underlie the horizontal plane including the top surface of the patterning film **331**. In this case, the thickness of the metallic material of the cladding liner **335** can rapidly decrease with a recess depth of the cavity **332** as measured from the horizontal plane including the top surface of the patterning film **331**. In one embodiment, the aspect ratio of the cavities **332** in the patterning film **331** may be at least 1.5, and may be in a range from 2 to 10, such as from 2.5 to 6. The lateral thickness of the portions of the cladding liner **335** located on sidewalls of the patterning film **331** decreases with a vertical

distance from a horizontal plane including the top surface of the patterning film **331**. In one embodiment, the aspect ratio of the cavities **332** in the patterning film **331** and the directionality of the anisotropic deposition process that deposits the cladding liner **335** can be selected such that the lateral thickness of the cladding liner **335** becomes zero above a horizontal plane including a bottom surface of the patterning film **331**. In this case, a bottommost portion of a sidewall of the patterning film **331** may be physically exposed around an opening through the patterning film **331**. (358) In this embodiment, the cladding liner **335** may consist essentially of a metal or metal nitride, such as at least one material selected from Ru, Co, Mo, W, TaN, TiN, or WN. The thickness of the horizontally-extending portion of the cladding liner **335** that overlies the patterning film **331** may be in a range from 5 nm to 100 nm, such as from 10 nm to 30 nm, although lesser and greater thicknesses may also be employed.

(359) In one embodiment, the cladding liner **335** comprises a horizontally-extending portion that overlies the top surface of the patterning film **331** and a plurality of vertically-extending tubular portions having a respective upper edge that is adjoined to the horizontally-extending portion. The plurality of vertically-extending tubular portions of the cladding liner **335** can be located on sidewalls of the cavities (i.e., openings) **332** in the patterning film **331**, and each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a variable lateral width that increases with a vertical distance from the upper source-level semiconductor layer **118**. In this case, each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a variable lateral thickness that decreases with a vertical distance downward from the horizontal plane including the top surface of the patterning film **331**. In one embodiment, the each of the plurality of vertically-extending tubular portions of the cladding liner **335** may have a respective bottom edge that is located on a respective sidewall of the patterning film **331** in the respective cavity **332**.

(360) In one embodiment, the cladding liner **335** is not present on the physically exposed surface portions of the inter-tier dielectric layer **180** in the cavities **332**. In another embodiment, a thin layer of the cladding liner **335** may be formed on the physically exposed surface portions of the inter-tier dielectric layer **180**, and an isotropic etch process may be performed to remove any portion of the cladding liner **335** that is deposited on the physically exposed surface portions of the inter-tier dielectric layer **180**. The isotropic etch process may comprise a wet etch process, or a dry etch process such as a chemical dry etch process.

(361) Referring to FIG. **46C**, a second anisotropic etch process can be performed to transfer the pattern of the openings (i.e., cavities) in the patterning film **331** and the cladding liner **335** through the first-tier alternating stack (**132**, **142**). The third exemplary structure illustrated in FIG. **46C** corresponds to a time point during the second anisotropic etch process at which the bottom surfaces of the via openings, such as the first-tier memory openings **149**, vertically extend through an upper subset of the layers in the first-tier alternating stack (**132**, **142**) and a lower subset of the layers in the first-tier alternating stack (**132**, **142**) has not yet been etched through. The chemistry of the second anisotropic etch process can be selected such that the materials of the first-tier alternating stack (**132**, **142**) and the first retro-stepped dielectric material portion **165** are etched selective to the material of the upper source-level semiconductor layer **118**. For example, if the first insulating layers **132** comprise silicon oxide, the first sacrificial material layers **142** comprise silicon nitride, and the first retro-stepped dielectric material portion **165** comprise silicon oxide, the second anisotropic etch process may have an etch chemistry employing a mixture of CF<sub>4</sub>, O<sub>2</sub>, optionally Ar, and optionally C<sub>4</sub>F<sub>8</sub> and/or CF<sub>2</sub>Br<sub>2</sub>. The pattern of the openings can be transferred through the first-tier alternating stack (**132**, **142**) by the second anisotropic etch process.

(362) In one embodiment, the materials of the first-tier alternating stack (**132**, **142**) are etched concurrently with the material of the first retro-stepped dielectric material portion **165** during the second anisotropic etch process. The chemistry of the initial etch step may alternate to optimize

etching of the first and second materials in the first-tier alternating stack (**132**, **142**) while providing a comparable average etch rate to the material of the first retro-stepped dielectric material portion **165**. The sidewalls of the various first-tier openings (**149**, **129**) may be substantially vertical, or may be tapered.

(363) Referring to FIG. **46D**, the second anisotropic etch process is continued until the via openings extend through each layer within the first-tier alternating stack (**132**, **142**) and the in-process source-level material layers **110'** underneath each opening in the patterning film **331**. Generally, via openings (such as the first-tier memory openings **149** and the first-tier support openings **119**) may be formed through an alternating stack of first material layers and second material layers by performing an anisotropic etch process that transfers a pattern of the cavities in the patterning film **331** through each layer within the alternating stack employing a combination of the cladding liner **335** and the patterning film **331** as an etch mask. The second anisotropic etch process can include multiple etch steps having different etch chemistries optimized for sequentially etching the various layers within the first-tier alternating stack (**132**, **142**) and the in-process source-level material layers **110'**. Generally, the etch chemistries described above with reference to the processing steps of FIGS. **25B-25D**, **26B-26D**, or **27B-27D** may be employed to etch the various layers of the in-process source-level material layers **110'**.

(364) In one embodiment, the entirety of the top surface of the patterning film **331** may be covered by a remaining portion of the cladding liner **335** after the second anisotropic etch process as illustrated in FIG. **46D**.

(365) Referring to FIG. **47**, the cladding liner **335** can be removed by selective etching. In this case, the top surface of the patterning film **331** may be planar. Alternatively, the cladding liner **335** can be consumed at a terminal portion of the second anisotropic etch process, and collateral etching of the patterning film **331** may be insubstantial. In this case, the top surface of the patterning film **331** may be substantially planar.

(366) Elimination or minimization of the loss of the material of the patterning film **331** provides a uniform vertical cross-sectional profile for the portions of the patterning film **331** that overlie the region of the via openings (such as the first-tier memory openings **149** and the first-tier support openings **119**) in underlying material layers. In this case, the uniform vertical-cross-sectional profile of the portions of the patterning film **331** overlying the region of the via openings provides uniform vertical cross-sectional profiles with reduced bowing for the via openings through the underlying material layers. For example, the first-tier memory openings **149** can be formed with the same vertical cross-sectional profile or similar vertical cross-sectional profile. By reducing the bowing and/or other variations in lateral dimensions of the first-tier memory openings **149**, portions of the memory stack structures **55** formed in the first-tier memory openings **149** can have uniform structural characteristics, and thus, can have uniform electrical characteristics.

(367) The patterning film **331** can then be removed by ashing and/or by selective etching.

(368) The methods of the processing steps of FIGS. **46A-46D** and **47** can be employed to pattern a second-tier structure including a second-tier alternating stack of second insulating layers **232** and second sacrificial material layers **242**. In this case, second-tier memory openings can be formed with the same vertical cross-sectional profile or similar vertical cross-sectional profile. By reducing the variations in lateral dimensions of the second-tier memory openings, portions of the memory stack structures **55** formed in the second-tier memory openings can have uniform structural characteristics, and thus, can have uniform electrical characteristics.

(369) Subsequently, the processing steps of FIGS. **28A-45** can be performed to form a three-dimensional memory device illustrated in FIG. **45**. Generally, a memory film **50** and a vertical semiconductor channel **60** may be formed in each respective via opening, and the second material layers may be replaced with electrically conductive word lines to form the three-dimensional memory device.

(370) FIGS. **48A** and **48B** are sequential vertical cross-sectional views of a memory opening in a

second configuration of the third exemplary structure during the second anisotropic etch process, which corresponds to the processing steps of FIGS. **46C** and **46D**. In this case, the cladding liner **335** can be collaterally etched during the second anisotropic etch process, and the top surface of the patterning film **331** can be physically exposed prior to the end of the second anisotropic etch process.

(371) Referring to FIG. **49**, a region of the second configuration of the third exemplary structure is illustrated after the second anisotropic etch process. In case the top surface of the patterning film **331** is physically exposed prior to the end of the second anisotropic etch process, the top surface of the patterning film **331** can be vertically recessed by different vertical recess distances depending on the pattern factor of the cavities in the patterning film **331**, i.e., depending on the local fraction of the areas of the cavities in the patterning film **331** relative to a unit area of the patterning film **331** having a size of a lateral scale of movement of the etchant ions employed during the second anisotropic etch process. The maximum differential  $\delta h$  between the least recessed portion of the top surface of the patterning film **331** and the most recessed portion of the top surface of the patterning film **331** is illustrated in FIG. **49**. However, the bowing of the memory openings **149** is still reduced even with the recessed portion of the top surface of the patterning film **331**.

(372) FIGS. **50A-50G** are sequential vertical cross-sectional views of a region of a memory opening in a third configuration of the third exemplary structure during formation of the memory opening according to the third embodiment of the present disclosure.

(373) Referring to FIG. **50A**, the third configuration of the third exemplary structure can be the same as the second exemplary structure of FIGS. **23A-23C** and/or the third exemplary structure illustrated in FIG. **46A**. Generally, a set of material layers comprising at least one source-level semiconductor layer (**112**, **118**) over a substrate **8**. In one embodiment, the set of material layers may comprise in-process source-level material layers **110'** as described above. An alternating stack of first material layers and second material layers (such as the first insulating layers **132** and the first sacrificial material layers **142**) can be formed over a substrate **8**, and a hard mask layer can be formed over the alternating stack. For example, the hard mask layer comprises, and/or consists essentially of, a carbon-based patterning film **331** hard mask layer comprising at least 60% of carbon in atomic concentration. Alternatively, other hard mask materials described above may be used to form the hard mask layer. A photoresist layer **337** can be applied and patterned over the patterning film **331** in the same manner as in the processing steps of FIGS. **23A-23C**. Openings are formed in the photoresist layer **337** by lithographic exposure and development, and cavities (i.e., openings) **332** can be formed in the patterning film **331** by performing a first anisotropic etch process that transfers the pattern of the openings in the photoresist layer **337** through the patterning film **331**. Generally, a pattern of cavities **332** can be formed in the hard mask layer **331** by patterning the hard mask layer **331**. The photoresist layer **337** can be subsequently removed, for example, by ashing or by dissolution in an organic solvent.

(374) Referring to FIG. **50B**, a second anisotropic etch process can be performed to transfer the pattern of the openings (i.e., cavities) in the patterning film **331** through the first-tier alternating stack (**132**, **142**). The patterning film **331** is employed as an etch mask for the second anisotropic etch process. Optionally, a cladding liner (not shown) such as a cladding liner **335** described above may be formed and employed as an additional etch mask for the second anisotropic etch process. In this case, any of the previously described embodiments for forming and utilizing a cladding liner may be employed. Via openings, such as the first-tier memory openings **149**, are formed underneath the pattern of cavities **332** in the photoresist layer **337** through first-tier alternating stack (**132**, **142**). The chemistry of the second anisotropic etch process can be selected such that the materials of the first-tier alternating stack (**132**, **142**) and the first retro-stepped dielectric material portion **165** are etched selective to the material of the upper source-level semiconductor layer **118**. For example, if the first insulating layers **132** comprise silicon oxide, the first sacrificial material layers **142** comprise silicon nitride, and the first retro-stepped dielectric material portion **165**

comprise silicon oxide, the second anisotropic etch process may have an etch chemistry employing a mixture of CF.sub.4, O.sub.2, optionally Ar, and optionally C.sub.4F.sub.8 and/or CF.sub.2Br.sub.2. Generally, the pattern of the openings (i.e., the cavities **332**) in the hard mask layer **331** can be transferred through the first-tier alternating stack (**132**, **142**) by the second anisotropic etch process. A surface of the upper source-level semiconductor layer **118** can be physically exposed at the bottom of one or more via openings through the first-tier alternating stack (**132**, **142**) and/or the first retro-stepped dielectric material portion **165** (such as the first-tier memory openings **149**).

(375) In one embodiment, the materials of the first-tier alternating stack (**132**, **142**) are etched concurrently with the material of the first retro-stepped dielectric material portion **165** during the second anisotropic etch process. The chemistry of the initial etch step may alternate to optimize etching of the first and second materials in the first-tier alternating stack (**132**, **142**) while providing a comparable average etch rate to the material of the first retro-stepped dielectric material portion **165**. The sidewalls of the various first-tier openings (**149**, **129**) may be substantially vertical, or may be tapered. Generally, via openings (such as the various first-tier openings (**149**, **129**)) can be formed through an alternating stack of first material layers and second material layers by performing an anisotropic etch process (such as the second anisotropic etch process) that transfers the pattern of the cavities **332** in the hard mask layer **331** through the alternating stack (**132**, **142**). In case a cladding liner (such as a cladding liner **335** described above is employed), such a cladding liner may be consumed during the second anisotropic etch process, or a residual portion of such a cladding liner (not shown) may remain on the hard mask layer **331**.

(376) Referring to FIG. **50C**, a cladding liner **434** can be formed on sidewalls of the cavities in the hard mask layer **331** and on a top surface of the hard mask layer **331**. In one embodiment, the cladding liner **434** can be conformally deposited on sidewalls of the via openings (such as the various first-tier openings (**149**, **129**)) through the first-tier alternating stack (**132**, **142**), and on bottom surfaces of the various first-tier openings (**149**, **129**).

(377) In one embodiment, the cladding liner **434** can be formed by depositing an aluminum oxide material. In one embodiment, the aluminum oxide material that is deposited to form the cladding liner **434** comprises and/or consists essentially of an amorphous aluminum oxide material. In one embodiment, the cladding liner **434** may be formed by conformally depositing an amorphous aluminum oxide material on sidewalls of the first-tier alternating stack (**132**, **142**) around the via openings (such as the various first-tier openings (**149**, **129**)), on sidewalls of the cavities in the hard mask layer **331**, and on a top surface of the hard mask layer **331**. In one embodiment, the cladding liner **434** may be deposited by a conformal deposition process, such as an atomic layer deposition (ALD) process. The thickness of the cladding liner **434** may be in a range from 1 nm to 30 nm, such as from 2 nm to 15 nm, although lesser and greater thicknesses may also be employed.

(378) Referring to FIG. **50D**, an upper portion of the amorphous aluminum oxide material in the cladding liner **434** can be converted into a polycrystalline aluminum oxide material portion **436**. In one embodiment, the upper portion of the amorphous aluminum oxide material that is converted into the polycrystalline aluminum oxide material portion **436** comprises a horizontally-extending portion of the amorphous aluminum oxide material located above a horizontal plane including a top surface of the hard mask layer **331**, and a plurality of tubular portions of the amorphous aluminum oxide material that are in contact with upper segments of cylindrical sidewalls of the cavities in the hard mask layer **331**. Lower portions of the amorphous aluminum oxide material in the cladding liner **434** that remain amorphous after formation of the polycrystalline aluminum oxide material portion **436** comprise amorphous aluminum oxide material portions **435**. Interfaces between the polycrystalline aluminum oxide material portion **436** and the amorphous aluminum oxide material portions **435** may be formed on sidewalls of the hard mask layer **331**. The combination of the polycrystalline aluminum oxide material portion **436** and the amorphous aluminum oxide material portions **435** comprises the aluminum oxide cladding liner (**435**, **436**).

(379) In one embodiment, the upper portion of the amorphous aluminum oxide material in contact with the top surface of the hard mask layer **331** can be converted into the polycrystalline aluminum oxide material portion **436** by performing a laser anneal process. The laser anneal process can selectively irradiate an upper horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** without irradiating the lower portions of the amorphous aluminum oxide material in contact with the sidewalls of the first-tier alternating stack around the via openings (such as the various first-tier openings (**149**, **129**)).

(380) In one embodiment, the angle of incidence of the laser beam that impinges on the horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** (as measured from the vertical direction that is perpendicular to the top surface of the hard mask layer **331**) can be greater than the arctangent of the ratio of the width of each cavity (opening) in the hard mask layer **331** to the thickness of the hard mask layer **331**. In this case, the laser beam does not impinge on any surface located below the horizontal plane including the bottom surface of the hard mask layer **331**. In one embodiment, the angle of incidence of the laser beam that impinges on the horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** is in a range from 60 degrees to 89.9 degrees, such as from 70 degrees to 89 degrees and/or from 75 degrees to 88 degrees) with respect to the vertical direction that is perpendicular to the top surface of the hard mask layer **331**.

(381) Generally, an upper portion of the amorphous aluminum oxide material in contact with a top surface of the hard mask layer **331** can be converted into the polycrystalline aluminum oxide material portion **436** while lower portions of the amorphous aluminum oxide material in contact with the sidewalls of the first-tier alternating stack (**132**, **142**) around the via openings (such as the various first-tier openings (**149**, **129**)) remain amorphous.

(382) Referring to FIG. **50E**, the lower amorphous aluminum oxide material portions **435** (which are the amorphous portions of the cladding liner (**435**, **436**)) can be removed selective to polycrystalline aluminum oxide material portion **436** and selective to the first-tier alternating stack (**132**, **142**) by performing a selective etch process. The selective etch process comprises a crystallinity-selective etch chemistry that etches an amorphous aluminum oxide material selectively to polycrystalline aluminum oxide material. In one embodiment, the selective etch process may comprise an atomic layer etch (ALE) process. In this case, a thermal ALE process using HF, SF<sub>6</sub> and/or XeF<sub>2</sub> as a fluorination reactant and trimethylaluminum (TMA) and/or dimethylaluminum chloride (DMAC) as a metal precursor ligand exchange reactant, etches aluminum atoms and oxygen atoms from the amorphous aluminum oxide material, and does not etch polycrystalline aluminum oxide material. This selective amorphous aluminum oxide etching method is described in J. A. Murdzek, et al., Journal of Vacuum Science & Technology, A **39**, 042602 (2021), incorporated herein by reference in its entirety. This thermal ALE method may be conducted at an elevated temperature (e.g., about 300 degrees Celsius) using fluorination and ligand-exchange reactions. The fluorination reaction converts the aluminum oxide to an aluminum fluoride. The ligand-exchange reaction then removes the aluminum fluoride by forming volatile products.

(383) The number of cycles in the ALE process can be selected such that the entirety of the amorphous aluminum oxide material portions **435** is removed while the polycrystalline aluminum oxide material portion **436** remain on the hard mask layer **331**. A semiconductor surface such as a surface of the upper source-level semiconductor layer **118** can be physically exposed at the bottom of each via opening (such as each of the various first-tier openings (**149**, **129**)).

(384) Referring to FIG. **50F**, the via openings (such as the various first-tier openings (**149**, **129**)) can be vertically extended through at least one source-level semiconductor layer (such as the upper source-level semiconductor layer **118**) by performing an additional anisotropic etch process employing a combination of the cladding liner **436** (which is the polycrystalline aluminum oxide



material portion **436** at this processing step) and the hard mask layer **331** as an etch mask.

(385) In one embodiment, a set of material layers located underneath the first-tier alternating stack (**132, 142**) may comprise a source-level semiconductor layer such as an upper source-level semiconductor layer **118**, a source-level sacrificial layer **104** located underneath the upper source-level semiconductor layer **118**, and an additional source-level semiconductor layer (such as a lower source-level semiconductor layer **112**) located underneath the source-level sacrificial layer **104**. In one embodiment, the set of material layers located underneath the first-tier alternating stack (**132, 142**) may comprise the in-process source-level material layers **110'** described above.

(386) The chemistry of the additional anisotropic etch process can be selected to sequentially etch through the various material layers of the in-process source-level material layers **110'**. In one embodiment, the additional anisotropic etch process vertically extends the via openings through the source-level sacrificial layer (such as the upper source-level semiconductor layer **118**) and into an upper portion of the additional source-level semiconductor layer (such as the lower source-level semiconductor layer **112**). For example, the chemistry of the additional anisotropic etch process can be selected to sequentially etch through the upper source-level semiconductor layer **118**, the upper sacrificial liner **105**, the source-level sacrificial layer **104**, and the lower sacrificial liner **103**, and to etch into an upper portion of the lower source-level semiconductor layer **112**.

(387) Referring to FIG. **50G**, the hard mask layer **331** may be removed after the additional anisotropic etch process. For example, a carbon based hard mask layer **331** can be removed by ashing. The cladding liner **436** (i.e., the polycrystalline aluminum oxide material portion **436**) may be collaterally removed during the additional anisotropic etch process, or may be removed (e.g., lifted off) during the removal (e.g., ashing) of the hard mask layer **331**.

(388) Subsequently, the various processing steps described above may be performed such as the processing steps described with reference to FIGS. **29A-45** or the processing steps described with reference to FIGS. **11B-19B**.

(389) Generally, memory opening fill structures **58** can be formed in the via openings after removing the hard mask layer **331**. Each of the memory opening fill structures **58** comprises a respective vertical semiconductor channel **60** and a respective vertical stack of memory elements (e.g., portions of the memory film **50**). In one embodiment, the source-level sacrificial layer **104** may be replaced with a source contact layer **114**. The second material layers (such as the first sacrificial material layers **142**) may be replaced with electrically conductive layers (such as first electrically conductive layers **146**) after formation of the memory opening fill structures **58**.

(390) FIGS. **51A-51E** are sequential vertical cross-sectional views of a region of a memory opening in a fourth configuration of the third exemplary structure during formation of the memory opening according to the third embodiment of the present disclosure.

(391) Referring to FIG. **51A**, the fourth configuration of the third exemplary structure may be the same as the third configuration of the third exemplary structure illustrated in FIG. **50B**.

(392) Referring to FIG. **51B**, a cladding liner **434** can be formed. In this case, the cladding liner **434** may be formed by non-conformally depositing an amorphous aluminum oxide material on a top surface of the hard mask layer **331** and on sidewalls of the cavities in the hard mask layer **331** without depositing the cladding liner **434** on sidewalls of the alternating stack (**132, 142**) exposed in the via openings (**129, 149**). According to an aspect of the present disclosure, the cladding liner **434** can be deposited by an anisotropic non-conformal deposition process, such as a physical vapor deposition process (e.g., sputtering). In one embodiment, the non-conformal deposition process can deposit the amorphous aluminum oxide material with a high degree of directionality such that that thickness of the deposited amorphous aluminum oxide material decreases rapidly with a vertical distance from the horizontal plane including the top surface of the hard mask layer **331**. In one embodiment, the deposited aluminum oxide material forms a continuous material layer (which is the cladding liner **434**) above the horizontal plane including the bottom surface of the hard mask layer **331**, and is either not deposited at all below the bottom surface of the hard mask layer **331** or

does not form a continuous material layer underneath the horizontal plane including the bottom surface of the hard mask layer **331**. In other words, if any amorphous aluminum oxide material is deposited on the sidewalls of the via openings (such as the various first-tier openings (**149**, **129**)) through the first-tier alternating stack (**132**, **142**), then it forms a discrete nanocluster of atoms and does not form a continuous material layer. The thickness of the horizontally-extending portion of the cladding liner **434** overlying the top surface of the hard mask layer **331** may have a thickness in a range from 1 nm to 30 nm, such as from 2 nm to 15 nm, although lesser and greater thicknesses may also be employed.

(393) Referring to FIG. **51C**, the upper portion of the amorphous aluminum oxide material in contact with a top surface of the hard mask layer **331** can be converted into a polycrystalline aluminum oxide material portion **436** while portions of the amorphous aluminum oxide material in contact with lower segments of the sidewalls of the cavities in the hard mask layer **331** remain amorphous. In one embodiment, the upper portion of the amorphous aluminum oxide material that is converted into the polycrystalline aluminum oxide material portion **436** comprises a horizontally-extending portion of the amorphous aluminum oxide material located above a horizontal plane including a top surface of the hard mask layer **331**, and a plurality of tubular portions of the amorphous aluminum oxide material that are in contact with upper segments of cylindrical sidewalls of the cavities in the hard mask layer **331**. Lower portions of the amorphous aluminum oxide material in the cladding liner **434** that remain amorphous after formation of the polycrystalline aluminum oxide material portion **436** comprise amorphous aluminum oxide material portions **435**. Interfaces between the polycrystalline aluminum oxide material portion **436** and the amorphous aluminum oxide material portions **435** may be formed on sidewalls of the hard mask layer **331**. The combination of the polycrystalline aluminum oxide material portion **436** and the amorphous aluminum oxide material portions **435** comprises the cladding liner (**435**, **436**).

(394) In one embodiment, the upper portion of the amorphous aluminum oxide material in contact with the top surface of the hard mask layer **331** can be converted into the polycrystalline aluminum oxide material portion **436** by performing a laser anneal process. The laser anneal process can selectively irradiates a horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** without irradiating the lower portions of the amorphous aluminum oxide material in contact with lower segments of the sidewalls of the cavities in the hard mask layer **331**.

(395) In one embodiment, the angle of incidence of the laser beam that impinges on the horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** (as measured from the vertical direction that is perpendicular to the top surface of the hard mask layer **331**) can be greater than the arctangent of the ratio of the width of each cavity (opening) in the hard mask layer **331** to the thickness of the hard mask layer **331**. In one embodiment, the angle of incidence of the laser beam that impinges on the horizontally-extending portion of the amorphous aluminum oxide material located on the top surface of the hard mask layer **331** is in a range from 60 degrees to 89.9 degrees, such as from 70 degrees to 89 degrees and/or from 75 degrees to 88 degrees) with respect to the vertical direction that is perpendicular to the top surface of the hard mask layer **331**.

(396) Generally, the upper portion of the amorphous aluminum oxide material in contact with a top surface of the hard mask layer **331** can be converted into the polycrystalline aluminum oxide material portion **436** while lower portions of the amorphous aluminum oxide material in contact with lower segments of the sidewalls of the cavities in the hard mask layer **331** remain amorphous.

(397) Referring to FIG. **51D**, an additional anisotropic etch process can be performed to vertically extend the via openings (such as the various first-tier openings (**149**, **129**)) through at least one source-level semiconductor layer (such as the upper source-level semiconductor layer **118**). For example, the processing steps of FIG. **50F** may be performed.

(398) Referring to FIG. **51E**, the hard mask layer **331** may be removed after the additional

anisotropic etch process. The cladding liner (**435**, **436**) may be collaterally removed during the additional anisotropic etch process, or may be removed (e.g., lifted-off) during removal (e.g., ashing) of the hard mask layer **331**. In one embodiment, the amorphous aluminum oxide material portions **435** may be removed during the additional anisotropic etch process, and the polycrystalline aluminum oxide material portion **436** may be removed during, or after, the additional anisotropic etch process.

(399) Subsequently, the various processing steps described above may be performed such as the processing steps described with reference to FIGS. **29A-45** or the processing steps described with reference to FIGS. **11B-19B**.

(400) FIGS. **52A-52C** are sequential vertical cross-sectional views of a region of a memory opening in a fifth configuration of the third exemplary structure during formation of the memory opening according to the third embodiment of the present disclosure.

(401) Referring to FIG. **52A**, the fifth configuration of the third exemplary structure may be the same as the fourth configuration of the third exemplary structure illustrated in FIG. **51B** by performing an anneal process that converts the entirety of the cladding liner **434** into a polycrystalline aluminum oxide material portion **436**. In other words, the entirety of the amorphous aluminum oxide material in the cladding liner **434** is converted into the polycrystalline aluminum oxide material portion **436**, which is a polycrystalline aluminum oxide material layer. Thus, the polycrystalline aluminum oxide material portion **436** constitutes a cladding liner after the anneal process.

(402) In one embodiment, converting the entirety of the amorphous aluminum oxide material into the polycrystalline aluminum oxide material layer comprises performing a rapid thermal anneal process in which the first-tier alternating stack (**132**, **142**), the hard mask layer **331**, and the amorphous aluminum oxide material of the cladding liner **434** are annealed at an elevated temperature at which the amorphous aluminum oxide material is converted into the polycrystalline aluminum oxide material layer. In one embodiment, the elevated temperature may be in a range from 700 degrees Celsius to 1,100 degrees Celsius, such as from 800 degrees Celsius to 1,000 degrees Celsius. In one embodiment, the rapid thermal anneal (RTA) process may be employed in which the duration of the peak temperature is in a range from 1 second to 20 seconds.

(403) Referring to FIG. **52B**, an additional anisotropic etch process can be performed to vertically extend the via openings (such as the various first-tier openings (**149**, **129**)) through at least one source-level semiconductor layer (such as the upper source-level semiconductor layer **118**). For example, the processing steps of FIG. **50F** may be performed.

(404) Referring to FIG. **52C**, the hard mask layer **331** may be removed after the additional anisotropic etch process. The cladding liner **436** may be collaterally removed during the additional anisotropic etch process, or may be removed (e.g., lifted-off) during the removal (e.g., ashing) of the hard mask layer **331**. In one embodiment, the cladding liner **436** may be removed during, or after, the additional anisotropic etch process.

(405) Subsequently, the various processing steps described above may be performed such as the processing steps described with reference to FIGS. **29A-45** or the processing steps described with reference to FIGS. **11B-19B**.

(406) FIGS. **53A-53G** are sequential vertical cross-sectional view of a region of a memory opening in a first configuration of a fourth exemplary structure during formation of a memory opening **49** or a first-tier memory opening **149** according to a fourth embodiment of the present disclosure.

Generally, the first configuration of the fourth exemplary structure may be derived from any of the previously described exemplary structures having an insulating cap layer **70** or an inter-tier dielectric layer **180** as a topmost material layer, such as the first exemplary structure illustrated in FIG. **3** or the second exemplary structure illustrated in FIG. **22**, by forming a composite hard mask layer (**331A**, **92**, **331C**) and a patterned photoresist layer **337** thereabove. While FIG. **53A** is derived from the second exemplary structure illustrated in FIG. **22** by forming the composite hard

mask layer (331A, 92, 331C) and the patterned photoresist layer 337 thereupon, embodiments are expressly contemplated herein in which the composite hard mask layer (331A, 92, 331C) and the patterned photoresist layer 337 are formed on a top surface of the insulating cap layer 70 in the first exemplary structure of FIG. 3.

(407) Generally, an alternating stack (132, 142) of first material layers (such as first insulating layers 132) and second material layers (such as first sacrificial material layers 142) can be formed over a substrate 8. The composite hard mask layer (331A, 92, 331C) can be formed over the alternating stack (132, 142). The composite hard mask layer (331A, 92, 331C) comprises a layer stack including a lower patterning film 331A, a first cladding material layer 92 overlying the lower patterning film 331A, and an upper patterning film 331C overlying the first cladding material layer 92.

(408) Each of the lower patterning film 331A and the upper patterning film 331C may independently comprise any material that may be employed for any of the previously described patterning films such as the patterning film 331 described above with reference to FIGS. 23A-23C. In some embodiments, the lower patterning film 331A comprises a first carbon-based material including carbon at a first atomic percentage in a range from 75% to 100%, and the upper patterning film 331C comprises a second carbon-based material including carbon at a second atomic percentage in a range from 75% to 100%. The lower patterning film 331A and/or the upper patterning film 331C may comprise doped carbon, such as boron and/or tungsten doped carbon. Each of the lower patterning film 331A and the upper patterning film 331C may be deposited by a respective chemical vapor deposition process. The total thickness of the composite hard mask layer (331A, 92, 331C) may be in a range from 1,000 nm to 5,000 nm, such as from 1,200 nm to 3,000 nm, although lesser and greater thicknesses may also be employed. The thickness of the lower patterning film 331A may be in a range from 700 nm to 2,000 nm, such as from 900 nm to 1,500 nm, although lesser and greater thicknesses may also be employed. The thickness of the upper patterning film 331C may be in a range from 700 nm to 3,000 nm, such as from 1,000 nm to 2,000 nm, although lesser and greater thicknesses may also be employed.

(409) According to an aspect of the present disclosure, the first cladding material layer 92 comprises a material that can provide higher etch resistance than the upper patterning film 331C during a subsequent first anisotropic etch process that employs the upper patterning film 331C as an etch mask. Further, the material in the first cladding material layer 92 may provide higher etch resistance than the material of the lower patterning film 331A during a subsequent second anisotropic etch process that employs a combination of the first cladding material layer 92 and the lower patterning film 331A as an etch mask.

(410) The first cladding material layer 92 may comprise a layer stack of multiple material layers or a single material layer. In one embodiment illustrated in FIG. 53A, the first cladding material layer 92 may comprise a single material layer.

(411) In one embodiment, the first cladding material layer 92 comprises a metal layer comprising at least one transition metal element, such as tungsten, titanium, tantalum, niobium, molybdenum, or ruthenium. In one embodiment, the metal layer may consist essentially of tungsten, titanium, tantalum, or molybdenum. The thickness of the metal layer may be in a range from 20 nm to 200 nm, such as from 40 nm to 100 nm, although lesser and greater thicknesses may also be employed.

(412) In one embodiment, the first cladding material layer 92 may comprise, and/or may consist essentially of, a conductive metallic compound material selected from a metallic nitride material and a metallic carbide material. Exemplary metallic nitride materials comprise WN, TiN, TaN, or MoN. In this embodiment, the first cladding material layer 92 may be deposited by physical vapor deposition process. Exemplary metallic carbide materials comprise WC, TiC, or TaC. The thickness of the first cladding material layer 92 may be in a range from 20 nm to 200 nm, such as from 40 nm to 100 nm, although lesser and greater thicknesses may also be employed.

(413) In one embodiment, the first cladding material layer 92 may comprise, and/or may consist

essentially of, a non-metallic material. In one embodiment, the non-metallic material may comprise, and/or may consist essentially of, a semiconductor material, which may be an elemental semiconductor material such as silicon or germanium; an alloy of at least two elemental semiconductor materials; or a compound semiconductor material. In one embodiment, the non-metallic material may comprise, and/or may consist essentially of, a wide band-gap semiconductor material such as silicon carbide, aluminum nitride or boron nitride. In one embodiment, the non-metallic material may comprise, and/or may consist essentially of, a dielectric metal oxide material having a dielectric constant greater than 7.9. For example, the non-metallic material may comprise, and/or may consist essentially of, aluminum oxide, titanium oxide, tantalum oxide, hafnium oxide, yttrium oxide, lanthanum, oxide, etc. The thickness of the first cladding material layer **92** may be in a range from 20 nm to 200 nm, such as from 40 nm to 100 nm, although lesser and greater thicknesses may also be employed.

(414) Generally, the first cladding material layer **92** comprises a material that can provide higher etch resistivity than the material of the upper patterning film **331C**. The material in the first cladding material layer **92** may provide higher etch resistivity than the material of the lower patterning film **331A**.

(415) The patterned photoresist layer **337** can be formed by applying a photoresist material layer and lithographically patterning the photoresist material layer. The pattern in the patterned photoresist layer **337** may be the same as the pattern of the first-tier memory openings **149** and the first-tier support openings **129** described with reference to FIGS. **23A-23C**, the pattern of the memory openings **49** and the support openings **19** described with reference to FIGS. **5A-10D**, or any pattern of openings to be transferred through an underlying stack of first material layers and second material layers. Generally, the patterned photoresist layer **337** includes a set of openings therethrough, and is formed over the composite hard mask layer (**331A**, **92**, **331C**).

(416) Referring to FIG. **53B**, a hard-mask-open anisotropic etch process can be performed to transfer the pattern of the openings in the patterned photoresist layer **337** through the composite hard mask layer (**331A**, **92**, **331C**). The hard-mask-open anisotropic etch process can comprise a first hard-mask-open anisotropic etch step that transfers the pattern in the patterned photoresist layer **337** through the upper patterning film **331C** and stops on the first cladding material layer **92**, which functions as an etch stop. The patterned photoresist layer **337** may be partly consumed during the first hard-mask-opening anisotropic etch step.

(417) Referring to FIG. **53C**, a second hard-mask-open anisotropic etch step may be performed to transfer the pattern in the patterned photoresist layer **337** through the first cladding material layer **92**. Subsequently, a third hard-mask-open anisotropic etch step may be performed to transfer the pattern in the patterned photoresist layer **337** through the lower patterning film **331A**. A top surface of an underlying material layer (such as a top surface of an inter-tier dielectric layer **180**) can be physically exposed at the bottom of each opening through the composite hard mask layer (**331A**, **92**, **331B**). The patterned photoresist layer **337** may be collaterally consumed during the hard-mask-open anisotropic etch process. Generally, the composite hard mask layer (**331A**, **92**, **331C**) can be patterned by transferring a pattern in the patterned photoresist layer **337** through the composite hard mask layer (**331A**, **92**, **331C**), which can be effected by performing the hard-mask-open anisotropic etch process.

(418) Referring to FIG. **53D**, via openings (such as first-tier memory openings **149** and/or first-tier support openings **129**, or memory openings **49** and/or support openings **19**) can be formed through an upper region of the alternating stack (**132**, **142**) by performing an anisotropic etch process. The anisotropic etch process has an etch chemistry that etches the material of the first material layers (such as the first insulating layers **132**) and the second material layers (such as the first sacrificial material layers **142**) selective to the material of the upper patterning film **331C**. The anisotropic etch process transfers a pattern of the cavities (i.e., openings) in the composite hard mask layer (**331A**, **92**, **331C**) through the alternating stack (**132**, **142**). The upper patterning film **331C** is

employed as a first etch mask at least during an initial phase of the anisotropic etch process. (419) Referring to FIG. 53E, the anisotropic etch process is continued to vertically extend the via openings (such as first-tier memory openings **149** and/or first-tier support openings **129**, or memory openings **49** and/or support openings **19**) from the upper region of the alternating stack (**132**, **142**) toward a middle region of the alternating stack (**132**, **142**), i.e., through underlying layers within the alternating stack (**132**, **142**). As the anisotropic etch process progresses, the via openings are vertically extended downward, while the material of the upper patterning film **331C** is collaterally consumed (i.e., eroded) at a consumption rate (as measured in nm/minute) that is lower than the etch rate of the alternating stack (**132**, **142**) by the selectivity of the anisotropic etch process. The selectivity of the anisotropic etch process may be typically in a range from 3 to 30, such as from 6 to 15, although lower and higher values for the selectivity may also be employed. The material of the upper patterning film **331C** also becomes faceted (e.g., tapered).

(420) According to an aspect of the present disclosure, the first cladding material layer **92** has higher etch resistance than the upper patterning film **331C** during the anisotropic etch process. Thus, the first cladding material layer **92** preferably has an even lower consumption (i.e., erosion) rate than the upper patterning film **331C** during the anisotropic etch process. This reduces the faceting of the first cladding material layer **92** and the lower patterning film **331A**. Thus, the overall composite hard mask layer (**331A**, **92**, **331C**) faceting is reduced, which reduces the bow of the memory openings.

(421) Referring to FIG. 53F, the entire upper patterning film **331C** may be completely consumed and a top surface of the first cladding material layer **92** may be physically exposed. In one embodiment, the first cladding material layer **92** may also become faceted (e.g., the faceting from the upper patterning film **331C** is transferred to the first cladding material layer **92**). However, the thickness of the lower patterning film **331A** is preferably greater than a critical mask height. The critical mask height is a height at which the mask height is insufficient to prevent the bow of the memory openings. For example, the thickness of the lower patterning film **331A** may be at least 700 nm, such as at least 900 nm, for example 1000 nm to 1500 nm, which is greater than the critical mask height. Therefore, even if the first cladding material layer **92** becomes faceted, the bow of the memory openings is significantly reduced or prevented.

(422) In one embodiment, in-process source-level material layers **110'** including at least one source-level semiconductor material layer can be located underneath the alternating stack (**132**, **142**). The at least one source-level semiconductor material layer may comprise, for example, a lower source-level semiconductor layer **112** and/or an upper source-level semiconductor layer **118** and/or a source-level sacrificial layer **104** (in case the source-level sacrificial layer **104** includes a semiconductor material). In this case, the anisotropic etch may extend the first-tier memory openings **149** or the memory openings **49** through the upper source-level semiconductor layer **118**, at least partially through the source-level sacrificial layer **104** and optionally partially through the lower source-level semiconductor layer **112**.

(423) Referring to FIG. 53G, remaining portions of the composite hard mask layer (**331A**, **92**, **331C**), such as the remaining portions of the lower patterning film **331A**, may be removed after the second anisotropic etch process, for example, by ashing.

(424) In an alternative embodiment illustrated in FIG. 53H, the first cladding material layer **92** comprises a layer stack of multiple material layers. The first cladding material layer **92** may comprise a bottom adhesion liner **921** and/or a top adhesion liner **923** and a metal layer **922** located between the adhesion liners (**921**, **923**). If employed, the bottom adhesion liner **921** can be deposited directly on a top surface of the lower patterning film **331A**, and the top adhesion liner **923** can be deposited on a top surface of the metal layer **922**. If employed, each of the bottom adhesion liner **921** and the top adhesion liner **923** may comprise a respective material selected from a boron-carbon alloy material, a boron-nitrogen alloy material, a metallic nitride material including a conductive nitride of a transition metal element, and a metallic carbide material including a

carbide of a transition metal element. In one embodiment, one or both of the bottom adhesion liner **921** and the top adhesion liner **923** may comprise a boron-carbon alloy material containing boron atoms at an atomic concentration greater than 10% and/or greater than 30%, and containing carbon atoms at an atomic concentration greater than 30% and/or greater than 50%. In one embodiment, one or both of the bottom adhesion liner **921** and the top adhesion liner **923** may comprise a boron-nitrogen alloy material containing boron atoms at an atomic concentration greater than 30% and containing carbon atoms at an atomic concentration greater than 30% (such as stoichiometric boron nitride BN). In one embodiment, one or both of the bottom adhesion liner **921** and the top adhesion liner **923** may comprise a metallic nitride material such as WN, TiN, TaN, or MoN. Each of the bottom adhesion liner **921** and the top adhesion liner **923**, if present, may be formed by a respective physical vapor deposition process or by a respective chemical vapor deposition process, and may have a respective thickness in a range from 1 nm to 30 nm, such as from 3 nm to 15 nm, although lesser and greater thicknesses may also be employed. Generally, in case the first cladding material layer **92** comprises the metal layer **922**, then the first cladding material layer **92** may, or may not, comprise a bottom adhesion liner **921** and/or a top adhesion liner **923**.

(425) Subsequently, the processing steps described above with reference to FIGS. **29-45** or with reference to FIGS. **11A-19B** may be performed. Generally, memory opening fill structures **58** may be formed in the via openings (which may be first-tier memory openings **149** and/or first-tier support openings **129**, or memory openings **49** and/or support openings **19**) after removing the composite hard mask layer (**331A**, **92**, **331C**). Each of the memory opening fill structures **58** comprises a respective vertical semiconductor channel **60** and a respective vertical stack of memory elements (such as portions of a charge storage layer **54** located at levels of the sacrificial material layers (**42**, **142**)). As described above, the second material layers (such as first sacrificial material layers **142** or sacrificial material layers **42**) can be replaced with electrically conductive layers (**146**, **246**) after formation of the memory opening fill structures **58**.

(426) The etch methods of the present embodiment may also be employed to form various second-tier openings (**249**, **229**) at the processing steps of FIGS. **31A** and **31B**.

(427) FIGS. **54A-54G** are sequential vertical cross-sectional view of a region of a memory opening in a second configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(428) The second configuration of the fourth exemplary structure can be derived from the first configuration of the fourth exemplary structure illustrated in FIG. **53A** by modifying the composite hard mask layer (**331A**, **92**, **331C**) of the first configuration of the fourth exemplary structure. Specifically, the composite hard mask layer (**331A**, **92**, **331C**) of the first configuration of the fourth exemplary structure can be modified to insert an intermediate patterning film **331B** and a second cladding material layer **94** between the first cladding material layer **92** and the upper patterning film **331C**.

(429) The intermediate patterning film **331B** can be formed over and directly on a top surface of the first cladding material layer **92**. The intermediate patterning film **331B** can include any patterning material that may be employed for the lower patterning film **331A** or for the upper patterning film **331C**. The material of the intermediate patterning film **331B** may be the same as, or may be different from, the material of the lower patterning film **331A** and/or the material of the upper patterning film **331C**. The thickness of the intermediate patterning film **331B** may be in a range from 100 nm to 2,000 nm, such as from 300 nm to 1,000 nm, although lesser and greater thicknesses may also be employed.

(430) The second cladding material layer **94** can be formed over, and directly on a top surface of the intermediate patterning film **331B**. Any material composition and/or any material stack that may be employed for the first cladding material layer **92** may be employed for the second cladding material layer **94**. Generally, the second cladding material layer **94** may be the same as any of the embodiments of the first cladding material layer **92** described above. While FIG. **54A** illustrates an

embodiment in which the first cladding material layer **92** is composed of a single material layer and the second cladding material layer **94** includes a bottom adhesion liner **941**, a metal layer **942**, and the top adhesion liner **943**, each of the first cladding material layer **92** and the second cladding material layer **94** illustrated in FIG. **54A** may be independently selected from any of the configurations for the first cladding material layer **92** described with reference to FIG. **53A** or **53H**. (431) Generally, each of the first cladding material layer **92** and the second cladding material layer **94** comprises a respective cladding material that can be selected from a metal that consists essentially of at least one transition metal element, a conductive metallic compound material selected from a metallic nitride material and a metallic carbide material, a semiconductor material, and a dielectric metal oxide material having a dielectric constant greater than 7.9. In one embodiment, the first cladding material layer **92** and the second cladding material layer **94** may have different material compositions.

(432) Referring to FIG. **54B**, a hard-mask-open anisotropic etch process can be subsequently performed to transfer the pattern in the patterned photoresist layer **337** through the composite hard mask layer (**331A**, **92**, **331B**, **94**, **331C**). The upper patterning film **331C**, the second cladding material layer **94**, and the intermediate patterning film **331B** can be sequentially etched through during the hard-mask-open anisotropic etch process.

(433) Referring to FIG. **54C**, the hard-mask-open anisotropic etch process can be continued to transfer the pattern in the patterned photoresist layer **337** through the first cladding material layer **92** and the lower patterning film **331A**. In one embodiment, the patterned photoresist layer **337** may be collaterally removed from above the composite hard mask layer (**331A**, **92**, **331B**, **94**, **331C**) by the end of the hard-mask-open anisotropic etch process.

(434) Referring to FIG. **54D**, via openings (such as first-tier memory openings **149** and/or first-tier support openings **129**, or memory openings **49** and/or support openings **19**) can be formed through an upper region of the alternating stack (**132**, **142**) by performing the anisotropic etch process described above. The upper patterning film **331C** is employed as a first etch mask at least during an initial phase of the anisotropic etch process.

(435) Referring to FIG. **54E**, the anisotropic etch process is continued to vertically extend the via openings (such as first-tier memory openings **149** and/or first-tier support openings **129**, or memory openings **49** and/or support openings **19**) from the upper region of the alternating stack (**132**, **142**) toward a middle region of the alternating stack (**132**, **142**), i.e., through underlying layers within the alternating stack (**132**, **142**). As the anisotropic etch process progresses, the via openings are vertically extended downward, while the material of the upper patterning film **331C** is collaterally consumed at a consumption rate (as measured in nm/minute) that is lower than the etch rate of the alternating stack (**132**, **142**) by the selectivity of the first anisotropic etch process, as described above.

(436) Referring to FIG. **54F**, the upper composite hard mask layers (e.g., layers **331C**, **94** and **331B**) may be consumed by the etch process, and the top surface of the first cladding material layer **92** can be physically exposed, as described above with respect to FIG. **53F**.

(437) Referring to FIG. **54G**, remaining portions of the composite hard mask layer (**331A**, **92**, **331C**), such as the remaining portions of the lower patterning film **331A**, may be removed after the second anisotropic etch process, for example, by ashing. Subsequently, the processing steps described above with reference to FIGS. **29-45** or with reference to FIGS. **11A-19B** may be performed. The etch methods of the fourth embodiment of the present disclosure may also be employed to form various second-tier openings (**249**, **229**) at the processing steps of FIGS. **31A** and **31B**.

(438) As discussed above, each of the first cladding material layer **92** and the second cladding material layer **94** may independently comprise a single material layer or a stack of multiple material layers.

(439) FIGS. **55A-55C** are vertical cross-sectional views of a region of a memory opening in



alternative embodiments of the second configuration of the fourth exemplary structure after application and patterning of a photoresist layer according to the fourth embodiment of the present disclosure. In the embodiment illustrated in FIG. 55A, the first cladding material layer **92** comprises a layer stack of multiple material layers such as a bottom adhesion liner **921**, a metal layer **922**, and a top adhesion liner **923**, and the second cladding material layer **92** consists of a single material layer. In the embodiment illustrated in FIG. 55B, the first cladding material layer **92** comprises a layer stack of multiple material layers such as a bottom adhesion liner **921**, a metal layer **922**, and a top adhesion liner **923**, and the second cladding material layer **92** comprises a layer stack of multiple material layers such as a bottom adhesion liner **941**, a metal layer **942**, and a top adhesion liner **943**. In the embodiment illustrated in FIG. 55C, the first cladding material layer **92** consists of a single material layer, and the second cladding material layer **94** consists of another single material layer. Further, embodiments are contemplated herein in which three or more cladding material layers are vertically interlaced with four or more patterning films.

(440) FIGS. 56A-56H are sequential vertical cross-sectional view of a region of a memory opening in a third configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure. The third configuration of the fourth exemplary structure as illustrated in FIG. 56A can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54A. The third configuration of the fourth exemplary structure as illustrated in FIG. 56B can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54B. The third configuration of the fourth exemplary structure as illustrated in FIG. 56C can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54C. Generally, a patterned photoresist layer **337** including a set of openings therethrough can be formed over a composite hard mask layer (**331A**, **92**, **331B**, **94**, **331C**), and the composite hard mask layer (**331A**, **92**, **331B**, **94**, **331C**) can be patterned by transferring a pattern in the patterned photoresist layer **337** through the composite hard mask layer (**331A**, **92**, **331B**, **94**, **331C**) by performing a hard-mask-open anisotropic etch process.

(441) Referring to FIG. 56D, a selective cladding material deposition process can be performed to grow an additional cladding material after the hard-mask-open anisotropic etch process. During the selective cladding material deposition process, the additional cladding material grows from sidewalls of openings through the first cladding material layer **92** and/or from sidewalls of openings through the second cladding material layer **94**, and does not grow from surfaces of the lower patterning film **331A**, from surfaces of the upper patterning film **331C**, from surfaces of the intermediate patterning film **331B**, or from surfaces of the alternating stack (**132**, **142**). In the example illustrated in FIG. 56D, the additional cladding material grows from sidewalls of openings through the second cladding material layer **94**, and does not grow from surfaces of the lower patterning film **331A**, from surfaces of the upper patterning film **331C**, from surfaces of the intermediate patterning film **331B**, or from sidewalls of openings through first cladding material layer **92**. Generally, the additional cladding material grows from sidewalls of openings through one or more cladding material layers (**92**, **94**). A tubular cladding structure **53C** can be formed on each physically exposed sidewalls of the second cladding material layer **94**.

(442) Generally, the additional cladding material that grows from the physically exposed sidewalls of the second cladding material layer **94** may comprise any cladding material that can be selectively grown from the surfaces of the second cladding material layer **94** while suppressing growth from the physically exposed surfaces of the lower patterning film **331A**, the intermediate patterning film **331B**, and the upper patterning film **331C**. In one embodiment, the additional cladding material may comprise a material that may be employed for the first cladding material layer **92** or for the second cladding material layer **94** as discussed above. In one embodiment, the additional cladding material may comprise a material that can provide higher etch resistance than the upper patterning film **331C** and/or than the lower patterning film **331A** during subsequent anisotropic etch processes.

(443) In one embodiment, the tubular cladding structures 53C may comprise at least one transition metal element such as tungsten, titanium, tantalum, niobium, molybdenum, or ruthenium. The lateral thickness of each tubular cladding structure 53C may be in a range from 2 nm to 50 nm, such as from 4 nm to 25 nm, although lesser and greater lateral thicknesses may also be employed. The selective deposition process that forms the tubular cladding structures 53C may comprise an atomic layer deposition process or a chemical vapor deposition process. In some embodiment, an etchant can be flowed simultaneously with a reactant to provide selective growth of the additional cladding material. In an illustrative example, a tungsten deposition process that flows only tungsten hexafluoride gas without any nucleation-assist gas proceeds only on metallic surfaces or semiconductor surfaces, and does not proceed on dielectric surfaces.

(444) Referring to FIG. 56E, the anisotropic etch process can be performed. For example, the anisotropic etch process may have the same etch chemistry as the anisotropic etch process described with reference to FIG. 54D. In one embodiment, the tubular cladding structures 53C function as an additional mask structure during the first anisotropic etch process to reduce or prevent faceting or erosion of the second cladding material layer 94 during the anisotropic etch process.

(445) The third configuration of the fourth exemplary structure as illustrated in FIG. 56F can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54E.

(446) The third configuration of the fourth exemplary structure as illustrated in FIG. 56G can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54F. However, the faceting of the first cladding material layer 92 during the anisotropic etch process may also be reduced or eliminated due to the presence of the tubular cladding structures 53C in FIG. 56G, due to the reduced widening of the memory opening 149.

(447) The third configuration of the fourth exemplary structure as illustrated in FIG. 56H can be the same as the second configuration of the fourth exemplary structure illustrated in FIG. 54G. Subsequently, the processing steps described above with reference to FIGS. 29-45 or with reference to FIGS. 11A-19B may be performed. The etch methods of the present disclosure may also be employed to form various second-tier openings (249, 229) at the processing steps of FIGS. 31A and 31B.

(448) FIGS. 57A-57H are sequential vertical cross-sectional view of a region of a memory opening in a fourth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(449) Referring to FIG. 57, the fourth configuration of the fourth exemplary structure as illustrated in FIG. 57A may be the same as, or may be derived from, any of the second configurations of the fourth exemplary structure described above with an additional limitation that the materials of the first cladding material layer 92 and the second cladding material layer 94 are selected such that an additional cladding material can subsequently grow from surfaces of the material of the first cladding material layer 92 while suppressing growth from surfaces of the material of the second cladding material layer 94 and while suppressing growth from surfaces of the patterning films (331A, 331B, 331C).

(450) Referring to FIG. 57B, the processing steps of FIG. 56B can be performed to transfer the pattern in the patterned photoresist layer 337 through the upper patterning film 331C, the second cladding material layer 94, and the intermediate patterning film 331B.

(451) Referring to FIG. 57C, the processing steps of FIG. 56C can be performed to transfer the pattern in the patterned photoresist layer 337 through the first cladding material layer 92 and the lower patterning film 331A.

(452) Referring to FIG. 57D, a selective cladding material deposition process can be performed to grow an additional cladding material after the hard-mask-open anisotropic etch process. During the selective cladding material deposition process, the additional cladding material grows from sidewalls of openings through the first cladding material layer 92 and/or from sidewalls of

openings through the second cladding material layer **94**, and does not grow from surfaces of the lower patterning film **331A**, from surfaces of the upper patterning film **331C**, from surfaces of the intermediate patterning film **331B**, or from surfaces of the alternating stack (**132**, **142**). In the example illustrated in FIG. **57D**, the additional cladding material grows from sidewalls of openings through the first cladding material layer **92**, and does not grow from surfaces of the lower patterning film **331A**, from surfaces of the upper patterning film **331C**, from surfaces of the intermediate patterning film **331B**, from sidewalls of openings through second cladding material layer **94**, or from surfaces of the alternating stack (**132**, **142**). Generally, the additional cladding material grows from sidewalls of openings through one or more cladding material layers (**92**, **94**). A tubular cladding structure **53C** can be formed on each physically exposed sidewalls of the first cladding material layer **92**.

(453) Referring to FIG. **57E**, the anisotropic etch process can be performed. For example, the anisotropic etch process may have the same etch chemistry as the first anisotropic etch process described with reference to FIG. **54D**. In one embodiment, the tubular cladding structures **53C** function as an additional mask structure during the anisotropic etch process to reduce or prevent erosion of the first cladding material layer **92**.

(454) Referring to FIGS. **57F** to **57H**, the respective steps of FIGS. **56F** to **56H** can be performed. Subsequently, the processing steps described above with reference to FIGS. **29-45** or with reference to FIGS. **11A-19B** may be performed. The etch methods of the present disclosure may also be employed to form various second-tier openings (**249**, **229**) at the processing steps of FIGS. **31A** and **31B**.

(455) FIGS. **58A-58H** are sequential vertical cross-sectional view of a region of a memory opening in a fifth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(456) Referring to FIG. **58**, the fifth configuration of the fourth exemplary structure as illustrated in FIG. **58A** may be the same as, or may be derived from, any of the second configurations of the fourth exemplary structure described above with an additional limitation that the materials of the first cladding material layer **92** and the second cladding material layer **94** are selected such that an additional cladding material can subsequently grow from surfaces of the material of the first cladding material layer **92** and from surfaces of the material of the second cladding material layer **94** while suppressing growth from surfaces of the patterning films (**331A**, **331B**, **331C**).

(457) Referring to FIG. **58B**, the processing steps of FIG. **56B** can be performed to transfer the pattern in the patterned photoresist layer **337** through the upper patterning film **331C**, the second cladding material layer **94**, and the intermediate patterning film **331B**.

(458) Referring to FIG. **58C**, the processing steps of FIG. **56C** can be performed to transfer the pattern in the patterned photoresist layer **337** through the first cladding material layer **92** and the lower patterning film **331A**.

(459) Referring to FIG. **58D**, a selective cladding material deposition process can be performed to grow an additional cladding material after the hard-mask-open anisotropic etch process. During the selective cladding material deposition process, the additional cladding material grows from sidewalls of openings through the first cladding material layer **92** and from sidewalls of openings through the second cladding material layer **94**, and does not grow from surfaces of the lower patterning film **331A**, from surfaces of the upper patterning film **331C**, from surfaces of the intermediate patterning film **331B**, or from surfaces of the alternating stack (**132**, **142**). The tubular cladding structure **53C** can be formed on each physically exposed sidewalls of the first cladding material layer **92** and the second cladding material layer **94**.

(460) Referring to FIGS. **58E** to **58H**, the respective steps of FIGS. **56E** to **56H** can be performed. Subsequently, the processing steps described above with reference to FIGS. **29-45** or with reference to FIGS. **11A-19B** may be performed. The etch methods of the present disclosure may also be employed to form various second-tier openings (**249**, **229**) at the processing steps of FIGS. **31A** and

31B.

(461) FIGS. 59A-59H are sequential vertical cross-sectional view of a region of a memory opening in a sixth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(462) Referring to FIG. 59A, the sixth configuration of the fourth exemplary structure may be the same as the third configuration of the fourth exemplary structure illustrated in FIG. 56A.

(463) Referring to FIG. 59B, the sixth configuration of the fourth exemplary structure may be the same as the third configuration of the fourth exemplary structure illustrated in FIG. 56B.

(464) Referring to FIG. 59C, the sixth configuration of the fourth exemplary structure may be the same as the third configuration of the fourth exemplary structure illustrated in FIG. 56C.

(465) Referring to FIG. 59D, via openings (such as first-tier memory openings 149 and/or first-tier support openings 129, or memory openings 49 and/or support openings 19) can be formed through an upper region of the alternating stack (132, 142) by performing the anisotropic etch process. The upper patterning film 331C is employed as a first etch mask at least during the initial phase of the anisotropic etch process.

(466) Referring to FIG. 59E, the anisotropic etch process is continued to vertically extend the via openings (such as first-tier memory openings 149 and/or first-tier support openings 129, or memory openings 49 and/or support openings 19) from the upper region of the alternating stack (132, 142) toward a middle region of the alternating stack (132, 142), i.e., through underlying layers within the alternating stack (132, 142). As the anisotropic etch process progresses, the via openings are vertically extended downward, while the material of the upper patterning film 331C is collaterally consumed (i.e., eroded). A top surface of the second cladding material layer 94 can be physically exposed at this point in the anisotropic etch process.

(467) Referring to FIG. 59F, the anisotropic etch process (e.g., a first anisotropic etch process) is terminated and a selective cladding material deposition process can be performed to grow an additional cladding material after the top surface of the second cladding material layer 94 is physically exposed. The additional cladding material can grow from the top surface and sidewalls of the second cladding material layer 94, and does not grow from surfaces of the lower patterning film 331A, from surfaces of the intermediate patterning film 331B, or from surfaces of the alternating stack (132, 142). The deposited additional cladding material can form an additional cladding material layer 53D including a horizontally-extending portion that overlies the second cladding material layer 94, and vertically-extending tubular portions that contact a sidewall of a respective opening in the second cladding material layer 94.

(468) In one embodiment, the selective cladding material deposition process grows the additional cladding material grows from physically exposed surfaces of the second cladding material layer 94, and suppresses growth of the additional cladding material from surfaces of the lower patterning film 331A, from surfaces of the upper patterning film 331C, from surfaces of the intermediate patterning film 331B, or from surfaces of the alternating stack (132, 142). As discussed above, ordinal are herein employed to merely identify similar elements, and the second cladding material layer 94 may be referred to as a first cladding material layer in the Claims of the instant application.

(469) Generally, the additional cladding material that grows from the physically exposed sidewalls of the second cladding material layer 94 may comprise any cladding material that can be selectively grown from the surfaces of the second cladding material layer 94 while suppressing growth from the physically exposed surfaces of the lower patterning film 331A, the intermediate patterning film 331B, and the alternating stack (132, 142). In one embodiment, the additional cladding material may comprise a material that may be employed for the first cladding material layer 92 or for the second cladding material layer 94 in previously described embodiments. In one embodiment, the additional cladding material may comprise a material that can provide higher etch resistance than the intermediate patterning film 331B and/or than the lower patterning film 331A.

during subsequent anisotropic etch processes.

(470) In one embodiment, the additional cladding material layer **53D** may comprise at least one transition metal element such as tungsten, titanium, tantalum, niobium, molybdenum, or ruthenium. The vertical thickness of the horizontally-extending portion of the additional cladding material layer **53D** may be in a range from 2 nm to 100 nm, such as from 4 nm to 60 nm, although lesser and greater lateral thicknesses may also be employed. The selective deposition process that forms the additional cladding material layer **53D** may comprise an atomic layer deposition process or a chemical vapor deposition process. In some embodiments, an etchant can be flowed simultaneously with a reactant to provide selective growth of the additional cladding material. In an illustrative example, a tungsten deposition process that flows only tungsten hexafluoride gas without any nucleation-assist gas proceeds only on metallic surfaces or semiconductor surfaces, and does not proceed on dielectric surfaces.

(471) In an alternative embodiment, the additional cladding material layer **53D** may be formed by a highly non-conformal deposition process such as a physical vapor deposition employing a high degree of collimation, such that the additional cladding material layer **53D** is deposited on the top surface of the second cladding material layer **94**. However, the additional cladding material layer **53D** does not extend into the vias below the masking layers.

(472) Subsequently, a second anisotropic etch process can be performed. For example, the second anisotropic etch process may have the same etch chemistry as the additional anisotropic etch process described with reference to FIG. **54E**. The additional cladding material layer **53D** may function as an additional etch mask structure during an initial phase of the second anisotropic etch process until the additional cladding material layer **53D** is collaterally consumed during the second anisotropic etch process. The additional cladding material layer **53D**, the second cladding material layer **94**, and the intermediate patterning film **331B** may be collaterally consumed during the second anisotropic etch process, and a top surface of the first cladding material layer **92** may be physically exposed at the end of the intermediate anisotropic etch process.

(473) Referring to FIGS. **59G** to **57H**, the respective steps of FIGS. **56G** to **56H** can be performed. Subsequently, the processing steps described above with reference to FIGS. **29-45** or with reference to FIGS. **11A-19B** may be performed. The etch methods of the present disclosure may also be employed to form various second-tier openings (**249**, **229**) at the processing steps of FIGS. **31A** and **31B**.

(474) FIGS. **60A-60H** are sequential vertical cross-sectional view of a region of a memory opening in a seventh configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure. Referring to FIGS. **60A** to **60H**, the respective steps of FIGS. **59A** to **59H** can be performed, with the modification that the additional cladding material layer **53D** is formed on the surface of the first cladding material layer **92** when the upper surface of the first cladding material layer **92** is exposed, instead of or in addition to forming the additional cladding material layer **53D** on the second cladding material layer **94**.

(475) FIGS. **61A-61M** are sequential vertical cross-sectional views of a region of a memory opening in an eighth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(476) Referring to FIG. **61A**, the eighth configuration of the fourth exemplary structure can be derived from the second exemplary structure illustrated in FIG. **22** by applying a first patterning film **431A** over the top surface of the second exemplary structure illustrated in FIG. **22**. A portion of the memory array region **100** is illustrated in FIG. **61A**. Generally, at least one material layer can be formed over a substrate **8**, which can be the same as the substrate **8** described above. The at least one material layer may comprise an alternating stack of first material layers and second material layers such as an alternating stack of insulating layers (**32**, **132**) and sacrificial material layers (**42**, **142**) described with reference to the first exemplary structure or the second exemplary structure.

The first patterning film **431A** may have the same material composition as the patterning film **331** described above, and may have a thickness in a range from 30% to 90% of the thickness of the patterning film **331** described above. In one embodiment, the first patterning film **431A** comprises a first carbon-based material including carbon at a first atomic percentage in a range from 75% to 100%.

(477) Referring to FIG. **61B**, a first patterned photoresist layer **731** can be formed over the first patterning film **431A**. The first patterned photoresist layer **731** can be formed by applying a blanket photoresist material layer and by lithographically patterning the blanket photoresist material layer within a pattern including memory openings and support openings. The pattern of the openings in the first patterned photoresist layer **731** may be the same as the pattern of the first-tier memory openings **149** and the first-tier support openings **119** described above, or may be the same as the pattern of the memory openings **49** and the support openings **19** described above. The openings through the first patterned photoresist layer **731** are herein referred to as first openings.

(478) Referring to FIG. **61C**, an anisotropic etch process can be performed to etch upper portions of the first patterning film **431A** that are not masked by the first patterned photoresist layer **731**. Recess cavities **429** can be formed at least in the upper region of the first patterning film **431A** in the areas that are not masked by the first patterned photoresist layer **431A**. In one embodiment, the recess cavities **429** may have a respective depth that is less than a thickness of the first patterning film **431A**. The depth of the recess cavities **429** can be in a range from 10% to 90%, such as from 30% to 80%, of the thickness of the first patterning film **431A**. In this embodiment, recessed surfaces of the first patterning film **431A** may be physically exposed at a bottom of the recess cavities **429**. In one embodiment, the bottom surface of each recess cavity **429** can be a recessed horizontal surface of the first patterning film **431A**. In one embodiment, each the recess cavities **429** may have a respective horizontal cross-sectional shape of a circle or an ellipse. Generally, the pattern of the recess cavities **429** may include the pattern of the first-tier memory openings **149** and the first-tier support openings **119** described above, or may be the same as the pattern of the memory openings **49** and the support openings **19** described above. The first patterned photoresist layer **731** can be subsequently removed by any suitable method.

(479) Referring to FIG. **61D**, a cladding material layer **433L** can be conformally deposited on physically exposed surfaces of the recess cavities **429** and over a top surface of the first patterning film **431A**. The cladding material layer **433L** may include any of the cladding materials described above. In one embodiment, the cladding material layer **433L** may comprise, and/or may consist essentially of, a material selected from a transition metal, a metal nitride material, a metal carbide material, a semiconductor material, or a dielectric metal oxide material having a dielectric constant greater than 7.9. The thickness of the cladding material layer **433L** may be in a range from 5 nm to 30 nm, such as from 10 nm to 20 nm, although lesser and greater thicknesses may also be employed. Generally, the thickness of the cladding material layer **433L** may be in a range from 2% to 20% of the maximum lateral dimension of the recess cavities **429** as formed at the processing steps of FIG. **61C**.

(480) Referring to FIG. **61E**, an anisotropic etch process (e.g., a sidewall spacer etch process) can be performed to remove horizontally-extending portions of the cladding material layer **433L** by anisotropically etching the cladding material layer **433L**, wherein a remaining portion of the cladding material layer **433L** located inside the recess cavity **429** comprises the cylindrical cladding film (i.e., cladding film sidewall spacers) **433**. A two-dimensional array of cylindrical cladding films **433** can be formed on the first patterning film **431A**. Each of the cylindrical cladding films **433** can be formed on a sidewall of a respective recess cavity **429**. Each of the cylindrical cladding films **433** comprises a cladding material that is selected from a transition metal, a metal nitride material, a metal carbide material, a semiconductor material, or a dielectric metal oxide material having a dielectric constant greater than 7.9.

(481) Referring to FIG. **61F**, a second patterning film **431B** can be formed over the cylindrical

cladding film **433** and the first patterning film **431A** such that it fills the recess cavities **429** and preferably extends above the top surface of the first patterning film **431A**. Generally, the second patterning film **431B** may have any material composition that the patterning film **331** described above may have, and may have a thickness in a range from 10% to 80% of the thickness of the patterning film **331** described above. In one embodiment, the first patterning film **431A** comprises a second carbon-based material including carbon at a first atomic percentage in a range from 75% to 100%. The material composition of the second patterning film **431B** may be the same as or may be different from the material composition of the first patterning film **431A**. The second patterning film **431B** may be self-planarizing, or may be planarized. Alternatively, the thickness of the second patterning film **431B** may be selected such that the a topographical variation of the top surface of the second patterning film **431B** does not adversely impact a lithographic patterning process to be subsequently employed.

(482) At least one masking material layer (**471**, **472**) can be over the second patterning film **431B**. In one embodiment, the at least one masking material layer (**471**, **472**) may comprise at least one of a spin-on-glass (SOG) layer **471** and/or a spin-on-carbon (SOC) layer **472**. In one embodiment, the at least one masking material layer (**471**, **472**) may comprise a layer stack including a spin-on-glass layer **471** and a spin-on-carbon layer **472**. Generally, any material that may assist transfer of a lithographic pattern in a photoresist layer to be subsequently formed may be employed for the at least one masking material layer (**471**, **472**).

(483) A second patterned photoresist layer **473** can be formed over the at least one masking material layer (**471**, **472**) by applying a blanket photoresist material layer on a top surface of the at least one masking material layer (**471**, **472**), and by lithographically patterning the blanket photoresist material layer with a lithographic pattern. In one embodiment, the lithographic pattern formed in the second patterned photoresist layer **473** may be the same as the pattern of the first openings. The openings formed in the second patterned photoresist layer **473** are herein referred to as second openings **439**. In one embodiment, the pattern of the second openings **439** formed in the second patterned photoresist layer **473** may be the same as the pattern of the first openings formed in the first patterned photoresist layer **471**. In one embodiment, the size of the second openings in the second patterned photoresist layer **473** may be scaled down such that the periphery of each second opening in the second photoresist layer **473** is located between an inner sidewall and an outer sidewall of a respective underlying cylindrical cladding film **433** in a plan view. In one embodiment, the bottom periphery of each second opening **439** in the second photoresist layer **473** may be located between an inner sidewall and an outer sidewall of a respective underlying cylindrical cladding film **433** in the plan view. A plan view refers to a view along a vertical direction, such as a see-through top-down view.

(484) Referring to FIG. **61G**, an anisotropic etch process can be performed to transfer the pattern in the second patterned photoresist layer **473** through the at least one masking material layer (**471**, **472**). Unmasked portions of the at least one masking material layer (**471**, **472**) can be anisotropically etched underneath the second openings in the second patterned photoresist layer **473**. The remaining portion of the at least one masking material layer (**471**, **472**) comprises a masking structure (**471**, **472**). The masking structure (**471**, **472**) may comprise a layer stack including a spin-on-glass layer **471** and a spin-on-carbon layer **472**. In one embodiment, the masking structure (**471**, **472**) may include at least one two-dimensional array of the second openings **439**. Generally, the masking structure (**471**, **472**) is formed over the second patterning film **431B** with at least one discrete second opening **439**. The discrete second openings **439** may have an areal overlap within an area of the respective one of the recess cavities **429**, which is the area laterally enclosed by an outer sidewall of a respective one of the cylindrical cladding film **433**. Generally, each discrete second opening **439** in the masking structure (**471**, **472**) may have an area that overlaps with an entirety of an area enclosed by an inner sidewall of a respective underlying cylindrical cladding film **433**, and is located entirely within an area enclosed by an outer sidewall

of the respective underlying cylindrical cladding film **433**. Thus, the area of each discrete second opening **439** in the masking structure (**471**, **472**) in a plan view may be located entirely within an area enclosed by an outer sidewall of a respective underlying cylindrical cladding film **433**. The pattern of the discrete second openings **439** in the masking structure (**471**, **472**) is herein referred to as a first pattern. The second photoresist layer **473** may be removed by any suitable method after extending the second openings **439** into the masking structure (**471**, **472**).

(485) Referring to FIG. **61H**, a first mask open etch step can be performed to transfer the first pattern of the discrete second openings **439** in the masking structure (**471**, **472**) through the second patterning film **431B** selective to the cylindrical cladding film **433**. The first mask open etch step may employ a first mask open anisotropic etch process, which etches the material of the second patterning film **431B** selective to the material(s) of the masking structure (**471**, **472**) and selective to the material of the cylindrical cladding films **433**. A predominant portion (i.e., more than 50) of each portion of the second patterning film **431B** that is laterally surrounded by a respective cylindrical cladding film **433** can be removed by the first mask open etch step. In one embodiment, the entirety of each portion of the second patterning film **431B** that is laterally surrounded by a respective cylindrical cladding film **433** can be removed by the first mask open etch step. The masking structure (**471**, **472**) may be collaterally removed during the first mask open etch step.

(486) Referring to FIG. **61I**, a second mask open etch step can be performed to transfer a second pattern of the second openings **439** in the area defined by an inner sidewall of the cylindrical cladding film **433** through the first patterning film **431A**. The second mask open etch step may employ a second mask open anisotropic etch process, which etches unmasked portions of the first patterning film **431A** and may collaterally etch the second patterning film **431B**. The second pattern can be a composite pattern employing a combination of the cylindrical cladding films **433** and the second patterning film **431B**. Portions of the first patterning film **431A** that are not covered by the combination of the cylindrical cladding films **433** and the second patterning film **431B** are etched during the second mask open anisotropic etch process. The first patterning film **431A** can be etched through in areas that are not covered by the combination of the cylindrical cladding films **433** and the second patterning film **431B**. A top surface of the at least one underlying material layer (e.g., layer **180**) that underlies the first patterning film **431A** can be physically exposed underneath each opening through the first patterning film **431A**.

(487) Referring to FIG. **61J**, the second pattern can be transferred into the at least one material layer by performing a main etch process. The main etch may form the memory openings **149** and/or the support openings through the alternating stack (**132**, **142**) which underly the respective first and the second openings (**429**, **439**). The second patterning film **431B** can be collaterally removed during an initial step of the main etch process.

(488) Referring to FIG. **61K**, after the second patterning film **431B** is removed, the combination of the first patterning film **431A** and the cylindrical cladding films **433** can be employed as an etch mask during the remainder of the main etch process. In one embodiment, the main etch process comprises a reactive ion etch process in which a collateral etch rate of the first patterning film **431A** is limited by a flux of etchant ions, and a collateral etch rate of the cylindrical cladding film **433** is lower than an average of the collateral etch rate of the first patterning film **431A**. In one embodiment, a top surface of the first patterning film **431A** may be vertically recessed below a top surface of the cylindrical cladding film **433** such that a region of the top surface of the first patterning film **431A** that is proximal to the cylindrical cladding film **433** has a concave surface **431C** in a terminal portion of the reactive ion etch process. In one embodiment, the at least one underlying material layer comprises an alternating stack of first insulating layers **132** and first sacrificial material layers **142**, or an alternating stack of insulating layers **32** and sacrificial material layers **42**. In this case, the alternating stack may be etched through during the anisotropic etch process.

(489) The concave surface **431C** has a middle portion located closer to the alternating stack than a



peripheral portion. The concave surface **431C** acts as an ion trap which traps the ions used during the reaction ion etching. The ion trap prevents or reduces the trapped ions from being deflected sideways by the etch mask (e.g., first patterning film **431** and cylindrical cladding film **433**) onto the sidewalls of the via openings (**49**, **149**). The decrease in deflected ions decreases undesirable bowing and/or critical diameter enlargement of the via openings. In contrast, for prior art etch masks having a convex top surface, ions are deflected sideways onto the sidewalls of the via openings, which causes undesirable bowing and/or critical diameter enlargement of the via openings.

(490) Referring to FIG. **61L**, in case the at least one underlying material layer comprises an in-process source-level material layers **110'**, via openings (such as first-tier memory openings **149** or memory openings **49**) may be vertically extended into the in-process source-level material layers **110'**.

(491) Referring to FIG. **61M**, remaining portions of the first patterning film **431A** and the cylindrical cladding film **433** can be removed. For example, the remaining portions of the first patterning film **431A** and the cylindrical cladding film **433** can be removed during the etch of the in-process source-level material layers **110'**. Alternatively, an ashing process can be performed to remove the first patterning film **431A** and to lift-off and remove the cylindrical cladding film **433** after forming the via openings in the in-process source-level material layers **110'**.

(492) Subsequently, various processing steps described above with reference to the first or second exemplary structure may be performed. For example, a memory opening fill structure may be formed in each via opening that is formed through the alternating stack by the main etch process. Each of the memory opening fill structures may comprise a respective vertical semiconductor channel **60** and a respective vertical stack of memory elements.

(493) FIGS. **62A-62G** are sequential vertical cross-sectional views of a region of a memory opening in a ninth configuration of the fourth exemplary structure during formation of the memory opening according to the fourth embodiment of the present disclosure.

(494) Referring to FIG. **62A**, the ninth configuration of the fourth exemplary structure can be derived from the second exemplary structure illustrated in FIGS. **23A-23C** by removing the photoresist layer **337** selective to the patterning film **331**. Generally, at least one material layer can be formed over a substrate **8**, which can be the same as the substrate **8** described above. The at least one material layer may comprise an alternating stack of first material layers and second material layers such as an alternating stack of insulating layers (**32**, **132**) and sacrificial material layers (**42**, **142**) described with reference to the first exemplary structure or the second exemplary structure. The patterning film **331** may have the same material composition as any of the patterning films described above, and may have the same thickness range as any of the patterning films described above. In one embodiment, the patterning film **331** comprises a carbon-based material including carbon at an atomic percentage in a range from 75% to 100%. Discrete openings **449** are formed through the patterning film **331**. The discrete openings through the patterning film **331** may comprise at least one two-dimensional array of openings.

(495) Referring to FIG. **62B**, a first cladding material can be anisotropically deposited over the patterning film **331** employing a first anisotropic deposition process, such as a physical vapor deposition process or a plasma-enhanced chemical vapor deposition process. The first cladding material may be any of the cladding materials described above. In one embodiment, the first cladding material may be selected from a transition metal, a metal nitride material, a metal carbide material, a semiconductor material, or a dielectric metal oxide material having a dielectric constant greater than 7.9. The deposited first cladding material forms a first cladding material layer **333**. The first cladding material layer **333** includes a first horizontally-extending cladding material portion overlying a top surface of the patterning film **331**, first cylindrical tapered cladding material portions located on a sidewall of a respective one of the discrete openings **449**, and optional first horizontal plate portions located at a bottom of a respective one of the discrete openings **449** and

directly on a top surface of an underlying material layer (e.g., layer **180**). The optional first horizontal plate portions may be omitted depending on the width of the discrete openings **449** and the deposition process used to deposit the first cladding material layer **333**. In one embodiment, the first cylindrical tapered cladding material portions can have a variable lateral thickness that increases with a vertical distance from the substrate **8**. The maximum lateral thickness of each first cylindrical tapered cladding material portion may be in a range from 2% to 20%, such as from 5% to 15%, of the maximum lateral dimension of a respective discrete opening **449** in the patterning film **331** in which the respective first cylindrical tapered cladding material portion is formed.

(496) A second cladding material can be anisotropically deposited over the first cladding material layer **333** employing a second anisotropic deposition process, such as a physical vapor deposition process or a plasma-enhanced chemical vapor deposition process. The second cladding material may be any of the cladding materials described above. In one embodiment, the second cladding material may be selected from a transition metal, a metal nitride material, a metal carbide material, a semiconductor material, or a dielectric metal oxide material having a dielectric constant greater than 7.9. In one embodiment, the second cladding material may have a different material composition than the first cladding material. In one embodiment, the second cladding material may comprise a material that can provide a lower etch resistance than the first cladding material during a subsequent main etch process, which may be a reactive ion etch process. The deposited second cladding material forms a second cladding material layer **335**. The second cladding material layer **335** includes a second horizontally-extending cladding material portion overlying a top surface of the first horizontally-extending cladding material portion of the first cladding material layer **333**, a second cylindrical tapered cladding material portions located on a sidewall of a respective one of the first cylindrical tapered cladding material portions, and an optional second horizontal plate portions overlying a respective one of the first horizontal plate portions of the first cladding material layer **333**. In one embodiment, the optional second horizontal plate portions may be omitted. The second cylindrical tapered cladding material portions can have a variable lateral thickness that increases with a vertical distance from the substrate **8**. The maximum lateral thickness of each second cylindrical tapered cladding material portion may be in a range from 3% to 30%, such as from 6% to 20%, of the maximum lateral dimension of a respective discrete opening **449** in the patterning film **331** in which the respective second cylindrical tapered cladding material portion is formed. In one embodiment, the lateral thickness of each second cylindrical tapered cladding material portion within a horizontal plane including the top surface of the patterning film **331** can be greater than the lateral thickness of each first cylindrical tapered cladding material portion within the horizontal plane.

(497) In one embodiment, the thickness of the second cladding material layer **335** is less than the thickness of the first cladding material layer **333**. For example, the first horizontally-extending cladding material portion of the first cladding material layer **333** may be at least 20% thicker, such as 25% to 500% thicker than the second horizontally-extending cladding material portion of the second cladding material layer **335**. In one embodiment, the first and the second cladding material layers (**333**, **335**) may comprise two different metal layers, such as a tantalum layer and a ruthenium layer.

(498) Referring to FIG. **62C**, a mask open etch step can be performed to remove the second horizontally-extending cladding material portion and the second horizontal plate portions of the second cladding material layer **335** and the first horizontally-extending cladding material portion and the first horizontal plate portions of the first cladding material layer **333**. For example, a mask open anisotropic etch process can be performed to anisotropically etch the second horizontally-extending cladding material portion and the second horizontal plate portions of the second cladding material layer **335** and the first horizontally-extending cladding material portion and the first horizontal plate portions of the first cladding material layer **333**. The second cylindrical tapered cladding material portions **335'** of the second cladding material layer **335** and the first cylindrical

tapered cladding material portions **333'** of the first cladding material layer **333** remain after the mask open etch step. Specifically, a nested stack of a first cylindrical tapered cladding material portion **333'** and a second cylindrical tapered cladding material portion **335'** can be located on a sidewall of each opening **449** through the patterning film **331**.

(499) Referring to FIG. **62D**, a main etch process can be performed, which anisotropically etches portions of the at least one underlying material layer that underlie the discrete opening in the patterning film **331**. The main etch process comprises an anisotropic etch process, such as a reactive ion etch process. The combination of the patterning film **331**, the second cylindrical tapered cladding material portions **335'**, and the first cylindrical tapered cladding material portion **333'** can be employed as an etch mask during the anisotropic etch process.

(500) In one embodiment, the patterning film **331** has a higher average collateral etch rate than the second cylindrical tapered cladding material portions **335'** and the first cylindrical tapered cladding material portions **333'** during the main etch process. Thus, the top surface of the patterning film **331** becomes lower than the top surfaces of the second cylindrical tapered cladding material portions **335'** and the first cylindrical tapered cladding material portions **333'** by a greater vertical offset distance as the main etch process progresses. The top surface of the patterning film **331** is a concave top surface **331C** that functions as the above described ion trap. The ion trap prevents or reduces lateral deflection of the ions used during the reactive ion etch process into the via cavities **149**, as described above.

(501) In one embodiment, the main etch process comprises a reactive ion etch process in which a collateral etch rate of the patterning film **331** is limited by a flux of etchant ions. In this case, impinging ions of the reactive ion etch process have a finite angular spread in the impinging direction. Thus, points on the concave top surface **331C** of the patterning film **331** that are distal from adjacent openings **449** in the patterning film **331**, such as the point A illustrated in FIG. **62D**, are bombarded with more ions during the reactive ion etch process than points on the top surface of the patterning film **331** that are partially shielded from the impinging ions on one side, such as the point B illustrated in FIG. **62D**. The geometrical shielding effect causes the concave top surface **331C** of the patterning film **331** to develop concave surface profiles as the reactive ion etch process progresses.

(502) In one embodiment, the etch rate of the peripheral portion of the etch mask (**331**, **333'**, **335'**) is lower than the etch rate of the central portion of the etch mask (**331**, **333'**, **335'**) during the main etch. For example, the materials of the first and second cylindrical tapered cladding material portions (**333'**, **335'**) may have a lower etch rate than the carbon based material of the patterning film **331** during the main etch to form the concave top surface **331C** of the ion trap.

(503) Referring to FIG. **62E**, the at least one underlying material layer can be etched through as the main etch process progresses. In one embodiment, the at least one underlying material layer comprises an alternating stack of first insulating layers **132** and first sacrificial material layers **142**, or an alternating stack of insulating layers **32** and sacrificial material layers **42**. In this case, the alternating stack may be etched through during the anisotropic etch process.

(504) In one embodiment, a collateral etch rate of the first cladding material of the first cylindrical tapered cladding material portions **333'** during the main etch process is higher than a collateral etch rate of the second cladding material of the second cylindrical tapered cladding material portions **335'** during the main etch process. In one embodiment, a top surface **331C** of the patterning film **331** is vertically recessed below a top surface of the first cylindrical tapered cladding material portions **333'** such that a region of the top surface **331C** of the patterning film **331** that is proximal to a most proximal one of the first cylindrical tapered cladding material portions **333'** has a concave surface profile in a terminal portion of the reactive ion etch process. In one embodiment, the top surfaces of the second cylindrical tapered cladding material portion **335'** may be more distal from the substrate **8** (i.e., protrude upward higher) than the top surfaces of the first cylindrical tapered cladding material portions **333'** in the terminal portion of the reactive ion etch process.

(505) Referring to FIG. **62F**, in case the at least one underlying material layer comprises an in-process source-level material layers **110'**, via openings (such as first-tier memory openings **149** or memory openings **49**) may be vertically extended into the in-process source-level material layers **110'**.

(506) Referring to FIG. **62G**, remaining portions of the patterning film **331**, the first cylindrical tapered cladding material portions **333'**, and the second cladding material of the second cylindrical tapered cladding material portions **335'** can be removed. For example, an ashing process can be performed to remove the patterning film **331**, which lifts off and remove the remaining cladding material portions (**333'**, **335'**).

(507) Subsequently, various processing steps described above with reference to the first or second exemplary structure may be performed. For example, a memory opening fill structure may be formed in each via opening that is formed through the alternating stack by the main etch process. Each of the memory opening fill structures may comprise a respective vertical semiconductor channel **60** and a respective vertical stack of memory elements.

(508) In one embodiment, the at least one underlying material layer comprises an alternating stack of first material layers and second material layers. In one embodiment, the first material layers comprise insulating layers (**132**, **32**), and the second material layers are formed as, or are subsequently replaced with, electrically conductive layers (**146**, **46**).

(509) The embodiment ion traps can be employed to form via openings with reduced bowing and/or reduced widening of the top portion of the via openings. Vertical cross-sectional profiles of the via openings can be improved, such that memory opening fill structures with enhanced performance and/or with increased process yield are formed in the via openings.

(510) FIGS. **63A-63N** are sequential vertical cross-sectional views of a region of a memory opening in a fifth exemplary structure during formation of etch stop structures according to a fifth embodiment of the present disclosure.

(511) Referring to FIG. **63A**, a fifth exemplary structure according to the fifth embodiment of the present disclosure is illustrated, which can be derived from the second exemplary structure illustrated in FIGS. **23A-23C** by performing an anisotropic etch process that transfers the pattern of the openings in the patterning film **331** through a subset of layers within an underlying stack of first material layers (such as the first insulating layers **132**) and second material layers (such as the first sacrificial material layers **142**). An in-process via opening is formed underneath each opening through the patterning film **331**. The photoresist layer **337** may be removed selective to the patterning film **331** prior to the anisotropic etch process or after the anisotropic etch process, or may be collaterally consumed during the anisotropic etch process. In case the underlying layers comprise an alternating stack of first insulating layers **132** and first sacrificial material layers **142**, a first insulating cap layer **170** and an inter-tier dielectric layer **180**, a first-tier memory opening **149** can be formed underneath an opening in the patterning film **331**. In one embodiment, the chemistry of the anisotropic etch process can be selected such that the inter-tier dielectric layer **180**, the first insulating cap layer **170**, and a subset of the first insulating layers **132** and the first sacrificial material layers **142** located in an upper portion of the alternating stack (**132**, **142**) are etched by the anisotropic etch process. The duration of the anisotropic etch process can be selected such that the aspect ratio of the in-process via opening (i.e., the ratio of the depth of the in-process via opening to the maximum width of the in-process via opening) underneath the horizontal plane including the bottom surface of the patterning film **331** is in a range from 3 to 20, such as from 5 to 10. The aspect ratio is selected such that the thickness of materials to be subsequently collaterally deposited by anisotropic deposition processes is insignificant compared to the vertical thickness of top portions of the deposited material to be formed over the patterning film **331**.

(512) Generally speaking, an alternating stack of first material layers (such as the first insulating layers **132**) and second material layers (such as the first sacrificial material layers **142**) over a substrate **8**. A mask layer (such as a patterning film **331**) can be formed over the alternating stack

(132, 142). At least one opening, such as a plurality of openings, can be formed in the mask layer (such as the patterning film 331). An in-process via opening (such as a first-tier memory opening 149) through a subset of layers within the alternating stack (132, 142) can be formed by performing an anisotropic etch process employing the mask layer (such as the patterning film 331) as an etch mask after formation of the opening in the mask layer (such as the patterning film 331). The ratio of the number of layers of the alternating stack (132, 142) that are etched through by the in-process via opening to the total number of layers within the alternating stack (132, 142) may be in a range from 0.01 to 0.3, such as from 0.02 to 0.2, and/or from 0.04 to 0.1, although lesser and greater ratios may also be employed.

(513) Referring to FIG. 63B, a first etch mask material layer 533A can be formed after formation of the in-process via opening (such as a first-tier memory opening 149) over the mask layer (such as the patterning film 331). In one embodiment, the first etch mask material layer 533A can be formed by anisotropically depositing a first etch mask material. In one embodiment, the first etch mask material is deposited by performing at least one physical vapor deposition process, and/or at least one plasma-enhanced chemical vapor deposition process.

(514) In one embodiment, the first etch mask material may be selected from carbon-based materials comprising carbon atoms at a respective atomic percentage that is greater than 50%, silicon carbide, elemental metal, intermetallic alloy, metallic nitride material, dielectric metal oxide material, or a layer stack of any of the above. In one embodiment, the first etch mask material comprises a carbon-based material including carbon atoms at an atomic percentage greater than 95%, such as diamond-like carbon. In one embodiment, the first etch mask material comprises at least one metal selected from tungsten, ruthenium, tantalum, titanium, molybdenum, niobium, rhenium, osmium, iridium, platinum, or rhodium. In one embodiment, the first etch mask material comprises a dielectric metal oxide material or silicon carbide.

(515) The vertical thickness of the first etch mask material layer 533A after the anisotropic deposition process may be in a range from 200 nm to 500 nm, such as from 300 nm to 400 nm, although lesser and greater thicknesses may also be employed.

(516) Referring to FIG. 63C, an isotropic etch back process that etches the first etch mask material selective to materials of the patterning film 331 and the materials of the underlying alternating stack (132, 142) can be performed. The isotropic etch back process can be an isotropic wet etch process. Generally, the duration of the isotropic etch back process can be selected such that the isotropic recess distance for the first etch mask material is greater than the maximum lateral thickness of the first etch mask material below a first horizontal plane HP1 including the top surface of the patterning film 331. In one embodiment, the first etch mask material layer 533A can be formed entirely above a first horizontal plane including a top surface of the mask layer (such as the patterning film 331). In one embodiment, a peripheral planar surface segment of the mask layer may be physically exposed around one, a plurality or each of the openings in the first etch mask material layer 533A. In one embodiment, the area of the bottom surface of the first etch mask material layer 533A may be less than the area of the top surface of the mask layer 331.

(517) The vertical thickness of the horizontally-extending portion of the first etch mask material after the isotropic etch back process may be in a range from 100 nm to 400 nm, such as from 200 nm to 300 nm, although lesser and greater thicknesses may also be employed.

(518) Referring to FIG. 63D, a first cladding liner 535A comprising a first cladding material can be formed on a top surface of the first etch material layer 533A and on a sidewall of the first etch mask material layer 533A. In one embodiment, the first cladding liner 535A may be formed by anisotropically depositing the first cladding material over the first etch mask material layer 533A. In one embodiment, the first cladding material may be different from the first etch mask material. For example, the first cladding material may comprise doped carbon, elemental metal, intermetallic alloy, metallic nitride material, or dielectric metal oxide material. In one embodiment, the first etch mask material comprises carbon doped with a metal, such as tungsten and/or ruthenium doped

carbon. In one embodiment, the first etch mask material comprises at least one metal selected from tungsten, ruthenium, tantalum, titanium, molybdenum, niobium, rhenium, osmium, iridium, platinum, or rhodium. In one embodiment, the first etch mask material comprises an intermetallic alloy, such as a metal silicide, for example titanium silicide, tungsten silicide, molybdenum silicide or nickel silicide.

(519) Referring to FIG. 63E, the first cladding material is isotropically recessed (e.g., isotropically etched) to reduce the area of the sidewalls of the mask layer (such as the patterning film 331) that is masked by the first cladding material. For example, the first cladding liner 535A can be removed from the sidewalls of the patterning film 331, such that the first cladding liner 535A remains only on the first etch mask material layer 533A.

(520) In an alternative embodiment, the processing steps described with reference to FIGS. 63D and 63E can be replaced with a selective material deposition process that grows the first cladding material from physically exposed surfaces of the first etch mask material layer 533A while suppressing growth of the first cladding material from physically exposed surfaces of the mask layer (such as the patterning film 331).

(521) In some embodiments, a vertically-extending portion of the first cladding liner 535A may have a variable lateral width that increases with a vertical distance from a topmost surface of the alternating stack (132, 142).

(522) Generally, the first cladding material and the first etch mask material are selected such that the first cladding material provides a higher etch resistance to the etch chemistry of an anisotropic etch process to be subsequently employed than the etch resistance that the first etch mask material provides to the etch chemistry of the anisotropic etch process. In case the first cladding material is anisotropically deposited and isotropically recessed, the etch chemistry of the isotropic etch process is selected to minimize collateral etching of the first etch mask material and the material of the etch mask (such as the patterning film 331). In case the first cladding material is grown employing a selective material deposition process, the first cladding material can be selectively grown from physically exposed surfaces of the first etch mask material while suppressing growth from the physically exposed surfaces of the mask layer (such as the patterning film 331) and the materials of the underlying layers (such as the first insulating layers 132 and the first sacrificial material layers 142). In one embodiment, the first etch mask material layer 533A comprises undoped diamond-like carbon and the first cladding liner 535A comprises metal doped carbon or a metal or a metal silicide.

(523) The vertical thickness of the horizontally-extending portion of the first cladding liner 535A may be less than the vertical thickness of the first etch mask material layer 533A. In one embodiment, the vertical thickness of the horizontally-extending portion of the first cladding liner 535A after an isotropic recess etch process or after a selective deposition process may be in a range from 5 nm to 100 nm, such as from 20 nm to 50 nm, although lesser and greater thicknesses may also be employed.

(524) Generally, a combination of a first etch mask material layer 533A and a first cladding liner 535A can be formed over the mask layer (such as the patterning film 331). The combination has a pattern that replicates a pattern in the mask layer.

(525) Referring to FIG. 63F, the processing steps described with reference to FIG. 63B may be performed again to form a second etch mask material layer 533B including a second etch mask material. The second etch mask material can be selected from any of the materials that may be employed for the first etch mask material. Generally, the second etch mask material layer 533B may comprise the same material as the first etch mask material layer 533A, or may comprise a different material than the first etch mask material layer 533A.

(526) Referring to FIG. 63G, the processing steps described with reference to FIG. 63C may be performed to isotropically recess the second etch mask material.

(527) Generally, the second etch mask material layer 533B can be formed by anisotropically

depositing a second etch mask material and isotropically recessing the second etch mask material. In one embodiment, the second etch mask material layer **533B** is formed entirely above a second horizontal plane **HP2** including a top surface of the first cladding liner **535A**.

(528) Referring to FIG. **63H**, the processing steps described with reference to FIG. **63D** can be performed to form a second cladding material layer **535B** including a second cladding material. The second cladding material can be selected from any of the materials that may be employed for the second etch mask material. In one embodiment, the second cladding liner **535B** may be formed by anisotropically depositing the second cladding material over the second etch mask material layer **533B**. The second cladding material may be the same as the first cladding material, or may be different from the first cladding material.

(529) Referring to FIG. **63I**, the second cladding material is isotropically recessed to reduce the area of the sidewalls of the first etch mask material layer **533A** that is masked by the second cladding material.

(530) In an alternative embodiment, the processing steps described with reference to FIGS. **63H** and **63I** can be replaced with a selective material deposition process that grows the second cladding material from physically exposed surfaces of the second etch mask material layer **533B** while suppressing growth of the second cladding material from physically exposed surfaces of the mask layer (such as the patterning film **331**). The second cladding material may or may not grow from physically exposed surfaces of the first etch mask material layer **533A**.

(531) In some embodiments, a vertically-extending portion of the second cladding liner **535B** may have a variable lateral width that increases with a vertical distance from a topmost surface of the alternating stack (**132**, **142**).

(532) The second cladding material and the second etch mask material are selected such that the second cladding material provides a higher etch resistance to the etch chemistry of an anisotropic etch process to be subsequently employed than the etch resistance that the second etch mask material provides to the etch chemistry of the anisotropic etch process.

(533) Generally, a combination of a second etch mask material layer **533B** and a second cladding liner **535B** can be formed over the first cladding liner **535A**. The combination has a pattern that replicates the pattern of the first cladding liner **535A**, which replicates a pattern in the mask layer.

(534) Referring to FIG. **63J**, the processing steps described with reference to FIG. **63B** may be optionally be performed again to form an optional third etch mask material layer **533C** including a third etch mask material. The third etch mask material can be selected from any of the materials that may be employed for the first etch mask material. Generally, the third etch mask material layer **533C** may comprise the same material as or different material than the first etch mask material layer **533A** and/or the second etch mask material layer **533B**.

(535) Referring to FIG. **63K**, the processing steps described with reference to FIG. **63C** may optionally be performed to isotropically recess the third etch mask material.

(536) Generally, the third etch mask material layer **533C** can be formed by anisotropically depositing a third etch mask material and isotropically recessing the third etch mask material. In one embodiment, the third etch mask material layer **533C** is formed entirely above a third horizontal plane **HP3** including a top surface of the second cladding liner **535B**.

(537) Referring to FIG. **63L**, the processing steps described with reference to FIG. **63D** can optionally be performed to form a third cladding material layer **535C** including a third cladding material. The third cladding material can be selected from any of the materials that may be employed for the third etch mask material. In one embodiment, the third cladding liner **535C** may be formed by anisotropically depositing the third cladding material over the third etch mask material layer **533C**. The third cladding material may be the same as or may be different from the first cladding material and/or the second cladding material.

(538) Referring to FIG. **63M**, the third cladding material is isotropically recessed to reduce the area of the sidewalls of the second etch mask material layer **533B** that is masked by the third cladding

material.

(539) In an alternative embodiment, the processing steps described with reference to FIGS. **63L** and **63M** can be replaced with a selective material deposition process that grows the third cladding material from physically exposed surfaces of the third etch mask material layer **533C** while suppressing growth of the third cladding material from physically exposed surfaces of the mask layer (such as the patterning film **331**). The third cladding material may, or may not, grow from physically exposed surfaces of the first etch mask material layer **533A** and/or from physically exposed surfaces of the second etch mask material layer **533B**.

(540) In some embodiments, a vertically-extending portion of the third cladding liner **535C** may have a variable lateral width that increases with a vertical distance from a topmost surface of the alternating stack (**132**, **142**).

(541) The third cladding material and the third etch mask material are selected such that the third cladding material provides a higher etch resistance to the etch chemistry of an anisotropic etch process to be subsequently employed than the etch resistance that the third etch mask material provides to the etch chemistry of the anisotropic etch process.

(542) Generally, a combination of a third etch mask material layer **533C** and a third cladding liner **535C** can be formed over the second cladding liner **535B**. The combination has a pattern that replicates the pattern of the second cladding liner **535B**, which replicates a pattern in the mask layer.

(543) While an embodiment is described in which a stack of the etch mask material layers (**533A**, **533B**, **533C**) and the cladding liners (**535A**, **535B**, **535C**) comprises three etch mask material layers and three cladding liners, embodiments are expressly contemplated herein in which the total number of etch mask material layers and cladding liners is 2 or more than 3, such as 4, 5, etc.

(544) Referring to FIG. **63N**, an optional sacrificial liner **339** may be optionally deposited over the stack of the etch mask material layers (**533A**, **533B**, **533C**) and the cladding liners (**535A**, **535B**, **535C**) and on sidewalls of each in-process via opening (such as each of the first-tier memory openings **149**). The sacrificial liner **339** can be deposited by a conformal deposition process, such as a low pressure chemical vapor deposition process. The sacrificial liner **339** may comprise a sacrificial material such as a metal (e.g., ruthenium or tungsten), silicon oxide, silicon nitride, silicon carbide, or a dielectric metal oxide. The thickness of the sacrificial liner **339** may be in a range from 1 nm to 10 nm, such as from 2 nm to 5 nm, although lesser and greater thicknesses may also be employed.

(545) FIG. **63O** is a vertical cross-sectional views of a region of a memory opening in a first alternative configuration of the fifth exemplary structure according to the first alternative configuration of the fifth embodiment of the present disclosure. The structure of FIG. **63O** may be derived from the fifth exemplary structure shown in FIG. **63M** by omitting the patterning layer **331**. In this first alternative configuration, the first etch mask material layer **533A** may be formed directly on the inter-tier dielectric layer **180**.

(546) FIG. **63P** is a vertical cross-sectional views of a region of a memory opening in a second alternative configuration of the fifth exemplary structure according to the second alternative configuration of the fifth embodiment of the present disclosure. The structure of FIG. **63P** may be derived from the fifth exemplary structure shown in FIG. **63N** by omitting the patterning layer **331**. In this alternative configuration, the first etch mask material layer **533A** may be formed directly on the inter-tier dielectric layer **180**.

(547) FIGS. **64A-64E** are sequential vertical cross-sectional view of a region of a memory opening in the fifth exemplary structure during an anisotropic etch process that forms memory openings according to the fifth embodiment of the present disclosure.

(548) Referring to FIG. **64A**, the anisotropic etch process may comprise an optional anisotropic line etch step which anisotropically etches horizontally-extending portions of the sacrificial liner **339**. Horizontally-extending portions of the sacrificial liner **339** may be fully removed from above



the topmost cladding liner (such as the third cladding liner 535C), and partially or fully removed from bottom portions of the in-process via openings (such as the first-tier memory openings 149). (549) Referring to FIG. 64B, the anisotropic etch process may comprise a main etch step, i.e., a main etch process. The anisotropic etch process vertically extends the in-process via openings, and forms via openings (such as first-tier memory openings 149) that vertically extend through the first-tier alternating stack (132, 142). The main etch process anisotropically etches portions of the at least one underlying material layer that underlie the discrete opening in the stack of the etch mask material layers (533A, 533B, 533C) and the cladding liners (535A, 535B, 535C) and in the mask layer (such as the patterning film 331). The main etch process comprises an anisotropic etch process, such as a reactive ion etch process. The combination of the stack of the etch mask material layers (533A, 533B, 533C) and the cladding liners (535A, 535B, 535C) and the optional mask layer (such as the patterning film 331, if present) can be employed as a composite etch mask structure during the anisotropic etch process.

(550) The materials of the etch mask material layers (533A, 533B, 533C) and the cladding liners (535A, 535B, 535C) are collaterally consumed during the various steps of the anisotropic etch process. The anisotropic etch process may comprise a first step in which materials of the first-tier alternating stack (132, 142) are removed selective to the third etch mask material and the third cladding material, a second step in which materials of the first-tier alternating stack (132, 142) are removed selective to the second etch mask material and the second cladding material, a third step in which materials of the first-tier alternating stack (132, 142) are removed selective to the first etch mask material and the first cladding material, and an optional fourth step in which materials of the first-tier alternating stack (132, 142) and/or any underlying material layers (such as the in-process source-level material layers 110') are removed selective to the material of the mask layer (such as the patterning film 331).

(551) In one embodiment, the first step of the anisotropic etch process collaterally removes a horizontally-extending portion of the third cladding liner 535C while leaving the vertically-extending portions of the third cladding liner 535C surrounding the exposed top surface of third etch mask material layer 533C. In one embodiment, the first step of the anisotropic etch process may have an etch chemistry that provides a higher etch selectivity for the third etch mask material relative to the third cladding material. In other words, the third etch mask material is etched at a greater rate than the third cladding material. The anisotropic etch process proceeds to collaterally vertically recesses the exposed third etch mask material layer 533C at a greater rate than the vertically-extending portion of the third cladding liner 535C. Therefore, the vertically-extending portion of the third cladding liner 535C protrudes above a top surface of a remaining portion of the third etch mask material layer 533C. In one embodiment, the top surface of the remaining portion of the third etch mask material layer 533C develops a concave vertical cross-sectional profile, and is adjoined to an inner sidewall of the vertically-extending portion of the third cladding liner 535C.

(552) Typically, impinging ions of a reactive ion etch process have a finite angular spread in the impinging direction. Upon development of a concave surface profile in the third etch mask material layer 533C, points on the concave top surface of the third etch mask material layer 533C that are distal from a neighboring vertically protruding portion of the third cladding liner 535C, such as the point A illustrated in FIG. 64B, are bombarded with more ions during the reactive ion etch process than points on the concave top surface of the third etch mask material layer 533C that are partially shielded from the impinging ions on one side, such as the point B illustrated in FIG. 64B. The combination of a higher erosion rate of the third etch mask material than the third cladding material and the geometrical shielding effect causes the top surface of the third etch mask material layer 535 to develop a concave surface profiles as the first step of the reactive ion etch process progresses. Ions that impinge on the concave top surface of the third etch mask material layer 533C during a latter portion of the first step of the anisotropic etch process are trapped between vertically protruding portions of the third cladding liner 535C, and scattering of the impinging ions from

above the third etch mask material layer **533C** into the via openings (such as the first-tier memory openings **149**) can be reduced or eliminated.

(553) The concave surface at point A has a middle portion located closer to the alternating stack than a peripheral portion at point B. The concave surface acts as an ion trap which traps the ions used during the reaction ion etching. The ion trap prevents or reduces the trapped ions from being deflected sideways by the etch mask onto the sidewalls of the via openings **149**.

(554) Referring to FIG. **64C**, as the first step of the anisotropic etch process progresses, the third etch mask material layer **533C** can be consumed. The second cladding liner **535B** and a remaining portion of the third cladding liner **535C** can be employed as etch mask structures during a second step of the anisotropic etch process that follows the first step of the anisotropic etch process. The second step of the anisotropic etch process may have the same etch chemistry as or different etch chemistry than the first step of the anisotropic etch process.

(555) In one embodiment, the second step of the anisotropic etch process collaterally removes a horizontally-extending portion of the second cladding liner **535B** while leaving the vertically-extending portions of the second cladding liner **535B** surrounding the exposed top surface of second etch mask material layer **533B**. In one embodiment, the second step of the anisotropic etch process may have an etch chemistry that provides a higher etch selectivity for the second etch mask material relative to the second cladding material. The anisotropic etch process proceeds to collaterally vertically recesses the exposed second etch mask material layer **533B** at a greater rate than the vertically-extending portion of the second cladding liner **535B** to form the concave upper surface in the second etch mask material layer **533B**. Thus, the second etch mask material layer **533B** continues to act as an ion trap even after the third etch mask material layer **533C** is completely removed.

(556) Referring to FIG. **64D**, as the second step of the anisotropic etch process progresses, the second etch mask material layer **533B** can be consumed. The first cladding liner **535A** and a remaining portion of the second cladding liner **535B** can be employed as etch mask structures during a third step of the anisotropic etch process that follows the second step of the anisotropic etch process. The third step of the anisotropic etch process may have the same etch chemistry or a different etch chemistry than the second step of the anisotropic etch process.

(557) In one embodiment, the third step of the anisotropic etch process collaterally removes a horizontally-extending portion of the first cladding liner **535A** while leaving the vertically-extending portions of the first cladding liner **535A** surrounding the exposed top surface of first etch mask material layer **533A**. In one embodiment, the third step of the anisotropic etch process may have an etch chemistry that provides a higher etch selectivity for the first etch mask material relative to the first cladding material. The anisotropic etch process proceeds to collaterally vertically recesses the exposed first etch mask material layer **533A** at a greater rate than the vertically-extending portion of the first cladding liner **535A** to form the concave upper surface in the first etch mask material layer **533A**. Thus, the first etch mask material layer **533A** continues to act as an ion trap even after the second and third etch mask material layers (**533B** and **533C**) are completely removed. Therefore, by forming plural etch mask material layers and respective plural cladding liners, the composite etch mask structure can function as an ion trap for a longer period of time than if a single etch mask material layer and a single cladding liner is used.

(558) Generally, via openings (such as first-tier memory openings **149**) can be formed through the entirety of an alternating stack of first material layers (such as the first insulating layers **132**) and second material layers (such as the first sacrificial material layers **142**) by vertically extending the in-process via openings (such as first-tier memory opening **149**) employing an anisotropic etch process after formation of the composite etch mask structure.

(559) In a non-limiting illustrative example, the first material layers (such as the first insulating layers **132**) comprise silicon oxide layers, the second material layers (such as the first sacrificial material layers **142**) comprise silicon nitride layers, and the anisotropic etch process comprises at

least one reactive ion etch step that employs at least one of O.sub.2, N.sub.2O, H.sub.2, CO.sub.2, and NH.sub.3.

(560) Although the foregoing refers to particular preferred embodiments, it will be understood that the disclosure is not so limited. It will occur to those of ordinary skill in the art that various modifications may be made to the disclosed embodiments and that such modifications are intended to be within the scope of the disclosure. Compatibility is presumed among all embodiments that are not alternatives of one another. The word “comprise” or “include” contemplates all embodiments in which the word “consist essentially of” or the word “consists of” replaces the word “comprise” or “include,” unless explicitly stated otherwise. Where an embodiment employing a particular structure and/or configuration is illustrated in the present disclosure, it is understood that the present disclosure may be practiced with any other compatible structures and/or configurations that are functionally equivalent provided that such substitutions are not explicitly forbidden or otherwise known to be impossible to one of ordinary skill in the art. All of the publications, patent applications and patents cited herein are incorporated herein by reference in their entirety.

## Claims

1. A method of forming a structure, comprising: forming an alternating stack of first material layers and second material layers over a substrate; forming a first etch mask material layer comprising a first etch mask material over the alternating stack; forming a first cladding liner comprising a first cladding material on a top surface of the first etch mask material layer and on a sidewall of the first etch mask material layer; and forming a via opening through the alternating stack by performing an anisotropic etch process that employs a combination of at least the first cladding liner and the first etch mask material layer; wherein: the anisotropic etch process comprises a first anisotropic etch step that etches materials of the alternating stack selective to the first etch mask material and the first cladding material; the first anisotropic etch step collaterally removes a horizontally-extending portion of the first cladding liner and collaterally vertically recesses the first etch mask material layer such that a vertically-extending portion of the first cladding liner protrudes above a top surface of a remaining portion of the first etch mask material layer during the first anisotropic etch step; and the top surface of the remaining portion of the first etch mask material layer has a concave vertical cross-sectional profile which functions as an ion trap during the first anisotropic etch step.
2. The method of claim 1, wherein the step of forming the first etch mask material layer comprises anisotropically depositing the first etch mask material and isotropically recessing the first etch mask material.
3. The method of claim 2, wherein the step of forming the first cladding liner comprises anisotropically depositing the first cladding material over the first etch mask material layer and isotropically recessing the first cladding material.
4. The method of claim 2, wherein the step of forming the first cladding liner comprises performing a selective material deposition process that grows the first cladding material from physically exposed surfaces of the first etch mask material layer.
5. The method of claim 1, further comprising: forming a mask layer over the alternating stack prior to forming the first etch mask material layer; and forming an opening in the mask layer.
6. The method of claim 5, wherein: the first etch mask material layer is located entirely above a first horizontal plane including a top surface of the mask layer; and the composite etch mask structure further comprises the mask layer.
7. The method of claim 1, wherein the first anisotropic etch step employs a first etch chemistry having a higher etch selectivity for the first etch mask material than for the first cladding material.
8. The method of claim 7, wherein the top surface of the remaining portion of the first etch mask material layer is adjoined to an inner sidewall of the vertically-extending portion of the first

cladding liner.

9. The method of claim 1, wherein a vertically-extending portion of the first cladding liner has a variable lateral width that increases with a vertical distance from a topmost surface of the alternating stack.

10. The method of claim 1, further comprising forming a combination of a second etch mask material layer and a second cladding liner over the first cladding liner, wherein the combination of the second etch mask layer and the second cladding liner has a pattern that replicates a pattern of the first cladding liner.

11. The method of claim 10, wherein: the second cladding liner comprises a same material as the first cladding liner; and the second etch mask material layer comprises a same material as the first etch mask material layer.

12. The method of claim 10, wherein: the second etch mask material layer is formed by anisotropically depositing a second etch mask material and isotropically recessing the second etch mask material; and the second cladding liner is formed by anisotropically depositing a second cladding material and isotropically recessing the second cladding material.

13. The method of claim 12, wherein the second etch mask material layer is formed entirely above a second horizontal plane including a top surface of the first cladding liner.

14. The method of claim 12, further comprising forming a combination of a third etch mask material layer and a third cladding liner over the second cladding liner, wherein the combination of the third etch mask layer and the third cladding liner has a pattern that replicates the pattern of the second cladding liner.

15. The method of claim 14, wherein: the third etch mask material layer is formed by anisotropically depositing a third etch mask material and isotropically recessing the third etch mask material; and the third cladding liner is formed by anisotropically depositing a third cladding material and isotropically recessing the second cladding material.

16. The method of claim 1, wherein each of the first etch mask material and the first cladding material is selected from: carbon-based material comprising carbon atoms at a respective atomic percentage that is greater than 50%; silicon carbide; elemental metal; intermetallic alloy; metallic nitride material; or dielectric metal oxide material.

17. The method of claim 1, wherein: the first etch mask material comprises a carbon-based material including carbon atoms at an atomic percentage greater than 95%; and the first cladding material comprises a metal doped carbon or a metal or a metal silicide.

18. The method of claim 5, further comprising forming an in-process via opening through a subset of layers within the alternating stack by performing an additional anisotropic etch process employing the mask layer after formation of the opening in the mask layer.

19. The method of claim 18, wherein: the first etch mask material layer is formed after formation of the in-process via opening; and the via opening is formed by vertically extending the in-process via opening using the anisotropic etch process that employs the combination of at least the mask layer, the first cladding liner and the first etch mask material layer.

20. The method of claim 19, wherein: the first material layers comprise silicon oxide layers; the second material layers comprise silicon nitride layers; and the anisotropic etch process comprises a reactive ion etch step that employs at least one of  $O_{2}$ ,  $N_{2}O$ ,  $H_{2}$ ,  $CO_{2}$ , or  $NH_{3}$ .

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