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Air spacer and capping structures in semiconductor devices

Abstract

A semiconductor device with air spacers and air caps and a method of fabricating the same are disclosed. The semiconductor device includes a substrate and a fin structure disposed on the substrate. The fin structure includes a first fin portion and a second fin portion. The semiconductor device further includes a source/drain (S/D) region disposed on the first fin portion, a contact structure disposed on the S/D region, a gate structure disposed on the second fin portion, an air spacer disposed between a sidewall of the gate structure and the contact structure, a cap seal disposed on the gate structure, and an air cap disposed between a top surface of the gate structure and the cap seal.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a divisional of U.S. patent application Ser. No. 17/006,167, titled “Air Spacer and Capping Structures in Semiconductor Devices,” filed Aug. 28, 2020, which claims the benefit of U.S. Provisional Patent Application No. 63/002,036, titled “Isolation Structures of Semiconductor Devices,” filed Mar. 30, 2020, each of which is incorporated by reference herein in its entirety.

BACKGROUND

(1) With advances in semiconductor technology, there has been increasing demand for higher storage capacity, faster processing systems, higher performance, and lower costs. To meet these demands, the semiconductor industry continues to scale down the dimensions of semiconductor devices, such as metal oxide semiconductor field effect transistors (MOSFETs), including planar MOSFETs and fin field effect transistors (finFETs). Such scaling down has increased the complexity of semiconductor manufacturing processes.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) Aspects of this disclosure are best understood from the following detailed description when read with the accompanying figures.

(2) FIG. 1A illustrates an isometric view a semiconductor device with air spacer and capping structures, in accordance with some embodiments.

(3) FIGS. 1B-1I illustrate cross-sectional views a semiconductor device with air spacer and capping structures, in accordance with some embodiments.

(4) FIG. 2 is a flow diagram of a method for fabricating a semiconductor device with air spacer and capping structures, in accordance with some embodiments.

(5) FIGS. 3A-18C illustrate top views and cross-sectional views of a semiconductor device with air spacer and capping structures at various stages of its fabrication process, in accordance with some embodiments.

(6) Illustrative embodiments will now be described with reference to the accompanying drawings. In the drawings, like reference numerals generally indicate identical, functionally similar, and/or structurally similar elements.

DETAILED DESCRIPTION

(7) The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the process for forming a first feature over a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. As used herein, the formation of a first feature on a second feature means the first feature is formed in direct contact with the second feature. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(8) Spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper,” and the like may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

(9) It is noted that references in the specification to “one embodiment,” “an embodiment,” “an example embodiment,” “exemplary,” etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases do not necessarily refer to the same embodiment. Further, when a particular feature, structure or characteristic is described in connection with an embodiment, it would be within the knowledge of one skilled in the art to effect such feature, structure or characteristic in connection with other embodiments whether or not explicitly described.

(10) It is to be understood that the phraseology or terminology herein is for the purpose of description and not of limitation, such that the terminology or phraseology of the present specification is to be interpreted by those skilled in relevant art(s) in light of the teachings herein.

(11) As used herein, the term “high-k” refers to a high dielectric constant. In the field of semiconductor device structures and manufacturing processes, high-k refers to a dielectric constant that is greater than the dielectric constant of SiO₂ (e.g., greater than 3.9).

(12) As used herein, the term “p-type” defines a structure, layer, and/or region as being doped with p-type dopants, such as boron.

(13) As used herein, the term “n-type” defines a structure, layer, and/or region as being doped with n-type dopants, such as phosphorus.

(14) As used herein, the term “nanostructured” defines a structure, layer, and/or region as having a horizontal dimension (e.g., along an X- and/or Y-axis) and/or a vertical dimension (e.g., along a Z-axis) less than, for example, 100 nm.

(15) In some embodiments, the terms “about” and “substantially” can indicate a value of a given quantity that varies within 5% of the value (e.g., $\pm 1\%$, $\pm 2\%$, $\pm 3\%$, $\pm 4\%$, $\pm 5\%$ of the value). These values are merely examples and are not intended to be limiting. The terms “about” and “substantially” can refer to a percentage of the values as interpreted by those skilled in relevant art(s) in light of the teachings herein.

(16) The fin structures disclosed herein may be patterned by any suitable method. For example, the fin structures may be patterned using one or more photolithography processes, including double-patterning or multi-patterning processes. Double-patterning or multi-patterning processes can combine photolithography and self-aligned processes, allowing patterns to be created that have, for example, pitches smaller than what is otherwise obtainable using a single, direct photolithography process. For example, a sacrificial layer is formed over a substrate and patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers may then be used to pattern the fin structures.

(17) The reliability and performance of semiconductor devices with FETs (e.g., finFETs or GAA FETs) have been negatively impacted by the scaling down of semiconductor devices. The scaling down has resulted in smaller electrical isolation regions (e.g., spacers and capping structures) between gate structures and source/drain (S/D) contact structures and/or between gate structures and interconnect structures. Such smaller electrical isolation regions may not adequately reduce parasitic capacitance between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures. Further, the smaller electrical isolation regions may not adequately prevent current leakage between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures, which can lead to degradation of the semiconductor device reliability and performance.

(18) The present disclosure provides example semiconductor devices with FETs (e.g., finFETs or GAA FETs) having air spacers and air caps and provides example methods of forming such semiconductor devices. In some embodiments, the air spacers can be disposed between the sidewalls of the gate structures and the S/D contact structures and can extend along the width of the gate structures. In some embodiments, the air caps can be disposed between the conductive structures (e.g., metal lines and/or metal vias) of the interconnect structures and the underlying top surfaces of the gate structures. The air spacers and air caps provide electrical isolation between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures with improved device reliability and performance. The low dielectric constant of air in air spacers and air caps can reduce the parasitic capacitance by about 20% to about 50% compared to semiconductor devices without air spacers and air caps. Further, the presence of air spacers and air caps minimizes current leakage paths between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures. Reducing the parasitic capacitance and/or current leakage in the semiconductor devices can improve the device reliability and performance compared to semiconductor devices without air spacers and air caps.

(19) A semiconductor device **100** having FETs **102A-102B** is described with reference to FIGS. **1A-1I**, according to some embodiments. FIG. **1A** illustrates an isometric view of semiconductor device **100**, according to some embodiments. FIG. **1B** and FIG. **1C** illustrate cross-sectional views

along respective lines A-A and B-B of semiconductor device **100** of FIG. **1A**, according to some embodiments. Semiconductor device **100** can have different cross-sectional views along line A-A of FIG. **1A** as illustrated in FIGS. **1B** and **1D-1I**, according to various embodiments. The discussion of elements in FIGS. **1A-1I** with the same annotations applies to each other, unless mentioned otherwise. The discussion of FET **102A** applies to FET **102B**, unless mentioned otherwise. FETs **102A-102B** can be n-type, p-type, or a combination thereof.

(20) Semiconductor device **100** can be formed on a substrate **106**. Substrate **106** can be a semiconductor material, such as silicon, germanium (Ge), silicon germanium (SiGe), silicon carbide (SiC), gallium arsenide (GaAs), gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), silicon germanium carbide (SiGeC), and a combination thereof. Further, substrate **106** can be doped with p-type dopants (e.g., boron, indium, aluminum, or gallium) or n-type dopants (e.g., phosphorus or arsenic).

(21) Referring to FIGS. **1A-1C**, FET **102A** can include (i) a fin structure **108** extending along an X-axis, (ii) a gate structure **112** extending along a Y-axis, (iii) epitaxial regions **110**, (iv) inner spacers **114** having first and second inner spacers **113A-113B**, (v) outer spacers **116**, (vi) air spacers **118**, (vii) air cap **120**, (viii) air spacer seals **122**, (ix) air cap seal **124**, (x) source/drain (S/D) contact structures **126**, (xi) S/D capping layer **128**, and (xii) via structure **130**. Fin structure **108** can include fin recessed regions **108A** underlying epitaxial regions **110** and a fin raised region **108B** underlying gate structure **112**. In some embodiments, fin structure **108** can include a material similar to substrate **106**.

(22) Epitaxial regions **110** can be grown on fin recessed regions **108A** and can be S/D regions of FET **102A**. Epitaxial regions **110** can include epitaxially-grown semiconductor material that can include the same material or a different material from the material of substrate **106**. Epitaxial regions **110** can be p- or n-type. In some embodiments, n-type epitaxial regions **110** can include SiAs, SiC, or SiCP and p-type epitaxial regions **110** can include SiGe, SiGeB, GeB, SiGeSnB, a III-V semiconductor compound, or a combination thereof.

(23) S/D contact structures **126** can be disposed on epitaxial regions **110** and can be configured to electrically connect epitaxial regions **110** to other elements of FET **102A** and/or of the integrated circuit (not shown) through via structure **130**. In some embodiments, via structure **130** can be disposed on one of S/D contact structures **126** and S/D capping layer **128** can be disposed on another of S/D contact structures **126**. S/D capping layer **128** can electrically isolate S/D contact structure **126** from other overlying elements of FET **102A**. Each of S/D contact structures **126** can include a S/D contact plug **126A** and a silicide layer **126B**. S/D contact plugs **130** can include conductive materials, such as ruthenium (Ru), iridium (Ir), nickel (Ni), Osmium (Os), rhodium (Rh), Al, molybdenum (Mo), tungsten (W), cobalt (Co), and copper (Cu). In some embodiments, via structure **130** can include conductive materials, such as Ru, Co, Ni, Al, Mo, W, Ir, Os, Cu, and Pt.

(24) In some embodiments, S/D capping layer **128** can include dielectric materials, such as silicon nitride (SiN), zirconium silicide (ZrSi), silicon carbon nitride (SiCN), zirconium aluminum oxide (ZrAlO), titanium oxide (TiO.sub.2), tantalum oxide (Ta.sub.2O.sub.5), zirconium oxide (ZrO.sub.2), lanthanum oxide (La.sub.2O.sub.3), zirconium nitride (ZrN), silicon carbide (SiC), zinc oxide (ZnO), silicon oxycarbide (SiOC), hafnium oxide (HfO.sub.2), aluminum oxide (Al.sub.2O.sub.3), silicon oxycarbonitride (SiOCN), Si, hafnium silicide (HfSi.sub.2), aluminum oxynitride (AlON), yttrium oxide (Y.sub.2O.sub.3), tantalum carbon nitride (TaCN), and silicon oxide (SiO.sub.2). In some embodiments, S/D capping layer **128** can have a thickness along a Z-axis in a range from about 1 nm to about 50 nm. Below this range of thickness, S/D capping layer **128** may not adequately provide electrical isolation between S/D contact structure **126** and other overlying elements of FET **102A**. On the other hand, if the thickness is greater than 50 nm, the processing time (e.g., deposition time, polishing time, etc.) of S/D capping layer increases, and consequently increases device manufacturing cost.

(25) Gate structure **112** can include a high-k gate dielectric layer **112A** and a conductive layer **112B** disposed on high-k gate dielectric layer **112A**. Conductive layer **112B** can be a multi-layered structure. The different layers of conductive layer **112B** are not shown for simplicity. Conductive layer **112B** can include a work function metal (WFM) layer disposed on high-k dielectric layer **112A**, and a gate metal fill layer on the WFM layer. High-k gate dielectric layer can include a high-k dielectric material, such as HfO_2 , TiO_2 , hafnium zirconium oxide (HfZrO), Ta_2O_3 , hafnium silicate (HfSiO_4), ZrO_2 , and zirconium silicate (ZrSiO_2). The WFM layer can include titanium aluminum (TiAl), titanium aluminum carbide (TiAlC), tantalum aluminum (TaAl), tantalum aluminum carbide (TaAlC), and a combination thereof. The gate metal fill layer can include a suitable conductive material, such as W, Ti, silver (Ag), Ru, Mo, Cu, Co, Al, Ir, Ni, and a combination thereof.

(26) Gate structure **112** can be electrically isolated from adjacent S/D contact structures **126** and/or via structure **130** by first inner spacers **113A**, outer spacers **116**, and air spacers **118**, as shown in FIG. **1B**. Further, gate structure **112** can be electrically isolated from adjacent epitaxial regions **110** by first and second inner spacers **113A-113B**, as shown in FIG. **1C**. In some embodiments, gate structure **112** can be further electrically isolated from overlying interconnect structures (e.g. metal line **142** as shown in FIG. **1H**) by air cap **120** and air cap seal **124**.

(27) Each of inner spacers **113A-113B**, outer spacers **116**, and air spacers **118** extends along the width of gate structure **112** along a Y-axis. First inner spacers **113A** can be disposed on and in physical contact with the sidewalls of gate structure **112** and outer spacers **116** can be disposed on first inner spacers **113A**. In some embodiments, outer spacers **116** can be disposed on and in physical contact with the sidewalls of gate structure **112** when inner spacers **113A-113B** are not included in FET **102A**. Air spacers **118** can be interposed between outer spacers and etch stop layers (ESLs) **134**, which are configured to protect gate structure **112** and/or epitaxial regions **110** during processing of FET **102A**.

(28) Air spacers **118** are cavities filled with air formed between outer spacers **116** and ESLs **134**. In some embodiments, the cavities of air spacers **118** can be sealed by air spacer seals **122**. Air spacer seals **122** can prevent materials from entering the cavities of air spacers **118** during the formation of layers overlying air spacers **118**. Similarly, air cap **120** is a cavity filled with air formed between gate structure **112** and air cap seal **124**. Air cap seal **124** can prevent materials from entering the cavity of air cap **120** during the formation of layers overlying air cap **120**. In some embodiments, air spacer seals **122** can extend into air cap **120** and can be suspended over gate structure **112**, as shown in FIGS. **1B-1C** or can be disposed on gate structure **112**, as shown in FIG. **1D**. The different configurations of air spacer seals **122** within air cap **120** can be used to adjust the volume of air cap **120**. In some embodiments, portions of air spacer seals **122** can be disposed on ESLs **134** and the top surfaces of these portions of air spacer seals **122** can be substantially coplanar with the top surfaces of S/D capping layer **128** and via structure **130**, as shown in FIGS. **1B-1D**. In some embodiments, these portions of air spacer seals **122** may be absent and the top surfaces of ESLs **134** is substantially coplanar with the top surfaces of S/D capping layer **128** and via structure **130**, as shown in FIG. **1E**.

(29) In some embodiments, S/D capping layer **128**, inner spacers **113A-113B**, outer spacers **116**, air spacer seals **122**, air cap seal **124**, and ESLs **134** can include an insulating material similar to or different from each other. In some embodiments, the insulating material can include SiN, ZrSi, SiCN, ZrAlO, TiO_2 , Ta_2O_5 , ZrO_2 , La_2O_3 , ZrN, SiC, ZnO, SiOC, (HfO_2 , Al_2O_3 , SiOCN, Si, HfSi_2 , AlON, Y_2O_3 , TaCN, SiO_3 , or a combination thereof. In some embodiments, each of first inner spacers **113A**, outer spacers **116**, and ESLs **134** can have a thickness along an X-axis substantially equal to or different from each other. In some embodiments, each of air spacers **118** can have a thickness along an X-axis equal to or greater than the thickness of each of first inner spacers **113A**, outer spacers **116**, and/or ESLs **134** along the X-axis. In some embodiments, each of air spacers **118** can have a thickness along an

X-axis twice the thickness of each of outer spacers **116** along the X-axis. The thickness of each of first inner spacers **113A**, outer spacers **116**, air spacers **118**, and ESLs **134** can range from about 1 nm to about 10 nm. In some embodiments, air spacers **118** can have a height along a Z-axis equal to or greater than a height of gate structure **112** along the Z-axis and the height of air spaces **118** can range from about 1 nm to about 50 nm.

(30) In some embodiments, the thickness of air spacer seals **122** disposed above air spacers **118** is substantially equal to the thickness of air spacers **118** along an X-axis. In some embodiments, the thickness of air spacer seals **122** disposed above ESLs **134** and within air cap **120** can be substantially equal to or greater than the thickness of ESLs **134** along an X-axis and can range from about 1 nm to about 15 nm. In some embodiments, air cap **120** can have a thickness T1 substantially equal to or smaller than thickness T2 of air cap seal **124**. Thickness T1 can range from about 1 nm to about 15 nm and thickness T2 can range from about 1 nm to about 25 nm.

(31) The above discussed dimension ranges of first inner spacers **113A**, outer spacers **116**, air spacers **118**, air cap **120**, air spacer seals **122**, air cap seal **124**, and/or ESLs **134** provide adequate electrical isolation between gate structure and adjacent epitaxial regions **110**, S/D contact structure **126**, via structure **130**, and/or interconnect structures ((e.g. metal line **142** as shown in FIG. 1H). Below the dimension ranges, first inner spacers **113A**, outer spacers **116**, air spacers **118**, air cap **120**, air spacer seals **122**, air cap seal **124**, and/or ESLs **134** may not adequately provide the electrical isolation to gate structure **112**. On the other hand, if the dimensions are higher than the above discussed ranges, the processing time (e.g., deposition time, etching time, etc.) for forming first inner spacers **113A**, outer spacers **116**, air spacers **118**, air cap **120**, air spacer seals **122**, air cap seal **124**, and/or ESLs **134** increases, and consequently increases device manufacturing cost.

(32) In some embodiments, air spacers **118**, air cap **120**, air spacer seals **122**, and air cap seal **124** can have the structures shown in FIG. 1F instead of the structures shown in FIG. 1B. FIG. 1F illustrates the region of FET **102A** within area **103A** of FIG. 1B for different configurations of air spacers **118**, air cap **120**, air spacer seals **122**, and air cap seal **124**. Air spacer seals **122** on ESLs **134** and air cap **120** can have rounded corners **122c** with a radius of curvature of about 0.5 nm to about 5 nm, which can be a result of the etching rate used during the formation of air spacer seals **122**, which is described in further detail below. Air spacer seals **122** surrounding air spacers **118** can have thicknesses T3 of about 0.5 nm to about 10 nm and seams **122s** with lengths of about 0.5 nm to about 5 nm, which can be a result of the deposition rate used during the formation of air spacer seals **122**, which is described in further detail below. The deposition rate used for forming air spacer seals **122** can also form “necks” **122n** with lengths of about 0.5 nm to about 5 nm along a Z-axis prior to forming seams **122s**. Similarly, the deposition rates used for forming air cap seal **124** can form “necks” **124n** with lengths of about 0.5 nm to about 5 nm along a Z-axis prior to forming seams **124s**, as shown in FIG. 1F.

(33) In some embodiments, FET **102A** can have nanostructured channel regions **138** with gate structure **112** surrounding each of nanostructured channel regions **138**, as shown in FIG. 1G, instead of raised fin region **108B** and gate structure **112** of FIGS. 1B-1F and 1H-1I. Such gate structure **112** can be referred to as “gate-all-around (GAA) structure **112**” and FET **102A** with GAA structure **112** can be referred to as “GAA FET **102A**.” Nanostructured channel regions **138** can include (i) an elementary semiconductor, such as Si or Ge; (ii) a compound semiconductor including a III-V semiconductor material; (iii) an alloy semiconductor including SiGe, germanium stannum, or silicon germanium stannum; or (iv) a combination thereof. The portions of gate structure **112** surrounding nanostructured channel regions **138** can be electrically isolated from adjacent epitaxial regions **110** by spacers **140**. Spacers **140** can include a material similar to outer spacers **116**.

(34) In some embodiments, the structure of FIG. 1B can have a metal line **142** of an interconnect structure, as shown in FIG. 1H when via structure **130** is present or can have a dielectric layer **144** of the interconnect structure, as shown in FIG. 1I when via structure **130** is not disposed on S/D

structure **126**.

(35) Semiconductor device **100** can further include interlayer dielectric (ILD) layer **132** and shallow trench isolation (STI) regions **136**. ILD layer **118** can be disposed on ESLs **134** and can include a dielectric material. STI regions **136** can include an insulating material.

(36) FIG. 2 is a flow diagram of an example method **200** for fabricating FET **102A** of semiconductor device **100**, according to some embodiments. For illustrative purposes, the operations illustrated in FIG. 2 will be described with reference to the example fabrication process for fabricating FET **102A** as illustrated in FIGS. 3A-18C. FIGS. 3A-18A are top views of FET **102A** at various stages of fabrication, according to some embodiments. FIGS. 3B-18B and 3C-18C are views of regions **103A-103B** of FIGS. 1B-1C at various stages of fabrication, according to some embodiments. Operations can be performed in a different order or not performed depending on specific applications. It should be noted that method **200** may not produce a complete FET **102A**. Accordingly, it is understood that additional processes can be provided before, during, and after method **200**, and that some other processes may only be briefly described herein. Elements in FIGS. 3A-18C with the same annotations as elements in FIGS. 1A-1I are described above.

(37) In operation **205**, a polysilicon structure and epitaxial regions are formed on a fin structure and inner spacers are formed on the polysilicon structure. For example, as shown in FIGS. 3A-3C, a polysilicon structure **312** and a hard mask layer **346** can be formed on fin structure **108**. During subsequent processing, polysilicon structure **312** can be replaced in a gate replacement process to form gate structure **112**. Following the formation of spacers **114** along the sidewalls of polysilicon structure **312**, epitaxial regions **110** can be selectively formed on recessed fin regions **108B**, as shown in FIG. 1B.

(38) Referring to FIG. 2, in operation **210**, outer spacers and sacrificial spacers are formed on the inner spacers. For example, as shown in FIGS. 5A-5C, outer spacers **116** and sacrificial spacers **518** can be formed on inner spacers **114**. The formation of outer spacers and sacrificial spacers can include sequential operations of (i) selectively etching portions of second inner spacers **113B** that are above fin structure **108**, as shown in FIGS. 4A-4C, (ii) selectively thinning down portions of first inner spacers **113A** that are above fin structure **108**, as shown in FIGS. 4A-4C, (iii) depositing and patterning outer spacers **116** on the structures of FIGS. 4A-4C, and (iv) depositing and patterning sacrificial spacers **518** on outer spacers **116** to form the structures of FIGS. 5A-5C. During subsequent processing, sacrificial spacers **518** are removed to form air spacers **118**. The patterning of outer spacers **116** and sacrificial spacers **518** can include a dry etching process with etchants, such as chlorine-based gas, oxygen, hydrogen, bromine-based gas, and a combination thereof. Sacrificial spacers **518** can include an insulating material different from the insulating material of first inner spacers **113A**, outer spacers **116**, S/D capping layers **128**, ILD layer **132**, and ESLs **134**. In some embodiments, portions of outer spacers on epitaxial regions **110** can have a thickness T_4 smaller than thickness T_5 of portions of outer spacers on first inner spacers **113A**. Thickness T_4 - T_5 can range from about 0.5 nm to about 10 nm.

(39) Referring to FIG. 2, in operation **215**, an ILD layer and ESLs are formed on the sacrificial spacers. For example, as shown in FIGS. 6A-6C, ILD layer **132** and ESLs **134** can be formed on outer spacers **116**. The formation of ILD layer **132** and ESLs **134** can include sequential operations of (i) depositing ESLs **134** on the structures of FIGS. 5A-5C using a chemical vapor deposition (CVD) process, (ii) depositing ILD layer **132** on ESLs **134** using a CVD process or a suitable dielectric material deposition process, and (iii) performing a chemical mechanical polishing (CMP) process to remove hard mask layer **346** and substantially coplanarize the top surfaces of polysilicon structure **312**, first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, ESLs **134**, and ILD layer **132** with each other, as shown in FIGS. 6A-6C.

(40) Referring to FIG. 2, in operation **220**, the polysilicon structure is replaced with a gate structure and a sacrificial cap is formed on the gate structure. For example, as shown in FIGS. 7A-7C, polysilicon structure **312** can be replaced with gate structure **112** and a sacrificial cap **720** can be

formed on gate structure **112**. The formation of gate structure **112** can include sequential operations of (i) etching polysilicon structure **312** to form a cavity (not shown), (ii) depositing high-k gate dielectric layer **112A** within the cavity using a CVD process, an atomic layer deposition (ALD) process, or a suitable high-k dielectric material deposition process, (iii) depositing conductive layer **112B** on high-k gate dielectric layer **112A** using a CVD process, an atomic layer deposition (ALD) process, or a suitable conductive material deposition process, (iv) performing a CMP process to substantially coplanarize the top surface of gate structure **112** with the top surfaces of polysilicon structure **312**, first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, ESLs **134**, and ILD layer **132**, and (v) etching back gate structure **112**, as shown in FIGS. 7B-7C. The etching back can include a dry etching process with etchants that have a higher etch selectivity for the materials of gate structure **112** than the materials of first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, and ESLs **134**. The etchants can include chlorine-based gas, methane (CH₄), boron chloride (BCl₃), oxygen, or a combination thereof.

(41) The formation of sacrificial cap **720** can include sequential operations of (i) etching back first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, and ESLs **134**, as shown in FIGS. 7B-7C, (ii) depositing the material of sacrificial cap **720** on ILD layer **132** and the etched back gate structure **112**, first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, and ESLs **134** using a CVD process or a suitable insulating material deposition process, and (iii) performing a CMP process to substantially coplanarize the top surface of sacrificial cap **720** with the top surface of ILD layer **132** to form the structures of FIGS. 7B-7C. The etching back can include a dry etching process with etchants that have a higher etch selectivity for the materials of first inner spacers **113A**, outer spacers **116**, sacrificial spacers **518**, and ESLs **134** than the materials of gate structure **112**. The etchants can include a hydrogen fluoride (HF) based gas, a carbon fluoride (C_xF_y) based gas, or a combination thereof.

(42) Referring to FIG. 2, in operation **225**, S/D contact structures are formed on the epitaxial regions. For example, as shown in FIGS. 8A-8C, S/D contact structures **126** can be formed on epitaxial regions **110**. The formation of S/D contact structures **126** can include sequential operations of (i) etching portions of ILD layer **132**, ESLs **134** outer spacers **116** and epitaxial regions **110** to form contact openings (not shown), (ii) forming silicide layers **126B** within the contact openings, as shown in FIGS. 8B-8C, (iii) filling the contact openings with the material(s) of S/D contact plugs **126B** using a CVD process or a suitable conductive material deposition process, (iv) performing a CMP process to substantially coplanarize the top surface of S/D contact plugs **126B** with the top surface of sacrificial cap **720** (not shown in FIGS. 8A-8C; shown in FIGS. 17A-17C), and (v) etching back S/D contact plugs **126B** to form S/D contact structures **126** shown in FIGS. 8B-8C. The etching back can include a dry etching process with etchants, such as chlorine-based gas, methane (CH₄), boron chloride (BCl₃), oxygen, and a combination thereof.

(43) S/D contact structures **126** of FIGS. 17A-17C are formed if S/D capping layers **128** and/or via structure **130** are not subsequently formed. On the other hand, S/D contact structures of FIGS. 8A-8C are formed if S/D capping layers **128** and via structure **130** are subsequently formed. The formation of S/D capping layers **128** and via structure **130** can include sequential operations of (i) depositing the material of S/D capping layers **128** on the etched back S/D contact plugs **126B** using a CVD process or a suitable insulating material deposition process, (ii) performing a CMP process to substantially coplanarize the top surface of S/D capping layers **128** with the top surface of sacrificial cap **720**, (iii) etching a portion of S/D capping layers **128** to form a via opening (not shown), (iv) depositing the material of via structure **130** within the via opening using a CVD process, an atomic layer deposition (ALD) process, or a suitable conductive material deposition process, and (v) performing a CMP process to substantially coplanarize the top surface of via structure **130** with the top surface of sacrificial cap **720**, as shown in FIGS. 8A-8C.

(44) Referring to FIG. 2, in operation **230**, air spacers are formed between the outer spacers and the ESLs. For example, as shown in FIGS. 10A-10C, air spacers **118** can be formed between outer

spacers **116** and the ESLs **134**. The formation of air spacers can include sequential operations of (i) etching back sacrificial cap **720**, as shown FIGS. **9A-9C** and (ii) removing sacrificial spacers **518**, as shown in FIGS. **10A-10C**. In some embodiments, the etching back of sacrificial cap **720** and the removal of sacrificial spacers **518** can include using a chemical etching process with similar etchants, such as chlorine-based gas, hydrogen, oxygen, fluorine-based gas, and a combination thereof, but with different concentrations of the etchants and at different etching temperatures. The etch selectivity of the etchants for the materials of sacrificial cap **720** and sacrificial spacers **518** are dependent on the etchant concentration and etching temperature. The etchants used for selectively etching sacrificial cap **720** have a lower hydrogen concentration than the etchants used for selectively removing sacrificial spacers **518**. In addition, the temperature (e.g., between about 30° C. and about 150° C.) used for selectively etching sacrificial cap **720** is lower than the temperature used for selectively removing sacrificial spacers **518**. In some embodiments, the removal of sacrificial spacers **518** can include using a chemical etching process with etchants, such as helium, hydrogen, oxygen, fluorine-based gas, and a combination thereof.

(45) Referring to FIG. **2**, in operation **235**, air spacer seals are formed on the air spacers, the sacrificial cap, and the ESLs. For example, as shown in FIGS. **12A-12C**, air spacer seals **122** can be formed on air spacers **118**, sacrificial cap **720**, and ESLs **134**. The formation of air spacer seals **122** can include sequential operations of (i) depositing the material of air spacer seals **122** on the structures of FIGS. **10A-10C** to form a sealing layer **122***, as shown in FIGS. **11A-11C** and (ii) etching sealing layer **122*** to form the structures of FIGS. **12A-12C**. In some embodiments, the deposition of sealing layer **122*** is performed at a deposition rate of about 1 nm/min to about 5 nm/min and at a deposition temperature of about 100° C. to about 400° C. to prevent any conformal deposition of the material of air spacer seals **122** within air spacers **118**. If the material of air spacer seals **122** is deposited at a deposition rate slower than about 1 nm/min and at a deposition temperature lower than about 100° C., air seals **122** may be formed within air spacers **118** as discussed above with reference to FIG. **1F**. In some embodiments, the etching of sealing layer **122*** can include an anisotropic dry etching process at a temperature of about 50° C. to about 100° C. with etchants, such as chlorine-based gas, fluorine-based gas, oxygen, and a combination thereof.

(46) Referring to FIG. **2**, in operation **240**, an air cap and an air cap seal are formed on the gate structure. For example, as shown in FIGS. **14A-14C**, air cap **120** and air cap seal **124** can be formed on gate structure **112**. The formation of air cap **120** can include removing sacrificial cap **720** to form the structures of FIGS. **13A-13C**. In some embodiments, the removal of sacrificial cap **720** can include using an isotropic chemical etching process with etchants, such as chlorine-based gas, hydrogen, oxygen, fluorine-based gas, and a combination thereof at an etching temperature of about 30° C. to about 150° C.

(47) The formation of air cap seal **124** can include sequential operations of (i) depositing the material of air cap seal **124** on the structures of FIGS. **12A-12C** and (ii) performing a CMP process to substantially coplanarize the top surface of air cap seal **124** with the top surface of ILD layer **132**, as shown in FIGS. **14A-14C**. Similar to the deposition of the material of air spacer seals **122**, the material of air cap seal **124** can be deposited at a deposition rate of about 1 nm/min to about 5 nm/min and at a deposition temperature of about 100° C. to about 400° C. to prevent any conformal deposition of the material within air cap **120**.

(48) In some embodiments, the structures of FIGS. **15A-15C** with the top surfaces of ESLs **134** substantially coplanar with the top surfaces of ILD layer **132** can be formed if ESLs **134** are not etched back during the formation of sacrificial cap **720** in operation **220**.

(49) In some embodiments, the structures of FIGS. **16A-16C** with cylindrical via structure **130** can be formed if cylindrical via openings are formed within S/D capping layer **128** during the formation of via structure **130** in operation **225**.

(50) In some embodiments, the structures of FIGS. **17A-17C** with the top surfaces of S/D contact plugs **126A** substantially coplanar with the top surfaces of ILD layer **132** and air cap seal **124** can

be formed if S/D capping layer **128** and via structure **130** are not formed in operation **225**.

(51) In some embodiments, the structures of FIGS. **18A-18C** with air spacer seals **122** disposed on gate structure **112** can be formed if sacrificial cap **720** is removed instead of etching back during the formation of air spacers **118** in operation **230**.

(52) The present disclosure provides example semiconductor devices (e.g., semiconductor device **100**) with FETs (e.g., FET **102A** or GAA FET **102A**) having air spacers (e.g., air spacers **118**) and air caps (e.g., air cap **120**) and provides example methods (e.g., method **200**) of forming such semiconductor devices. In some embodiments, the air spacers can be disposed between the sidewalls of gate structures (e.g., gate structure **112**) and S/D contact structures (e.g., S/D contact structures **126**) and can extend along the width of the gate structures. In some embodiments, the air caps can be disposed between the conductive structures (e.g., metal line **142**) of the interconnect structures and the underlying top surfaces of the gate structures. The air spacers and air caps provide electrical isolation between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures with improved device reliability and performance. The low dielectric constant of air in air spacers and air caps can reduce the parasitic capacitance by about 20% to about 50% compared to semiconductor devices without air spacers and air caps. Further, the presence of air spacers and air caps minimizes current leakage paths between the gate structures and the S/D contact structures and/or between the gate structures and the interconnect structures. Reducing the parasitic capacitance and/or current leakage in the semiconductor devices can improve the device reliability and performance compared to semiconductor devices without air spacers and air caps.

(53) In some embodiments, a semiconductor device includes a substrate and a fin structure disposed on the substrate. The fin structure includes a first fin portion and a second fin portion. The semiconductor device further includes a source/drain (S/D) region disposed on the first fin portion, a contact structure disposed on the S/D region, a gate structure disposed on the second fin portion, an air spacer disposed between a sidewall of the gate structure and the contact structure, a cap seal disposed on the gate structure, and an air cap disposed between a top surface of the gate structure and the cap seal.

(54) In some embodiments, a semiconductor device includes a substrate, a fin structure with first and second fin portions disposed on the substrate, a nanostructured channel region disposed on the first fin portion, a gate-all-around (GAA) structure surrounding the nanostructured channel region, a source/drain (S/D) region disposed on the second fin portion, an interlayer dielectric (ILD) layer disposed on the S/D region, an air spacer disposed between the gate structure and the ILD layer, a cap seal disposed on the gate structure, wherein top surfaces of the cap seal and the ILD layer are substantially coplanar with each other, and an air cap disposed between a top surface of the gate structure and the cap seal.

(55) In some embodiments, a method includes forming a polysilicon structure on a fin structure, forming an epitaxial region on the fin structure, replacing the polysilicon structure with a gate structure, forming a contact structure on the epitaxial region, forming an air spacer between the gate structure and the contact structure, forming a spacer seal on the air spacer, forming an air cap on the gate structure, and forming a cap seal on the air cap and the spacer seal.

(56) The foregoing disclosure outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A method, comprising: forming a polysilicon structure on a fin structure; forming a gate spacer along a sidewall of the polysilicon structure; forming an epitaxial region on the fin structure; replacing the polysilicon structure with a gate structure adjacent to the gate spacer; forming an air spacer between the gate structure and the gate spacer; forming a spacer seal on the air spacer; forming, on the gate structure, an air cap comprising etching the gate structure to expose a sidewall of the gate spacer; and forming a cap seal on the air cap and the spacer seal.
2. The method of claim 1, wherein forming the air spacer comprises: forming a sacrificial spacer along a sidewall of the polysilicon structure; and removing the sacrificial spacer after replacing the polysilicon structure.
3. The method of claim 2, wherein forming the air cap comprises: forming a sacrificial cap on the gate structure and the sacrificial spacer; and removing the sacrificial cap after forming the spacer seal.
4. The method of claim 1, wherein forming the air cap comprises: etching the gate structure to expose sidewalls of gate spacers adjacent to the gate structure; and depositing a sacrificial layer directly on the gate structure and along the sidewalls of the gate spacers.
5. The method of claim 1, wherein forming the air cap comprises: etching a top portion of the gate structure; forming a sacrificial cap on the gate structure; thinning down the sacrificial cap; and removing the thinned down sacrificial cap after forming the spacer seal.
6. The method of claim 1, wherein forming the spacer seal comprises forming a first seal portion on the air spacer and a second seal portion on the air cap.
7. The method of claim 1, wherein forming the spacer seal comprises forming a first seal portion on the air spacer and a second seal portion directly on the gate structure.
8. The method of claim 1, wherein forming the spacer seal on the air spacer comprises: depositing a sealing layer on the air spacer and the gate structure; and etching the sealing layer to form an opening on the gate structure.
9. The method of claim 1, wherein forming the cap seal comprises depositing an insulating layer directly on a top surface of the air cap and directly on a top surface and sidewalls of the spacer seal.
10. A method, comprising: depositing a dielectric layer along a sidewall of a polysilicon structure; replacing the polysilicon structure with a gate structure on a substrate; forming a gate spacer comprising a spacer layer and a first air gap along a sidewall of the gate structure, wherein the first air gap extends above a top surface of the gate structure; depositing a sealing layer on the dielectric layer, the first air gap, and the gate structure; etching the sealing layer to form a first seal along a sidewall of the dielectric layer and a second seal on the first air gap; forming a capping structure comprising a second air gap on the top surface of the gate structure and adjacent to the first air gap; and forming a conductive structure adjacent to the first air gap and the capping structure.
11. The method of claim 10, wherein etching the sealing layer forms a third seal on the gate structure.
12. The method of claim 10, wherein forming the gate spacer comprises: forming a sacrificial spacer along a sidewall of the polysilicon structure; and etching the sacrificial spacer to form the first air gap.
13. The method of claim 10, wherein forming the gate spacer comprises: forming an oxide spacer along a sidewall of the polysilicon structure; forming a sacrificial spacer on the oxide spacer; and etching the sacrificial spacer to expose a sidewall of the oxide spacer.
14. The method of claim 10, wherein forming the capping structure comprises: depositing an insulating layer on the gate structure and the spacer layer; and etching the insulating layer to expose a top surface and a sidewall of the spacer layer.
15. The method of claim 14, wherein forming the capping structure further comprises: etching the

insulating layer to form the second air gap along a sidewall of the spacer layer and on the gate structure.

16. A method, comprising: forming a gate structure on a substrate; forming first gate spacers along sidewalls of the gate structure; forming second gate spacers on the first gate spacers; depositing etch stop layers on the second gate spacers; removing the second gate spacers to form air spacers between the first gate spacers and the etch stop layers; depositing a sealing layer on top of the air spacers, in contact with top surfaces and sidewalls of the first gate spacers and the etch stop layers, and on a top surface of the gate structure; and etching the sealing layer to remove first portions of the sealing layer from the top surfaces of the first gate spacers, while second portions of the sealing layer remain on the top surfaces of the etch stop layer.

17. The method of claim 16, further comprising forming an air cap on the gate structure after depositing the sealing layer.

18. The method of claim 16, wherein etching the sealing layer comprises removing third portions of the sealing layer from the top surface of the gate structure.

19. The method of claim 16, further comprising depositing a sacrificial capping layer on the first and second gate spacers and the gate structure.

20. The method of claim 19, further comprising removing the sacrificial capping layer after removing the second gate spacers.
