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United States Patent	12396156
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Tang; Yi

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### Memory structure and manufacturing method thereof, and semiconductor structure

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#### Abstract

The present disclosure relates to a memory structure and a manufacturing method thereof, and a semiconductor structure. The semiconductor structure includes an epitaxial structure, a grounding structure, a columnar capacitor structure, a bit line structure, and a word line structure. The grounding structure wraps one end of the epitaxial structure in a first direction; the columnar capacitor structure wraps the other end of the epitaxial structure in the first direction; the bit line structure surrounds the epitaxial structure, and is located between the grounding structure and the columnar capacitor structure; and the word line structure surrounds the epitaxial structure, and is located between the bit line structure and the columnar capacitor structure.

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<b>Appl. No.:</b>	<b>17/817134</b>
<b>Filed:</b>	<b>August 03, 2022</b>

#### Prior Publication Data

<b>Document Identifier</b>	<b>Publication Date</b>
US 20230380140 A1	Nov. 23, 2023

#### Foreign Application Priority Data

CN	202210545501.2	May. 19, 2022
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#### Publication Classification

**Int. Cl.: H10B12/00** (20230101); **G11C7/18** (20060101); **G11C8/14** (20060101); **H10D62/10** (20250101)

**U.S. Cl.:**

**CPC H10B12/30** (20230201); **G11C7/18** (20130101); **G11C8/14** (20130101); **H10B12/488** (20230201); **H10D62/106** (20250101);

## Field of Classification Search

**CPC:** H10B (12/488); H10B (12/482); H10B (12/03); H10B (12/30); H10D (62/106)

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## Background/Summary

### CROSS-REFERENCE TO RELATED APPLICATION

(1) This application claims the priority of Chinese Patent Application No. 202210545501.2, submitted to the Chinese Intellectual Property Office on May 19, 2022, the disclosure of which is incorporated herein in its entirety by reference.

### TECHNICAL FIELD

(2) The present disclosure relates to the technical field of design and manufacturing of integrated circuits, and in particular, to a memory structure and a manufacturing method thereof, and a semiconductor structure.

### BACKGROUND

(3) With continuous development of integrated circuit manufacturing processes, the market puts forward higher requirements for performance and reliability of semiconductor products. For semiconductor memory devices, the performance and reliability of transistors therein directly affect

the storage performance and reliability of the products.

(4) However, in conventional semiconductor memory devices, epitaxial silicon in field effect transistors has potential floating properties, and a current flowing through drains increases the potential of silicon epitaxial layers and increases channel conductance. As a drain voltage increases, a leakage current also increases to form unsaturated characteristics. At a high drain voltage, carriers near a drain terminal will generate avalanche multiplication, which makes the drain current increase rapidly with the drain voltage, resulting in an abnormal subthreshold slope and device threshold voltage drift, etc., such that not only device gains are reduced to cause unstable device operation, but also a drain breakdown voltage is reduced to cause a single-tube latch-up effect, resulting in disordered chip functions or circuit failure or even burnout.

## SUMMARY

(5) According to various embodiments of the present disclosure, a first aspect provides a semiconductor structure, including an epitaxial structure, a grounding structure, a columnar capacitor structure, a bit line structure, and a word line structure. The grounding structure wraps one end of the epitaxial structure in a first direction; the columnar capacitor structure wraps the other end of the epitaxial structure in the first direction; the bit line structure surrounds the epitaxial structure, and is located between the grounding structure and the columnar capacitor structure; and the word line structure surrounds the epitaxial structure, and is located between the bit line structure and the columnar capacitor structure. By sequentially arranging the grounding structure, the bit line structure, the word line structure, and the columnar capacitor structure on the epitaxial structure in an extension direction of the epitaxial structure, a shared epitaxial structure is grounded to prevent charges from accumulating in the epitaxial structure to produce a floating body effect, thereby improving the performance and reliability of semiconductor products.

(6) According to some embodiments, a second aspect of the present disclosure provides a memory structure, including: a substrate, a first-type doped well region being formed in the substrate; an epitaxial layer, covering the first-type doped well region; and a target laminated structure, located on the epitaxial layer; where, the target laminated structure includes a plurality of laminated semiconductor structures in the embodiments of the present disclosure, and word line structures in adjacent two of the semiconductor structures are insulated from each other in a direction perpendicular to the substrate.

(7) According to some embodiments, a third aspect of the present disclosure provides a method of manufacturing a memory structure, including: providing a substrate, a first-type doped well region being formed in the substrate; forming an epitaxial layer on the substrate, the epitaxial layer covering the first-type doped well region; and forming a target laminated structure on the epitaxial layer, the target laminated structure including a plurality of semiconductor structures laminated in a thickness direction according to any embodiment of the present disclosure.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) To describe the technical solutions in the embodiments of the present disclosure more clearly, the accompanying drawings required to describe the embodiments are briefly described below. Apparently, the accompanying drawings described below are only some embodiments of the present disclosure. Those of ordinary skill in the art may further obtain other accompanying drawings on these accompanying drawings without creative efforts.

(2) FIG. 1 is a stereoscopic diagram of a semiconductor structure according to one embodiment of the present disclosure;

(3) FIG. 2 is a schematic structural diagram of a cross section of a structure as shown in FIG. 1 along direction AA';

(4) FIG. 3 is a schematic flowchart of a method of manufacturing a memory structure according to one embodiment of the present disclosure;

(5) FIG. 4 to FIG. 15B are schematic structural diagrams of different steps in a method of manufacturing a memory structure according to one embodiment of the present disclosure, where FIG. 4 to FIG. 13B are stereoscopic diagrams in different steps; FIG. 14 to FIG. 15A are stereoscopic diagrams of corresponding steps intercepted in a direction perpendicular to ox direction; FIG. 15B is a left view of FIG. 15A; oy direction is a first direction; ox direction is a second direction; and oz direction is a height/thickness direction.

#### DETAILED DESCRIPTION

(6) To facilitate the understanding of the present disclosure, the present disclosure is described more completely below with reference to the related accompanying drawings. The preferred embodiments of the present disclosure are shown in the accompanying drawings. However, the present disclosure may be embodied in various forms without being limited to the embodiments described herein. On the contrary, these embodiments are provided to make the present disclosure more thorough and comprehensive.

(7) Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by those skilled in the technical field of the present disclosure. The terms used in the specification of the present disclosure are merely for the purpose of describing specific embodiments, rather than to limit the present disclosure.

(8) It should be understood that when an element or a layer is described as “being on”, “being adjacent to”, “being connected to” or “being coupled to” another element or layer, it can be on, adjacent to, connected to, or coupled to the another element or layer directly, or intervening elements or layers may be present. On the contrary, when an element is described as “being directly on”, “being directly adjacent to”, “being directly connected to” or “being directly coupled to” another element or layer, there are no intervening elements or layers. It should be understood that although terms such as first, second, and third may be used to describe various elements, components, regions, layers, doped types and/or sections, these elements, components, regions, layers, doped types and/or sections should not be limited by these terms. These terms are only used to distinguish one element, component, region, layer, doping type or section from another element, component, region, layer, doping type or section. Therefore, without departing from the teachings of the present application, a first element, component, region, layer, doping type or section discussed below may be a second element, component, region, layer, doping type or section. For example, the first doping type may be the second doping type, and similarly, the second doping type may be the first doping type; or the first doping type and the second doping type are different doping types, for example, the first doping type may be P-type and the second doping type may be N-type, or the first doping type may be N-type and the second doping type may be P-type.

(9) Spatial relationship terms such as “under”, “beneath”, “lower”, “below”, “above”, and “upper” can be used herein to describe the relationship shown in the figure between one element or feature and another element or feature. It should be understood that in addition to the orientations shown in the figure, the spatial relationship terms further include different orientations of used and operated devices. For example, if a device in the accompanying drawings is turned over, an element or feature described as being “beneath another element”, “below it”, or “under it” is oriented as being “on” the another element or feature. Therefore, the exemplary terms “beneath” and “under” may include two orientations of above and below. In addition, the device may further include other orientations (for example, a rotation by 90 degrees or other orientations), and the spatial description used herein is interpreted accordingly.

(10) In the specification, the singular forms of “a”, “an” and “the/this” may also include plural forms, unless clearly indicated otherwise. It should also be understood that terms “include” and/or “comprise”, when used in this specification, may determine the presence of features, integers, steps, operations, elements and/or components, but do not exclude the presence or addition of one

or more other features, integers, steps, operations, elements, components and/or groups. In this case, in this specification, the term “and/or” includes any and all combinations of related listed items.

(11) It should be noted that the mutual insulation between the two described in the embodiments of the present disclosure includes, but is not limited to, the existence of one or more of an insulating material, an insulating air gap, or a gap between the two.

(12) It should be noted that, the drawings provided in the embodiments merely illustrate the basic concepts of the present disclosure schematically. Although the drawings only show components related to the present disclosure rather than being drawn according to the quantities, shapes, and sizes of components in actual implementation, patterns, quantities, and proportions of components in actual implementation may be changed randomly, and the component layout may be more complex.

(13) The kink effect refers to non-saturated characteristics of a drain current and drain voltage of a field effect transistor. The production factor is that at a high drain voltage, carriers near a drain terminal will produce avalanche multiplication, which makes the drain current increase rapidly with the drain voltage. Epitaxial silicon in the field effect transistor has potential floating properties, and when a current flows through a forward-biased pn junction of a drain, the potential of a silicon epitaxy layer increases, and channel conductance also increases. Therefore, as the drain voltage increases, leakage current also increases to form unsaturated characteristics, or even cause disordered chip functions or circuit failure or even burnout.

(14) The present disclosure aims to provide a memory structure and a manufacturing method thereof, and a semiconductor structure, to effectively avoid potential floating properties of epitaxial silicon in field effect transistors, and improve the performance and reliability of semiconductor products.

(15) In some embodiments of the present disclosure, please referring to FIG. 1 and FIG. 2, a semiconductor structure is provided. The semiconductor structure includes an epitaxial structure (not shown in FIG. 1), a grounding structure **10**, a columnar capacitor structure **30**, a bit line structure **210**, and a word line structure **40**. The grounding structure **10** wraps one end of the epitaxial structure in a first direction such as oy direction; the columnar capacitor structure **30** wraps the other end of the epitaxial structure in the first direction such as oy direction; the bit line structure **210** surrounds the epitaxial structure, and is located between the grounding structure **10** and the columnar capacitor structure **30**; and the word line structure **40** surrounds the epitaxial structure, and is located between the bit line structure **210** and the columnar capacitor structure **30**. By sequentially arranging the grounding structure **10**, the bit line structure **210**, the word line structure **40**, and the columnar capacitor structure **30** on the epitaxial structure in the oy direction, a shared epitaxial structure is grounded to prevent charges from accumulating in the epitaxial structure to produce a floating body effect, thereby improving the performance and reliability of semiconductor products.

(16) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, a cross section of the epitaxial structure intersecting with the first direction is in a rounded shape. For example, a cross section of the epitaxial structure perpendicular to the oy direction is in a rounded shape. The rounded shape includes at least one of a rounded rectangle, an ellipse, a rounded polygon, and a circle, and prevents a contact surface of the epitaxial structure with any one of the grounding structure **10**, the bit line structure **210**, the word line structure **40**, and the columnar capacitor structure **30** formed on the epitaxial structure from having a sharp corner to induce a tip discharge/leakage phenomenon, thereby improving the performance and reliability of manufactured products.

(17) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, a part of the epitaxial structure covered by the word line structure **40** includes: a first semiconductor pillar **221** extending in the oy direction and provided with a cross section, intersecting with the first

direction, being in a rounded shape; and a first channel layer **211** surrounding the first semiconductor pillar **221** and located between the word line structure **40** and the first semiconductor pillar **221**. For example, the cross section of the first semiconductor pillar **221** perpendicular to the oy direction is in a rounded angle, and the rounded angle includes at least one of rounded rectangle, an ellipse, a rounded polygon, and a circle. The word line structure **40** may be configured to include a gate oxide layer **41** and a gate metal layer **42** sequentially laminated from inside to outside. The first semiconductor pillar **221** is grounded via the grounding structure **10** to prevent the word line structure **40** from causing, under the action of an applied voltage, a floating body effect in the first semiconductor pillar **221**, thereby improving the performance and reliability of semiconductor products. Since contact surfaces between the first channel layer **211** and the first semiconductor pillar **221** are rounded surfaces, and the cross section of the first channel layer **211** perpendicular to the oy direction is in a rounded shape, the tip discharge/leakage phenomenon is effectively avoided, thereby improving the performance and reliability of manufactured products. The gate oxide layer **41** may be made of a material with a high-k dielectric constant. For example, the material of the gate oxide layer **41** may include, but is not limited to, one or more of aluminum oxide (Al.sub.2O.sub.3), hafnium oxide (HfO.sub.2), hafnium oxide nitrogen (HfON), zirconium oxide (ZrO.sub.2), tantalum oxide (Ta.sub.2O.sub.5), titanium oxide (TiO.sub.2), or strontium titanium oxide (SrTiO.sub.3). The gate metal layer **42** may include, but is not limited to, any one or several of titanium nitride (TiN), titanium (Ti), tungsten silicide (Si.sub.2W), and tungsten (W), etc.

(18) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, the first channel layer **211** includes a first-type doped layer. A part of the epitaxial structure covered by the bit line structure **210** and a part of the epitaxial structure covered by the columnar capacitor structure **30** each include: a second semiconductor pillar **222** extending in the oy direction and provided with a cross section, intersecting with the first direction, being in a rounded shape; and a second-type doped layer including a first part located between the second semiconductor pillar **222** and the bit line structure **210**, and a second part located between the second semiconductor pillar **222** and the columnar capacitor structure **30**. For example, the cross section of the second semiconductor pillar **222** perpendicular to the oy direction is in a rounded angle, and the rounded angle includes at least one of rounded rectangle, an ellipse, a rounded polygon, and a circle. The first part of the second-type doped layer may be defined as a second channel layer **212**, and the second part of the second-type doped layer may be defined as a third channel layer **213**. The first channel layer **211**, the second channel layer **212**, and the third channel layer **213** form an initial channel layer. The second semiconductor pillar **222** and the first semiconductor pillar **221** form a target semiconductor layer. The target semiconductor layer and the initial channel layer surrounding an outer surface of the target semiconductor layer form an epitaxial structure. The bit line structure **210**, the word line structure **40**, and the columnar capacitor structure **30** share the epitaxial structure and are grounded via the grounding structure **10** to prevent charges from accumulating in the epitaxial structure to produce a floating body effect, thereby improving the performance and reliability of semiconductor products.

(19) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, the first semiconductor pillar **221** and the second semiconductor pillar **222** are made of germanium-silicon; and the first channel layer **211** and the second-type doped layer are made of silicon, to form the word line structure **40** on the outer surface of the first channel layer **211** and form the bit line structure **210** and the columnar capacitor structure **30** respectively at two opposite ends of the second-type doped layer in the oy direction, so as to form memory cell structures sharing the epitaxial structure. The epitaxial structure is grounded via the grounding structure **10** to prevent charges from accumulating in the epitaxial structure to produce a floating body effect, thereby improving the performance and reliability of the memory cell structures. Moreover, the contact surface of the epitaxial structure with any one of the grounding structure **10**, the bit line structure

**210**, the word line structure **40**, and the columnar capacitor structure **30** formed on the epitaxial structure is a rounded surface to avoid a sharp corner from inducing a tip discharge/leakage phenomenon, thereby improving the performance and reliability of the memory cell structures.

(20) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, the first-type doped layer has a doping concentration range of  $[1\text{E}14\text{ cm}^{-3}, 1\text{E}18\text{ cm}^{-3}]$ . For example, the first-type doped layer may be P-type, and P-type impurity ions may include, but are not limited to, one or more of boron (B) ions, gallium (Ga) ions, boron fluoride ( $\text{BF}_{\text{sub}2}$ ) ions, and indium (In) ions. For example, the first channel layer **211** is a first-type doped layer, and the first-type doped layer may have a doping concentration of  $1\text{E}14\text{ cm}^{-3}$ ,  $1\text{E}15\text{ cm}^{-3}$ ,  $1\text{E}16\text{ cm}^{-3}$ ,  $1\text{E}17\text{ cm}^{-3}$ , or  $1\text{E}18\text{ cm}^{-3}$ . For example, an in-situ doping process may control the doping concentration of the first-type doped layer as  $[1\text{E}14\text{ cm}^{-3}, 1\text{E}18\text{ cm}^{-3}]$ , such that the gate controllability of the word line structure **40** is improved, and the conductive impedance and the energy consumption are reduced. The second-type doped layer has a doping concentration range of  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ , and the second-type doped layer may have a doping concentration of  $1\text{E}18\text{ cm}^{-3}$ ,  $1\text{E}19\text{ cm}^{-3}$ ,  $1\text{E}20\text{ cm}^{-3}$ , or  $1\text{E}21\text{ cm}^{-3}$ . The second-type doped layer may be N-type, and N-type impurity ions may include, but are not limited to, one or several of phosphorus (P) ions, arsenic (As) ions, and antimony (Sb) ions. For example, the in-situ doping process may control the doping concentration of the second-type doped layer as  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ , such that the conductive impedance and the energy consumption of the epitaxial structure are reduced.

(21) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, a part of the epitaxial structure covered by the word line structure **40** has a thickness of  $[30\text{ nm}, 80\text{ nm}]$ . For example, the part of the epitaxial structure covered by the word line structure **40** may have a thickness of 30 nm, 35 nm, 45 nm, 55 nm, 65 nm, 75 nm, or 80 nm. In this embodiment, while ensuring the electrical performance of the word line structures **40**, adjacent two of the word line structures **40** in a stacking direction such as oz direction are prevented from being insulated from each other. Every two of the ox direction, the oy direction, and the oz direction are perpendicular to each other.

(22) In some embodiments of the present disclosure, please still referring to FIG. 1 and FIG. 2, the semiconductor structure further includes a bit line protection structure **281**, a capacitor isolation structure **282**, and a bit line isolation structure **29**. The bit line protection structure **281** is located between the bit line structure **210** and the word line structure **40**, such that the bit line structure **210** and the word line structure **40** are electrically isolated in the oy direction. The capacitor isolation structure **282** is located between the word line structure **40** and the columnar capacitor structure **30**, such that the word line structure **40** and the columnar capacitor structure **30** are electrically isolated in the oy direction. The bit line isolation structure **29** surrounds the epitaxial structure, and is located between the grounding structure **10** and the bit line structure **210**, such that the grounding structure **10** and the bit line structure **210** are electrically isolated in the oy direction.

(23) In some embodiments, please still referring to FIG. 1 and FIG. 2, the grounding structure **10** is made of a metal conductive material and/or a non-metal conductive material; and/or, the bit line structure **210** is made of a metal conductive material. The metal conductive material includes, but is not limited to, one or more of cobalt (Co), nickel (Ni), titanium (Ti), tungsten (W), tantalum (Ta), tantalum titanium (TaTi), tungsten nitride (WN), copper (Cu), and aluminum (Al). The non-metal conductive material includes, but is not limited to, doped polycrystalline silicon.

(24) In some embodiments, please referring to FIG. 3, the present disclosure provides a method of manufacturing a memory structure, including: Step **S111**: provide a substrate, a first-type doped well region being formed in the substrate; Step **S112**: form an epitaxial layer on the substrate, the epitaxial layer covering the first-type doped well region; and Step **S113**: form a target laminated structure on the epitaxial layer, the target laminated structure including a plurality of semiconductor structures laminated in a thickness direction according to any embodiment of the present disclosure.

(25) In some embodiments, please referring to FIG. 3 and FIG. 4, the substrate **100** is provided, and a first-type doped well region (not shown in the drawing) is formed in the substrate **100**. The substrate may be made of a semiconductor material, an insulating material, a conductor material, or any combination thereof. The substrate **100** may be of a single-layer structure or a multi-layer structure. For example, the substrate **100** may be, for example, a silicon (Si) substrate, a silicon germanium (SiGe) substrate, a silicon germanium carbon (SiGeC) substrate, a silicon carbide (SiC) substrate, a gallium arsenide (GaAs) substrate, an indium arsenide (InAs) substrate, an indium phosphide (InP) substrate, or another III/V semiconductor substrate or II/VI semiconductor substrate. Alternatively, also for example, the substrate may be a layered substrate including, for example, Si/SiGe, Si/SiC, silicon-on-insulator (SOI), or silicon-germanium-on-insulator. Therefore, the type of the substrate should not limit the protection scope of the present disclosure. The P-type ions are implanted into the substrate **100** by using an ion implantation process to form the first-type doped well region (not shown in the drawing). The P-type ions may include, but are not limited to, one or several of boron (B) ions, gallium (Ga) ions, boron fluoride (BF<sub>3</sub>) ions, and indium (In) ions. The doping concentration of the first-type doped well region in the substrate **100** may be [1E12 cm<sup>-3</sup>, 1E18 cm<sup>-3</sup>]. For example, the doping concentration of the first-type doped well region may be 1E12 cm<sup>-3</sup>, 1E13 cm<sup>-3</sup>, 1E14 cm<sup>-3</sup>, 1E15 cm<sup>-3</sup>, 1E16 cm<sup>-3</sup>, 1E17 cm<sup>-3</sup>, or 1E18 cm<sup>-3</sup>.

(26) In some embodiments, please referring to FIG. 3 to FIG. 10, the process of forming a target laminated structure on the epitaxial layer **101** may include: Step S1131: form an initial laminated structure on the epitaxial layer **101**, the initial laminated structure including initial channel layers **21** and target semiconductor layers **22** alternately laminated in sequence from bottom to top; Step S1132: form a plurality of isolation structures **24**, extending in a first direction and arranged at intervals in a second direction, in the initial laminated structure, bottoms of the isolation structures **24** being in contact with an upper surface of the epitaxial layer **101**; Step S1133: form a word line trench **25** extending in the second direction, side walls of the word line trench **25** being covered by a protective layer **26**, the word line trench **25** exposing the upper surface of the epitaxial layer **101**, and parts, located in the word line trench **25**, of the target semiconductor layers **22** being suspended and exposed; Step S1134: remove an oxide formed in an in-situ oxidation period after the target semiconductor layers **22** exposed in the word line trench **25** are oxidized in situ, such that the target semiconductor layers **22** exposed in the word line trench **25** are rounded, a rounded part of each of the target semiconductor layers **22** forming a first semiconductor pillar **221**; and Step S1135: form a first channel layer **211** on an outer surface of the first semiconductor pillar **221**, the first channel layer **211** surrounding the first semiconductor pillar **221**.

(27) In some embodiments, please referring to FIG. 4, in step S1131, initial channel layers **21** and target semiconductor layers **22** alternately laminated in sequence in the oz direction may be formed on the epitaxial layer **101** by using the deposition process. The material of the initial channel layer **21** may include, but is not limited to, silicon (Si). The material of the target semiconductor layer **22** may include, but is not limited to, silicon-germanium (SiGe). The target semiconductor layer **22** made of silicon-germanium can completely transfer a silicon lattice of the substrate **100** into the laminated initial channel layer **21** made of silicon, thereby ensuring that each initial channel layer **21** made of silicon can have the same silicon lattice as the substrate **100**. The deposition process may include, but is not limited to, one or more of a chemical vapor deposition (CVD), an atomic layer deposition (ALD) process, a high-density plasma (HDP) process, a plasma enhanced deposition process, and a spin-on dielectric (SOD) layer process. The initial channel layer **21** may have a thickness of [60 nm, 100 nm]. For example, the initial channel layer **21** may have a thickness of 60 nm, 70 nm, 80 nm, 90 nm, or 100 nm. The target semiconductor layer **22** may have a thickness of [5 nm, 20 nm]. For example, the target semiconductor layer **22** may have a thickness of 5 nm, 10 nm, 15 nm, or 20 nm. The target semiconductor layer **22** itself provides tensile stress, and each layer should not be too thick, otherwise problems such as body tilt are likely to occur. The target semiconductor layer **22** inevitably has defects during manufacturing, and increasing its



thickness means increasing the probability and/or number of defect locations. If the target semiconductor layer **22** made of silicon-germanium is too thick and has too many defects, the lattice mismatch of the initial channel layer **21** on the top is likely to be more serious.

(28) In some embodiments, please still referring to FIG. 5 and FIG. 6, in step **S1132**, a plurality of first trenches **23** extending in the first direction (such as oy direction) and arranged at intervals in the second direction (such as ox direction) may be formed in the initial laminated structure by using a wet etching process; and then, an isolation material is deposited in the first trenches **23** to form an isolation structure **24** in each of the first trenches **23**. The bottoms of the isolation structures **24** are in contact with the upper surface of the epitaxial layer **101**, facilitating mutual isolation of a plurality of subsequently manufactured bit line structures in the ox direction.

(29) In some embodiments, please still referring to FIG. 7A and FIG. 7B, in step **S1133**, a first through hole **2411** and a second through hole **2412** isolated in the oy direction may be first provided on the isolation structure **24**, and a corrosive solution may be injected via the first through hole **2411** and the second through hole **2412** for etching to form a first word line trench **251** and a second word line trench **252** that extend in the oz direction and are isolated from each other in the oy direction. The first word line trench **251** and the second word line trench **252** are configured to define shapes and positions of subsequently manufactured word line structures. The corrosive solution may be a BOE buffer etching solution. BOE is formed by mixing HF and NH<sub>4</sub>F in different ratios, for example, HF:NH<sub>4</sub>F=1:6. HF is a main etching solution, and NH<sub>4</sub>F is used as a buffer agent. The concentration of (H<sup>+</sup>) is fixed by using NH<sub>4</sub>F to maintain a certain etching rate, and silicon at a target position is etched and removed to form the first word line trench **251** and the second word line trench **252**.

(30) In some embodiments, please still referring to FIG. 8 and FIG. 9, a protective material is deposited in the first word line trench **251** and the second word line trench **252** to form a first protective side wall **261** in the first word line trench **251** and a second protective side wall **262** in the second word line trench **252**, and parts of the initial channel layers **21** located between the first protective side wall **261** and the second protective side wall **262** may be removed by using a dry etching process, such that parts, located between the first protective side wall **261** and the second protective side wall **262**, of the target semiconductor layers **22** are exposed and suspended to form the word line trench **25**, and the first protective side wall **261** and the second protective side wall **262** form a protective layer **26** on side walls of the word line trench **25**. The dry etching process includes, but is not limited to, one or more of reactive ion etching (RIE), inductively coupled plasma (ICP) etching, or high-concentration plasma (HDP) etching.

(31) In some embodiments, please still referring to FIG. 9 and FIG. 10, in step **S1134**, the target semiconductor layers **22** exposed in the word line trench **25** may be oxidized in situ, and then an oxide formed in the in-situ oxidation period is removed, such that the target semiconductor layers **22** exposed in the word line trench **25** are rounded, and a rounded part of each of the target semiconductor layers **22** forms a first semiconductor pillar **221**. Next, a first channel layer **211** may be formed on an outer surface of the first semiconductor pillar **221** by using a deposition process, and the first channel layer **211** surrounds the first semiconductor pillar **221**. The first channel layer **211** is grown on the outer surface of the rounded first semiconductor pillar **221**, such that the first channel layer **211** may be more uniform, and the doping concentration of the first channel layer **211** is conveniently controlled by an in-situ doping process to control the performance of subsequently manufactured word line structures. The deposition process may include, but is not limited to, one or more of a chemical vapor deposition (CVD), an atomic layer deposition (ALD) process, a high-density plasma (HDP) process, a plasma enhanced deposition process, and a spin-on dielectric (SOD) layer process. The first channel layer **211** may be a first-type doped layer, and the doping concentration range may be [1E14 cm<sup>-3</sup>, 1E18 cm<sup>-3</sup>]. For example, the doping concentration of the first channel layer **211** may be 1E14 cm<sup>-3</sup>, 1E15 cm<sup>-3</sup>, 1E16 cm<sup>-3</sup>, 1E17 cm<sup>-3</sup>, or 1E18 cm<sup>-3</sup>. The first-type doped layer may be P-type, and P-type impurity ions may include, but are not limited to,

one or more of boron (B) ions, gallium (Ga) ions, boron fluoride (BF<sub>3</sub>) ions, and indium (In) ions.

(32) In some embodiments, please still referring to FIG. 3 and FIG. 11 to FIG. 13A, the first channel layer **211** includes a first-type doped layer. The process of forming a target laminated structure on the epitaxial layer **101** further includes: Step **S1136**: fill a first dielectric layer **27** into the word line trench **25**, an upper surface of the first dielectric layer **27** being flush with an upper surface of the initial laminated structure; Step **S1137**: etch the initial laminated structure with the first dielectric layer **27** as a mask, such that a part, other than the first semiconductor pillar **221**, of each of the target semiconductor layers **22** is suspended and exposed; Step **S1138**: round an exposed part of each of the target semiconductor layers **22** and forming a second semiconductor pillar **222**; Step **S1139**: form a second-type doped layer, the second-type doped layer wrapping an outer surface of the second semiconductor pillar **222**; and Step **S11310**: form an isolation material layer **28**, and define a bit line trench **Sb1** and a capacitor region **Scap**, laminated bit line structures being formed in the bit line trench **Sb1**, and laminated columnar capacitor structures being formed in the capacitor region **Scap**.

(33) In some embodiments, please still referring to FIG. 11, in step **S1136**, the first dielectric layer **27** may be filled into the word line trench **25** by using one or more of an atomic layer deposition process, a plasma vapor deposition process, and a rapid thermal oxidation (RTO) process, and then the first dielectric layer **27** may be flattened by using a chemical mechanical polishing process, such that the upper surface of the first dielectric layer **27** is flush with the upper surface of the initial laminated structure. The first dielectric layer **27** is made of silicon dioxide.

(34) In some embodiments, please still referring to FIG. 12A, in step **S1137**, the initial laminated structure may be etched by using a dry etching process with the first dielectric layer **27** as a mask, such that a part, other than the first semiconductor pillar **221**, of each of the target semiconductor layers **22** is suspended and exposed.

(35) In some embodiments, please still referring to FIG. 12B, in step **S1138**, the suspended and exposed parts of the target semiconductor layers **22** may be oxidized in situ, and then an oxide formed in the in-situ oxidation period is removed, such that a part of each of the target semiconductor layers **22** outside the first dielectric layer **27** is rounded to form a second semiconductor pillar **222**, and a channel layer subsequently formed on the outer side of the second semiconductor pillar **222** has good uniformity, thereby improving the performance and reliability of manufactured semiconductor products.

(36) In some embodiments, please still referring to FIG. 13A, in step **S1139**, a second-type doped layer may be formed on the outer surface of the second semiconductor pillar **222** by using the deposition process, and the second-type doped layer wraps the outer surface of the second semiconductor pillar **222**. In step **S11310**, the isolation material layer **28** may be formed by using the deposition process, the bit line trench **Sb1** and the capacitor region **Scap** are defined, the second-type doped layers in the bit line trench **Sb1** are exposed and suspended, and the laminated bit line structures are formed in the bit line trench **Sb1**. The second-type doped layers in the capacitor region **Scap** are exposed and suspended, and the laminated columnar capacitor structures are formed in the capacitor region **Scap**. The second-type doped layer has a doping concentration range of  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ . For example, the second-type doped layer may have a doping concentration of  $1\text{E}18\text{ cm}^{-3}$ ,  $1\text{E}19\text{ cm}^{-3}$ ,  $1\text{E}20\text{ cm}^{-3}$ , or  $1\text{E}21\text{ cm}^{-3}$ . The second-type doped layer may be N-type, and N-type impurity ions may include, but are not limited to, one or several of phosphorus (P) ions, arsenic (As) ions, and antimony (Sb) ions. For example, the in-situ doping process may control the doping concentration of the second-type doped layer as  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ , such that the conductive impedance and the energy consumption of the epitaxial structure are reduced.

(37) In some embodiments, please still referring to FIG. 13B, the isolation material layer **28** includes a first isolation material layer. After the bit line trench is defined, the method further

includes: Step **S11311**: deposit a bit line material layer in the bit line trench **Sb1** to form bit line structures **210** laminated from bottom to top, the bit line structure **210** surrounding the second-type doped layer, the first isolation material layer being formed between the laminated bit line structures and the first dielectric layer **27**, and the first isolation material layer forming a bit line protection structure **281**.

(38) In some embodiments, please still referring to FIG. **13B**, in step **S11311**, the bit line material layer may be deposited in the bit line trench **Sb1** by using the deposition process to form the bit line structures **210** laminated from bottom to top, and the bit line structure **210** surrounds the second-type doped layer. In the oz direction, and adjacent two of the bit line structures **210** are in ohmic contact. In the ox direction, adjacent two of the bit line structures **210** are insulated from each other, and a bit line protection structure **281** is formed between the laminated bit line structures **210** and the first dielectric layer **27** for electrically isolating the bit line structures **210** from the word line structures **40** in the oy direction. The bit line protection structure **281** may be made of silicon nitride or silicon oxynitride.

(39) In some embodiments, please referring to FIG. **14**, the isolation material layer **28** further includes a second isolation material layer. After the capacitor region **Scap** is defined, the method further includes: Step **S11312**: form a first electrode layer **31**, a high dielectric material layer **32**, and a second electrode layer **33** sequentially laminated on an outer surface of each second-type doped layer in the capacitor region **Scap** to form columnar capacitor structures **30** laminated from bottom to top, the second isolation material layer being formed between the laminated columnar capacitor structures **30** and the first dielectric layer **27**, and the second isolation material layer forming a capacitor isolation structure **282**.

(40) In some embodiments, please still referring to FIG. **14**, in step **S11312**, the first electrode layer **31**, the high dielectric material layer **32**, and the second electrode layer **33** may be sequentially laminated on the outer surface of each second-type doped layer in the capacitor region **Scap** by using the deposition process, such that the first electrode layer **31**, the high dielectric material layer **32**, and the second electrode layer **33** in the capacitor region **Scap** form the columnar capacitor structure **30**, and the capacitor isolation structure **282** is formed between the laminated columnar capacitor structures **30** and the first dielectric layer **27**. In the ox direction, adjacent two of the columnar capacitor structures **30** are insulated from each other. In the oz direction, adjacent two of the columnar capacitor structures **30** are insulated from each other. The material of the first electrode layer **31** and the material of the second electrode layer **33** may be the same or different, and may be selected from one or more of cobalt (Co), nickel (Ni), titanium (Ti), tungsten (W), tantalum (Ta), tantalum titanium (TaTi), tungsten nitride (WN), copper (Cu), and aluminum (Al). The high dielectric material layer **32** may be formed by using the atomic layer deposition process or the plasma vapor deposition process, and may be made of silicon nitride and/or silicon oxynitride. The capacitor isolation structure **282** is configured to electrically isolate the word line structures **40** from the columnar capacitor structures **30** in the oy direction, and may be made of silicon nitride and/or silicon oxynitride.

(41) In some embodiments, please still referring to FIG. **14** to FIG. **15B**, the isolation material layer further includes a third isolation material layer **283**. The third isolation material layer **283** is formed on a side of the laminated bit line structures **210** distant from the first dielectric layer **27**. The process of forming a target laminated structure on the epitaxial layer **101** further includes: Step **S11313**: etch the third isolation material layer **283**, such that parts of the second semiconductor pillars **222** at a side distant from the capacitor region **Scap** in the first direction are exposed and suspended; Step **S11314**: form a bit line isolation structure **29** on the exposed parts of the second semiconductor pillars **222**, and define a grounding electrode region; and Step **S11315**: form a conductive material layer in the grounding electrode region to form grounding structures **10** laminated from bottom to top, each of the grounding structures **10** wrapping an end of one of the target semiconductor layers **22** distant from the capacitor region **Scap** in the first direction.

(42) In some embodiments, please still referring to FIG. 14 to FIG. 15B, in step S11313, a part of the third isolation material layer 283 may be removed by using an etching process, such that the parts of the second semiconductor pillars 222 at the side distant from the capacitor region Scap in the oy direction are exposed and suspended. Then, in step S11314, the bit line isolation structure 29 may be formed on the exposed parts of the second semiconductor pillars 222 by using the deposition process, and the grounding electrode region is defined. To ensure the isolation effect, the length of the bit line isolation structure 29 in the oy direction may be set as [5 nm, 50 nm]. For example, the length of the bit line isolation structure 29 in the oy direction may be 5 nm, 15 nm, 25 nm, 35 nm, 45 nm, or 50 nm. If the bit line isolation structure 29 in the oy direction is too short, the isolation effect is likely to be deteriorated. On the contrary, if the bit line isolation structure 29 in the oy direction is too long, the volume of products is likely to increase. In step S11315, the conductive material layer may be formed in the grounding electrode region by using the deposition process to form the grounding structures 10 laminated from bottom to top, each of the grounding structures 10 wraps an end of one of the target semiconductor layers 22 distant from the capacitor region Scap in the oy direction. In the oz direction, adjacent two of the grounding structures 10 are electrically connected to each other. The etching process may include, but is not limited to, one or more of reactive ion etching (RIE), inductively coupled plasma (ICP) etching, or high-concentration plasma (HDP) etching. The deposition process may include, but is not limited to, one or more of a chemical vapor deposition (CVD), an atomic layer deposition (ALD) process, a high-density plasma (HDP) process, a plasma enhanced deposition process, and a spin-on dielectric (SOD) layer process.

(43) In some embodiments, please still referring to FIG. 15A and FIG. 15B, the process of forming a target laminated structure on the epitaxial layer 101 further includes: Step S11316: remove a first dielectric layer 27, such that the first channel layers 211 in the word line trench 25 are exposed and suspended; and Step S11317: form a word line structure 40 on the outer surface of each of the first channel layers 211, the word line structure 40 surrounding the first channel layer 211, where adjacent two of the word line structures 40 are insulated from each other in a direction perpendicular to the upper surface of the substrate 100, such as oz direction.

(44) In some embodiments, please still referring to FIGS. 15A and 15b, in step S11316, the first dielectric layer 27 may be removed by using the etching process, such that the first channel layers 211 in the word line trench are exposed and suspended. In step S11317, a gate oxide layer 41 may be formed on the outer surface of each of the first channel layers 211 by using the atomic layer deposition process, the plasma vapor deposition process, or the rapid thermal oxidation (RTO) process, and then a gate metal layer 42 is deposited on the outer surface of each gate oxide layer 41 by using the deposition process to form the word line structure 40. The gate oxide layer 41 surrounds the first channel layer 211; and the gate metal layer 42 surrounds the gate oxide layer 41. In the direction perpendicular to the upper surface of the substrate 100, such as the oz direction, adjacent two of the word line structures 40 are insulated from each other, so as to subsequently select a required word line. In the ox direction, adjacent two of the word line structures 40 are in ohmic contact. The gate oxide layer 41 may be made of a material with a high-k dielectric constant. For example, the gate oxide layer 41 may be made of a material with a high-k dielectric constant. For example, the material of the gate oxide layer 41 may include, but is not limited to, one or more of aluminum oxide ( $\text{Al}_2\text{O}_3$ ), hafnium oxide ( $\text{HfO}_2$ ), hafnium oxide nitrogen ( $\text{HfON}$ ), zirconium oxide ( $\text{ZrO}_2$ ), tantalum oxide ( $\text{Ta}_2\text{O}_5$ ), titanium oxide ( $\text{TiO}_2$ ), or strontium titanium oxide ( $\text{SrTiO}_3$ ). The gate metal layer 42 may include, but is not limited to, any one or several of titanium nitride ( $\text{TiN}$ ), titanium ( $\text{Ti}$ ), tungsten silicide ( $\text{Si}_2\text{W}$ ), and tungsten ( $\text{W}$ ), etc.

(45) It should be understood that although the steps in the flowchart of FIG. 3 are sequentially displayed according to the arrows, these steps are not necessarily executed in the order indicated by the arrows. Unless clearly described otherwise, the execution order of the steps is not strictly

limited, and these steps may be executed in other orders. Moreover, at least some of the steps in FIG. 3 may include a plurality of sub-steps or stages. The sub-steps or stages are not necessarily executed at the same time, but may be executed at different times. The sub-steps or stages are not necessarily carried out sequentially, but may be executed alternately with other steps or at least some of sub-steps or stages of other steps.

(46) In some embodiments, please still referring to FIG. 15A and FIG. 15B, a memory structure is provided. The memory structure includes: a substrate **100**, a first-type doped well region (not shown in the drawing) being formed in the substrate **100**; an epitaxial layer **101** covering the first-type doped well region; and a target laminated structure located on the epitaxial layer **101**. The target laminated structure includes a plurality of laminated semiconductor structures according to any embodiment of the present disclosure, and word line structures in adjacent two of the semiconductor structures are insulated from each other in a direction perpendicular to the substrate **100**, such as oz direction. By sequentially arranging the grounding structure **10**, the bit line structure **210**, the word line structure **40**, and the columnar capacitor structure **30** on the epitaxial structure in the oy direction, a shared epitaxial structure is grounded to prevent charges from accumulating in the epitaxial structure to produce a floating body effect, thereby improving the performance and reliability of semiconductor products.

(47) In some embodiments, a cross section of the epitaxial structure intersecting with the first direction is in a rounded shape. For example, a cross section of the epitaxial structure perpendicular to the oy direction is in a rounded shape. The rounded shape includes at least one of a rounded rectangle, an ellipse, a rounded polygon, and a circle, and prevents a contact surface of the epitaxial structure with any one of the grounding structure **10**, the bit line structure **210**, the word line structure **40**, and the columnar capacitor structure **30** formed on the epitaxial structure from having a sharp corner to induce a tip discharge/leakage phenomenon, thereby improving the performance and reliability of manufactured products.

(48) It may be noted that the foregoing embodiments are merely for the purpose of description instead of limiting the present disclosure.

(49) The embodiments of this specification are described in a progressive manner, and each embodiment focuses on differences from other embodiments. The same or similar parts between the embodiments may refer to each other.

(50) The technical characteristics of the above embodiments can be employed in arbitrary combinations. To provide a concise description of these embodiments, all possible combinations of all the technical characteristics of the above embodiments may not be described; however, these combinations of the technical characteristics should be construed as falling within the scope defined by the specification as long as no contradiction occurs.

(51) The above embodiments are only intended to illustrate several implementations of the present disclosure in detail, and they should not be construed as a limitation to the patentable scope of the present disclosure. It should be noted that those of ordinary skill in the art can further make variations and improvements without departing from the conception of the present disclosure. These variations and improvements all fall within the protection scope of the present disclosure. Therefore, the protection scope of the present disclosure should be subject to the protection scope defined by the claims.

## Claims

1. A semiconductor structure, comprising: an epitaxial structure; a grounding structure, wrapping one end of the epitaxial structure in a first direction; a columnar capacitor structure, wrapping the other end of the epitaxial structure in the first direction; a bit line structure, surrounding the epitaxial structure and located between the grounding structure and the columnar capacitor structure; and a word line structure, surrounding the epitaxial structure and located between the bit

line structure and the columnar capacitor structure; wherein a part of the epitaxial structure covered by the word line structure comprises: a first semiconductor pillar, extending in the first direction and provided with a cross section, intersecting with the first direction, being in a rounded shape; and a first channel layer, surrounding the first semiconductor pillar and located between the word line structure and the first semiconductor pillar; wherein the first channel layer comprises a first-type doped layer; and a part of the epitaxial structure covered by the bit line structure and a part of the epitaxial structure covered by the columnar capacitor structure each comprise: a second semiconductor pillar, extending in the first direction and provided with a cross section, intersecting with the first direction, being in a rounded shape; and a second-type doped layer, comprising a first part located between the second semiconductor pillar and the bit line structure, and a second part located between the second semiconductor pillar and the columnar capacitor structure; wherein the first semiconductor pillar and the second semiconductor pillar are made of germanium-silicon; and the first channel layer and the second-type doped layer are made of silicon.

2. The semiconductor structure according to claim 1, wherein a cross section of the epitaxial structure intersecting with the first direction is in a rounded shape.

3. The semiconductor structure according to claim 1, wherein the first-type doped layer has a doping concentration range of  $[1\text{E}14\text{ cm}^{-3}, 1\text{E}18\text{ cm}^{-3}]$ ; and/or the second-type doped layer has a doping concentration range of  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ .

4. The semiconductor structure according to claim 1, wherein a part of the epitaxial structure covered by the word line structure has a thickness of  $[30\text{ nm}, 80\text{ nm}]$ .

5. The semiconductor structure according to claim 1, further comprising at least one of the following structures: a bit line protection structure, located between the bit line structure and the word line structure; a capacitor isolation structure, located between the word line structure and the columnar capacitor structure; and a bit line isolation structure, surrounding the epitaxial structure and located between the grounding structure and the bit line structure.

6. The semiconductor structure according to claim 1, wherein the grounding structure is made of a metal conductive material and/or a non-metal conductive material; and/or the bit line structure is made of a metal conductive material.

7. A memory structure, comprising: a substrate, a first-type doped well region being formed in the substrate; an epitaxial layer, covering the first-type doped well region; and a target laminated structure, located on the epitaxial layer; wherein, the target laminated structure comprises a plurality of laminated semiconductor structures according to claim 1, and word line structures are in adjacent two of the semiconductor structures are insulated from each other in a direction perpendicular to an upper surface of the substrate.

8. A method of manufacturing a memory structure, comprising: providing a substrate, a first-type doped well region being formed in the substrate; forming an epitaxial layer on the substrate, the epitaxial layer covering the first-type doped well region; and forming a target laminated structure on the epitaxial layer, the target laminated structure comprising a plurality of semiconductor structures laminated in a thickness direction according to claim 1.

9. The method according to claim 8, wherein the forming a target laminated structure on the epitaxial layer comprises: forming an initial laminated structure on the epitaxial layer, the initial laminated structure comprising initial channel layers and target semiconductor layers alternately laminated in sequence from bottom to top; forming a plurality of isolation structures, extending in a first direction and arranged at intervals in a second direction, in the initial laminated structure, bottoms of the isolation structures being in contact with an upper surface of the epitaxial layer; forming a word line trench extending in the second direction, side walls of the word line trench being covered by a protective layer, the word line trench exposing the upper surface of the epitaxial layer, and parts, located in the word line trench, of the target semiconductor layers being suspended and exposed; removing an oxide formed in an in-situ oxidation period after the target semiconductor layers exposed in the word line trench are oxidized in situ, such that the target

semiconductor layers exposed in the word line trench are rounded, a rounded part of each of the target semiconductor layers forming a first semiconductor pillar; and forming a first channel layer on an outer surface of the first semiconductor pillar, the first channel layer surrounding the first semiconductor pillar.

10. The method according to claim 9, wherein the first channel layer comprises a first-type doped layer; and the forming a target laminated structure on the epitaxial layer further comprises: filling a first dielectric layer into the word line trench, an upper surface of the first dielectric layer being flush with an upper surface of the initial laminated structure; etching the initial laminated structure with the first dielectric layer as a mask, such that a part, other than the first semiconductor pillar, of each of the target semiconductor layers is suspended and exposed; rounding an exposed part of each of the target semiconductor layers, and forming a second semiconductor pillar; forming a second-type doped layer, the second-type doped layer wrapping an outer surface of the second semiconductor pillar; and forming an isolation material layer, and defining a bit line trench and a capacitor region, laminated bit line structures being formed in the bit line trench, and laminated columnar capacitor structures being formed in the capacitor region.

11. The method according to claim 10, wherein the isolation material layer comprises a first isolation material layer; and after the bit line trench is defined, the method further comprises: depositing a bit line material layer in the bit line trench to form the bit line structures laminated from bottom to top, the bit line structure surrounding the second-type doped layer, the first isolation material layer being formed between the laminated bit line structures and the first dielectric layer, and the first isolation material layer forming a bit line protection structure.

12. The method according to claim 10, wherein the isolation material layer comprises a second isolation material layer; and after the capacitor region is defined, the method further comprises: forming a first electrode layer, a high dielectric material layer, and a second electrode layer sequentially laminated on an outer surface of each second-type doped layer in the capacitor region, to form the columnar capacitor structures laminated from bottom to top, the second isolation material layer being formed between the laminated columnar capacitor structures and the first dielectric layer, and the second isolation material layer forming a capacitor isolation structure.

13. The method according to claim 11, wherein the isolation material layer comprises a third isolation material layer, and the third isolation material layer is formed on a side of the laminated bit line structures distant from the first dielectric layer; and the forming a target laminated structure on the epitaxial layer further comprises: etching the third isolation material layer, such that parts of the second semiconductor pillars at a side distant from the capacitor region in the first direction are exposed and suspended; forming a bit line isolation structure on the exposed parts of the second semiconductor pillars, and defining a grounding electrode region; and forming a conductive material layer in the grounding electrode region to form grounding structures laminated from bottom to top, each of the grounding structures wrapping an end of one of the target semiconductor layers distant from the capacitor region in the first direction.

14. The method according to claim 13, wherein the forming a target laminated structure on the epitaxial layer further comprises: removing the first dielectric layer, such that the first channel layers in the word line trench are exposed and suspended; and forming a word line structure on an outer surface of each of the first channel layers, the word line structure surrounding the first channel layer, wherein adjacent two of the word line structures are insulated from each other in a direction perpendicular to an upper surface of the substrate.

15. The method according to claim 10, wherein the first-type doped layer has a doping concentration range of  $[1\text{E}14\text{ cm}^{-3}, 1\text{E}18\text{ cm}^{-3}]$ ; and/or the second-type doped layer has a doping concentration range of  $[1\text{E}18\text{ cm}^{-3}, 1\text{E}21\text{ cm}^{-3}]$ .

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