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United States Patent	12389585
Kind Code	B2
Date of Patent	August 12, 2025
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Method of fabricating a semiconductor memory device

Abstract

A semiconductor memory device includes a capacitor having a bottom electrode and a top electrode, a dielectric layer between the bottom and top electrodes, and an interface layer between the top electrode and the dielectric layer, the interface layer including a metal oxide and an additional constituent at a grain boundary of the interface layer.

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Appl. No.: 17/701866

Filed: March 23, 2022

Prior Publication Data

Document Identifier	Publication Date
US 20220216209 A1	Jul. 07, 2022

Foreign Application Priority Data

KR	10-2019-0138567	Nov. 01, 2019
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Related U.S. Application Data

division parent-doc US 16903586 20200617 US 11342329 child-doc US 17701866

Publication Classification

Int. Cl.: H10B12/00 (20230101); H01L21/02 (20060101); H10D1/68 (20250101)

U.S. Cl.:

CPC H10B12/03 (20230201); H01L21/02186 (20130101); H10B12/30 (20230201); H10D1/692 (20250101);

Field of Classification Search

CPC: H01L (21/02186); H01L (28/40); H01L (28/60); H01L (29/92); H10B (12/02); H10B (12/03); H10B (12/033); H10B (12/30); H10B (12/315); H10D (1/62); H10D (1/68); H10D (1/692)

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION (1) This application is a division of U.S. patent application Ser. No. 16/903,586 filed on Jun. 17, 2020, which is incorporated by reference herein in its entirety. (2) Korean Patent Application No. 10-2019-0138567, filed on Nov. 1, 2019, in the Korean Intellectual Property Office, and entitled: “Semiconductor Memory Device and Method of Fabricating the Same,” is incorporated by reference herein in its entirety.

BACKGROUND

1. Field

(1) The present disclosure relates to a semiconductor, and more particularly, to a semiconductor memory device and a method of fabricating the same.

2. Description of the Related Art

(2) Semiconductor devices are beneficial in the electronic industry because of their small size, multi-functionality, and/or low fabrication cost. In particular, the semiconductor devices are being highly integrated with the remarkable development of the electronic industry. For example, line widths of patterns of semiconductor devices are being reduced for high integration thereof.

SUMMARY

(3) According to some example embodiments, a semiconductor memory device may include a capacitor having a bottom electrode and a top electrode, a dielectric layer between the bottom and top electrodes, and an interface layer between the top electrode and the dielectric layer, the interface layer including a metal oxide and an additional constituent at a grain boundary of the interface layer.

(4) According to some example embodiments, a semiconductor memory device may include a capacitor having a bottom electrode, a dielectric layer on the bottom electrode, a top electrode on the dielectric layer, and an upper interface layer between the dielectric layer and the top electrode. The upper interface layer may include a metal oxide and an additional constituent contained in the metal oxide. The additional constituent may have a maximum amount of about 5 at %.

(5) According to some example embodiments, a semiconductor memory device may include a capacitor connected to a transistor on a substrate. The capacitor may include a plurality of bottom electrodes that are supported by a support pattern connected to sidewalls of the bottom electrodes adjacent to the support pattern, a top electrode on the bottom electrodes, a dielectric layer between the top electrode and the bottom electrodes, the dielectric layer extending along surfaces of the bottom electrodes, and an upper interface layer between the dielectric layer and the top electrode. The upper interface layer may include a metal oxide and an additional constituent capable of being present at a grain boundary in the upper interface layer. The metal oxide may include titanium oxide (TiOx). The additional constituent may include aluminum (Al), silicon (Si), or a combination thereof.

(6) According to some example embodiments, a method of fabricating a semiconductor memory device may include forming a capacitor bottom electrode on a substrate, forming a capacitor dielectric layer on the capacitor bottom electrode, forming an upper interface layer on the capacitor dielectric layer, and forming a top electrode on the upper interface layer. The upper interface layer may include a metal oxide and an additional constituent doped into the metal oxide. The additional constituent may be capable of being present at a grain boundary of the metal oxide.

(7) According to some example embodiments, a method of fabricating a semiconductor memory device may include providing a substrate on which are formed a plurality of bottom electrodes that are connected to each other through a support pattern, forming on the bottom electrodes a dielectric

layer that continuously extends along surfaces of the bottom electrodes and a surface of the support pattern, forming on the dielectric layer an upper interface layer that continuously extends along the bottom electrodes and the support pattern, and forming on the upper interface layer a top electrode that covers the bottom electrodes. The upper interface layer may include a titanium oxide and an additional constituent capable of being present at a grain boundary of the titanium oxide. The additional constituent may have a maximum amount of about 5 at %.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1A illustrates a cross-sectional view of a capacitor according to some example embodiments.
- (2) FIG. 1B illustrates a cross-sectional view of a method of forming an interface layer included in a capacitor according to some example embodiments.
- (3) FIG. 1C illustrates a cross-sectional view of a method of forming an interface layer included in a capacitor according to some example embodiments.
- (4) FIG. 1D illustrates a cross-sectional view of a capacitor according to some example embodiments.
- (5) FIG. 2A illustrates a plan view showing a semiconductor memory device that includes a capacitor according to some example embodiments.
- (6) FIG. 2B illustrates a cross-sectional view along lines A1-A2 and B1-B2 of FIG. 2A.
- (7) FIG. 2C illustrates a cross-sectional view along lines A1-A2 and B1-B2 of FIG. 2A.
- (8) FIGS. 3A to 3R illustrate cross-sectional views along lines A1-A2 and B1-B2 of FIG. 2A, showing stages in a method of fabricating a semiconductor memory device including a capacitor according to some example embodiments.
- (9) FIGS. 4A to 4C illustrate cross-sectional views along lines A1-A2 and B1-B2 of FIG. 2A, showing stages in a method of fabricating a semiconductor memory device that includes a capacitor according to some example embodiments.

DETAILED DESCRIPTION OF EMBODIMENTS

- (10) FIG. 1A illustrates a cross-sectional view of a capacitor according to some example embodiments. FIG. 1B illustrates a cross-sectional view of a method of forming an interface layer included in a capacitor according to some example embodiments. FIG. 1C illustrates a cross-sectional view of another method of forming an interface layer included in a capacitor according to some example embodiments. FIG. 1D illustrates a cross-sectional view of a capacitor according to some example embodiments.
- (11) Referring to FIG. 1A, a capacitor **1** may include a bottom electrode **10**, a dielectric layer **30** on the bottom electrode **10**, a top electrode **50** opposite to the bottom electrode **10** across the dielectric layer **30**, and an interface layer **40** between the top electrode **50** and the dielectric layer **30**. The bottom electrode **10** and the top electrode **50** may independently include one or more of an impurity-doped polysilicon layer, an impurity-doped silicon-germanium layer, a metal nitride layer, e.g., a titanium nitride layer or a hafnium nitride layer, and a metal layer including metal, e.g., tungsten, copper, or aluminum. The dielectric layer **30** may include an oxide layer of, e.g., hafnium (Hf), niobium (Nb), titanium (Ti), tantalum (Ta), zirconium (Zr), chromium (Cr), cobalt (Co), iridium (Ir), molybdenum (Mo), osmium (Os), rhenium (Re), rhodium (Rh), ruthenium (Ru), tungsten (W), vanadium (V), or any combination thereof.
- (12) The interface layer **40** may include a metal oxide, and further include an additional constituent, e.g., a metallic or semiconductor constituent. The interface layer **40** may have semiconductor properties. For example, the interface layer **40** may include titanium oxide (e.g., TiOx) as the metal oxide, and further include aluminum (Al), silicon (Si), or a combination thereof

as the additional constituent. For example, the interface layer **40** may have a composition of AlTiO.sub.2 or SiTiO.sub.2 .

(13) The additional constituent of the interface layer **40** may have an amount of about 5 at % or less, based on a total amount of the interface layer **40**. The additional constituent may be present at a pathway, e.g., a grain boundary, along which charges move, and may serve to prevent charges from traveling along a grain boundary of the interface layer **40**. For this reason, the dielectric layer **30** may maintain its dielectric constant, and the capacitor **1** may suppress its current leakage, with the result that the capacitor **1** may have high capacitance. In addition, the additional constituent may complement the grain boundary of the interface layer **40**, and it may thus be possible to substantially reduce or prevent damage to the dielectric layer **30** in a subsequent process.

(14) The interface layer **40** may have a bulk structure or a single-layered structure. For example, the additional constituent may have a uniform concentration in the interface layer **40**. In another example, the additional constituent may have a non-uniform concentration in the interface layer **40**. For example, when the additional constituent includes aluminum (Al), the aluminum may have a concentration that gradually decreases along a direction oriented from the top electrode **50** toward the dielectric layer **30**.

(15) The interface layer **40** may be formed as discussed below. The following formation is a mere example, and the present disclosure is not limited thereto.

(16) For example, referring to FIG. **1B**, the interface layer **40** may be formed as a single layer including metal oxide and particles of the additional constituent element. For example, a base layer **40a** may be provided on the dielectric layer **30** that is formed by depositing a metal oxide. The base layer **40a** may be formed of a metal oxide (e.g., TiO.sub.2) that is deposited by a deposition process, e.g., a chemical vapor deposition (CVD), a physical vapor deposition (PVD), or an atomic layer deposition (ALD), on the dielectric layer **30**. Next, an oxide with the additional constituent, e.g., aluminum oxide (e.g., Al.sub.2O.sub.3), may be deposited on the base layer **40a** by a deposition process, e.g., a chemical vapor deposition (CVD), a physical vapor deposition (PVD), or an atomic layer deposition (ALD), thereby forming an additional layer **40b**. For example, as illustrated in FIG. **1B**, the additional layer **40b** may cover an entire exposed surface of the base layer **40a**, e.g., to improve coverage of a grain boundary along the entire base layer **40a**. For example, during the deposition of the additional layer **40b**, the additional constituent (e.g. aluminum (Al)) may diffuse into the base layer **40a**, e.g., through the base layer **40a** toward the dielectric layer **30**. In another example, an annealing process may be separately performed to diffuse the additional constituent into the base layer **40a**.

(17) Therefore, the finalized interface layer **40** may be formed to have a bulk structure in which a concentration gradient of the additional constituent is present or absent. For example, the finalized interface layer **40** may include the base layer **40a** with particles of the additional layer **40b** diffused therein in uniform or non-uniform distribution, e.g., the two separate layers **40a** and **40b** in FIG. **1B** are merely a schematic representation of separate deposition operations rather than the finalized interface layer **40**.

(18) In another example, aluminum (Al) may be deposited simultaneously with the metal oxide (e.g., TiO.sub.2) on the dielectric layer **30** to form the base layer **40a**. This process may therefore form the interface layer **40**, i.e., the base layer **40a** doped with aluminum (Al), on the dielectric layer **30** without the additional layer **40b**.

(19) Referring to FIG. **1C**, the interface layer **40** may have a multi-layered or laminated structure in which at least one first layer **41** and at least one second layer **42** are alternately and repeatedly deposited on the dielectric layer **30**. The first layer **41** and the second layer **42** may have different constituents from each other or the same or similar constituent.

(20) In some embodiments, the first layer **41** may be formed by depositing a metal oxide, e.g., TiO.sub.2 , and the second layer **42** may be formed by depositing an aluminum-containing material, e.g., Al.sub.2O.sub.3 , AlN, AlC, or any combination thereof. For example, a lowermost first layer

41 may be adjacent to or in contact with the dielectric layer **30**, and an uppermost second layer **42** may be adjacent to or in contact with the top electrode **50**. In another example, a lowermost first layer **41** and an uppermost first layer **41** may be adjacent to or in contact with the dielectric layer **30** and the top electrode **50**, respectively. In yet another example, a lowermost second layer **42** and an uppermost second layer **42** may be adjacent to or in contact with the dielectric layer **30** and the top electrode **50**, respectively. In still another example, a lowermost second layer **42** may be adjacent to or in contact with the dielectric layer **30**, and an uppermost first layer **41** may be adjacent to or in contact with the top electrode **50**. In some embodiments, the first and second layers **41** and **42** may be formed by depositing titanium aluminum oxide (e.g., TiAlO). For example, each of the first and second layers **41** and **42** may be deposited by a deposition process, e.g., the first and second layers **41** and **42** may completely cover each other.

(21) Referring to FIG. 1D, the capacitor **1** may further include an interface layer **20** (referred to hereinafter as a lower interface layer) between the dielectric layer **30** and the bottom electrode **10** in addition to the interface layer **40** (referred to hereinafter as an upper interface layer) between the top electrode **50** and the dielectric layer **30**. The lower interface layer **20** may be formed by the same or similar method used for forming the upper interface layer **40**.

(22) The lower interface layer **20** may have an identical or similar structure to that of the upper interface layer **40**. For example, the lower interface layer **20** may include a metal oxide (e.g., TiOx), and further include an additional constituent such as a metallic constituent (e.g., aluminum (Al)) or a semiconductor constituent (e.g., silicon (Si)). The additional constituent may have an amount of about 5 at % or less of a total amount of the lower interface layer **20**, and may prevent charges from moving through a grain boundary of the lower interface layer **20**, e.g., as the grain boundary of the lower interface layer **20** imparts crystallinity to the dielectric layer **30** to improve the dielectric constant and completely separates between the dielectric layer **30** and the bottom electrode **10**.

(23) For example, the lower interface layer **20** may be formed identically or similarly to that discussed with reference to FIG. 1B, thereby having a bulk structure. The additional constituent may have a concentration that is constant or gradually decreases or increases along a direction oriented from the dielectric layer **30** toward the bottom electrode **10**. For example, in each of the upper and lower interface layers **40** and **20**, the additional constituent may have a concentration that gradually decreases along a downward direction from the top electrode **50** toward the bottom electrode **10**, e.g., in accordance with a diffusion profile of the additional constituent controlled by heat during the deposition or annealing processes. In another example, the additional constituent may have a concentration that gradually decreases along the downward direction in the upper interface layer **40**, and that gradually increases along the downward direction in the lower interface layer **20**.

(24) In another example, the lower interface layer **20** may be formed identically or similarly to that discussed with reference to FIG. 1C, thereby having a laminated structure. The description with reference to FIG. 1C may be applicable identically or similarly to the lower interface layer **20**. As such, the upper and lower interface layers **40** and **20** may have the same structure or a mirror image, e.g., symmetry, with respect to the dielectric layer **30**.

(25) FIG. 2A illustrates a plan view of a semiconductor memory device that includes a capacitor according to some example embodiments. FIG. 2B illustrates a cross-sectional view along lines A1-A2 and B1-B2 of FIG. 2A, according to some example embodiments. FIG. 2C illustrates a cross-sectional view along lines A1-A2 and B1-B2 of FIG. 2A, according to some other example embodiments.

(26) Referring to FIGS. 2A and 2B, a substrate **301** may be provided therein with a device isolation pattern **302** that defines active sections ACT. The substrate **301** may be a semiconductor substrate. Each of the active sections ACT may have an isolated, e.g., island, shape. When viewed in a plan view, each of the active sections ACT may have a bar shape elongated in a third direction D3.

When viewed in a plan view, the active sections ACT may correspond to portions of the substrate **301** that are surrounded by the device isolation pattern **302**. The substrate **301** may include a semiconductor material. The active sections ACT may be arranged parallel to each other in the third direction D3, and one of the active sections ACT may have an end portion adjacent to a central portion of a neighboring one of the active sections ACT.

(27) Word lines WL may run across the active sections ACT. The word lines WL may be disposed in corresponding grooves GR formed on the device isolation pattern **302** and the active sections ACT. The word lines WL may be parallel to a first direction D1 that intersects the third direction D3. The word lines WL may include a conductive material. A gate dielectric layer **307** may be disposed between the word line WL and an inner surface of groove GR. The gate dielectric layer **307** may include one or more of, e.g., thermal oxide, silicon nitride, silicon oxynitride, and high-k dielectric. Each of the word lines WL may have a curved bottom surface.

(28) A first impurity region **312a** may be disposed in a center of each active section ACT between a pair of word lines WL (right side of FIG. 2B), and a pair of second impurity regions **312b** may be disposed in opposite edge portions of each active section ACT (left side of FIG. 2B). The first and second impurity regions **312a** and **312b** may be doped with, e.g., N-type impurities. The first impurity region **312a** may correspond to a common drain region, and the second impurity regions **312b** may correspond to source regions. Each word line WL and its adjacent first and second impurity regions **312a** and **312b** may constitute a transistor.

(29) The word lines WL may have their top surfaces lower than those of the active sections ACT, e.g., a distance between a bottom of the substrate **301** and top surfaces of the word lines WL may be smaller than a distance between the bottom of the substrate **301** and top surfaces of the active sections ACT. A word-line capping pattern **310** may be disposed on each, e.g., top surface of the, word line WL. The word-line capping patterns **310** may have their linear shapes that extend along longitudinal directions of the word lines WL, and may cover the top surfaces of the word lines WL. The word-line capping patterns **310** may be formed of, e.g., a silicon nitride layer.

(30) An interlayer dielectric pattern **305** may be disposed on the substrate **301**. The interlayer dielectric pattern **305** may be formed of a single-layered or multi-layered structure that includes at least one of, e.g., a silicon oxide layer, a silicon nitride layer, and a silicon oxynitride layer. The interlayer dielectric pattern **305** may be formed to have island shapes that are spaced apart from each other when viewed in a plan view. The interlayer dielectric pattern **305** may simultaneously cover end portions of two adjacent active sections ACT.

(31) Upper portions of the substrate **301**, the device isolation pattern **302**, and the word-line capping pattern **310** may be partially recessed to provide a first recess R1. The first recess R1 may have a net shape when viewed in a plan view. Bit lines BL may be disposed on the interlayer dielectric pattern **305**. The bit lines BL may run across the word-line capping patterns **310** and the word lines WL.

(32) As disclosed in FIG. 2A, the bit lines BL may extend in a second direction D2 that intersects the first and third directions D1 and D3. Each of the bit lines BL may include a polysilicon pattern **330**, an ohmic pattern **331**, and a metal-containing pattern **332** that are sequentially stacked.

(33) The polysilicon pattern **330** may include, e.g., impurity-doped polysilicon or impurity-undoped polysilicon. The ohmic pattern **331** may include metal silicide. The metal-containing pattern **332** may include one or more of metal (e.g., tungsten, titanium, or tantalum) and conductive metal nitride (e.g., titanium nitride, tantalum nitride, or tungsten nitride). Bit-line capping patterns **337** may be disposed on corresponding bit lines BL. The bit-line capping patterns **337** may include a dielectric material, e.g., silicon nitride.

(34) A bit-line contact DC may be disposed in the first recess R1 that intersects the bit line BL. The bit-line contact DC may include, e.g., impurity-doped polysilicon or impurity-undoped polysilicon. The bit-line contact DC may be electrically coupled to the first impurity region **312a**, and may electrically connect the first impurity region **312a** to the bit line BL.

(35) A buried dielectric pattern **341** may be disposed in a portion of the first recess **R1**, which portion is not occupied by the bit-line contact **DC**. The buried dielectric pattern **341** may have a single-layered or multi-layered structure that includes one or more of, e.g., a silicon oxide layer, a silicon nitride layer, and a silicon oxynitride layer.

(36) As shown in FIG. 2A, storage node contacts **BC** may be disposed between a pair of adjacent bit lines **BL**. The plurality of storage node contacts **BC** may be spaced apart from each other. The storage node contacts **BC** may include, e.g., impurity-doped polysilicon or impurity-undoped polysilicon. The storage node contacts **BC** may have their concave top surfaces.

(37) The bit line **BL** and the storage node contact **BC** may have therebetween a bit-line spacer including a first spacer **321** and a second spacer **325** that are spaced apart from each other across an air gap **AG**. The first spacer **321** may cover a sidewall of the bit line **BL** and a sidewall of the bit-line capping pattern **337**. The second spacer **325** may be adjacent to the storage node contact **BC**. The first spacer **321** and the second spacer **325** may include the same material. For example, the first and second spacers **321** and **325** may include silicon nitride.

(38) The second spacer **325** may have a bottom surface lower than that of the first spacer **321**, e.g., a distance between the bottom surface of the substrate **301** and a bottom surface of the second spacer **325** may be smaller than a distance between the bottom of the substrate **301** and a bottom surface of the first spacer **321**. The second spacer **325** may have a top end whose level is lower than that of a top end of the first spacer **321**, e.g., a distance between the bottom surface of the substrate **301** and a top surface of the second spacer **325** may be smaller than a distance between the bottom of the substrate **301** and a top surface of the first spacer **321**. Therefore, it may be possible to increase a margin for forming a landing pad **LP** which will be discussed below and then to prevent disconnection between the landing pad **LP** and the storage node contact **BC**. The first spacer **321** may extend to cover a sidewall of the bit-line contact **DC** and a sidewall and a bottom surface of the first recess **R1**.

(39) A storage node ohmic layer **309** may be disposed on the storage node contact **BC**. The storage node ohmic layer **309** may include, e.g., metal silicide. The storage node ohmic layer **309**, the first and second spacers **321** and **325**, and the bit-line capping pattern **337** may be covered with a diffusion break pattern **311a**. The diffusion break pattern **311a** may include metal nitride, e.g., titanium nitride or tantalum nitride. A landing pad **LP** may be disposed on the diffusion break pattern **311a**. The landing pad **LP** may include a material containing metal, e.g., tungsten. The landing pad **LP** may have an upper portion that covers a top surface of the bit-line capping pattern **337** and has a width greater than that of the storage node contact **BC** (e.g., in top view in FIG. 2A).

(40) As shown in FIG. 2A, a center of the landing pad **LP** may shift in the first direction **D1** from a center of the storage node contact **BC**. A portion of the bit line **BL** may vertically overlap the landing pad **LP**. One upper sidewall of the bit-line capping pattern **337** may overlap the landing pad **LP** and may be covered with a third spacer **327**. A second recess **R2** may be formed on other upper sidewall of the bit-line capping pattern **337**, e.g., the bit-line capping pattern **337** may be between the second recess **R2** and the bit-line capping pattern **337** in the first direction **D1** (left side of FIG. 2A).

(41) A first capping pattern **358a** may be provided between neighboring landing pads **LP**. The first capping pattern **358a** may have a liner shape, and may have an interior filled with a second capping pattern **360a**. The first and second capping patterns **358a** and **360a** may independently include, e.g., a silicon nitride layer, a silicon oxide layer, a silicon oxynitride layer, or a porous layer. The first capping pattern **358a** may have its porosity greater than that of the second capping pattern **360a**.

(42) The air gap **AG** between the first and second spacers **321** and **325** may extend into a space between the landing pads **LP**. The air gap **AG** may expose a bottom surface of the first capping pattern **358a**. The air gap **AG** may extend toward the diffusion break pattern **311a**. For example, the diffusion break pattern **311a** may be recessed between the landing pad **LP** and the bit-line capping

pattern **337**.

(43) Bottom electrodes BE may be disposed on corresponding landing pads LP. The bottom electrode BE may include one or more of a metal nitride layer, e.g., an impurity-doped polysilicon layer or a titanium nitride layer, and a metal layer, e.g., a tungsten layer, an aluminum layer, or a copper layer. The bottom electrode BE may have a circular columnar shape, a hollow cylindrical shape, or a cup shape. A support pattern **374a** may be provided between neighboring bottom electrodes BE, supporting the bottom electrodes BE. The support pattern **374a** may include a dielectric material, e.g., silicon nitride, silicon oxide, or silicon oxynitride.

(44) Between the bottom electrodes BE, the first and second capping patterns **358a** and **360a** may be covered with an etch stop layer **370**. The etch stop layer **370** may include a dielectric material, e.g., silicon nitride, silicon oxide, or silicon oxynitride. A dielectric layer DL may cover a surface of each of the bottom electrode BE, the support pattern **374a**, and the etch stop layer **370**. The dielectric layer DL may be covered with a top electrode TE. An interface layer IFt may be provided between the dielectric layer DL and the top electrode TE. The top electrode TE may include one or more of, e.g., an impurity-doped polysilicon layer, an impurity-doped silicon-germanium layer, a metal nitride layer such as a titanium nitride layer, and a metal layer including tungsten, aluminum, or copper. A capacitor CAP may be constituted by the bottom electrode BE, the dielectric layer DL, the interface layer IFt, and the top electrode TE. Accordingly, there may be provided a semiconductor memory device **1000** including the capacitor CAP.

(45) The bottom electrode BE, the dielectric layer DL, the interface layer IFt, and the top electrode TE of the capacitor CAP may respectively correspond to the bottom electrode **10**, the dielectric layer **30**, the interface layer **40**, and the top electrode **50** of FIG. **1A**. The explanation of the interface layer **40** discussed with reference to FIGS. **1A** to **1C** is applicable identically or similarly to the interface layer IFt in FIG. **2B**. For example, the interface layer IFt may include a metal oxide (e.g., TiOx), and further include an additional metallic constituent (e.g., aluminum (Al)) or a semiconductor constituent (e.g., silicon (Si)). The additional constituent may have an amount of about 5 at % or less of a total amount of the interface layer IFt. The interface layer IFt may have a bulk structure in which the additional constituent has a uniform or non-uniform concentration. Alternatively, the interface layer IFt may have a laminated structure with a stacked structure of a plurality of layers having the same constituent or different constituents.

(46) In another example, as shown in FIG. **2C**, an interface layer IFb may further be provided between the bottom electrode BE and the dielectric layer DL. The interface layer IFb may correspond to the interface layer **20** of FIG. **1D**. The description of the interface layer **20** in FIG. **1D** is applicable identically or similarly to the interface layer IFb.

(47) FIGS. **3A** to **3R** illustrate cross-sectional views along lines A1-A2 and B1-B2 of FIG. **2A**, showing stages in a method of fabricating a semiconductor memory device that includes a capacitor according to some example embodiments.

(48) Referring to FIG. **3A**, the device isolation pattern **302** may be formed in the substrate **301**, thereby defining the active sections ACT. For example, a trench TR may be formed in the substrate **301**, and the trench TR may be filled with a dielectric material to form the device isolation pattern **302**. The active sections ACT and the device isolation pattern **302** may be etched to form grooves GR. Each of the grooves GR may have a curved bottom surface. The substrate **301** may be a semiconductor substrate, e.g., a silicon wafer.

(49) Word lines WL may be formed in corresponding grooves GR. A pair of word lines WL may run across the active sections ACT. Before the word lines WL are formed, the gate dielectric layer **307** may be formed on an inner surface of each of the grooves GR. The gate dielectric layer **307** may be formed by a thermal oxidation process, a chemical vapor deposition process, and/or an atomic layer deposition process. The grooves GR may be filled with a conductive layer deposited on the substrate **301**, and then an etch-back process or a chemical mechanical polishing process may be performed to form the word lines WL in the grooves GR. The word lines WL may be

recessed to have their top surfaces lower than those of the active sections ACT. The grooves GR may be filled with a dielectric layer, e.g., a silicon nitride layer, formed on the substrate **301**, and then the dielectric layer may be planarized to form word-line capping patterns **310** on corresponding word lines WL.

(50) The word-line capping patterns **310** and the device isolation pattern **302** may be used as a mask to implant impurities into the active sections ACT. Therefore, the first and second impurity regions **312a** and **312b** may be formed in the active sections ACT. The first and second impurity regions **312a** and **312b** may have their conductivity types different from that of the substrate **301**. For example, when the substrate **301** has P-type conductivity, each of the first and second impurity regions **312a** and **312b** may have N-type conductivity.

(51) Referring to FIG. 3B, the interlayer dielectric pattern **305** and a polysilicon mask pattern **330a** may be formed on the substrate **301**. For example, a dielectric layer and a first polysilicon layer may be sequentially formed on the substrate **301**. The first polysilicon layer may be patterned to form the polysilicon mask pattern **330a**. The polysilicon mask pattern **330a** may be used as an etching mask to etch the dielectric layer, the device isolation pattern **302**, the substrate **301**, and the word-line capping patterns **310** to form the first recess R1 and the interlayer dielectric pattern **305**. The interlayer dielectric pattern **305** may have a plurality of island shapes that are spaced apart from each other. A plurality of first recesses R1 may have a net shape, e.g., matrix pattern, when viewed in a plan view. The first recesses R1 may expose the first impurity regions **312a**.

(52) Referring to FIG. 3C, a second polysilicon layer **329** may be formed on the substrate **301**, thereby filling the first recess R1. And then, the second polysilicon layer **329** may undergo a planarization process to remove the second polysilicon layer **329** on the polysilicon mask pattern **330a** and to expose the polysilicon mask pattern **330a**.

(53) An ohmic layer **331a**, a metal-containing layer **332a**, and a capping layer **337a** may be sequentially formed on the polysilicon mask pattern **330a** and the second polysilicon layer **329**. The ohmic layer **331a** may be formed of metal silicide, e.g., cobalt silicide. A metal layer may be deposited on the polysilicon mask pattern **330a** and the second polysilicon layer **329**, and then an annealing process may be performed to form the ohmic layer **331a**. The annealing process may cause the metal layer to react with the polysilicon mask pattern **330a** and the second polysilicon layer **329**, thereby forming the metal silicide. A non-reacted metal layer may be removed.

(54) First mask patterns **339** may be formed on the capping layer **337a**, defining a planar shape of a bit line BL which will be discussed below. The first mask patterns **339** may extend in the second direction D2 illustrated in FIG. 2A.

(55) Referring to FIG. 3D, an etching process may be performed in which the first mask patterns **339** are used as an etching mask to sequentially etch the capping layer **337a**, the metal-containing layer **332a**, the ohmic layer **331a**, the polysilicon mask pattern **330a**, and the second polysilicon layer **329** to form the bit line BL, the bit-line contact DC, and the bit-line capping pattern **337**. The bit line BL may include the polysilicon pattern **330**, the ohmic pattern **331**, and the metal-containing pattern **332**. The etching process may partially expose a top surface of the interlayer dielectric pattern **305**, and may also partially expose an inner sidewall and a bottom surface of the first recess R1. The first mask patterns **339** may be removed after the formation of the bit line BL and the bit-line contact DC.

(56) Referring to FIG. 3E, a first spacer layer may be conformally formed on the substrate **301**. The first spacer layer may conformally cover the bottom surface and the inner sidewall of the first recess R1. The first spacer layer may be, e.g., a silicon nitride layer. The first recess R1 may be filled with a dielectric layer, e.g., a silicon nitride layer, formed on the substrate **301**, and then the dielectric layer may be anisotropically etched to leave the buried dielectric pattern **341** in the first recess R1. When the anisotropic etching process is performed, the first spacer layer may also be etched to form the first spacer **321**.

(57) A sacrificial spacer layer may be conformally formed on the substrate **301**, and then an

anisotropic etching process may be performed to form a sacrificial spacer **323** that covers a sidewall of the first spacer **321**. The sacrificial spacer **323** may include a material having an etch selectivity with respect to the first spacer **321**. The sacrificial spacer **323** may be formed of, e.g., a silicon oxide layer.

(58) The second spacer **325** may be formed to cover a sidewall of the sacrificial spacer **323**. The second spacer **325** may be formed of, e.g., a silicon nitride layer. The second impurity region **312b** may be exposed after the formation of the sacrificial spacer **323** or of the second spacer **325**.

(59) Referring to FIG. 3F, a space between a plurality of bit lines BL may be filled with a polysilicon layer formed on the substrate **301**, and then the polysilicon layer may be etched to form a preliminary storage node contact **350** and to expose upper portions of the first spacer **321**, the sacrificial spacer **323**, and the second spacer **325**. The upper portions of the sacrificial spacer **323** and the second spacer **325** may be removed to have top surfaces of the sacrificial spacer **323** and the second spacer **325** to be substantially coplanar, e.g., along a slanted plane with respect to the bottom of the substrate **301**, and to have their top ends at a same level or similar to that of a top surface of the preliminary storage node contact **350**. Therefore, the first spacer **321** may be exposed at the upper portion thereof.

(60) This process may increase a process margin for forming the landing pad LP which will be discussed below. When removing the upper portions of the sacrificial spacer **323** and the second spacer **325**, the upper portion of the first spacer **321** may also be partially removed to cause the first spacer **321** to have a remaining upper portion, e.g., a portion extending along a sidewall of the bit-line capping pattern **337** above the sacrificial spacer **323** and the second spacer **325**, with a small width along the first direction D1.

(61) Referring to FIG. 3G, a third spacer layer may be conformally formed on the substrate **301** and then anisotropically etched to form the third spacer **327** that covers a sidewall of the exposed upper portion of the first spacer **321**. The third spacer **327** may cover an exposed top end of the sacrificial spacer **323**. The preliminary storage node contact **350** may be etched to expose the upper portion of the second spacer **325** and also to form a storage node contact BC. The third spacer **327** may complement, e.g., cover in a complementary pattern, a damaged upper portion of the first spacer **321** and may cover the sacrificial spacer **323**, thereby serving to prevent the bit line BL from being damaged, e.g., deteriorated, by an etchant used for etching the storage node contact BC and a cleaning solution used in a subsequent cleaning process. As a result, the bit line BL may be protected from damage.

(62) The storage node ohmic layer **309** may be formed on the storage node contact BC, and a diffusion break layer **311** may be conformally formed on the substrate **301**. A landing pad layer **352** may be formed on the substrate **301** and may fill a space between the bit-line capping patterns **337**. The landing pad layer **352** may be, e.g., a tungsten layer. Second mask patterns **340** may be formed on the landing pad layer **352**. The second mask patterns **340** may be formed of, e.g., an amorphous carbon layer (ACL). The second mask patterns **340** may define positions of the landing pads LP which will be discussed below. The second mask patterns **340** may be formed to vertically overlap the storage node contacts BC.

(63) Referring to FIG. 3H, an anisotropic etching process may be performed in which the second mask patterns **340** are used as an etching mask to remove a portion of the landing pad layer **352**. Therefore, the landing pads LP may be formed, and openings **354** may be formed to expose the diffusion break layer **311**.

(64) Referring to FIG. 3I, an isotropic etching process may be performed in which the diffusion break layer **311** exposed to the openings **354** is patterned to form diffusion break patterns **311a** that are separated from each other and simultaneously to expose the third spacers **327** and portions of top surfaces of the bit-line capping patterns **337**. Depending on the degree of progress of the isotropic etching process, the diffusion break patterns **311a** may be over-etched to partially expose a bottom surface of the landing pad LP.

(65) Referring to FIG. 3J, an anisotropic etching process may be performed to remove portions of the bit-line capping patterns **337** exposed to the openings **354** and also to remove the third spacers **327**, and as a result the sacrificial spacers **323** may be exposed. In this case, the second recess **R2** may be formed on the bit-line capping pattern **337**. Afterwards, the second mask patterns **340** may be removed.

(66) Referring to FIG. 3K, an isotropic etching process may be performed in which the sacrificial spacer **323** is removed to form the air gap **AG** between the first spacer **321** and the second spacer **325**. After that, a thermal decomposition layer **356** may be formed to fill the openings **354** and the second recesses **R2**. The thermal decomposition layer **356** may also be formed on the landing pads **LP**. The thermal decomposition layer **356** may close an upper portion of the air gap **AG**.

(67) Referring to FIG. 3L, a first annealing process may be performed to thermally decompose and remove an upper portion of the thermal decomposition layer **356**. The partial removal of the thermal decomposition layer **356** may expose top surfaces and upper sidewalls of the landing pads **LP**, and may form thermal decomposition patterns **356a** that are spaced apart from each other. A first capping layer **358** may be conformally formed on the thermal decomposition patterns **356a** and the landing pads **LP**.

(68) Referring to FIG. 3M, a second annealing process may be performed to thermally decompose the thermal decomposition patterns **356a**. The thermal decomposition patterns **356a**, which has been thermally decomposed, may be out-gassed through the first capping layer **358**. Therefore, the air gap **AG** may expand from a space between the first and second spacers **321** and **325** into a space between the landing pads **LP**. A second capping layer **360** may be formed on the first capping layer **358**.

(69) Referring to FIG. 3N, an etch-back process or a chemical mechanical polishing process may be performed in which the first capping layer **358** and the second capping layer **360** are planarized to form the first capping pattern **358a** and the second capping pattern **360a** that are restricted between the landing pads **LP**. The planarization may remove portions of the first capping layer **358** and the second capping layer **360** from the landing pads **LP**, and thus the landing pads **LP** may be exposed.

(70) The etch stop layer **370** may be formed on the landing pads **LP**, the first capping pattern **358a**, and the second capping pattern **360a**. A first mold layer **372**, a support layer **374**, and a second mold layer **376** may be formed on the etch stop layer **370**. The etch stop layer **370** and the support layer **374** may be formed of, e.g., a silicon nitride layer. The first mold layer **372** and the second mold layer **376** may be formed of a material having an etch selectivity with respect to the support layer **374**. For example, the first mold layer **372** and the second mold layer **376** may be formed of a silicon oxide layer.

(71) Referring to FIG. 3O, the second mold layer **376**, the support layer **374**, the first mold layer **372**, and the etch stop layer **370** may be sequentially patterned to form electrode holes **EH** that expose the landing pads **LP**. A conductive layer may be formed to fill the electrode holes **EH**, and then an etch-back process or a chemical mechanical polishing process may be performed to remove the conductive layer on the second mold layer **376** and also to form the bottom electrode **BE** in the electrode hole **EH**. A third mask pattern **378** may be formed on the second mold layer **376**. The third mask pattern **378** may have a plurality of openings **378h**. The opening **378h** may expose top surfaces of adjacent bottom electrodes **BE** and also expose the second mold layer **376** between the adjacent bottom electrodes **BE**.

(72) Referring to FIG. 3P, an anisotropic etching process may be performed in which the third mask pattern **378** is used as an etching mask to remove the second mold layer **376** exposed to the opening **378h** and also to remove the support layer **374** below the second mold layer **376**. Accordingly, the support pattern **374a** may be formed, and the first mold layer **372** below the opening **378h** may be exposed.

(73) Referring to FIG. 3Q, the third mask pattern **378** may be removed to expose the second mold

layer **376**. An isotropic etching process may be performed in which the first and second mold layers **372** and **376** are all removed to expose surfaces of the bottom electrode BE, the support pattern **374a**, and the etch stop layer **370**.

(74) Referring to FIG. **3R**, the dielectric layer DL may be formed on the exposed surface of the bottom electrode BE. In this case, the dielectric layer DL may also be formed on exposed surfaces of the support pattern **374a** and the etch stop layer **370**. The interface layer IFt may be formed on the dielectric layer DL. The interface layer IFt may correspond to the interface layer **40** discussed with reference to FIGS. **1A** to **1C**.

(75) The description of the interface layer **40** in FIGS. **1A** to **1C** is applicable identically or similarly to the interface layer IFt. For example, the interface layer IFt may include a metal oxide (e.g., TiOx), and further include an additional metallic constituent (e.g., aluminum (Al)) or a semiconductor constituent (e.g., silicon (Si)). The additional constituent may have an amount of about 5 at % or less, based on a total amount of the interface layer IFt.

(76) The interface layer IFt may have a bulk structure in which the additional constituent has a uniform or non-uniform concentration. Alternatively, the interface layer IFt may have a laminated structure including a stacked structure of a plurality of layers having the same constituent or different constituents.

(77) Referring back to FIG. **2B**, the top electrode TE may be formed on the interface layer IFt, covering the bottom electrodes BE. Therefore, the semiconductor memory device **1000** may be fabricated with the capacitor CAP having the bottom electrode BE, the top electrode TE, the dielectric layer DL between the bottom and top electrodes BE and TE, and the interface layer IFt between the top electrode TE and the dielectric layer DL.

(78) The capacitor CAP may correspond to the capacitor **1** of FIG. **1A**. The description of the capacitor **1** in FIGS. **1A** to **1C** is applicable identically or similarly to the capacitor CAP. For example, as discussed above with reference to FIG. **1A**, charges may be prevented from moving through a grain boundary of the interface layer IFt, and as a result the capacitor **1** may have high capacitance.

(79) FIGS. **4A** to **4C** illustrate cross-sectional views along lines A1-A2 and B1-B2 of FIG. **2A**, showing stages in a method of fabricating a semiconductor memory device that includes a capacitor according to some example embodiments.

(80) Referring to FIG. **4A**, surfaces of the bottom electrodes BE may be exposed by the processes discussed in FIGS. **3A** to **3Q**. An interface layer IFb may be formed on the exposed surface of the bottom electrode BE. In this case, the interface layer IFb may also be formed on the exposed surface of the support pattern **374a** and on the exposed surface of the etch stop layer **370**. When the interface layer IFb is formed, a constituent of the interface layer IFb may diffuse into the bottom electrode BE. Thus, a portion of the bottom electrode BE may be changed into the interface layer IFb. In another example, a deposition condition may be controlled such that the interface layer IFb is deposited at a relatively high rate on the bottom electrode BE and at a relatively low rate on the support pattern **374a** and the etch stop layer **370**.

(81) The interface layer IFb may have a thickness that is non-uniform due to a difference in diffusion rate or deposition rate. For example, the interface layer IFb may have a first thickness T1 on the bottom electrode BE, a second thickness T2 on the support pattern **374a**, and a third thickness T3 on the etch stop layer **370**. The second thickness T2 may be less than the first thickness T1, and the third thickness T3 may be less than the first thickness T1 and identical or similar to the second thickness T2.

(82) The interface layer IFb may correspond to the interface layer **20** discussed above with reference to FIG. **1D**. The description of the interface layer **20** of FIG. **1D** is applicable identically or similarly to the interface layer IFb. For example, the interface layer IFb may include a metal oxide (e.g., TiOx), and further include an additional metallic constituent (e.g., aluminum (Al)) or a semiconductor constituent (e.g., silicon (Si)). The additional constituent may have an amount of

about 5 at % or less, based on a total amount of the interface layer IFb, and may prevent charges from moving through a grain boundary of the interface layer IFb. The interface layer IFb may have a bulk structure in which the additional constituent has a uniform or non-uniform concentration. Alternatively, the interface layer IFb may have a laminated structure in which are stacked a plurality of layers having the same constituent or different constituents.

(83) Referring to FIG. 4B, an etching process may be performed to remove a portion of the interface layer IFb. When the interface layer IFb has semiconductor properties, neighboring bottom electrodes BE may be electrically connected to each other. Therefore, the interface layer IFb may be partially removed on the support pattern 374a and the etch stop layer 370, e.g., the interface layer IFb may include discontinuous portions separated by the support pattern 374a. In some embodiments, the etching process may be performed without an etching mask.

(84) As discussed above, because the interface layer IFb has a relatively larger thickness (e.g., T1) on the bottom electrode BE and relatively smaller thicknesses (e.g., T2 and T3) on the support pattern 374a and the etch stop layer 370, the interface layer IFb may remain on the bottom electrode BE even if the etching process is performed without an etching mask.

(85) Referring to FIG. 4C, the dielectric layer DL may be formed on the interface layer IFb, and the interface layer IFt may be formed on the dielectric layer DL. The dielectric layer DL may cover the interface layer IFb, the support pattern 374a, and the etch stop layer 370. The dielectric layer DL corresponds to the dielectric layer 30 of FIG. 1A. The description of the dielectric layer 30 of FIG. 1A is applicable identically or similarly to the dielectric layer DL. The dielectric layer DL may include an oxide layer of hafnium (Hf), niobium (Nb), titanium (Ti), tantalum (Ta), zirconium (Zr), chromium (Cr), cobalt (Co), iridium (Ir), molybdenum (Mo), osmium (Os), rhenium (Re), rhodium (Rh), ruthenium (Ru), tungsten (W), vanadium (V), or any combination thereof.

(86) The interface layer IFt corresponds to the interface layer 40 discussed with reference to FIGS. 1A to 1C. The description of the interface layer 40 in FIGS. 1A to 1C is applicable identically or similarly to the interface layer IFt. For example, the interface layer IFt may include a metal oxide (e.g., TiOx), and further include an additional metallic constituent (e.g., aluminum (Al)) or a semiconductor constituent (e.g., silicon (Si)). The additional constituent may have an amount of about 5 at % or less, based on a total amount of the interface layer IFt, and may prevent charges from moving through a grain boundary of the interface layer IFt. The interface layer IFt may have a bulk structure in which the additional constituent has a uniform or non-uniform concentration. Alternatively, the interface layer IFt may have a laminated structure in which are stacked a plurality of layers having the same constituent or different constituents.

(87) Referring back to FIG. 2C, the top electrode TE may be formed on the interface layer IFt, covering the bottom electrodes BE. Accordingly, the semiconductor memory device 1000 may be fabricated with the capacitor CAP including the bottom electrode BE, the top electrode TE, the dielectric layer DL between the bottom and top electrodes BE and TE, the interface layer IFb between the bottom electrode BE and the dielectric layer DL, and the interface layer IFt between the top electrode TE and the dielectric layer DL.

(88) By way of summation and review, with the reduction in design rule of semiconductor memory devices, e.g., a dynamic random access memory (DRAM), the surface of a capacitor may be decreased, thereby causing reduced capacitance. Accordingly, the capacitor is required to have an improved structure to securely obtain high capacitance even if the semiconductor memory device is highly integrated.

(89) Therefore, example embodiments provide a semiconductor memory device with increased reliability and a method of fabricating the same. Example embodiments also provide a semiconductor memory device with high capacitance and a method of fabricating the same.

(90) That is, example embodiments provide a semiconductor memory device with a capacitor having a dielectric layer with an interface thereon that includes a metal oxide (e.g., TiO.sub.2) doped with an additional constituent (e.g., aluminum) to supplement the interface (e.g., TiO.sub.2)

grain boundaries, thereby improving barrier/leakage characteristics of the interface. Accordingly, damage to the dielectric layer is substantially minimized or prevented in subsequent processes, thereby maintaining high capacitance of the capacitor and substantially minimizing or preventing leakage in the dielectric layer.

(91) Example embodiments have been disclosed herein, and although specific terms are employed, they are used and are to be interpreted in a generic and descriptive sense only and not for purpose of limitation. In some instances, as would be apparent to one of ordinary skill in the art as of the filing of the present application, features, characteristics, and/or elements described in connection with a particular embodiment may be used singly or in combination with features, characteristics, and/or elements described in connection with other embodiments unless otherwise specifically indicated. Accordingly, it will be understood by those of skill in the art that various changes in form and details may be made without departing from the spirit and scope of the present invention as set forth in the following claims.

Claims

1. A method of fabricating a semiconductor memory device, the method comprising: providing a substrate having thereon bottom electrodes that are connected to each other through a support pattern; forming an etch stop layer on the substrate between the bottom electrodes; forming on the etch stop layer a dielectric layer that continuously extends along surfaces of the bottom electrodes and a surface of the support pattern; forming on the dielectric layer an upper interface layer that continuously extends along the bottom electrodes and the support pattern; and forming on the upper interface layer a top electrode that covers the bottom electrodes, wherein the upper interface layer includes a first metal oxide and a first additional constituent doped into the first metal oxide, the first additional constituent being present at a grain boundary of the first metal oxide.
2. The method as claimed in claim 1, wherein the first metal oxide includes titanium oxide, and the first additional constituent includes aluminum, silicon, or a combination thereof and has a maximum amount of about 5 at %, based on a total amount of the upper interface layer.
3. The method as claimed in claim 1, wherein forming the upper interface layer includes: forming a titanium oxide layer on the dielectric layer; and doping aluminum into the titanium oxide layer simultaneously with forming the titanium oxide layer.
4. The method as claimed in claim 1, wherein forming the upper interface layer includes alternately and repeatedly forming a titanium oxide layer and an aluminum-containing layer on the dielectric layer, the aluminum-containing layer includes Al_2O_3 , AlN, AlC, or any combination thereof.
5. The method as claimed in claim 1, wherein the etch stop layer and the support pattern each includes a silicon nitride layer.
6. The method as claimed in claim 1, wherein forming the upper interface layer includes: forming a titanium oxide layer on the dielectric layer; and forming an aluminum oxide layer on the titanium oxide layer, such that aluminum of the aluminum oxide layer is doped into the titanium oxide layer.
7. The method as claimed in claim 6, wherein the aluminum has a uniform concentration in the upper interface layer.
8. The method as claimed in claim 6, wherein the aluminum has a concentration that gradually decreases as approaching the dielectric layer.
9. The method as claimed in claim 1, wherein, before forming the dielectric layer, forming a lower interface layer on the bottom electrodes, such that the lower interface layer includes a second metal oxide and a second additional constituent at a grain boundary of the second metal oxide.
10. The method as claimed in claim 9, wherein the second metal oxide includes titanium oxide, and the second additional constituent includes aluminum, silicon, or a combination thereof at a maximum amount of about 5 at %, based on a total amount of the lower interface layer.

11. A method of fabricating a semiconductor memory device, the method comprising: providing a substrate having thereon bottom electrodes that are connected to each other through a support pattern; forming on the bottom electrodes a lower interface layer that continuously extends along surfaces of the bottom electrodes and a surface of the support pattern; removing a portion of the lower interface layer from the surface of the support pattern, such that the lower interface layer remains on the bottom electrodes; forming on the lower interface layer a dielectric layer that continuously extends along the surfaces of the bottom electrodes and the surface of the support pattern; forming on the dielectric layer an upper interface layer that continuously extends along the bottom electrodes and the support pattern; and forming on the upper interface layer a top electrode that covers the bottom electrodes, wherein the upper interface layer includes a first titanium oxide and a first additional constituent at a grain boundary of the first titanium oxide, and wherein the lower interface layer includes a second titanium oxide and a second additional constituent at a grain boundary of the second titanium oxide.

12. The method as claimed in claim 11, wherein the first additional constituent includes aluminum, silicon, or a combination thereof and has a maximum amount of about 5 at %, based on a total amount of the upper interface layer.

13. The method as claimed in claim 11, wherein the second additional constituent includes aluminum, silicon, or a combination thereof and has a maximum amount of about 5 at %, based on a total amount of the lower interface layer.
