US009917250B2

(12) **United States Patent**
Kim et al.

(10) **Patent No.: US 9,917,250 B2**
(45) **Date of Patent: Mar. 13, 2018**

(54) **SWITCHING DEVICE, METHOD OF FABRICATING THE SAME, AND RESISTIVE RANDOM ACCESS MEMORY INCLUDING THE SWITCHING DEVICE AS A SELECTION DEVICE**

(71) Applicant: **SK hynix Inc.**, Icheon (KR)

(72) Inventors: **Beom Yong Kim**, Suwon (KR); **Soo Gil Kim**, Seongnam (KR); **Won Ki Ju**, Icheon (KR)

(73) Assignee: **SK HYNIX INC.**, Icheon (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/206,092**

(22) Filed: **Jul. 8, 2016**

(65) **Prior Publication Data**

US 2017/0213958 A1 Jul. 27, 2017

(30) **Foreign Application Priority Data**

Jan. 27, 2016 (KR) 10-2016-0010338

(51) **Int. Cl.**
H01L 45/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 45/1266*** (2013.01); ***H01L 45/085*** (2013.01); *H01L 45/06* (2013.01); *H01L 45/08* (2013.01); *H01L 45/1253* (2013.01); *H01L 45/145* (2013.01); *H01L 45/1608* (2013.01)

(58) **Field of Classification Search**
CPC H01L 45/00; H01L 45/04; H01L 45/08; H01L 45/085; H01L 45/1253; H01L 45/1266; H01L 45/145; H01L 45/146; H01L 45/1608; H01L 45/1641
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,658,511	B1 *	2/2014	Fulgenico	H01L 21/31122 438/238
2003/0072126	A1 *	4/2003	Bhattacharyya	B82Y 10/00 361/311
2005/0124155	A1 *	6/2005	Brooks	H01L 21/76877 438/654
2008/0158937	A1 *	7/2008	Jung	G11C 11/24 365/149
2012/0236625	A1 *	9/2012	Ohba	H01L 27/2436 365/148
2014/0175356	A1 *	6/2014	Wang	H01L 45/1293 257/2
2014/0301127	A1 *	10/2014	Kim	G11C 13/0004 365/148
2015/0349251	A1 *	12/2015	Chang	H01L 45/1233 257/3
2017/0047513	A1 *	2/2017	Rolandi	G11C 13/0014
2017/0072604	A1 *	3/2017	Sjong	B29C 44/12
2017/0104031	A1 *	4/2017	Clark	H01L 27/2427

FOREIGN PATENT DOCUMENTS

KR	10-1436748 B1	9/2014

* cited by examiner

Primary Examiner — Eduardo A Rodela

(57) **ABSTRACT**

A switching device includes a first electrode and a second electrode that are disposed over a substrate, and an electrolyte layer disposed between the first electrode and the second electrode and including a porous oxide. The switching device performs threshold switching operation on the basis of oxidation-reduction reactions of metal ions that are provided from the first electrode or the second electrode to the electrolyte layer.

15 Claims, 10 Drawing Sheets

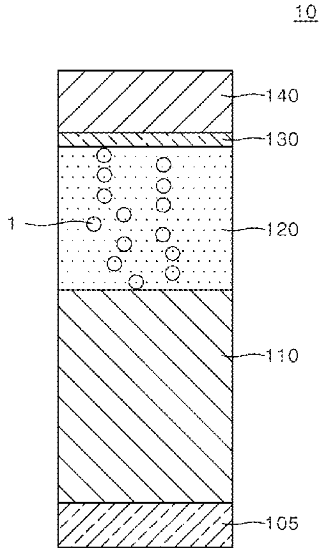


FIG. 1

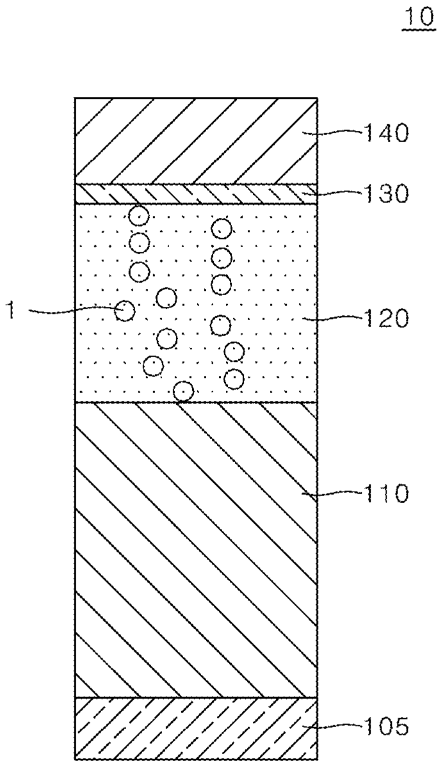


FIG. 2A

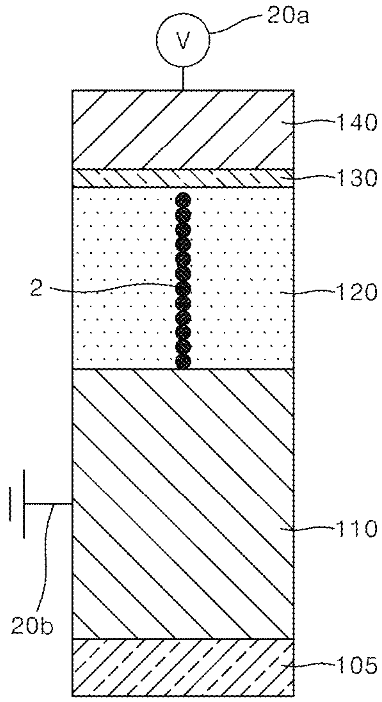


FIG. 2B

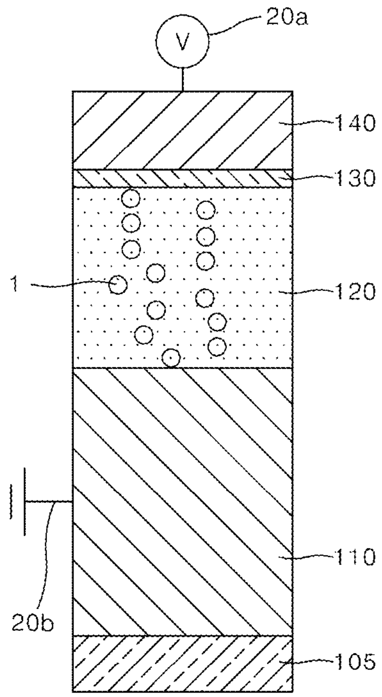


FIG. 3

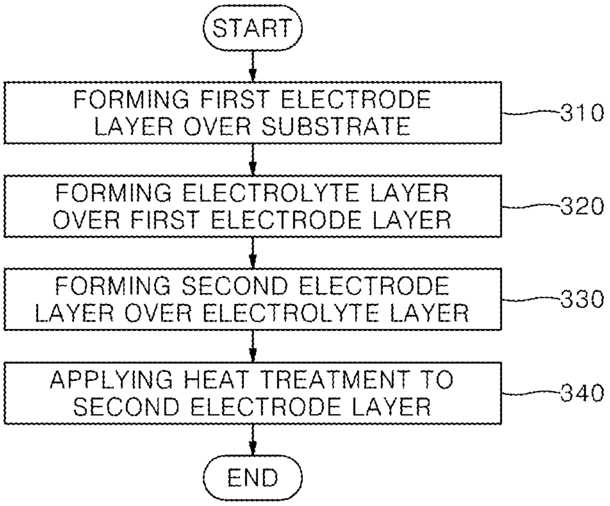

START
FORMING FIRST ELECTRODE LAYER OVER SUBSTRATE
310
FORMING ELECTROLYTE LAYER OVER FIRST ELECTRODE LAYER
320
FORMING SECOND ELECTRODE LAYER OVER ELECTROLYTE LAYER
330
APPLYING HEAT TREATMENT TO SECOND ELECTRODE LAYER
340
END

FIG. 4

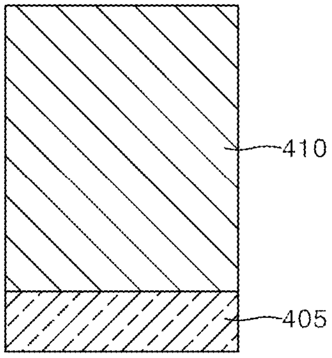


FIG. 5

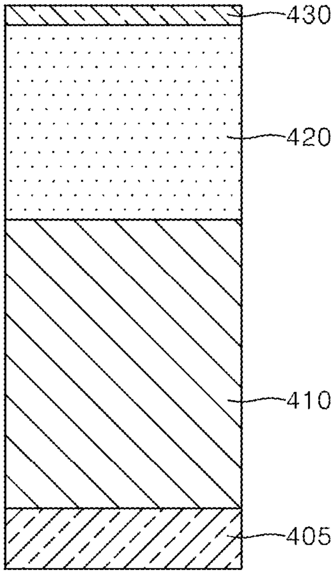


FIG. 6

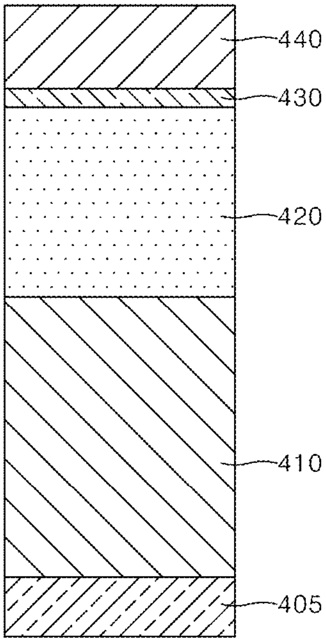


FIG. 7

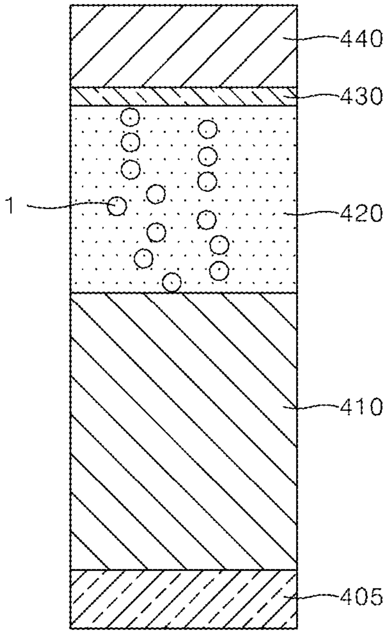


FIG. 8

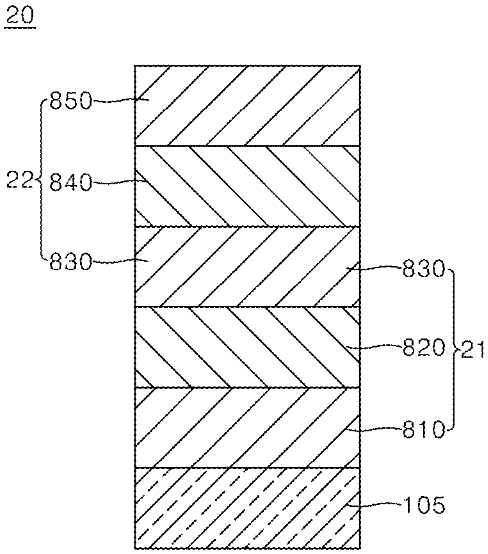
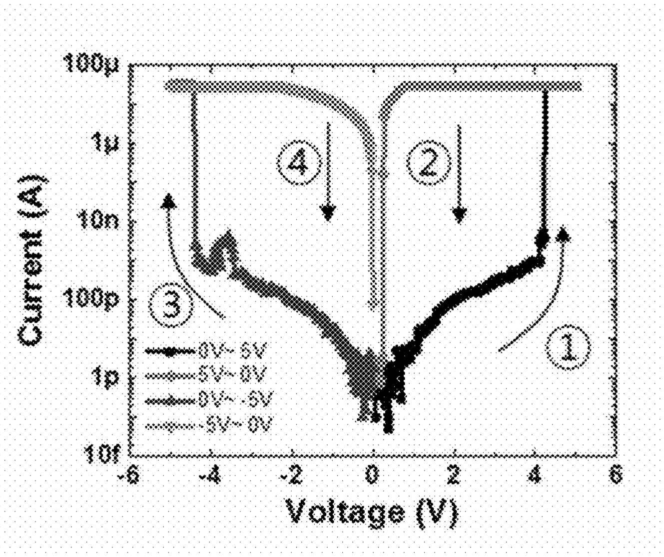


FIG. 9


100µ
1µ
10n
100p
1p
10f
Current (A)
-6
-4
-2
0
2
4
6
Voltage (V)
①
②
③
④
0V~5V
5V~0V
0V~-5V
-5V~0V

SWITCHING DEVICE, METHOD OF FABRICATING THE SAME, AND RESISTIVE RANDOM ACCESS MEMORY INCLUDING THE SWITCHING DEVICE AS A SELECTION DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims priority under 35 U.S.C 119(a) to Korean Patent Application No. 10-2016-0010338, filed on Jan. 27, 2016, which is herein incorporated by reference in its entirety.

BACKGROUND

1. Technical Field

Various embodiments of the present disclosure relate to a semiconductor memory and, more particularly, to a switching device, a method of fabricating the same, and a resistive random access memory including the switching device as a selection device.

2. Related Art

A cross-point memory array structure has been employed in a cell region of a memory device. More specifically, the cross-point memory array structure has been included in memories, such as a Resistive Random Access Memory (ReRAM), a Phase Change Random Access memory (PCRAM), a Magnetic Random Access Memory (MRAM) and so on, as a cell structure having a pillar, the pillar being interposed between electrodes disposed on different planes and intersecting with each other.

Meanwhile, in the cross-point memory array structure, there may be writing errors or reading errors on cell information due to a sneak current that occurs between adjacent cells. In order to suppress these errors, a selection device has been employed in a cell. As the selecting devices, switching devices, such as transistors, diodes, tunnel barrier devices, and ovonic threshold switches, have been suggested.

SUMMARY

According to an embodiment, there is provided a switching device. The switching device includes a first electrode and a second electrode that are disposed over a substrate, and an electrolyte layer disposed between the first electrode and the second electrode, the electrolyte layer including a porous oxide. The switching device performs a threshold switching operation on the basis of oxidation-reduction reaction of metal ions provided from the first electrode or the second electrode to the electrolyte layer.

According to an embodiment, there is provided a switching device. The switching device includes a first electrode, a porous oxide layer and a second electrode that are sequentially disposed over a substrate. One of the first electrode and the second electrode acts as an ion supplying part that provides metal ions to the porous oxide layer. The switching device is turned on as a conductive bridge is generated in the porous oxide layer by reduction of metal atoms from the metal ions when an absolute value of an external voltage applied between the first electrode and the second electrode increases to be greater than or equal to an absolute value of a turn-on threshold voltage. The switching device is turned off from the turned on state due to disconnection of at least a portion of the conductive bridge when the absolute value of the external voltage decreases to be smaller than or equal to an absolute value of a turn-off threshold voltage.

According to an embodiment, there is provided a resistive memory device. The resistive memory device includes a variable resistance device and a selection device that are disposed over a substrate. The selection device comprises a first electrode, a porous oxide layer including metal ions and a second electrode. The selection device performs a threshold switching operation on the basis of oxidation-reduction reaction of the metal ions.

According to an embodiment, there is provided a method of fabricating a switching device. The method includes forming a first electrode layer over a substrate, forming an electrolyte layer including porous oxide over the first electrode layer, forming a second electrode layer over the electrolyte layer and applying heat treatment to the second electrode layer to diffuse metal atoms in the second electrode layer into the electrolyte layer.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of a present disclosure will become more apparent in view of the attached drawings and accompanying detailed description, in which:

FIG. **1** is a cross-sectional view schematically illustrating a switching device according to an embodiment;

FIGS. **2**A and **2**B are schematic diagrams illustrating an operating method of a switching device according to an embodiment;

FIG. **3** is a flow chart illustrating a method of fabricating a switching device according to an embodiment;

FIGS. **4** to **7** are cross-sectional views illustrating a method of fabricating a switching device according to an embodiment;

FIG. **8** is a cross-sectional view illustrating a resistive memory device according to an embodiment; and

FIG. **9** is a current-voltage (I-V) graph illustrating operational characteristics of a switching device according to an embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The present disclosure will be described hereinafter with reference to the accompanying drawings, in which embodiments of the present disclosure are shown. In the drawings, the size, widths, and/or thickness of components may be slightly increased in order to clearly express the components of each device. The drawings are described in the observer's point overall, if an element is referred to be located on another element, it may be understood that the element is directly located on the other element, or an additional element may be interposed between the element and the other element. The same reference numerals refer to the same elements throughout the specification.

In addition, expression of the singular form should be understood to include the plural forms unless clearly used otherwise in the context. It will be understood that the terms "comprise" or "have" are intended to specify the presence of a feature, a number, a step, an operation, an element, a part or combinations thereof, but not used to preclude the presence or possibility of addition one or more other features, numbers, steps, operations, components, parts or combinations thereof. In addition, in performing a method or a fabricating method, each step constituting the method may be performed differently from the specified stipulated order as long as a specific sequence is not described apparently in the context. It means that each process may be performed in the same manner as stated order, may be performed substantially at the same time or may be performed in a reverse order.

In accordance with an embodiment of the present disclosure, there may be provided a switching device performing a threshold switching operation. A threshold switching operation of a switching device described in this specification will be understood, in which the switching device sequentially implements a turned-on state and a turned-off state, as described below, when an external voltage applied to the switching device varies.

At first, as an absolute value of the external voltage applied to the switching device gradually increases from an initial state, an operation current of the switching device may be nonlinearly increased after the applied external voltage becomes greater than a predetermined first threshold voltage. In accordance with this phenomenon, the switching device is turned on. After that, as the absolute value of the external voltage applied to the switching device gradually decreases from the turn-on state, the operation current of the switching device may be nonlinearly decreased after the applied external voltage becomes lower than a predetermined second threshold voltage. In accordance with this phenomenon, the switching device is turned off. As such, the switching device performs the threshold switching operation.

FIG. **1** is a cross-sectional view schematically illustrating a switching device **10** according to an embodiment.

Referring to FIG. **1**, the switching device **10** includes a first electrode **110**, an electrolyte layer **120**, and a second electrode **140** that are sequentially disposed on a substrate **105**. Additionally, an adhesion layer **130** may be disposed between the electrolyte layer **120** and the second electrode **140**. Although not illustrated, an adhesion layer may be additionally disposed between the electrolyte layer **120** and the first electrode **110**.

In an embodiment, the substrate **105** may be formed of silicon (Si) or gallium arsenic (GaAs), but embodiments are not limited thereto. In another embodiment, the substrate **105** may be formed of a ceramic, a polymer, or a metal, which can be processed by a semiconductor process. The substrate **105** may include integrated circuits formed therein.

Each of the first electrode **110** and the second electrode **140** may include any of a metal, a conductive metal nitride, and a conductive metal oxide. At least one of the first electrode **110** and the second electrode **140** may function as an ion supplying layer providing metal ions to the electrolyte layer **120**. Hereinafter, a case that the second electrode **140** disposed on the electrolyte layer **120** functions as the ion supplying layer will be described as an embodiment.

The first electrode **110** may include a conductive material selected from various metals, metal nitrides, and metal oxides that are employed in fabricating processes of silicon integrated circuits. In an embodiment, the first electrode **110** may include any of a metal such as aluminum (Al), tungsten (W), ruthenium (Ru), or the like, a metal nitride such as titanium nitride (TiN), tantalum nitride (TaN), tungsten nitride (WN), or the like, and a metal oxide such as ruthenium oxide (RuO_2), or the like.

The second electrode **140** may include a metal such as aluminum (Al), zinc (Zn), or magnesium (Mg). In an embodiment, the second electrode **140** may include a conductive material selected from various metals, metal nitrides, and metal oxides that are employed in fabricating processes of silicon integrated circuits. In an embodiment, the second electrode **140** may include an aluminum (Al) layer.

The second electrode **140** may be formed of a material having a relatively lower melting point than that of the first electrode **110**. Accordingly, a bonding force of metal atoms constituting the second electrode **140** may be relatively weaker than that of metal atoms constituting the first electrode **110**. As a result, metal ions **1** may be relatively easily introduced into the electrolyte layer **120** from the second electrode **140** when an external voltage is applied to the switching device **10**.

The electrolyte layer **120** may be disposed between the first electrode **110** and the second electrode **140**. The electrolyte layer **120** may accept the metal ions **1** introduced from the second electrode **140** when the external voltage is applied to the switching device **10**. The metal ion **1** may include an aluminum (Al) ion, a zinc (Zn) ion, or a magnesium (Mg) ion. The metal ion **1** may be an ion of a metal constituting the second electrode **140**.

In an embodiment, the metal ions **1** may be introduced into the electrolyte layer **120** before the external voltage is applied to the switching device **10**, by diffusing metal atoms constituting the second electrode **140** into the electrolyte layer **120** during a fabricating process that is to be described in connection with FIGS. **3** to **7**. Alternatively, as described above, the metal ions **1** may be introduced into the electrolyte layer **120** from the second electrode **140** when the switching device **10** operates by the applied external voltage.

The electrolyte layer **120** may include a material selected from various oxides that are employed to fabricate silicon integrated circuits. The electrolyte layer **120** may include a porous oxide. The porous oxide may include a silicon oxide or an aluminum oxide. In an embodiment, the electrolyte layer **120** may include a porous silicon oxide layer or a porous aluminum oxide layer. The electrolyte layer **120** may include a single silicon oxide layer or a single aluminum oxide layer, or may include a stack structure of two or more of the silicon oxide layer and the aluminum oxide layer. The porous oxide may have an amorphous phase. In addition, the porous oxide may have a composition that does not satisfy the stoichiometric ratio.

The adhesion layer **130** may be employed to increase an interfacial bonding force between the electrolyte layer **120** and the second electrode **140**. In an embodiment, the adhesion layer **130** may be a silicon layer. In some other embodiments, the adhesion layer **130** may be disposed between the electrolyte layer **120** and the first electrode **110**, or between the electrolyte layer **120** and the second electrode **140**, or both.

In the above-described embodiment, the second electrode **140** functions as the ion supplying layer. However, in some other embodiments, the first electrode **110** adjacent to the substrate **105** may function as the ion supplying layer instead of the second electrode **140**. In this embodiment, the first electrode **110** may include a metal such as aluminum (Al), zinc (Zn), or magnesium (Mg), and the first electrode **110** may be formed of a material having a lower melting point than that of the second electrode **140**.

FIGS. **2**A and **2**B are schematic diagrams illustrating an operating method of a switching device according to an embodiment. FIG. **2**A schematically illustrates an internal structure of the switching device in a turn-on state, and FIG. **2**B schematically illustrates the internal structure of the switching device whose state is changed from the turn-on state to a turn-off state. Hereinafter, the operating method of the switching device including a first operation mode and a second operation mode will be described using the switching device **10** illustrated in FIG. **1**. In this embodiment, the second electrode **140** may function as an ion supplying part providing metal ions into the electrolyte layer **120**.

Referring to FIG. **2**A, an external voltage is applied between the first electrode **110** and the second electrode **140** of the switching device **10** in an initial state. A power source **20***a* and a ground line **20***b* are provided to apply the external voltage to the switching device **10**.

In the first operation mode according to an embodiment, a positive bias is applied to the second electrode **140**, and a negative bias is applied to the first electrode **110**. Alternatively, a positive bias is applied to the second electrode **140**, and the first electrode **110** is grounded. While maintaining the polarity of the bias, the external voltage is applied to the switching device **10** so that an absolute value of the applied external voltage gradually increases. Due to the applied external voltage, an electric field is formed in the electrolyte layer **120**. Thus, metal ions **1** having positive charges are introduced from the second electrode **140** into the electrolyte layer **120** by the electric field, and the introduced metal ions **1** may be reduced into metal atoms **2** by electrons provided by the first electrode **110**. Then, as the absolute value of the applied external voltage gradually increases, the reduced metal atoms **2** may be sequentially arranged from an interface of the electrolyte layer **120** and the first electrode **110** to an inner portion of the electrolyte layer **120**.

When the applied external voltage reaches a predetermined first threshold voltage, the arranged metal atoms **2** form a conductive bridge across the electrolyte layer **120**, such that the first electrode **110** is electrically coupled to the second electrode **140** via the conductive bridge. When the conductive bridge is formed at a voltage greater than or equal to the first threshold voltage, the operation current of the switching device **10** may be increased nonlinearly. This state may be referred to as a turn-on state in the first operation mode of the switching device **10**, and the first threshold voltage may be defined as a turn-on threshold voltage.

After that, the absolute value of the external voltage applied between the first electrode **110** and the second electrode **140** of the switching device **10** in the turn-on state may gradually decrease. When the applied external voltage reaches a predetermined second threshold voltage, the reduced metal atoms **2** are re-oxidized, such that the reduced metal atoms **2** may be emitted into the electrolyte layer **120** in the form of metal ions **1**. Accordingly, as illustrated in FIG. **2**B, when the applied external voltage becomes smaller than or equal to the second threshold voltage, at least a portion of the conductive bridge is disconnected, and thus the operation current of the switching device **10** may be decreased nonlinearly. This state can be referred to as a turn-off state, and the second threshold voltage can be defined as a turn-off threshold voltage. The turn-off threshold voltage may be smaller than the turn-on threshold voltage. In other embodiments, the turn-off threshold voltage may be equal to the turn-on threshold voltage.

With respect to the re-oxidation of the reduced metal atoms **2**, it cannot be explicitly described by a particular theory. According to an example theory, as an external driving force to reduce the metal ion **1** is eliminated, a repulsive force generated between the reduced metal atoms **2** and the oxide of the electrolyte layer **120** is increased, and thus, the re-oxidation of the reduced metal atoms **2** may occur.

In the second operation mode according to an embodiment, a negative bias is applied to the second electrode **140**, and a positive bias is applied to the first electrode **110**. Alternatively, a negative bias is applied to the second electrode **140**, and the first electrode **110** is grounded. While maintaining the polarity of the bias, the external voltage gradually changes such that an absolute value of the applied external voltage increases. Due to the applied external voltage, an electric field is formed in the electrolyte layer **120**. Metal ions **1** distributed in the electrolyte layer **120** and electrons provided from the second electrode **140** are combined due to the electric field, and thus, the metal ions **1** may be reduced into metal atoms **2**.

As the absolute value of the applied external voltage increases, the reduced metal atoms **2** may be sequentially arranged from the interface of the electrolyte layer **120** and the second electrode **140** to an inner portion of the electrolyte layer **120**. When the absolute value of the applied external voltage reaches a predetermined first threshold voltage, the arranged metal atoms **2** form a conductive bridge across the electrolyte layer **120**, such that the first electrode **110** is electrically coupled to the second electrode **140** via the conductive bridge. When the conductive bridge is formed while the external voltage has the absolute value that is greater than or equal to that of the first threshold voltage, the operation current of the switching device **10** may be nonlinearly increased. This state may be referred to as a turn-on state in the second operation mode of the switching device **10**, and the first threshold voltage may be defined as a turn-on threshold voltage.

After that, the applied external voltage gradually changes, and thus the absolute value of the external voltage applied between the first electrode **110** and the second electrode **140** of the switching device **10** in the turned-on state may gradually decrease. When the absolute value of the applied external voltage reaches a predetermined second threshold voltage, the reduced metal atoms **2** may be re-oxidized, such that the reduced metal atoms **2** may be emitted into the electrolyte layer **120** in the form of metal ions **1**. Accordingly, as illustrated in FIG. **2**B, when the absolute value of the applied external voltage becomes smaller than or equal to the second threshold voltage, at least a portion of the conductive bridge is disconnected, and the operation current of the switching device **10** may be decreased nonlinearly. This state may be referred to as a turn-off state in the second operation mode of the switching device **10**, and the second threshold voltage may be defined as a turn-off threshold voltage. At this time, the absolute value of the turn-off threshold voltage may be smaller than the absolute value of the turn-on threshold voltage. In other embodiments, the turn-off threshold voltage may be equal to the turn-on threshold voltage.

With respect to the re-oxidation of the reduced metal atoms **2**, as described above in the first operation mode, the re-oxidation of the reduced metal atoms **2** may occur by the repulsive force generated between the reduced metal atoms **2** and the oxide of the electrolyte layer **120**.

In an embodiment, in the first or second operation mode, although the external voltage is not applied between the first electrode **110** and the second electrode **140**, metal ions **1** may be distributed in the electrolyte layer **120** in a sufficient density to perform the threshold switching operation. As illustrated in FIGS. **3** to **7**, the metal ions **1** may be provided into the electrolyte layer **120** by applying a heat treatment to the second electrode **140** of the switching device **10** such that metal atoms in the second electrode **140** are diffused into the electrolyte layer **120**.

The metal ions **1** provided to the electrolyte layer **120** by the heat treatment may react with electrons supplied from the second electrode **140** in the second operation mode, and thus the metal ions **1** may be reduced into the metal atoms

2. That is, even though the second operation mode is performed prior to the first operation mode, the threshold switching operation of the switching device **10** can be normally performed by the metal ions **1** that the heat treatment distributed in the electrolyte layer **120**.

In another embodiment, the second operation mode can be performed after the first operation mode is performed at least one time. Accordingly, after the first operation mode is performed, the metal ions **1** emitted into the electrolyte layer **120** may react with electrons provided from the second electrode **140** in the second operation mode, and thus the metal ions **1** may be reduced into the metal atoms **2**.

As described above, a switching device according to an embodiment shows a threshold switching characteristic in which its operation current varies nonlinearly as an applied external voltage reaches a turn-on threshold voltage or a turn-off threshold voltage.

FIG. **3** is a flow chart schematically illustrating a method of fabricating a switching device according to an embodiment. FIGS. **4** to **7** are cross-sectional views schematically illustrating the method of fabricating the switching device.

Referring to FIGS. **3** and **4**, a first electrode layer **410** is formed on a substrate **405** at step **310**. The substrate **405** may be formed of silicon (Si), gallium arsenide (GaAs), or the like, but embodiments are not limited thereto. The substrate **405** may be formed of a ceramic, a polymer, or a metal, which can be processed by a semiconductor process. The substrate **405** may include integrated circuits formed therein.

The first electrode layer **410** may include any one of a metal, a conductive nitride, and a conductive oxide. The first electrode layer **410** may include a conductive material selected from various metals, metal nitrides, and metal oxides, which are employed in fabricating processes of silicon integrated circuits.

In an embodiment, the first electrode layer **410** may include any of aluminum (Al), tungsten (W), ruthenium (Ru), titanium nitride (TiN), tantalum nitride (TaN), tungsten nitride (WN), ruthenium oxide (RuO_2), and the like. The first electrode layer **410** may include a single layer or a stacked structure of two or more of the above materials. In an embodiment, the first electrode layer **410** may be formed using any of a chemical vapor deposition (CVD) method, a sputtering method, an atomic layer deposition (ALD) method, and the like. The first electrode layer **410** may have a thickness of over about 50 nm.

Referring to FIGS. **3** and **5**, an electrolyte layer **420** is formed on the first electrode layer **410** at step **320**. The electrolyte layer **420** may include a porous silicon oxide layer or a porous aluminum oxide layer. In an embodiment, the electrolyte layer **420** may be formed using a physical vapor deposition (PVD) method or an atomic layer deposition (ALD) method. The process for forming the electrolyte layer **420** may be carried out at a temperature of about 50° C. to about 300° C. The electrolyte layer **420** formed through the above process does not satisfy the stoichiometric ratio, and may include a porous oxide having an amorphous phase. In an embodiment, the electrolyte layer **420** may have a thickness of about 2 nm to about 30 nm.

An adhesion layer **430** may be formed on the electrolyte layer **420**. The adhesion layer **430** may increase an interfacial bonding force between the electrolyte layer **420** and a second electrode layer **440** to be formed on the adhesion layer **430**. In an embodiment, the adhesion layer **430** may be a silicon layer. In an embodiment, the adhesion layer **430** may be formed using any of a chemical vapor deposition (CVD) method, a sputtering method, an atomic layer deposition (ALD) method, and the like. In an embodiment, the adhesion layer **430** may have a thickness of about 1 nm to about 5 nm. In some other embodiments, the adhesion layer **430** may be omitted.

Referring to FIGS. **3** and **6**, the second electrode layer **440** is formed over the electrolyte layer **420** at step **330**. The second electrode layer **440** may function as an ion supplying layer. The second electrode layer **440** may be formed of a material having a lower melting point than that of the first electrode layer **410**. Accordingly, a bonding energy of atoms constituting the second electrode layer **440** may be relatively lower than a bonding energy of atoms constituting the first electrode layer **410**. In an embodiment, the second electrode layer **440** may include one of an aluminum (Al) layer, a zinc (Zn) layer, a magnesium (Mg) layer, and a combination thereof. In an embodiment, the second electrode layer **440** may be formed using a physical vapor deposition (PVD) method, a chemical vapor deposition (CVD) method, or an atomic layer deposition (ALD) method. The second electrode layer **440** may have a thickness of about 5 nm to about 20 nm.

Referring to FIGS. **3** and **7**, a heat treatment may be applied to the second electrode layer **440** at step **340**. Through the heat treatment, metal atoms in the second electrode layer **440** may be diffused into the electrolyte layer **420**. The metal atoms diffused into the electrolyte layer **420** may be accepted into the electrolyte layer **420** in the form of metal ions **1**. The heat treatment applied to the second electrode layer **440** may be carried out at a temperature of about 100° C. to about 500° C. The heat treatment may be carried out in an inert gas ambience.

Then, the first electrode layer **410**, the electrolyte layer **420**, the adhesion layer **430**, and the second electrolyte layer **420** are patterned to fabricate the switching device **10** described above with reference to FIGS. **1**, **2**A, and **2**B.

According to an embodiment, the first electrode layer **410**, the electrolyte layer **420**, the adhesion layer **430**, and the second electrode layer **440** may be formed of materials that can be applied to a conventional process of fabricating silicon integrated circuits. In an embodiment, the first electrode layer **410** may be a titanium nitride (TiN) layer, the electrolyte layer **420** may be a porous silicon oxide layer, the adhesion layer **430** may be a silicon (Si) layer, and the second electrode layer **440** may be an aluminum (Al) layer.

Meanwhile, in some other embodiments, the heat treatment may be omitted. In this embodiment, metal ions may be supplied into an electrolyte layer by applying an external voltage to a switching device in a first operation mode, as described above with reference to FIGS. **1**, **2**A, and **2**B.

As described above, in the method of fabricating the switching device according to the embodiment, structural reliability of the switching device with respect to a material may be achieved by employing materials that can be applied to a conventional process of fabricating silicon integrated circuits. In addition, since the conventional process of fabricating the silicon integrated circuits is reliable, it is possible to improve the productivity in fabrication of the switching device.

FIG. **8** is a cross-sectional view schematically illustrating a resistive memory device **20** according to an embodiment.

Referring to FIG. **8**, the resistive memory device **20** includes a variable resistance device **21** and a selection device **22** that are disposed on a substrate **105**. The variable resistance device **21** includes a first memory electrode **810**, a resistance change memory layer **820**, and a second memory electrode **830** that are sequentially disposed on the substrate **105**. The variable resistance device **21** may have a memory characteristic in which resistance of the device **21** varies depending on an external voltage applied thereto and the varied resistance is stored in the device **21** when the applied external voltage is eliminated. In an embodiment, the variable resistance device **21** may be included in a memory cell of a random access memory (RRAM), a phase change random access memory (PRAM), or a magnetic random access memory (MRAM).

Each of the first memory electrode **810** and the second memory electrode **830** may include a metal, a conductive nitride, a conductive oxide, or the like. In an embodiment, each of the first memory electrode **810** and the second memory electrode **830** may include any of gold (Au), platinum (Pt), copper (Cu), silver (Ag), ruthenium (Ru), titanium (Ti), iridium (Ir), tungsten (W), titanium nitride (TiN), tantalum nitride (TaN), and a combination thereof.

In an embodiment, the resistance change memory layer **820** may include a metal oxide such as a titanium oxide (TiO_{2-x}), an aluminum oxide (Al_2O_3), a nickel oxide (NiO_x), a copper oxide (Cu_xO), a zirconium oxide (ZrO_2), a manganese oxide (MnO_2), a hafnium oxide (HfO_2), a tungsten oxide (WO_3), a tantalum oxide (Ta_2O_{5-x}), a niobium oxide (Nb_2O_5), an iron oxide (Fe_3O_4), or the like. In another embodiment, the resistance change memory layer **820** may include a perovskite material such as PCMO ($Pr_{0.7}Ca_{0.3}MnO_3$), LCMO($La_{1-x}Ca_xMnO_3$), BSCFO ($Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$), YBCO($YBa_2Cu_3O_{7-x}$), (Ba,Sr) TiO_3(Cr, Nb-doped), $SrZrO_3$(Cr,V-doped), (La, Sr)MnO_3, $Sr_{1-x}La_xTiO_3$, $La_{1-x}Sr_xFeO_3$, $La_{1-x}Sr_xCoO_3$, $SrFeO_{2.7}$, $LaCoO_3$, $RuSr_2GdCu_2O_3$, $YBa_2Cu_3O_7$, or the like. In still another embodiment, the resistance change memory layer **820** may include a material of a selenide series such as Ge_xSe_{1-x}(Ag,Cu,Te-doped), or a metal sulfide such as Ag_2S, Cu_2S, CdS, ZnS, or the like.

The selection device **22** includes a first electrode **830**, a porous oxide layer **840**, and a second electrode **850**. The first electrode **830** may be the second memory electrode **830** of the variable resistance device **21**. However, in some other embodiments, another electrode may be disposed on the second memory electrode **830** of the variable resistance device **21**, and may be used as a first electrode of the selection device **22**.

The selection device **22** may have substantially the same configuration as the switching device **10** of the embodiment described above with reference to FIGS. **1**, **2A**, and **2B**. In this embodiment, the porous oxide layer **840** may correspond to the electrolyte layer **120** of the switching device **10**. The porous oxide layer **840** may accept metal ions provided from an ion supplying layer that is one of the first electrode **830** and the second electrode **850**. When an external voltage is applied to the selection device **22**, a conductive bridge is generated or disconnected in the porous oxide layer **840** due to oxidation or reduction of the metal ions accepted by the porous oxide layer **840**, and thus the selection device **22** may perform a threshold switching operation. Although it is not illustrated, an adhesion layer may be disposed between the porous oxide layer **840** and the second electrode **850**, between the porous oxide layer **840** and the first electrode **830**, or both.

The resistive memory device **20** includes a structure in which the variable resistance device **21** and the selection device **22** are sequentially stacked on the substrate **105**. In another embodiment, the selection device **22** and the variable resistance device **21** may be sequentially stacked on the substrate **105**. That is, the selection device **22** is disposed between the variable resistance device **21** and the substrate **105**. In this embodiment, the second electrode of the selection device **22** may be the first memory electrode of the variable resistance device **21**.

In a fabricating method of the resistive memory device **20**, the layers for the variable resistance device and the layers for the selection device are formed on the substrate, and then the layers are patterned. As a result, the resistive memory device **20** including the variable resistance device **21** and the selection device **22** of FIG. **8** may be manufactured on the substrate **105**.

The layers for the variable resistance device may be formed using any of a known chemical vapor deposition (CVD) method, a sputtering method, an atomic layer deposition (ALD) method, and the like. Also, the layers for the selection device may be formed using the method described above with reference to FIGS. **3** to **7**.

FIG. **9** is a current-voltage (I-V) graph illustrating operational characteristics of a switching device according to an embodiment. The current-voltage (I-V) graph was obtained by performing the following experiment.

A titanium nitride (TiN) layer was formed on an insulative substrate as a first electrode layer using a sputtering method, and had a thickness of about 100 nm. A silicon oxide (SiO_2) layer was formed as an electrolyte layer, and had a thickness of about 30 nm. The silicon oxide (SiO_2) layer was formed using an ALD method at a temperature of about 300° C. A silicon (Si) layer was formed on the silicon oxide (SiO_2) layer as an adhesion layer in a thickness of about 5 nm. The silicon (Si) layer was formed using the ALD method. An aluminum (Al) layer was formed on the silicon (Si) layer as a second electrode layer. The aluminum (Al) layer functioned as an ion supplying layer. The aluminum (Al) layer was formed in a thickness of about 5 nm. After that, the titanium nitride (TiN) layer, the silicon oxide (SiO_2) layer, the silicon (Si) layer, and the aluminum (Al) layer were patterned to fabricate the switching device.

In a first operation mode of the switching device, a positive external voltage was applied to the second electrode, and the first electrode was grounded. The external voltage applied to the second electrode gradually varied in a range of 0 V to 5 V. An operation current of the switching device was measured while the external voltage varied. At this time, a compliance current, i.e., an upper limit of the operation current, was limited to 30 μA. After the switching device was turned on by the external voltage in the range of 0 V to 5 V, the operation current of the switching device was measured while the external voltage decreased from the turned-on state.

In addition, in a second operation mode of the switching device, a negative external voltage was applied to the second electrode, the first electrode was grounded, and the external voltage gradually varied in a rage of 0 V to −5 V. The operation current of the switching device was measured while the external voltage varied. At this time, the compliance current was limited to 30 μA. After the switching device was turned on by the applied external voltage in the range of 0 V to −5 V, the operation current of the switching device was measured while an absolute value of the external voltage decreased from the turned-on state.

Referring to FIG. **9**, reference numerals ① and ② show current-voltage graphs in the first operation mode, and reference numerals ③ and ④ show current-voltage graphs in the second operation mode.

In the first operation mode, as the external voltage increased, the operation current rapidly increased when the applied external voltage reached 4 V, and it means that 4 V is a turn-on threshold voltage. Also, as the applied external voltage decreased from the turn-on threshold voltage, the operation current rapidly decreased when the applied external voltage reached 0.3 V, and therefore, it means that 0.3 V is a turn-off threshold voltage.

In the second operation mode, as an absolute value of the external voltage increased, the operation current rapidly increased when the external voltage reached −4.2 V, and therefore, −4.2 V becomes a turn-on threshold voltage. Also, as the absolute value of the external voltage decreased from the turn-on threshold voltage, the operation current rapidly decreased when the external voltage reached −0.3 V, therefore, −0.3 V becomes a turn-off threshold voltage. As such, the switching device of the embodiment can be found to represent a threshold switching characteristic in both of the first and second operation modes.

Embodiments of the present disclosure have been disclosed above for illustrative purposes. Those skilled in the art will appreciate that various modifications, additions and substitutions are possible, without departing from the scope and spirit of the present disclosure as disclosed in the accompanying claims.

What is claimed is:

1. A switching device comprising:

a first electrode and a second electrode that are disposed over a substrate;

an electrolyte layer disposed between the first electrode and the second electrode, the electrolyte layer including a porous oxide layer, and

at least one adhesion layer disposed between the electrolyte layer and the first electrode, between the electrolyte layer and the second electrode, or both,

wherein at least one of the first electrode and the second electrode acts as an ion supplying part that provides metal ions to the porous oxide layer,

wherein the at least one adhesion layer is disposed between the one or more ion supplying parts and the porous oxide layer,

wherein the switching device performs a threshold switching operation on the basis of oxidation-reduction reactions of metal ions provided from the first electrode or the second electrode to the electrolyte layer,

wherein the switching device is turned on when an absolute value of a varying external voltage applied between the first electrode and the second electrode increases to be greater than or equal to an absolute value of a turn-on threshold voltage,

wherein the switching device is turned off from the turned-on state when the absolute value of the varying external voltage applied between the first electrode and the second electrode decreases to be smaller than or equal to an absolute value of a turn-off threshold voltage, and

wherein the turn-on state corresponds to a low resistance state, and the turn-off state corresponds to a high resistance state.

2. The switching device of claim **1**,

wherein the porous oxide layer comprises a porous silicon oxide layer or a porous aluminum oxide layer, and

wherein the metal ion comprises any one of an aluminum ion, a zinc ion, and a magnesium ion.

3. The switching device of claim **1**, wherein the absolute value of the turn-off threshold voltage is smaller than the absolute value of the turn-on threshold voltage.

4. The switching device of claim **1**, wherein the absolute value of the turn-off threshold voltage is equal to the absolute value of the turn-on threshold voltage.

5. The switching device of claim **1**,

wherein the switching device is turned on by generation of a conductive bridge in the electrolyte layer when the absolute value of the varying external voltage is greater than or equal to the absolute value of the turn-on threshold voltage, and

wherein the switching device is turned off by a disconnection of at least a portion of the conductive bridge when the absolute value of the varying external voltage is smaller than or equal to the absolute value of the turn-off threshold voltage.

6. The switching device of claim **5**,

wherein the conductive bridge is generated in the electrolyte layer by the reduction of metal atoms from the metal ions, and

wherein the conductive bridge is disconnected due to the oxidation of the metal atoms into the metal ions.

7. A switching device comprising:

a first electrode, an electrolyte layer, and a second electrode that are sequentially disposed over a substrate, the electrolyte layer including a porous oxide layer, and

an adhesion layer,

wherein one of the first electrode and the second electrode acts as an ion supplying part that provides metal ions to the porous oxide layer,

wherein the adhesion layer is disposed between the porous oxide layer and the ion supplying part,

wherein the switching device is turned on as a conductive bridge is generated in the porous oxide layer by reduction of metal atoms from the metal ions when an absolute value of a varying external voltage applied between the first electrode and the second electrode increases to be greater than or equal to an absolute value of a turn-on threshold voltage, and

wherein the switching device is turned off from the turned-on state due to disconnection of at least a portion of the conductive bridge when the absolute value of the varying external voltage decreases to be smaller than or equal to an absolute value of a turn-off threshold voltage.

8. The switching device of claim **7**,

wherein the porous oxide layer comprises a porous silicon oxide layer or a porous aluminum oxide layer, and

wherein the ion supplying part comprises any one of an aluminum layer, a magnesium layer, and a zinc layer.

9. A method of fabricating a switching device, the method comprising:

forming a first electrode layer over a substrate;

forming an electrolyte layer including a porous oxide layer over the first electrode layer;

forming a second electrode layer over the electrolyte layer;

applying heat treatment to the second electrode layer to diffuse metal atoms in the second electrode layer into the electrolyte layer, and

wherein the method further comprises forming an adhesion layer between the electrolyte layer and the second electrode layer, the adhesion layer including a silicon layer,

wherein the switching device is turned on when an absolute value of a varying external voltage applied between the first electrode layer and the second electrode layer increases to be greater than or equal to an absolute value of a turn-on threshold voltage,

wherein the switching device is turned off from the turned-on state when the absolute value of the varying external voltage applied between the first electrode layer and the second electrode layer decreases to be smaller than or equal to an absolute value of a turn-off threshold voltage, and

wherein the turn-on state corresponds to a low resistance state, and the turn-off state corresponds to a high resistance state.

10. The method of claim **9**, wherein the first electrode layer comprises any one of a metal, a conductive nitride, and a conductive oxide.

11. The method of claim **9**, wherein forming the electrolyte layer comprises forming a porous silicon oxide layer or a porous aluminum oxide layer over the first electrode layer.

12. The method of claim **9**, wherein forming the electrolyte layer is performed using a physical vapor deposition (PVD) or an atomic layer deposition (ALD) at a temperature of about 50° C. to about 300° C.

13. The method of claim **9**, wherein forming the second electrode layer is performed using any one of a physical vapor deposition (PVD), a chemical vapor deposition (CVD), and an atomic layer deposition (ALD).

14. The method of claim **9**, wherein forming the second electrode layer comprises forming any one of an aluminum layer, a zinc layer, and a magnesium layer.

15. The method of claim **9**, wherein applying the heat treatment to the second electrode layer is performed at a temperature of about 100° C. to about 500° C. in an inert gas ambience.

* * * * *