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Inventor(s)	Lin; Yu-Yu et al.

Integrated circuit structure and method for operating the same

Abstract

The integrated circuit structure includes a substrate and a first resistive memory string over the substrate. The first resistive memory string includes memory cells, and each of the memory cells includes a word line transistor and a resistor. The word line transistor includes a channel region, a gate over the channel region, and a plurality of source/drain regions on opposite sides of the channel region. The resistor is over the word line transistor and is connected with the word line transistor in parallel. The word line transistors of two adjacent memory cells share a same one of the source/drain regions, and the memory cells are connected in series using the sharing ones of the source/drain regions.

Inventors:	Lin; Yu-Yu (New Taipei, TW), Lee; Feng-Min (Hsinchu, TW)
Applicant:	MACRONIX INTERNATIONAL CO., LTD. (Hsinchu, TW)
Family ID:	1000008764550
Assignee:	MACRONIX INTERNATIONAL CO., LTD. (Hsinchu, TW)
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Primary Examiner: Lappas; Jason

Attorney, Agent or Firm: McClure, Qualey & Rodack, LLP

Background/Summary

BACKGROUND

Field of Invention

(1) The present invention relates to an integrated circuit structure. More particularly, the present invention relates to a method for forming an integrated circuit structure and a method for operating an integrated circuit structure.

Description of Related Art

(2) The semiconductor industry has experienced rapid growth due to continuous improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, this improvement in integration density has come from repeated reductions in minimum feature size, which allows more components to be integrated into a given area.

SUMMARY

(3) The invention provides an integrated circuit structure (IC structure). The IC structure includes a substrate and a first resistive memory string over the substrate. The first resistive memory string includes memory cells, and each of the memory cells includes a word line transistor and a resistor. The word line transistor includes a channel region, a gate over the channel region, and a plurality of source/drain regions on opposite sides of the channel region. The resistor is over the word line transistor and is connected with the word line transistor in parallel. The word line transistors of two

adjacent memory cells share a same one of the source/drain regions, and the memory cells are connected in series using the sharing ones of the source/drain regions.

(4) In some embodiments, the each of the memory cells further includes a pair of contacts over the source/drain regions. The resistor is over a first one of the pair of contacts and free from coverage of a second one of the pair of contacts.

(5) In some embodiments, the each of the memory cells further includes a metal line laterally extending from above the resistor across the gate to above the second one of the pair of contacts. The resistor is connected with the word line transistor in parallel using the pair of contacts and the metal line.

(6) In some embodiments, from a top view, the metal lines of the memory cells are arranged in two rows with each of the metal lines being shifted relative to a next one of the metal lines along lengthwise directions of the gates.

(7) In some embodiments, the IC structure further includes a string select transistor and a ground select line transistor. The string select transistor has a source/drain region electrically coupled to a first terminal one of the source/drain regions in the first resistive memory string. The ground select line transistor has a source/drain region electrically coupled to a second terminal one of the source/drain regions in the first resistive memory string. A gate of the string select transistor is electrically coupled to a gate of the ground select line transistor.

(8) In some embodiments, the IC structure further includes a second resistive memory string and an assist transistor. The assist transistor is electrically coupled a first terminal one of source/drain regions in the second resistive memory string to the second terminal one of the source/drain regions in the first resistive memory string.

(9) The invention provides an integrated circuit structure (IC structure). The IC structure includes a substrate having a diffusion region thereon and a resistive memory string. The resistive memory string includes first and second sub-strings, a first metal line, and a third metal contact. The first sub-string includes first and second gates extending over the diffusion region, and a first metal contact over the diffusion region and between the first and second gates. The second sub-string includes third and fourth gates extending over the diffusion region, and a second metal contact over the diffusion region and between the third and fourth gates. The first metal line laterally extends from above the first metal contact of the first sub-string across the second and third gates to above the second metal contact of the second sub-string. The third metal contact is over the diffusion region and between the second and third gates. The third metal contact is configured to applied with an operation voltage.

(10) In some embodiments, the first and second metal contacts define a metal contact-free region therebetween underlying the first metal line.

(11) In some embodiments, the second sub-string further includes fourth and fifth metal contacts, a first resistor, and a second metal line. The fourth and fifth metal contacts are over the diffusion region and at opposite sides of the fourth gate. The first resistor is over the fourth metal contact. The second metal line laterally extends from above the first resistor across the fourth gate to above the fifth metal contact.

(12) In some embodiments, the first and second metal contacts are arranged at a first row, and the third, fourth, and fifth metal contacts are arranged at a second row.

(13) In some embodiments, the first sub-string further includes sixth and seventh metal contacts, a second resistor, and a third metal line. The sixth and seventh metal contacts are over the diffusion region and at opposite sides of the first gate. The second resistor is over the sixth metal contact. The third metal line laterally extends from above the second resistor across the first gate to above the seventh metal contact.

(14) In some embodiments, the first and second metal contacts are arranged at a first row, and the third, fourth, fifth, sixth, and seventh metal contacts are arranged at a second row.

(15) In some embodiments, the IC structure further includes a resistor vertically between the first

metal contact and the first metal line.

(16) The invention provides a method for operating an integrated circuit structure (IC structure). The IC structure includes a resistive memory string over a substrate. The resistive memory string has a plurality of sub-strings connected in series. Each of the sub-strings includes a plurality of word line transistors and a pair of terminal transistors connected in series, thereby forming a pickup terminal between two of the terminal transistors respectively in adjacent two of the sub-strings. The each of the sub-strings further includes a plurality of resistors, each connected in parallel with a respective one of the word line transistors. The method includes alternating applying a first operation voltage and a second operation voltage on the pickup terminals of the resistive memory string; performing a program operation on the resistive memory string; performing an erase operation on the resistive memory string.

(17) In some embodiments, the first operation voltage is a programming voltage, and the second operation voltage is a ground voltage.

(18) In some embodiments, the step of performing the program operation or the step of performing the erase operation includes activating the pair of terminal transistors of one of the sub-strings, the one of the sub-strings acting as a selected cell group. The step of activating allows for forming a voltage difference between the pair of terminal transistors in the one of the sub-strings, facilitating a current flowing through the one of the sub-strings.

(19) In some embodiments, the method further includes deactivating one of the word line transistors in the one of the sub-strings, allowing for the current flowing through the resistor connected in parallel with the deactivated one of the word line transistors.

(20) In some embodiments, the method further includes activating one of the word line transistors in the one of the sub-strings, allowing for the current flowing through the activated one of the word line transistors but bypassing the resistor connected in parallel with the activated one of the word line transistors.

(21) In some embodiments, the step of performing the program operation or the step of performing the erase operation includes activating a first one of the pair of terminal transistors in one of the sub-strings; deactivating a second one of the pair of terminal transistors in the one of the sub-strings, the one of the sub-strings acting as an operation voltage inhibition region. The step of activating accompanying the step of deactivating allows for a consistent voltage between the pair of terminal transistors in the one of the sub-strings, eliminating an operation disturbance in the one of the sub-strings.

(22) In some embodiments, the method further comprises activating the word line transistors in the one of the sub-strings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) The invention can be more fully understood by reading the following detailed description of the embodiment, with reference made to the accompanying drawings as follows:

(2) FIG. 1A is a schematic diagram of a memory cell in accordance with some embodiments of the present disclosure.

(3) FIG. 1B illustrates a schematic circuit diagram of a resistive memory string including a plurality of memory cells in accordance with some embodiments of the present disclosure.

(4) FIG. 1C illustrates a schematic top view of a semiconductor structure including a resistive memory string in accordance with some embodiments of the present disclosure.

(5) FIGS. 1D and 1E illustrate schematic cross-sectional views obtained from reference cross-sections D1-D1' and E1-E1' in FIG. 1C.

(6) FIGS. 1F and 1G illustrate schematic top views of semiconductor structures including resistive

memory strings with circuits for operating the resistive memory strings in accordance with some embodiments of the present disclosure.

(7) FIG. 2A illustrates a schematic circuit diagram of a resistive memory string in accordance with some embodiments of the present disclosure.

(8) FIGS. 2B and 2C illustrate schematic equivalent circuit diagrams of methods for operating the resistive memory string in FIG. 2A.

(9) FIG. 2D illustrates a schematic top view of a semiconductor structure including a resistive memory string in accordance with some embodiments of the present disclosure.

(10) FIGS. 2E and 2F illustrate schematic cross-sectional views obtained from reference cross-sections E2-E2' and F2-F2' in FIG. 2D.

(11) FIG. 3A illustrates a schematic circuit diagram of a resistive memory string in accordance with some embodiments of the present disclosure.

(12) FIG. 3B illustrates a schematic top view of a semiconductor structure including a resistive memory string in accordance with some embodiments of the present disclosure.

(13) FIG. 3C illustrates a local enlarged view of a region in FIG. 3B.

(14) FIGS. 3D and 3E illustrate schematic cross-sectional views obtained from reference cross-sections D3-D3' and E3-E3' in FIG. 3B.

DETAILED DESCRIPTION

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

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

(17) As used herein, “around,” “about,” “approximately,” or “substantially” may mean within 20 percent, or within 10 percent, or within 5 percent of a given value or range. One skilled in the art will realize, however, that the value or range recited throughout the description are merely examples, and may be reduced with the down-scaling of the integrated circuits. Numerical quantities given herein are approximate, meaning that the term “around,” “about,” “approximately,” or “substantially” can be inferred if not expressly stated.

(18) Resistive memory devices, known as ReRAMs, offer diverse array configurations, including the NOR-like and NAND-like setups. The NAND-type ReRAM string can be used in the mixed-mode matrix-vector multiplication (MVM) architecture. Within this architecture, each weight unit cell can be designed with a resistive memory cell in parallel with a transistor. These memory cells can vary in type, from ReRAMs to PCMs (phase change memories). When combined, they can form a serially connected NAND-type resistive memory string. However, this architecture faces challenges during specific operations like reading or programming/erasing. For instance, accessing a selected memory cell requires turning off its associated transistor, while transistors in unselected

cells stay active. This design choice, combined with the serial connection of multiple resistive memory cells, can lead to increased series resistance, which can effect the efficiency of the selected memory cell.

(19) Therefore, the present disclosure in various embodiments provides a layout to improve the long NAND-type resistive memory string, such that the series (or loading) resistance associated with the selected memory cell can be decreased. An additional pickup connection to the long NAND-type resistive memory string is introduced. The additional pickup connection can divide the lengthy resistance string (R-string) into shorter. Furthermore, an inhibit scheme on the non-selected memory cells can be applied on the resistive memory string, ensuring the non-selected memory cells remain undisturbed during operations.

(20) Reference is made to FIGS. 1A-1E. FIG. 1A is a schematic diagram of a memory cell **101** in accordance with some embodiments of the present disclosure. FIG. 1B illustrates a schematic circuit diagram of a resistive memory string **100** including a plurality of memory cells **101** in accordance with some embodiments of the present disclosure. In some embodiments, the resistive memory string **100** can be an NAND-type resistive memory string. FIG. 1C illustrates a schematic top view of a semiconductor structure **10** including the resistive memory string **100** in accordance with some embodiments of the present disclosure. FIGS. 1D and 1E illustrate schematic cross-sectional views obtained from reference cross-sections D1-D1' and E1-E1' in FIG. 1C.

(21) As shown in FIG. 1A, the memory cell **101** can include a current-carrying node **102**, a current-carrying node **103**, a control terminal **104**, a transistor **105**, and a programmable resistor **106**. In some embodiments, the memory cell **101** can be a variable resistance cell, and the programmable resistor **106** can be interchangeably referred to as a resistive memory cell. A voltage V_s on the first current-carrying node **102** can be characterized as a source voltage for the memory cell **101**, and a voltage V_D on the second current-carrying node **103** can be characterized as a drain voltage for the memory cell **101**. The transistor **105** and the programmable resistor **106** are connected in parallel to the current-carrying nodes **102** and **103**. The transistor **105** has a gate connected to the control terminal **104**. The control terminal **104** can correspond to a word line (e.g., word lines **120-124** as shown FIG. 1C) in a memory array. A voltage V_G on the control terminal **104** can be characterized as a gate voltage for the transistor **105**.

(22) In some embodiments, a cell current can be applied to the current-carrying node **103**, having a current amplitude that is set in design, or adjustable, to establish a voltage drop in the memory cell **101**, depending on the voltage range of the voltage sense amplifier, and the resistance values in the memory cells for the programmable resistor **106**. The current amplitude can be tuned according to a particular embodiment of the memory array, so that a usable range of voltages can be generated on the resistive memory string **100** (see FIG. 1B) for supply to the summing node. Also, the range of programmable resistances of the programmable resistor **106** and the configuration of the programmable threshold of the transistor **105** can be designed to operate with the selected current level and a specified sensing range.

(23) In some embodiments, the transistor **105** can be implemented using a MOS transistor, having an n-channel or a p-channel, configured to operate as a switch that provides a low resistance path when on, effectively bypassing the programmable resistor **106**, so that that the voltage drop across the memory cell **101** can be small; and that provides a high resistance path when off, effectively blocking current through the switch, so that the voltage drop across the memory cell **101** is a function primarily of the resistance of the programmable resistance and the current through the memory cell **101**.

(24) As shown in FIG. 1B, the resistive memory string **100** may include a plurality of memory cells **101** where each of the memory cells **101** can include the transistor **105** and the programmable resistor **106** electrically connected in parallel. In the resistive memory string **100**, a current direction plays a role in manipulating the resistance of specific programmable resistors **106**. To achieve this, each memory cell **101** in the resistive memory string **100** is equipped with a parallel

transistor **105**. When the aim is to program the resistance of the programmable resistor **106** in the target memory cell **101**, the associated parallel transistor **105** in that target cell is turned off. This action isolates the programmable resistors **106**, ensuring that the programming current flows directly through it. Concurrently, to ensure the rest of the memory string **100** remains operational and the current doesn't mistakenly alter other programmable resistors **106**, the parallel transistors **105** in all other memory cells **101** within the resistive memory string **100** are kept turned on. This regulation can allow precise control over individual programmable resistors **106** in the memory string **100**, ensuring accurate data storage and retrieval.

(25) By way of example and not limitation, the resistive memory string **100** may include five memory cells **101** in series between a summing node **107** and a reference line (e.g., a ground line **108**). Other embodiments may contain more or fewer number of memory cells **101**. The summing node **107** is coupled to a voltage sensing sense amplifier to generate a signal representing the sum-of-products output of resistive memory string **100**. A current source **109** is coupled to the resistive memory string **100** to apply a constant current during the sensing operation. In some embodiments, five word lines can be coupled to the control terminals **104** of the memory cells **101** in each of the resistive memory strings **100** in the memory array. In some embodiments, a voltage applied to the control terminals **104** (or word lines) correspond to the variable inputs **n1**, **n2**, **n3**, **n4**, and **n5**. In some embodiments, the transistor **105** can be interchangeably referred to as a word line transistor.

(26) In some embodiments, the memory cells **101** have weights set as a function of the current in the resistive memory string **100**, the threshold voltage (V_t) of the transistor **105** in the memory cell **101**, and the programmed resistance of the resistor **106**. The variable resistance of each of the memory cells **101** in the resistive memory string **100** is a function of the current in the resistive memory string **100**, the threshold voltage (V_t) of the transistor **105** in the memory cell **101**, a voltage applied on the word line to the gate of the memory cell **101**, and the programmed resistance of the resistor **106**.

(27) As shown in FIG. 1C, the resistive memory string **100** can include a sequence of source/drain regions **110-115**, which act as source/drain terminals of a sequence of the five transistors **105** in this illustration. The gates of the five transistors **105** can be provided on word lines **120-124**. Parallel resistors **106** are implemented in each of the memory cells **101** using a current path that bridges the transistor **105**. Contacts **198**, **199** can connect to overlying conductors (not shown), which can connect to other metal connections of a memory string, or to peripheral circuitry supporting the sum-of-products configuration. In some embodiments, the contacts **198** and **199** can be interchangeably referred to as pickup connections.

(28) Specifically, the memory cells **101** can be constructed after a contact formation process, and a subsequent metal routing process can be performed to connect two of the memory cells **101** with each other. Every source/drain region (e.g., source/drain regions **111-114**) in the resistive memory string **100** can be interconnected with two adjacent source/drain regions, excluding the source/drain region at the ending terminal ones (e.g., source/drain regions **110** and **115**) of the resistive memory string **100**. Each conductive terminal has dual contacts (e.g., two of the contacts **170-175** and the contacts **160-164** (see FIGS. 1D and 1E)) to facilitate these interconnections with neighboring source/drain regions. The metal routing (e.g., metal connections **130-134**) can connect the memory cell **101** using one of the contacts (either from the contacts **160-164** or **170-174**) to another one of the contacts on the neighboring conductive terminal, thereby constructing the resistive memory string **100**.

(29) With the configuration of the memory cells **101** containing parallel resistors **106** bridging the transistors **105**, and the source/drain regions **110-115** acting as source/drain terminals, the design can be compact. This layout can allow for higher memory density, which means more data can be stored in a smaller area. The design offers a versatile method of interconnecting the memory cells **101**. Every source/drain region (e.g., the source/drain regions **111-114**) connects to two neighboring terminals, except at the ending terminal ones (e.g., the source/drain regions **110** and **115**). This

flexibility can improve data flow, potentially speeding up read/write operations.

(30) Specifically, in a first one of the memory cells **101** formed over the source/drain regions **110** and **111**, a contact **160** (see FIG. 1D) including the programmable resistor **106** can be formed to be in electrical contact with the source/drain region **110**, a contact **170** can be formed to be in electrical contact with the source/drain region **111**, and a metal connection **130** can be formed to laterally extend from above the programmable resistor **106** across the word line **120** to above the contact **170**. That is, the pair of contacts **160** and **170** is formed over the source/drain regions **110** and **111**, wherein the programmable resistor **106** is over the contact **160** and free from coverage of the contact **170**.

(31) In a second one of the memory cells **101** formed over the source/drain regions **111** and **112**, a contact **161** (see FIG. 1E) including the programmable resistor **106** can be formed to be in electrical contact with the source/drain region **111**, a contact **171** can be formed to be in electrical contact with the source/drain region **112**, and a metal connection **131** can be formed to laterally extend from above the programmable resistor **106** across the word line **121** to above the contact **171**. In other words, the pair of contacts **161** and **171** is formed over the source/drain regions **111** and **112**, wherein the programmable resistor **106** is over the contact **161** and free from coverage of the contact **171**.

(32) In a third one of the memory cells **101** formed over the source/drain regions **112** and **113**, a contact **162** (see FIG. 1D) including the programmable resistor **106** can be formed to be in electrical contact with the source/drain region **112**, a contact **172** can be formed to be in electrical contact with the source/drain region **113**, and a metal connection **132** can be formed to laterally extend from above the programmable resistor **106** across the word line **122** to above the contact **172**. In other words, the pair of contacts **162** and **172** is formed over the source/drain regions **112** and **113**, wherein the programmable resistor **106** is over the contact **162** and free from coverage of the contact **172**.

(33) In a fourth one of the memory cells **101** formed over the source/drain regions **113** and **114**, a contact **163** (see FIG. 1E) including the programmable resistor **106** can be formed to be in electrical contact with the source/drain region **113**, a contact **173** can be formed to be in electrical contact with the source/drain region **114**, and a metal connection **133** can be formed to laterally extend from above the programmable resistor **106** across the word line **123** to above the contact **173**. In other words, the pair of contacts **163** and **173** is formed over the source/drain regions **113** and **114**, wherein the programmable resistor **106** is over the contact **163** and free from coverage of the contact **173**.

(34) In a fifth one of the memory cells **101** formed over the source/drain regions **114** and **115**, a contact **164** (see FIG. 1D) including the programmable resistor **106** can be formed to be in electrical contact with the source/drain region **114**, a contact **174** can be formed to be in electrical contact with the source/drain region **115**, and a metal connection **134** can be formed to laterally extend from above the programmable resistor **106** across the word line **124** to above the contact **174**. In other words, the pair of contacts **164** and **174** is formed over the source/drain regions **114** and **115**, wherein the programmable resistor **106** is over the contact **164** and free from coverage of the contact **174**.

(35) The metal connections **130-134** can be arranged in two rows **r1** and **r2** with each of the metal connection **130-134** being shifted relative to a next one of the metal connection **130-134** along lengthwise directions of the word lines **120-124** from the top view, optimizing space utilization and ensuring a clear path for currents. This setup can minimize interference and cross-talk between adjacent paths, ensuring clearer and more accurate data transfer. Specifically, the metal connections **131** and **133** can be arranged in the row **r1**, and the metal connections **130**, **132**, and **134** can be arranged in the row **r2** in parallel with the row **r1**. Similarly, the programmable resistors **106** can be arranged in the two rows **r1** and **r2** with each of the programmable resistors **106** being shifted relative to a next one of the programmable resistors **106** along the lengthwise directions of the word

lines **120-124**.

(36) Therefore, the resistive memory string **100** can offer a compact, flexible, and reliable layout for memory storage, with an architecture optimized for efficient data flow, manufacturing consistency, and easy integration into broader semiconductor systems.

(37) As shown in FIGS. **1D** and **1E**, a diffusion region **181** can be formed over a substrate **180**. The substrate **180** can be a semiconductor substrate, such as a monocrystalline silicon bulk semiconductor, a semiconductor-on-insulator (SOI) substrate, or the like, which may be doped (e.g., with a p-type or an n-type impurity) or undoped. The SOI substrate can a layer of a semiconductor material formed on an insulator layer. The insulator layer may be, for example, a buried oxide (BOX) layer, a silicon oxide layer, or the like. The insulator layer is provided on a substrate, typically a silicon or glass substrate. Other substrates, such as a multi-layered or gradient substrate may also be used. In some embodiments, the substrate **180** may be a carrier wafer, such as a lower cost wafer or a reclaim wafer. In some embodiments, the substrate **180** may include silicon; germanium; a compound semiconductor including silicon carbide, gallium arsenide, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide; an alloy semiconductor including silicon germanium, gallium arsenide phosphide, aluminum indium arsenide, aluminum gallium arsenide, gallium indium arsenide, gallium indium phosphide, and/or gallium indium arsenide phosphide; the like; or combinations thereof.

(38) The word lines **120-124** formed over the diffusion region **181**. In some embodiments, the word lines **120-124** may be made of tungsten (W), cobalt (Co), ruthenium (Ru), molybdenum (Mo), aluminum (Al), copper (Cu), combinations thereof, or other suitable materials. In some embodiments, the word lines **120-124** can be interchangeably referred to as gates, poly gates, metal gates, gate structures, gate strips, gate lines, gate layers, or gate patterns.

(39) The source/drain regions **110-115** formed at opposite sides of the word lines **120-124**, and can be formed by implanting n-type dopants (N.sup.+) (e.g., phosphorus or arsenic) or p-type dopants (P.sup.+) in a diffusion region **181** (or an active region) of a substrate **180**, such that the source/drain regions **110-115** can be N.sup.+ poly-silicon layers or P.sup.+ poly-silicon layers. In some embodiments, the source/drain regions **110-115** can be interchangeably referred to as current conducting terminals, source/drain patterns, or doped semiconductive layers. Channel regions **182** are formed underlying the word lines **120-124**. Each of the transistors **105** may include the channel region **182**, a corresponding one of the word lines **120-124**, and a corresponding pair of the source/drain regions **110-115**. The transistors **105** in two adjacent memory cells **101** share a same one of the source/drain regions **110-115**, and the memory cells **101** are connected in series using the sharing ones of the source/drain regions **110-115**.

(40) The programmable resistors **106** are formed to dispose in the contacts **160-164** and spaced away from the metal connections **130-134** by a vertical distance. In some embodiments, the programmable resistors **106** may include transition metal oxide layers, for example, which can be programmed to variable resistance values using programming pulses and verify operations as is for resistive RAM implementations. By way of example and not limitation, the programmable resistors can include two-terminal devices having first and second electrodes, with a metal oxide in between that can be programmed to multiple resistance values. In such embodiments, the metal-oxide layer may include one or more metal oxides from the group of tungsten oxide, titanium oxide, nickel oxide, aluminum oxide, copper oxide, zirconium oxide, niobium oxide, tantalum oxide, titanium nickel oxide, Cr-doped SrZrO.sub.3, Cr-doped SrTiO.sub.3, PCMO and LaCaMnO. In some embodiments, the programmable resistive element between the electrodes may comprise WO/Cu or Ag, TiO/Cu or Ag, NiO/Cu or Ag, AlO/Cu or Ag, CuO/Cu or Ag, ZrO/Cu or Ag, NbO/Cu or Ag, TaO/Cu or Ag, TiNO/Cu or Ag, Cr-doped SrZrO.sub.3/Cu or Ag, Cr-doped SrTiO.sub.3/Cu or Ag, PCMO/Cu or Ag, LaCaMnO/Cu or Ag, and SiO.sub.2/Cu or Ag.

(41) In some embodiments, the programmable resistors **106** can comprise phase change memory elements. Embodiments of the phase change materials include phase change based memory

materials, including chalcogenide based materials and other materials. Chalcogens include any of the four elements oxygen (O), sulfur(S), selenium (Se), and tellurium (Te), forming part of group VIA of the periodic table. Chalcogenides comprise compounds of a chalcogen with a more electropositive element or radical. Chalcogenide alloys comprise combinations of chalcogenides with other materials such as transition metals. A chalcogenide alloy usually contains one or more elements from group IVA of the periodic table of elements, such as germanium (Ge) and tin (Sn). Often, chalcogenide alloys include combinations including one or more of antimony (Sb), gallium (Ga), indium (In), and silver (Ag). Many phase change based memory materials have been described in technical literature, including alloys of: Ga/Sb, In/Sb, In/Se, Sb/Te, Ge/Te, Ge/Sb/Te, In/Sb/Te, Ga/Se/Te, Sn/Sb/Te, In/Sb/Ge, Ag/In/Sb/Te, Ge/Sn/Sb/Te, Ge/Sb/Se/Te and Te/Ge/Sb/S. In the family of Ge/Sb/Te alloys, a wide range of alloy compositions may be workable. The compositions can be characterized as $\text{Te}_a\text{Ge}_b\text{Sb}_{100-(a+b)}$. In other examples, a transition metal such as chromium (Cr), iron (Fe), nickel (Ni), niobium (Nb), palladium (Pd), platinum (Pt) and mixtures or alloys thereof may be combined with Ge/Sb/Te to form a phase change alloy that has programmable resistance properties.

(42) Chalcogenides and other phase change materials are doped with impurities, in some embodiments, to modify conductivity, transition temperature, melting temperature, and other properties of memory elements using the doped chalcogenides. Representative impurities used for doping chalcogenides include nitrogen, silicon, oxygen, silicon dioxide, silicon nitride, copper, silver, gold, aluminum, aluminum oxide, tantalum, tantalum oxide, tantalum nitride, titanium and titanium oxide.

(43) Other programmable resistance structures, as alternative to those based on phase change cells and metal oxide cells described above, include solid state electrolyte (conductive bridge) memory cells and magnetoresistive memory cells, spin transfer torque material, and magnetic material, and can be applicable to the present disclosure.

(44) In some embodiments, the contacts **160-164** each has two portions (or segments, e.g., lower portion and upper portion) sandwiching the programmable resistors **106**. Specifically, the contact **160** (see FIG. 1D) can have a lower portion **160a** and an upper portion **160b**, the lower portion **160a** is situated between the source/drain region **110** and the programmable resistors **106**, and the upper portion **160b** is situated between the programmable resistors **106** and the metal connection **130**. In some embodiments, the contacts **160-164**, **170-175**, **198**, and **199** may be made of tungsten (W), cobalt (Co), ruthenium (Ru), molybdenum (Mo), aluminum (Al), copper (Cu), combinations thereof, or other suitable materials. In some embodiments, the contacts **160-164**, **170-175**, **198**, and **199** can be interchangeably referred to as metal contacts, metal plugs, conductive contact, metal vias, or inter-layer connectors.

(45) In some embodiments, the metal connections **130-134** may be made of tungsten (W), cobalt (Co), ruthenium (Ru), molybdenum (Mo), aluminum (Al), copper (Cu), combinations thereof, or other suitable materials. In some embodiments, the metal connections **130-134** can be interchangeably referred to as metal lines, metal segments, metal strips, metal patterns, metal bridge elements, or metal routings. In some embodiments, the metal connections **130-134** may be made of a different material than the contacts **160-164**, **170-175**, **198**, and **199**. In some embodiments, the metal connections **130-134** may be made of a same material as the contacts **160-164**, **170-175**, **198**, and **199**.

(46) Reference is made to FIG. 1F. FIG. 1F illustrates a top view of a semiconductor structure **20** including a resistive memory string **200** with a circuit **285** for operating the resistive memory string **200** in accordance with some embodiments of the present disclosure. In some embodiments, the resistive memory string **200** can be an NAND-type resistive memory string. The description provided refers to another embodiment of a resistive memory string **200**, specifically featuring a different arrangement compared to the embodiment showcased in FIGS. 1A-1E. In this variant shown in FIG. 1F, memory cells **201**, transistors **205**, source/drain regions **210-219**, contacts **220-**

228, 270-278, 298, 299, metal connections 230-238, and programmable resistors 206 are fundamentally similar to those in FIGS. 1A-1E in terms of their material and manufacturing methods. That means that the memory cells 201 can correspond to the memory cells 101, the transistors 205 can correspond to the transistors 105, the source/drain regions 210-219 can correspond to source/drain regions 110-115, the word lines 220-228 can correspond to the word lines 120-124, the contacts 270-278, 298, and 299 can correspond to the contacts 170-174, the metal connections 230-238 can correspond to the metal connections 130-134, and the programmable resistors 206 can correspond to the programmable resistors 106 in the previous figures.

(47) The distinct difference in this embodiment lies in the arrangement of the memory cells 201 and an additional circuit 285 electrically coupled to the resistive memory string 200. The resistive memory string 200 may include nine memory cells 201 connected in series. The circuit 285 can include cell select transistors 283 and ground select line transistors 284. Source/drain regions of the cell select transistors 283 are electrically coupled to the source/drain regions 232, 234, 236, and 238 through the programmable resistors 206, and source/drain regions of the ground select line transistors 284 are electrically coupled to the source/drain regions 231, 233, 235, and 237. Gates of the cell select transistors 283 are electrically coupled to gates of the ground select line transistors 284, respectively.

(48) Selecting at least one of the memory cells 201 within the resistive memory string 200 is for operations like reading, writing, or erasing data in that selected memory cell 201. This selection can be done using operating voltages applied to the selected transistors (e.g., cell select transistors 283, ground select line transistors 284). The gates of the cell select transistors 283 and the ground select line transistors 284 are interlinked electrically. This means that when a specific voltage is applied to the gate of one, the other can respond correspondingly. Operating voltages are applied to these gates to control the 'on' (or activating) and 'off' (deactivating) states of these transistors. Turning a transistor 'on' (i.e., making it conductive) or 'off' (i.e., making it non-conductive) can determine the path of the current in the resistive memory string 200.

(49) When reading the memory cell 201, the cell select transistor 283 and the ground select line transistor 284 associated with the desired memory cell's in the resistive memory string 200 are turned 'on' by applying the appropriate operating voltage thereon. Meanwhile, other cell select transistors 283 and ground select line transistors 284 associated with undesired memory cells 201 in the memory string 200 are turned 'off'. This isolates the target memory cell 201, ensuring the current flows specifically through memory cell 201. The resistance of the programmable resistor 206 in the memory cell 201 can then be measured. Depending on the resistance, the memory cell's state (either '0' or '1') can be determined. To write data to the memory cell 201, a higher voltage (e.g., write voltage or programming voltage) is applied. As before, only the cell select transistor 283 and the ground select line transistor 284 associated with the target memory cell 201 are turned 'on'. This high voltage causes a change in the resistance of the programmable resistor 206 in the memory cell 201, thereby storing a '0' or a '1'. To erase data to the memory cell 201, a different voltage (e.g. erase voltage) is applied. Just like in the read and write operations, the cell select transistor 283 and the ground select line transistor 284 associated with the target memory cell 201 are turned 'on' during the erase operation. This erase voltage resets the resistance of the programmable resistor 106 in the memory cell 101 to its initial state.

(50) Therefore, the application of specific operating voltages to the gates of the cell select transistors 283 and the ground select line transistors 284 can be a precise method for selecting and operating individual memory cells 201 within the resistive memory string 200. This technique ensures accurate reading, writing, and erasing of data in the desired memory cell 201 while preventing unintentional changes to neighboring memory cells 201.

(51) Reference is made to FIG. 1G. FIG. 1G illustrates a top view of a semiconductor structure 30 including a resistive memory string 300 with a circuit 385 for operating the resistive memory string

300 in accordance with some embodiments of the present disclosure. While FIG. 1G shows an embodiment of the semiconductor structure **30** with different structure configurations than the semiconductor structure **20** in FIG. 1F. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(52) As shown in FIG. 1G, the difference between the embodiment in FIG. 1G and the embodiment in FIG. 1F is in that the resistive memory string **300** can include a plurality of resistive memory string **200** connected in series with at least one assist transistor **386**. In some embodiments, the resistive memory string **200** shown in FIG. 1G can be interchangeably referred to as a sub-resistive memory string. Specifically, taking two series-connected resistive memory strings **200** as an example, the assist transistor **386** can be electrically coupled a second terminal one (i.e., the source/drain region **219**) of the source/drain regions **210-219** in the first resistive memory string **200** to the first terminal one (i.e., the source/drain regions **210**) of the source/drain regions **210-219** in the second resistive memory string **200**.

(53) In addition, the circuit **385** can include string select transistors **383** and ground select line transistors **384**. Source/drain regions of the string select transistors **383** can be electrically coupled to the second terminal ones (i.e., the source/drain regions **219**) of the source/drain regions **210-219** in the first and second resistive memory strings **200**. Source/drain regions of the ground select line transistors **384** can be electrically coupled to the first terminal ones (i.e., the source/drain regions **210**) of the source/drain regions **210-219** in the first and second resistive memory strings **200** opposite to the first terminal ones. Gates of the string select transistors **383** are electrically coupled to gates of the ground select line transistors **384**, respectively.

(54) Selecting at least one of resistive memory string **200** (or sub-string) is for operations like reading, writing, or erasing data in that selected resistive memory string **200**. This selection can be done using operating voltages applied to the select transistors (e.g., string select transistors **383**, ground select line transistors **384**). The gates of the string select transistors **383** and the ground select line transistors **384** are interlinked electrically. This means that when a specific voltage is applied to the gate of one, the other can respond correspondingly. Operating voltages are applied to these gates to control the 'on' (or activating) and 'off' (deactivating) states of these resistive memory string **200**. Turning a resistive memory string 'on' (i.e., making it conductive) or 'off' (i.e., making it non-conductive) can determine the path of the current in the resistive memory string **300**.

(55) Once the desired resistive memory string **200** is selected, a read voltage can be applied across the selected memory cells **201** in the resistive memory string **200**. Depending on the resistance state of the memory cell **201** (either low resistance or high resistance), the amount of current flowing through it can be determined. This current can then be used to ascertain whether the memory cell **201** is in a programmed or erased state. A write voltage (or programming voltage), higher than the read voltage, can be applied across the memory cells **201** in the resistive memory string **200**, causing it to change its resistance state. Depending on the type of resistive memory, the resistance could either increase or decrease, thus programming the memory cell **201** in the selected resistive memory string **200**. An erase voltage, typically different from the write voltage, can be applied to revert the memory cell **201** in the selected resistive memory string **200** to its initial state. In some embodiments, the operating voltages can be removed from the gates of both the string select transistor **383** and the ground select line transistor **384**. Turning the string select transistor **383** and the ground select line transistor **384** OFF can ensure that the selected memory string **200** (or sub-string) is isolated, preventing any unintentional operations on it.

(56) The presence of both string select transistors **383** and ground select line transistors **384** can allow for precise selection of individual resistive memory strings **200** (or sub-strings). This can ensure that only the desired resistive memory string **200** can be accessed for operations, minimizing interference and crosstalk with adjacent resistive memory strings **200**. In some

embodiments, the capability to turn OFF the string select transistor **383** and the ground select line transistor **384** after operations can ensure that unintentional reads/writes can be minimized. This isolation can further ensure data integrity and reduce power leakage in the semiconductor structure **30**.

(57) Reference is made to FIGS. 2A-2F. FIG. 2A illustrates a schematic circuit diagram of a resistive memory string **400** in accordance with some embodiments of the present disclosure. In some embodiments, the resistive memory string **400** can be an NAND-type resistive memory string. FIGS. 2B and 2C illustrate schematic equivalent circuit diagrams of methods for operating the resistive memory string **400** in FIG. 2A. FIG. 2D illustrates a schematic top view of a semiconductor structure **40** including the resistive memory string **400** in accordance with some embodiments of the present disclosure. FIGS. 2E and 2F illustrate schematic cross-sectional views obtained from reference cross-sections E2-E2' and F2-F2' in FIG. 2D.

(58) The description provided refers to another embodiment of the resistive memory string **400**, specifically featuring a different arrangement compared to the embodiment showcased in FIGS. 1A-1G. The resistive memory string **400** can include a plurality of sub-resistive memory strings **400a**, and the sub-resistive memory string **400a** can include at least one transistor **405a** and a pair of transistors **405b** at opposite terminal ends of the sub-resistive memory strings **400a**. As shown in FIG. 2A, each of the sub-resistive memory strings **400a** may include two memory cells **401**. Other embodiments may contain more or fewer number of the memory cells **401**.

(59) In some embodiments, the sub-resistive memory string **400a** can be interchangeably referred to as a cell group. In this variant shown in FIG. 2A, memory cells **401**, transistors **405a** and **405b**, and programmable resistors **406** are fundamentally similar to those in FIG. 1B in terms of their material and manufacturing methods. That means the memory cells **401** can correspond to the memory cells **101**, the transistors **405a** and **405b** can correspond to the transistors **105**, and the programmable resistors **406** can correspond to the programmable resistors **106** in the previous figures.

(60) The distinct difference in this embodiment lies in addition pair of transistors **405b**. The sub-resistive memory strings **400a** are electrically connected in series with the terminal transistors **405b** using a sharing source/drain region of the terminal transistors **405b**. In addition, a non-sharing source/drain region of the transistor **405b** is electrically coupled to another non-sharing source/drain region of the adjacent terminal transistor **405b**. In some embodiments, voltages applied to control terminals **404** (or word lines) of the memory cells **401** correspond to the variable inputs x1, x2, x3, and x4. In some embodiments, the transistor **405a** can be interchangeably referred to as a word line transistor, and the transistor **405b** can be interchangeably referred to as a terminal transistor.

(61) As shown in FIG. 2A, a power line PLA and a power line PLB are connected to the resistive memory string **400** from pickup terminals between every adjacent two sub-resistive memory strings **400a**, and the pickup terminal can be the sharing source/drain region of the adjacent two transistors **405b**. The pickup terminals for the power line PLA and the pickup terminals for the power line PLB are arranged alternately. The first operation voltage (e.g., high voltage or programming voltage V.sub.pgm) can be applied on the power line PLA, the second operation voltage (e.g., low voltage or ground voltage GND) can be applied on the power line PLB, and the second operation voltage is different (or lower) than the first operation voltage.

(62) In the process of determining which sub-resistive memory string **400a** to activate, the transistors **405b** located at the opposing endpoints of the sub-resistive memory string **400a** are toggled to an 'on' status. This configuration can allow one endpoint of the selected sub-resistive memory string **400a** to receive the first operation voltage supplied by power line PLA, while the opposite endpoint receives the second operation voltage supplied by the power line PLB. This arrangement can establish a voltage difference between these endpoints, facilitating the current flow from one end to the other within the selected sub-resistive memory string **400a**. Consequently,

this active configuration of the sub-resistive memory string **400a** can be referred to as 'selected'. Operations on the programmable resistors **406** within the selected memory cell **401**, such as reading, writing, or erasing data, can be facilitated by toggling the corresponding transistor **405a** within the selected sub-resistive memory string **400a**.

(63) On the other hand, the transistors **405b** located at the opposing endpoints of each of the non-selected sub-resistive memory strings **400a** adopt a mixed configuration, with one being 'on' status and the other being 'off' status. This configuration can ensure that both endpoints of the non-selected sub-resistive memory strings **400a** sustain a consistent operation voltage, either the first operation voltage supplied by the power line PLA or the second operation voltage supplied by the power line PLB. Absence of a voltage difference between these endpoints can precludes current flow within these non-selected sub-resistive memory strings **400a**, which in turn allows for preventing the programming interference.

(64) As illustrated in FIG. 2B, for a clearly explanation of the operation of the resistive memory string **400**, especially when selecting the sub-resistive memory strings **400a**, specific terminals within the string **400** are labeled as a, ia, SA, b, ib, and SB. The terminals a, ia, and SA are electrically connected to the power line PLA, while terminals b, ib, and SB are electrically connected to the power line PLB. Specifically, the selected sub-resistive memory string **400a** is situated between the terminals SA and SB. The non-selected sub-resistive memory strings **400a** associated with the terminals a, ia, B, and ib are situated outside the bounds demarcated by the terminals SA and SB. In greater detail, the terminal a can connect the power line PLA with the resistive memory string **400**, being situated closer to the terminal SA than to the terminal SB. The terminal ia can also connect the power line PLA with the resistive memory string **400** but is nearer to the terminal SB than to the terminal SA. The terminal b can connect the power line PLB with the resistive memory string **400**, being situated closer to the terminal SB than to the terminal SA. The terminal ib can connect the power line PLB with the resistive memory string **400**, being closer to the terminal SA than to the terminal SB.

(65) In FIG. 2B, when both the transistors **405b** within the sub-resistive memory string **400a**, situated between terminals SA and SB, are activated (or set to the "on" state), the terminal SA can receive the first operation voltage (e.g., a high voltage or programming voltage V.sub.pgm, sourced from the power line PLA). Simultaneously, the terminal SB can receive the second operation voltage (e.g., a low voltage or ground voltage GND, sourced from the power line PLB). This scenario can establish a voltage difference between the terminals SA and SB, enabling an electrical current to flow from the terminal SA to the terminal SB of the selected sub-resistive memory string **400a**. This facilitates the application of both first and second operation voltages to the memory cells **401** situated within the selected sub-resistive memory string **400a**, between the terminals SA and SB. In some embodiments, the regions between the terminals SA and SB can be referred to as the selected cell group region **441**.

(66) The regulation of this current flow can allow for the precise selection and operation of the memory cells **401** in the selected sub-resistive memory string **400a**. This is achieved by toggling the state of the transistor **405a** in the sub-resistive memory string **400a**, which, in turn, controls the actions of the programmable resistors **406** in the selected memory cell **401**.

(67) Specifically, in the selected cell group region **441**, if the transistor **405a** is deactivated (set to the "off" state or closed) by the corresponding word line, the current can pass (or circulate) the programmable resistor **406** that is connected in parallel with the deactivated transistor **405a**. This action can activate the associated memory cell **401**. This configuration can permit various tasks, such as reading, writing, or erasing data, to be executed on the programmable resistor **406**.

(68) Conversely, in the selected cell group region **441**, when the transistor **405a** is activated (set to the "on" state or opened) by the corresponding word line, the current predominantly circulates through the transistor **405a**, bypassing (or non-passing) the programmable resistor **406** that is connected in parallel with the activated transistor **405a**. As a result, this programmable resistor **406**

remains inactive or non-operational.

(69) For the sub-resistive memory string **400a** between the terminals SA and ib, and between the terminals a and ib, when one side's transistor **405b** is activated (or set to “on”) and the other side's is deactivated (or set to “off”), all voltages between the terminals a and SA will remain consistent with (or stabilize at) the first operation voltage (e.g., the programming voltage V.sub.pgm, provided by the power line PLA). Therefore, there is no voltage difference (or gradient) being established, ensuring that current doesn't flow through these non-selected sub-resistive memory strings **400a**, thus eliminating any potential operation disturbance. This region, maintained at the first operation voltage between the terminals a and SA, can be referred to as the first operation voltage inhibition region **442**.

(70) Similarly, for the sub-resistive memory string **400a** between the terminals SB and ia, and between the terminals b and ia, when one side's transistor **405b** is activated (or set to “on”) and the opposing side's is deactivated (or set to “off”), all voltages between the terminals SB and b will remain consistent with (or stabilize at) the second operation voltage (e.g., the ground voltage GND, provided by the power line PLB). Again, the absence of a voltage difference (or gradient) can ensure that current doesn't flow through these non-selected sub-resistive memory strings **400a**, thus eliminating any potential operation disturbance. This region, maintained at the second operation voltage between terminal b and terminal SB, can be referred to as the second operation voltage inhibition region **443**.

(71) That is, the transistors **405b** associated with the terminals a and b are activated. This can enable the delivery of an inhibit voltage (which could either be the first or second operation voltage) to the unselected sub-resistive memory string **400a** situated between the terminals a and b, which in turn prevents any potential operational disturbances in the first and second operation voltage inhibition regions **442** and **443**. In contrast, the transistors **405b** associated with the terminals ia and ib are inactivated. This can ensure that the first and second operation voltages don't interfere with the non-selected sub-resistive memory strings **400a** within the first and second operation voltage inhibition regions **442** and **443**.

(72) Within the first operation voltage inhibition region **442**, the word lines **421** and **422** can be selected to activate the transistors **405a**, thereby opening them. This action can ensure that the first operation voltage can be diverted away from the programmable resistors **406** that are connected in parallel to the transistors **405a**. Similarly, within the second operation voltage inhibition region **443**, the word lines **421** and **422** can be selected to activate the transistors **405a**, thereby opening them. This action can ensure that the second operation voltage can be diverted away from the programmable resistors **406** that are connected in parallel to the transistors **405a**.

(73) As shown in FIG. 2D, the resistive memory string **400** can include a sequence of source/drain regions **410-414**, which act as source/drain terminals of a sequence of the transistors **405a** and **405b** in this illustration. The gates of the transistors **405a** and **405b** can be provided on word lines **420-423**. Parallel resistors **406** are implemented in each of the memory cells **401** using a current path that bridges the transistor **405a**. Contacts **498** and **499** can connect to overlying conductors (not shown), which can connect to the power lines PLA and PLB. In some embodiments, the contacts **498** and **499** can be interchangeably referred to as pickup connections.

(74) Specifically, the resistive memory strings **400** can be constructed after a contact formation process, and a subsequent metal routing process can be performed to connect adjacent two of the memory cells **401** with each other, and adjacent two of the sub-resistive memory strings **400a** with each other. Every source/drain region (e.g., source/drain regions **411-413**) in the sub-resistive memory string **400a** can be interconnected with two adjacent source/drain regions, excluding the source/drain region at the ending terminal ones (e.g., source/drain regions **410** and **414**) of the sub-resistive memory string **400a**. Each conductive terminal has dual contacts (e.g., two of the contacts **470-473** and the contacts **460-461** (see FIGS. 2E and 2F)) to facilitate these interconnections with neighboring source/drain regions.

(75) In some embodiments, the metal routing (e.g., metal connections **431** and **432**) can connect the memory cell **401** using a first contact (either from the contact **460** or **461** shown in FIGS. 2E and 2F) to a second contact (either from the contact **471** or **472**) on the neighboring conductive terminal. In some embodiments, the metal routing (e.g., metal connections **430** and **433**) can connect a first sub-resistive memory string **400a** using a first contact (either from the contact **470** or **473**) to a second contact (either from the contact **473** or **470**) on the neighboring second sub-resistive memory string **400a**, thereby constructing the resistive memory string **400**.

(76) With the configuration of the memory cells **401** containing parallel resistors **406** bridging the transistors **405a**, and the source/drain regions **410-414** acting as source/drain terminals, the design can be compact. This layout can allow for higher memory density, which means more data can be stored in a smaller area. The design offers a method of interconnecting the memory cells **401** and the sub-resistive memory string **400a**. Every source/drain region (e.g., the source/drain regions **411-413**) connects to two neighboring terminals, except at the ending terminal ones (e.g., the source/drain regions **410** and **414**). This flexibility can improve data flow, potentially speeding up read/write operations.

(77) Specifically, in a first one of the memory cells **401** formed over the source/drain regions **411** and **412**, a contact **460** (see FIG. 2E) including the programmable resistor **406** can be formed to be in electrical contact with the source/drain region **411**, a contact **471** can be formed to be in electrical contact with the source/drain region **412**, and a metal connection **431** can be formed to laterally extend from above the programmable resistor **406** across the word line **421** to above the contact **471**. That is, the pair of contacts **460** and **471** is formed over the source/drain regions **411** and **412**, wherein the programmable resistor **406** is over the contact **460** and free from coverage of the contact **471**.

(78) In a second one of the memory cells **401** formed over the source/drain regions **412** and **413**, a contact **461** (see FIG. 2F) including the programmable resistor **406** can be formed to be in electrical contact with the source/drain region **412**, a contact **472** can be formed to be in electrical contact with the source/drain region **413**, and a metal connection **432** can be formed to laterally extend from above the programmable resistor **406** across the word line **422** to above the contact **472**. In other words, the pair of contacts **461** and **472** is formed over the source/drain regions **412** and **413**, wherein the programmable resistor **406** is over the contact **461** and free from coverage of the contact **472**.

(79) The contact **470** can be formed on the source/drain region **411** in a first one of the sub-resistive memory strings **400a**, and the metal connection **430** can be formed to laterally extend from above the contact **470** across the word lines **420** in the first and second ones of the sub-resistive memory strings **400a** to above the contact **473** formed on the source/drain region **411** in the second one of the sub-resistive memory strings **400a**. The contact **470** in the first one of the sub-resistive memory strings **400a** and the contact **473** in the second one of the sub-resistive memory strings **400a** can define a metal contact-free region therebetween underlying the metal connection **430**.

(80) Similarly, the contact **473** can be formed on the source/drain region **414** in the first one of the sub-resistive memory strings **400a**, and the metal connection **433** can be formed to laterally extend from above the contact **473** across the word lines **423** in the first and third ones of the sub-resistive memory strings **400a** to above the contact **473** formed on the source/drain region **414** in the third one of the sub-resistive memory strings **400a**. The contact **473** in the first one of the sub-resistive memory strings **400a** and the contact **470** in the third one of the sub-resistive memory strings **400a** can define a metal contact-free region therebetween underlying the metal connection **433**.

(81) The metal connections **430-433** can be arranged in two rows **r3** and **r4** with each of the metal connection **430-433** being shifted relative to a next one of the metal connection **430-433** along lengthwise directions of the word lines **420-423** from the top view, optimizing space utilization and ensuring a clear path for currents. This setup can minimize interference and cross-talk between adjacent paths, ensuring more accurate data transfer. Specifically, the metal connections **430** and

432 can be arranged in the row **r4**, and the metal connections **431** and **433** can be arranged in the row **r3** in parallel with the row **r4**. Similarly, the programmable resistors **406** can be arranged in the two rows **r3** and **r4** with each of the programmable resistors **406** being shifted relative to a next one of the programmable resistors **406** along the lengthwise directions of the word lines **420-423**. Therefore, the resistive memory string **400** can offer a compact, flexible, and reliable layout for memory storage.

(82) As shown in FIGS. 2D and 2E, a diffusion region **481** can be formed over a substrate **480**. The word lines **420-423** formed over the diffusion region **481**. The source/drain regions **410-414** formed at opposite sides of the word lines **420-423**. Channel regions **482** are formed underlying the word lines **420-423**. Each of the transistors **405a** and **405b** may include the channel region **482**, a corresponding one of the word lines **420-423**, and a corresponding pair of the source/drain regions **410-414**.

(83) The transistors **405a** in two adjacent memory cells **401** share the same source/drain region **412**, and the memory cells **401** are connected in series using the sharing source/drain region **412**. The transistors **405b** in two adjacent sub-resistive memory strings **400b** share the same source/drain region **410** or **414**, and the sub-resistive memory strings **400a** are connected in series using the sharing source/drain region **410** or **414**. The programmable resistors **406** are formed to dispose in the contacts **460** and **461**, and spaced away from the metal connections **431** and **432** by a vertical distance. In some embodiments, the metal connections **430-433** may be made of a different material than the contacts **460**, **461**, **470-473**, **498**, and **499**. In some embodiments, the metal connections **430-433** may be made of a same material as the contacts **460**, **461**, **470-473**, **498**, and **499**.

(84) In this variant shown in FIGS. 2A-2F, the substrate **480**, the diffusion region **481**, the source/drain regions **410-414**, the word lines **420-423**, the contacts **460**, **461**, **470-473**, **498**, and **499**, and the metal connections **430-433** are fundamentally similar to those in FIGS. 1A-1E in terms of their material and manufacturing methods. That means the substrate **480** can correspond to the substrate **180**, the diffusion region **481** can correspond to the diffusion region **181**, the source/drain regions **410-414** can correspond to source/drain regions **110-115**, the word lines **420-423** can correspond to the word lines **120-124**, the contacts **460**, **461**, **470-473**, **498**, and **499** can correspond to the contacts **160-164**, **170-174**, **198**, and **199**, and the metal connections **430-433** can correspond to the metal connections **130-134** in the previous figures.

(85) Reference is made to FIG. 2C. The in-storage computing, often referred to as computing-in-memory (CiM), can be integrated into the resistive memory string **400** to elevate its functional capacity. The in-storage computing may include a series of steps and begin by grounding both power lines **PLA** and **PLB**. Subsequently, all the transistors **405b** within the resistive memory string **400** are deactivated, ensuring data integrity. Subsequently, data inputs are directed towards the word lines **421** and **422**. Subsequently, the resistances of the system, whether in voltage or current forms, are measured to obtain the CiM results. Therefore, the implementation of in-storage computing operation within the resistive memory string **400** not only amplifies its computational prowess but also fosters a seamless interface between data storage and processing functionalities.

(86) Reference is made to FIGS. 3A-3E. FIG. 3A illustrates a schematic circuit diagram of a resistive memory string **500** in accordance with some embodiments of the present disclosure. FIG. 3B illustrates a schematic top view of a semiconductor structure **50** including the resistive memory string **500** in accordance with some embodiments of the present disclosure. FIG. 3B illustrates a local enlarged view of a region in FIG. 3B. FIGS. 3D and 3E illustrate schematic cross-sectional views obtained from reference cross-sections **D3-D3'** and **E3-E3'** in FIG. 3B.

(87) In this variant shown in FIGS. 3A-3E, the resistive memory string **500**, a sub-resistive memory strings **500a**, a substrate **580**, a diffusion region **581**, transistors **505a** and **505b**, word lines **520-523**, source/drain regions **510-514**, contacts **560**, **561**, **570-573**, **598**, and **599**, metal connections **530-533**, programmable resistors **506**, and memory cells **501** are fundamentally similar

to those in FIGS. 2A-2F in terms of their material and manufacturing methods. That means that the resistive memory string **500** can correspond to the resistive memory string **400**, the sub-resistive memory strings **500a** can correspond to the sub-resistive memory strings **400a**, the substrate **580** can correspond to the substrate **480**, the diffusion region **581** can correspond to the diffusion region **481**, transistors **505a** and **505b** can correspond to transistors **405a** and **405b**, the word lines **520-523** can correspond to the word lines **420-423**, the source/drain regions **510-514** can correspond to the source/drain regions **410-414**, the contacts **560-562**, **570-572**, **598**, and **599** can correspond to the contacts **460**, **461**, **470-473**, **498**, and **499**, the metal connections **530-533** can correspond to the metal connections **430-433**, the programmable resistors **506** can correspond to the programmable resistors **406**, the memory cells **501** can correspond to the memory cells **401** in the previous figures.

(88) The distinct difference in this embodiment lies in additional programmable resistors **506** formed to dispose in the contacts **573** and **570** and spaced away from the metal connections **530** and **533** by vertical distances. That is, the programmable resistor **506** can be positioned at the junction where it intersects with the two transistors **505b** within the series-connected sub-resistive memory strings **500a**. These programmable resistors **506** not only act as series components but also function as balancing weight memory cells **501**. Operational flexibility can be ensured, as programming, erasing, or reading voltages can be delivered through the power lines PLA and PLB.

(89) As shown in FIG. 3C, to provide a clearer description of the operational method of the resistive memory string **500**, new reference labels are assigned to the structure illustrated in FIG. 3C. In the selected sub-resistive memory string **500a**, the word lines are WL11, WL12, WL13, and WL14. In a set sub-resistive memory string **500a** neighboring the selected sub-resistive memory strings **500a**, the word lines are labeled as WL03 and WL04. Meanwhile, in another adjacent sub-resistive memory string **500a**, the word lines are labeled as WL21 and WL22. The power line PLA can establish an electrical connection at the pickup terminal situated between the word lines WL11 and WL04. The power line PLB can establish an electrical connection at the pickup terminal between the word lines WL14 and WL21. The programmable resistor **506** in parallel connected with the word lines WL04 and WL11 can be labeled as memory cell Cell0; the programmable resistor **506** in parallel connected with the word lines WL12 can be labeled as memory cell Cell1; the programmable resistor **506** in parallel connected with the word lines WL13 can be labeled as memory cell Cell2; the programmable resistor **506** in parallel connected with the word lines WL14 and WL21 can be labeled as memory cell Cell3; and the programmable resistor **506** in parallel connected with the word lines WL22 can be labeled as memory cell Cell4.

(90) When the transistors associated with the word lines WL03, WL04, WL11, WL13, WL14, WL21, and WL22 are activated (i.e., set to the “on” state) and the transistor associated with the word line WL12 is deactivated (i.e., set to the “off” state), the current will flow through the programmable resistor **506** connected in parallel with the deactivated transistor, including the word line WL12. Conversely, the current will skip the programmable resistor **506** connected in parallel with the activated transistors, including the word lines WL04, WL11, WL13, WL14, and WL21. The word lines WL03 and WL22 will facilitate the supply of inhibit voltages, provided by the power lines PLA and PLB, to the unselected memory cells, which in turn reduces operational disruptions in the resistive memory string **500**. The memory cell Cell1 can be changeably referred to as the selected memory cell.

(91) When the transistors associated with the word lines WL03, WL04, WL11, WL12, WL14, WL21, and WL22 are activated (i.e., set to the “on” state) and the transistor associated with the word line WL13 is deactivated (i.e., set to the “off” state), the current will flow through the programmable resistor **506** connected in parallel with the deactivated transistor, including the word line WL13. Conversely, the current will skip the programmable resistor **506** connected in parallel with the activated transistors, including the word lines WL04, WL11, WL12, WL14, and WL21. The word lines WL03 and WL22 will facilitate the supply of inhibit voltages, provided by the

power lines PLA and PLB, to the unselected memory cells, which in turn reduces operational disruptions in the resistive memory string **500**. The memory cell Cell2 can be changeable referred to as the selected memory cell.

(92) When the transistors associated with the word lines WL**03**, WL**04**, WL**11**, WL**12**, WL**13**, WL**21**, and WL**22** are activated (i.e., set to the “on” state) and the transistor associated with the word line WL**14** is deactivated (i.e., set to the “off” state), the current will flow through the programmable resistor **506** connected in parallel with the deactivated transistor, including the word line WL**14**. Conversely, the current will skip the programmable resistor **506** connected in parallel with the activated transistors, including the word lines WL**04**, WL**11**, WL**12**, WL**13**, and WL**21**. The word lines WL**03** and WL**22** will facilitate the supply of inhibit voltages, provided by the power lines PLA and PLB, to the unselected memory cells, which in turn reduces operational disruptions in the resistive memory string **500**. The memory cell Cell3 can be changeable referred to as the selected memory cell.

(93) The resistive memory strings described in this disclosure are versatile and can be employed for various applications, including sum-of-product computations, neural network processing, in-memory search or in-memory computing, and in-storage search or in-storage computing.

(94) Although the present invention has been described in considerable detail with reference to certain embodiments thereof, other embodiments are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the embodiments contained herein. The present disclosure in various embodiments provides a layout to improve the long NAND-type resistive memory string, such that the series (or loading) resistance associated with the selected memory cell can be decreased. An additional pickup connection to the long NAND-type resistive memory string is introduced. The additional pickup connection can divide the lengthy resistance string (R-string) into shorter. Furthermore, an inhibit scheme on the non-selected memory cells can be applied on the resistive memory string, ensuring the non-selected memory cells remain undisturbed during operations.

(95) It will be apparent to those skilled in the art that various modifications and variations can be made to the structure of the present invention without departing from the scope or spirit of the invention. In view of the foregoing, it is intended that the present invention cover modifications and variations of this invention provided they fall within the scope of the following claims.

Claims

1. An integrated circuit structure (IC structure), comprising: a substrate; and a first resistive memory string over the substrate and comprising a plurality of memory cells, each of the memory cells comprising: a word line transistor comprising a channel region, a gate over the channel region, and a plurality of source/drain regions on opposite sides of the channel region; and a resistor over the word line transistor and being electrically connected with the word line transistor in parallel, wherein the word line transistors of two adjacent memory cells share a same one of the source/drain regions, and the memory cells are connected in series using the sharing ones of the source/drain regions.
2. The IC structure of claim 1, wherein the each of the memory cells further comprises: a pair of contacts over the source/drain regions, wherein the resistor is over a first one of the pair of contacts and free from coverage of a second one of the pair of contacts.
3. The IC structure of claim 2, wherein the each of the memory cells further comprises: a metal line laterally extending from above the resistor across the gate to above the second one of the pair of contacts, wherein the resistor is connected with the word line transistor in parallel using the pair of contacts and the metal line.
4. The IC structure of claim 3, wherein from a top view, the metal lines of the memory cells are arranged in two rows with each of the metal lines being shifted relative to a next one of the metal

lines along lengthwise directions of the gates.

5. The IC structure of claim 1, further comprising: a string select transistor having a source/drain region electrically coupled to a first terminal one of the source/drain regions in the first resistive memory string; and a ground select line transistor having a source/drain region electrically coupled to a second terminal one of the source/drain regions in the first resistive memory string, wherein a gate of the string select transistor is electrically coupled to a gate of the ground select line transistor.

6. The IC structure of claim 5, further comprising: a second resistive memory string; and an assist transistor electrically coupled a first terminal one of source/drain regions in the second resistive memory string to the second terminal one of the source/drain regions in the first resistive memory string.

7. An integrated circuit structure (IC structure), comprising: a substrate having a diffusion region thereon; and a resistive memory string comprising: a first sub-string comprising first and second gates extending over the diffusion region, and a first metal contact over the diffusion region and between the first and second gates; a second sub-string comprising third and fourth gates extending over the diffusion region, and a second metal contact over the diffusion region and between the third and fourth gates; a first metal line laterally extending from above the first metal contact of the first sub-string across the second and third gates to above the second metal contact of the second sub-string; and a third metal contact over the diffusion region and between the second and third gates, the third metal contact being configured to applied with an operation voltage.

8. The IC structure of claim 7, wherein the first and second metal contacts define a metal contact-free region therebetween underlying the first metal line.

9. The IC structure of claim 7, wherein the second sub-string further comprises: fourth and fifth metal contacts over the diffusion region and at opposite sides of the fourth gate; a first resistor over the fourth metal contact; and a second metal line laterally extending from above the first resistor across the fourth gate to above the fifth metal contact.

10. The IC structure of claim 9, wherein the first and second metal contacts are arranged at a first row, and the third, fourth, and fifth metal contacts are arranged at a second row.

11. The IC structure of claim 10, wherein the first sub-string further comprises: sixth and seventh metal contacts over the diffusion region and at opposite sides of the first gate; a second resistor over the sixth metal contact; and a third metal line laterally extending from above the second resistor across the first gate to above the seventh metal contact.

12. The IC structure of claim 11, wherein the first and second metal contacts are arranged at a first row, and the third, fourth, fifth, sixth, and seventh metal contacts are arranged at a second row.

13. The IC structure of claim 7, further comprising: a resistor vertically between the first metal contact and the first metal line.

14. A method for operating an integrated circuit structure (IC structure), the IC structure comprising a resistive memory string over a substrate, the resistive memory string having a plurality of sub-strings connected in series, each of the sub-strings comprising a plurality of word line transistors and a pair of terminal transistors connected in series, thereby forming a pickup terminal between two of the terminal transistors in adjacent two of the sub-strings, the each of the sub-strings further comprising a plurality of resistors, each connected in parallel with a respective one of the word line transistors, the method comprising: alternating applying a first operation voltage and a second operation voltage on the pickup terminals of the resistive memory string; performing a program operation on the resistive memory string; and performing an erase operation on the resistive memory string.

15. The method of claim 14, wherein the first operation voltage is a programming voltage, and the second operation voltage is a ground voltage.

16. The method of claim 14, wherein the step of performing the program operation or the step of performing the erase operation comprises: activating the pair of terminal transistors of one of the

sub-strings, the one of the sub-strings acting as a selected cell group, wherein the step of activating allows for forming a voltage difference between the pair of terminal transistors in the one of the sub-strings, facilitating a current flowing through the one of the sub-strings.

17. The method of claim 16, further comprising: deactivating one of the word line transistors in the one of the sub-strings, allowing for the current flowing through the resistor connected in parallel with the deactivated one of the word line transistors.

18. The method of claim 16, further comprising: activating one of the word line transistors in the one of the sub-strings, allowing for the current flowing through the activated one of the word line transistors but bypassing the resistor connected in parallel with the activated one of the word line transistors.

19. The method of claim 14, wherein the step of performing the program operation or the step of performing the erase operation comprises: activating a first one of the pair of terminal transistors in one of the sub-strings; and deactivating a second one of the pair of terminal transistors in the one of the sub-strings, the one of the sub-strings acting as an operation voltage inhibition region, wherein the step of activating accompanying the step of deactivating allows for a consistent voltage between the pair of terminal transistors in the one of the sub-strings, eliminating an operation disturbance in the one of the sub-strings.

20. The method of claim 19, further comprising: activating the word line transistors in the one of the sub-strings.
