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United States Patent Application Publication

20250261378

Kind Code

A1

Publication Date

August 14, 2025

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3D FERROELECTRIC MEMORY

Abstract

Various embodiments of the present disclosure are directed towards a metal-ferroelectric-insulator-semiconductor (MFIS) memory device, as well as a method for forming the MFIS memory device. According to some embodiments of the MFIS memory device, a lower source/drain region and an upper source/drain region are vertically stacked. A semiconductor channel overlies the lower source/drain region and underlies the upper source/drain region. The semiconductor channel extends from the lower source/drain region to the upper source/drain region. A control gate electrode extends along a sidewall of the semiconductor channel and further along individual sidewalls of the lower and upper source/drain regions. A gate dielectric layer and a ferroelectric layer separate the control gate electrode from the semiconductor channel and the lower and upper source/drain regions.

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Family ID: 75379347

Appl. No.: 19/169058

Filed: April 03, 2025

Related U.S. Application Data

parent US continuation 18353954 20230718 parent-grant-document US 12302583 child US 19169058

parent US continuation 17854701 20220630 parent-grant-document US 11770935 child US 18353954

parent US division 16903545 20200617 parent-grant-document US 11411025 child US 17854701
us-provisional-application US 62924736 20191023

Publication Classification

Int. Cl.: **H10B51/20** (20230101); **H10B51/30** (20230101); **H10B51/40** (20230101); **H10D30/01** (20250101); **H10D30/63** (20250101); **H10D30/69** (20250101); **H10D64/01** (20250101)

U.S. Cl.:

CPC **H10B51/20** (20230201); **H10B51/30** (20230201); **H10B51/40** (20230201); **H10D30/025** (20250101); **H10D30/0415** (20250101); **H10D30/63** (20250101); **H10D30/701** (20250101); **H10D64/033** (20250101);

Background/Summary

REFERENCE TO RELATED APPLICATIONS [0001] This Application is a Continuation of U.S. application Ser. No. 18/353,954, filed on Jul. 18, 2023, which is a Continuation of U.S. application Ser. No. 17/854,701, filed on Jun. 30, 2022 (now U.S. Pat. No. 11,770,935, issued on Sep. 26, 2023), which is a Divisional of U.S. application Ser. No. 16/903,545, filed on Jun. 17, 2020 (now U.S. Pat. No. 11,411,025, issued on Aug. 9, 2022), which claims the benefit of U.S. Provisional Application No. 62/924,736, filed on Oct. 23, 2019. The contents of the above-referenced Patent Applications are hereby incorporated by reference in their entirety.

BACKGROUND

[0002] Two-dimensional (2D) memory arrays are prevalent in electronic devices and may include, for example, NOR flash memory arrays, NAND flash memory arrays, dynamic random-access memory (DRAM) arrays, and so on. However, 2D memory arrays are reaching scaling limits and are hence reaching limits on memory density. Three-dimensional (3D) memory arrays are a promising candidate for increasing memory density and may include, for example, 3D NAND flash memory arrays, 3D NOR flash memory arrays, and so on.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0004] FIGS. 1A-1C illustrate various views of some embodiments of a MFIS memory cell.

[0005] FIGS. 2A-2D illustrate various views of some embodiments of a three-dimensional (3D) memory array comprising MFIS memory cells configured as in FIGS. 1A-1C.

[0006] FIGS. 3A-3G illustrate cross-sectional views of various alternative embodiments of the 3D memory array of FIG. 2A in which constituents of the 3D memory array are varied.

[0007] FIGS. 4A-4D illustrate cross-sectional views of various alternative embodiments of the 3D memory array of FIG. 2A in which conductive lines comprising metal define source lines and bit lines.

[0008] FIGS. 5A-5C illustrate various views of some embodiments of an integrated circuit (IC) comprising a 3D memory array.

[0009] FIG. 6 illustrates a schematic view of some embodiments of a portion of the 3D memory array of FIGS. 5A-5C.

[0010] FIGS. 7A and 7B illustrate cross-sectional views of some alternative embodiments of the IC of FIGS. 5A-5C in which word lines are respectively at a bottom of the 3D memory array and a top of the 3D memory array.

[0011] FIGS. 8A and 8B illustrate cross-sectional views of some alternative embodiments of the IC of FIGS. 7A and 7B.

[0012] FIGS. 9A and 9B through FIGS. 18A and 18B illustrate a series of views of some embodiments of a method for forming an IC comprising a 3D memory array of MFIS memory cells.

[0013] FIG. 19 illustrates a block diagram of some embodiments of the method of FIGS. 9A and 9B through FIGS. 18A and 18B.

[0014] FIGS. 20A and 20B through FIGS. 27A and 27B illustrate a series of views of some embodiments of a method for forming an IC comprising a 3D memory array of MFIS memory cells in which word lines are respectively at a bottom of the 3D memory array and a top of the 3D memory array.

[0015] FIG. 28 illustrates a block diagram of some embodiments of the method of FIGS. 20A and 20B through FIGS. 27A and 27B.

DETAILED DESCRIPTION

[0016] The present disclosure provides many different embodiments, or examples, for implementing different features of this disclosure. 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.

[0017] 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.

[0018] Some three-dimensional (3D) memory devices comprise a plurality of memory cells defining a plurality of memory arrays at different elevations above a substrate. According to some embodiments, a lower source/drain region, a semiconductor channel, and an upper source/drain region are vertically stacked and define a common sidewall. A control gate electrode and a data storage layer extend vertically through the plurality of memory arrays along the common sidewall. The data storage layer is between and borders the semiconductor channel and the control gate electrode. Further, the data storage layer comprises a silicon nitride layer separated from the control gate electrode and the semiconductor channel by silicon oxide.

[0019] During program and erase operations, electrons tunnel into or out of the silicon nitride layer through silicon oxide, such that a bit of data may be represented by the amount of charge in the silicon nitride layer. A challenge is that program and erase operations are dependent upon high voltages for electron tunneling and hence for program and erase operations. Such high voltages may, for example, include voltages greater than about 10 volts or some other suitable voltage. Another challenge is that tunneling current is low and hence program and erase speeds are slow. Such slow speeds may, for example, be speeds greater than about 10 microseconds or some other

suitable amount of time. Yet another challenge is that power consumption is high during program and erase operations due to the high voltages and also due to the slow speeds.

[0020] Various embodiments of the present disclosure are directed towards a metal-ferroelectric-insulator-semiconductor (MFIS) memory device and a method for forming the same. Note that although MFIS stands for metal ferroelectric insulator semiconductor, doped polysilicon and other suitable conductive materials may be used in place of metal. According to some embodiments of the MFIS memory device, a lower source/drain region and an upper source/drain region are vertically stacked. A semiconductor channel overlies the lower source/drain region and underlies the upper source/drain region. Further, the semiconductor channel extends from the lower source/drain region to the upper source/drain region. A control gate electrode extends along a sidewall of the semiconductor channel and further along individual sidewalls of the lower and upper source/drain regions. The control gate electrode is separated from the semiconductor channel and the lower and upper source/drain regions by a ferroelectric layer and a gate dielectric layer.

[0021] The ferroelectric layer has a polarity representing a bit of data. During a program operation, a program voltage is applied across the ferroelectric layer from the control gate electrode to the semiconductor channel to set the polarity to a programmed state. During an erase operation, an erase voltage is applied across the ferroelectric layer from the control gate electrode to the semiconductor channel to set the polarity to an erased state. By employing the ferroelectric layer for data storage, as opposed to a silicon nitride layer, there is no dependence on carrier tunneling. As such, program and erase voltages may be reduced and program and erase speeds may be increased. For example, program and erase voltages may be reduced to less than about 5 volts and/or program and erase speeds may be reduced to less than about 100 nanoseconds. Other suitable values are, however, amenable. By reducing the program and erase voltages and by increasing the program and erase speeds, power consumption may be reduced.

[0022] With reference to FIGS. 1A-1C, various views **100A-100C** of some embodiments of a MFIS memory cell **102** is provided. FIG. 1A corresponds to a cross-sectional view **100A** along line A in FIG. 1C, whereas FIG. 1B corresponds to a cross-sectional view **100B** along line B in FIG. 1C. Further, FIG. 1C corresponds to a top view **100C**. The MFIS memory cell **102** may, for example, be or comprise a MFIS field-effect transistor (FET) or some other suitable type of semiconductor device having an MFIS stack.

[0023] A semiconductor channel **104** overlies a lower source/drain region **106l** and underlies an upper source/drain region **106u**. The semiconductor channel **104**, the lower source/drain region **106l**, and the upper source/drain region **106u** define a common sidewall **108** facing a gate dielectric layer **110**, a ferroelectric layer **112**, and a control gate electrode **114**. In some embodiments, the common sidewall **108** is flat and/or smooth. The gate dielectric layer **110**, the ferroelectric layer **112**, and the control gate electrode **114** extend along the common sidewall **108** from the lower source/drain region **106l** to the upper source/drain region **106u**.

[0024] The gate dielectric layer **110** and the ferroelectric layer **112** separate the control gate electrode **114** from the common sidewall **108**. The gate dielectric layer **110** is between the ferroelectric layer **112** and the common sidewall **108**, and the ferroelectric layer **112** is between the control gate electrode **114** and the gate dielectric layer **110**. Further, the ferroelectric layer **112** has a polarity representing a bit of data and is hence used for data storage.

[0025] During program and erase operations of the MFIS memory cell **102**, the lower and upper source/drain regions **106l**, **106u** are electrically coupled in parallel and used as a proxy for the semiconductor channel **104**. A program voltage is applied from the control gate electrode **114** to the semiconductor channel **104** (e.g., via the lower and upper source/drain regions **106l**, **106u**) to set the polarity to a programmed state. Further, an erase voltage having an opposite polarity as the program voltage is applied from the control gate electrode **114** to the semiconductor channel **104** (e.g., via the lower and upper source/drain regions **106l**, **106u**) to set the polarity to an erased state. The programmed state may, for example, represent a binary “1”, whereas the erased state may, for

example, represent a binary “0”, or vice versa.

[0026] The ferroelectric layer **112** screens an electric field produced by the control gate electrode **114** differently depending on whether the polarity is in the programmed state or the erased state. As such, the MFIS memory cell **102** has a programmed threshold voltage and an erased threshold voltage respectively while the polarity is in the programmed and erased states. During a read operation of the MFIS memory cell **102**, the control gate electrode **114** is biased with a read voltage between the programmed and erased threshold voltages and the resistance of the semiconductor channel **104** is measured. Depending upon whether the semiconductor channel **104** conducts, the polarity is either in the programmed or erased state.

[0027] By using the ferroelectric layer **112** for data storage, as opposed to a silicon nitride layer, there is no dependence on carrier tunneling for the program and erase operations. As such, program and erase voltages may be reduced and program and erase speeds may be increased. For example, the program and erase voltages may be reduced to less than about 5 volts and/or program and erase speeds may be reduced to less than about 100 nanoseconds. Other suitable values are, however, amenable. By reducing the program and erase voltages and by increasing the program and erase speeds, power consumption may be reduced.

[0028] With continued reference to FIGS. **1A-1C**, the semiconductor channel **104** extends from the lower source/drain region **106l** to the upper source/drain region **106u**. The semiconductor channel **104** may, for example, be doped or undoped and may, for example, be or comprise polysilicon and/or some other suitable semiconductor material(s). The semiconductor channel **104** may, for example, have a thickness (e.g., in an X direction) of about 10-30 nanometers, about 10-20 nanometers, about 20-30 nanometers, or some other suitable value.

[0029] The lower and upper source/drain regions **106l**, **106u** are doped and may, for example, be or comprise polysilicon and/or some other suitable semiconductor material(s). In some embodiments, the lower and upper source/drain regions **106l**, **106u** are or comprise doped polysilicon with a first doping type, and the semiconductor channel **104** is or comprises doped polysilicon with a second doping type opposite the first doping type. In some other embodiments, the lower and upper source/drain regions **106l**, **106u** are or comprise doped polysilicon, and the semiconductor channel **104** is or comprises undoped polysilicon.

[0030] The gate dielectric layer **110**, the ferroelectric layer **112**, and the control gate electrode **114** are at sides of the lower and upper source/drain regions **106l**, **106u**. As such, the gate dielectric layer **110**, the ferroelectric layer **112**, and the control gate electrode **114** are uncovered by the upper source/drain region **106u**. The control gate electrode **114** may, for example, be or comprise titanium nitride, doped polysilicon (e.g., N⁺ or P⁺), tantalum nitride, tungsten, some other suitable conductive material(s), or any combination of the foregoing.

[0031] The gate dielectric layer **110** may, for example, be or comprise silicon oxide (e.g., SiO₂), aluminum oxide (e.g., Al₂O₃), silicon oxynitride (e.g., SiON), silicon nitride (e.g., Si₃N₄), lanthanum oxide (e.g., La₂O₃), strontium titanium oxide (e.g., SrTiO₃), undoped hafnium oxide (e.g., HfO₂), some other suitable dielectric(s), or any combination of the foregoing. In some embodiments, the gate dielectric layer **110** is or comprises a high k dielectric material having a dielectric constant greater than about 3.9, about 10, or some other suitable value. In some embodiments, the gate dielectric layer **110** has a dielectric constant of about 3.9-15, about 3.9-10, about 10-15, or some other suitable value. If the dielectric constant is too low (e.g., less than about 3.9 or some other suitable value), an electric field across the gate dielectric layer **110** may be high. The high electric field may lead to a high time-dependent dielectric breakdown (TDDB) and may hence reduce reliability of the gate dielectric layer **110**.

[0032] In some embodiments, a thickness T_{gdl} of the gate dielectric layer **110** (e.g., in an X direction) is less than about 2.5 nanometers or some other suitable value. In some embodiments, the thickness T_{gdl} is about 1.5-2.5 nanometers, about 1.5-1.75 nanometers, about 1.75-2.5 nanometers, or some other suitable value. If the thickness T_{gdl} is too small (e.g., less than

about 1 nanometer or some other suitable value), leakage current may be high and hence data retention may be low. If the thickness $T_{\text{sub.gdl}}$ is too large (e.g., greater than about 2.5 nanometers or some other suitable value), the program and erase voltages may be large and the memory window (e.g., a difference between the program and erase threshold voltages) may be small. The former leads to low power efficiency, whereas the latter leads to low reliability.

[0033] The ferroelectric layer **112** is in the orthorhombic phase and may, for example, be or comprise hafnium oxide (e.g., $\text{HfO}_{2.2}$) doped with: 1) aluminum to less than about 20 atomic percent; 2) silicon to less than about 5 atomic percent; 3) zirconium to less than about 50 atomic percent; 4) lanthanum to less than about 50 atomic percent; 5) strontium to less than about 50 atomic percent; or 6) some other suitable element. Other atomic percentages are, however, amenable. Additionally, or alternatively, the ferroelectric layer **112** may, for example, be or comprise some other suitable ferroelectric material(s). In some embodiments, a dielectric constant of the ferroelectric layer **112** is greater than that of the gate dielectric layer **110**.

[0034] In some embodiments, a thickness $T_{\text{sub.fe}}$ of the ferroelectric layer **112** (e.g., in an X direction) is less than about 15 nanometers or some other suitable value. In some embodiments, the thickness $T_{\text{sub.gdl}}$ is about 5-15 nanometers, about 5-10 nanometers, about 10-15 nanometers, or some other suitable value. If the thickness $T_{\text{sub.fe}}$ is too small (e.g., less than about 5 nanometer or some other suitable value), the polarity may weekly switch between the programmed and erased states during the program and erase operations. As a result, reliability may be low. If the thickness $T_{\text{sub.fe}}$ is too large (e.g., greater than about 15 nanometers or some other suitable value), the program and erase voltages may be large and hence power efficiency may be low.

[0035] A dielectric structure **116** surrounds the MFIS memory cell **102**. The dielectric structure **116** separates the lower and upper source/drain regions **106l**, **106u** from each other and, as seen hereafter, separates the MFIS memory cell **102** from other MFIS memory cells when the MFIS memory cell **102** is integrated into a memory array. Note that a portion of the dielectric structure **116** separating the lower and upper source/drain regions **106l**, **106u** may also be known as a source/drain dielectric layer. The dielectric structure **116** may be or comprise, for example, silicon oxide and/or some other suitable dielectric(s).

[0036] With reference to FIGS. 2A-2D, various views **200A-200D** of some embodiments of a 3D memory array **202** comprising a plurality of MFIS memory cells **102** configured as in FIGS. 1A-1C is provided. FIG. 2A corresponds to a cross-sectional view **200A** along line C in FIG. 2D. FIG. 2B corresponds to a cross-sectional view **200B** along line D in FIG. 2D. FIG. 2C corresponds to a cross-sectional view **200C** along line E in FIG. 2D. FIG. 2D corresponds to a top view **200D** along lines C-E respectively in FIGS. 2A-2C. The 3D memory array **202** may, for example, provide high memory density, as well as high reliability (e.g., high endurance and high retention) for high speed and low power consumption applications.

[0037] The MFIS memory cells **102** are grouped into a first memory array **204a** and a second memory array **204b**. The first and second memory arrays **204a**, **204b** are vertically stacked over a dielectric substrate **206**, and the second memory array **204b** overlies the first memory array **204a**. The first and second memory arrays **204a**, **204b** have the same layout and each has 9 rows and 8 columns (best seen in FIG. 2D). In alternative embodiments, the first and second memory arrays **204a**, **204b** have more or less rows and/or more or less columns. For readability, the rows and the columns are not labeled. However, it is to be appreciated that the rows extend in an X direction (e.g., laterally in the cross-sectional views **200A**, **200B** of FIGS. 2A and 2B), whereas the columns extend in a Y direction (e.g., laterally in the cross-sectional view **200C** of FIG. 2C).

[0038] A plurality of control gate electrodes **114**, a ferroelectric layer **112**, and a gate dielectric layer **110** extend through the first and second memory arrays **204a**, **204b** and partially define the MFIS memory cells **102**. The control gate electrodes **114** are shared by MFIS memory cells in the first memory array **204a** and MFIS memory cells in the second memory array **204b**. For example, each MFIS memory cell in the first memory array **204a** may share a control gate electrode with an

overlying MFIS memory cell in the second memory array **204b**. Similarly, the ferroelectric layer **112** and the gate dielectric layer **110** are shared by MFIS memory cells in the first memory array **204a** and MFIS memory cells in the second memory array **204b**. The ferroelectric layer **112** may, for example, be shared because polarization of the ferroelectric layer **112** may be localized to a MFIS memory cell at which the polarization occurred.

[0039] The MFIS memory cells **102** are further grouped into pairs **208** of neighboring MFIS memory cells (e.g., MFIS pairs **208**) along corresponding rows. The MFIS memory cells in each of the MFIS pairs **208** share a corresponding one of the control gate electrodes **114**. A MFIS memory cell on a right side of a corresponding control gate electrode is as illustrated and described in FIGS. **1A-1C**. A MFIS memory cell on a left side of a corresponding control gate electrode is as illustrated and described in FIGS. **1A-1C**, except that FIGS. **1A** and **1C** should be flipped horizontally respectively along the Z axis and the Y axis. FIG. **1B** is the same regardless of whether an MFIS memory cell is on a left or right side of a corresponding control gate electrode.

[0040] The MFIS pairs **208** are arranged so an MFIS pair occurs every two columns along each row and occurs every other row along each column. Further, the MFIS pairs **208** are staggered along neighboring columns and neighboring rows so a pitch $P_{sub.y}$ of the MFIS pairs **208** in a Y direction spans a row and a pitch $P_{sub.x}$ of the MFIS pairs **208** in an X direction spans two columns. In some embodiments, the control gate electrodes **114** have individual widths $W_{sub.cg}$ in the Y direction that are less than about half the Y-direction pitch $P_{sub.y}$.

[0041] A plurality of semiconductor channels **104**, a plurality of lower source/drain regions **106l**, and a plurality of upper source/drain regions **106u** also partially define the MFIS memory cells **102**. Note that “lower” and “upper” are relative to the corresponding MFIS memory cells **102** of the lower and upper source/drain regions **106l**, **106u**. The semiconductor channels **104** extend correspondingly along the columns and are shared by the MFIS memory cells in the corresponding columns. A semiconductor channel may, for example, be shared by multiple MFIS memory cells because an electric field produced by an MFIS memory cell is localized to the MFIS memory cell. In alternative embodiments, the semiconductor channels **104** are individual to the MFIS memory cells **102** and are hence not shared. Similar to the semiconductor channels **104**, the lower and upper source/drain regions **106l**, **106u** extend correspondingly along the columns and are shared by the MFIS memory cells in the corresponding columns. Further, the upper source/drain regions **106u** define bit lines BL, and the lower source/drain regions **106l** define source lines SL. In alternative embodiments, the upper source/drain regions **106u** define the source lines SL, and the lower source/drain regions **106l** define the bit lines BL.

[0042] A plurality of array dielectric layers **210** and a dielectric structure **116** surround the first and second memory arrays **204a**, **204b**. The array dielectric layers **210** are individual to the first and second memory arrays **204a**, **204b** and are each atop the upper source/drain region **106u** of the individual memory array. The array dielectric layers **210** are a different material than the dielectric substrate **206** and may, for example, be or comprise silicon nitride and/or some other suitable dielectric(s). The dielectric structure **116** is along sidewalls of the MFIS memory cells **102** to laterally separate the MFIS memory cells **102** from each other.

[0043] While FIGS. **2A-2D** illustrate a 3D memory array with two memory-array levels, more memory-array levels are amenable. For example, the second memory array **204b** along with its corresponding one of the array dielectric layers **210** may be repeated above the second memory array **204b**. Further, while FIGS. **2A-2D** illustrate a 3D memory array with two memory-array levels, a two-dimensional (2D) memory array with a single memory-array level is also amenable. For example, the second memory array **204b** along with its corresponding one of the array dielectric layers **210** may be omitted.

[0044] With reference to FIG. **3A**, a cross-sectional view **300A** of some alternative embodiments of the 3D memory array **202** of FIG. **2A** is provided in which the 3D memory array **202** is uncovered by the gate dielectric layer **110** and the ferroelectric layer **112**. As a result, the gate dielectric layer

110 comprises a plurality of discrete gate dielectric segments, and the ferroelectric layer **112** comprises a plurality of discrete ferroelectric segments. The gate dielectric segments and the ferroelectric segments are shared by the first and second memory arrays **204a**, **204b** and have U-shaped profiles. In alternative embodiments, the gate dielectric segments and/or the ferroelectric segments have other suitable profiles. Further, the gate dielectric segments and the ferroelectric segments alternate with the lower and upper source/drain regions **106l**, **106u** along the rows. As in FIGS. 2A-2D, rows extend in an X direction.

[0045] With reference to FIGS. 3B and 3C, cross-sectional views **300B**, **300C** of some alternative embodiments of the 3D memory array **202** of FIG. 2A are provided in which the control gate electrodes **114** and the dielectric structure **116** bulge at the semiconductor channels **104**. Further, the gate dielectric layer **110** and the ferroelectric layer **112** wrap around sides of the bulges. In FIG. 3B, the semiconductor channels **104** have rectangular profiles and are set back from sidewalls of the lower and upper source/drain regions **106l**, **106u**. In FIG. 3C, the semiconductor channels **104** respectively have C-shaped and reverse C-shaped profiles. In alternative embodiments, the semiconductor channels **104** have other suitable profiles.

[0046] With reference to FIGS. 3D-3F, cross-sectional views **300D**-**300F** of some alternative embodiments of the 3D memory array **202** of FIG. 2A are provided in which the gate dielectric layer **110** comprises a plurality of discrete gate dielectric segments respectively underlying the upper source/drain regions **106u**. In FIGS. 3D and 3E, the semiconductor channels **104** respectively have C-shaped and reverse C-shaped profiles that respectively wrap around sides of the gate dielectric segments. In FIG. 3E, the control gate electrodes **114** and the dielectric structure **116** further bulge at the gate dielectric segments and the gate dielectric segments respectively have C-shaped and reverse C-shaped profiles respectively wrapping around sides of the bulges. In FIG. 3F, the semiconductor channels **104** have rectangular profiles and hence do not wrap around sides of the gate dielectric segments. In alternative embodiments, the semiconductor channels **104** and/or the gate dielectric segments have other suitable profiles.

[0047] With reference to FIG. 3G, a cross-sectional view **300G** of some alternative embodiments of the 3D memory array **202** of FIG. 2A is provided in which cavities **302** separate the control gate electrodes **114** from each other instead of the dielectric structure **116**. The cavities **302** include air and/or some other suitable gas(es). Further, the cavities **302** are sealed by a seal dielectric layer **304**. The seal dielectric layer **304** covers the 3D memory array **202** and the cavities **302** and may, for example, be or comprise silicon oxide and/or some other suitable dielectric(s).

[0048] While FIGS. 3A-3G illustrate cross-sectional views **300A**-**300G** of some alternative embodiments of FIG. 2A in which constituents are modified, it is to be appreciated that the modifications may also be applied to any of FIGS. 2B-2D. For example, when applying the modifications of FIG. 3A to FIGS. 2B-2D, the gate dielectric layer **110** and the ferroelectric layer **112** may be cleared from atop the array dielectric layer **210** of the second memory array **204b** in FIGS. 2B and 2C. FIG. 2D may remain unchanged. While FIG. 2D is described with regard to FIGS. 2A-2C, any of FIGS. 3A-3G may be taken along line C in embodiments of FIG. 2D which have been modified as necessary as described above. For example, FIG. 3G may be taken along line C in alternative embodiments of FIG. 2D in which the dielectric structure **116** has been replaced with the cavities **302**. As another example, FIGS. 3A-3C may be taken along line C in the embodiments of FIG. 2D without modification of FIG. 2D.

[0049] With reference to FIG. 4A, a cross-sectional view **400A** of some alternative embodiments of the 3D memory array of FIG. 2A is provided in which a plurality of metal lines **402** define the source lines SL and the bit lines BL instead of the lower and upper source/drain regions **106l**, **106u**. The metal lines **402** extend correspondingly along the columns. Further, the metal lines **402** are individual to the lower and upper source/drain regions **106l**, **106u** and electrically couple directly to the individual source/drain regions. In the case of the upper source/drain regions **106u**, the upper source/drain regions **106u** underlie and directly contact the corresponding metal lines. In the case

of the lower source/drain regions **106l**, the lower source/drain regions **106l** overlie and directly contact the corresponding metal lines.

[0050] The metal lines **402** have smaller resistances than the lower and upper source/drain regions **106l**, **106u** and hence reduce voltage drops along the source lines SL and the bit lines BL. The reduced voltage drops allow larger memory arrays and/or reduced power consumption. The metal lines **402** comprise corresponding metal layers **404** and corresponding barrier layers **406**. The barrier layers **406** are configured to prevent outward diffusion of material from the metal layers **404** to overlying structure and/or underlying structure. The metal layers **404** may, for example, be or comprise tungsten and/or some other suitable metal(s). The barrier layers **406** may, for example, be or comprise titanium nitride (e.g., TiN), tungsten nitride (e.g., WN), some other suitable barrier material(s), or any combination of the foregoing.

[0051] With reference to FIG. **4B**, a cross-sectional view **400B** of some alternative embodiments of 3D memory array of FIG. **4A** is provided in which dummy semiconductor channels **408** are on sidewalls of the metal lines **402** to protect the metal lines **402** from oxidation. Such oxidation may, for example, occur before and/or during deposition of the gate dielectric layer **110** and the ferroelectric layer **112**. Oxidation may increase resistances of the metal lines **402**, thereby increasing voltage drops along the metal lines **402**. This may, in turn, increase power consumption and/or limit the size of the 3D memory array **202**. The dummy semiconductor channels **408** are respectively as the semiconductor channels **104** are described. This may, for example, be due to formation by the same process or a similar process.

[0052] In some embodiments, the dummy semiconductor channels **408** have individual widths $W_{sub,dsc}$ that are the same as or substantially the same as individual widths $W_{sub,sc}$ of the semiconductor channels **104**. In alternative embodiments, the dummy semiconductor channels **408** have individual widths $W_{sub,dsc}$ that are different (e.g., greater or less) than the individual widths $W_{sub,sc}$ of the semiconductor channels **104**. The different widths may, for example, be due to different etch processes while forming recesses within which the dummy semiconductor channels **408** and the semiconductor channels **104** are formed and/or may, for example, be due to different etch rates while forming the recesses. Other suitable reasons are, however, amenable.

[0053] With reference to FIG. **4C**, a cross-sectional view **400C** of some alternative embodiments of the 3D memory array of FIG. **2A** is provided in which a plurality of silicide lines **410** are used in place of the plurality of metal lines **402**. Hence, the source lines SL and the bit lines BL are defined by the silicide lines **410**. The silicide lines **410** are a metal silicide and may, for example, be or comprise nickel silicide or some other suitable metal silicide.

[0054] As discussed with regard to FIG. **4B**, oxidation of the metal lines **402** may occur without dummy semiconductor channels **408** protecting sidewalls of the metal lines **402**. Such oxidation may, in turn, negatively impact performance of the 3D memory array **202**. The silicide lines **410** may have a comparable resistance to the metal lines **402** and may hence perform comparable to the metal lines **402**. Further, the silicide lines **410** may have a lower reactivity to oxygen than the metal lines **402**. Therefore, by replacing the metal lines **402** with the silicide lines **410**, the challenges associated with oxidation may be mitigated without the dummy semiconductor channels **408**. The dummy semiconductor channels **408** may add complexity to formation of the 3D memory array **202**, such that omitting the dummy semiconductor channels **408** may reduce costs and/or increase yields.

[0055] With reference to FIG. **4D**, a cross-sectional view **400D** of some alternative embodiments of the 3D memory array of FIG. **4C** is provided in which the lower and upper source/drain regions **106l**, **106u** are omitted. Instead, the silicide lines **410** are used as source/drain regions for the MFIS memory cells **102**.

[0056] While FIGS. **4A-4D** illustrate cross-sectional views **400A-400D** of some alternative embodiments of the 3D memory array of FIG. **2A** in an X direction, it is to be appreciated that top views of the alternative embodiments may be as illustrated in FIG. **2D**. For example, FIG. **2D** may

be taken along line C in any one of the FIGS. 4A-4D. Similarly, it is to be appreciated that cross-sectional views of the alternative embodiments in a Y direction may be as illustrated in FIG. 2C, except that the vertical stacks of layers would be modified to match FIGS. 4A-4D.

[0057] With reference to FIGS. 5A-5C, various views **500A-500C** of some embodiments of an integrated circuit (IC) comprising a 3D memory array **202** is provided. The 3D memory array **202** is as described at FIGS. 2A-2D and includes additional columns. In alternative embodiments, the 3D memory array **202** is as described at any of FIGS. 3A-3G and 4A-4D and further includes the additional columns. FIG. 5A corresponds to a cross-sectional view **500A** along line F in FIG. 5C, and FIG. 5B corresponds to a cross-sectional view **500B** along line G in FIG. 5C. Further, FIG. 5C corresponds to lines F and G respectively in FIGS. 5A and 5B.

[0058] The 3D memory array **202** overlies a semiconductor substrate **502** within an interconnect structure **504**. The semiconductor substrate **502** may, for example, be or comprise a bulk substrate of monocrystalline silicon and/or some other suitable type of semiconductor substrate. The interconnect structure **504** comprises an interconnect dielectric layer **506**, a plurality of wires **508**, and a plurality of vias **510**. The wires **508** and the vias **510** are alternately stacked in the interconnect dielectric layer **506** to define conductive paths over and under the 3D memory array **202**. The interconnect dielectric layer **506** may, for example, be or comprise silicon oxide and/or some other suitable dielectric(s). The wires **508** and the vias **510** may, for example, be or comprise metal and/or some other suitable conductive material(s).

[0059] The plurality of wires **508** define top word line wires TWL (shown in phantom in FIG. 5C) overlying the 3D memory array **202** and extending correspondingly along the rows of the 3D memory array **202**. Further, the plurality of vias **510** define top electrode vias TEV extending respectively from the control gate electrodes **114** respectively to the top word lines TWL. Hence, the top word lines TWL and the top electrode vias TEV electrically couple to and interconnect control gate electrodes in corresponding rows.

[0060] Semiconductor devices **512** are on the semiconductor substrate **502**, between the semiconductor substrate **502** and the interconnect structure **504**. The semiconductor devices **512** comprise corresponding pairs of source/drain regions **514**, corresponding gate electrodes **516**, and corresponding gate dielectric layers **518**. The gate electrodes **516** correspond to the pairs of source/drain regions **514** and are laterally sandwiched between the source/drain regions of the corresponding pairs. The gate dielectric layer **518** respectively underlie the gate electrodes **516** to separate the gate electrodes **516** from the semiconductor substrate **502**. The semiconductor devices **512** may, for example, be metal-oxide-semiconductor (MOS) FETs, fin FETs, nanostructure FETs, gate-all-around (GAA) FETs, or some other suitable type of semiconductor device. Further, the semiconductor devices **512** may, for example, implement read and write circuitry for the 3D memory array **202**.

[0061] A trench isolation structure **520** extends into the semiconductor substrate **502** to provide electrical isolation between the semiconductor devices **512** and other semiconductor devices (not shown) on the semiconductor substrate **502**. The trench isolation structure **520** may, for example, be or comprise silicon oxide and/or some other suitable dielectric(s). Further, the trench isolation structure **520** may, for example, be or comprise a shallow trench isolation (STI) structure and/or some other suitable type of trench isolation structure.

[0062] With reference to FIG. 6, a schematic view **600** of some embodiments of a portion of the 3D memory array **202** of FIGS. 5A-5C is provided within box BX of FIGS. 5A-5C. The box BX spans two rows and eight columns. The rows have corresponding top word lines TWL with subscripts denoting specific row numbers beginning at row m, where m is an integer value. The columns have corresponding bit lines BL and corresponding source lines SL with subscripts denoting specific column numbers beginning at column n, where n is an integer value.

[0063] The top word lines TWL extend correspondingly along the rows and electrically couple to the MFIS memory cells **102** in the corresponding rows via the control gate electrodes **114** in the

corresponding rows. The bit lines BL and the source lines SL extend correspondingly along the columns and electrically couple to the MFIS memory cells **102** in the corresponding columns via the lower and upper source/drain regions **106l**, **106u** (see, e.g., FIGS. 5A-5C) in the corresponding columns. Collectively, the top word lines TWL, the bit lines BL, and the source lines SL facilitate read and write operations on the MFIS memory cells **102**.

[0064] With reference to FIGS. 7A and 7B, cross-sectional views **700A**, **700B** of some alternative embodiments of the IC of FIGS. 5A-5C is provided in which word lines electrically couple to the control gate electrodes **114** respectively at a bottom of the 3D memory array **202** and a top of the 3D memory array **202**. The cross-sectional view **700A** of FIG. 7A corresponds to the cross-sectional view **500A** of FIG. 5A, and the cross-sectional view **700B** of FIG. 7B corresponds to the cross-sectional view **500B** of FIG. 5B.

[0065] Control gate electrodes at even numbered rows electrically couple to bottom word lines BWL at a bottom of the 3D memory array **202**, and control gate electrodes at odd numbered rows electrically couple to top word lines TWL at a top of the 3D memory array **202**, or vice versa. Further, the control gate electrodes **114** have different cross-sectional profiles depending upon whether electrically coupled to top or bottom word lines. Control gate electrodes electrically coupled to the bottom word lines BWL have protrusions that protrude respectively to the bottom word lines BWL and that define bottom electrode vias BEV. Control gate electrodes electrically coupled to the top word lines TWL lack upward and downward protrusions and are electrically coupled to the top word lines TWL by separate top electrode vias TEV.

[0066] By splitting the word lines between the bottom of the 3D memory array **202** and the top of the 3D memory array **202**, a pitch of the word lines in a Y direction (e.g., into and out of the page; see, for example, FIG. 5C) may be reduced. Design constraints regarding the spacing of the word lines may otherwise limit the pitch. By reducing the pitch of the word lines, scaling down of the 3D memory array **202** may be enhanced.

[0067] With reference to FIGS. 8A and 8B, cross-sectional views **800A**, **800B** of some alternative embodiments of the IC of FIGS. 7A and 7B is provided in which the bottom electrode vias BEV are independent of the control gate electrodes **114**. The control gate electrodes **114** have the same or substantially the same profile regardless of whether electrically coupled to top or bottom word lines. Further, the control gate electrodes **114** extend through a cap dielectric layer **802** between the 3D memory array **202** and the bottom electrode vias BEV. Control gate electrodes electrically coupled to the bottom word lines BWL extend through the cap dielectric layer **802** respectively to the bottom electrode vias BEV. Control gate electrodes electrically coupled to the top word lines TWL extend through the cap dielectric layer **802** to the interconnect dielectric layer **506**. The cap dielectric layer **802** may be or comprise, for example, silicon nitride and/or some other suitable dielectric(s).

[0068] The 3D memory array **202** is uncovered by the gate dielectric layer **110** and the ferroelectric layer **112** as in FIG. 3A. As such, the gate dielectric layer **110** comprises a plurality of discrete gate dielectric segments, and the ferroelectric layer **112** comprises a plurality of discrete ferroelectric segments. A plurality of spacers **804** separate the control gate electrodes **114** from the ferroelectric segments. Further, the dielectric structure **116** extends through the cap dielectric layer **802**, the gate dielectric segments, and the ferroelectric segments. The spacers **804** may be or comprise, for example, silicon nitride and/or some other suitable dielectric(s).

[0069] As seen hereafter, the spacers **804** may be formed by a self-aligned process and used with a top one of the array dielectric layers **210** as a mask to form openings within which the control gate electrodes **114** are formed. This may lead to a reduction in the number of photomasks used while forming the 3D memory array **202**. Because photolithography is expensive, the reduction may lead to a substantial cost savings. Further, as seen hereafter, the spacers **804** protect the ferroelectric layer **112** while forming openings within which the control gate electrodes **114** are formed. This, in turn, reduces the likelihood of damage to the ferroelectric layer **112** and may hence enhance

performance of the MFIS memory cells **102**. Further yet, by forming the bottom electrode vias BEV independent of the control gate electrodes **114**, aspect ratios (e.g., ratios of height to width) of the openings within which the control gate electrodes **114** are formed may be reduced. This, in turn, may reduce the complexity of the etch used to form the openings and may enlarge the process window (e.g., the resiliency).

[0070] While the embodiments of the ICs in FIGS. **7A**, **7B**, **8A**, and **8B** were not accompanied with top views, it is to be appreciated that the top view **500C** of FIG. **5C** is representative of these top views with a few modifications. Top electrode vias TEV and top word lines TWL at even numbered rows or odd numbered rows, but not both, instead correspond to bottom electrode vias BEV and bottom word lines BWL and should therefore be shown in phantom. Further, sizes of electrode vias and/or shapes of electrode vias may be different. Accordingly, the cross-sectional views **700A**, **800A** of FIGS. **7A** and **8A** may, for example, be taken along line F in FIG. **5C** (as modified above), and the cross-sectional views **700B**, **800B** of FIGS. **7B** and **8B** may, for example, be taken along line G in FIG. **5C** (as modified above).

[0071] With reference to FIGS. **9A** and **9B** through FIGS. **18A** and **18B**, a series of views of some embodiments of a method for forming an IC comprising a 3D memory array of MFIS memory cells is provided. Figures labeled with a suffix of B illustrate cross-sectional views along line H, I, or J (whichever is present) in like-numbered figures with a suffix of A. Figures with a suffix of A illustrate top views along line H, I, or J (whichever is present) in like-numbered figures with a suffix of B. The method may, for example, be employed to form the IC of FIGS. **5A-5C** or other suitable ICs.

[0072] As illustrated by the top and cross-sectional views **900A**, **900B** of FIGS. **9A** and **9B**, a semiconductor device **512** and a trench isolation structure **520** are formed on a semiconductor substrate **502**. The semiconductor device **512** comprises a pair of source/drain regions **514**, a gate electrode **516**, and a gate dielectric layer **518**. The gate electrode **516** and the gate dielectric layer **518** are stacked between the source/drain regions **514**. The trench isolation structure **520** surrounds the semiconductor device **512** to electrically isolate the semiconductor device **512** from other semiconductor devices (not shown).

[0073] Also illustrated by the top and cross-sectional views **900A**, **900B** of FIGS. **9A** and **9B**, an interconnect structure **504** is partially formed over the semiconductor device **512** and the semiconductor substrate **502**. The interconnect structure **504** comprises a lower interconnect dielectric layer **506a**, a plurality of lower wires **508a**, and a plurality of lower vias **510a**. The lower wires **508a** and the lower vias **510a** are alternately stacked in the lower interconnect dielectric layer **506a** and define conductive paths leading from the semiconductor device **512** and other semiconductor devices (not shown) on the semiconductor substrate **502**.

[0074] As illustrated by the top and cross-sectional views **1000A**, **1000B** of FIGS. **10A** and **10B**, a first memory film **1002a** and a second memory film **1002b** are deposited over the interconnect structure **504** of FIGS. **9A** and **9B**. For ease of illustration, only a top portion of the interconnect structure **504** corresponding to the lower interconnect dielectric layer **506a** is shown. A remainder of the interconnect structure **504** is as shown in FIGS. **9A** and **9B**. The first and second memory films **1002a**, **1002b** comprise corresponding source/drain layers **1004**, corresponding source/drain dielectric layers **116a**, and corresponding array dielectric layers **210** that are vertically stacked. The source/drain dielectric layers **116a** are each between two of the source/drain layers **1004**. The array dielectric layers **210** are respectively at a top of the first and second memory films **1002a**, **1002b** and are a different material than portions of the lower interconnect dielectric layer **506a** extending along a top surface of the lower interconnect dielectric layer **506a**.

[0075] In some embodiments, the source/drain layers **1004** are or comprise doped polysilicon and/or some other suitable semiconductor material(s). In some embodiments, the source/drain dielectric layers **116a** are or comprise silicon oxide and/or some other suitable dielectric(s). In some embodiments, the array dielectric layers **210** are or comprise silicon nitride and/or some other

suitable dielectric(s).

[0076] While two memory films are deposited stacked over the interconnect structure **504**, more or less memory films may be deposited in alternative embodiments. For example, the second memory film **1002b** may be omitted, such that only a single memory film may be deposited. As another example, the second memory film **1002b** may be repeatedly deposited, such that three or more memory films may be deposited. In alternative embodiments, to form a 3D memory array according to FIG. **4A**, barrier layers **406** and metal layers **404** may be deposited stacked with the source/drain layers **1004**, the source/drain dielectric layers **116a**, and the array dielectric layers **210**. In alternative embodiments, to form a 3D memory array according to FIG. **4C**, silicide layers may be deposited stacked with the source/drain layers **1004**, the source/drain dielectric layers **116a**, and the array dielectric layers **210**. In alternative embodiments, to form a 3D memory array according to FIG. **4D**, silicide layers may be deposited in place of the source/drain layers **1004**.

[0077] As illustrated by the top and cross-sectional views **1100A**, **1100B** of FIGS. **11A** and **11B**, the first and second memory films **1002a**, **1002b** are patterned to form a plurality of trenches **1102**. The trenches **1102** are laterally elongated in parallel in a direction (e.g., a Y direction) transverse to the cross-sectional view **1100B** of FIG. **11B**. In some embodiments, the direction is the direction that columns of the 3D memory array being formed extend and/or the trenches **1102** have the same or substantially the same dimensions as each other. Further, the patterning divides the source/drain layers **1004** into lower source/drain regions **106l** and upper source/drain regions **106u**. The lower source/drain regions **106l** are at lower sides of corresponding source/drain dielectric layers, and the upper source/drain regions **106u** are at upper sides of corresponding source/drain dielectric layers. The patterning may, for example, be performed by a photolithography/etching process and/or some other suitable patterning process. The photolithography/etching process may, for example, use dry etching and/or some other suitable type of etching.

[0078] As illustrated by the top and cross-sectional views **1200A**, **1200B** of FIGS. **12A** and **12B**, the source/drain dielectric layers **116a** are laterally recessed through the trenches **1102**. The recessing recesses sidewalls of the source/drain dielectric layers **116a**, relative to neighboring sidewalls of the lower and upper source/drain regions **106l**, **106u**, to form recesses **1202** with a lateral depth $D_{sub.r}$. Note that the recesses **1202** are shown in phantom in FIG. **12A**. In some embodiments, the lateral depth $D_{sub.r}$ is about 10-30 nanometers, about 10-20 nanometers, about 20-30 nanometers, or some other suitable depth. The lateral recessing may, for example, be performed by wet etching and/or some other suitable type of etching.

[0079] As illustrated by the top and cross-sectional views **1300A**, **1300B** of FIGS. **13A** and **13B**, a semiconductor layer **1302** is formed filling the trenches **1102** (see, e.g., FIGS. **12A** and **12B**) and the recesses **1202** (see, e.g., FIGS. **12A** and **12B**). In some embodiments, the semiconductor layer **1302** is doped. In alternative embodiments, the semiconductor layer **1302** is undoped. In some embodiments, the semiconductor layer **1302** is or comprises polysilicon and/or some other suitable semiconductor material(s).

[0080] A process for forming the semiconductor layer **1302** may, for example, comprise: 1) depositing the semiconductor layer **1302**; and 2) performing a planarization into the semiconductor layer **1302** until the array dielectric layer **210** of the second memory film **1002b** is reached. Alternatively, other suitable processes may form the semiconductor layer **1302**. The planarization may, for example, be performed by a chemical mechanical polish (CMP) or some other suitable planarization.

[0081] While the semiconductor layer **1302** is formed fully filling the trenches **1102** and the recesses **1202**, the semiconductor layer **1302** may be formed lining and partially filling the trenches **1102** and the recesses **1202** in alternative embodiments. Such alternative embodiments may, for example, arise while forming a 3D memory array according to FIGS. **3C-3E**. In some embodiments in which the semiconductor layer **1302** is formed lining and partially filling the trenches **1102** and the recesses **1202**, a gate dielectric layer is formed lining and partially filling the trenches and the

recesses **1202** over the semiconductor layer **1302**. Such alternative embodiments may, for example, arise while forming a 3D memory array according to FIGS. 3D and 3E.

[0082] As illustrated by the top and cross-sectional views **1400A**, **1400B** of FIGS. **14A** and **14B**, the trenches **1102** are cleared. However, the recesses **1202** (see, e.g., FIGS. **12A** and **12B**) are not cleared or are minimally cleared. By doing so, a plurality of semiconductor channels **104** are formed localized to the recesses **1202** from the semiconductor layer **1302**. The clearing may, for example, be performed by dry etching and/or some other suitable type of etching. Alternatively, other suitable processes for clearing the trenches **1102** may, for example, be performed. In some embodiments, the array dielectric layer **210** of the second memory film **1002b** is used as a mask during the etching.

[0083] As illustrated by the top and cross-sectional views **1500A**, **1500B** of FIGS. **15A** and **15B**, a gate dielectric layer **110**, a ferroelectric layer **112**, and a control electrode layer **1502** (collectively the trench layers) are formed filling the trenches **1102**. The gate dielectric layer **110** is formed lining and partially filling the trenches **1102**, and the ferroelectric layer **112** is formed lining and partially filling the trenches **1102** over the gate dielectric layer **110**. The control electrode layer **1502** is formed filling a remainder of the trenches **1102** over the ferroelectric layer **112**. In some embodiments, the control electrode layer **1502** is or comprises titanium nitride, doped polysilicon, tantalum nitride, tungsten, some other suitable conductive material(s), or any combination of the foregoing. In some embodiments, the ferroelectric layer **112** is or comprises doped hafnium oxide (e.g., doped with aluminum, silicon, zirconium, lanthanum, strontium, or the like) and/or some other suitable ferroelectric material(s). In some embodiments, the gate dielectric layer **110** is or comprises silicon oxide, aluminum oxide, silicon oxynitride, silicon nitride, lanthanum oxide, strontium titanium oxide, undoped hafnium oxide, or some other suitable dielectric material(s), or any combination of the foregoing. In some embodiments, the gate dielectric layer **110** is or comprises a high k dielectric layer.

[0084] A process for forming the trench layers may, for example, comprise: 1) depositing the gate dielectric layer **110**; 2) depositing the ferroelectric layer **112** over the gate dielectric layer **110**; 3) depositing the control electrode layer **1502** over the ferroelectric layer **112**; and 4) performing a planarization into the control electrode layer **1502** until the ferroelectric layer **112** is reached. Alternatively, other suitable processes may form the trench layers. For example, the planarization may alternatively be performed until the second memory film **1002b** is reached. The planarization may, for example, be performed by a CMP or some other suitable planarization.

[0085] As illustrated by the top and cross-sectional views **1600A**, **1600B** of FIGS. **16A** and **16B**, the control electrode layer **1502** is patterned to form a plurality of gate isolation openings **1602** dividing the control electrode layer **1502** into a plurality of control gate electrodes **114**. The control gate electrodes **114** are arranged in a plurality of rows and a plurality of columns, such that a control gate electrode occurs every other column along each row and such that a control gate electrode occurs every other row along each column. Further, the control gate electrodes **114** are staggered along neighboring columns and neighboring rows, such that a pitch $P_{sub.y}$ of the control gate electrodes **114** in the Y direction spans a row and a pitch $P_{sub.x}$ of the control gate electrodes **114** in the X direction spans two columns. In some embodiments, the control gate electrodes **114** have individual widths $W_{sub.cg}$ that are less than about half the Y-direction pitch $P_{sub.y}$.

[0086] The patterning may, for example, be performed by a photolithography/etching process and/or some other suitable patterning process. The photolithography/etching process may, for example, use the ferroelectric layer **112** as an etch stop and/or may, for example, use dry etching and/or some other suitable type of etching.

[0087] Dividing the control electrode layer **1502** into the control gate electrodes **114** completes a first memory array **204a** and a second memory array **204b**. The first and second memory arrays **204a**, **204b** are vertically stacked and are made up of a plurality of MFIS memory cells **102**. In some embodiments, the MFIS memory cells **102** are as described at FIGS. **1A-1C** and/or FIGS.

2A-2D. Each of the MFIS memory cells **102** has a localized portion of the ferroelectric layer **112**, which has a polarity representing a bit of data.

[0088] During program and erase operations for any one of the MFIS memory cells **102**, the lower and upper source/drain regions **106l**, **106u** of the MFIS memory cell are electrically coupled in parallel and used as a proxy for the semiconductor channel **104** of the MFIS memory cell. A program voltage is applied from the control gate electrode **114** of the MFIS memory cell to the semiconductor channel **104** (e.g., via the lower and upper source/drain regions **106l**, **106u**) to set the polarity to a programmed state. Further, an erase voltage having an opposite polarity as the program voltage is applied from the control gate electrode **114** to the semiconductor channel **104** (e.g., via the lower and upper source/drain regions **106l**, **106u**) to set the polarity to an erased state. The programmed state may, for example, represent a binary “1”, whereas the erased state may, for example, represent a binary “0”, or vice versa.

[0089] The ferroelectric layer **112** screens an electric field produced by the control gate electrode **114** differently depending on whether the polarity is in the programmed state or the erased state. As such, the MFIS memory cell has a programmed threshold voltage and an erased threshold voltage respectively while the polarity is in the programmed and erased states. During a read operation of the MFIS memory cell, the control gate electrode **114** is biased with a read voltage between the programmed and erased threshold voltages and the resistance of the semiconductor channel **104** is measured. Depending upon whether the semiconductor channel **104** conducts, the polarity is either in the programmed or erased state.

[0090] By using the ferroelectric layer **112** for data storage, as opposed to a silicon nitride layer, there is no dependence on carrier tunneling for the program and erase operations. As such, program and erase voltages may be reduced and program and erase speeds may be increased. For example, the program and erase voltages may be reduced to less than about 5 volts and/or program and erase speeds may be reduced to less than about 100 nanoseconds. Other suitable values are, however, amenable. By reducing the program and erase voltages and by increasing the program and erase speeds, power consumption may be reduced.

[0091] As illustrated by the top and cross-sectional views **1700A**, **1700B** of FIGS. **17A** and **17B**, an inter-gate dielectric layer **116b** is formed filling the gate isolation openings **1602** (see, e.g., FIGS. **16A** and **16B**). The inter-gate dielectric layer **116b** may, for example, be or comprise silicon oxide and/or some other suitable dielectric(s). A process for forming the inter-gate dielectric layer **116b** may, for example, comprise: 1) depositing an inter-gate dielectric layer **116b** filling the gate isolation openings **1602**; and 2) performing a planarization into the inter-gate dielectric layer **116b** until the ferroelectric layer **112** is exposed. In alternative embodiments, the inter-gate dielectric layer **116b** is formed by some other suitable process. Further, in alternative embodiments, the planarization stops before the ferroelectric layer **112** is exposed and top electrode vias hereafter formed are formed in a top portion of the inter-gate dielectric layer **116b**.

[0092] As illustrated by the top and cross-sectional views **1800A**, **1800B** of FIGS. **18A** and **18B**, the interconnect structure **504** is completed. An upper interconnect dielectric layer **506b** is formed over the first and second memory arrays **204a**, **204b**, and a plurality of upper wires **508b** and a plurality of upper vias **510b** are formed stacked in the upper interconnect dielectric layer **506b**. At least some of the upper wires **508b** define top word lines TWL, and at least some of the upper vias **510b** define top electrode vias TEV. The top word lines TWL extend correspondingly along rows of the control gate electrodes **114**, and the top electrode vias TEV extend respectively from the top word lines TWL respectively to the control gate electrodes **114**.

[0093] While FIGS. **9A** and **9B** through FIGS. **18A** and **18B** are described with reference to various embodiments of a method, it will be appreciated that the structures shown in FIGS. **9A** and **9B** through FIGS. **18A** and **18B** are not limited to the method but rather may stand alone separate of the method. While FIGS. **9A** and **9B** through FIGS. **18A** and **18B** are described as a series of acts, it will be appreciated that the order of the acts may be altered in other embodiments. While FIGS.

9A and **9B** through **FIGS. 18A** and **18B** illustrate and describe as a specific set of acts, some acts that are illustrated and/or described may be omitted in other embodiments. Further, acts that are not illustrated and/or described may be included in other embodiments.

[0094] With reference to **FIG. 19**, a block diagram **1900** of some embodiments of the method of **FIGS. 9A** and **9B** through **FIGS. 18A** and **18B** is provided.

[0095] At **1902**, an interconnect structure is partially formed over a semiconductor device and a semiconductor substrate. See, for example, **FIGS. 9A** and **9B**.

[0096] At **1904**, a memory film is deposited over the interconnect structure, wherein the memory film comprises a pair of source/drain layers and a source/drain dielectric layer between the source/drain layers. See, for example, **FIGS. 10A** and **10B**.

[0097] At **1906**, the memory film is patterned to form a plurality of trenches extending laterally in parallel in a first direction. See, for example, **FIGS. 11A** and **11B**.

[0098] At **1908**, sidewalls of the source/drain dielectric layer are laterally recessed in the trenches in a second direction transverse to the first direction to form recesses. See, for example, **FIGS. 12A** and **12B**.

[0099] At **1910**, a semiconductor layer is deposited filling the trenches and the recesses. See, for example, **FIGS. 13A** and **13B**.

[0100] At **1912**, the semiconductor layer is patterned to clear the semiconductor layer from the trenches while the semiconductor layer persists in the recesses. See, for example, **FIGS. 14A** and **14B**.

[0101] At **1914**, a gate dielectric layer and a ferroelectric layer are deposited lining and partially filling the trenches. See, for example, **FIGS. 15A** and **15B**.

[0102] At **1916**, a control electrode layer is deposited filling a remainder of the trenches. See, for example, **FIGS. 15A** and **15B**.

[0103] At **1918**, the control electrode layer is patterned to divide the control electrode layer into a plurality of control gate electrodes in a plurality of rows and a plurality of columns. See, for example, **FIGS. 16A** and **16B**.

[0104] At **1920**, the interconnect structure is completed over the memory film and the control gate electrodes. See, for example, **FIGS. 17A** and **17B** and **FIGS. 18A** and **18B**.

[0105] While the block diagram **1900** of **FIG. 19** is illustrated and described herein as a series of acts or events, it will be appreciated that the illustrated ordering of such acts or events is not to be interpreted in a limiting sense. For example, some acts may occur in different orders and/or concurrently with other acts or events apart from those illustrated and/or described herein. Further, not all illustrated acts may be required to implement one or more aspects or embodiments of the description herein, and one or more of the acts depicted herein may be carried out in one or more separate acts and/or phases.

[0106] With reference to **FIGS. 20A** and **20B** through **FIGS. 27A** and **27B**, a series of views of some embodiments of a method for forming an IC comprising a 3D memory array of MFIS memory cells is provided in which word lines are respectively at a bottom and a top of the 3D memory array. Figures labeled with a suffix of B illustrate cross-sectional views along line K, L, or M (whichever is present) in like-numbered figures with a suffix of A. Figures with a suffix of A illustrate top views along line K, L, or M (whichever is present) in like-numbered figures with a suffix of B. The method may, for example, be employed to form the IC of **FIGS. 8A** and **8B** or other suitable ICs.

[0107] As illustrated by the top and cross-sectional views **2000A**, **2000B** of **FIGS. 20A** and **20B**, a semiconductor device **512** and a trench isolation structure **520** are formed on a semiconductor substrate **502** as illustrated and described at **FIGS. 9A** and **9B**.

[0108] Also illustrated by the top and cross-sectional views **2000A**, **2000B** of **FIGS. 20A** and **20B**, an interconnect structure **504** is partially formed over the semiconductor device **512** and the semiconductor substrate **502**. The interconnect structure **504** comprises a lower interconnect

dielectric layer **506a**, a cap dielectric layer **802**, a plurality of lower wires **508a**, and a plurality of lower vias **510a**. The lower wires **508a** and the lower vias **510a** are alternately stacked in the lower interconnect dielectric layer **506a** and define conductive paths leading from the semiconductor device **512** and other semiconductor devices (not shown) on the semiconductor substrate **502**. Further, the lower wires **508a** define bottom word lines BWL at a top of the interconnect structure **504**, and the lower vias **510a** define bottom electrode vias BEV respectively overlying the bottom word lines BWL. The cap dielectric layer **802** covers the lower interconnect dielectric layer **506a** and the bottom electrode vias BEV.

[0109] As illustrated by the top and cross-sectional views **2100A**, **2100B** of FIGS. **21A** and **21B**, the acts at FIGS. **10A** and **10B** through FIGS. **14A** and **14B** are performed on the interconnect structure **504** of FIGS. **20A** and **20B**. For ease of illustration, only a top portion of the interconnect structure **504** is shown. A remainder of the interconnect structure **504** is as shown in FIGS. **20A** and **20B**.

[0110] According to the acts at FIGS. **10A** and **10B** through FIGS. **14A** and **14B**, a first memory film **1002a** and a second memory film **1002b** are deposited as illustrated and described at FIGS. **10A** and **10B**. The first and second memory films **1002a**, **1002b** are patterned to form a plurality of trenches **1102** as illustrated and described at FIGS. **11A** and **11B**. The source/drain dielectric layers **116a** are laterally recessed through the trenches **1102** to form recesses **1202** (see, e.g., FIGS. **12A** and **12B**) as illustrated and described at FIGS. **12A** and **12B**. A semiconductor layer **1302** is formed filling the trenches **1102** and the recesses **1202** as illustrated and described at FIGS. **13A** and **13B**. The trenches **1102** are cleared as illustrated and described at FIGS. **14A** and **14B**.

[0111] As illustrated by the top and cross-sectional views **2200A**, **2200B** of FIGS. **22A** and **22B**, a gate dielectric layer **110**, a ferroelectric layer **112**, and a spacer layer **2202** are formed lining and partially filling the trenches **1102**. The ferroelectric layer **112** is formed lining and partially filling the trenches **1102** over the gate dielectric layer **110**, and the spacer layer **2202** is formed lining and partially filling the trenches **1102** over the ferroelectric layer **112**. The spacer layer **2202** may, for example, be or comprise silicon nitride and/or some other suitable dielectric(s).

[0112] As illustrated by the top and cross-sectional views **2300A**, **2300B** of FIGS. **23A** and **23B**, an etching process is performed into the spacer layer **2202**, the ferroelectric layer **112**, the gate dielectric layer **110**, and the cap dielectric layer **802** to extend the trenches **1102** to the bottom electrode vias BEV. Initially, the spacer layer **2202** is etched back and spacers **804** are formed from the spacer layer **2202** along sidewalls of the trenches **1102**. Thereafter, the spacers **804** and the array dielectric layer **210** of the second memory film **1002b** serve as a mask while etching through the ferroelectric layer **112**, the gate dielectric layer **110**, and the cap dielectric layer **802**. These two steps of the etching process may, for example, be performed by the same etch or by different etches.

[0113] In alternative embodiments, instead of forming the spacer layer **2202** at FIGS. **22A** and **22B** and subsequently performing the etching process at FIGS. **23A** and **23B**, a photolithography/etching process may be performed to form openings at bottoms of the trenches **1102** that extend respectively to the bottom electrode vias BEV. The method may then proceed as described hereafter. These alternative embodiments may, for example, be employed to form the IC of FIGS. **7A** and **7B** or other suitable ICs.

[0114] As illustrated by the top and cross-sectional views **2400A**, **2400B** of FIGS. **24A** and **24B**, a control electrode layer **1502** is formed filling the trenches **1102**. A process for forming the control electrode layer **1502** may, for example, comprise: 1) depositing the control electrode layer **1502**; and 2) performing a planarization into the control electrode layer **1502** until the array dielectric layer **210** of the second memory film **1002b** is reached. Alternatively, other suitable processes may form the control electrode layer **1502**. The planarization may, for example, be performed by a CMP or some other suitable planarization.

[0115] As illustrated by the views of FIGS. **25A** and **25B** and FIGS. **26A** and **26B**, the acts at FIGS.

16A and 16B and **FIGS. 17A and 17B** are performed. At the top and cross-sectional views **2500A, 2500B** of **FIGS. 25A and 25B**, the control electrode layer **1502** is patterned to form a plurality of gate isolation openings **1602** dividing the control electrode layer **1502** into a plurality of control gate electrodes **114** as illustrated and described at **FIGS. 16A and 16B**. At the top and cross-sectional views **2600A, 2600B** of **FIGS. 26A and 26B**, an inter-gate dielectric layer **116b** is formed filling the gate isolation openings **1602** (see, e.g., **FIGS. 25A and 25B**) as illustrated and described at **FIGS. 17A and 17B**.

[0116] As illustrated by the top and cross-sectional views **2700A, 2700B** of **FIGS. 27A and 27B**, the interconnect structure **504** is completed as described at **FIGS. 18A and 18B**. However, in contrast with **FIGS. 18A and 18B**, top word lines TWL and top electrode vias TEV are formed at even numbered rows or odd numbered rows, but not both.

[0117] While **FIGS. 20A and 20B** through **FIGS. 27A and 27B** are described with reference to various embodiments of a method, it will be appreciated that the structures shown in **FIGS. 20A and 20B** through **FIGS. 27A and 27B** are not limited to the method but rather may stand alone separate of the method. While **FIGS. 20A and 20B** through **FIGS. 27A and 27B** are described as a series of acts, it will be appreciated that the order of the acts may be altered in other embodiments. While **FIGS. 20A and 20B** through **FIGS. 27A and 27B** illustrate and describe as a specific set of acts, some acts that are illustrated and/or described may be omitted in other embodiments. Further, acts that are not illustrated and/or described may be included in other embodiments.

[0118] With reference to **FIG. 28**, a block diagram **2800** of some embodiments of the method of **FIGS. 20A and 20B** through **FIGS. 27A and 27B** is provided.

[0119] At **2802**, an interconnect structure is partially formed over a semiconductor device and a semiconductor substrate, wherein the interconnect structure comprises bottom word lines and bottom electrode vias respectively overlying the bottom word lines at a top of the interconnect structure. See, for example, **FIGS. 20A and 20B**.

[0120] At **2804**, a memory film is deposited over the interconnect structure, wherein the memory film comprises a pair of source/drain layers and a source/drain dielectric layer between the source/drain layers. See, for example, **FIGS. 21A and 21B** and **FIGS. 10A and 10B**.

[0121] At **2806**, the memory film is patterned to form a plurality of trenches extending laterally in parallel in a first direction. See, for example, **FIGS. 21A and 21B** and **FIGS. 11A and 11B**.

[0122] At **2808**, sidewalls of the source/drain dielectric layer are laterally recessed in the trenches in a second direction transverse to the first direction to form recesses. See, for example, **FIGS. 21A and 21B** and **FIGS. 12A and 12B**.

[0123] At **2810**, a semiconductor layer is deposited filling the trenches and the recesses. See, for example, **FIGS. 21A and 21B** and **FIGS. 13A and 13B**.

[0124] At **2812**, the semiconductor layer is patterned to clear the semiconductor layer from the trenches while the semiconductor layer persists in the recesses. See, for example, **FIGS. 21A and 21B** and **FIGS. 14A and 14B**.

[0125] At **2814**, a gate dielectric layer, a ferroelectric layer, and a spacer layer are deposited lining and partially filling the trenches. See, for example, **FIGS. 22A and 22B**.

[0126] At **2816**, an etch is performed to etch back the spacer layer, the ferroelectric layer, and the gate dielectric layer and to extend the trenches to the bottom electrode vias. See, for example, **FIGS. 23A and 23B**.

[0127] At **2818**, a control electrode layer is deposited filling the trenches. See, for example, **FIGS. 24A and 24B**.

[0128] At **2820**, the control electrode layer is patterned to divide the control electrode layer into a plurality of control gate electrodes in a plurality of rows and a plurality of columns. See, for example, **FIGS. 25A and 25B**.

[0129] At **2822**, the interconnect structure is completed over the memory film and the control gate electrodes. See, for example, **FIGS. 26A and 26B** and **FIGS. 27A and 27B**.

[0130] While the block diagram **2800** of FIG. **28** is illustrated and described herein as a series of acts or events, it will be appreciated that the illustrated ordering of such acts or events is not to be interpreted in a limiting sense. For example, some acts may occur in different orders and/or concurrently with other acts or events apart from those illustrated and/or described herein. Further, not all illustrated acts may be required to implement one or more aspects or embodiments of the description herein, and one or more of the acts depicted herein may be carried out in one or more separate acts and/or phases.

[0131] In some embodiments, the present disclosure provides a memory device including: a lower source/drain region and an upper source/drain region overlying the lower source/drain region; a semiconductor channel that overlies the lower source/drain region and that underlies the upper source/drain region; a control gate electrode extending along a sidewall of the semiconductor channel and along individual sidewalls of the lower and upper source/drain regions; and a gate dielectric layer and a ferroelectric layer separating the control gate electrode from the semiconductor channel and the lower and upper source/drain regions. In some embodiments, the semiconductor channel is completely and laterally between opposite sidewalls of the upper source/drain region, wherein the opposite sidewalls respectively face and face away from the control gate electrode. In some embodiments, the control gate electrode is fully uncovered by the upper source/drain region. In some embodiments, the sidewall of the semiconductor channel is offset from the individual sidewalls of the lower and upper source/drain regions. In some embodiments, the ferroelectric layer extends along the sidewall of the semiconductor channel from top to bottom and further extends along the individual sidewalls of the lower and upper source/drain regions from top to bottom. In some embodiments, the memory device further includes a second semiconductor channel and a source/drain dielectric layer overlying the lower source/drain region and underlying the upper source/drain region, wherein the source/drain dielectric layer is between the semiconductor channel and the second semiconductor channel. In some embodiments, the memory device further includes a second semiconductor channel bordering the control gate electrode on an opposite side of the control gate electrode as the semiconductor channel, wherein the ferroelectric layer and the gate dielectric layer wrap around a bottom of the control gate electrode and separate the control gate electrode from the second semiconductor channel.

[0132] In some embodiments, the present disclosure provides another memory device including: a first semiconductor channel; a second semiconductor channel overlying the first semiconductor channel; and a control gate electrode and a ferroelectric layer bordering the first and second semiconductor channels, wherein the ferroelectric layer separates the control gate electrode from the first and second semiconductor channels. In some embodiments, the memory device further includes a high k gate dielectric layer separating the ferroelectric layer from the first and second semiconductor channels. In some embodiments, the control gate electrode, the ferroelectric layer, and the first semiconductor channel partially define a MFIS FET. In some embodiments, the memory device further includes a second control gate electrode laterally spaced from the control gate electrode and also bordering the first and second semiconductor channels, wherein the ferroelectric layer separates the second control gate electrode from the first and second semiconductor channels. In some embodiments, the memory device further includes a lower source/drain region and an upper source/drain region that are vertically stacked with the second semiconductor channel. In some embodiments, the upper source/drain region completely covers the first and second semiconductor channels. In some embodiments, the control gate electrode bulges individually at the first and second semiconductor channels.

[0133] In some embodiments, the present disclosure provides a method for forming a memory device, the method including: depositing a memory film over a substrate, wherein the memory film includes a pair of source/drain layers and a source/drain dielectric layer between the source/drain layers; performing a first etch into the memory film to form a trench through memory film;

recessing a sidewall of the source/drain dielectric layer relative to sidewalls of the source/drain layers through the trench to form a recess; depositing a semiconductor layer filling the recess and the trench; performing a second etch into the semiconductor layer to clear the semiconductor layer from the trench; depositing a ferroelectric layer lining the trench and further lining the semiconductor layer at the recess; and depositing an electrode layer filling the trench over the ferroelectric layer. In some embodiments, the method further includes performing a third etch into the electrode layer to form a plurality of control gate electrodes bordering the semiconductor layer at the recess. In some embodiments, the method further includes depositing a high k gate dielectric layer lining the trench between the depositing of the semiconductor layer and the depositing of the ferroelectric layer. In some embodiments, the semiconductor layer is deposited on the sidewall of the source/drain dielectric layer and the sidewalls of the source/drain layers, wherein the semiconductor layer is cleared from the sidewalls of the source/drain layers but not the sidewall of the source/drain dielectric layer by the second etch. In some embodiments, the method further includes depositing a second memory film over the memory film, wherein the second memory film includes a pair of second source/drain layers and a second source/drain dielectric layer between the second source/drain layers, wherein the first etch is also performed into the second memory film, and wherein the recessing recesses a sidewall of the second source/drain dielectric layer relative to sidewalls of the second source/drain layers through the trench to form a second recess simultaneous with the recess. In some embodiments, the recessing recesses a second sidewall of the source/drain dielectric layer relative to second sidewalls of the source/drain layers through the trench to form a second recess, and wherein the second recess is on an opposite side of the trench as the recess.

[0134] The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A memory device, comprising: a stack structure comprising: a first metal-containing line; a first source/drain region overlying the first metal-containing line; a first semiconductor channel overlying the first source/drain region; a second source/drain region overlying the first semiconductor channel; and a second metal-containing line overlying the second source/drain region; a gate electrode bordering the stack structure; and a ferroelectric layer separating the gate electrode from the stack structure, wherein the gate electrode has a height greater than a separation between a bottom surface of the first metal-containing line and a top surface of the second metal-containing line, and wherein the first and second metal-containing lines have individual widths equal to or less than individual widths of the first and second source/drain regions.
2. The memory device according to claim 1, wherein the individual widths of the first and second metal-containing lines are about equal to the individual widths of the first and second source/drain regions.
3. The memory device according to claim 1, wherein the first metal-containing line, the first source/drain region, the second source/drain region, and the second metal-containing line form a common sidewall facing the gate electrode.
4. The memory device according to claim 1, wherein the first and second metal-containing lines are metal silicide and respectively border the first and second source/drain regions.
5. The memory device according to claim 1, wherein each of the first and second metal-containing

lines comprises a pair of conductive barrier layers and a metal layer vertically between and bordering the pair of conductive barrier layers.

6. The memory device according to claim 1, further comprising: a dummy semiconductor channel underlying and bordering the first source/drain region and extending along a sidewall of the first metal-containing line.

7. The memory device according to claim 1, wherein the stack structure further comprises: a third metal-containing line overlying the second metal-containing line; a third source/drain region overlying the third metal-containing line; a second semiconductor channel overlying the third source/drain region; a fourth source/drain region overlying the second semiconductor channel; and a fourth metal-containing line overlying the fourth source/drain region, wherein the height of the gate electrode is greater than a separation between the bottom surface of the first metal-containing line and a top surface of the fourth metal-containing line.

8. A memory device, comprising: a first source/drain region; a first semiconductor channel overlying the first source/drain region; a second source/drain region overlying the first semiconductor channel; a first gate electrode and a second gate electrode that laterally border the first and second source/drain regions and the first semiconductor channel; a ferroelectric layer separating the first and second gate electrodes from the first and second source/drain regions and the first semiconductor channel; and a first air gap between the first and second gate electrodes, wherein the first and second gate electrodes have individual sidewalls in the first air gap.

9. The memory device according to claim 8, wherein a height of the first air gap is greater than a separation between a bottom surface of the first source/drain region and a top surface of the second source/drain region.

10. The memory device according to claim 8, further comprising: a third source/drain region overlying the second source/drain region; a second semiconductor channel overlying the third source/drain region; and a fourth source/drain region overlying the second semiconductor channel, wherein a height of the first air gap is greater than a separation between a bottom surface of the first source/drain region and a top surface of the fourth source/drain region.

11. The memory device according to claim 8, wherein the ferroelectric layer has individual sidewalls in the first air gap.

12. The memory device according to claim 8, further comprising: a third gate electrode and a fourth gate electrode, wherein the first and second source/drain regions and the first semiconductor channel are between and border the first and third gate electrodes and are between and border the second and fourth gate electrodes; and a second air gap laterally between the third and fourth gate electrodes, wherein the third and fourth gate electrodes have individual sidewalls in the second air gap.

13. The memory device according to claim 8, further comprising: a second air gap spaced from the first air gap and bordering the first and second source/drain regions and the first semiconductor channel; and a dielectric cap layer having a first bottom-surface portion and a second bottom-surface portion overlying and exposed respectively in the first and second air gaps, wherein the dielectric cap layer is continuous from the first air gap to the second air gap.

14. The memory device according to claim 8, wherein the first source/drain region, the first semiconductor channel, and the second source/drain region form a first stack structure, and wherein the memory device further comprises: a second stack structure elongated laterally in parallel with the first stack structure, wherein the first air gap is between and borders the first and second stack structures and is separated from the second stack structure by the ferroelectric layer.

15. A memory device, comprising: a vertical stack laterally elongated in a first direction and comprising a first source/drain region, a semiconductor channel overlying the first source/drain region, and a second source/drain region overlying the semiconductor channel; a plurality of first gate electrodes that are spaced in a first line extending in the first direction and that border a first sidewall of the vertical stack; a plurality of second gate electrodes that are spaced in a second line

extending in the first direction and that border a second sidewall of the vertical stack on an opposite side of the vertical stack as the first sidewall of the vertical stack; and a ferroelectric layer separating the plurality of first gate electrodes and the plurality of second gate electrodes from the vertical stack, wherein the plurality of first gate electrodes comprise a first electrode and a second electrode that border in the first line, and wherein the plurality of second gate electrodes comprise a third electrode laterally between and offset from the first and second electrodes in the first direction.

16. The memory device according to claim 15, wherein the plurality of second gate electrodes comprise a fourth electrode bordering the third electrode in the second line, and wherein the second electrode is laterally between and offset from the third and fourth electrodes in the first direction.

17. The memory device according to claim 15, further comprising: a first word line overlying and electrically coupled to the first electrode by a first via, which extends from the first word line to the first electrode; and a second word line underlying and electrically coupled to the third electrode, wherein the first and second word lines are elongated in a second direction transverse to the first direction and are laterally offset from each other in the first direction.

18. The memory device according to claim 17, wherein the second electrode has a bottom protrusion protruding to the second word line.

19. The memory device according to claim 17, further comprising: a second via extending from the second electrode to the second word line.

20. The memory device according to claim 15, wherein the first and second source/drain regions are metal silicide and contact the semiconductor channel.
