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MEMORY DEVICES HAVING VERTICAL TRANSISTORS AND METHODS FOR FORMING THE SAME

Abstract

In certain aspects, a memory device includes a vertical transistor, a storage unit, and a bit line. The vertical transistor includes a semiconductor body extending in a first direction. The semiconductor body includes a doped source, a doped drain, and a channel portion. The storage unit is coupled to a first terminal. The first terminal is one of the source and the drain. The bit line extends in a second direction perpendicular to the first direction and in contact with a second terminal. The second terminal is another one of the source and the drain that is formed on at least one side of a protrusion of the semiconductor body and a side of a base of the semiconductor body connected to the protrusion of the semiconductor body.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 17/539,784, filed on Dec. 1, 2021, which is continuation of International Application No. PCT/CN 2021/127790, filed on Oct. 31, 2021, both of which are hereby incorporated by reference in their entireties. This application is also related to U.S. application Ser. No. 17/539,760, filed on Dec. 1, 2021, U.S. application Ser. No. 17/539,802, filed on Dec. 1, 2021, U.S. application Ser. No. 17/539,818, filed on Dec. 1, 2021, and U.S. application Ser. No. 17/539,742, filed on Dec. 1, 2021, all of which are hereby incorporated by reference in their entireties.

BACKGROUND

[0002] The present disclosure relates to memory devices and fabrication methods thereof.

[0003] Planar memory cells are scaled to smaller sizes by improving process technology, circuit design, programming algorithm, and fabrication process. However, as feature sizes of the memory cells approach a lower limit, planar process and fabrication techniques become challenging and costly. As a result, memory density for planar memory cells approaches an upper limit.

[0004] A three-dimensional (3D) memory architecture can address the density limitation in planar memory cells. The 3D memory architecture includes a memory array and peripheral circuits for facilitating operations of the memory array.

SUMMARY

[0005] In one aspect, a memory device includes a vertical transistor, a storage unit, and a bit line. The vertical transistor includes a semiconductor body extending in a first direction. The semiconductor body includes a doped source, a doped drain, and a channel portion. The storage unit is coupled to a first terminal. The first terminal is one of the source and the drain. The bit line extends in a second direction perpendicular to the first direction and in contact with a second terminal. The second terminal is another one of the source and the drain that is formed on all sides of a protrusion of the semiconductor body. The bit line is separated from the channel portion of the semiconductor body by the second terminal.

[0006] In another aspect, a memory system includes a memory device configured to store data and a memory controller coupled to the memory device. The memory device includes a vertical transistor, a storage unit, and a bit line. The vertical transistor includes a semiconductor body extending in a first direction. The semiconductor body includes a doped source, a doped drain, and a channel portion. The storage unit is coupled to a first terminal. The first terminal is one of the source and the drain. The bit line extends in a second direction perpendicular to the first direction and in contact with a second terminal. The second terminal is another one of the source and the drain that is formed on all sides of a protrusion of the semiconductor body. The bit line is separated from the channel portion of the semiconductor body by the second terminal. The memory controller is configured to control the vertical transistor and the storage unit through the bit line.

[0007] In still another aspect, a method for forming a memory device is disclosed. A semiconductor

body extending vertically from a first side of a substrate and surrounded by a gate dielectric is formed. The substrate is removed from a second side opposite to the first side of the substrate to expose a first end of the semiconductor body and the gate dielectric. Part of the gate dielectric is removed to expose part of the semiconductor body. A sidewall and a top of the exposed part of the semiconductor body are doped. The doped top of the exposed part of the semiconductor body is removed.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The accompanying drawings, which are incorporated herein and form a part of the specification, illustrate aspects of the present disclosure and, together with the description, further serve to explain the principles of the present disclosure and to enable a person skilled in the pertinent art to make and use the present disclosure.

[0009] FIG. 1A illustrates a schematic view of a cross-section of a 3D memory device, according to some aspects of the present disclosure.

[0010] FIG. 1B illustrates a schematic view of a cross-section of another 3D memory device, according to some aspects of the present disclosure.

[0011] FIG. 1C illustrates a schematic view of a cross-section of still another 3D memory device, according to some aspects of the present disclosure.

[0012] FIG. 2 illustrates a schematic diagram of a memory device including peripheral circuits and an array of memory cells each having a vertical transistor, according to some aspects of the present disclosure.

[0013] FIG. 3 illustrates a schematic circuit diagram of a memory device including peripheral circuits and an array of dynamic random-access memory (DRAM) cells, according to some aspects of the present disclosure.

[0014] FIG. 4 illustrates a schematic circuit diagram of a memory device including peripheral circuits and an array of phase-change memory (PCM) cells, according to some aspects of the present disclosure.

[0015] FIG. 5A illustrates a schematic circuit diagram of a memory device including peripheral circuits and an array of ferroelectric random-access memory (FRAM) cells, according to some aspects of the present disclosure.

[0016] FIG. 5B illustrates a schematic circuit diagram of a 1T1C FRAM cell, according to some aspects of the present disclosure.

[0017] FIG. 6 illustrates a plan view of an array of memory cells each including a vertical transistor in a memory device, according to some aspects of the present disclosure.

[0018] FIG. 7A illustrates a side view of a cross-section of a 3D memory device including vertical transistors, according to some aspects of the present disclosure.

[0019] FIG. 7B illustrates an enlarged side view of a cross-section of the vertical transistor in FIG. 7A, according to some aspects of the present disclosure.

[0020] FIG. 8 illustrates a plan view of another array of memory cells each including a vertical transistor in a memory device, according to some aspects of the present disclosure.

[0021] FIG. 9A illustrates a side view of a cross-section of another 3D memory device including vertical transistors, according to some aspects of the present disclosure.

[0022] FIG. 9B illustrates an enlarged side view of a cross-section of the vertical transistor in FIG. 9A, according to some aspects of the present disclosure.

[0023] FIG. 10A illustrates a side view of a cross-section of still another 3D memory device including vertical transistors and stacked storage units, according to some aspects of the present disclosure.

[0024] FIG. **10B** illustrates an enlarged side view of a cross-section of the stacked storage units in FIG. **10A**, according to some aspects of the present disclosure.

[0025] FIG. **11** illustrates a layout view of an array of memory cells each including a vertical transistor, according to some aspects of the present disclosure.

[0026] FIGS. **12A-12E** illustrates layout views of various arrays of memory cells each including a vertical transistor, according to various aspects of the present disclosure.

[0027] FIGS. **13A-13M** illustrate a fabrication process for forming a 3D memory device including vertical transistors, according to some aspects of the present disclosure.

[0028] FIGS. **14A-14M** illustrate a fabrication process for forming another 3D memory device including vertical transistors, according to some aspects of the present disclosure.

[0029] FIGS. **15A-15E** illustrate a fabrication process for forming a 3D memory device including vertical transistors and stacked storage units, according to some aspects of the present disclosure.

[0030] FIG. **16** illustrates a flowchart of a method for forming a 3D memory device including vertical transistors, according to some aspects of the present disclosure.

[0031] FIG. **17** illustrates a flowchart of a method for forming an array of memory cells each including a vertical transistor, according to some aspects of the present disclosure.

[0032] FIG. **18** illustrates a flowchart of a method for forming another array of memory cells each including a vertical transistor, according to some aspects of the present disclosure.

[0033] FIG. **19** illustrates a flowchart of a method for forming a 3D memory device including vertical transistors and stacked storage units, according to some aspects of the present disclosure.

[0034] FIG. **20** illustrates a block diagram of an exemplary system having a memory device, according to some aspects of the present disclosure.

[0035] The present disclosure will be described with reference to the accompanying drawings.

DETAILED DESCRIPTION

[0036] Although specific configurations and arrangements are discussed, it should be understood that this is done for illustrative purposes only. As such, other configurations and arrangements can be used without departing from the scope of the present disclosure. Also, the present disclosure can also be employed in a variety of other applications. Functional and structural features as described in the present disclosures can be combined, adjusted, and modified with one another and in ways not specifically depicted in the drawings, such that these combinations, adjustments, and modifications are within the scope of the present disclosure.

[0037] In general, terminology may be understood at least in part from usage in context. For example, the term “one or more” as used herein, depending at least in part upon context, may be used to describe any feature, structure, or characteristic in a singular sense or may be used to describe combinations of features, structures or characteristics in a plural sense. Similarly, terms, such as “a,” “an,” or “the,” again, may be understood to convey a singular usage or to convey a plural usage, depending at least in part upon context. In addition, the term “based on” may be understood as not necessarily intended to convey an exclusive set of factors and may, instead, allow for existence of additional factors not necessarily expressly described, again, depending at least in part on context.

[0038] It should be readily understood that the meaning of “on,” “above,” and “over” in the present disclosure should be interpreted in the broadest manner such that “on” not only means “directly on” something but also includes the meaning of “on” something with an intermediate feature or a layer therebetween, and that “above” or “over” not only means the meaning of “above” or “over” something but can also include the meaning it is “above” or “over” something with no intermediate feature or layer therebetween (i.e., directly on something).

[0039] 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.

[0040] As used herein, the term “substrate” refers to a material onto which subsequent material layers are added. The substrate itself can be patterned. Materials added on top of the substrate can be patterned or can remain unpatterned. Furthermore, the substrate can include a wide array of semiconductor materials, such as silicon, germanium, gallium arsenide, indium phosphide, etc. Alternatively, the substrate can be made from an electrically non-conductive material, such as a glass, a plastic, or a sapphire wafer.

[0041] As used herein, the term “layer” refers to a material portion including a region with a thickness. A layer can extend over the entirety of an underlying or overlying structure or may have an extent less than the extent of an underlying or overlying structure. Further, a layer can be a region of a homogeneous or inhomogeneous continuous structure that has a thickness less than the thickness of the continuous structure. For example, a layer can be located between any pair of horizontal planes between, or at, a top surface and a bottom surface of the continuous structure. A layer can extend horizontally, vertically, and/or along a tapered surface. A substrate can be a layer, can include one or more layers therein, and/or can have one or more layers thereupon, thereabove, and/or therebelow. A layer can include multiple layers. For example, an interconnect layer can include one or more conductors and contact layers (in which interconnect lines and/or vertical interconnect access (via) contacts are formed) and one or more dielectric layers.

[0042] Transistors are used as the switch or selecting devices in the memory cells of some memory devices, such as DRAM, PCM, and ferroelectric DRAM (FRAM). However, the planar transistors commonly used in existing memory cells usually have a horizontal structure with buried word lines in the substrate and bit lines above the substrate. Since the source and drain of a planar transistor are disposed laterally at different locations, which increases the area occupied by the transistor. The design of planar transistors also complicates the arrangement of interconnected structures, such as word lines and bit lines, coupled to the memory cells, for example, limiting the pitches of the word lines and/or bit lines, thereby increasing the fabrication complexity and reducing the production yield. Moreover, because the bit lines and the storage units (e.g., capacitors or PCM elements) are arranged on the same side of the planar transistors (above the transistors and substrate), the bit line process margin is limited by the storage units, and the coupling capacitance between the bit lines and storage units, such as capacitors, are increased. Planar transistors may also suffer from a high leakage current as the saturated drain current keeps increasing, which is undesirable for the performance of memory devices.

[0043] On the other hand, as the number of memory cells keeps increasing, to maintain the same chip size, the dimensions of the components in the memory cell array, such as transistors, storage units (e.g., capacitors), word lines, and/or bit lines, need to keep decreasing in order not to significantly reduce the memory cell array efficiency. The continuous reduction of the device dimensions of the storage units, however, is facing a great challenge. For example, the aspect ratio in etching the capacitor holes has reached its limit with the existing design and instruments and thus, may not be continuously increased to increase the memory cell density.

[0044] Some memory devices thus replace the planar transistors with vertical transistors to increase the performance and/or the memory cell array efficiency. However, different from a planar transistor in which the substrate body can be easily biased with a certain potential to fully deplete the charge, the upper and lower ends of the semiconductor body in a vertical transistor are fully doped to form the source and drain in those memory devices, which can cause the floating body effect. For example, the semiconductor body of the vertical transistor may become floating due to the diode formed between the channel and the bit line. As a result, the charge accumulated in the semiconductor body may cause adverse effects, for example, the opening of parasitic transistors in the structure and causing off-state leakages, resulting in higher current consumption and in case of

DRAM in loss of information from the memory cells. It may also cause the history effect, the dependence of the threshold voltage of the transistor on its previous states.

[0045] To address one or more of the aforementioned issues, the present disclosure introduces a solution in which vertical transistors replace the conventional planar transistors as the switch and selecting devices in a memory cell array of memory devices (e.g., DRAM, PCM, and FRAM). Compared with planar transistors, the vertically arranged transistors (i.e., the drain and source are overlapped in the plan view) can reduce the area of the transistor as well as simplify the layout of the interconnect structures, e.g., metal wiring the word lines and bit lines, which can reduce the fabrication complexity and improve the yield. For example, the pitches of word lines and/or bit lines may be reduced for ease of fabrication. The vertical structures of the transistors also allow the bit lines and storage units, such as capacitors, to be arranged on opposite sides of the transistors in the vertical direction (e.g., one above and on below the transistors), such that the process margin of the bit lines can be increased and the coupling capacitance between the bit lines and the storage units can be decreased.

[0046] Consistent with the scope of the present disclosure, one end of the semiconductor body can be partially doped, such that the channel portion of the semiconductor body can be coupled to a body line to bias the semiconductor body at a certain potential to suppress the floating body effect. In some implementations, one or more sides of a protrusion of the semiconductor body is doped to form the source/drain in contact with the bit line, while the remainder of the protrusion (e.g., the top) is in contact with the body line to enable the depletion of the charge from the channel.

[0047] According to some aspects of the present disclosure, the memory cell array having vertical transistors and the peripheral circuits of the memory cell array can be formed on different wafers and bonded together in a face-to-face manner. Thus, the thermal budget of fabricating the memory cell array does not affect the fabrication of the peripheral circuits. The stacked memory cell array and peripheral circuits can also reduce the chip size compared with the side-by-side arrangement, thereby improving the array efficiency. The face-to-face bonding can also allow backside processes on vertical transistors to form the partially doped protrusion of the semiconductor body as well as the bit line and body line from the backside after the bonding.

[0048] According to some aspects of the present disclosure, the array of memory cells can be arranged in a staggered layout, as opposed to the cross-point orthogonal layout (a.k.a., straight or aligned layout), in the plan view to further increase the cell density and reduce the unit cell size. In some implementations, a minimum cell distance is kept the same between any adjacent memory cells in the staggered layout to minimize the unit cell size. To maintain the same minimum cell distance in the staggered layout, dummy memory cells coupled to a slit structure separating adjacent word lines or a serpentine-shaped slit structure can be introduced into the memory design in various implementations.

[0049] According to some aspects of the present disclosure, each vertical transistor can be coupled to multiple stacked storage units (e.g., ferroelectric capacitors), as opposed to a single storage unit, to further increase the memory cell density. That is, the storage units can be scaled up vertically in 3D to overcome the fabrication limits. In some implementations, multiple plate lines of a ferroelectric memory device (e.g., FRAM) are formed in stack structure having interleaved conductive layers and dielectric layers above the vertical transistors, and each plate line is coupled to a respective one of the stacked storage units.

[0050] FIG. 1A illustrates a schematic view of a cross-section of a 3D memory device **100**, according to some aspects of the present disclosure. 3D memory device **100** represents an example of a bonded chip. The components of 3D memory device **100** (e.g., memory cell array and peripheral circuits) can be formed separately on different substrates and then jointed to form a bonded chip. 3D memory device **100** can include a first semiconductor structure **102** including the peripheral circuits of a memory cell array. 3D memory device **100** can also include a second semiconductor structure **104** including the memory cell array. The peripheral circuits (a.k.a. control

and sensing circuits) can include any suitable digital, analog, and/or mixed-signal circuits used for facilitating the operations of the memory cell array. For example, the peripheral circuit can include one or more of a page buffer, a decoder (e.g., a row decoder and a column decoder), a sense amplifier, a driver (e.g., a word line driver), an input/output (I/O) circuit, a charge pump, a voltage source or generator, a current or voltage reference, any portions (e.g., a sub-circuit) of the functional circuits mentioned above, or any active or passive components of the circuit (e.g., transistors, diodes, resistors, or capacitors). The peripheral circuits in first semiconductor structure **102** use complementary metal-oxide-semiconductor (CMOS) technology, e.g., which can be implemented with logic processes (e.g., technology nodes of 90 nm, 65 nm, 60 nm, 45 nm, 32 nm, 28 nm, 22 nm, 20 nm, 16 nm, 14 nm, 10 nm, 7 nm, 5 nm, 3 nm, 2 nm, etc.), according to some implementations.

[0051] As shown in FIG. **1A**, 3D memory device **100** can also include second semiconductor structure **104** including an array of memory cells (memory cell array) that can use transistors as the switch and selecting devices. In some implementations, the memory cell array includes an array of DRAM cells or any array of FRAM cells. For ease of description, a DRAM cell array or a FRAM cell array may be used as examples for describing the memory cell array in the present disclosure. But it is understood that the memory cell array is not limited to DRAM or FRAM cell array and may include any other suitable types of memory cell arrays that can use transistors as the switch and selecting devices, such as PCM cell array, static random-access memory (SRAM) cell array, resistive memory cell array, magnetic memory cell array, spin transfer torque (STT) memory cell array, to name a few, or any combination thereof.

[0052] Second semiconductor structure **104** can be a DRAM device in which memory cells are provided in the form of an array of DRAM cells. In some embodiments, each DRAM cell includes a capacitor for storing a bit of data as a positive or negative electrical charge as well as one or more transistors (a.k.a. pass transistors) that control (e.g., switch and selecting) access to it. In some implementations, each DRAM cell is a one-transistor, one-capacitor (1T1C) cell. Since transistors always leak a small amount of charge, the capacitors will slowly discharge, causing information stored in them to drain. As such, a DRAM cell has to be refreshed to retain data, for example, by the peripheral circuit in first semiconductor structure **102**, according to some implementation.

[0053] Alternatively, second semiconductor structure **104** can be a FRAM device in which memory cells are provided in the form of an array of FRAM cells. In some embodiments, each FRAM cell includes a ferroelectric capacitor for storing binary information of the respective FRAM cell based on the switch between two polarization states of ferroelectric materials under an external electric field. In some implementations, each FRAM cell is a one-transistor, one-capacitor (1T1C) cell for storing multiple bits of binary information. In some implementations, each FRAM cell is a one-transistor, multi-capacitors (1TnC) cell, where n is a positive integer greater than 1. Consistent with the scope of the present disclosure, each 1TnC FRAM cell can include multiple ferroelectric capacitors stacked vertically, each of which is coupled to one of multiple parallel, laterally extended plate lines.

[0054] As shown in FIG. **1A**, 3D memory device **100** further includes a bonding interface **106** vertically between (in the vertical direction, e.g., the z-direction in FIG. **1A**) first semiconductor structure **102** and second semiconductor structure **104**. As described below in detail, first and second semiconductor structures **102** and **104** can be fabricated separately (and in parallel in some implementations) such that the thermal budget of fabricating one of first and second semiconductor structures **102** and **104** does not limit the processes of fabricating another one of first and second semiconductor structures **102** and **104**. Moreover, a large number of interconnects (e.g., bonding contacts) can be formed through bonding interface **106** to make direct, short-distance (e.g., micron-level) electrical connections between first semiconductor structure **102** and second semiconductor structure **104**, as opposed to the long-distance (e.g., millimeter or centimeter-level) chip-to-chip data bus on the circuit board, such as printed circuit board (PCB), thereby eliminating chip

interface delay and achieving high-speed I/O throughput with reduced power consumption. Data transfer between the memory cell array in second semiconductor structure **104** and the peripheral circuits in first semiconductor structure **102** can be performed through the interconnects (e.g., bonding contacts) across bonding interface **106**. By vertically integrating first and second semiconductor structures **102** and **104**, the chip size can be reduced, and the memory cell density can be increased.

[0055] It is understood that the relative positions of stacked first and second semiconductor structures **102** and **104** are not limited. For example, FIG. **1B** illustrates a schematic view of a cross-section of another exemplary 3D memory device **101**, according to some implementations. Different from 3D memory device **100** in FIG. **1A** in which second semiconductor structure **104** including the memory cell array is above first semiconductor structure **102** including the peripheral circuits, in 3D memory device **101** in FIG. **1B**, first semiconductor structure **102** including the peripheral circuit is above second semiconductor structure **104** including the memory cell array. Nevertheless, bonding interface **106** is formed vertically between first and second semiconductor structures **102** and **104** in 3D memory device **101**, and first and second semiconductor structures **102** and **104** are joined vertically through bonding (e.g., hybrid bonding) according to some implementations. Hybrid bonding, also known as “metal/dielectric hybrid bonding,” is a direct bonding technology (e.g., forming bonding between surfaces without using intermediate layers, such as solder or adhesives) and can obtain metal-metal (e.g., copper-to-copper) bonding and dielectric-dielectric (e.g., silicon oxide-to-silicon oxide) bonding simultaneously. Data transfer between the memory cell array in second semiconductor structure **104** and the peripheral circuits in first semiconductor structure **102** can be performed through the interconnects (e.g., bonding contacts) across bonding interface **106**.

[0056] It is also understood that the memory cell array having vertical transistors and the peripheral circuits of the memory cell array may be formed on the same wafer in a side-by-side manner, i.e., next to one another. The number of wafers needed to fabricate the same number of memory devices and the complexity involved in the bonding process can be reduced compared with the face-to-face bonding scheme. For example, FIG. **1C** illustrates a schematic view of a cross-section of still another 3D memory device **103**, according to some aspects of the present disclosure. As shown in FIG. **1C**, memory device **103** can include a memory cell array region **112** and a peripheral circuit region **114** arranged side-by-side in the same device plane, as opposed to be stacked one over another in different device planes. A memory cell array can be formed in memory cell array region **112**, and the peripheral circuits of the memory cell array can be formed in peripheral circuit region **114** disposed beside memory cell array region **112**.

[0057] It is noted that x, y, and z axes are included in FIGS. **1A-1C** to further illustrate the spatial relationship of the components in 3D memory devices **100**, **101**, and **103**. Substrate **110** of 3D memory device **100**, **101**, or **103** includes two lateral surfaces extending laterally in the x-y plane: a top surface on the front side of the wafer on which 3D memory device **100**, **101**, or **103** can be formed, and a bottom surface on the backside opposite to the front side of the wafer. The z-axis is perpendicular to both the x and y axes. As used herein, whether one component (e.g., a layer or a device) is “on,” “above,” or “below” another component (e.g., a layer or a device) of 3D memory device **100**, **101**, or **103** is determined relative to substrate **110** of 3D memory device **100**, **101**, or **103** in the z-direction (the vertical direction perpendicular to the x-y plane, e.g., the thickness direction of the substrate) when substrate **110** is positioned in the lowest plane of 3D memory device **100**, **101**, or **103** in the z-direction. The same notion for describing the spatial relationships is applied throughout the present disclosure.

[0058] As shown in FIGS. **1A-1C**, 3D memory device **100**, **101**, or **103** can further include a pad-out interconnect layer **108** for pad-out purposes, i.e., interconnecting with external devices using contact pads on which bonding wires can be soldered. Pad-out interconnect layer **108** and substrate **110** can be disposed on opposite sides of the device plane having the memory cell array and

peripheral circuits in the z-direction. In other words, the memory cell array and peripheral circuits are disposed vertically between pad-out interconnect layer **108** and substrate **110** in 3D memory device **100**, **101**, or **103**, according to some implementations. As shown in FIGS. **1A** and **1B**, the relative positions of substrate **110** and pad-out interconnect layer **108** are not limited with respect to first and second semiconductor structures **102** and **104**. In one example as shown in FIG. **1A**, substrate **110** may be part of first semiconductor structure **102** having the peripheral circuit, and pad-out interconnect layer **108** may be part of second semiconductor structure **104** having the memory cell array. In another example as shown in FIG. **1B**, substrate **110** may be part of second semiconductor structure **104** having the memory cell array, and pad-out interconnect layer **108** may be part of first semiconductor structure **102** having the peripheral circuit. In other words, in bonded 3D memory device **100** or **101**, the pad-out may be achieved from either the memory cell array side or from the peripheral circuit side in different examples.

[0059] FIG. **2** illustrates a schematic diagram of a memory device **200** including peripheral circuits and an array of memory cells each having a vertical transistor, according to some aspects of the present disclosure. Memory device **200** can include a memory cell array **201** and peripheral circuits **202** coupled to memory cell array **201**. 3D memory devices **100** and **101** may be examples of memory device **200** in which memory cell array **201** and peripheral circuits **202** may be included in second and first semiconductor structures **104** and **102**, respectively. 3D memory device **103** may be another example of memory device **200** in which memory cell array **201** and peripheral circuits **202** may be included in memory cell array region **112** and peripheral circuit region **114**, respectively. Memory cell array **201** can be any suitable memory cell array in which each memory cell **208** includes a vertical transistor **210** and one or more storage units **212** coupled to vertical transistor **210**. In some implementations, memory cell array **201** is a DRAM cell array, and storage unit **212** is a capacitor for storing charge as the binary information stored by the respective DRAM cell. In some implementations, memory cell array **201** is a PCM cell array, and storage unit **212** is a PCM element (e.g., including chalcogenide alloys) for storing binary information of the respective PCM cell based on the different resistivities of the PCM element in the amorphous phase and the crystalline phase. In some implementations, memory cell array **201** is a FRAM cell array, and storage unit **212** is a ferroelectric capacitor for storing binary information of the respective FRAM cell based on the switch between two polarization states of ferroelectric materials under an external electric field.

[0060] As shown in FIG. **2**, memory cells **208** can be arranged in a two-dimensional (2D) array having rows and columns. Memory device **200** can include word lines **204** coupling peripheral circuits **202** and memory cell array **201** for controlling the switch of vertical transistors **210** in memory cells **208** located in a row, as well as bit lines **206** coupling peripheral circuits **202** and memory cell array **201** for sending data to and/or receiving data from memory cells **208** located in a column. That is, each word line **204** is coupled to a respective row of memory cells **208**, and each bit line is coupled to a respective column of memory cells **208**.

[0061] Consistent with the scope of the present disclosure, vertical transistors **210**, such as vertical metal-oxide-semiconductor field-effect transistors (MOSFETs), can replace the conventional planar transistors as the pass transistors of memory cells **208** to reduce the area occupied by the pass transistors, the coupling capacitance, as well as the interconnect routing complexity, as described below in detail. As shown in FIG. **2**, in some implementations, different from planar transistors in which the active regions are formed in the substrates, vertical transistor **210** includes a semiconductor body **214** extending vertically (in the z-direction) above the substrate (not shown). That is, semiconductor body **214** can extend above the top surface of the substrate to expose not only the top surface of semiconductor body **214**, but also one or more side surfaces thereof. As shown in FIG. **2**, for example, semiconductor body **214** can have a cuboid shape to expose four sides thereof. It is understood that semiconductor body **214** may have any suitable 3D shape, such as polyhedron shapes or a cylinder shape. That is, the cross-section of semiconductor body **214** in

the plan view (e.g., in the x-y plane) can have a square shape, a rectangular shape (or a trapezoidal shape), a circular (or an oval shape), or any other suitable shapes. It is understood that consistent with the scope of the present disclosure, for semiconductor bodies that have a circular or oval shape of their cross-sections in the plan view, the semiconductor bodies may still be considered to having multiple sides, such that the gate structures are in contact with more than one side of the semiconductor bodies. As described below with respect to the fabrication process, semiconductor body **214** can be formed from the substrate (e.g., by etching and/or epitaxy) and thus, has the same semiconductor material (e.g., silicon crystalline silicon) as the substrate (e.g., a silicon substrate). [0062] As shown in FIG. 2, vertical transistor **210** can also include a gate structure **216** in contact with one or more sides of semiconductor body **214**, i.e., in one or more planes of the side surface(s) of the active region. In other words, the active region of vertical transistor **210**, i.e., semiconductor body **214**, can be at least partially surrounded by gate structure **216**. Gate structure **216** can include a gate dielectric **218** over one or more sides of semiconductor body **214**, e.g., in contact with four side surfaces of semiconductor body **214** as shown in FIG. 2. Gate structure **216** can also include a gate electrode **220** over and in contact with gate dielectric **218**. Gate dielectric **218** can include any suitable dielectric materials, such as silicon oxide, silicon nitride, silicon oxynitride, or high dielectric constant (high-k) dielectrics. For example, gate dielectric **218** may include silicon oxide, i.e., gate oxide. Gate electrode **220** can include any suitable conductive materials, such as polysilicon, metals (e.g., tungsten (W), copper (Cu), aluminum (Al), etc.), metal compounds (e.g., titanium nitride (TiN), tantalum nitride (TaN), etc.), or silicides. For example, gate electrode **220** may include doped polysilicon, i.e., a gate poly. In some implementations, gate electrode **220** includes multiple conductive layers, such as a W layer over a TiN layer. It is understood that gate electrode **220** and word line **204** may be a continuous conductive layer in some examples. In other words, gate electrode **220** may be viewed as part of word line **204** that forms gate structure **216**, or word line **204** may be viewed as the extension of gate electrode **220** to be coupled to peripheral circuits **202**.

[0063] As shown in FIG. 2, semiconductor body **214** of vertical transistor **210** can include a pair of a source and a drain (S/D, doped regions, a.k.a., source electrode and drain electrode) formed at the two ends of semiconductor body **214** in the vertical direction (the z-direction), respectively. The source and drain can be doped with any suitable P-type dopants, such as boron (B) or Gallium (Ga), or any suitable N-type dopants, such as phosphorus (P) or arsenic (As). Semiconductor body **214** of vertical transistor **210** can also include a channel portion, i.e., the remaining portion other than the source and drain in which channel(s) are formed during transistor operation. In some implementations, semiconductor body **214** of vertical transistor **210** includes single crystalline silicon, and the channel portion includes undoped single crystalline silicon or doped single crystalline silicon having a different type of dopant from the source and the drain. The source and drain can be separated by gate structure **216** in the vertical direction (the z-direction). In other words, gate structure **216** is formed vertically between the source and drain. As a result, one or more channels (not shown) of vertical transistor **210** can be formed in the channel portion of semiconductor body **214** vertically between the source and drain when a gate voltage applied to gate electrode **220** of gate structure **216** is above the threshold voltage of vertical transistor **210**. That is, each channel of vertical transistors **210** is also formed in the vertical direction along which semiconductor body **214** extends, according to some implementations. Consistent with the scope of the present disclosure, the channel portion of semiconductor body **214** can be in contact with a body line (not shown in FIG. 2) to allow the depletion of the charge from the channels through the body line to reduce the floating body effect and the resulting issues described above.

[0064] In some implementations, as shown in FIG. 2, vertical transistor **210** is a multi-gate transistor. That is, gate structure **216** can be in contact with more than one side of semiconductor body **214** (e.g., four sides in FIG. 2) to form more than one gate, such that more than one channel can be formed in the channel portion of semiconductor body **214** between the source and drain in

operation. That is, different from the planar transistor that includes only a single planar gate (and resulting in a single planar channel), vertical transistor **210** shown in FIG. 2 can include multiple vertical gates on multiple sides of semiconductor body **214** due to the 3D structure of semiconductor body **214** and gate structure **216** that surrounds the multiple sides of semiconductor body **214**. As a result, compared with planar transistors, vertical transistor **210** shown in FIG. 2 can have a larger gate control area to achieve better channel control with a smaller subthreshold swing. During the off state, since the channel is fully depleted, the leakage current (.sub.loff) of vertical transistor **210** can be significantly reduced a well. The multi-gate vertical transistors can include, for example, double-gate vertical transistors (e.g., dual-side gate vertical transistors), tri-gate vertical transistors (e.g., tri-side gate vertical transistors), and gate all around (GAA) vertical transistors.

[0065] It is understood that although vertical transistor **210** is shown as a multi-gate transistor in FIG. 2, the vertical transistors disclosed herein may also include single-gate transistors. That is, gate structure **216** may be in contact with a single side of semiconductor body **214**, for example, for the purpose of increasing the transistor and memory cell density. It is also understood that although gate dielectric **218** is shown as being separate (i.e., a separate structure) from other gate dielectrics of adjacent vertical transistors (not shown), gate dielectric **218** may be part of a continuous dielectric layer having multiple gate dielectrics of vertical transistors.

[0066] In planar transistors and some lateral multiple-gate transistors (e.g., FinFET), the active regions, such as semiconductor bodies (e.g., Fins), extend laterally (in the x-y plane), and the source and the drain are disposed at different locations in the same lateral plane (the x-y plane). In contrast, in vertical transistor **210**, semiconductor body **214** extends vertically (in the z-direction), and the source and the drain are disposed in the different lateral planes, according to some implementations. In some implementations, the source and the drain are formed at two ends of semiconductor body **214** in the vertical direction (the z-direction), respectively, thereby being overlapped in the plan view. As a result, the area (in the x-y plane) occupied by vertical transistor **210** can be reduced compared with planar transistor and lateral multiple-gate transistors. Also, the metal wiring coupled to vertical transistors **210** can be simplified as well since the interconnects can be routed in different planes. For example, bit lines **206** and storage units **212** may be formed on opposite sides of vertical transistor **210**. In one example, bit line **206** may be coupled to the source or the drain at the upper end of semiconductor body **214**, while storage unit **212** may be coupled to the other source or the drain at the lower end of semiconductor body **214**.

[0067] As shown in FIG. 2, storage unit **212** can be coupled to the source or the drain of vertical transistor **210**. Storage unit **212** can include any devices that are capable of storing binary data (e.g., 0 and 1), including but not limited to, capacitors for DRAM cells, ferroelectric capacitors for FRAM cells, and PCM elements for PCM cells. In some implementations, vertical transistor **210** controls the selection and/or the state switch of the respective storage unit **212** coupled to vertical transistor **210**. Although a single storage unit **212** is shown in FIG. 2, it is understood that in some examples, multiple storage units **212** (e.g., multiple ferroelectric capacitors) may be stacked in the z-direction and coupled to vertical transistor **210**, for example, in a 1TnC memory cell.

[0068] In some implementations as shown in FIG. 3, each memory cell **208** is a DRAM cell **302** including a transistor **304** (e.g., implementing using vertical transistors **210** in FIG. 2) and a capacitor **306** (e.g., an example of storage unit **212** in FIG. 2). The gate of transistor **304** (e.g., corresponding to gate electrode **220**) may be coupled to word line **204**, one of the source and the drain of transistor **304** may be coupled to bit line **206**, the other one of the source and the drain of transistor **304** may be coupled to one electrode of capacitor **306**, and the other electrode of capacitor **306** may be coupled to the ground.

[0069] In some implementations as shown in FIG. 4, each memory cell **208** is a PCM cell **402** including a transistor **404** (e.g., implementing using vertical transistors **210** in FIG. 2) and a PCM element **406** (e.g., an example of storage unit **212** in FIG. 2). The gate of transistor **404** (e.g.,

corresponding to gate electrode **220**) may be coupled to word line **204**, one of the source and the drain of transistor **404** may be coupled to the ground, the other one of the source and the drain of transistor **404** may be coupled to one electrode of PCM element **406**, and the other electrode of PCM element **406** may be coupled to bit line **206**.

[0070] In some implementations as shown in FIG. 5A, each memory cell **208** is a FRAM cell **502** including a transistor **504** (e.g., implementing using vertical transistors **210** in FIG. 2) and a ferroelectric capacitor **506** (e.g., an example of storage unit **212** in FIG. 2). The gate of transistor **504** (e.g., corresponding to gate electrode **220**) may be coupled to word line **204**, one of the source and the drain of transistor **504** may be coupled to bit line **206**, the other one of the source and the drain of transistor **504** may be coupled to one electrode of ferroelectric capacitor **506**, and the other electrode of ferroelectric capacitor **506** may be coupled to a plate line **508**. That is, different from DRAM cell **302** and PCM cell **402** that is controlled by two lines—word line **204** and bit line **206** (a.k.a., two-end memory cell), FRAM cell **502** can be controlled by three lines—word line **204**, bit line **206**, and plate line **508** (a.k.a., three-end memory cell). Although FIG. 5A shows a 1T1C configuration of FRAM cell **502**, it is understood that FRAM cell **502** may be in a 1TnC configuration in other examples. For example, as shown in FIG. 5B, FRAM cell **502** in 1TnC configuration may include n ferroelectric capacitors **506-1**, **506-2**, . . . , and **506-n** coupled to the other one of the source and the drain of transistor **504**. That is, one electrode of each ferroelectric capacitor **506-1**, **506-2**, . . . , or **506-n** may be coupled to the same source/drain of transistor **504**, and the other electrode of each ferroelectric capacitor **506-1**, **506-2**, . . . , or **506-n** may be coupled to a respective one of n plate lines **508-1**, **508-2**, . . . , and **508-n**, such that each ferroelectric capacitor **506-1**, **506-2**, . . . , or **506-n** may be individually controlled by the respective plate line **508-1**, **508-2**, . . . , or **508-n**.

[0071] Peripheral circuits **202** can be coupled to memory cell array **201** through bit lines **206**, word lines **204**, and any other suitable metal wirings. As described above, peripheral circuits **202** can include any suitable circuits for facilitating the operations of memory cell array **201** by applying and sensing voltage signals and/or current signals through word lines **204** and bit lines **206** to and from each memory cell **208**. Peripheral circuits **202** can include various types of peripheral circuits formed using CMOS technologies.

[0072] According to some aspects of the present disclosure, at one end of the semiconductor body of a vertical transistor that is away from the storage unit, only part of the semiconductor body is doped to form one of the source and drain (e.g., the drain of a DRAM cell or FRAM cell) in contact with the bit line, while the remaining portion (i.e., the channel portion) of the semiconductor body is in contact with a body line for channel charge depletion, thereby reducing the floating body effect of the vertical transistor. For example, FIG. 6 illustrates a plan view of an array of memory cells **602** each including a vertical transistor in a memory device **600**, according to some aspects of the present disclosure. As shown in FIG. 6, memory device **600** can include a plurality of word lines **604** each extending in a first lateral direction (the x-direction, referred to as the word line direction). Memory device **600** can also include a plurality of bit lines **606** each extending in a second lateral direction perpendicular to the first lateral direction (the y-direction, referred to as the bit line direction). It is understood that FIG. 6 does not illustrate a cross-section of memory device **600** in the same lateral plane, and word lines **604** and bit lines **606** may be formed in different lateral planes for ease of routing as described below in detail.

[0073] Memory cells **602** can be formed at the intersections of word lines **604** and bit lines **606**. In some implementations, each memory cell **602** includes a vertical transistor (e.g., vertical transistor **210** in FIG. 2) having a semiconductor body (e.g., semiconductor body **214** in FIG. 2) and a gate structure (e.g., gate structure **216** in FIG. 2). The semiconductor body can extend in the vertical direction (the z-direction, not shown) perpendicular to the first and second lateral directions. The vertical transistor can be a multi-gate transistor or a single-gate transistor. In some implementations, the array of memory cells **602** can be arranged in rows and columns in the plan

view. Each row of memory cells **602** can extend in the word line direction, and each column of memory cells **602** can extend in the bit line direction. Rows of memory cells **602** can be separated in the bit line direction, and columns of memory cells **602** can be separated in the word line direction. As shown in FIG. **6**, in some implementations, the array of memory cells **602** is arranged in a cross-point orthogonal layout in which memory cells **602** are formed in each cross-point (intersection) of word lines **604** and bit lines **606**, two adjacent rows of memory cells **602** in the bit line direction are aligned (not staggered) with one another, and two adjacent columns of memory cells **602** in the word line direction are aligned (not staggered) with one another as well. The unit cell size of the cross-point orthogonal layout in FIG. **6** may be, for example, 4F_{sup.2} (a.k.a., 4F² cell size).

[0074] The semiconductor body can include a doped source **608**, a doped drain **608**, and a channel portion **610**. At one end of the semiconductor body in the vertical direction (the end away from the storage unit, e.g., as shown in the plan view of FIG. **6**), the semiconductor body is partially doped to form doped source/drain **608** and channel portion **610** surrounded by source/drain **608**, according to some implementations. For each column of memory cells **602**, the respective bit line **606** is coupled to sources/drains **608**, but not channel portions **610**, of the semiconductor bodies, according to some implementations. That is, bit line **606** can be in contact with source/drain **608**, but separated from channel portion **610**, of the semiconductor body of respective memory cells **602** by source/drain **608**. Different from vertical transistors in some memory devices in which the end of the semiconductor body away from the storage unit is fully doped and thus, fully covered with the source/drain and in contact with the bit line, channel portion **610** of the semiconductor body can be coupled to a body line (not shown in FIG. **6**) to release the channel charge from the semiconductor body through the body line.

[0075] As shown in FIG. **6**, in some implementations, source/drain **608** is formed on all sides of the semiconductor body, and bit line **606** fully circumscribes (e.g., surrounding and contacting) the semiconductor body in the plan view. In some implementations, source/drain **608** is laterally between bit line **606** and channel portion **610** in x-direction and y-direction in the plan view. It is understood that although the semiconductor body shown in FIG. **6** has a circular-shaped cross-section in the plan view, source/drain **608** may be formed on all sides of a semiconductor body having a cross-section with any suitable shape as described above, such as all four sides of a semiconductor body having a rectangle or square-shaped cross-section in the plan view.

[0076] FIG. **7A** illustrates a side view of a cross-section of a 3D memory device **700** including vertical transistors, according to some aspects of the present disclosure. 3D memory device **700** may be one example of memory device **600**. It is understood that FIG. **7A** is for illustrative purposes only and may not necessarily reflect the actual device structure (e.g., interconnections) in practice. As one example of 3D memory device **100** described above with respect to FIG. **1A**, 3D memory device **700** is a bonded chip including first semiconductor structure **102** and second semiconductor structure **104** stacked over first semiconductor structure **102**. First and second semiconductor structures **102** and **104** are jointed at bonding interface **106** therebetween, according to some implementations. As shown in FIG. **7A**, first semiconductor structure **102** can include substrate **110**, which can include silicon (e.g., single crystalline silicon, c-Si), silicon germanium (SiGe), gallium arsenide (GaAs), germanium (Ge), silicon-on-insulator (SOI), or any other suitable materials.

[0077] First semiconductor structure **102** can include peripheral circuits **712** on substrate **110**. In some implementations, peripheral circuits **712** include a plurality of transistors **714** (e.g., planar transistors and/or 3D transistors). Trench isolations (e.g., shallow trench isolations (STIs)) and doped regions (e.g., wells, sources, and drains of transistors **714**) can be formed on or in substrate **110** as well.

[0078] In some implementations, first semiconductor structure **102** further includes an interconnect layer **716** above peripheral circuits **712** to transfer electrical signals to and from peripheral circuits

712. Interconnect layer **716** can include a plurality of interconnects (also referred to herein as “contacts”), including lateral interconnect lines and vertical interconnect access (VIA) contacts. As used herein, the term “interconnects” can broadly include any suitable types of interconnects, such as middle-end-of-line (MEOL) interconnects and back-end-of-line (BEOL) interconnects. Interconnect layer **716** can further include one or more interlayer dielectric (ILD) layers (also known as “intermetal dielectric (IMD) layers”) in which the interconnect lines and via contacts can form. That is, interconnect layer **716** can include interconnect lines and via contacts in multiple ILD layers. In some implementations, peripheral circuits **712** are coupled to one another through the interconnects in interconnect layer **716**. The interconnects in interconnect layer **716** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof.

[0079] As shown in FIG. 7A, first semiconductor structure **102** can further include a bonding layer **718** at bonding interface **106** and above interconnect layer **716** and peripheral circuits **712**. Bonding layer **718** can include a plurality of bonding contacts **719** and dielectrics electrically isolating bonding contacts **719**. Bonding contacts **719** can include conductive materials, such as Cu. The remaining area of bonding layer **718** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **719** and surrounding dielectrics in bonding layer **718** can be used for hybrid bonding. Similarly, as shown in FIG. 7A, second semiconductor structure **104** can also include a bonding layer **720** at bonding interface **106** and above bonding layer **718** of first semiconductor structure **102**. Bonding layer **720** can include a plurality of bonding contacts **721** and dielectrics electrically isolating bonding contacts **721**. Bonding contacts **721** can include conductive materials, such as Cu. The remaining area of bonding layer **720** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **721** and surrounding dielectrics in bonding layer **720** can be used for hybrid bonding. Bonding contacts **721** are in contact with bonding contacts **719** at bonding interface **106**, according to some implementations.

[0080] Second semiconductor structure **104** can be bonded on top of first semiconductor structure **102** in a face-to-face manner at bonding interface **106**. In some implementations, bonding interface **106** is disposed between bonding layers **720** and **718** as a result of hybrid bonding (also known as “metal/dielectric hybrid bonding”), which is a direct bonding technology (e.g., forming bonding between surfaces without using intermediate layers, such as solder or adhesives) and can obtain metal-metal bonding and dielectric-dielectric bonding simultaneously. In some implementations, bonding interface **106** is the place at which bonding layers **720** and **718** are met and bonded. In practice, bonding interface **106** can be a layer with a certain thickness that includes the top surface of bonding layer **718** of first semiconductor structure **102** and the bottom surface of bonding layer **720** of second semiconductor structure **104**.

[0081] In some implementations, second semiconductor structure **104** further includes an interconnect layer **722** above bonding layer **720** to transfer electrical signals. Interconnect layer **722** can include a plurality of interconnects, such as MEOL interconnects and BEOL interconnects. In some implementations, the interconnects in interconnect layer **722** also include local interconnects, such as bit line contacts (not shown), word line contacts **727**, and body line contacts **751**. Interconnect layer **722** can further include one or more ILD layers in which the interconnect lines and via contacts can form. The interconnects in interconnect layer **722** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low dielectric constant (low-k) dielectrics, or any combination thereof. In some implementations, peripheral circuits **712** include a word line driver/row decoder coupled to word line contacts **727** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some

implementations, peripheral circuits **712** include a bit line driver/column decoder coupled to the bit line contacts in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some implementations, peripheral circuits **712** include a voltage source or the ground that is coupled to body line contacts **751** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. [0082] In some implementations, second semiconductor structure **104** includes a DRAM device in which memory cells are provided in the form of an array of DRAM cells **724** (e.g., an example of memory cells **602** in FIG. 6) above interconnect layer **722** and bonding layer **720**. It is understood that the cross-section of 3D memory device **700** in FIG. 7A may be made along the word line direction (the x-direction), and one word line **734** extending laterally in the x-direction may be coupled to a row of DRAM cells **724**. Each DRAM cell **724** can include a vertical transistor **726** (e.g., an example of vertical transistors **210** in FIG. 2) and a capacitor **728** (e.g., an example of storage unit **212** in FIG. 2) coupled to vertical transistor **726**. DRAM cell **724** can be in the 1T1C configuration (i.e., a 1T1C cell) consisting of one transistor and one capacitor. It is understood that DRAM cell **724** may be of any suitable configurations, such as nT1C, 1TnC, nTnC, etc.

[0083] Vertical transistor **726** can be a MOSFET used to switch a respective DRAM cell **724**. In some implementations, vertical transistor **726** includes a semiconductor body **730** (i.e., the active region in which multiple channels can form) extending vertically (in the z-direction), and a gate structure **736** in contact with one or more sides of semiconductor body **730**. In some implementations in which vertical transistor **726** is a GAA vertical transistor, semiconductor body **730** has a cuboid shape or a cylinder shape, and gate structure **736** is in contact with all sides of semiconductor body **730**, i.e., fully circumscribing semiconductor body **730** in the plan view. In some implementations in which vertical transistor **726** is a tri-gate vertical transistor, a double-gate vertical transistor, or a single-gate vertical transistor, semiconductor body **730** has a cuboid shape or a cylinder shape, and gate structure **736** is in contact with one or some sides, but not all sides, of semiconductor body **730**, i.e., partially circumscribing semiconductor body **730** in the plan view. Gate structure **736** includes a gate electrode **734** and a gate dielectric **732** laterally between gate electrode **734** and semiconductor body **730** in at least the word line direction, according to some implementations. For example, for semiconductor body **730** having a cylinder shape, semiconductor body **730**, gate dielectric **732**, and gate electrode **734** may be disposed radially from the center of vertical transistor **726** in this order. In some implementations, gate dielectric **732** surrounds and contacts semiconductor body **730**, and gate electrode **734** surrounds and contacts gate dielectric **732**.

[0084] In some implementations, gate dielectric **732** includes dielectric materials, such as silicon oxide, silicon nitride, or high-k dielectrics including, but not limited to, aluminum oxide (Al.sub.2O.sub.3), hafnium oxide (HfO.sub.2), tantalum oxide (Ta.sub.2O.sub.5), zirconium oxide (ZrO.sub.2), titanium oxide (TiO.sub.2), or any combination thereof. In some implementations, gate electrode **734** includes conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, gate electrode **734** includes multiple conductive layers, such as a W layer over a TiN layer. In one example, gate structure **736** may be a “gate oxide/gate poly” gate in which gate dielectric **732** includes silicon oxide and gate electrode **734** includes doped polysilicon. In another example, gate structure **736** may be a high-k metal gate (HKMG) in which gate dielectric **732** includes a high-k dielectric and gate electrode **734** includes a metal.

[0085] As shown in FIG. 7A, in some implementations, semiconductor body **730** has two ends (the upper end and lower end) in the vertical direction (the z-direction), and both ends extend beyond gate electrode/word line **734**, respectively, in the vertical direction (the z-direction) into ILD layers. That is, semiconductor body **730** can have a larger vertical dimension (e.g., the depth) than that of gate electrode/word line **734** (e.g., in the z-direction), and neither the upper end nor the lower end of semiconductor body **730** is flush with the respective end of gate electrode/word line **734**. Thus,

short circuits between bit lines **723** and word lines/gate electrodes **734** or between word lines/gate electrodes **734** and capacitors **728** can be avoided.

[0086] As shown in FIG. 7A and the enlarged view of FIG. 7B, semiconductor body **730** of vertical transistor **726** can include a source and a drain (both referred to as **738** as their locations may be interchangeable) as well as a channel portion **739** from the doping perspective, i.e., whether a particular portion of semiconductor body **730** is doped or the type of dopant thereof. In one example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped to form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped to form the other one of source and drain **738** (e.g., the drain of vertical transistor **726**). The remaining undoped/intrinsic portion of semiconductor body **730** thus may become channel portion **739**. In another example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped with N-type dopant(s) to form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped with N-type dopant(s) to form the other one of source and drain **738** (e.g., the drain of vertical transistor **726**). The remaining portion of semiconductor body **730** thus may become channel portion **739**, which may be doped with P-type dopant(s). In still another example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped with P-type dopant(s) to form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped with P-type dopant(s) to form the other one of source and drain **738** (e.g., the drain of vertical transistor **726**). The remaining portion of semiconductor body **730** thus may become channel portion **739**, which may be doped with N-type dopant(s). In some implementations, semiconductor body **730** has a base **756** and a protrusion **754** from the shape perspective, i.e., the relative dimensions and geometric relationships between different portions of semiconductor body **730**, as shown in FIG. 7B. For example, base **756** may have a larger lateral dimension than protrusion **754**. Protrusion **754** can protrude entirely from the interior of base **756**, i.e., all sides of protrusion **754** being within the boundary of base **756** in the plan view. In some implementations, base **756** faces word line/gate electrode **734**, and protrusion **754** faces bit line **723**.

[0087] One of source and drain **738** (e.g., at the lower end in FIG. 7A) can be formed on one end (e.g., the lower end in FIG. 7A) of base **756**. The other one of source and drain **738** (e.g., at the upper end in FIG. 7A) can be formed on one or more sides of protrusion **754** of semiconductor body **730**. In some implementations, as shown in FIGS. 7A and 7B, one of source and drain **738** that is away from capacitor **728** (e.g., the drain of vertical transistor **726**) is formed on all sides of protrusion **754**. Channel portion **739** can be formed in both base **756** and protrusion **754** of semiconductor body **730**. That is, both base **756** and protrusion **754** of semiconductor body **730** can have portions that are undoped or doped with a different type of dopant from source and drain **738**, becoming channel portion **739**. As shown in FIGS. 7A and 7B, different from the lower end (i.e., bottom) of base **756** that is doped to become part of source/drain **738**, the upper end (i.e., top) of protrusion **754** is not doped with the same type of dopant as source and drain **738** to become part of source/drain **738**, but remains as part of channel portion **739**, according to some implementations. As shown in FIG. 7B, gate dielectric **732** of gate structure **736** is in contact with base **756** of semiconductor body **730**, but does not extend further to be in contact with protrusion **754** of semiconductor body **730**, according to some implementations. In other words, gate dielectric **732** can be separated from protrusion **754** of semiconductor body **730**.

[0088] In some implementations, semiconductor body **730** includes semiconductor materials, such as single crystalline silicon, polysilicon, amorphous silicon, Ge, any other semiconductor materials, or any combinations thereof. In one example, semiconductor body **730** may include single crystalline silicon, and channel portion **739** of semiconductor body **730** may include undoped single crystalline silicon or doped single crystalline silicon having a different type of dopant from

source and drain **738**. Source and drain **738** can be doped with N-type dopants (e.g., P or As) or P-type dopants (e.g., B or Ga) at a desired doping level. In some implementations, source and drain **738** are doped with N-type dopants (e.g., P or As), and channel portion **739** is undoped/intrinsic or doped with P-type dopants (e.g., B or Ga).

[0089] As described above, since gate electrode **734** may be part of a word line or extend in the word line direction (e.g., the x-direction in FIG. 6) as a word line, although not directly shown in FIG. 7A, second semiconductor structure **104** of 3D memory device **700** can also include a plurality of word lines (e.g., an example of word lines **604** in FIG. 6, referred to as **734** as well) each extending in the word line direction (the x-direction). Each word line **734** can be coupled to a row of DRAM cells **724**. That is, bit line **723** and word line **734** can extend in two perpendicular lateral directions, and semiconductor body **730** of vertical transistor **726** can extend in the vertical direction perpendicular to the two lateral directions in which bit line **723** and word line **734** extend. Word lines **734** are in contact with word line contacts **727**, according to some implementations. In some implementations, word lines **734** include conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, word line **734** includes multiple conductive layers, such as a W layer over a TiN layer.

[0090] As shown in FIG. 7A, second semiconductor structure **104** of 3D memory device **700** can also include a plurality of bit lines **723** (e.g., an example of bit lines **606** in FIG. 6) each extending in the bit line direction (the y-direction in FIG. 6). Each bit line **723** can be coupled to a column of DRAM cells **724**. In some implementations, bit line **723** is coupled to one of source and drain **738** that is away from capacitor **728** (e.g., the drain of vertical transistor **726**). For example, as shown in FIG. 7B, bit line **723** may be in contact with source/drain **738** that is formed on all sides of protrusion **754** of semiconductor body **730**, but separated from channel portion **739** of semiconductor body **730** by source/drain **738**. That is, bit line **723** is not in contact with channel portion **739** of semiconductor body **730** in which the channels of vertical transistor **726** are formed to suppress the floating body effect, according to some implementations.

[0091] As shown in FIG. 7A, second semiconductor structure **104** of 3D memory device **700** can further include a body line **748** extending laterally (in the bit line direction and/or word line direction) and coupled to channel portion **739** of semiconductor body **730**. Body line **748** can also be coupled to body line contact **751**, which can be in turn coupled to peripheral circuits **712** in first semiconductor structure **102** through interconnect layers **722** and **716** and bonding layers **718** and **720**. As a result, channel portion **739** of semiconductor body **730** can be coupled to a certain potential, for example, by a voltage source or the ground in peripheral circuits **712**, through body line **748**, body line contact **751**, and any other suitable interconnects in interconnect layers **722** and **716** and bonding layers **718** and **720**, such that channel charge in channel portion **739** of semiconductor body **730** can be released during operation of 3D memory device **700** to mitigate the floating body effect and the resulting issues. It is understood that in some examples, body line **748** may be coupled to a voltage source or the ground not in peripheral circuits **712** as long as the charge of the channels in semiconductor body **730** can be depleted.

[0092] As described above, the upper end (top) of protrusion **754** of semiconductor body **730** is not covered by source/drain **738**, such that body line **748** can be in contact with channel portion **739** of semiconductor body **730**. In some implementations, the upper end of protrusion **754** extends beyond bit line **723** such that body line **748** in contact with the upper end of protrusion **754** is separated from bit line **723** to avoid short circuits. In some implementations, body line **748** includes a polysilicon layer **750** in contact with channel portion **739** of semiconductor body **730** to reduce the contact resistance between body line **748** and semiconductor body **730**. In some implementations, body line **748** further includes a metal layer **752** (e.g., W or Cu layer) in contact with polysilicon layer **750** to reduce the sheet resistance of body line **748**. It is understood that the structure and/or materials of body line **748** may vary in other examples as long as body line **748**

can couple channel portion **739** of semiconductor body **730** to a certain potential with reasonable contact and sheet resistances.

[0093] Body line **748** and capacitor **728** can be coupled to opposite ends of vertical transistor **726** in the z-direction. For example, body line **748** may be coupled to the upper end of vertical transistor **726**, while capacitor **728** may be coupled to the lower end of vertical transistor **726**, as shown in FIG. 7A. In some implementations, bit line **723** is between capacitor **728** and body line **748** in the z-direction as bit line **723** is in contact with the sides of protrusion **754** of semiconductor body **730** while body line **748** is in contact with the upper end of protrusion **754**. In some implementations, capacitor **728** is between bonding interface **106** and vertical transistor **726** in the z-direction, and word line **734** is between bonding interface **106** and bit line **723** in the z-direction. The relative spatial relationships of various components in second semiconductor structure **104** of 3D memory device **700** that are described above as well as depicted in FIG. 7A may result from the face-to-face bonding process between first and second semiconductor structures **102** and **104** as well as the backside process for forming protrusion **754**, bit line **723**, and body line **748** as described below in detail with respect to the fabrication processes, which enable the design of vertical transistor **726** with reduced floating body effect.

[0094] As shown in FIG. 7A, in some implementations, capacitor **728** includes a first electrode **742** below and coupled to source or drain **738** of vertical transistor **726**, e.g., at the lower end of base **756** of semiconductor body **730**. Capacitor **728** can also include a capacitor dielectric **744** in contact with first electrode **742**, and a second electrode **746** in contact with capacitor dielectric **744**. That is, capacitor dielectric **744** can be sandwiched between electrodes **742** and **746**. In some implementations, each first electrode **742** is coupled to source or drain **738** of a respective vertical transistor **726** in the same DRAM cell **724**, while all second electrodes **746** are parts of a common plate coupled to the ground, e.g., a common ground. Although not shown in FIG. 7A, it is understood that second semiconductor structure **104** may further include a capacitor contact in contact with the common plate of second electrodes **746** for coupling second electrodes **746** of capacitor **728** to peripheral circuits **712** or to the ground directly.

[0095] It is understood that the structure and configuration of capacitor **728** are not limited to the interdigitated capacitor (a.k.a., finger capacitor) example in FIG. 7A and may include any suitable structure and configuration, such as a planar capacitor, a stack capacitor, a multi-fins capacitor, a cylinder capacitor, a trench capacitor, or a substrate-plate capacitor. In some implementations, capacitor dielectric **744** includes dielectric materials, such as silicon oxide, silicon nitride, or high-k dielectrics including, but not limited to, Al.sub.2O.sub.3 , HfO.sub.2 , Ta.sub.2O.sub.5 , ZrO.sub.2 , TiO.sub.2 , or any combination thereof. It is understood that in some examples, capacitor **728** may be a ferroelectric capacitor used in a FRAM cell, and capacitor dielectric **744** may be replaced by a ferroelectric layer having ferroelectric materials, such as lead zirconate titanate (PZT) or strontium bismuth tantalate (SBT). In some implementations, electrodes **742** and **746** include conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof.

[0096] Although not shown in FIG. 7A, it is understood that in some examples, second semiconductor structure **104** may further include a pad-out interconnect layer (e.g., pad-out interconnect layer **108** in FIG. 1A) above body line **748**. The pad-out interconnect layer may include interconnects, e.g., contact pads, in one or more ILD layers. The pad-out interconnect layer and interconnect layer **722** can be formed on opposite sides of DRAM cells **724**. Vertical transistors **726** are disposed vertically between capacitors **728** and the pad-out interconnect layer, according to some implementations. In some implementations, the interconnects in the pad-out interconnect layer can transfer electrical signals between 3D memory device **700** and outside circuits, e.g., for pad-out purposes. It is also understood that the pad-out of 3D memory devices is not limited to from second semiconductor structure **104** having DRAM cells **724** and may be from first semiconductor structure **102** having peripheral circuit **712**. For example, as shown in FIG. 1B, 3D

memory device **101** may include a pad-out interconnect layer in first semiconductor structure **102**. [0097] It is further understood that the memory cell array is not limited to the example shown in FIGS. **6**, **7A**, and **7B** in which the bit line fully circumscribes the protrusion of the semiconductor body in the plan view, and the source/drain is formed on all sides of the protrusion of the semiconductor body. For example, FIG. **8** illustrates a plan view of another array of memory cells **802** each including a vertical transistor in a memory device **800**, according to some aspects of the present disclosure. As shown in FIG. **8**, memory device **800** can include a plurality of word lines **804** each extending in a first lateral direction (the x-direction, referred to as the word line direction). Memory device **800** can also include a plurality of bit lines **806** each extending in a second lateral direction perpendicular to the first lateral direction (the y-direction, referred to as the bit line direction). It is understood that FIG. **8** does not illustrate a cross-section of memory device **800** in the same lateral plane, and word lines **804** and bit lines **806** may be formed in different lateral planes for ease of routing as described below in detail.

[0098] Memory cells **802** can be formed at the intersections of word lines **804** and bit lines **806**. In some implementations, each memory cell **802** includes a vertical transistor (e.g., vertical transistor **210** in FIG. **2**) having a semiconductor body (e.g., semiconductor body **214** in FIG. **2**) and a gate structure (e.g., gate structure **216** in FIG. **2**). The semiconductor body can extend in the vertical direction (the z-direction, not shown) perpendicular to the first and second lateral directions. The vertical transistor can be a multi-gate transistor or a single-gate transistor. In some implementations, the array of memory cells **802** can be arranged in rows and columns in the plan view. Each row of memory cells **802** can extend in the word line direction, and each column of memory cells **802** can extend in the bit line direction. Rows of memory cells **802** can be separated in the bit line direction, and columns of memory cells **802** can be separated in the word line direction. As shown in FIG. **8**, in some implementations, the array of memory cells **802** is arranged in a cross-point orthogonal layout in which memory cells **802** are formed in each cross-point (intersection) of word lines **804** and bit lines **806**, two adjacent rows of memory cells **802** in the bit line direction are aligned (not staggered) with one another, and two adjacent columns of memory cells **802** in the word line direction are aligned (not staggered) with one another as well. The unit cell size of the cross-point orthogonal layout in FIG. **8** may be, for example, $4F_{\text{sup}}/2$ (a.k.a., $4F/2$ cell size).

[0099] The semiconductor body can include a doped source **808**, a doped drain **808**, and a channel portion **810**. At one end of the semiconductor body in the vertical direction (the end away from the storage unit, e.g., as shown in the plan view of FIG. **8**), the semiconductor body is partially doped to form doped source/drain **808** and channel portion **810**, according to some implementations. Different from memory cell **602** in FIG. **6** in which channel portion **610** is surrounded by source/drain **608**, in FIG. **8**, channel portion **810** is not surrounded by source/drain **808**, according to some implementations. Instead, source/drain **808** abuts only one side of channel portion **810** in the plan view, according to some implementations. For each column of memory cells **802**, the respective bit line **806** is coupled to sources/drains **808**, but not channel portions **810**, of the semiconductor bodies, according to some implementations. That is, bit line **806** can be in contact with source/drain **808**, but separated from channel portion **810**, of the semiconductor body of respective memory cells **802** by source/drain **808**. Different from vertical transistors in some memory devices in which the end of the semiconductor body away from the storage unit is fully doped and thus, fully covered with the source/drain and in contact with the bit line, channel portion **810** of the semiconductor body can be coupled to a body line (not shown in FIG. **8**) to release the channel charge from the semiconductor body through the body line.

[0100] Different from memory cell **602** in FIG. **6** in which source/drain **608** is formed on all sides of the semiconductor body, and bit line **606** fully circumscribes the semiconductor body in the plan view, as shown in FIG. **8**, in some implementations, source/drain **808** is formed on one or some, but not all, sides of the semiconductor body, and bit line **806** partially circumscribes (e.g., surrounding

and contacting) the semiconductor body in the plan view. In some implementations, source/drain **808** is laterally between bit line **806** and channel portion **810** in the x-direction, but not in the y-direction, in the plan view. It is understood that although the semiconductor body shown in FIG. **8** has a semicircular-shaped cross-section in the plan view, source/drain **808** may be formed on one or some sides of a semiconductor body having a cross-section with any suitable shape as described above, such as one of the four sides of a semiconductor body having a rectangle or square-shaped cross-section in the plan view.

[0101] FIG. **9A** illustrates a side view of a cross-section of another 3D memory device **900** including vertical transistors, according to some aspects of the present disclosure. 3D memory device **900** may be one example of memory device **900**. It is understood that FIG. **9A** is for illustrative purposes only and may not necessarily reflect the actual device structure (e.g., interconnections) in practice. As one example of 3D memory device **100** described above with respect to FIG. **1A**, 3D memory device **900** is a bonded chip including first semiconductor structure **102** and second semiconductor structure **104** stacked over first semiconductor structure **102**. First and second semiconductor structures **102** and **104** are jointed at bonding interface **106** therebetween, according to some implementations. As shown in FIG. **9A**, first semiconductor structure **102** can include substrate **110**, which can include silicon (e.g., single crystalline silicon, c-Si), SiGe, GaAs, Ge, SOI, or any other suitable materials.

[0102] First semiconductor structure **102** can include peripheral circuits **712** on substrate **110**. In some implementations, peripheral circuits **712** include a plurality of transistors **714** (e.g., planar transistors and/or 3D transistors). Trench isolations (e.g., STIs) and doped regions (e.g., wells, sources, and drains of transistors **714**) can be formed on or in substrate **110** as well.

[0103] In some implementations, first semiconductor structure **102** further includes an interconnect layer **716** above peripheral circuits **712** to transfer electrical signals to and from peripheral circuits **712**. Interconnect layer **716** can include a plurality of interconnects, including lateral interconnect lines VIA contacts. Interconnect layer **716** can further include one or more ILD layers in which the interconnect lines and via contacts can form. That is, interconnect layer **716** can include interconnect lines and via contacts in multiple ILD layers. In some implementations, peripheral circuits **712** are coupled to one another through the interconnects in interconnect layer **716**. The interconnects in interconnect layer **716** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof.

[0104] As shown in FIG. **9A**, first semiconductor structure **102** can further include a bonding layer **718** at bonding interface **106** and above interconnect layer **716** and peripheral circuits **712**. Bonding layer **718** can include a plurality of bonding contacts **719** and dielectrics electrically isolating bonding contacts **719**. Bonding contacts **719** can include conductive materials, such as Cu. The remaining area of bonding layer **718** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **719** and surrounding dielectrics in bonding layer **718** can be used for hybrid bonding. Similarly, as shown in FIG. **9A**, second semiconductor structure **104** can also include a bonding layer **720** at bonding interface **106** and above bonding layer **718** of first semiconductor structure **102**. Bonding layer **720** can include a plurality of bonding contacts **721** and dielectrics electrically isolating bonding contacts **721**. Bonding contacts **721** can include conductive materials, such as Cu. The remaining area of bonding layer **720** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **721** and surrounding dielectrics in bonding layer **720** can be used for hybrid bonding. Bonding contacts **721** are in contact with bonding contacts **719** at bonding interface **106**, according to some implementations.

[0105] Second semiconductor structure **104** can be bonded on top of first semiconductor structure **102** in a face-to-face manner at bonding interface **106**. In some implementations, bonding interface **106** is disposed between bonding layers **720** and **718** as a result of hybrid bonding, which is a direct

bonding technology (e.g., forming bonding between surfaces without using intermediate layers, such as solder or adhesives) and can obtain metal-metal bonding and dielectric-dielectric bonding simultaneously. In some implementations, bonding interface **106** is the place at which bonding layers **720** and **718** are met and bonded. In practice, bonding interface **106** can be a layer with a certain thickness that includes the top surface of bonding layer **718** of first semiconductor structure **102** and the bottom surface of bonding layer **720** of second semiconductor structure **104**.

[0106] In some implementations, second semiconductor structure **104** further includes an interconnect layer **722** above bonding layer **720** to transfer electrical signals. Interconnect layer **722** can include a plurality of interconnects, such as MEOL interconnects and BEOL interconnects. In some implementations, the interconnects in interconnect layer **722** also include local interconnects, such as bit line contacts (not shown), word line contacts **727**, and body line contacts **751**.

Interconnect layer **722** can further include one or more ILD layers in which the interconnect lines and via contacts can form. The interconnects in interconnect layer **722** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof. In some implementations, peripheral circuits **712** include a word line driver/row decoder coupled to word line contacts **727** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some implementations, peripheral circuits **712** include a bit line driver/column decoder coupled to the bit line contacts in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some implementations, peripheral circuits **712** include a voltage source or the ground that is coupled to body line contacts **751** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**.

[0107] In some implementations, second semiconductor structure **104** includes a DRAM device in which memory cells are provided in the form of an array of DRAM cells **724** (e.g., an example of memory cells **602** in FIG. 6) above interconnect layer **722** and bonding layer **720**. It is understood that the cross-section of 3D memory device **900** in FIG. 9A may be made along the word line direction (the x-direction), and one word line **934** extending laterally in the x-direction may be coupled to a row of DRAM cells **724**. Each DRAM cell **724** can include a vertical transistor **926** (e.g., an example of vertical transistors **210** in FIG. 2) and a capacitor **728** (e.g., an example of storage unit **212** in FIG. 2) coupled to vertical transistor **926**. DRAM cell **724** can be in the 1T1C configuration (i.e., a 1T1C cell) consisting of one transistor and one capacitor. It is understood that DRAM cell **724** may be of any suitable configurations, such as nT1C, 1TnC, nTnC, etc.

[0108] Vertical transistor **926** can be a MOSFET used to switch a respective DRAM cell **724**. In some implementations, vertical transistor **926** includes a semiconductor body **930** (i.e., the active region in which multiple channels can form) extending vertically (in the z-direction), and a gate structure **936** in contact with one or more sides of semiconductor body **930**. In some implementations in which vertical transistor **926** is a GAA vertical transistor, semiconductor body **930** has a cuboid shape or a cylinder shape, and gate structure **936** is in contact with all sides of semiconductor body **930**, i.e., fully circumscribing semiconductor body **930** in the plan view. In some implementations in which vertical transistor **926** is a tri-gate vertical transistor, a double-gate vertical transistor, or a single-gate vertical transistor, semiconductor body **930** has a cuboid shape or a cylinder shape, and gate structure **936** is in contact with one or some sides, but not all sides, of semiconductor body **930**, i.e., partially circumscribing semiconductor body **930** in the plan view. Gate structure **936** includes a gate electrode **934** and a gate dielectric **932** laterally between gate electrode **934** and semiconductor body **930** in at least the word line direction, according to some implementations. For example, for semiconductor body **930** having a cylinder shape, semiconductor body **930**, gate dielectric **932**, and gate electrode **934** may be disposed radially from the center of vertical transistor **926** in this order. In some implementations, gate dielectric **932**

surrounds and contacts semiconductor body **930**, and gate electrode **934** surrounds and contacts gate dielectric **932**.

[0109] In some implementations, gate dielectric **932** includes dielectric materials, such as silicon oxide, silicon nitride, or high-k dielectrics including, but not limited to Al.sub.2O.sub.3, HfO.sub.2, Ta.sub.2O.sub.5, ZrO.sub.2, TiO.sub.2, or any combination thereof. In some implementations, gate electrode **934** includes conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, gate electrode **934** includes multiple conductive layers, such as a W layer over a TiN layer. In one example, gate structure **936** may be a “gate oxide/gate poly” gate in which gate dielectric **932** includes silicon oxide and gate electrode **934** includes doped polysilicon. In another example, gate structure **936** may be a HKMG in which gate dielectric **932** includes a high-k dielectric and gate electrode **934** includes a metal.

[0110] As shown in FIG. **9A**, in some implementations, semiconductor body **930** has two ends (the upper end and lower end) in the vertical direction (the z-direction), and both ends extend beyond gate electrode/word line **934**, respectively, in the vertical direction (the z-direction) into ILD layers. That is, semiconductor body **930** can have a larger vertical dimension (e.g., the depth) than that of gate electrode/word line **934** (e.g., in the z-direction), and neither the upper end nor the lower end of semiconductor body **930** is flush with the respective end of gate electrode/word line **934**. Thus, short circuits between bit lines **923** and word lines/gate electrodes **934** or between word lines/gate electrodes **934** and capacitors **728** can be avoided.

[0111] As shown in FIG. **9A** and the enlarged view of FIG. **9B**, semiconductor body **930** of vertical transistor **926** can include a source and a drain (both referred to as **938** as their locations may be interchangeable) as well as a channel portion **939** from the doping perspective, i.e., whether a particular portion of semiconductor body **930** is doped or the type of dopant thereof. In one example, the lower end of semiconductor body **930** that is coupled to capacitor **728** may be fully doped to form one of source and drain **938** (e.g., the source of vertical transistor **926**), while the upper end of semiconductor body **930** away from capacitor **728** may be partially doped to form the other one of source and drain **938** (e.g., the drain of vertical transistor **926**). The remaining undoped portion of semiconductor body **930** thus may become channel portion **939**. In another example, the lower end of semiconductor body **930** that is coupled to capacitor **728** may be fully doped with N-type dopant(s) to form one of source and drain **938** (e.g., the source of vertical transistor **926**), while the upper end of semiconductor body **930** away from capacitor **728** may be partially doped with N-type dopant(s) to form the other one of source and drain **938** (e.g., the drain of vertical transistor **926**). The remaining portion of semiconductor body **930** thus may become channel portion **939**, which may be doped with P-type dopant(s). In still another example, the lower end of semiconductor body **930** that is coupled to capacitor **728** may be fully doped with P-type dopant(s) to form one of source and drain **938** (e.g., the source of vertical transistor **926**), while the upper end of semiconductor body **930** away from capacitor **728** may be partially doped with P-type dopant(s) to form the other one of source and drain **938** (e.g., the drain of vertical transistor **926**). The remaining portion of semiconductor body **930** thus may become channel portion **939**, which may be doped with N-type dopant(s). In some implementations, semiconductor body **930** has a base **956** and a protrusion **954** from the shape perspective, i.e., the relative dimensions and geometric relationships between different portions of semiconductor body **930**, as shown in FIG. **9B**. For example, base **956** may have a larger lateral dimension than protrusion **954**. Different from 3D memory device **700** in which protrusion **754** protrudes entirely from the interior of base **756**, protrusion **954** protrudes partially from the interior of base **956** and partially from the boundary of base **956**, i.e., one or some sides of protrusion **954** being within the boundary of base **956** while the remaining side(s) of protrusion **954** being aligned with the boundary of base **956** in the plan view. In some implementations, base **956** faces word line/gate electrode **934**, and protrusion **954** faces bit line **923**.

[0112] One of source and drain **938** (e.g., at the lower end in FIG. **9A**) can be formed on one end (e.g., the lower end in FIG. **9A**) of base **956**. The other one of source and drain **938** (e.g., at the upper end in FIG. **9A**) can be formed on one or more sides of protrusion **954** of semiconductor body **930**. In some implementations, as shown in FIGS. **9A** and **9B**, one of source and drain **938** that is away from capacitor **728** (e.g., the drain of vertical transistor **926**) is formed on one or some, but not all, sides of protrusion **954**. Channel portion **939** can be formed in both base **956** and protrusion **954** of semiconductor body **930**. That is, both base **956** and protrusion **954** of semiconductor body **930** can have portions that are undoped or doped with a different type of dopant from source and drain **938**, becoming channel portion **939**. As shown in FIGS. **9A** and **9B**, different from the lower end (i.e., bottom) of base **956** that is doped to become part of source/drain **938**, the upper end (i.e., top) of protrusion **954** is not doped with the same type of dopant as source and drain **938** to become part of source/drain **938**, but remains as part of channel portion **939**, according to some implementations. As shown in FIG. **9B**, gate dielectric **932** of gate structure **936** is in contact with not only base **956** of semiconductor body **730**, but also extends further to be in contact with protrusion **954** of semiconductor body **930**, according to some implementations. In other words, gate dielectric **932** can be in contact with protrusion **954** of semiconductor body **930**, which is different from gate dielectric **732** in FIG. **7A** that is separated from protrusion **754** of semiconductor body **730**.

[0113] In some implementations, semiconductor body **930** includes semiconductor materials, such as single crystalline silicon, polysilicon, amorphous silicon, Ge, any other semiconductor materials, or any combinations thereof. In one example, semiconductor body **930** may include single crystalline silicon, and channel portion **939** of semiconductor body **930** may include undoped single crystalline silicon or doped single crystalline silicon having a different type of dopant from source and drain **938**. Source and drain **938** can be doped with N-type dopants (e.g., P or As) or P-type dopants (e.g., B or Ga) at a desired doping level. In some implementations, source and drain **938** are doped with N-type dopants (e.g., P or As), and channel portion **939** is undoped/intrinsic or doped with P-type dopants (e.g., B or Ga).

[0114] As described above, since gate electrode **934** may be part of a word line or extend in the word line direction (e.g., the x-direction in FIG. **8**) as a word line, although not directly shown in FIG. **9A**, second semiconductor structure **104** of 3D memory device **900** can also include a plurality of word lines (e.g., an example of word lines **804** in FIG. **8**, referred to as **934** as well) each extending in the word line direction (the x-direction). Each word line **934** can be coupled to a row of DRAM cells **724**. That is, bit line **923** and word line **934** can extend in two perpendicular lateral directions, and semiconductor body **930** of vertical transistor **726** can extend in the vertical direction perpendicular to the two lateral directions in which bit line **923** and word line **934** extend. Word lines **934** are in contact with word line contacts **727**, according to some implementations. In some implementations, word lines **934** include conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, word line **934** includes multiple conductive layers, such as a W layer over a TiN layer.

[0115] As shown in FIG. **9A**, second semiconductor structure **104** of 3D memory device **900** can also include a plurality of bit lines **923** (e.g., an example of bit lines **806** in FIG. **8**) each extending in the bit line direction (the y-direction in FIG. **8**). Each bit line **923** can be coupled to a column of DRAM cells **724**. In some implementations, bit line **923** is coupled to one of source and drain **938** that is away from capacitor **728** (e.g., the drain of vertical transistor **926**). For example, as shown in FIG. **9B**, bit line **923** may be in contact with source/drain **938** that is formed on one or some sides of protrusion **954** of semiconductor body **930**, but separated from channel portion **939** of semiconductor body **930** by source/drain **938**. The rest of the sides of protrusion **954** can be in contact with gate dielectric **932**. That is, bit line **923** is not in contact with channel portion **939** of semiconductor body **930** in which the channels of vertical transistor **726** are formed to suppress the

floating body effect, according to some implementations.

[0116] As shown in FIG. 9A, second semiconductor structure **104** of 3D memory device **900** can further include body line **748** extending laterally (in the bit line direction and/or word line direction) and coupled to channel portion **939** of semiconductor body **930**. Body line **748** can be also coupled to body line contact **751**, which can be in turn coupled to peripheral circuits **712** in first semiconductor structure **102** through interconnect layers **722** and **716** and bonding layers **718** and **720**. As a result, channel portion **939** of semiconductor body **930** can be coupled to a certain potential, for example, by a voltage source or the ground in peripheral circuits **712**, through body line **748**, body line contact **751**, and any other suitable interconnects in interconnect layers **722** and **716** and bonding layers **718** and **720**, such that channel charge in channel portion **939** of semiconductor body **930** can be released during operation of 3D memory device **900** to mitigate the floating body effect and the resulting issues. It is understood that in some examples, body line **748** may be coupled to a voltage source or the ground not in peripheral circuits **712** as long as the charge of the channels in semiconductor body **930** can be depleted.

[0117] As described above, the upper end (top) of protrusion **954** of semiconductor body **930** is not covered by source/drain **938**, such that body line **748** can be in contact with channel portion **939** of semiconductor body **930**. In some implementations, the upper end of protrusion **954** extends beyond bit line **923** such that body line **748** in contact with the upper end of protrusion **954** is separated from bit line **923** to avoid short circuits. In some implementations, body line **748** includes polysilicon layer **750** in contact with channel portion **939** of semiconductor body **930** to reduce the contact resistance between body line **748** and semiconductor body **930**. In some implementations, body line **748** further includes metal layer **752** (e.g., W or Cu layer) in contact with polysilicon layer **750** to reduce the sheet resistance of body line **748**. It is understood that the structure and/or materials of body line **748** may vary in other examples as long as body line **748** can couple channel portion **939** of semiconductor body **930** to a certain potential with reasonable contact and sheet resistances.

[0118] Body line **748** and capacitor **728** can be coupled to opposite ends of vertical transistor **926** in the z-direction. For example, body line **748** may be coupled to the upper end of vertical transistor **926**, while capacitor **728** may be coupled to the lower end of vertical transistor **926**, as shown in FIG. 9A. In some implementations, bit line **923** is between capacitor **728** and body line **748** in the z-direction as bit line **923** is in contact with the sides of protrusion **954** of semiconductor body **930** while body line **748** is in contact with the upper end of protrusion **954**. In some implementations, capacitor **728** is between bonding interface **106** and vertical transistor **926** in the z-direction, and word line **934** is between bonding interface **106** and bit line **923** in the z-direction. The relative spatial relationships of various components in second semiconductor structure **104** of 3D memory device **900** that are described above as well as depicted in FIG. 9A may result from the face-to-face bonding process between first and second semiconductor structures **102** and **104** as well as the backside process for forming protrusion **954**, bit line **923**, and body line **748** as described below in detail with respect to the fabrication processes, which enable the design of vertical transistor **726** with reduced floating body effect.

[0119] As shown in FIG. 9A, in some implementations, capacitor **728** includes first electrode **742** below and coupled to source or drain **938** of vertical transistor **926**, e.g., at the lower end of base **956** of semiconductor body **930**. Capacitor **728** can also include capacitor dielectric **744** in contact with first electrode **742**, and second electrode **746** in contact with capacitor dielectric **744**. That is, capacitor dielectric **744** can be sandwiched between electrodes **742** and **746**. In some implementations, each first electrode **742** is coupled to source or drain **938** of a respective vertical transistor **926** in the same DRAM cell **724**, while all second electrodes **746** are parts of a common plate coupled to the ground, e.g., a common ground. Although not shown in FIG. 9A, it is understood that second semiconductor structure **104** may further include a capacitor contact in contact with the common plate of second electrodes **746** for coupling second electrodes **746** of

capacitor **728** to peripheral circuits **712** or to the ground directly.

[0120] It is understood that the structure and configuration of capacitor **728** are not limited to the interdigitated capacitor (a.k.a., finger capacitor) example in FIG. **9A** and may include any suitable structure and configuration, such as a planar capacitor, a stack capacitor, a multi-fins capacitor, a cylinder capacitor, a trench capacitor, or a substrate-plate capacitor. In some implementations, capacitor dielectric **744** includes dielectric materials, such as silicon oxide, silicon nitride, or high-k dielectrics including, but not limited to, Al.sub.2O.sub.3 , HfO.sub.2 , Ta.sub.2O.sub.5 , ZrO.sub.2 , TiO.sub.2 , or any combination thereof. It is understood that in some examples, capacitor **728** may be a ferroelectric capacitor used in a FRAM cell, and capacitor dielectric **744** may be replaced by a ferroelectric layer having ferroelectric materials, such as PZT or SBT. In some implementations, electrodes **742** and **746** include conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof.

[0121] Although not shown in FIG. **9A**, it is understood that in some examples, second semiconductor structure **104** may further include a pad-out interconnect layer (e.g., pad-out interconnect layer **108** in FIG. **1A**) above body line **748**. The pad-out interconnect layer may include interconnects, e.g., contact pads, in one or more ILD layers. The pad-out interconnect layer and interconnect layer **722** can be formed on opposite sides of DRAM cells **724**. Vertical transistors **926** are disposed vertically between capacitors **728** and the pad-out interconnect layer, according to some implementations. In some implementations, the interconnects in the pad-out interconnect layer can transfer electrical signals between 3D memory device **900** and outside circuits, e.g., for pad-out purposes. It is also understood that the pad-out of 3D memory devices is not limited to from second semiconductor structure **104** having DRAM cells **724** and may be from first semiconductor structure **102** having peripheral circuit **712**. For example, as shown in FIG. **1B**, 3D memory device **101** may include a pad-out interconnect layer in first semiconductor structure **102**.

[0122] As described above, according to some aspects of the present disclosure, a memory cell can include multiple storage units (e.g., capacitors, ferroelectric capacitors, or PCM elements), such as a 1TnC or nTnC DRAM cell or FRAM cell. The multiple capacitors (including ferroelectric capacitors) can be stacked vertically to further increase the capacitance density, the cell density, and/or achieve multi-bits information storage in a single memory cell under the current fabrication limitations of etching high aspect ratio capacitor holes. For example, FIG. **10A** illustrates a side view of a cross-section of still another 3D memory device **1000** including vertical transistors and stacked storage units, according to some aspects of the present disclosure. It is understood that FIG. **10A** is for illustrative purposes only and may not necessarily reflect the actual device structure (e.g., interconnections) in practice. As one example of 3D memory device **100** described above with respect to FIG. **1A**, 3D memory device **1000** is a bonded chip including first semiconductor structure **102** and second semiconductor structure **104** stacked over first semiconductor structure **102**. First and second semiconductor structures **102** and **104** are jointed at bonding interface **106** therebetween, according to some implementations. As shown in FIG. **10A**, first semiconductor structure **102** can include substrate **110**, which can include silicon (e.g., single crystalline silicon, c-Si), SiGe, GaAs, Ge, SOI, or any other suitable materials.

[0123] First semiconductor structure **102** can include peripheral circuits **712** on substrate **110**. In some implementations, peripheral circuits **712** include a plurality of transistors **714** (e.g., planar transistors and/or 3D transistors). Trench isolations (e.g., STIs) and doped regions (e.g., wells, sources, and drains of transistors **714**) can be formed on or in substrate **110** as well.

[0124] In some implementations, first semiconductor structure **102** further includes an interconnect layer **716** above peripheral circuits **712** to transfer electrical signals to and from peripheral circuits **712**. Interconnect layer **716** can include a plurality of interconnects, including lateral interconnect lines and VIA contacts. Interconnect layer **716** can further include one or more ILD layers in which the interconnect lines and via contacts can form. That is, interconnect layer **716** can include interconnect lines and via contacts in multiple ILD layers. In some implementations, peripheral

circuits **712** are coupled to one another through the interconnects in interconnect layer **716**. The interconnects in interconnect layer **716** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof.

[0125] As shown in FIG. **10A**, first semiconductor structure **102** can further include bonding layer **718** at bonding interface **106** and above interconnect layer **716** and peripheral circuits **712**. Bonding layer **718** can include bonding contacts **719** and dielectrics electrically isolating bonding contacts **719**. Bonding contacts **719** can include conductive materials, such as Cu. The remaining area of bonding layer **718** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **719** and surrounding dielectrics in bonding layer **718** can be used for hybrid bonding. Similarly, as shown in FIG. **10A**, second semiconductor structure **104** can also include bonding layer **720** at bonding interface **106** and above bonding layer **718** of first semiconductor structure **102**. Bonding layer **720** can include bonding contacts **721** and dielectrics electrically isolating bonding contacts **721**. Bonding contacts **721** can include conductive materials, such as Cu. The remaining area of bonding layer **720** can be formed with dielectric materials, such as silicon oxide. Bonding contacts **721** and surrounding dielectrics in bonding layer **720** can be used for hybrid bonding. Bonding contacts **721** are in contact with bonding contacts **719** at bonding interface **106**, according to some implementations.

[0126] Second semiconductor structure **104** can be bonded on top of first semiconductor structure **102** in a face-to-face manner at bonding interface **106**. In some implementations, bonding interface **106** is disposed between bonding layers **720** and **718** as a result of hybrid bonding, which is a direct bonding technology (e.g., forming bonding between surfaces without using intermediate layers, such as solder or adhesives) and can obtain metal-metal bonding and dielectric-dielectric bonding simultaneously. In some implementations, bonding interface **106** is the place at which bonding layers **720** and **718** are met and bonded. In practice, bonding interface **106** can be a layer with a certain thickness that includes the top surface of bonding layer **718** of first semiconductor structure **102** and the bottom surface of bonding layer **720** of second semiconductor structure **104**.

[0127] In some implementations, second semiconductor structure **104** further includes interconnect layer **722** above bonding layer **720** to transfer electrical signals. Interconnect layer **722** can include a plurality of interconnects, such as MEOL interconnects and BEOL interconnects. In some implementations, the interconnects in interconnect layer **722** also include local interconnects, such as bit line contacts (not shown), plate line contacts **1007**, word line contacts **727**, and body line contacts **751**. Interconnect layer **722** can further include one or more ILD layers in which the interconnect lines and via contacts can form. The interconnects in interconnect layer **722** can include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can be formed with dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof. In some implementations, peripheral circuits **712** include a word line driver/row decoder coupled to word line contacts **727** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some implementations, peripheral circuits **712** include a bit line driver/column decoder coupled to the bit line contacts in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**. In some implementations, peripheral circuits **712** include a voltage source or the ground that is coupled to body line contacts **751** in interconnect layer **722** through bonding contacts **721** and **719** in bonding layers **720** and **718** and interconnect layer **716**.

[0128] In some implementations, second semiconductor structure **104** includes a FRAM device in which memory cells are provided in the form of an array of FRAM cells **1024** (e.g., an example of FRAM cells **502** in FIG. **5B**) above interconnect layer **722** and bonding layer **720**. It is understood that the cross-section of 3D memory device **1000** in FIG. **10A** may be made along the word line

direction (the x-direction), and one word line **734** extending laterally in the x-direction may be coupled to a row of FRAM cells **1024**. Each FRAM cell **1024** can include vertical transistor **726** (e.g., an example of vertical transistors **210** in FIG. 2) and a plurality of vertically stacked ferroelectric capacitors **1028** (e.g., an example of storage unit **212** in FIG. 2) coupled to vertical transistor **726**. FRAM cell **1024** can be in the 1TnC configuration (i.e., a 1TnC cell) consisting of one transistor and multiple ferroelectric capacitors. It is understood that FRAM cell **1024** may be of any suitable configurations, such as nTnC, etc.

[0129] Vertical transistor **726** can be a MOSFET used to switch a respective FRAM cell **1024**. In some implementations, vertical transistor **726** includes semiconductor body **730** (i.e., the active region in which multiple channels can form) extending vertically (in the z-direction), and gate structure **736** in contact with one or more sides of semiconductor body **730**. In some implementations in which vertical transistor **726** is a GAA vertical transistor, semiconductor body **730** has a cuboid shape or a cylinder shape, and gate structure **736** is in contact with all sides of semiconductor body **730**, i.e., fully circumscribing semiconductor body **730** in the plan view. In some implementations in which vertical transistor **726** is a tri-gate vertical transistor, a double-gate vertical transistor, or a single-gate vertical transistor, semiconductor body **730** has a cuboid shape or a cylinder shape, and gate structure **736** is in contact with one or some sides, but not all sides, of semiconductor body **730**, i.e., partially circumscribing semiconductor body **730** in the plan view. Gate structure **736** includes gate electrode **734** and gate dielectric **732** laterally between gate electrode **734** and semiconductor body **730** in at least the word line direction, according to some implementations. For example, for semiconductor body **730** having a cylinder shape, semiconductor body **730**, gate dielectric **732**, and gate electrode **734** may be disposed radially from the center of vertical transistor **726** in this order. In some implementations, gate dielectric **732** surrounds and contacts semiconductor body **730**, and gate electrode **734** surrounds and contacts gate dielectric **732**.

[0130] In some implementations, gate dielectric **732** includes dielectric materials, such as silicon oxide, silicon nitride, or high-k dielectrics including, but not limited to, Al.sub.2O.sub.3, HfO.sub.2, Ta.sub.2O.sub.5, ZrO.sub.2, TiO.sub.2, or any combination thereof. In some implementations, gate electrode **734** includes conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, gate electrode **734** includes multiple conductive layers, such as a W layer over a TiN layer. In one example, gate structure **736** may be a “gate oxide/gate poly” gate in which gate dielectric **732** includes silicon oxide and gate electrode **734** includes doped polysilicon. In another example, gate structure **736** may be a HKMG in which gate dielectric **732** includes a high-k dielectric and gate electrode **734** includes a metal.

[0131] As shown in FIG. 10A, in some implementations, semiconductor body **730** has two ends (the upper end and lower end) in the vertical direction (the z-direction), and both ends extend beyond gate electrode/word line **734**, respectively, in the vertical direction (the z-direction) into ILD layers. That is, semiconductor body **730** can have a larger vertical dimension (e.g., the depth) than that of gate electrode/word line **734** (e.g., in the z-direction), and neither the upper end nor the lower end of semiconductor body **730** is flush with the respective end of gate electrode/word line **734**. Thus, short circuits between bit lines **723** and word lines/gate electrodes **734** or between word lines/gate electrodes **734** and capacitors **728** can be avoided.

[0132] As shown in FIGS. 10 and 7B, semiconductor body **730** of vertical transistor **726** can include a source and a drain (both referred to as **738** as their locations may be interchangeable) as well as channel portion **739** from the doping perspective, i.e., whether a particular portion of semiconductor body **730** is doped or the type of dopant thereof. In one example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped to form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped to form the other one of source and

drain **738** (e.g., the drain of vertical transistor **726**). The remaining undoped portion of semiconductor body **730** thus may become channel portion **739**. In another example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped with N-type dopant(s) form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped with N-type dopant(s) to form the other one of source and drain **738** (e.g., the drain of vertical transistor **726**). The remaining portion of semiconductor body **730** thus may become channel portion **739**, which may be doped with P-type dopant(s). In still another example, the lower end of semiconductor body **730** that is coupled to capacitor **728** may be fully doped with P-type dopant(s) form one of source and drain **738** (e.g., the source of vertical transistor **726**), while the upper end of semiconductor body **730** away from capacitor **728** may be partially doped with P-type dopant(s) to form the other one of source and drain **738** (e.g., the drain of vertical transistor **726**). The remaining portion of semiconductor body **730** thus may become channel portion **739**, which may be doped with N-type dopant(s). In some implementations, semiconductor body **730** has base **756** and protrusion **754** from the shape perspective, i.e., the relative dimensions and geometric relationships between different portions of semiconductor body **730**, as shown in FIG. **7B**. For example, base **756** may have a larger lateral dimension than protrusion **754**. Protrusion **754** can protrude entirely from the interior of base **756**, i.e., all sides of protrusion **754** being within the boundary of base **756** in the plan view. In some implementations, base **756** faces word line/gate electrode **734**, and protrusion **754** faces bit line **723**.

[0133] One of source and drain **738** (e.g., at the lower end in FIG. **10A**) can be formed on one end (e.g., the lower end in FIG. **10A**) of base **756**. The other one of source and drain **738** (e.g., at the upper end in FIG. **10A**) can be formed on one or more sides of protrusion **754** of semiconductor body **730**. In some implementations, as shown in FIGS. **10** and **7B**, one of source and drain **738** that is away from ferroelectric capacitors **1028** (e.g., the drain of FRAM cell **1024**) is formed on all sides of protrusion **754**. Channel portion **739** can be formed in both base **756** and protrusion **754** of semiconductor body **730**. That is, both base **756** and protrusion **754** of semiconductor body **730** can have portions that are undoped or doped with a different type of dopant from source and drain **738**, becoming channel portion **739**. As shown in FIGS. **10** and **7B**, different from the lower end (i.e., bottom) of base **756** that is doped to become part of source/drain **738**, the upper end (i.e., top) of protrusion **754** is not doped with the same type of dopant as source and drain **738** to become part of source/drain **738**, but remains as part of channel portion **739**, according to some implementations. As shown in FIG. **7B**, gate dielectric **732** of gate structure **736** is in contact with base **756** of semiconductor body **730**, but does not extend further to be in contact with protrusion **754** of semiconductor body **730**, according to some implementations. In other words, gate dielectric **732** can be separated from protrusion **754** of semiconductor body **730**.

[0134] In some implementations, semiconductor body **730** includes semiconductor materials, such as single crystalline silicon, polysilicon, amorphous silicon, Ge, any other semiconductor materials, or any combinations thereof. In one example, semiconductor body **730** may include single crystalline silicon, and channel portion **739** of semiconductor body **730** may include undoped single crystalline silicon or doped single crystalline silicon having a different type of dopant from source and drain **738**. Source and drain **738** can be doped with N-type dopants (e.g., P or As) or P-type dopants (e.g., B or Ga) at a desired doping level. In some implementations, source and drain **738** are doped with N-type dopants (e.g., P or As), and channel proportion **739** is undoped/intrinsic or doped with P-type dopants (e.g., B or Ga).

[0135] As described above, since gate electrode **734** may be part of a word line or extend in the word line direction as a word line, although not directly shown in FIG. **10A**, second semiconductor structure **104** of 3D memory device **1000** can also include a plurality of word lines (referred to as **734** as well) each extending in the word line direction (the x-direction). Each word line **734** can be coupled to a row of FRAM cells **1024**. That is, bit line **723** and word line **734** can extend in two

perpendicular lateral directions, and semiconductor body **730** of vertical transistor **726** can extend in the vertical direction perpendicular to the two lateral directions in which bit line **723** and word line **734** extend. Word lines **734** are in contact with word line contacts **727**, according to some implementations. In some implementations, word lines **734** include conductive materials including, but not limited to W, Co, Cu, Al, TiN, TaN, polysilicon, silicides, or any combination thereof. In some implementations, word line **734** includes multiple conductive layers, such as a W layer over a TiN layer.

[0136] As shown in FIG. **10A**, second semiconductor structure **104** of 3D memory device **1000** can also include a plurality of bit lines **723** each extending in the bit line direction. Each bit line **723** can be coupled to a column of FRAM cells **1024**. In some implementations, bit line **723** is coupled to one of source and drain **738** that is away from ferroelectric capacitors **1028** (e.g., the drain of vertical transistor **726**). For example, as shown in FIG. **7B**, bit line **723** may be in contact with source/drain **738** that is formed on all sides of protrusion **754** of semiconductor body **730**, but separated from channel portion **739** of semiconductor body **730** by source/drain **738**. That is, bit line **723** is not in contact with channel portion **739** of semiconductor body **730** in which the channels of vertical transistor **726** are formed to suppress the floating body effect, according to some implementations.

[0137] As shown in FIG. **10A**, second semiconductor structure **104** of 3D memory device **1000** can further include body line **748** extending laterally (in the bit line direction and/or word line direction) and coupled to channel portion **739** of semiconductor body **730**. Body line **748** can be also coupled to body line contact **751**, which can be in turn coupled to peripheral circuits **712** in first semiconductor structure **102** through interconnect layers **722** and **716** and bonding layers **718** and **720**. As a result, channel portion **739** of semiconductor body **730** can be coupled to a certain potential, for example, by a voltage source or the ground in peripheral circuits **712**, through body line **748**, body line contact **751**, and any other suitable interconnects in interconnect layers **722** and **716** and bonding layers **718** and **720**, such that channel charge in channel portion **739** of semiconductor body **730** can be released during operation of 3D memory device **1000** to mitigate the floating body effect and the resulting issues. It is understood that in some examples, body line **748** may be coupled to a voltage source or the ground not in peripheral circuits **712** as long as the charge of the channels in semiconductor body **730** can be depleted.

[0138] As described above, the upper end (top) of protrusion **754** of semiconductor body **730** is not covered by source/drain **738**, such that body line **748** can be in contact with channel portion **739** of semiconductor body **730**. In some implementations, the upper end of protrusion **754** extends beyond bit line **723** such that body line **748** in contact with the upper end of protrusion **754** is separated from bit line **723** to avoid short circuits. In some implementations, body line **748** includes polysilicon layer **750** in contact with channel portion **739** of semiconductor body **730** to reduce the contact resistance between body line **748** and semiconductor body **730**. In some implementations, body line **748** further includes metal layer **752** (e.g., W or Cu layer) in contact with polysilicon layer **750** to reduce the sheet resistance of body line **748**. It is understood that the structure and/or materials of body line **748** may vary in other examples as long as body line **748** can couple channel portion **739** of semiconductor body **730** to a certain potential with reasonable contact and sheet resistances.

[0139] Body line **748** and ferroelectric capacitors **1028** can be coupled to opposite ends of vertical transistor **726** in the z-direction. For example, body line **748** may be coupled to the upper end of vertical transistor **726**, while ferroelectric capacitors **1028** may be coupled to the lower end of vertical transistor **726**, as shown in FIG. **10A**. In some implementations, bit line **723** is between ferroelectric capacitors **1028** and body line **748** in the z-direction as bit line **723** is in contact with the sides of protrusion **754** of semiconductor body **730** while body line **748** is in contact with the upper end of protrusion **754**. In some implementations, ferroelectric capacitors **1028** are between bonding interface **106** and vertical transistor **726** in the z-direction, and word line **734** is between

bonding interface **106** and bit line **723** in the z-direction. The relative spatial relationships of various components in second semiconductor structure **104** of 3D memory device **1000** that are described above as well as depicted in FIG. **10A** may result from the face-to-face bonding process between first and second semiconductor structures **102** and **104** as well as the backside process for forming protrusion **754**, bit line **723**, and body line **748** as described below in detail with respect to the fabrication processes, which enable the design of vertical transistor **726** with reduced floating body effect.

[0140] It is understood that vertical transistors **726** and bit lines **723** in FIG. **10A** are provided for illustrative purposes only and may be replaced with any other suitable counterparts disclosed herein, such as vertical transistors **926** and bit lines **923** in FIG. **9A**. It is also understood that the vertical transistors in 3D memory device **1000** may be any other suitable vertical transistors as long as the vertical transistor includes a semiconductor body extending vertically, one end of which can be coupled to multiple vertically stacked storage units, such as ferroelectric capacitors **1028** disclosed herein.

[0141] As shown in FIGS. **10A** and **10B**, second semiconductor structure **104** can include a plurality of ferroelectric capacitors **1028** (e.g., an example of ferroelectric capacitors **506-1**, **506-2**, . . . , **506-n** in FIG. **5B**) stacked vertically (in the z-direction) and coupled to a respective vertical transistor **726** (e.g., an example of transistor **504** in FIG. **5B**) for each FRAM cell **1024** (e.g., an example of FRAM cell **502** in FIG. **5B**). Second semiconductor structure **104** can also include a plurality of plate lines **1047** (e.g., an example of plate lines **508-1**, **508-2**, . . . , **508-n** in FIG. **5B**) each extending laterally (i.e., perpendicular to the vertical direction) and coupled to a respective one of ferroelectric capacitors **1028**. As shown in the enlarged view of FIG. **10B**, each ferroelectric capacitor **1028** includes a first electrode **1046**, a second electrode **1042**, and a ferroelectric section **1044** (an example of a storage section of a storage unit) sandwiched laterally between first electrode **1046** and second electrode **1042** in the word line direction and/or the bit line direction, according to some implementations. In some implementations, second electrodes **1042** of stacked ferroelectric capacitors **1028** of the same FRAM cell **1024** are parts of a continuous electrode layer **1006** coupled to the lower end of semiconductor body **730** (e.g., source/drain **738**), and ferroelectric sections **1044** of stacked ferroelectric capacitors **1028** of the same FRAM cell **1024** are parts of a continuous ferroelectric layer **1008** (an example of a storage layer of a storage unit) over electrode layer **1006**. Electrode layer **1006** can include a conductive material, such as a metal. In some implementations, each first electrode **1046** and a respective plate line **1047** are parts of a respective continuous conductive layer **1047**. That is, similar to gate electrode/word line **734**, first electrode **1046** may be viewed as part of plate line **1047**, or plate line **1047** may be viewed as the extension of first electrode **1046**. On the other hand, first electrodes **1046** of stacked ferroelectric capacitors **1028** of the same FRAM cell **1024** are spaced apart for one another in the vertical direction, according to some implementations. Two adjacent first electrodes **1046** (and conductive layers **1047**) can be separated by a respective one of dielectric layer **1045**. For electrode layer **1006** having a cylinder shape, electrode layer **1006**, ferroelectric layer **1008**, and conductive layers **1047** may be disposed radially from the center of electrode layer **1006** in this order. In some implementations, ferroelectric layer **1008** surrounds and contacts electrode layer **1006**, and conductive layers **1047** surround and contact ferroelectric layer **1008**.

[0142] As shown in FIG. **10A**, stacked ferroelectric capacitors **1028** can be provided in the form of electrode layers **1006** and ferroelectric layers **1008** extending vertically (in the z-direction) through a stack structure **1002** including interleaved conductive layers **1047** and dielectric layers **1045**. In some implementations, second semiconductor structure **104** of 3D memory device **1000** further includes stack structure **1002** having a plurality of pairs each including a conductive layer **1047** and a dielectric layer **1045**. Each conductive layer **1047** and dielectric layer **1045** can extend laterally in the word line direction and/or the bit line direction. Stack structure **1002** can be disposed between bonding interface **106** and vertical transistors **726** in the z-direction. Word line **734** can be disposed

vertically between stack structure **1002** and bit line **723** in the z-direction. The stacked and interleaved conductive layers **1047** and dielectric layers **1045** in stack structure **1002** alternate in the vertical direction, according to some implementations. The number of the pairs of conductive layers **1047** and dielectric layers **1045** in stack structure **1002** can determine the number of stacked ferroelectric capacitors **1028** in each FRAM cell **1024**. Thus, the capacitance of FRAM cell **1024** can be scaled up vertically without increasing the planar area and increasing the process complexity (e.g., etching a high aspect ratio capacitor hole). Conductive layer **1047** can include conductive materials including, but not limited to, W, Co, Cu, Al, polysilicon, doped silicon, silicides, or any combination thereof. In some implementations, each conductive layer **1047** includes a metal layer, such as a W layer.

[0143] As described above, conductive layer **1047** can include plate line **1047** and first electrode **1046** in contact with and ferroelectric layer **1008**. In some implementations, edges of dielectric layers **1045** and conductive layers **1047** can define staircase structure **1004** of stack structure **1002**, which includes a plurality of stairs (levels) for plate line interconnections (e.g., landing plate line contacts **1007**). Conductive layer/plate line **1047** can extend laterally, ending at a respective stair of staircase structure **1004**. In some implementations, every two adjacent stairs of staircase structure **1004** are offset by a distance in a lateral direction (e.g., the x-direction in FIG. **10A**). Each offset thus can form a “landing area” for interconnection with plate line contacts **1007** in the vertical direction. As shown in FIG. **10A**, second semiconductor structure **104** of 3D memory device **1000** can further include plate line contacts **1007** in contact with conductive layers **1047**, respectively, at staircase structure **1004**. Thus, each one of multiple first electrodes **1046** in the same FRAM cell **1024** can be individually coupled to peripheral circuits **712** through a respective plate line **1047**, a respective plate line contact **1007**, and interconnects in interconnect layers **722** and **716** and bonding layers **720** and **718**. Each ferroelectric capacitor **1028** can be coupled to a respective plate line **1047**.

[0144] As shown in FIG. **10A**, second semiconductor structure **104** of 3D memory device **1000** can further include electrode layer **1006** and ferroelectric layer **1008** over electrode layer **1006**. Each of electrode layer **1006** and ferroelectric layer **1008** can extend through stack structure **1002** to in the z-direction to form vertically stacked ferroelectric capacitors **1028** of each FRAM cell **1024**. In some implementations, electrode layer **1006** is a continuous layer and includes a plurality of second electrodes **1042**, and ferroelectric layer **1008** is a continuous layer and includes a plurality of ferroelectric sections **1044**. First electrodes **1046**, second electrodes **1042**, and ferroelectric sections **1044** can form a plurality of ferroelectric capacitors **1028** stacked in the vertical direction for each FRAM cell **1024**. Electrode layer **1006** can be shared by all ferroelectric capacitors **1028** of the same FRAM cell **1024** and serve as a common electrode to couple each ferroelectric capacitor **1028** of the same FRAM cell **1024** to a respective vertical transistor **726**. Electrode layer **1006** can include conductive materials including, but not limited to, W, Co, Cu, Al, polysilicon, doped silicon, silicides, or any combination thereof. In some implementations, electrode layer **1006** includes a metal layer, such as a W layer.

[0145] It is understood that FRAM cell **1024** is illustrated as an example of a memory cell having multiple vertically stacked storage units, ferroelectric capacitors **1028** are illustrated as an example of vertically stacked storage units. In some examples, the memory cell may be a DRAM cell, and the vertically stacked storage units may be vertically stacked capacitors. It is also understood that ferroelectric layer **1008** is illustrated as an example of a storage layer including storage sections, and ferroelectric sections **1044** are illustrated as an example of the storage sections. Ferroelectric layer **1008** may be a storage layer including a ferroelectric material. In some examples, the storage layer may include a dielectric material, such as high-K dielectrics, of capacitors.

[0146] Although not shown in FIG. **10A**, it is understood that in some examples, second semiconductor structure **104** may further include a pad-out interconnect layer (e.g., pad-out interconnect layer **108** in FIG. **1A**) above body line **748**. The pad-out interconnect layer may

include interconnects, e.g., contact pads, in one or more ILD layers. The pad-out interconnect layer and interconnect layer **722** can be formed on opposite sides of FRAM cells **1024**. Vertical transistors **726** are disposed vertically between ferroelectric capacitors **1028** and the pad-out interconnect layer, according to some implementations. In some implementations, the interconnects in the pad-out interconnect layer can transfer electrical signals between 3D memory device **1000** and outside circuits, e.g., for pad-out purposes. It is also understood that the pad-out of 3D memory devices is not limited to from second semiconductor structure **104** having FRAM cells **1024** and may be from first semiconductor structure **102** having peripheral circuit **712**. For example, as shown in FIG. **1B**, 3D memory device **101** may include a pad-out interconnect layer in first semiconductor structure **102**.

[0147] As described above with respect to FIGS. **6** and **8**, the arrays of memory cells disclosed herein can be arranged in cross-point orthogonal layouts, which have a 4F2 cell size. According to some aspects of the present disclosure, the unit cell size of an array of memory cells can be further reduced by changing the layout from cross-point orthogonal layouts to staggered layouts with fixed minimum cell distances. For example, FIG. **11** illustrates a layout view of an array of memory cells **1102** each including a vertical transistor, according to some aspects of the present disclosure.

Memory cell **1102** may include any suitable memory cell that includes a vertical transistor and one or more storage units coupled to the vertical transistor, such as memory cells disclosed herein.

[0148] The array of memory cells **1102** can be arranged in rows and columns. Each row of memory cells **1102** extends in the word line direction (the x-direction), and each column of memory cells extends in the bit line direction (the y-direction), according to some implementations. That is, rows of memory cells **1102** can be arranged in the bit line direction, and columns of memory cells **1102** can be arranged in the word line direction. As shown in FIG. **11**, the array of memory cells **1102** can be arranged in a staggered layout, as opposed to a cross-point orthogonal layout. For example, two adjacent rows of memory cells **1102** may be staggered (not aligned) with one another, and two adjacent columns of memory cells **1102** may be staggered (not aligned) with one another as well in the plan view.

[0149] As shown in FIG. **11**, each of a set of four memory cells **1102** is coupled to the same word line **1104**, which is formed between two adjacent slit structures **1108** in the bit line direction (the y-direction), according to some implementations. Slit structure **1108** can include one or more dielectric materials, such as silicon oxide or silicon nitride, to separate adjacent word lines **1104** in the bit line direction. In some implementations, each of the set of four memory cells **1102** is coupled to a respective one of four bit lines **1106**. As a result, although the set of four memory cells share the same word line **1104**, each of the set of four memory cells **1102** can be individually controlled by a respective bit line **1106**. In other words, the combination of a specific word line **1104** and a specific bit line **1106** corresponds to a respective memory cell **1102**, according to some implementations. In some implementation, a set of memory cells **1102** coupled to the same word line **1104** may include n memory cells **1102** in the same column, where n is a positive integer greater than 1, and n memory cells **1102** may be coupled to n bit lines **1106**, respectively, to enable individual control of each memory cell **1102**. In other words, multiple bit lines **1106** can be coupled to memory cells **1102** in the same column. As a result, each bit line **1106** may not fully circumscribe the semiconductor body of a respective memory cell **1102** (e.g., having the design shown in FIGS. **7A** and **7B**), but may partially circumscribe the semiconductor body of a respective memory cell **1102** (e.g., having the design shown in FIGS. **9A** and **9B**), in case there are multiple memory cells in the same column that are coupled to the same word line **1104**.

[0150] In the plan view of FIG. **11**, each bit line **1106** can be coupled to a source/drain **1110** of a respective memory cell **1102** through a respective bit line contact **1114** and separated from a channel portion **1112** of the semiconductor body of the respective memory cell **1102**, which is coupled to a body line (not shown) to reduce the floating body effect. It is understood that the design of source/drain **1110** and channel portion **1112** shown in FIG. **11** is for illustrative purposes

only and may vary in other examples as long as source/drain **1110** of each memory cell **1102** can be coupled to a respective bit line **1106**. The set of four memory cells **1102** coupled to word line **1104**, as shown in FIG. **11**, are referred to herein as “function memory cells” as they can be controlled by word line **1104** and bit lines **1106**. In contrast, a memory cell that is coupled to slit structure **1108** (not shown in FIG. **11**) is referred to herein as a “dummy memory cell” as it cannot be controlled by word line **1104**.

[0151] To reduce the unit cell size, the staggered layout of memory cells **1102** is designed such that the minimum cell distances between any memory cell **1102** and its adjacent memory cells **1102** are kept the same. For example, as shown in FIG. **11**, the minimum distance **D1** between a first memory cell A and a second memory cell B in the same column of memory cell A may be the same as the minimum distance **D2** between memory cell A and a third memory cell C in an adjacent column, i.e., $D1=D2$. The distance between two memory cells may be measured between the geometric centers of the two memory cells in the plan view, such as the centers of two circles, as shown in FIG. **11**. It is understood that for a particular memory cell, there may be more than one adjacent memory cells in the same column or adjacent columns. Thus, the minimum distance may be the distance between the memory cell and the closest memory cell in the same or adjacent column, i.e., the smallest value of the distances from different adjacent memory cells.

[0152] As shown in FIG. **11**, in some examples, the minimum distance $D1/D2$ may also be the same as the distance **D3** between memory cell B and memory cell C, i.e., $D1=D2=D3$. That is, memory cells A, B, and C are disposed in vertices of an equilateral triangle (A), respectively, in the plan view, according to some implementations. Thus, the staggered layout of memory cells **1102** shown in FIG. **11** may also be referred to as the “delta” (A) arrangement. According to the delta arrangement shown in FIG. **11**, the minimum cell distances between any memory cell **1102** and its adjacent memory cells **1102** are kept the same, such that the unit cell size can be minimized.

[0153] FIGS. **12A-12E** illustrates layout views of various arrays of memory cells each including a vertical transistor, according to various aspects of the present disclosure. FIGS. **12-12E** may illustrate various examples of staggered layouts with the delta arrangement disclosed in FIG. **11**. As shown in FIG. **12A**, each slit structure **1108** has a straight shape extending in the word line direction (the x-direction) in the plan view and separate two adjacent word lines **1104** in the bit line direction (the y-direction), according to some implementations. The memory cells thus can include a plurality sets of function memory cells **1202**, and each set of function memory cells **1202** is coupled to a respective word line **1104**. Within each set of function memory cells **1202**, function memory cells **1202** are arranged according to the delta arrangement disclosed above with respect to FIG. **11**, such that the minimum cell distances between any function memory cell **1202** and its adjacent function memory cells **1202** in the same set (i.e., coupling to the same word line **1104**) can be kept the same. The unit cell size of the staggered layout disclosed in FIG. **12A** can be reduced to $2.64F_{\text{sup.2}}$ (i.e., $2.64F^2$ cell size).

[0154] However, since the staggered layout disclosed in FIG. **12A** does not include any dummy memory cell coupled to slit structure **1108** between adjacent sets of function memory cells **1202**, the delta arrangement may not be applied across adjacent sets of memory cells. For example, the distance between two adjacent function memory cells **1202** in two adjacent sets of function memory cells **1202**, respectively, in the same column across slit structure **1108** may not be the same as (e.g., greater than) the minimum distances (e.g., $D1/D2/D3$ in FIG. **11**) of function memory cells **1202** within each set of function memory cells **1202**.

[0155] Thus, to further reduce the unit cell size, as shown in FIG. **12B**, one or more sets of dummy memory cells **1204** can be introduced. In some implementations, each dummy memory cell **1204** of the same set is coupled to a respective slit structure **1108** having a straight shape in the plan view. In some implementations, dummy memory cell **1204** is not coupled to any word line **1104** or bit line **1106**. As a result, in some columns (e.g., **C1**) of the staggered layout shown in FIG. **12B**, the distance between two adjacent function memory cells **1202** in two adjacent sets of function

memory cells **1202**, respectively, in the same column across slit structure **1108** therebetween can be the same as the minimum distance (e.g., D1/D2/D3 in FIG. **11**) of function memory cells **1202** within each set of function memory cells **1202**; and in some columns (e.g., C2), the distance between dummy memory cell **1204** and an adjacent function memory cell **1202** in an adjacent set of function memory cells **1202** in the same column is the same as the minimum distance (e.g., D1/D2/D3 in FIG. **11**) as well. Thus, by introducing dummy memory cells **1204** into the staggered layout in FIG. **12B**, the delta arrangement may be applied to all the memory cells **1202** and **1204** even across different sets of memory cells **1202** and **1204**. The unit cell size of the staggered layout disclosed in FIG. **12B** can be further reduced to $2.17F_{sup.2}$ (i.e., $2.17F^2$ cell size).

[0156] However, different from function memory cells **1202**, dummy memory cells **1204** cannot be controlled by word lines **1104** and bit lines **1106** to store information and thus, the actual cell density may still be limited by dummy memory cells **1204** even with reduced unit cell size. Thus, to further increase the actual cell density, as shown in FIG. **12C**, slit structures **1208** each having a serpentine shape can be introduced. In some implementations, different from slit structure **1108** having a straight shape, slit structure **1208** has a serpentine shape to follow the staggered pattern of function memory cells **1202** between adjacent rows. As a result, even without introducing dummy memory cells **1204**, in each column of the staggered layout shown in FIG. **12C**, the distance between two adjacent function memory cells **1202** in two adjacent sets of function memory cells **1202**, respectively, in the same column across serpentine-shaped slit structure **1208** therebetween can be the same as the minimum distance (e.g., D1/D2/D3 in FIG. **11**) of function memory cells **1202** within each set of function memory cells **1202**. It is understood that the specific serpentine shape of slit structure **1208** shown in FIG. **12C** is for illustrative purposes only and may vary in other examples as long as the shape follows the staggered pattern of function memory cells **1202** between adjacent rows to allow the distance between two adjacent function memory cells **1202** in two adjacent sets in any column across slit structure **1208** being the same as the minimum distances. Similar to the staggered layout shown in FIG. **12B**, the unit cell size of the staggered layout disclosed in FIG. **12C** may be $2.17F_{sup.2}$ (i.e., $2.17F^2$ cell size) as the delta arrangement may be applied to all function memory cells **1202** even across different sets of function memory cells **1202**. The actual cell density can be increased compared with the staggered layout shown in FIG. **12B** by eliminating dummy memory cells **1204** in the staggered layout shown in FIG. **12C**. [0157] As shown in FIG. **12C**, serpentine-shaped slit structures **1208** and straight-shaped slit structures **1108** may be interleaved in the staggered layout, i.e., having the same number and ratio ($\frac{1}{2}$) among slit structures **1108** and **1208**. However, the unit cell size of the staggered layout in FIG. **12C** is still limited by straight-shaped slit structures **1108**. Thus, the unit cell size can be further reduced by increasing the ratio of serpentine-shaped slit structures **1208** among all slit structures **1108** and **1208**, i.e., decreasing the ratio of straight-shaped slit structures **1108**. For example, in the staggered layout of FIG. **12D**, three serpentine-shaped slit structures **1208** may be arranged between two adjacent straight-shaped slit structures **1108**, increasing the ratio of straight-shaped slit structures **1108** among all slit structures **1108** and **1208** to $\frac{3}{5}$. In a general case shown in FIG. **12E**, assuming k serpentine-shaped slit structures **1208** may be arranged between two adjacent straight-shaped slit structures **1108**, the ratio of straight-shaped slit structures **1108** among all slit structures **1108** and **1208** is set as $k/(k+2)$, where k is a positive integer.

[0158] FIG. **20** illustrates a block diagram of a system **2000** having a memory device, according to some aspects of the present disclosure. System **2000** can be a mobile phone, a desktop computer, a laptop computer, a tablet, a vehicle computer, a gaming console, a printer, a positioning device, a wearable electronic device, a smart sensor, a virtual reality (VR) device, an augmented reality (AR) device, or any other suitable electronic devices having storage therein. As shown in FIG. **20**, system **2000** can include a host **2008** and a memory system **2002** having one or more memory devices **2004** and a memory controller **2006**. Host **2008** can be a processor of an electronic device, such as a central processing unit (CPU), or a system-on-chip (SoC), such as an application

processor (AP). Host **2008** can be configured to send or receive the data to or from memory devices **2004**.

[0159] Memory device **2004** can be any memory devices disclosed herein, such as 3D memory devices **100**, **101**, and **103**, memory devices **200**, **600**, and **800**, and 3D memory devices **700**, **900**, and **1000**. In some implementations, memory device **2004** includes an array of memory cells each including a vertical transistor, as described above in detail.

[0160] Memory controller **2006** is coupled to memory device **2004** and host **2008** and is configured to control memory device **2004**, according to some implementations. Memory controller **2006** can manage the data stored in memory device **2004** and communicate with host **2008**. Memory controller **2006** can be configured to control operations of memory device **2004**, such as read, write, and refresh operations. Memory controller **2006** can also be configured to manage various functions with respect to the data stored or to be stored in memory device **2004** including, but not limited to refresh and timing control, command/request translation, buffer and schedule, and power management. In some implementations, memory controller **2006** is further configured to determine the maximum memory capacity that the computer system can use, the number of memory banks, memory type and speed, memory particle data depth and data width, and other important parameters. Any other suitable functions may be performed by memory controller **2006** as well. Memory controller **2006** can communicate with an external device (e.g., host **2008**) according to a particular communication protocol. For example, memory controller **2006** may communicate with the external device through at least one of various interface protocols, such as a USB protocol, an MMC protocol, a peripheral component interconnection (PCI) protocol, a PCI-express (PCI-E) protocol, an advanced technology attachment (ATA) protocol, a serial-ATA protocol, a parallel-ATA protocol, a small computer small interface (SCSI) protocol, an enhanced small disk interface (ESDI) protocol, an integrated drive electronics (IDE) protocol, a Firewire protocol, etc.

[0161] FIGS. **13A-13M** illustrate a fabrication process for forming a 3D memory device including vertical transistors, according to some aspects of the present disclosure. FIGS. **14A-14M** illustrate a fabrication process for forming another 3D memory device including vertical transistors, according to some aspects of the present disclosure. FIG. **16** illustrates a flowchart of a method **1600** for forming a 3D memory device including vertical transistors, according to some aspects of the present disclosure. Examples of the 3D memory devices depicted in FIGS. **13A-13M** include 3D memory device **700** depicted in FIG. **7A**. Examples of the 3D memory device depicted in FIGS. **14A-14M** include 3D memory device **900** depicted in FIG. **9A**. FIGS. **13A-13M**, **14A-14M**, and **16** will be described together. It is understood that the operations shown in method **1600** are not exhaustive and that other operations can be performed as well before, after, or between any of the illustrated operations. Further, some of the operations may be performed simultaneously, or in a different order than shown in FIG. **16**.

[0162] Referring to FIG. **16**, method **1600** starts at operation **1602**, in which a peripheral circuit is formed on a first substrate. The first substrate can include a silicon substrate. In some implementations, an interconnect layer is formed above the peripheral circuit. The interconnect layer can include a plurality of interconnects in one or more ILD layers.

[0163] As illustrated in FIG. **13H**, a plurality of transistors **1342** are formed on a silicon substrate **1338**. Transistors **1342** can be formed by a plurality of processes including, but not limited to, photolithography, dry/wet etch, thin film deposition, thermal growth, implantation, chemical mechanical polishing (CMP), and any other suitable processes. In some implementations, doped regions are formed in silicon substrate **1338** by ion implantation and/or thermal diffusion, which function, for example, as the source and drain of transistors **1342**. In some implementations, isolation regions (e.g., STIs) are also formed in silicon substrate **1338** by wet/dry etch and thin film deposition. Transistors **1342** can form peripheral circuits **1340** on silicon substrate **1338**.

[0164] As illustrated in FIG. **13H**, an interconnect layer **1344** can be formed above peripheral circuits **1340** having transistors **1342**. Interconnect layer **1344** can include interconnects of MEOL

and/or BEOL in a plurality of ILD layers to make electrical connections with peripheral circuits **1340**. In some implementations, interconnect layer **1344** includes multiple ILD layers and interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1344** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, chemical vapor deposition (CVD), physical vapor deposition (PVD), atomic layer deposition (ALD), electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **13H** can be collectively referred to as interconnect layer **1344**.

[0165] Method **1600** proceeds to operation **1604**, as illustrated in FIG. **16**, in which a first bonding layer is formed above the peripheral circuit (and the interconnect layer). The first bonding layer can include a first bonding contact. As illustrated in FIG. **13H**, a bonding layer **1346** is formed above interconnect layer **1344** and peripheral circuits **1340**. Bonding layer **1346** can include a plurality of bonding contacts **1347** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1344** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1347** can then be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1344** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0166] Method **1600** proceeds to operation **1606**, as illustrated in FIG. **16**, in which a semiconductor body extending vertically from a second substrate is formed. The second substrate can include a silicon substrate. To form the semiconductor body, a word line sandwiched between two dielectric layers is formed above the substrate, an opening extending through the word line and the dielectric layers is formed to expose part of the substrate, and the semiconductor body is epitaxially grown from the exposed part of the substrate in the opening. To form the semiconductor body, a gate dielectric is formed on a sidewall of the opening prior to epitaxially growing the semiconductor body.

[0167] In some implementations, the semiconductor body extending vertically is formed from a first side (e.g., the front side) of the second substrate and surrounded by the gate dielectric. To form the semiconductor body, at operation **1702** in FIG. **17**, a sacrificial layer, a first dielectric layer, a word line, and a second dielectric layer are subsequently formed on the substrate. The sacrificial layer can include silicon nitride, the first and second dielectric layers can include silicon oxide, and the word line can include a metal.

[0168] As illustrated in FIG. **13A**, a sacrificial layer **1304**, a first dielectric layer **1306**, a word line **1308**, and a second dielectric layer **1309** are sequentially formed on a silicon substrate **1302**. In some implementations, silicon nitride, silicon oxide, a metal (e.g., W), and silicon oxide are subsequently deposited onto silicon substrate **1302** using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. It is understood that the materials of first and second dielectric layers **1306** and **1309** may include any suitable dielectric materials other than silicon oxide, and the material of word line **1308** may include any suitable conductive materials other than metals. It is also understood that the sacrificial material of sacrificial layer **1304** is not limited to silicon nitride and may include any suitable sacrificial materials that are different from the materials of first dielectric layer **1306** and silicon substrate **1302**. Silicon substrate **1302** can be intrinsic (i.e., undoped) or doped with a first type of dopant, such as P-type of dopants (e.g., e.g., B or Ga).

[0169] At operation **1704** in FIG. **17**, an opening extending through the sacrificial layer, the first dielectric layer, the word line, and the second dielectric layer is formed to expose part of the substrate. As illustrated in FIG. **13A**, an array of openings **1310** is formed, each of which extends vertically (in the z-direction) through the stack of second dielectric layer **1309**, word line **1308**, first dielectric layer **1306**, and sacrificial layer **1304** to silicon substrate **1302**. As a result, parts of silicon substrate **1302** can be exposed from openings **1310**. In some implementations, a lithography process is performed to pattern the array of openings **1310** using an etch mask (e.g., a photoresist mask), for example, based on the design of word lines and bit lines, and one or more dry etching and/or wet etching processes, such as reactive ion etch (RIE), are performed to etch openings **1310** through second dielectric layer **1309**, word line **1308**, first dielectric layer **1306**, and sacrificial layer **1304** until being stopped by silicon substrate **1302**.

[0170] At operation **1706** in FIG. **17**, a gate dielectric is formed on a sidewall of the opening. As illustrated in FIG. **13B**, gate dielectrics **1318** are formed on sidewalls of openings **1310**, respectively. To form gate dielectrics **1318**, a gate dielectric layer, such as a layer of silicon oxide or high-k dielectric, can be deposited into openings **1310** to cover the sidewall and bottom of each opening **1310** using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The gate dielectric layer can then be partially etched using dry etching and/or wet etching, such as RIE, to remove parts thereof on the bottoms of openings **1310** to still expose parts of silicon substrate **1302** from openings **1310**. The remainder of the gate dielectric layer on the sidewall of opening **1310** can thus become gate dielectric **1318**. Gate dielectric **1318** and part of word line **1308** that is in contact with gate dielectric **1318** can thus become a gate structure of a vertical transistor to be formed.

[0171] At operation **1708** in FIG. **17**, the semiconductor body is epitaxially grown from the exposed part of the substrate over the gate dielectric in the opening. As illustrated in FIG. **13C**, an array of semiconductor bodies **1312** are formed over gate dielectrics **1318** in openings **1310** (shown in FIG. **13B**), respectively. Semiconductor body **1312** can be epitaxially grown from the respective exposed part of silicon substrate **1302** in the respective opening **1310** over the respective gate dielectric **1318**. The fabrication processes for epitaxially growing semiconductor body **1312** can include, but not limited to, vapor-phase epitaxy (VPE), liquid-phase epitaxy (LPE), molecular-beam epitaxy (MPE), or any combinations thereof. The epitaxy can occur upward (toward the positive z-direction) from the exposed parts of silicon substrate **1302** in openings **1310**.

Semiconductor body **1312** thus can have the same material as silicon substrate **1302**, i.e., single crystalline silicon. The same as silicon substrate **1302**, semiconductor body **1312** can be intrinsic (i.e., undoped) or doped with the first type of dopant, such as P-type of dopants (e.g., B or Ga). Depending on the shape of opening **1310**, semiconductor body **1312** can have the same shape as opening **1310**, such as a cuboid shape or a cylinder shape. In some implementations, a planarization process, such as CMP, is performed to remove excessive parts of semiconductor bodies **1312** beyond the top surface of second dielectric layer **1309**. As a result, an array of semiconductor bodies **1312** (e.g., single crystalline silicon bodies) each surrounded by a respective gate dielectric **1318** and extending vertically (in the z-direction) from silicon substrate **1302** through the stack of second dielectric layer **1309**, word line **1308**, first dielectric layer **1306**, and sacrificial layer **1304** is formed thereby, according to some implementations.

[0172] Referring back to FIG. **16**, method **1600** proceeds to operation **1608** in which a first end of the semiconductor body is doped. As illustrated in FIG. **13D**, the exposed upper end of each semiconductor body **1312**, i.e., one of the two ends of semiconductor body **1312** in the vertical direction (the z-direction) that is away from silicon substrate **1302**, is doped to form a source/drain **1321**. In some implementations, an implantation process and/or thermal diffusion process are performed to dope P-type dopants or N-type dopants to the exposed upper ends of semiconductor bodies **1312** to form sources/drains **1321**. In some implementations, a silicide layer is formed on source/drain **1321** by performing a silicidation process at the exposed upper ends of semiconductor

bodies **1312**.

[0173] Method **1600** proceeds to operation **1610**, as illustrated in FIG. **16**, in which a storage unit is formed on the doped first end of the semiconductor body. The storage unit can include a capacitor, a ferroelectric capacitor, or a PCM element. In some implementations, to form a storage unit that is a capacitor, a first electrode is formed on the doped first end of the semiconductor body, a capacitor dielectric is formed on the first electrode, and a second electrode is formed on the capacitor dielectric. In some implementations, an interconnect layer is formed above the word line. The interconnect layer can include a plurality of interconnects in one or more ILD layers.

[0174] As illustrated in FIG. **13E**, one or more ILD layers are formed over the top surface of second dielectric layer **1309**, for example, by depositing dielectrics using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. It is understood that in some examples in which the ILD layers include silicon oxide, the same material as second dielectric layer **1309**, the boundary and interface between the ILD layer and second dielectric layer **1309** may become indistinguishable after the deposition. As illustrated in FIG. **13E**, first electrodes **1324**, capacitor dielectrics **1326**, and second electrodes **1328** are subsequently formed in the ILD layers to form capacitors in contact with semiconductor bodies **1312**. In some implementations, each first electrode **1324** is formed on a respective source/drain **1321**, i.e., the doped upper end of a respective semiconductor body **1312** by patterning and etching an electrode opening aligned with respective source/drain **1321** using lithography and etching processes and depositing conductive materials to fill the electrode opening using thin film deposition processes. Similarly, in some implementations, second electrode **1328** is formed on capacitor dielectrics **1326** by patterning and etching an electrode opening using lithography and etching processes and depositing conductive materials to fill the electrode opening using thin film deposition processes.

[0175] As illustrated in FIG. **13F**, an interconnect layer **1332** can be formed above word line **1320**. Interconnect layer **1332** can include interconnects of MEOL and/or BEOL in a plurality of ILD layers to make electrical connections with word line **1320** and second electrode **1328**. In some implementations, interconnect layer **1332** includes multiple ILD layers and interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1332** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited on second electrode **1328** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **13F** can be collectively referred to as interconnect layer **1332**.

[0176] Method **1600** proceeds to operation **1612**, as illustrated in FIG. **16**, in which a second bonding layer is formed above the semiconductor body (and the interconnect layer). The second bonding layer can include a second bonding contact. As illustrated in FIG. **13F**, a bonding layer **1336** is formed above interconnect layer **1332** and semiconductor bodies **1312**. Bonding layer **1336** can include a plurality of bonding contacts **1337** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1332** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1337** can then be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1332** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0177] Method **1600** proceeds to operation **1614**, as illustrated in FIG. **16**, in which the first

substrate and the second substrate are bonded in a face-to-face manner. The bonding can include hybrid bonding. In some implementations, the first bonding contact is in contact with the second bonding contact at a bonding interface after the bonding. In some implementations, the second substrate is above the first substrate after the bonding. In some implementations, the first substrate is above the second substrate after the bonding.

[0178] As illustrated in FIG. 13G, silicon substrate **1338** and components formed thereon (e.g., transistors **1342** in peripheral circuits **1340**) are flipped upside down, and bonding layer **1346** facing down is bonded with bonding layer **1336** facing up, i.e., in a face-to-face manner, thereby forming a bonding interface **1350**. In some implementations, a treatment process, e.g., a plasma treatment, a wet treatment, and/or a thermal treatment, is applied to the bonding surfaces prior to the bonding. Although not shown FIG. 13G, silicon substrate **1302** and components formed thereon (e.g., semiconductor bodies **1312**) can be flipped upside down, and bonding layer **1336** facing down can be bonded with bonding layer **1346** facing up, i.e., in a face-to-face manner, thereby forming bonding interface **1350**. After the bonding, bonding contacts **1337** in bonding layer **1336** and bonding contacts **1347** in bonding layer **1346** are aligned and in contact with one another, such that semiconductor bodies **1312** can be electrically connected to peripheral circuits **1340** across bonding interface **1350**. It is understood that in the bonded chip, semiconductor bodies **1312** may be either above or below peripheral circuits **1340**. Nevertheless, bonding interface **1350** can be formed vertically between peripheral circuits **1340** and semiconductor bodies **1312** after the bonding.

[0179] Method **1600** proceeds to operation **1616**, as illustrated in FIG. 16, in which the second substrate is removed to expose a second end opposite to the first end of the semiconductor body. In some implementations, to remove the second substrate, the substrate is polished from the second side of the substrate until being stopped by the sacrificial layer. As illustrated in FIG. 13H, silicon substrate **1302** (shown in FIG. 13G) is removed from the backside to expose the upper ends of semiconductor bodies **1312** (used to be the lower ends before flipping over). In some implementations, silicon substrate **1302** is polished from the backside, for example, using a CMP process, until being stopped by sacrificial layer **1304** and the upper ends of semiconductor bodies **1312**.

[0180] Method **1600** proceeds to operation **1618**, as illustrated in FIG. 16, in which part of the semiconductor body is doped from the exposed second end of the semiconductor body. In some implementations, a protrusion of the semiconductor body is formed from the exposed second end of the semiconductor body prior to doping the part of the semiconductor body. The doped part and the another part of the semiconductor body can be in the protrusion of the semiconductor body. In some implementations, part of the protrusion of the semiconductor body is doped.

[0181] To form the protrusion of the semiconductor body and dope the part of the protrusion, at operation **1710** in FIG. 17, part of the gate dielectric is removed, for example, by dry etching and/or wet etching, to expose part of the semiconductor body. As illustrated in FIG. 13I, part of gate dielectric **1318** is removed from the upper end of semiconductor body **1312** to expose part of semiconductor body **1312**. The exposed part of semiconductor body **1312** not surrounded by gate dielectric **1318** may be viewed as a protrusion of semiconductor body **1312**, and the rest of semiconductor body **1312** is still surrounded by gate dielectric **1318** may be viewed as a base of semiconductor body **1312**. In some implementations, a wet etchant (e.g., hydrofluoric acid (HF)) for selectively etching gate dielectric **1318** (e.g., including silicon oxide) against sacrificial layer **1304** (e.g., including silicon nitride) and semiconductor body **1312** (e.g., silicon). The etching rate and/or duration can be controlled to ensure only part of gate dielectric **1318** is removed. In some implementations, the upper end of the remainder of gate dielectric **1318** is not above the bottom surface of sacrificial layer **1304**.

[0182] As illustrated in FIG. 13I, a recess **1352** is formed surrounding the protrusion of semiconductor body **1312** after removing the part of gate dielectric **1318**. In some implementations,

part of the protrusion of semiconductor body **1312** is further removed, for example by dry etching and/or wet etching, to enlarge recess **1352**, i.e., the opening in sacrificial layer **1304**.
[0183] At operation **1712** in FIG. **17**, a sidewall and a top of the exposed part of the semiconductor body are doped. As illustrated in FIG. **13J**, the sidewall and the top of the exposed part (i.e., the protrusion) of semiconductor body **1312** are doped to form a doped region **1325**. In some implementations, an implantation process and/or thermal diffusion process are performed to dope P-type dopants or N-type dopants through recess **1352** to the exposed upper ends of semiconductor bodies **1312** to form doped region **1325**. In some implementations in which silicon substrate **1302** and semiconductor body **1312** is doped with the first type of dopant (e.g., P-type dopants), doped region **1325** is doped with a second type of dopant (e.g., N-type dopants) different from silicon substrate **1302** and semiconductor body **1312**. The implantation process and/or thermal diffusion process can be controlled such that the dopant is limited to the exposed surface, e.g., the sidewall and the top of the protrusion of semiconductor body **1312** and does not diffuse to the entire protrusion. In other words, the protrusion of semiconductor body **1312** can include both doped region **1325** and the remaining portion (either undoped or doped with a different type of dopant) after doping.

[0184] At operation **1714** in FIG. **17**, the doped top of the exposed part of the semiconductor body is removed. In some implementations, to remove the doped top of the exposed part of the semiconductor body, the sacrificial layer is thinned, and the exposed part of the semiconductor body is polished until being stopped by the thinned sacrificial layer.

[0185] As illustrated in FIG. **13J**, sacrificial layer **1304** is thinned, for example, using wet etching and/or dry etching, such that the top surface of thinned sacrificial layer **1304** becomes lower than the doped top of the exposed part (i.e., the protrusion) of semiconductor body **1312**. As illustrated in FIG. **13K**, the doped top of the protrusion of semiconductor body **1312** is removed, leaving the remainder of doped region **1325** on the sidewall of the protrusion to become another source/drain **1323**. The portion of the protrusion of semiconductor body **1312** that is undoped or doped with a different type of dopant can thus be exposed from the upper end. In some implementations, the protrusions of semiconductor bodies **1312** are polished, for example, using a CMP process, to remove part of doped region **1325** (i.e., the doped top of the protrusion) until being stopped by the top surface of thinned sacrificial layer **1304**. As a result, the upper end of the protrusion of semiconductor body **1312** can become flush with the top surface of thinned sacrificial layer **1304**. Source/drain **1323** can be formed on the sidewall, but not the top, of the protrusion of semiconductor body **1312**.

[0186] Accordingly, vertical transistors each having semiconductor body **1312**, sources/drains **1321** and **1323**, gate dielectric **1318**, and the gate electrode (part of word line **1320** in contact with gate dielectric **1318**) are formed thereby, as shown in FIG. **13K**, according to some implementations. As described above, capacitors each having first and second electrodes **1324** and **1328** and capacitor dielectric **1326** are thereby formed as well, and DRAM cells **1380** each having a vertical transistor and a capacitor coupled to the vertical transistor are thereby formed, as shown in FIG. **13K**, according to some implementations.

[0187] Referring back to FIG. **16**, method **1600** proceeds to operation **1620** in which a bit line in contact with the doped part of the semiconductor body is formed. In some implementations, the bit line is in contact with the doped part of the protrusion of the semiconductor body. As illustrated in FIG. **13L**, bit line **1334** is formed in recess **1352** (shown in FIG. **13K**) to be in contact with source/drain **1323**. The upper end of bit line **1334** can be lower than the upper end of the protrusion of semiconductor body **1312**, such that bit line **1334** does not cover the exposed upper end of the portion of the protrusion that is undoped or doped with a different type of dopant. To form bit line **1334**, in some implementations, sacrificial layer **1304** (shown in FIG. **13K**) is first removed, for example, using wet etching and/or dry etching, and a conductive layer, such as a metal (e.g., W) layer, is deposited using by one or more thin film deposition processes including, but not limited to,

CVD, PVD, ALD, or any combination thereof. The thickness of the conductive layer can be controlled to be smaller than the height of the protrusion of semiconductor body **1312** by controlling the deposition rate and/or duration or etching back the conductive layer after deposition. The conductive layer can then be patterned using lithography and dry etching and/or wet etching processes to form a plurality of bit lines **1334** each surrounding and contacting a respective source/drain **1323**.

[0188] As illustrated in FIG. **13L**, a dielectric layer **1354** is formed between and above bit lines **1334** to electrically insulate bit lines **1334**. Dielectric layer **1354** can be formed by depositing a layer of dielectric material, such as silicon oxide, using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof to cover bit lines **1334**. In some implementations, a planarization process, such as CMP, is performed to remove excessive dielectric material covering the upper ends of the protrusions of semiconductor bodies **1312**, such that the upper ends of the protrusions are flush with the top surface of dielectric layer **1354** and thus, still remain exposed.

[0189] Method **1600** proceeds to operation **1622**, as illustrated in FIG. **16**, in which a body line in contact with another part of the semiconductor body is formed. In some implementations, the body line is in contact with the another part of the protrusion of the semiconductor body that is undoped or doped with a different type of dopant from the doped part.

[0190] To form the body line, at operation **1716** in FIG. **17**, a polysilicon layer in contact with the top of the exposed part (the protrusion) of the semiconductor body is formed. As illustrated in FIG. **13M**, a polysilicon layer **1358** is formed in contact with the top of the protrusion of semiconductor body **1312**. That is, the exposed upper end of the portion of the protrusion that is undoped or doped with a different type of dopant can be in contact with polysilicon layer **1358**. Polysilicon layer **1358** can be formed by depositing a layer of polysilicon using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof on dielectric layer **1354** and the exposed upper ends of the portions of semiconductor bodies **1312**. As shown in FIG. **13M**, because the upper end of bit line **1334** is lower than the upper end of the protrusion of semiconductor bodies **1312** and is covered with dielectric layer **1354**, bit line **1334** is electrically insulated from polysilicon layer **1358** by dielectric layer **1354**. Since polysilicon layer **1358** and semiconductor body **1312** can have the same semiconductor material, such as silicon, the contact resistance therebetween can be reduced.

[0191] At operation **1718**, a metal layer in contact with the polysilicon layer is formed. As illustrated in FIG. **13M**, a metal layer **1360** is formed in contact with polysilicon layer **1358** to reduce the sheet resistance. Metal layer **1360** can be formed by depositing a layer of metal, such as W, using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof on polysilicon layer **1358**. A body line **1356** including polysilicon layer **1358** and metal layer **1360** is thereby formed to be in contact with the portions of semiconductor bodies **1312** that are undoped or doped with a different type of dopant, according to some implementations. In some implementations, a body line contact **1362** is formed extending through dielectric layer **1354** and other ILD layers, for example, by wet/dry etching processes, followed by depositing conductive materials. Body line contact **1362** can be in contact with body line **1356** and the interconnects in interconnect layer **1332**.

[0192] Although not shown, it is understood that a pad-out interconnect layer may be formed above body line **1356**. The pad-out interconnect layer may include interconnects, such as pad contacts, formed in one or more ILD layers. The pad contacts may include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can include dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof. It is also understood that in some examples, the pad-out interconnect layer may be formed on the backside of silicon substrate **1338**, and through substrate contacts (TSC) may be formed extending vertically through silicon substrate

1338. Silicon substrate **1338** may be thinned prior to forming the pad-out interconnect layer and TSCs, for example, using planarization processes and/or etching processes.

[0193] As described above, FIGS. **13A-13M** and **17** illustrate a fabrication process and method of forming DRAM cells **1380** having vertical transistors corresponding to vertical transistors **726** in FIG. **7A**. In some implementations as shown in FIGS. **14A-14M** and **18**, a fabrication process and method of forming DRAM cells **1480** having vertical transistors corresponding to vertical transistors **926** in FIG. **9A** is illustrated.

[0194] Referring to FIG. **16**, method **1600** starts at operation **1602**, in which a peripheral circuit is formed on a first substrate. The first substrate can include a silicon substrate. In some implementations, an interconnect layer is formed above the peripheral circuit. The interconnect layer can include a plurality of interconnects in one or more ILD layers.

[0195] As illustrated in FIG. **14H**, a plurality of transistors **1442** are formed on a silicon substrate **1438**. Transistors **1442** can be formed by a plurality of processes including, but not limited to, photolithography, dry/wet etch, thin film deposition, thermal growth, implantation, CMP, and any other suitable processes. In some implementations, doped regions are formed in silicon substrate **1438** by ion implantation and/or thermal diffusion, which function, for example, as the source and drain of transistors **1442**. In some implementations, isolation regions (e.g., STIs) are also formed in silicon substrate **1438** by wet/dry etch and thin film deposition. Transistors **1442** can form peripheral circuits **1440** on silicon substrate **1438**.

[0196] As illustrated in FIG. **14H**, an interconnect layer **1444** can be formed above peripheral circuits **1440** having transistors **1442**. Interconnect layer **1444** can include interconnects of MEOL and/or BEOL in a plurality of ILD layers to make electrical connections with peripheral circuits **1440**. In some implementations, interconnect layer **1444** includes multiple ILD layers and interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1444** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **14H** can be collectively referred to as interconnect layer **1444**.

[0197] Method **1600** proceeds to operation **1604**, as illustrated in FIG. **16**, in which a first bonding layer is formed above the peripheral circuit (and the interconnect layer). The first bonding layer can include a first bonding contact. As illustrated in FIG. **14H**, a bonding layer **1446** is formed above interconnect layer **1444** and peripheral circuits **1440**. Bonding layer **1446** can include a plurality of bonding contacts **1447** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1444** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1447** then can be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1444** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0198] Method **1600** proceeds to operation **1606**, as illustrated in FIG. **16**, in which a semiconductor body extending vertically from a second substrate is formed. The second substrate can include a silicon substrate. To form the semiconductor body, a word line sandwiched between two dielectric layers is formed above the substrate, an opening extending through the word line and the dielectric layers is formed to expose part of the substrate, and the semiconductor body is epitaxially grown from the exposed part of the substrate in the opening. To form the semiconductor

body, a gate dielectric is formed on a sidewall of the opening prior to epitaxially growing the semiconductor body.

[0199] In some implementations, the semiconductor body extending vertically is formed from a first side (e.g., the front side) of the second substrate. To form the semiconductor body, at operation **1802** in FIG. **18**, a first dielectric layer, a word line, and a second dielectric layer are subsequently formed on the substrate. The first and second dielectric layers can include silicon oxide, and the word line can include a metal.

[0200] As illustrated in FIG. **14A**, a first dielectric layer **1406**, a word line **1408**, and a second dielectric layer **1409** are sequentially formed on a silicon substrate **1402**. In some implementations, silicon oxide, a metal (e.g., W), and silicon oxide are subsequently deposited onto silicon substrate **1402** using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. It is understood that the materials of first and second dielectric layers **1406** and **1409** may include any suitable dielectric materials other than silicon oxide, and the material of word line **1408** may include any suitable conductive materials other than metals. Silicon substrate **1402** can be intrinsic (i.e., undoped) or doped with a first type of dopant, such as P-type of dopants (e.g., e.g., B or Ga).

[0201] At operation **1804** in FIG. **18**, an opening extending through the first dielectric layer, the word line, and the second dielectric layer is formed to expose part of the substrate. As illustrated in FIG. **14A**, an array of openings **1410** is formed, each of which extends vertically (in the z-direction) through the stack of second dielectric layer **1409**, word line **1408**, and first dielectric layer **1406** to silicon substrate **1402**. As a result, parts of silicon substrate **1402** can be exposed from openings **1410**. In some implementations, a lithography process is performed to pattern the array of openings **1410** using an etch mask (e.g., a photoresist mask), for example, based on the design of word lines and bit lines, and one or more dry etching and/or wet etching processes, such as RIE, are performed to etch openings **1410** through second dielectric layer **1409**, word line **1408**, and first dielectric layer **1406** until being stopped by silicon substrate **1402**.

[0202] At operation **1806** in FIG. **18**, a gate dielectric is formed on a sidewall of the opening. As illustrated in FIG. **14B**, gate dielectrics **1418** are formed on sidewalls of openings **1410**, respectively. To form gate dielectrics **1418**, a gate dielectric layer, such as a layer of silicon oxide or high-k dielectric, can be deposited into openings **1410** to cover the sidewall and bottom of each opening **1410** using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The gate dielectric layer can then be partially etched using dry etching and/or wet etching, such as RIE, to remove parts thereof on the bottoms of openings **1410** to still expose parts of silicon substrate **1402** from openings **1410**. The remainder of the gate dielectric layer on the sidewall of opening **1410** can thus become gate dielectric **1418**. Gate dielectric **1418** and part of word line **1408** that is in contact with gate dielectric **1418** can thus become a gate structure of a vertical transistor to be formed.

[0203] At operation **1808** in FIG. **18**, the semiconductor body is epitaxially grown from the exposed part of the substrate over the gate dielectric in the opening. As illustrated in FIG. **14C**, an array of semiconductor bodies **1412** are formed over gate dielectrics **1418** in openings **1410** (shown in FIG. **14B**), respectively. Semiconductor body **1412** can be epitaxially grown from the respective exposed part of silicon substrate **1402** in the respective opening **1410** over the respective gate dielectric **1418**. The fabrication processes for epitaxially growing semiconductor body **1412** can include, but not limited to, VPE, LPE, MPE, or any combinations thereof. The epitaxy can occur upward (toward the positive z-direction) from the exposed parts of silicon substrate **1402** in openings **1410**. Semiconductor body **1412** thus can have the same material as silicon substrate **1402**, i.e., single crystalline silicon. The same as silicon substrate **1402**, semiconductor body **1412** can be intrinsic (i.e., undoped) or doped with the first type of dopant, such as P-type of dopants (e.g., e.g., B or Ga). Depending on the shape of opening **1410**, semiconductor body **1412** can have the same shape as opening **1410**, such as a cuboid shape or a cylinder shape. In some

implementations, a planarization process, such as CMP, is performed to remove excessive parts of semiconductor bodies **1412** beyond the top surface of second dielectric layer **1409**. As a result, an array of semiconductor bodies **1412** (e.g., single crystalline silicon bodies) each surrounded by a respective gate dielectric **1418** and extending vertically (in the z-direction) from silicon substrate **1402** through the stack of second dielectric layer **1409**, word line **1408**, and first dielectric layer **1406** is formed thereby, according to some implementations.

[0204] Referring back to FIG. **16**, method **1600** proceeds to operation **1608** in which a first end of the semiconductor body is doped. As illustrated in FIG. **14D**, the exposed upper end of each semiconductor body **1412**, i.e., one of the two ends of semiconductor body **1412** in the vertical direction (the z-direction) that is away from silicon substrate **1402**, is doped to form a source/drain **1421**. In some implementations, an implantation process and/or thermal diffusion process are performed to dope P-type dopants or N-type dopants to exposed upper ends of semiconductor bodies **1412** to form sources/drains **1421**. In some implementations, a silicide layer is formed on source/drain **1421** by performing a silicidation process at the exposed upper ends of semiconductor bodies **1412**.

[0205] Method **1600** proceeds to operation **1610**, as illustrated in FIG. **16**, in which a storage unit is formed on the doped first end of the semiconductor body. The storage unit can include a capacitor, a ferroelectric capacitor, or a PCM element. In some implementations, to form a storage unit that is a capacitor, a first electrode is formed on the doped first end of the semiconductor body, a capacitor dielectric is formed on the first electrode, and a second electrode is formed on the capacitor dielectric. In some implementations, an interconnect layer is formed above the word line. The interconnect layer can include a plurality of interconnects in one or more ILD layers.

[0206] As illustrated in FIG. **14E**, one or more ILD layers are formed over the top surface of second dielectric layer **1409**, for example, by depositing dielectrics using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. It is understood that in some examples in which the ILD layers include silicon oxide, the same material as second dielectric layer **1409**, the boundary and interface between the ILD layer and second dielectric layer **1409** may become indistinguishable after the deposition. As illustrated in FIG. **14E**, first electrodes **1424**, capacitor dielectrics **1426**, and second electrodes **1428** are subsequently formed in the ILD layers to form capacitors in contact with semiconductor bodies **1412**. In some implementations, each first electrode **1424** is formed on a respective source/drain **1421**, i.e., the doped upper end of a respective semiconductor body **1412** by patterning and etching an electrode opening aligned with respective source/drain **1421** using lithography and etching processes and depositing conductive materials to fill the electrode opening using thin film deposition processes. Similarly, in some implementations, second electrode **1428** is formed on capacitor dielectrics **1426** by patterning and etching an electrode opening using lithography and etching processes and depositing conductive materials to fill the electrode opening using thin film deposition processes.

[0207] As illustrated in FIG. **14F**, an interconnect layer **1432** can be formed above word line **1420**. Interconnect layer **1432** can include interconnects of MEOL and/or BEOL in a plurality of ILD layers to make electrical connections with word line **1420** and second electrode **1428**. In some implementations, interconnect layer **1432** includes multiple ILD layers and interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1432** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited on second electrode **1428** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **14F** can be collectively referred to as interconnect layer **1432**.

[0208] Method **1600** proceeds to operation **1612**, as illustrated in FIG. **16**, in which a second bonding layer is formed above the semiconductor body (and the interconnect layer). The second bonding layer can include a second bonding contact. As illustrated in FIG. **14F**, a bonding layer **1436** is formed above interconnect layer **1432** and semiconductor bodies **1412**. Bonding layer **1436** can include a plurality of bonding contacts **1437** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1432** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1437** can then be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1432** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0209] Method **1600** proceeds to operation **1614**, as illustrated in FIG. **16**, in which the first substrate and the second substrate are bonded in a face-to-face manner. The bonding can include hybrid bonding. In some implementations, the first bonding contact is in contact with the second bonding contact at a bonding interface after the bonding. In some implementations, the second substrate is above the first substrate after the bonding. In some implementations, the first substrate is above the second substrate after the bonding.

[0210] As illustrated in FIG. **14G**, silicon substrate **1438** and components formed thereon (e.g., transistors **1442** in peripheral circuits **1440**) are flipped upside down, and bonding layer **1446** facing down is bonded with bonding layer **1436** facing up, i.e., in a face-to-face manner, thereby forming a bonding interface **1450**. In some implementations, a treatment process, e.g., a plasma treatment, a wet treatment, and/or a thermal treatment, is applied to the bonding surfaces prior to the bonding. Although not shown FIG. **14G**, silicon substrate **1402** and components formed thereon (e.g., semiconductor bodies **1412**) can be flipped upside down, and bonding layer **1436** facing down can be bonded with bonding layer **1446** facing up, i.e., in a face-to-face manner, thereby forming bonding interface **1450**. After the bonding, bonding contacts **1437** in bonding layer **1436** and bonding contacts **1447** in bonding layer **1446** are aligned and in contact with one another, such that semiconductor bodies **1412** can be electrically connected to peripheral circuits **1440** across bonding interface **1450**. It is understood that in the bonded chip, semiconductor bodies **1412** may be either above or below peripheral circuits **1440**. Nevertheless, bonding interface **1450** can be formed vertically between peripheral circuits **1440** and semiconductor bodies **1412** after the bonding.

[0211] Method **1600** proceeds to operation **1616**, as illustrated in FIG. **16**, in which the second substrate is removed to expose a second end opposite to the first end of the semiconductor body. In some implementations, to remove the second substrate, the substrate is polished from the second side of the substrate until being stopped by the first dielectric layer. As illustrated in FIG. **14H**, silicon substrate **1402** (shown in FIG. **14G**) is removed from the backside to expose the upper ends of semiconductor bodies **1412** (used to be the lower ends before flipping over). In some implementations, silicon substrate **1402** is polished from the backside, for example, using a CMP process, until being stopped by first dielectric layer **1406** and the upper ends of semiconductor bodies **1412**.

[0212] Method **1600** proceeds to operation **1618**, as illustrated in FIG. **16**, in which part of the semiconductor body is doped from the exposed second end of the semiconductor body. In some implementations, a protrusion of the semiconductor body is formed from the exposed second end of the semiconductor body prior to doping the part of the semiconductor body. The doped part and the another part of the semiconductor body can be in the protrusion of the semiconductor body. In some implementations, part of the protrusion of the semiconductor body is doped.

[0213] To form the protrusion of the semiconductor body and dope the part of the protrusion, at

operation **1810** in FIG. **18**, an etch mask covering part of the exposed first end of the semiconductor body is formed. As illustrated in FIG. **14I**, an etch mask **1451** is formed on first dielectric layer **1406**. Etch mask **1451** can be patterned to cover part of the exposed upper end of semiconductor body **1412**, leaving the remaining part of the exposed upper end of semiconductor body **1412** uncovered. In some implementations, a layer of etch mask material, such as carbon, photoresist, etc., is deposited on first dielectric layer **1406** and the exposed upper ends of semiconductor bodies **1412** using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The layer of etch mask material can then be patterned to form openings therethrough each aligned with part of the upper end of a respective semiconductor body **1412** using lithography and dry etching and/or wet etching, as shown in FIG. **14I**. Each opening through etch mask **1451** is patterned to expose part of the upper end of a respective semiconductor body **1412**, leaving the remaining part of the upper end of semiconductor body **1412** still being covered by etch mask **1451**.

[0214] At operation **1812** in FIG. **18**, part of the semiconductor body is removed from an uncovered part of the exposed first end of the semiconductor body to expose the sidewall of the remainder of the semiconductor body. As illustrated in FIG. **14I**, part of semiconductor body **1412** and part of gate dielectric **1418** that are not covered by etch mask **1451** are removed, for example, using dry etching and/or wet etching, from the upper end thereof to form a recess **1452**. Recess **1452** can expose part of semiconductor body **1412** that has a sidewall not in contact with gate dielectric **1418** as shown in FIG. **14I**. The exposed part of semiconductor body **1412** not fully surrounded by gate dielectric **1418** may be viewed as a protrusion of semiconductor body **1412**, and the rest of semiconductor body **1412** is still fully surrounded by gate dielectric **1418** may be viewed as a base of semiconductor body **1412**. In some implementations, an RIE process is performed through the openings of etch mask **1451** to etch the uncovered parts of semiconductor body **1412** and gate dielectric **1418**. The etching rate and/or duration can be controlled to ensure only parts of gate dielectric **1418** and semiconductor body **1412** are removed. One or some sides, but not all sides, of the remaining protrusion of semiconductor body **1412** are still in contact with gate dielectric **1418**, while the rest side(s) of the protrusion are exposed from recess **1452** and are not in contact with gate dielectric **1418**, according to some implementations.

[0215] At operation **1814** in FIG. **18**, a sidewall of a remainder of the semiconductor body is doped. As illustrated in FIG. **14J**, the sidewall of the remainder (e.g., the protrusion) of semiconductor body **1412** is doped to form another source/drain **1423**. In some implementations, an implantation process and/or thermal diffusion process are performed to dope P-type dopants or N-type dopants through recess **1452** to the exposed upper ends of semiconductor bodies **1412** to form a doped region, i.e., source/drain **1423**. In some implementations in which silicon substrate **1402** and semiconductor body **1412** is doped with the first type of dopant (e.g., P-type dopants), source/drain **1423** is doped with a second type of dopant (e.g., N-type dopants) different from silicon substrate **1402** and semiconductor body **1412**. The implantation process and/or thermal diffusion process can be controlled such that the dopant is limited to the exposed surface, e.g., the sidewall of the protrusion of semiconductor body **1412** and does not diffuse to the entire protrusion. In other words, the protrusion of semiconductor body **1412** can include both source/drain **1423** and the remaining portion (either undoped or doped with a different type of dopant) after doping. As shown in FIG. **14I**, since the top of the protrusion of semiconductor body **1412** remains covered by etch mask **1451** during the doping, the top of the protrusion remains undoped or doped with a different type of dopant. That is, source/drain **1423** can be formed on one or some sidewalls, but not the top, of the protrusion of semiconductor body **1412**.

[0216] Accordingly, vertical transistors each having semiconductor body **1412**, sources/drains **1421** and **1423**, gate dielectric **1418**, and the gate electrode (part of word line **1420** in contact with gate dielectric **1418**) are formed thereby, as shown in FIG. **14J**, according to some implementations. As described above, capacitors each having first and second electrodes **1424** and **1428** and capacitor

dielectric **1426** are thereby formed as well, and DRAM cells **1480** each having a vertical transistor and a capacitor coupled to the vertical transistor are thereby formed, as shown in FIG. **14J**, according to some implementations.

[0217] At operation **1816** in FIG. **18**, the etch mask is removed to expose a top of the remainder of the semiconductor body. As illustrated in FIG. **14K**, etch mask **1451** (shown in FIG. **14J**) is removed, for example, using wet etching and/or dry etching, to expose the top of the protrusion of semiconductor body **1412** as well as first dielectric layer **1406**.

[0218] Referring back to FIG. **16**, method **1600** proceeds to operation **1620** in which a bit line in contact with the doped part of the semiconductor body is formed. In some implementations, the bit line is in contact with the doped sidewall of the remainder of the semiconductor body. As illustrated in FIG. **14K**, bit line **1434** is formed in recess **1452** to be in contact with source/drain **1423**. The upper end of bit line **1434** can be lower than the upper end of the protrusion of semiconductor body **1412**, such that bit line **1434** does not cover the exposed upper end of the portion of the protrusion that is undoped or doped with a different type of dopant. To form bit line **1434**, in some implementations, a conductive layer, such as a metal (e.g., W) layer, is deposited using by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof to partially fill recess **1452**. The thickness of bit line **1434** can be controlled to be smaller than the height of the protrusion of semiconductor body **1412** by controlling the deposition rate and/or duration. In some implementations, the conductive layer fully fills recess **1452**, and the excessive conductive layer is removed using CMP, followed by etching back the conductive layer in recess **1452** to control the thickness of resulting bit line **1434** to be smaller than the height of the protrusion of semiconductor body **1412**.

[0219] As illustrated in FIG. **14L**, a dielectric layer **1454** is formed over bit line **1434** in recess **1452** (shown in FIG. **14K**) to electrically insulate bit lines **1434**. Dielectric layer **1454** can be formed by depositing a layer of dielectric material, such as silicon oxide, to fill recesses **1452** using by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. In some implementations, a planarization process, such as CMP, is performed to remove excessive dielectric material covering the upper ends of the protrusions of semiconductor bodies **1412**, such that the upper ends of the protrusions are flush with the top surface of dielectric layer **1454** and thus, still remain exposed.

[0220] Method **1600** proceeds to operation **1622**, as illustrated in FIG. **16**, in which a body line in contact with another part of the semiconductor body is formed. In some implementations, the body line is in contact with the another part of the remainder of the semiconductor body.

[0221] To form the body line, at operation **1818** in FIG. **18**, a polysilicon layer in contact with the top of the remainder (the protrusion) of the semiconductor body is formed. As illustrated in FIG. **14M**, a polysilicon layer **1458** is formed in contact with the top of the protrusion of semiconductor body **1412**. That is, the exposed upper end of the protrusion can be in contact with polysilicon layer **1458**. Polysilicon layer **1458** can be formed by depositing a layer of polysilicon using by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof on dielectric layer **1454** and the exposed upper ends of semiconductor bodies **1412**. As shown in FIG. **14M**, because the upper end of bit line **1434** is lower than the upper end of the protrusion of semiconductor bodies **1412** and is covered with dielectric layer **1454**, bit line **1434** is electrically insulated from polysilicon layer **1458** by dielectric layer **1454**. Since polysilicon layer **1458** and semiconductor body **1412** can have the same semiconductor material, such as silicon, the contact resistance therebetween can be reduced.

[0222] At operation **1820**, a metal layer in contact with the polysilicon layer is formed. As illustrated in FIG. **14M**, a metal layer **1460** is formed in contact with polysilicon layer **1458** to reduce the sheet resistance. Metal layer **1460** can be formed by depositing a layer of metal, such as W, using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof on polysilicon layer **1458**. A body line **1456** including

polysilicon layer **1458** and metal layer **1460** is thereby formed to be in contact with the portions of semiconductor bodies **1412** that are undoped or doped with a different type of dopant, according to some implementations. In some implementations, a body line contact **1462** is formed extending through ILD layers, for example, by wet/dry etching processes, followed by depositing conductive materials. Body line contact **1462** can be in contact with body line **1456** and the interconnects in interconnect layer **1432**.

[0223] Although not shown, it is understood that a pad-out interconnect layer may be formed above body line **1456**. The pad-out interconnect layer may include interconnects, such as pad contacts, formed in one or more ILD layers. The pad contacts may include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can include dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof. It is also understood that in some examples, the pad-out interconnect layer may be formed on the backside of silicon substrate **1438**, and TSCs may be formed extending vertically through silicon substrate **1438**. Silicon substrate **1438** may be thinned prior to forming the pad-out interconnect layer and TSCs, for example, using planarization processes and/or etching processes.

[0224] FIGS. **15A-15E** illustrate a fabrication process for forming a 3D memory device including vertical transistors and stacked storage units, according to some aspects of the present disclosure. FIG. **19** illustrates a flowchart of a method **1900** for forming a 3D memory device including vertical transistors and stacked storage units, according to some aspects of the present disclosure. Examples of the 3D memory devices depicted in FIGS. **15A-15E** and **19** include 3D memory device **1000** depicted in FIG. **10A**. FIGS. **15A-15E** and **19** will be described together. It is understood that the operations shown in method **1900** are not exhaustive and that other operations can be performed as well before, after, or between any of the illustrated operations. Further, some of the operations may be performed simultaneously, or in a different order than shown in FIG. **19**.

[0225] Referring to FIG. **19**, method **1900** starts at operation **1902**, in which a peripheral circuit is formed on a first substrate. The first substrate can include a silicon substrate. In some implementations, an interconnect layer is formed above the peripheral circuit. The interconnect layer can include a plurality of interconnects in one or more ILD layers.

[0226] As illustrated in FIG. **15D**, a plurality of transistors **1542** are formed on a silicon substrate **1538**. Transistors **1542** can be formed by a plurality of processes including, but not limited to, photolithography, dry/wet etch, thin film deposition, thermal growth, implantation, CMP, and any other suitable processes. In some implementations, doped regions are formed in silicon substrate **1538** by ion implantation and/or thermal diffusion, which function, for example, as the source and drain of transistors **1542**. In some implementations, isolation regions (e.g., ST Is) are also formed in silicon substrate **1538** by wet/dry etch and thin film deposition. Transistors **1542** can form peripheral circuits **1540** on silicon substrate **1538**.

[0227] As illustrated in FIG. **15D**, an interconnect layer **1544** can be formed above peripheral circuits **1540** having transistors **1542**. Interconnect layer **1544** can include interconnects of MEOL and/or BEOL in a plurality of ILD layers to make electrical connections with peripheral circuits **1540**. In some implementations, interconnect layer **1544** includes multiple ILD layers and interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1544** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **15D** can be collectively referred to as interconnect layer **1544**.

[0228] Method **1900** proceeds to operation **1904**, as illustrated in FIG. **19**, in which a first bonding

layer is formed above the peripheral circuit (and the interconnect layer). The first bonding layer can include a first bonding contact. As illustrated in FIG. 15D, a bonding layer **1546** is formed above interconnect layer **1544** and peripheral circuits **1540**. Bonding layer **1546** can include a plurality of bonding contacts **1547** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1544** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1547** can then be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1544** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0229] Method **1900** proceeds to operation **1906**, as illustrated in FIG. 19, in which a semiconductor body extending vertically from a first side (e.g., the front side) of a second substrate is formed. The second substrate can include a silicon substrate. To form the semiconductor body, a word line sandwiched between two dielectric layers is formed above the substrate, an opening extending through the word line and the dielectric layers is formed to expose part of the substrate, and the semiconductor body is epitaxially grown from the exposed part of the substrate in the opening. To form the semiconductor body, a gate dielectric is formed on a sidewall of the opening prior to epitaxially growing the semiconductor body.

[0230] As illustrated in FIG. 15A, an array of semiconductor bodies **1512** each extending vertically from a silicon substrate **1502** is formed. Semiconductor body **1512** can be surrounded by a gate dielectric **1518** and extend vertically through a word line **1508** sandwiched between dielectric layers **1506** and **1509**. The fabrication process for forming semiconductor body **1512** and gate dielectric **1518** may be the same as the fabrication process described above with respect to semiconductor body **1312** or **1412** and gate dielectric **1318** or **1418** and thus, are not repeated.

[0231] Method **1900** proceeds to operation **1908**, as illustrated in FIG. 19, in which a first end of the semiconductor body is doped. As illustrated in FIG. 15A, the upper end of each semiconductor body **1512**, i.e., one of the two ends of semiconductor body **1512** in the vertical direction (the z-direction) that is away from silicon substrate **1502**, is doped to form a source/drain **1521**. In some implementations, an implantation process and/or thermal diffusion process are performed to dope P-type dopants or N-type dopants to the upper ends of semiconductor bodies **1512** to form sources/drains **1521**. In some implementations, a silicide layer is formed on source/drain **1521** by performing a silicidation process at the upper ends of semiconductor bodies **1512**.

[0232] Method **1900** proceeds to operation **1910**, as illustrated in FIG. 19, in which interleaved dielectric layers and conductive layers are formed above the semiconductor body. In some implementations, to form the dielectric layers and conductive layers, the dielectric layers and the conductive layers are alternately deposited. In some implementations, a staircase structure is formed at the edges of the dielectric layers and the conductive layers.

[0233] As illustrated in FIG. 15A, a plurality of interleaved dielectric layers **1524** and conductive layers **1522** are formed above semiconductor bodies **1512**. In some implementations, dielectric layers **1524** and conductive layers **1522** are alternately deposited using one or more thin film deposition processes including, but not limited to, PVD, CVD, ALD, or any combination thereof. In some implementations, dielectric layer **1524** includes silicon oxide, and conductive layer **1522** includes a metal, such as W. In some implementations, electrode contacts **1519** are formed prior to the formation of dielectric layers **1524** and conductive layers **1522**. Each electrode contact **1519** can be in contact with source/drain **1521** of a respective semiconductor body **1512**. To form electrode contact **1519**, a contact hole can be aligned with a corresponding semiconductor body **1512** and etched through ILD layers to expose source/drain **1521**, and a conductive material can be deposited to fill the contact hole using one or more thin film deposition processes including, but not

limited to, PVD, CVD, ALD, or any combination thereof.

[0234] As illustrated in FIG. 15A, a staircase structure **1526** is formed at the edges of interleaved dielectric layers **1524** and conductive layers **1522**. Staircase structure **1526** can be formed by the so-called “trim-etch” processes, which, in each cycle, trims (e.g., etching incrementally and inwardly, often from all directions) a patterned photoresist layer, followed by etching the exposed portions of interleaved dielectric layers **1524** and conductive layers **1522** using the trimmed photoresist layer as an etch mask to form one step/level of staircase structure **1526**. The process can be repeated until all the steps/levels of staircase structure **1526** are formed.

[0235] Method **1900** proceeds to operation **1912**, as illustrated in FIG. 19, in which an electrode layer including a conductive material and coupled to a first end of the semiconductor body and a storage layer over the electrode layer are formed. The electrode layer and the storage layer can extend vertically through the dielectric layers and the conductive layers. In some implementations, to form the electrode layer and the storage layer, an opening extending through the dielectric layers and the conductive layers is formed, the storage layer is deposited on a sidewall of the opening, and the electrode layer is formed over the storage layer in the opening. The storage layer can include a ferroelectric material, and the electrode layer can include a metal.

[0236] As illustrated in FIG. 15B, an array of openings **1528** are formed each extending vertically through interleaved dielectric layers **1524** and conductive layers **1522**. Each opening **1528** can expose a respective electrode contact **1519** or source/drain **1521** of a respective semiconductor body **1512** if electrode contact **1519** is not formed. Opening **1528** can be formed by first patterning an etch mask (not shown) with openings aligned with electrode contacts **1519** or sources/drains **1521** using lithography, followed by dry etching/and or wet etching through interleaved dielectric layers **1524** and conductive layers **1522**, such as deep reactive ion etch (DRIE), which can be stopped at electrode contact **1519** or source/drain **1521**.

[0237] As illustrated in FIG. 15C, opening **1528** (shown in FIG. 15B) is filled with a storage layer **1529** and an electrode layer **1530**. Electrode layer **1530** can include a conductive material, such as a metal. In some implementations, storage layer **1529** is first formed on the sidewall of opening **1528** by depositing a ferroelectric material on the sidewall and the bottom of opening **1528** using one or more thin film deposition processes including, but not limited to ALD, CVD, PVD, or any combination thereof, followed by dry etching and/or wet etching to remove the ferroelectric material that is deposited on the bottom of opening **1528**. Electrode layer **1530** can then be formed over storage layer **1529** by depositing a metal, such as W, to fill the remaining space of opening **1528** using one or more thin film deposition processes including, but not limited to ALD, CVD, PVD, or any combination thereof. The bottom of electrode layer **1530** can be in contact with electrode contact **1519** or source/drains **1521**, such that electrode layer **1530** can be coupled to the upper end of semiconductor body **1512**, and storage layer **1529** can be formed over electrode layer **1530** and in contact with conductive layers **1522**. Both electrode layer **1530** and storage layer **1529** can extend vertically through interleaved dielectric layers **1524** and conductive layers **1522**. Electrode layer **1530**, storage layer **1529**, and conductive layers **1522** can thus form vertically stacked storage units, such as ferroelectric capacitors.

[0238] In some implementations, an interconnect layer is formed above the word line. The interconnect layer can include a plurality of interconnects in one or more ILD layers. In some implementations, to form the interconnect layer, a plurality of contacts in contact with the conductive layers, respectively, at the staircase structure are formed.

[0239] As illustrated in FIG. 15D, an interconnect layer **1432** can be formed above word line **1520**. Interconnect layer **1532** can include interconnects of MEOL and/or BEOL in a plurality of ILD layers to make electrical connections with word line **1520** and conductive layers **1522**. The interconnects can include a word line contact **1535** in contact with word line **1508** and plate line contacts **1533** each in contact with a respective one of conductive layers **1522** at staircase structure **1526**. In some implementations, interconnect layer **1532** includes multiple ILD layers and

interconnects therein formed in multiple processes. For example, the interconnects in interconnect layers **1532** can include conductive materials deposited by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, electroplating, electroless plating, or any combination thereof. Fabrication processes to form the interconnects can also include photolithography, CMP, wet/dry etch, or any other suitable processes. The ILD layers can include dielectric materials deposited using one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. The ILD layers and interconnects illustrated in FIG. **15D** can be collectively referred to as interconnect layer **1532**.

[0240] Method **1900** proceeds to operation **1914**, as illustrated in FIG. **19**, in which a second bonding layer is formed above the dielectric layers and the conductive layers (and the interconnect layer). The second bonding layer can include a second bonding contact. As illustrated in FIG. **15D**, a bonding layer **1536** is formed above interconnect layer **1532** and interleaved dielectric layers **1524** and conductive layers **1522**. Bonding layer **1536** can include a plurality of bonding contacts **1537** surrounded by dielectrics. In some implementations, a dielectric layer (e.g., ILD layer) is deposited on the top surface of interconnect layer **1532** by one or more thin film deposition processes including, but not limited to, CVD, PVD, ALD, or any combination thereof. Bonding contacts **1537** can then be formed through the dielectric layer and in contact with the interconnects in interconnect layer **1532** by first patterning contact holes through the dielectric layer using patterning process (e.g., photolithography and dry/wet etch of dielectric materials in the dielectric layer). The contact holes can be filled with a conductor (e.g., Cu). In some implementations, filling the contact holes includes depositing a barrier layer, an adhesion layer, and/or a seed layer before depositing the conductor.

[0241] Method **1900** proceeds to operation **1916**, as illustrated in FIG. **19**, in which the first substrate and the second substrate are bonded in a face-to-face manner. The bonding can include hybrid bonding. In some implementations, the first bonding contact is in contact with the second bonding contact at a bonding interface after the bonding. In some implementations, the second substrate is above the first substrate after the bonding. In some implementations, the first substrate is above the second substrate after the bonding.

[0242] As illustrated in FIG. **15D**, silicon substrate **1502** and components formed thereon (e.g., semiconductor bodies **1512** and the stacked storage units) are flipped upside down, and bonding layer **1536** facing down is bonded with bonding layer **1546** facing up, i.e., in a face-to-face manner, thereby forming a bonding interface **1550**. In some implementations, a treatment process, e.g., a plasma treatment, a wet treatment, and/or a thermal treatment, is applied to the bonding surfaces prior to the bonding. Although not shown FIG. **15D**, silicon substrate **1538** and components formed thereon (e.g., transistors **1542**) can be flipped upside down, and bonding layer **1546** facing down can be bonded with bonding layer **1536** facing up, i.e., in a face-to-face manner, thereby forming bonding interface **1550**. After the bonding, bonding contacts **1537** in bonding layer **1536** and bonding contacts **1547** in bonding layer **1546** are aligned and in contact with one another, such that semiconductor bodies **1512** and the stacked storage units can be electrically connected to peripheral circuits **1540** across bonding interface **1550**. It is understood that in the bonded chip, semiconductor bodies **1512** and the stacked storage units may be either above or below peripheral circuits **1540**. Nevertheless, bonding interface **1550** can be formed vertically between peripheral circuits **1540** and semiconductor bodies **1512**/stacked storage units after the bonding.

[0243] Method **1900** proceeds to operation **1918**, as illustrated in FIG. **19**, in which the second substrate is removed to expose a second end opposite to the first end of the semiconductor body. As illustrated in FIG. **15E**, silicon substrate **1502** (shown in FIG. **15D**) is removed from the backside to expose the upper ends of semiconductor bodies **1512** (used to be the lower ends before flipping over). In some implementations, silicon substrate **1502** is polished from the backside, for example, using a CMP process, until being stopped the upper ends of semiconductor bodies **1512**.

[0244] Method **1900** proceeds to operation **1920**, as illustrated in FIG. **19**, in which at least part of

the semiconductor body is doped from the exposed second end of the semiconductor body. As illustrated in FIG. 15E, at least part of semiconductor body **1512** is doped to form another source/drain **1523** from the upper end of semiconductor body **1512**. Method **1900** proceeds to operation **1922**, as illustrated in FIG. 19, in which a bit line coupled to the doped part of the semiconductor body is formed. As illustrated in FIG. 15E, a bit line **1534** is formed to be coupled to source/drain **1523**. In some implementations, a body line coupled to another part of the semiconductor body is formed. As illustrated in FIG. 15E, a body line **1556** including a polysilicon layer **1558** and a metal layer **1560** is formed to be coupled to a portion of semiconductor body **1512**. The fabrication process for forming source/drain **1523**, bit line **1534**, and body line **1556** may be the same as the fabrication process described above with respect to source/drain **1323** or **1423**, bit line **1334** or **1434**, and body line **1356** or **1456** and thus, are not repeated.

[0245] Although not shown, it is understood that a pad-out interconnect layer may be formed above body line **1556**. The pad-out interconnect layer may include interconnects, such as pad contacts, formed in one or more ILD layers. The pad contacts may include conductive materials including, but not limited to, W, Co, Cu, Al, doped silicon, silicides, or any combination thereof. The ILD layers can include dielectric materials including, but not limited to, silicon oxide, silicon nitride, silicon oxynitride, low-k dielectrics, or any combination thereof. It is also understood that in some examples, the pad-out interconnect layer may be formed on the backside of silicon substrate **1538**, and through TSCs may be formed extending vertically through silicon substrate **1538**. Silicon substrate **1538** may be thinned prior to forming the pad-out interconnect layer and TSCs, for example, using planarization processes and/or etching processes.

[0246] According to one aspect of the present disclosure, a memory device includes a vertical transistor, a storage unit, and a bit line. The vertical transistor includes a semiconductor body extending in a first direction. The semiconductor body includes a doped source, a doped drain, and a channel portion. The storage unit is coupled to a first terminal. The first terminal is one of the source and the drain. The bit line extends in a second direction perpendicular to the first direction and in contact with a second terminal. The second terminal is another one of the source and the drain that is formed on all sides of a protrusion of the semiconductor body. The bit line is separated from the channel portion of the semiconductor body by the second terminal.

[0247] In some implementations, the bit line fully circumscribes the protrusion of the semiconductor body in a plan view.

[0248] In some implementations, the first terminal is formed on one end of a base of the semiconductor body. In some implementations, the channel portion is formed in the base and the protrusion of the semiconductor body.

[0249] In some implementations, the memory device further includes a body line coupled to the channel portion of the semiconductor body.

[0250] In some implementations, the body line and the storage unit are coupled to opposite ends of the vertical transistor in the first direction.

[0251] In some implementations, the bit line is between the storage unit and the body line in the first direction.

[0252] In some implementations, the body line includes a polysilicon layer in contact with the channel portion of the semiconductor body, and a metal layer in contact with the polysilicon layer.

[0253] In some implementations, the semiconductor body includes single crystalline silicon, and the channel portion includes undoped single crystalline silicon or doped single crystalline silicon having a different type of dopant from the source and the drain.

[0254] In some implementations, the memory device further includes a word line extending in a third direction perpendicular to the first direction and the second direction. In some implementations, the vertical transistor further includes a gate structure in contact with one or more sides of the semiconductor body in the third direction.

[0255] In some implementations, the gate structure includes a gate dielectric separated from the

protrusion of the semiconductor body.

[0256] In some implementations, the vertical transistor and the storage unit form a DRAM cell, a PCM cell, or a FRAM cell.

[0257] According to another aspect of the present disclosure, a memory system includes a memory device configured to store data and a memory controller coupled to the memory device. The memory device includes a vertical transistor, a storage unit, and a bit line. The vertical transistor includes a semiconductor body extending in a first direction. The semiconductor body includes a doped source, a doped drain, and a channel portion. The storage unit is coupled to a first terminal. The first terminal is one of the source and the drain. The bit line extends in a second direction perpendicular to the first direction and in contact with a second terminal. The second terminal is another one of the source and the drain that is formed on all sides of a protrusion of the semiconductor body. The bit line is separated from the channel portion of the semiconductor body by the second terminal. The memory controller is configured to control the vertical transistor and the storage unit through the bit line.

[0258] According to still another aspect of the present disclosure, a method for forming a memory device is disclosed. A semiconductor body extending vertically from a first side of a substrate and surrounded by a gate dielectric is formed. The substrate is removed from a second side opposite to the first side of the substrate to expose a first end of the semiconductor body and the gate dielectric. Part of the gate dielectric is removed to expose part of the semiconductor body. A sidewall and a top of the exposed part of the semiconductor body are doped. The doped top of the exposed part of the semiconductor body is removed.

[0259] In some implementations, a bit line in contact with the doped sidewall of the exposed part of the semiconductor body is formed, and a body line in contact with a top of the exposed part of the semiconductor body is formed after removing the doped top of the exposed part of the semiconductor body.

[0260] In some implementations, to form the body line, a polysilicon layer in contact with the top of the exposed part of the semiconductor body is formed, and a metal layer in contact with the polysilicon layer is formed.

[0261] In some implementations, a second end opposite to the first end of the semiconductor body is formed prior to removing the substrate.

[0262] In some implementations, a storage unit is formed on the doped second end of the semiconductor body prior to removing the substrate.

[0263] In some implementations, to form the storage unit, a first electrode is formed on the doped second end of the semiconductor body, a capacitor dielectric is formed on the first electrode, a second electrode is formed on the capacitor dielectric.

[0264] In some implementations, to form the semiconductor body, a sacrificial layer, a first dielectric layer, a word line, and a second dielectric layer are sequentially formed on the substrate, an opening extending through the sacrificial layer, the first dielectric layer, the word line, and the second dielectric layer is formed to expose part of the substrate, the gate dielectric is formed on a sidewall of the opening, and the semiconductor body is epitaxially grown from the exposed part of the substrate over the gate dielectric in the opening.

[0265] In some implementations, to remove the substrate, the substrate is polished from the second side of the substrate until being stopped by the sacrificial layer.

[0266] In some implementations, to remove the doped top of the exposed part of the semiconductor body, the sacrificial layer is thinned, and the exposed part of the semiconductor body is polished until being stopped by the thinned sacrificial layer.

[0267] The foregoing description of the specific implementations can be readily modified and/or adapted for various applications. Therefore, such adaptations and modifications are intended to be within the meaning and range of equivalents of the disclosed implementations, based on the teaching and guidance presented herein.

[0268] The breadth and scope of the present disclosure should not be limited by any of the above-described exemplary implementations, but should be defined only in accordance with the following claims and their equivalents.

Claims

1. A memory device, comprising: a vertical transistor comprising a semiconductor body extending in a first direction, the semiconductor body comprising a doped source, a doped drain, and a channel portion; a storage unit coupled to a first terminal, the first terminal being one of the source and the drain; and a bit line extending in a second direction intersecting with the first direction and in contact with a second terminal, the second terminal being another one of the source and the drain that is formed on at least one side of a protrusion of the semiconductor body and a side of a base of the semiconductor body connected to the protrusion of the semiconductor body.
2. The memory device of claim 1, wherein the bit line fully circumscribes the protrusion of the semiconductor body in a plan view perpendicular to the first direction.
3. The memory device of claim 2, further comprising: a gate electrode extending in a third direction perpendicular to the first direction and the second direction; and a gate dielectric extending in the first direction and disposed between the gate electrode and the channel portion, wherein the gate dielectric is separated from the protrusion of the semiconductor body.
4. The memory device of claim 3, wherein in the plan view perpendicular to the first direction, the second terminal surrounds the protrusion of the semiconductor body, and the bit line surrounds the second terminal.
5. The memory device of claim 1, wherein the bit line partially circumscribes the protrusion of the semiconductor body in a plan view perpendicular to the first direction.
6. The memory device of claim 5, further comprising: a gate electrode extending in a third direction perpendicular to the first direction and the second direction; and a gate dielectric extending in the first direction and disposed between the gate electrode and the channel portion, wherein the second terminal is formed on a first side of the protrusion of the semiconductor body, and a portion of the gate dielectric is connected to a second side of the protrusion of the semiconductor body opposite to the first side of the protrusion of the semiconductor body in the third direction.
7. The memory device of claim 1, wherein the bit line is separated from channel portion of the semiconductor body by the second terminal.
8. The memory device of claim 1, wherein a thickness of the bit line in the first direction is less than a thickness of the second terminal in the first direction.
9. The memory device of claim 1, wherein the first terminal is formed on one end of the base of the semiconductor body; and the channel portion is formed in the base and the protrusion of the semiconductor body.
10. The memory device of claim 1, further comprises a body line coupled to the channel portion of the semiconductor body, wherein: the body line and the storage unit are coupled to opposite ends of the vertical transistor in the first direction; and the bit line is between the storage unit and the body line in the first direction.
11. The memory device of claim 10, wherein the body line comprises a polysilicon layer in contact with the channel portion of the semiconductor body, and a metal layer in contact with the polysilicon layer.
12. A memory device, comprising: a vertical transistor comprising a semiconductor body extending in a first direction, the semiconductor body comprising a doped source, a doped drain, and a channel portion; a storage unit coupled to a first terminal, the first terminal being one of the source and the drain; and a bit line extending in a second direction intersecting with the first direction and in contact with a second terminal, the second terminal being another one of the source and the drain, wherein the second terminal circumscribes a protrusion of the semiconductor body in a plan

view perpendicular to the first direction, and the bit line circumscribes the second terminal in the plan view perpendicular to the first direction.

13. The memory device of claim 12, further comprising: a gate electrode extending in a third direction perpendicular to the first direction and the second direction; and a gate dielectric extending in the first direction and disposed between the gate electrode and the channel portion, wherein the gate dielectric is separated from the protrusion of the semiconductor body.

14. The memory device of claim 12, wherein the bit line is separated from the channel portion of the semiconductor body by the second terminal.

15. The memory device of claim 12, wherein a thickness of the bit line in the first direction is less than a thickness of the second terminal in the first direction.

16. The memory device of claim 12, wherein the first terminal is formed on one end of a base of the semiconductor body; and the channel portion is formed in the base and the protrusion of the semiconductor body.

17. The memory device of claim 12, further comprises a body line coupled to the channel portion of the semiconductor body, wherein: the body line and the storage unit are coupled to opposite ends of the vertical transistor in the first direction; and the bit line is between the storage unit and the body line in the first direction.

18. The memory device of claim 17, wherein the body line comprises a polysilicon layer in contact with the channel portion of the semiconductor body, and a metal layer in contact with the polysilicon layer.

19. A method for forming a memory device, comprising: forming a vertical transistor comprising a semiconductor body extending in a first direction, the semiconductor body comprising a doped source, a doped drain, and a channel portion; forming a storage unit coupled to a first terminal, the first terminal being one of the source and the drain; and forming a bit line extending in a second direction intersecting with the first direction and in contact with a second terminal, the second terminal being another one of the source and the drain that is formed on at least one side of a protrusion of the semiconductor body and a side of a base of the semiconductor body connected to the protrusion of the semiconductor body.

20. The method of claim 19, further comprising: forming a body line coupled to the channel portion of the semiconductor body, wherein the body line and the storage unit are coupled to opposite ends of the vertical transistor in the first direction, and the bit line is between the storage unit and the body line in the first direction.
