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Back-end-of-line CMOS inverter having reduced size and reduced short-channel effects and methods of forming the same

Abstract

An embodiment inverter circuit may include a gate electrode formed over an interlayer dielectric layer, a gate dielectric layer formed over the gate electrode, a first-conductivity-type semiconductor layer formed over the gate dielectric layer, a second-conductivity-type semiconductor layer formed over the gate dielectric layer and laterally displaced from the first-conductivity-type semiconductor layer, a first source electrode formed in contact with the first-conductivity-type semiconductor layer, a second source electrode formed in contact with the second-conductivity-type semiconductor layer, and a shared drain electrode formed in contact with the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer. At least one of the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer may include a metal-oxide semiconductor and/or a multi-layer structure formed in a back-end-of-line (BEOL) process that may be incorporated with other BEOL circuit components such as capacitors, inductors, resistors, and integrated passive devices.

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Background/Summary

BACKGROUND

(1) The semiconductor industry has grown due to continuous improvements in integration density of various electronic components (e.g., transistors, diodes, resistors, inductors, capacitors, etc.). For the most part, these improvements in integration density have come from successive reductions in minimum feature size, which allow more components to be integrated into a given area. In this regard, individual transistors, interconnects, and related structures have become increasingly smaller and there is an ongoing need to develop new materials, processes, and designs of semiconductor devices and interconnects to allow further progress.

(2) Transistors made of oxide semiconductors are an attractive option for back-end-of-line (BEOL) integration since such transistors may be processed at low temperatures and thus, may not damage

previously fabricated devices. For example, the fabrication conditions and techniques may not damage previously fabricated front-end-of-line (FEOL) and middle end-of-line (MEOL) devices. Circuits based on oxide semiconductor-based transistor devices may further include other components that may be fabricated in a BEOL process, such as capacitors, inductors, resistors, and integrated passive devices.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Aspects of this disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
- (2) FIG. 1 is a vertical cross-sectional view of a first structure after formation of complementary metal-oxide-semiconductor (CMOS) transistors, first metal interconnect structures formed in lower-level dielectric material layers, and an isolation dielectric layer, according to various embodiments.
- (3) FIG. 2A is a three-dimensional perspective view of a semiconductor circuit that may be formed in a BEOL process, according to various embodiments.
- (4) FIG. 2B is a schematic equivalent circuit describing the semiconductor circuit of FIG. 2A, according to various embodiments.
- (5) FIG. 2C is a further three-dimensional perspective view of the semiconductor circuit of FIG. 2A showing various dimensions of components of the semiconductor circuit, according to various embodiments.
- (6) FIG. 3A is a top view of an intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (7) FIG. 3B is a vertical cross-sectional view of the intermediate structure of FIG. 3A, according to various embodiments.
- (8) FIG. 4A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (9) FIG. 4B is a vertical cross-sectional view of the intermediate structure of FIG. 4A, according to various embodiments.
- (10) FIG. 5A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (11) FIG. 5B is a vertical cross-sectional view of the intermediate structure of FIG. 5A, according to various embodiments.
- (12) FIG. 6A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (13) FIG. 6B is a vertical cross-sectional view of the intermediate structure of FIG. 6A, according to various embodiments.
- (14) FIG. 7A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (15) FIG. 7B is a vertical cross-sectional view of the intermediate structure of FIG. 7A, according to various embodiments.
- (16) FIG. 8A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.
- (17) FIG. 8B is a vertical cross-sectional view of the intermediate structure of FIG. 8A, according to various embodiments.
- (18) FIG. 9A is a top view of a further intermediate structure that may be used in the formation of a

semiconductor circuit, according to various embodiments.

(19) FIG. 9B is a vertical cross-sectional view of the intermediate structure of FIG. 9A, according to various embodiments.

(20) FIG. 10A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.

(21) FIG. 10B is a vertical cross-sectional view of the intermediate structure of FIG. 10A, according to various embodiments.

(22) FIG. 11A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.

(23) FIG. 11B is a first vertical cross-sectional view of the intermediate structure of FIG. 11A, according to various embodiments.

(24) FIG. 11C is a second vertical cross-sectional view of the intermediate structure of FIG. 11A, according to various embodiments.

(25) FIG. 12A is a top view of a further intermediate structure that may be used in the formation of a semiconductor circuit, according to various embodiments.

(26) FIG. 12B is a first vertical cross-sectional view of the intermediate structure of FIG. 12A, according to various embodiments.

(27) FIG. 12C is a second vertical cross-sectional view of the intermediate structure of FIG. 12A, according to various embodiments.

(28) FIG. 13A is a top view of a semiconductor circuit formed by the processes described with reference to FIGS. 3A to 13C, according to various embodiments.

(29) FIG. 13B is a first vertical cross-sectional view of the semiconductor circuit of FIG. 13A, according to various embodiments.

(30) FIG. 13C is a second vertical cross-sectional view of the semiconductor circuit of FIG. 13A, according to various embodiments.

(31) FIG. 14A is a top view of a further embodiment semiconductor circuit that may be formed by processes similar to those described above with reference to FIGS. 3A to 13C, according to various embodiments.

(32) FIG. 14B is a first vertical cross-sectional view of the semiconductor circuit of FIG. 14A, according to various embodiments.

(33) FIG. 14C is a second vertical cross-sectional view of the semiconductor circuit of FIG. 14A, according to various embodiments.

(34) FIG. 14D is a three-dimensional perspective view of the semiconductor circuit of FIG. 14A, according to various embodiments.

(35) FIG. 15A is a top view of a further embodiment semiconductor circuit that may be formed by processes similar to those described above with reference to FIGS. 3A to 13C, according to various embodiments.

(36) FIG. 15B is a first vertical cross-sectional view of the semiconductor circuit of FIG. 15A, according to various embodiments.

(37) FIG. 15C is a second vertical cross-sectional view of the semiconductor circuit of FIG. 15A, according to various embodiments.

(38) FIG. 15D is a three-dimensional perspective view of the semiconductor circuit of FIG. 15A, according to various embodiments.

(39) FIG. 16 is a flowchart illustrating operations of a method of forming a semiconductor circuit, according to various embodiments.

DETAILED DESCRIPTION

(40) The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify this disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or

on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, this disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

(41) 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. Unless explicitly stated otherwise, each element having the same reference numeral is presumed to have the same material composition and to have a thickness within a same thickness range.

(42) Various embodiments of this disclosure provide semiconductor circuits and methods that may be advantageous in terms of manufacturing flexibility, reduced size, and reduced short channel effects. In this regard, an embodiment semiconductor circuit (e.g., a CMOS inverter) is provided that may be formed in a BEOL process and may be incorporated with other BEOL circuit components such as capacitors, inductors, resistors, and integrated passive devices. As such, the disclosed semiconductor circuit may include materials that may be processed at low temperatures. As a result, the fabrication of such a semiconductor circuit may not damage previously fabricated devices (e.g., FEOL and MEOL devices). Further, various embodiment semiconductor circuits may include twin conduction channels (e.g., a p-type channel and an n-type channel separated in a first horizontal direction by an isolation oxide) formed over a back-gate electrode. The semiconductor circuit may have a reduced size relative to alternative structures that do not include such a twin-channel/back gate configuration. The embodiment semiconductor circuits may allow longer channel lengths without increased device size, which may mitigate short-channel effects.

(43) An embodiment inverter circuit may include a gate electrode formed over an interlayer dielectric layer, a gate dielectric layer formed over the gate electrode, a first-conductivity-type semiconductor layer formed over the gate dielectric layer, a second-conductivity-type semiconductor layer formed over the gate dielectric layer and laterally displaced from the first-conductivity-type semiconductor layer, a first source electrode formed in contact with the first-conductivity-type semiconductor layer, a second source electrode formed in contact with the second-conductivity-type semiconductor layer, and a shared drain electrode formed in contact with the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer. At least one of the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer may include a metal-oxide semiconductor and/or a multi-layer structure formed in BEOL process that may be incorporated with other BEOL circuit components such as capacitors, inductors, resistors, and integrated passive devices.

(44) In a further embodiment, a semiconductor circuit may include a gate electrode formed over an interlayer dielectric layer such that the gate electrode is parallel to a horizontal interface of the interlayer dielectric layer, a p-type metal-oxide semiconductor layer formed over the gate electrode such that the p-type metal-oxide semiconductor layer is adjacent to a horizontal surface of the gate electrode, an n-type metal-oxide semiconductor layer formed over the gate electrode such that the n-type metal-oxide semiconductor layer is adjacent to the horizontal surface of the gate electrode and is laterally displaced from the p-type metal-oxide semiconductor layer, a first source electrode formed in contact with the p-type metal-oxide semiconductor layer, a second source electrode formed in contact with the n-type metal-oxide semiconductor layer, and a shared drain electrode

electrically connecting the p-type metal-oxide semiconductor layer and the n-type metal-oxide semiconductor layer.

(45) An embodiment method of forming a semiconductor circuit may include forming a gate electrode over an interlayer dielectric layer, forming a gate dielectric layer over the gate electrode, forming a first-conductivity-type semiconductor layer over the gate dielectric layer, forming a second-conductivity-type semiconductor layer over the gate dielectric layer such that the second-conductivity-type semiconductor layer is laterally displaced from the first-conductivity-type semiconductor layer, forming a first source electrode in contact with the first-conductivity-type semiconductor layer, forming a second source electrode in contact with the second-conductivity-type semiconductor layer, and forming a shared drain electrode in contact with the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer.

(46) FIG. 1 illustrates a semiconductor structure **100**, according to various embodiments. The semiconductor structure **100** includes a substrate **102**, which may be a semiconductor substrate such as a commercially available silicon substrate. The substrate **102** may include a semiconductor material layer **104** or at least at an upper portion thereof. The semiconductor material layer **104** may be a surface portion of a bulk semiconductor substrate or may be a top semiconductor layer of a semiconductor-on-insulator (SOI) substrate. In one embodiment, the semiconductor material layer **104** includes a single crystalline semiconductor material such as single crystalline silicon. In one embodiment, the substrate **102** may include a single crystalline silicon substrate including a single crystalline silicon material.

(47) Shallow trench isolation structures **106** including a dielectric material such as silicon oxide may be formed in an upper portion of the semiconductor material layer **104**. Suitably doped semiconductor wells, such as p-type wells and n-type wells, may be formed within each area that is laterally enclosed by a portion of the shallow trench isolation structures **106**. Field effect transistors **108** may be formed over a top surface of the semiconductor material layer **104**. For example, each of the field effect transistors **108** may include a source electrode **110**, a drain electrode **112**, a semiconductor channel **114** that includes a surface portion of the substrate **102** extending between the source electrode **110** and the drain electrode **112**, and a gate structure **116**. The semiconductor channel **114** may include a single crystalline semiconductor material.

(48) Each gate structure **116** may include a gate dielectric layer **118**, a gate electrode **120**, a gate cap dielectric **122**, and a dielectric gate spacer **124**. A source-side metal-semiconductor alloy region **126** may be formed on each source electrode **110**, and a drain-side metal-semiconductor alloy region **128** may be formed on each drain electrode **112**. The devices formed on the top surface of the semiconductor material layer **104** may include complementary metal-oxide-semiconductor (CMOS) transistors and optionally additional semiconductor devices (such as resistors, diodes, capacitors, etc.), and are collectively referred to as CMOS circuitry **134**.

(49) The semiconductor structure **100** of FIG. 1 may include a memory array region **130** in which an array of memory cells may be subsequently formed. The first exemplary structure may further include a peripheral region **132** in which metal wiring for the array of memory devices is provided. Generally, the field effect transistors **108** in the CMOS circuitry **134** may be electrically connected to an electrode of a respective memory cell by a respective set of metal interconnect structures.

(50) Devices (such as field effect transistors **108**) in the peripheral region **132** may provide functions that operate the array of memory cells to be subsequently formed. Specifically, devices in the peripheral region may be configured to control the programming operation, the erase operation, and the sensing (read) operation of the array of memory cells. For example, the devices in the peripheral region **132** may include a sensing circuitry and/or a programming circuitry.

(51) One or more of the field effect transistors **108** in the CMOS circuitry **134** may include a semiconductor channel **114** that contains a portion of the semiconductor material layer **104** in the substrate **102**. In embodiments in which the semiconductor material layer **104** includes a single crystalline semiconductor material such as single crystalline silicon, the semiconductor channel **114**

of each of the field effect transistors **108** in the CMOS circuitry **134** may include a single crystalline semiconductor channel such as a single crystalline silicon channel. In one embodiment, a plurality of field effect transistors **108** in the CMOS circuitry **134** may include a respective node that is subsequently electrically connected to a node of a respective memory cell to be subsequently formed. For example, a plurality of field effect transistors **108** in the CMOS circuitry **134** may include a respective source electrode **110** or a respective drain electrode **112** that is subsequently electrically connected to a node of a respective memory cell to be subsequently formed.

(52) In one embodiment, the CMOS circuitry **134** may include a programming control circuit configured to control gate voltages of a set of field effect transistors **108** that may be used for programming a respective memory cell (e.g., a ferroelectric memory cell) and to control gate voltages of transistors (e.g., thin-film transistors) to be subsequently formed. In this embodiment, the programming control circuit may be configured to provide a first programming pulse that programs a respective ferroelectric dielectric material layer in a selected ferroelectric memory cell into a first polarization state in which electrical polarization in the ferroelectric dielectric material layer points toward a first electrode of the selected ferroelectric memory cell, and to provide a second programming pulse that programs the ferroelectric dielectric material layer in the selected ferroelectric memory cell into a second polarization state in which the electrical polarization in the ferroelectric dielectric material layer points toward a second electrode of the selected ferroelectric memory cell.

(53) In one embodiment, the substrate **102** may include a single crystalline silicon substrate, and the field effect transistors **108** may include a respective portion of the single crystalline silicon substrate as a semiconducting channel. As used herein, a “semiconducting” element refers to an element having electrical conductivity in the range from 1.0×10^{-6} S/cm to $1.0 \times 10^{+5}$ S/cm. As used herein, a “semiconductor material” refers to a material having electrical conductivity in the range from 1.0×10^{-6} S/cm to $1.0 \times 10^{+5}$ S/cm in the absence of electrical dopants therein and is capable of producing a doped material having electrical conductivity in a range from 1.0 S/cm to $1.0 \times 10^{+5}$ S/cm upon suitable doping with an electrical dopant.

(54) According to an embodiment, the field effect transistors **108** may be subsequently electrically connected to drain electrodes and gate electrodes of access transistors including semiconducting metal oxide plates to be formed above the field effect transistors **108**. In one embodiment, a subset of the field effect transistors **108** may be subsequently electrically connected to at least one of the drain electrodes and the gate electrodes. For example, the field effect transistors **108** may include first word line drivers configured to apply a first gate voltage to first word lines through a first subset of lower-level metal interconnect structures to be subsequently formed, and second word line drivers configured to apply a second gate voltage to second word lines through a second subset of the lower-level metal interconnect structures. Further, the field effect transistors **108** may include bit line drivers configured to apply a bit line bias voltage to bit lines to be subsequently formed, and sense amplifiers configured to detect electrical current that flows through the bit lines during a read operation.

(55) Various metal interconnect structures formed within dielectric material layers may be subsequently formed over the substrate **102** and the semiconductor devices thereupon (such as field effect transistors **108**). In an illustrative example, the dielectric material layers may include, for example, a first dielectric material layer **136** that may be a layer that surrounds the contact structure connected to the source and drains (sometimes referred to as a contact-level dielectric material layer), a first interconnect-level dielectric material layer **138**, and a second interconnect-level dielectric material layer **140**. The metal interconnect structures may include device contact via structures **142** formed in the first dielectric material layer **136** and contacting a respective component of the CMOS circuitry **134**, first metal line structures **144** formed in the first interconnect-level dielectric material layer **138**, first metal via structures **146** formed in a lower portion of the second interconnect-level dielectric material layer **140**, and second metal line

structures **148** formed in an upper portion of the second interconnect-level dielectric material layer **140**.

(56) Each of the dielectric material layers (**136, 138, 140**) may include a dielectric material such as undoped silicate glass, a doped silicate glass, organosilicate glass, amorphous fluorinated carbon, porous variants thereof, or combinations thereof. Each of the metal interconnect structures (**142, 144, 146, 148**) may include at least one conductive material, which may be a combination of a metallic liner (such as a metallic nitride or a metallic carbide) and a metallic fill material. Each metallic liner may include TiN, TaN, WN, TiC, TaC, and WC, and each metallic fill material portion may include W, Cu, Al, Co, Ru, Mo, Ta, Ti, TiN, alloys thereof, and/or combinations thereof.

(57) Other suitable metallic liner and metallic fill materials within the contemplated scope of disclosure may also be used. In one embodiment, the first metal via structures **146** and the second metal line structures **148** may be formed as integrated line and via structures by a dual damascene process. The dielectric material layers (**136, 138, 140**) are herein referred to as lower-lower-level dielectric material layers. The metal interconnect structures (**142, 144, 146, 148**) formed within in the lower-level dielectric material layers are herein referred to as lower-level metal interconnect structures.

(58) While the disclosure is described using an embodiment in which an array of memory cells may be formed over the second line-and-via-level dielectric material layer **140**, embodiments are expressly contemplated herein in which the array of memory cells may be formed at a different metal interconnect level.

(59) An array of thin-film transistors and an array of ferroelectric memory cells (or other types of memory cells) may be subsequently deposited over the dielectric material layers (**136, 138, 140**) that have formed therein the metal interconnect structures (**142, 144, 146, 148**). The set of all dielectric material layers that are formed prior to formation of an array of thin-film transistors or an array of ferroelectric memory cells is collectively referred to as lower-level dielectric material layers (**136, 138, 140**). The set of all metal interconnect structures that is formed within the lower-level dielectric material layers (**136, 138, 140**) is herein referred to as first metal interconnect structures (**142, 144, 146, 148**). Generally, first metal interconnect structures (**142, 144, 146, 148**) formed within at least one lower-level dielectric material layer (**136, 138, 140**) may be formed over the semiconductor material layer **104** that is located in the substrate **102**.

(60) According to an embodiment, thin-film transistors may be subsequently formed in a metal interconnect level that overlies that metal interconnect levels that contain the lower-level dielectric material layers (**136, 138, 140**) and the first metal interconnect structures (**142, 144, 146, 148**). In one embodiment, a planar dielectric material layer having a uniform thickness may be formed over the lower-level dielectric material layers (**136, 138, 140**). The planar dielectric material layer is herein referred to as an insulating matrix layer **150**. The insulating matrix layer **150** may include a dielectric material such as undoped silicate glass, a doped silicate glass, organosilicate glass, or a porous dielectric material, and may be deposited by chemical vapor deposition. The thickness of the insulating matrix layer **150** may be in a range from 20 nm (i.e., 200 angstrom) to 300 nm (i.e., 3000 angstrom), although lesser and greater thicknesses may also be used.

(61) Generally, interconnect-level dielectric layers (such as the lower-level dielectric material layer (**136, 138, 140**)) containing therein the metal interconnect structures (such as the first metal interconnect structures (**142, 144, 146, 148**)) may be formed over semiconductor devices. The insulating matrix layer **150** may be formed over the interconnect-level dielectric layers. Other passive devices may be formed in BEOL processes. For example various capacitors, inductors, resistors, and integrated passive devices may be utilized with other BEOL devices.

(62) FIG. 2A is a three-dimensional perspective view of a semiconductor circuit **200** that may be formed in a BEOL process, and FIG. 2B is a schematic equivalent circuit **200b** describing the semiconductor circuit **200** of FIG. 2A, according to various embodiments. As shown in FIG. 2A,

the semiconductor circuit **200** may include a gate electrode **116** formed over an interlayer dielectric layer (not shown). For example, the semiconductor circuit **200** may be formed over the insulating matrix layer **150** (e.g., see FIG. **1**) or over one or more additional interconnect layers formed over the insulating matrix layer **150**. The semiconductor circuit **200** may further include a gate dielectric layer **118** formed over the gate electrode **116**, a first-conductivity-type semiconductor layer (e.g., a p-type semiconductor layer **206a**) formed over the gate dielectric layer **118**, and a second-conductivity-type semiconductor layer (e.g., an n-type semiconductor layer **206b**) formed over the gate dielectric layer **118** and laterally displaced from the first-conductivity-type semiconductor layer **206a**.

(63) The semiconductor circuit **200** may further include a first source electrode **110a** formed in contact with the first-conductivity-type semiconductor layer **206a** and a second source electrode **110b** formed in contact with the second-conductivity-type semiconductor layer **206b**. The semiconductor circuit **200** may further include a shared drain electrode **112** in contact with the first conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**. The semiconductor circuit **200** may be formed over an interlayer dielectric layer having horizontal interface (e.g., see the insulating matrix layer **150** of FIG. **1**).

(64) As shown in FIG. **2A**, the gate electrode **116** may include a surface **117** that is parallel to the horizontal interface of the interlayer dielectric layer **150** (e.g., see FIG. **1**) and is proximate to the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**. The first-conductivity-type semiconductor layer **206a** may include a first channel layer **119a** that is proximate to the surface **117** of the gate electrode **116** and is formed horizontally (e.g., parallel to the surface **117** of the gate electrode **116**). Similarly, the second-conductivity-type semiconductor layer **206b** may include a second channel layer **119b** that is adjacent to the surface **117** of the gate electrode **116** and is formed horizontally. As such, the semiconductor circuit **200** may include twin conduction channels (**119a**, **119b**) and a back gate electrode **116** that may be used to form an inverter circuit **200b**, as described in greater detail with reference to FIG. **2B**, below.

(65) As shown in FIG. **2A**, the semiconductor circuit **200** may include a further interlayer dielectric layer (e.g., the fourth interlayer dielectric layer **304d** of FIGS. **7A** **15C**) to laterally surrounding the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** such that the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** are electrically insulated from one another by the further interlayer dielectric layer **304d**. The fourth interlayer dielectric layer **304d** may also be referred to as an isolation oxide, or isolation dielectric, as the fourth interlayer dielectric layer **304d** isolates the first-conductivity-type semiconductor layer **206a** from the second-conductivity-type semiconductor layer **206b**. As shown in FIG. **2A**, the first source electrode **110a** may be electrically connected to a voltage supply **208** (e.g., that may be held at a source voltage **VDD**) and the second source electrode **110b** that may be connected to a ground voltage terminal **210** (e.g., that may be held at a ground (**GND**) voltage). The gate electrode **116** may be connected to an input signal (**V_{in}**) terminal **212** and the shared drain electrode **112** may be electrically connected to an output signal (**V_{out}**) terminal **214**. As such, the semiconductor circuit **200** may be configured as an inverter circuit **200b**, as shown in FIG. **2B**.

(66) FIG. **2B** is a schematic equivalent circuit **200b** describing the semiconductor circuit **200** of FIG. **2A**, according to various embodiments. In this regard, the p-type semiconductor layer **206a** may be configured to include a horizontal p-channel layer **119a** of a p-channel metal oxide semiconductor field effect transistor (MOSFET) (i.e., a pFET **216**) and the n-type semiconductor layer **206b** may be configured to include a horizontal n-channel layer **119b** of an n-channel MOSFET transistor (i.e., an nFET **218**). Thus, the pFET **216** may include the p-type semiconductor layer **206a**, the first source electrode **110a**, the shared drain electrode **112**, the gate dielectric layer **118**, and the gate electrode **116**. Similarly, the nFET **218** may include the n-type semiconductor layer **206b**, the second source electrode **110b**, the shared drain electrode **112**, the gate dielectric

layer **118**, and the gate electrode **116**.

(67) With reference to FIG. 2B, a low voltage applied to the input signal terminal **212** turns on the pFET **216** and turns off the nFET **218**. Since the source of the pFET **216** (i.e., the first source electrode **110a**) is connected to the voltage supply **208** that has a high voltage VDD, the output voltage Vout (i.e., the voltage at the shared drain electrode **112**) will have a high voltage. Similarly, a high voltage placed on the input signal terminal **212** turns on the nFET **218** and turns off the pFET **216**. Since the source of the nFET **218** (i.e., the second source electrode **110b**) is connected to a ground voltage terminal **210**, the output voltage Vout (i.e., the voltage at the shared drain electrode **112**) will have a low voltage GND. In this way, a high input signal applied at Vin is converted to a low output signal Vout and a low input signal applied at Vin is converted to a high output signal Vout. As such, the semiconductor circuit **200** may be configured and operate as an inverter circuit **200b**.

(68) The interlayer dielectric layer on which the semiconductor circuit **200** is formed (e.g., see lower-level dielectric material layers (**136**, **138**, **140**) in FIG. 1) may include one or more electrical interconnect structures (e.g., see first metal interconnect structures (**142**, **144**, **146**, **148**) in FIG. 1) which may be electrically connected to the semiconductor circuit **200** of FIGS. 2A and 2B. In this regard, one or more of the first source electrode **110a**, the second source electrode **110b**, the shared drain electrode **112**, and the gate electrode **116**, may be electrically connected to the one or more electrical interconnect structures (**142**, **144**, **146**, **148**) formed in one or more dielectric material layers (**136**, **138**, **140**) below the semiconductor circuit **200**. In other embodiments, one or more of the first source electrode **110a**, the second source electrode **110b**, the shared drain electrode **112**, and the gate electrode **116**, may be electrically connected to one or more electrical interconnect structures to be subsequently formed above the semiconductor circuit **200**.

(69) In one or more embodiments, one or both of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b** may include metal-oxide semiconductors. For example, the p-type semiconductor layer **206a** may include one or more of NiO, SnO, Cu₂O, etc., and the n-type semiconductor layer **206b** may include one or more of amorphous silicon, Al₂O₅Zn₂ doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga₂O₃, ZnO, GaO, InO, In₂O₃, InZnO, ZnO, TiO_x, and alloys thereof. In some embodiments, the n-type semiconductor layer **206b** may have a composition given by In_x Ga_y Zn_z MO, wherein 0<x<1; 0≤y≤1; 0≤z≤1; and M is one of Ti, Al, Ag, Ce, and Sn. In other embodiments, the n-type semiconductor layer **206b** may include an alloy of oxygen, a group-III element, and a group-V element. In other embodiments, the one or more of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b** may be formed of a metal-oxide semiconductor having a multi-layer structure.

(70) In some embodiments, one or more of the gate dielectric layer **118** may include a high-k dielectric material and may include one or more of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, hafnium dioxide-alumina, etc. As described in greater detail below, one or more of the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112** may include one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, Al, etc. Other suitable conductor materials may be within the contemplated scope of disclosure. For example, in some embodiments, one or more of the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112** may further include one or more alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O, deposited by chemical vapor deposition or by atomic layer deposition.

(71) As described above, the p-type semiconductor layer **206a** may be configured to include a p-channel layer **119a** (e.g., see FIG. 2A) of a pFET **216** device (e.g., see FIG. 2B) and the n-type semiconductor layer **206b** may be configured to include an n-channel layer **119b** (e.g., see FIG. 2A) of an nFET **218** device (e.g., see FIG. 2B). As such, in instances in which the respective devices

(pFET **216**, nFET **218**) are activated, current may flow as indicated by the dashed arrows (**220a**, **220b**) in FIG. 2A. In this regard, when the pFET **216** is activated (e.g., by applying a low or zero bias to the gate electrode **116**) positive charge carriers (i.e., “holes”) may flow from the first source electrode **110a** to the shared drain electrode **112** (e.g., see FIG. 2A) giving rise to a first current **220a**. Similarly, when the nFET **218** is activated (e.g., by applying a high bias to the gate electrode **116**) negative charge carriers (i.e., electrons) may flow from the shared drain electrode **112** to the second source electrode **110b** but, since the current carried by a negative charge is opposite to its motion, the charge motion in the nFET **218** gives rise to a second current **220b**, which is in the same direction as first current **220a** that flows in the pFET **216**.

(72) FIG. 2C is a further three-dimensional perspective view showing various dimensions of components of the semiconductor circuit **200** of FIG. 2A, according to various embodiments. Each of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b** may have a respective channel length **222** and a respective channel width (**224a**, **224b**). For example, the p-type semiconductor layer **206a** may have a first channel width **224a** and the n-type semiconductor layer **206b** may have a second channel width **224b**. The channel length **222** may have a value greater than 10 nm in various embodiments. An increased value of the channel length **222** may mitigate short channel effects. However, increasing the channel length **222** may result in reduced driving current and a greater size of the semiconductor circuit **200**. Thus, it may be possible to optimize the channel length **222** to determine a value sufficiently large to avoid short channel effects while also keeping the size of the semiconductor circuit **200** as small as possible.

(73) The respective channel widths (**224a**, **224b**) may each have a value that is greater than 10 nm, according to various embodiments. In some embodiments, the first channel width **224a** may be approximately equal to the second channel width **224b**. In other embodiments, the first channel width **224a** and the second channel width **224b** may have different values. For example, in some embodiments, it may be advantageous to select different values of the first channel width **224a** and the second channel width **224b** to tune electrical properties of the respective first channel layer **119a** and second channel layer **119b**, for example, to compensate for differing carrier mobilities and/or to adjust respective values of electrical current.

(74) Each of the first source electrode **110a** and the second source electrode **110b** may have respective source widths (**224a**, **224b**) that are approximately equal to the respective channel widths (**224a**, **224b**) as shown, for example, in FIG. 2C. Each of the source/drain electrodes (**110a**, **110b**, **112**) may also have a source/drain length **226** and source/drain thickness **228**, which each may have values that are greater than 5 nm (e.g., 5 nm to 50 nm). The further interlayer dielectric layer **304d** may have a thickness **230** that is greater than 5 nm (e.g., greater than 5 nm and less than 100 nm) and a width **231** that may be comparable to the source widths (**224a**, **224b**). The gate electrode **116** may have a gate length **232** and a gate width **233** that may each be greater than 10 nm less than 500 nm. The gate electrode **116** may have a gate thickness **236** that may have a value that is greater than 5 nm and less than 50 nm. The gate dielectric **118** may have a gate dielectric thickness **238** that is greater than 2 nm and less than 20 nm. The p-type semiconductor layer **206a** may have a p-type thickness **240a**, and the n-type semiconductor layer **206b** may have an n-type thickness **240b**, each of which may each be greater than 2 nm and less than 50 nm.

(75) FIG. 3A is a top view of an intermediate structure **300** that may be used in the formation of a semiconductor circuit **200** and FIG. 3B is a vertical cross-sectional view of the intermediate structure **300** of FIG. 3A, according to various embodiments. The vertical plane defining the view in FIG. 3B is indicated by the cross section B-B' in FIG. 3A. As shown in FIGS. 3A and 3B, the intermediate structure **300** may include a substrate **302**, a first interlayer dielectric layer **304a**, an etch-stop layer **306L**, a second interlayer dielectric layer **304b**, and a patterned photoresist **308**. The substrate **302** may be formed in a BEOL process and, as such, may be formed over an interlayer dielectric layer (e.g., an interlayer dielectric or insulating matrix layer **150** from FIG. 1). For example, the substrate **302** may include undoped silicate glass, a doped silicate glass (e.g.,

deposited by decomposition of tetraethylorthosilicate (TEOS)), organosilicate glass, silicon oxynitride, or silicon carbide nitride. Other suitable dielectric materials are within the contemplated scope of disclosure. The dielectric material of the substrate **302** may be deposited by a conformal deposition process (such as a chemical vapor deposition process) or a self-planarizing deposition process (such as spin coating). The thickness of the substrate **302** may each be in a range from approximately 15 nm to approximately 60 nm, such as from approximately 20 nm to approximately 40 nm, although smaller and larger thicknesses may also be used.

(76) The first interlayer dielectric layer **304a** may include, but is not limited to, silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, aluminum oxide, hafnium dioxide-alumina, or various other insulating structures such as a multi-layer stack structure including alternating insulating layers. The first interlayer dielectric layer **304a** may be deposited by a conformal deposition process (e.g., chemical vapor deposition (CVD), atomic layer deposition (ALD), physical vapor deposition (PVD), plasma enhanced chemical vapor deposition (PECVD), etc.) or by a self-planarizing deposition process (such as spin coating). In this example, the first interlayer dielectric layer **304a** may be formed as a planar blanket (i.e., un-patterned) layer having a planar top surface and a planar bottom surface. Excess portions of the first interlayer dielectric layer **304a** may be removed by a planarization process, for example, by chemical mechanical planarization (CMP). A thickness of the first interlayer dielectric layer **304a** may be in a range from approximately 5 nm to approximately 50 nm, such as from approximately 20 nm to approximately 40 nm, although other embodiments may include smaller and larger thicknesses.

(77) The etch-stop layer **306L** may include an etch-stop material such as silicon nitride, silicon carbide, silicon nitride carbide, or a dielectric metal oxide (such as aluminum oxide, titanium oxide, tantalum oxide, etc.). The etch-stop layer **306L** may be deposited by a conformal or non-conformal deposition process. In one embodiment, the etch-stop layer **306L** may be deposited by CVD, ALD, or PVD. A thickness of the etch-stop layer **306L** may be in a range from approximately 2 nm to approximately 20 nm, such as from approximately 3 nm to approximately 12 nm, although smaller and larger thicknesses may also be used.

(78) The second interlayer dielectric layer **304b** may be formed over the first oxide semiconductor layer **206La** using materials and processes similar to those described above with reference to the first interlayer dielectric layer **304a**. In this regard, the second interlayer dielectric layer **304b** may be the same material as the first interlayer dielectric layer **304a**. Alternatively, the first interlayer dielectric layer **304a** and the second interlayer dielectric layer **304b** may be different materials. The second interlayer dielectric layer **304b** may include, but is not limited to, silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, aluminum oxide, hafnium dioxide-alumina, or various other insulating structures such as a multi-layer stack structure including alternating insulating layers. The second interlayer dielectric layer **304b** may be deposited by a conformal deposition process (e.g., CVD, ALD, PVD, PECVD, etc.) or by a self-planarizing deposition process (such as spin coating). Excess portions of the second interlayer dielectric layer **304b** may be removed by a planarization process, for example, by CMP.

(79) The patterned photoresist **308** may be formed by deposition of a uniform layer of photoresist (not shown) followed by patterning the uniform layer of photoresist using lithographic techniques. According to some embodiments, the patterned photoresist **308** may be formed as a periodic array of rectangular shapes over the second interlayer dielectric layer **304b**. For example, the view of FIGS. 3A and 3B may correspond to one repeat unit of the periodic array of rectangular shapes. The patterned photoresist **308** may then be used as a mask to pattern the second interlayer dielectric layer **304b**, as described in greater detail with reference to FIGS. 4A and 4B, below.

(80) FIG. 4A is a top view of a further intermediate structure **400** that may be used in the formation of a semiconductor circuit **200** and FIG. 4B is a vertical cross-sectional view of the intermediate

structure **400** of FIG. 4A, according to various embodiments. The vertical plane defining the view in FIG. 4B is indicated by the cross section B-B' in FIG. 4A. The intermediate structure **400** may be formed from the intermediate structure **300** of FIGS. 3A and 3B by patterning the second interlayer dielectric layer **304b** using the patterned photoresist **308** and an etching process to form a gate opening in the second interlayer dielectric layer **304b** (not shown), depositing an electrically conductive material into the gate openings to thereby form the gate electrode **116**, and planarizing the resulting structure.

(81) The electrically conductive material may include a metallic liner material and a metallic fill material. The metallic liner material may include a conductive metallic nitride or a conductive metallic carbide such as Ti, Al, TiN, TiN/W, Ti/Al/Ti, TaN, W, Cu, WN, WCN, PdCo, TiC, TaC, and/or WC. A thickness of the metallic liner material may be in a range from approximately 1 nm to approximately 10 nm, such as from approximately 3 nm to approximately 8 nm, although smaller and larger thicknesses may also be used. The metallic fill material may include W, Cu, Al, Co, Ru, Mo, Ta, Ti, TiN, alloys thereof, and/or combinations thereof. Other suitable metallic liner and metallic fill materials within the contemplated scope of this disclosure may also be used. A thickness of the metallic fill material may be in a range from approximately 5 nm to approximately 500 nm, such as from approximately 20 nm to approximately 40 nm, although smaller and larger thicknesses may also be used. The metallic liner material and metallic fill materials may be formed by suitable deposition process, which may include one or more of a CVD process, a PVD process, an ALD process, an electroplating process, etc. Other suitable deposition processes are within the contemplated scope of disclosure.

(82) Excess portions of the conductive material may then be removed from above a horizontal plane including the top surface of the second interlayer dielectric layer **304b** by a planarization process such as CMP, although other suitable planarization processes may be used. The remaining portions of the conductive material form the gate electrode **116**. In some embodiments, the gate electrode **116** may be formed by deposition of one or more alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O, deposited by chemical vapor deposition or by atomic layer deposition.

(83) FIG. 5A is a top view of a further intermediate structure **500** that may be used in the formation of a semiconductor circuit **200** and FIG. 5B is a vertical cross-sectional view of the intermediate structure **500** of FIG. 5A, according to various embodiments. The vertical plane defining the view in FIG. 5B is indicated by the cross section B-B' in FIG. 5A. The intermediate structure **500** may be formed from the intermediate structure **400** of FIGS. 4A and 4B by forming a gate dielectric layer **118**, a first oxide semiconductor layer **206La**, a third interlayer dielectric layer **304c**, and a patterned photoresist **308** over the intermediate structure **400** of FIGS. 4A and 4B.

(84) The gate dielectric layer **118** may include, but is not limited to, silicon dioxide, silicon nitride, silicon oxynitride, hafnium oxide, hafnium silicon oxide, tantalum oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, aluminum oxide, hafnium dioxide-alumina, or various other insulating structures such as a multi-layer stack structure including alternating insulating layers. Other suitable dielectric materials are within the contemplated scope of disclosure. In other embodiments, the gate dielectric layer **118** may include an alternating multi-layer structure (not shown) including silicon oxide and silicon nitride. In other embodiments, the gate dielectric layer **118** may include a ferroelectric material.

(85) The gate dielectric layer **118** may be formed by any suitable technique such as ALD, CVD, PECVD, PVD, etc. A thickness of the gate dielectric layer **118** may be in a range from approximately 2 nm to approximately 20 nm, such as from approximately 5 nm to approximately 12 nm, although other embodiments may include smaller and larger thicknesses. Following the deposition of the gate dielectric layer **118**, the intermediate structure **500** may optionally be annealed. The optional annealing process may be performed at a temperature in a range from 200° C. to 400° C. using a rapid thermal annealing or furnace annealing process. The annealing may be

performed in an environment of nitrogen, oxygen, or a mixture thereof.

(86) The first oxide semiconductor layer **206La** may be first-conductivity-type semiconductor layer such as a p-type semiconducting material including, but not limited to, NiO, SnO, Cu₂O, etc., which may be formed by any suitable method such as ALD, CVD, PECVD, PVD, etc. A thickness of the first oxide semiconductor layer **206La** may be in a range from approximately 2 nm to approximately 50 nm, such as from approximately 5 nm to approximately 15 nm, although other embodiments may include smaller and larger thicknesses. Following the deposition of the first oxide semiconductor layer **206La**, the intermediate structure **500** may optionally be annealed. The optional annealing process may be performed at a temperature in a range from 200° C. to 400° C. using a rapid thermal annealing or furnace annealing process. The annealing may be performed in an environment of nitrogen, oxygen, or a mixture thereof. In other embodiments, the first oxide semiconductor layer **206La** may be an n-type semiconducting layer.

(87) The third interlayer dielectric layer **304c** may be formed using materials and processes described above with reference to the formation of the first interlayer dielectric layer **304a**, and the second interlayer dielectric layer **304b**. In this regard, the third interlayer dielectric layer **304c** may be formed by depositing an interlayer dielectric layer followed by performing a planarization process (e.g., CMP) to remove a portion of the interlayer dielectric above a top surface of the third interlayer dielectric layer **304c**.

(88) The patterned photoresist **308** may also be formed using processes described above. In this regard, a uniform layer of photoresist (not shown) may be deposited over a top surface of the third interlayer dielectric layer **304c**. The uniform layer of photoresist may then be patterned using lithographic techniques to form the patterned photoresist **308**. The patterned photoresist may then be used as a mask to pattern the third interlayer dielectric layer **304c**, the third interlayer dielectric layer **304c**, and the first oxide semiconductor layer **206La**, as described in greater detail with reference to FIGS. **6A** and **6B**, below.

(89) FIG. **6A** is a top view of a further intermediate structure **600** that may be used in the formation of a semiconductor circuit **200** and FIG. **6B** is a vertical cross-sectional view of the intermediate structure **600** of FIG. **6A**, according to various embodiments. The vertical plane defining the view in FIG. **6B** is indicated by the cross section B-B' in FIG. **6A**. The intermediate structure **600** may be formed from the intermediate structure **500** of FIGS. **5A** and **5B** by performing an anisotropic etch process to remove portions of the third interlayer dielectric layer **304c** and the first oxide semiconductor layer **206La** that are not masked by the patterned photoresist **308**. The resulting intermediate structure **600** includes the patterned first-conductivity-type semiconductor layer **206a**, described above with reference to FIGS. **2A** and **2C**, along with a remaining portion of the third interlayer dielectric layer **304c**. The patterned photoresist **308** may then be removed by ashing or by dissolution with a solvent.

(90) FIG. **7A** is a top view of a further intermediate structure **700** that may be used in the formation of a semiconductor circuit **200** and FIG. **7B** is a vertical cross-sectional view of the intermediate structure **700** of FIG. **7A**, according to various embodiments. The vertical plane defining the view in FIG. **7B** is indicated by the cross section B-B' in FIG. **7A**. The intermediate structure **700** may be formed from the intermediate structure **600** of FIGS. **6A** and **6B** by removing the patterned photoresist **308** and depositing a fourth interlayer dielectric layer **304d** over the intermediate structure **600** after the patterned photoresist **308** has been removed.

(91) The fourth interlayer dielectric layer **304d** may be formed using materials and processes described above with reference to the formation of the first interlayer dielectric layer **304a**, the second interlayer dielectric layer **304b**, and the third interlayer dielectric layer **304c**. As shown, the fourth interlayer dielectric layer **304d** may partially or completely surround the first-conductivity-type semiconductor layer **206a**. In this regard, at the processing stage of FIGS. **7A** and **7B**, the fourth interlayer dielectric layer **304d** surrounds (encapsulates) the first-conductivity-type semiconductor layer **206a**. However, after a planarization process (described below with reference

to FIGS. 10A and 10B), the fourth interlayer dielectric layer 304d may only partially surround the first-conductivity-type semiconductor layer 206a. The fourth interlayer dielectric layer 304d may be used to protect the first-conductivity-type semiconductor layer 206a during further processing operations, as described in greater detail with reference to FIGS. 8A and 8B, below.

(92) FIG. 8A is a top view of a further intermediate structure 800 that may be used in the formation of a semiconductor circuit 200 and FIG. 8B is a vertical cross-sectional view of the intermediate structure 800 of FIG. 8A, according to various embodiments. The vertical plane defining the view in FIG. 8B is indicated by the cross section B-B' in FIG. 8A. The intermediate structure 800 may be formed from the intermediate structure 700 of FIGS. 7A and 7B by forming a patterned photoresist 308 over the intermediate structure 600 and performing an anisotropic etch process to etch portions of the intermediate structure 700 that are not masked by the patterned photoresist 308. As shown, the anisotropic etch process may generate a via opening 702. The patterned photoresist 308 may then be removed (e.g., by ashing or by dissolution with a solvent). A second oxide semiconductor layer 206Lb may then be deposited over the resulting structure to thereby fill the via opening 702, as described in greater detail with reference to FIGS. 9A and 9B, below.

(93) FIG. 9A is a top view of a further intermediate structure 900 that may be used in the formation of a semiconductor circuit 200 and FIG. 9B is a vertical cross-sectional view of the intermediate structure 900 of FIG. 9A, according to various embodiments. The vertical plane defining the view in FIG. 9B is indicated by the cross section B-B' in FIG. 9A. The intermediate structure 900 may be formed from the intermediate structure 800 of FIGS. 8A and 8B by forming a second oxide semiconductor layer 206Lb over the intermediate structure 800 to thereby fill the via opening 702. The second oxide semiconductor layer 206Lb may be second-conductivity-type semiconductor layer such as an n-type semiconducting material including, but not limited to, amorphous silicon, Al₂O₅Zn₂ doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga₂O₃, ZnO, GaO, InO, In₂O₃, InZnO, ZnO, TiO_x, and alloys thereof. Other suitable semiconducting materials are within the contemplated scope of disclosure. For example, in various embodiments, the second oxide semiconductor layer 206Lb may include a composition given by In.sub.xGa.sub.yZn.sub.zMO, wherein 0<x<1; 0≤y≤1; 0≤z≤1; and M is one of Ti, Al, Ag, Ce, and Sn. The second oxide semiconductor layer 206Lb may be formed by any suitable method such as ALD, CVD, PECVD, PVD, etc.

(94) A thickness of the second oxide semiconductor layer 206Lb may be in a range from approximately 2 nm to approximately 50 nm, such as from approximately 5 nm to approximately 15 nm, although other embodiments may include smaller and larger thicknesses. Following the deposition of the second oxide semiconductor layer 206Lb, the intermediate structure 900 may optionally be annealed. The optional annealing process may be performed at a temperature in a range from 200° C. to 400° C. using a rapid thermal annealing or furnace annealing process. The annealing may be performed in an environment of nitrogen, oxygen, or a mixture thereof.

(95) FIG. 10A is a top view of a further intermediate structure 1000 that may be used in the formation of a semiconductor circuit 200 and FIG. 10B is a vertical cross-sectional view of the intermediate structure 1000 of FIG. 10A, according to various embodiments. The vertical plane defining the view in FIG. 10B is indicated by the cross section B-B' in FIG. 10A. The intermediate structure 1000 may be formed from the intermediate structure 900 of FIGS. 9A and 9B by performing a planarization process (e.g., CMP) to remove at top portion of the second oxide semiconductor layer 206Lb and a portion of the fourth interlayer dielectric layer 304d to thereby expose a top surface of each of the p-type semiconductor layer 206a and the n-type semiconductor layer 206b. In some embodiments, an additional interlayer dielectric layer (not shown) may be formed over the intermediate structure 900 prior to performing the planarization process.

(96) FIG. 11A is a top view of a further intermediate structure 1100 that may be used in the formation of a semiconductor circuit 200 and FIG. 11B is a vertical cross-sectional view of the intermediate structure 1100 of FIG. 11A, according to various embodiments. The vertical planes

defining the views in FIGS. **11B** and **11C** are indicated by the cross sections B-B' and C-C', respectively, in FIG. **11A**. The intermediate structure **1100** may be formed from the intermediate structure **1000** of FIGS. **10A** and **10B** by depositing additional interlayer dielectric material to increase a thickness of the fourth interlayer dielectric layer **304d** over the intermediate structure **1000** of FIGS. **10A** and **10B**.

(97) The fourth interlayer dielectric layer **304d** may partially or completely surround the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**. In this regard, at the processing stage of FIGS. **11A** to **11C**, the fourth interlayer dielectric layer **304d** completely surrounds the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**. The fourth interlayer dielectric layer **304d** may be used to protect the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** during further processing operations, as described in greater detail with reference to FIGS. **12A** to **13C**, below.

(98) FIG. **12A** is a top view of a further intermediate structure **1200** that may be used in the formation of a semiconductor circuit **200**, FIG. **12B** is a first vertical cross-sectional view of the intermediate structure **1200** of FIG. **12A**, and FIG. **12C** is a second vertical cross-sectional view of the intermediate structure **1200** of FIG. **12A** according to various embodiments. The vertical planes defining the views in FIGS. **12B** and **12C** are indicated by the cross sections B-B' and C-C', respectively, in FIG. **12A**. The intermediate structure **1200** may be formed from the intermediate structure **1100** of FIGS. **11A** to **11C** by forming a patterned photoresist **308** over the intermediate structure **1100** and performing an anisotropic etch process to etch portions of the intermediate structure **1100** that are not masked by the patterned photoresist **308**. As shown, the anisotropic etch process may generate via openings **703**. An electrically conductive material may be subsequently deposited in the via openings **703** to thereby form the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112**, as described in greater detail with reference to FIGS. **13A** to **13C**, below.

(99) FIG. **13A** is a top view of the semiconductor circuit **200** formed by the processes described with reference to FIGS. **3A** to **12C**, FIG. **13B** is a first vertical cross-sectional view of the semiconductor circuit **200** of FIG. **13A**, and FIG. **13C** is a second vertical cross-sectional view of the semiconductor circuit **200** of FIG. **13A**, according to various embodiments. The vertical planes defining the views in FIGS. **13B** and **13C** are indicated by the cross sections B-B' and C-C', respectively, in FIG. **13A**. The semiconductor circuit **200** may be formed from the intermediate structure **1200** of FIGS. **12A** to **12C** by depositing an electrically conductive material in the via openings **702**, removing the patterned photoresist **308** (e.g., by ashing or by dissolution with a solvent), and by performing a planarization process (e.g., CMP) to remove excess portions of the conductive material and to remove a portion of the fourth interlayer dielectric layer **304d**. The remaining portions of the electrically conductive material form the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112**, as shown in FIGS. **13A** to **13C**.

(100) The electrically conductive material may include a metallic liner material and a metallic fill material. The metallic liner material may include a conductive metallic nitride or a conductive metallic carbide such as Ti, Al, TiN, TiN/W, Ti/Al/Ti, TaN, W, Cu, WN, WCN, PdCo, TiC, TaC, and/or WC. A thickness of the metallic liner material may be in a range from approximately 1 nm to approximately 10 nm, such as from approximately 3 nm to approximately 8 nm, although smaller and larger thicknesses may also be used. The metallic fill material may include W, Cu, Al, Co, Ru, Mo, Ta, Ti, TiN, alloys thereof, and/or combinations thereof. Other suitable metallic liner and metallic fill materials within the contemplated scope of this disclosure may also be used. A thickness of the metallic fill material may be in a range from approximately 5 nm to approximately 500 nm, such as from approximately 20 nm to approximately 40 nm, although smaller and larger thicknesses may also be used. The metallic liner material and metallic fill materials may be formed by suitable deposition process, which may include one or more of a CVD process, a PVD process,

an ALD process, an electroplating process, etc. Other suitable deposition processes are within the contemplated scope of disclosure.

(101) As mentioned above, the excess portions of the conductive material may be removed from above a horizontal plane including the top surface of the fourth interlayer dielectric layer **304d** by a planarization process such as CMP, although other suitable planarization processes may be used. The remaining portions of the conductive material form the second source electrode **110b**. In some embodiments, the second source electrode **110b** may be formed by deposition of one or more alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O, deposited by chemical vapor deposition or by atomic layer deposition.

(102) Various other embodiments may include a pFET **216** and an nFET **218** having additional numbers of parallel conduction channels (**119a**, **119b**). For example, some embodiments may include a pFET **216** having a number $P=1, 2, 3$, etc., of parallel p-type channel layers **119a**, and an nFET **218** having a number $N=1, 2, 3$, etc., of parallel n-type channel layers **119b**. Embodiments such as the semiconductor circuits **200d** and **200e** having multiple channel layers may allow additional circuit design flexibility in various circumstances. For example, the effective on-resistance of a pFET **216** and/or nFET **218** may be adjusted to compensate for differing material properties (e.g., different carrier mobilities of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b**) by forming semiconductor circuits having respective numbers (P, N) of p-type channel layers **119a** and n-type channel layers **119b**.

(103) FIG. **14A** is a top view of a further embodiment semiconductor circuit **200d** having additional number of parallel conduction channels **119a1**, **119a2**, **119b** that may be formed by the processes similar to those described above with reference to FIGS. **3A** to **13C**, FIG. **14B** is a first vertical cross-sectional view of the semiconductor circuit **200d** of FIG. **14A**, FIG. **14C** is a second vertical cross-sectional view of the semiconductor circuit **200d** of FIG. **14A**, FIG. **14D** is a three-dimensional perspective view of the semiconductor circuit **200d** that may be formed in a BEOL process, according to various embodiments. The vertical planes defining the views in FIGS. **14B** and **14C** are indicated by the cross sections B-B' and C-C', respectively, in FIG. **14A**. In the embodiment semiconductor circuit **200d**, two neighboring p-type semiconductor layers (e.g., see **206a1** and **206a2** in FIGS. **14B** and **14C**) may share a common first source electrode **110a** and a shared drain electrode **112**, while a single n-type semiconductor layer **206b** may be electrically connected to a second source electrode **110b** and the shared drain electrode **112**.

(104) With reference to FIGS. **14A-14D**, in the embodiment semiconductor circuit **200d**, two neighboring p-type semiconductor layers (e.g., see **206a1** and **206a2**) may share a common first source electrode **110a** and a shared drain electrode **112**, while a single n-type semiconductor layer **206b** may be electrically connected to a second source electrode **110b** and the shared drain electrode **112**. As such, the semiconductor circuit **200d** of FIGS. **14A-14D** may include a pFET **216** (e.g., see FIG. **2B**) that includes two parallel p-type channel layers (see FIG. **14D**, **119a1**, **119a2**), provided by the two neighboring p-type semiconductor layers (**206a1**, **206a2**), and an nFET **218** that may include a single n-type channel layer **119b**, provided by the single n-type semiconductor layer **206b**.

(105) FIG. **15A** is a top view of a further embodiment semiconductor circuit **200e** that may be formed by the processes similar to those described above with reference to FIGS. **3A** to **13C**, FIG. **15B** is a first vertical cross-sectional view of the semiconductor circuit **200e** of FIG. **15A**, FIG. **15C** is a second vertical cross-sectional view of the semiconductor circuit **200e** of FIG. **15A**, FIG. **15D** is a three-dimensional perspective view of the semiconductor circuit **200e** that may be formed in a BEOL process, according to various embodiments. The vertical planes defining the views in FIGS. **15B** and **15C** are indicated by the cross sections B-B' and C-C', respectively, in FIG. **15A**. In the embodiment semiconductor circuit **200e**, a single p-type semiconductor layer **206a** may be electrically connected to a first source electrode **110a** and a shared drain electrode **112**, while two neighboring n-type semiconductor layers (e.g., see **206b1** and **206b2** in FIGS. **15B** and **15C**) may

share a common second source electrode **110b** and the shared drain electrode **112**.

(106) FIG. **15D** is a three-dimensional perspective view of a further semiconductor circuit **200d** that may be formed in a BEOL process, according to various embodiments. In the embodiment semiconductor circuit **200e**, a single p-type semiconductor layer **206a** may be electrically connected to a first source electrode **110a** and a shared drain electrode **112**, while two neighboring n-type semiconductor layers (**206b1** and **206b2**) may share a common second source electrode **110b** and the shared drain electrode **112**. As such, the semiconductor circuit **200e** of FIGS. **15A-15D** may include a pFET **216** (e.g., see FIG. **2B**) that includes a single p-type channel layer **119a**, provided by the single p-type semiconductor layer **206a**, and an nFET **218** that may include two parallel n-type channel layers (**119b1**, **119b2**), provided by the two neighboring n-type semiconductor layers (**206b1**, **206b2**).

(107) As shown, the semiconductor circuit **200d** of FIGS. **14A-14D** may include a pFET **216** (e.g., see FIG. **2B**) that includes two parallel p-type channel layers (**119a1**, **119a2**), provided by the two neighboring p-type semiconductor layers (**206a1**, **206a2**), and an nFET **218** that may include a single n-type channel layer **119b**, provided by the single n-type semiconductor layer **206b**.

Alternatively, the semiconductor circuit **200e** of FIGS. **15A-15D** may include a pFET **216** (e.g., see FIG. **2B**) that includes a single p-type channel layer **119a**, provided by the single p-type semiconductor layer **206a**, and an nFET **218** that may include two parallel n-type channel layers (**119b1**, **119b2**), provided by the two neighboring n-type semiconductor layers (**206b1**, **206b2**).

(108) Various other embodiments may include a pFET **216** and an nFET **218** having additional numbers of parallel conduction channels (**119a**, **119b**). For example, some embodiments may include a pFET **216** having a number $P=1, 2, 3$, etc., of parallel p-type channel layers **119a**, and an nFET **218** having a number $N=1, 2, 3$, etc., of parallel n-type channel layers **119b**. In certain embodiments, the number of p-type channel layers **119a** may be equal to the number of n-type channel layers **119b** (i.e., $P=N$). In other embodiments, a number of p-type channel layers **119a** may be different from a number of n-type channel layers **119b** (i.e., $P \neq N$). Embodiments such as the semiconductor circuits **200d** and **200e** having multiple channel layers may allow additional circuit design flexibility in various circumstances. For example, the effective on-resistance of a pFET **216** and/or nFET **218** may be adjusted to compensate for differing material properties (e.g., different carrier mobilities of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b**) by forming semiconductor circuits having respective numbers (P, N) of p-type channel layers **119a** and n-type channel layers **119b**.

(109) FIG. **16** is a flowchart illustrating operations of a method **1600** of forming a semiconductor circuit (**200**, **200b**, **200d**, **200e**), according to various embodiments. In operation **1602**, the method **1600** may include forming a gate electrode **116** over an interlayer dielectric layer (**136**, **138**, **140**, **150**, **302**, **304a** to **304d**). In operation **1604**, the method **1600** may include forming a gate dielectric layer **118** over the gate electrode **116**. In operation **1606**, the method **1600** may include forming a first-conductivity-type semiconductor layer (e.g., p-type semiconductor layer **206a**) over the gate dielectric layer **118**. In operation **1608**, the method **1600** may include forming a second-conductivity-type semiconductor layer (e.g., n-type semiconductor layer **206b**) over the gate dielectric layer **118** such that the second-conductivity-type semiconductor layer **206b** is laterally displaced and isolated from the first-conductivity-type semiconductor layer **206a**. In operation **1610**, the method **1600** may include forming a first source electrode **110a** in contact with the first-conductivity-type semiconductor layer **206a**. In operation **1612**, the method **1600** may include forming a second source electrode **110b** in contact with the second-conductivity-type semiconductor layer **206b**. In operation **1614**, the method **1600** may include forming a shared drain electrode **112** in contact with the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**.

(110) The method **1600** may further include configuring the semiconductor circuit (**200**, **200b**, **200d**, **200e**) as an inverter circuit **200b** by performing operations including electrically connecting

the first source electrode **110a** to a voltage supply **208** (e.g., held at a high voltage VDD) and the second source electrode **110b** to a ground voltage terminal **210** (e.g., held at GND). The method **1600** may further include electrically connecting the gate electrode **116** to an input signal terminal **212** (having signal voltage V_{in}) and electrically connecting the shared drain electrode **112** to an output signal terminal **214** (having voltage V_{out}).

(111) The method **1600** may further include forming one of the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** to include an n-type semiconductor layer **206b** including at least one of amorphous silicon, Al.sub.2O.sub.5Zn.sub.2 doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga.sub.2O.sub.3, ZnO, GaO, InO, In.sub.2O.sub.3, InZnO, ZnO, TiO_x, and alloys thereof; and forming the other of the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** to include a p-type semiconductor layer **206a** including at least one of NiO, SnO, and Cu₂O. The method **1600** may further include forming the gate dielectric layer **118** to include at least one of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina; forming one or more of the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112** to include one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, and Al; and forming a further interlayer dielectric layer (**136, 138, 140, 150, 302, 304a** to **304d**) that partially surrounds the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** such that the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** are electrically insulated from one another by the further interlayer dielectric layer (**136, 138, 140, 150, 302, 304a** to **304d**).

(112) Referring to all drawings and according to various embodiments of the present disclosure, an inverter circuit (**200, 200b, 200d, 200e**) is provided. The inverter circuit (**200, 200b, 200d, 200e**) may include a gate electrode **116** formed over an interlayer dielectric layer (**136, 138, 140, 150, 302**), a gate dielectric layer **118** formed over the gate electrode **116**, a first-conductivity-type semiconductor layer **206a** formed over the gate dielectric layer **118**, and a second-conductivity-type semiconductor layer **206b** formed over the gate dielectric layer **118** and laterally displaced from the first-conductivity-type semiconductor layer **206a**. The inverter circuit (**200, 200b, 200d, 200e**) may further include a first source electrode **110a** formed in contact with the first-conductivity-type semiconductor layer **206a**, a second source electrode **110b** formed in contact with the second-conductivity-type semiconductor layer **206b**, and a shared drain electrode **112** formed in contact with the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**.

(113) In some embodiments, the interlayer dielectric layer (**136, 138, 140, 150, 302**) may include a horizontal interface (e.g., see FIG. 1), the gate electrode **116** may include a surface **117** that is parallel to the horizontal interface of the interlayer dielectric layer (**136, 138, 140, 150, 302**) and is proximate to the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b**, the first-conductivity-type semiconductor layer **206a** may include a first channel layer **119a** that is proximate to the surface **117** of the gate electrode **116** and is formed horizontally, and the second-conductivity-type semiconductor layer **206b** may include a second channel layer **119b** that is proximate to the surface **117** of the gate electrode **116** and is formed horizontally.

(114) In other embodiments, the first-conductivity-type semiconductor layer **206a** may be a p-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** may be an n-type semiconductor layer **206b**. The first source electrode **110a** may be electrically connected to a voltage supply **208**, the second source electrode **110b** may be electrically connected to a ground voltage terminal **210**, the gate electrode **116** may be electrically connected to an input signal terminal **212**, and the shared drain electrode **112** may be electrically connected to an output signal

terminal **214**. In some embodiments, at least one of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b** may include metal-oxide semiconductors. Further, at least one of the p-type semiconductor layer **206a** and the n-type semiconductor layer **206b** may include a metal-oxide semiconductor including a multi-layer structure.

(115) In some embodiments, the n-type semiconductor layer **206b** may include an alloy including, oxygen, a group-III element, and a group-V element, or the n-type semiconductor layer **206b** may include one or more of amorphous silicon, Al.sub.2O.sub.5Zn.sub.2 doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga.sub.2O.sub.3, ZnO, GaO, InO, In.sub.2O.sub.3, InZnO, ZnO, TiO_x, and alloys thereof. In other embodiments, the n-type semiconductor layer **206b** may include a composition given by In.sub.xGa.sub.yZn.sub.zMO, wherein $0 < x < 1$; $0 \leq y \leq 1$; $0 \leq z \leq 1$; and M is one of Ti, Al, Ag, Ce, and Sn. In various embodiments, the p-type semiconductor layer **206a** may include one or more of NiO, SnO, and Cu₂O, or other p-type metal-oxide semiconductor **206a**.

(116) The interlayer dielectric layer (**136, 138, 140, 150, 302**), on which the semiconductor circuit (**200, 200b, 200d, 200e**) may be formed, may further including one or more electrical interconnect structures (e.g., see first metal interconnect structures (**142, 144, 146, 148**) in FIG. 1) and one or more of the first source electrode **110a**, the shared drain electrode **112**, the second source electrode **110b**, and the gate electrode **116** may be electrically connected to the one or more electrical interconnect structures (**142, 144, 146, 148**). In various embodiments, the gate dielectric layer **118** may include one or more of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina.

(117) In some embodiments, the inverter circuit (**200, 200b, 200d, 200e**) may further include a further interlayer dielectric layer **304d** laterally surrounding and isolating the first-conductivity-type semiconductor layer **206a** from the second-conductivity-type semiconductor layer **206b** such that the first-conductivity-type semiconductor layer **206a** and the second-conductivity-type semiconductor layer **206b** are electrically insulated from one another by the further interlayer dielectric layer **304d**. In certain embodiments, one or more of the first source electrode **110a**, the shared drain electrode **112**, and the second source electrode **110b** include one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, and Al. One or more of the first source electrode **110a**, the shared drain electrode, and the second source electrode **110b**, may further include one or more alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O, deposited by chemical vapor deposition or by atomic layer deposition.

(118) In other embodiments, a semiconductor circuit (**200, 200b, 200d, 200e**) may be provided. The semiconductor circuit (**200, 200b, 200d, 200e**) may include a gate electrode **116** formed over an interlayer dielectric layer (**136, 138, 140, 150, 302**) such that the gate electrode **116** may be parallel to a horizontal interface of the interlayer dielectric layer (**136, 138, 140, 150, 302**), a p-type metal-oxide semiconductor layer **206a** formed over the gate electrode **116** such that the p-type metal-oxide semiconductor layer **206a** may be proximate to a horizontal surface **117** of the gate electrode **116**, and an n-type metal-oxide semiconductor layer **206b** formed over the gate electrode **116** such that the n-type metal-oxide semiconductor layer **206b** may be proximate to the horizontal surface of the gate electrode **116** and may be laterally displaced from the p-type metal-oxide semiconductor layer **206a**. The semiconductor circuit (**200, 200b, 200d, 200e**) may further include a first source electrode **110a** formed in contact with the p-type metal-oxide semiconductor layer **206a**, a second source electrode **110b** formed in contact with the n-type metal-oxide semiconductor layer **206b**, and a shared drain electrode **112** electrically connecting the p-type metal-oxide semiconductor layer **206a** and the n-type metal-oxide semiconductor layer **206b**.

(119) The semiconductor circuit (**200, 200b, 200d, 200e**) may further include a further interlayer dielectric layer **304d** laterally surrounding the p-type metal-oxide semiconductor layer **206a** and the n-type metal-oxide semiconductor layer **206b**, and a gate dielectric layer **118** disposed between the gate electrode **116** and the p-type metal-oxide semiconductor layer **206a** and between the gate

electrode **116** and the n-type metal-oxide semiconductor layer **206b**. In some embodiments, the gate dielectric layer **118** may include one or more of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina.

(120) In other embodiments, the n-type metal-oxide semiconductor layer **206b** may include one or more of amorphous silicon, Al.sub.2O.sub.5Zn.sub.2 doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga.sub.2O.sub.3, ZnO, GaO, InO, In.sub.2O.sub.3, InZnO, ZnO, TiO_x, and alloys thereof; the p-type metal-oxide semiconductor layer **206a** may include one or more of NiO, SnO, and Cu.sub.2O; and one or more of the first source electrode **110a**, the second source electrode **110b**, and the shared drain electrode **112** may include one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, Al, and alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O.

(121) Various embodiments of this disclosure provide semiconductor circuits (**200**, **200b**, **200d**, **200e**) and methods **1600** that may be advantageous in terms of manufacturing flexibility, reduced size, and reduced short channel effects. In this regard, an embodiment semiconductor circuit (**200**, **200b**, **200d**, **200e**) (e.g., a CMOS inverter **200b**) may be provided that may be formed in a BEOL process and may be incorporated with other BEOL circuit components such as capacitors, inductors, resistors, and integrated passive devices. As such, the embodiment semiconductor circuits (**200**, **200b**, **200d**, **200e**) may include materials that may be processed at low temperatures. As a result, the fabrication of such a semiconductor circuit (**200**, **200b**, **200d**, **200e**) may not damage previously fabricated devices (e.g., FEOL and MEOL devices). Further, various embodiment semiconductor circuits (**200**, **200b**, **200d**, **200e**) may include twin conduction channels (e.g., a p-type channel **119a** and an n-type channel **119b**) formed over a back gate electrode **116**. The semiconductor circuit (**200**, **200b**, **200d**, **200e**) may have a reduced size relative to alternative structures that do not include such a twin-channel/back gate configuration. The embodiment semiconductor circuits (**200**, **200b**, **200d**, **200e**) may allow longer channel lengths without increased device size, which may mitigate short-channel effects.

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

Claims

1. An inverter circuit, comprising: a gate electrode formed over an interlayer dielectric layer; a gate dielectric layer formed over the gate electrode; a first-conductivity-type semiconductor layer formed over the gate dielectric layer; a second-conductivity-type semiconductor layer formed over the gate dielectric layer, laterally displaced and isolated from the first-conductivity-type semiconductor layer; a first source electrode formed in contact with the first-conductivity-type semiconductor layer; a second source electrode formed in contact with the second-conductivity-type semiconductor layer; and a shared drain electrode formed in contact with the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer.
2. The inverter circuit of claim 1, wherein: the interlayer dielectric layer comprises a horizontal interface; the gate electrode comprises a surface that is parallel to the horizontal interface of the interlayer dielectric layer and is proximate to the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer; the first-conductivity-type semiconductor layer

comprises a first channel layer that is proximate to the surface of the gate electrode; and the second-conductivity-type semiconductor layer comprises a second channel layer that is proximate to the surface of the gate electrode.

3. The inverter circuit of claim 1, wherein: the first-conductivity-type semiconductor layer is a p-type semiconductor layer and the second-conductivity-type semiconductor layer is an n-type semiconductor layer; the first source electrode is electrically connected to a voltage supply and the second source electrode is electrically connected to a ground voltage terminal; the gate electrode is electrically connected to an input signal terminal; and the shared drain electrode is electrically connected to an output signal terminal.

4. The inverter circuit of claim 3, wherein at least one of the p-type semiconductor layer and the n-type semiconductor layer comprise metal-oxide semiconductors.

5. The inverter circuit of claim 3, wherein at least one of the p-type semiconductor layer and the n-type semiconductor layer comprises a metal-oxide semiconductor comprising a multi-layer structure.

6. The inverter circuit of claim 3, wherein the n-type semiconductor layer comprises an alloy comprising, oxygen, a group-III element, and a group-V element.

7. The inverter circuit of claim 3, wherein the n-type semiconductor layer comprises one or more of amorphous silicon, Al.sub.2O.sub.5Zn.sub.2 doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, Ga.sub.2O.sub.3, ZnO, GaO, InO, In.sub.2O.sub.3, InZnO, ZnO, TiOx, and alloys thereof.

8. The inverter circuit of claim 3, wherein the n-type semiconductor layer comprises a composition given by In.sub.xGa.sub.yZn.sub.zMO, wherein $0 < x < 1$; $0 \leq y \leq 1$; $0 \leq z \leq 1$; and M is one of Ti, Al, Ag, Ce, and Sn.

9. The inverter circuit of claim 3, wherein the p-type semiconductor layer comprises one or more of NiO, SnO, and Cu.sub.2O.

10. The inverter circuit of claim 1, wherein the interlayer dielectric layer further comprises one or more electrical interconnect structures, and wherein one or more of the first source electrode, the second source electrode, the shared drain electrode, and the gate electrode are electrically connected to the one or more electrical interconnect structures.

11. The inverter circuit of claim 1, wherein the gate dielectric layer comprises one or more of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina.

12. The inverter circuit of claim 1, further comprising a further interlayer dielectric layer laterally surrounding the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer such that the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer are electrically insulated from one another by the further interlayer dielectric layer.

13. The inverter circuit of claim 1, wherein one or more of the first source electrode, the second source electrode, and the shared drain electrode comprise one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, and Al.

14. The inverter circuit of claim 1, wherein one or more of the first source electrode, the second source electrode, and the shared drain electrode further comprise one or more alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O, deposited by chemical vapor deposition or by atomic layer deposition.

15. A semiconductor circuit, comprising: a gate electrode formed over an interlayer dielectric layer such that the gate electrode is parallel to a horizontal interface of the interlayer dielectric layer; a p-type metal-oxide semiconductor layer formed over the gate electrode such that the p-type metal-oxide semiconductor layer is proximate to a horizontal surface of the gate electrode; an n-type metal-oxide semiconductor layer formed over the gate electrode such that the n-type metal-oxide semiconductor layer is proximate to the horizontal surface of the gate electrode and is laterally

displaced and isolated from the p-type metal-oxide semiconductor layer; a first source electrode formed in contact with the p-type metal-oxide semiconductor layer; a second source electrode formed in contact with the n-type metal-oxide semiconductor layer; and a shared drain electrode electrically connecting the p-type metal-oxide semiconductor layer and the n-type metal-oxide semiconductor layer.

16. The semiconductor circuit of claim 15, further comprising: a further interlayer dielectric layer laterally surrounding the p-type metal-oxide semiconductor layer and the n-type metal-oxide semiconductor layer; and a gate dielectric layer disposed between the gate electrode and the p-type metal-oxide semiconductor layer and between the gate electrode and the n-type metal-oxide semiconductor layer, wherein the gate dielectric layer comprises one or more of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina.

17. The semiconductor circuit of claim 15, wherein the n-type metal-oxide semiconductor layer comprises one or more of amorphous silicon, $\text{Al}_{0.2}\text{O}_{0.5}\text{Zn}_{0.2}$ doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, $\text{Ga}_{0.2}\text{O}_{0.3}$, ZnO, GaO, InO, $\text{In}_{0.2}\text{O}_{0.3}$, InZnO, ZnO, TiOx, and alloys thereof, wherein the p-type metal-oxide semiconductor layer comprises one or more of NiO, SnO, and $\text{Cu}_{0.2}\text{O}$, and wherein one or more of the first source electrode, the second source electrode, and the shared drain electrode comprise one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, Al, and alloys of one or more of W, Mo, Co, Pd, Ti, and mixtures thereof, with or without N and/or O.

18. A method of forming a semiconductor circuit, comprising: forming a gate electrode over an interlayer dielectric layer; forming a gate dielectric layer over the gate electrode; forming a first-conductivity-type semiconductor layer over the gate dielectric layer; forming a second-conductivity-type semiconductor layer over the gate dielectric layer such that the second-conductivity-type semiconductor layer is laterally displaced and isolated from the first-conductivity-type semiconductor layer; forming a first source electrode in contact with the first-conductivity-type semiconductor layer; forming a second source electrode in contact with the second-conductivity-type semiconductor layer; and forming a shared drain electrode in contact with the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer.

19. The method of claim 18, further comprising configuring the semiconductor circuit as an inverter circuit by performing operations comprising: electrically connecting the first source electrode to a voltage supply and the second source electrode to a ground voltage terminal; electrically connecting the gate electrode to an input signal terminal; and electrically connecting the shared drain electrode to an output signal terminal.

20. The method of claim 18, further comprising: forming one of the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer to comprise an n-type semiconductor layer comprising at least one of amorphous silicon, $\text{Al}_{0.2}\text{O}_{0.5}\text{Zn}_{0.2}$ doped ZnO, InGaZnO, InGaO, InWO, InZnO, InSnO, $\text{Ga}_{0.2}\text{O}_{0.3}$, ZnO, GaO, InO, $\text{In}_{0.2}\text{O}_{0.3}$, InZnO, ZnO, TiOx, and alloys thereof; forming the other of the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer to comprise a p-type semiconductor layer comprising at least one of NiO, SnO, and $\text{Cu}_{0.2}\text{O}$; forming the gate dielectric layer to comprise at least one of silicon oxide, aluminum oxide, hafnium oxide, hafnium lanthanum oxide, hafnium silicon oxide, hafnium tantalum oxide, hafnium titanium oxide, hafnium zirconium oxide, zirconium oxide, titanium oxide, tantalum oxide, and hafnium dioxide-alumina; forming one or more of the first source electrode, the second source electrode, and the shared drain electrode to comprise one or more of TiN, W, WN, WCN, Co, PdCo, Mo, Cu, TaN, Ti, and Al; and forming a further interlayer dielectric layer that partially surrounds the first-conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer such that the first-

conductivity-type semiconductor layer and the second-conductivity-type semiconductor layer are electrically insulated from one another by the further interlayer dielectric layer.
