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Lee et al.

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(54) **METHOD FOR SEMICONDUCTOR DEVICE FABRICATION WITH IMPROVED SOURCE DRAIN EPITAXY**

(58) **Field of Classification Search**
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(Continued)

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(57) **ABSTRACT**

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A method includes receiving a precursor having a substrate and first and second pluralities of gate structures, the first pluralities having a greater pitch than the second pluralities. The method further includes depositing a dielectric layer covering the substrate and the first and second pluralities; and performing an etching process to the dielectric layer. The etching process removes a first portion of the dielectric layer over the substrate, while a second portion of the dielectric layer remains over sidewalls of the first and second pluralities. The second portion of the dielectric layer is thicker over the sidewalls of the second plurality than over the sidewalls of the first plurality. The method further includes etching the substrate to form third and fourth pluralities of recesses adjacent the first and second pluralities, respectively; and epitaxially growing fifth and sixth pluralities of semiconductor features in the third and fourth pluralities, respectively.

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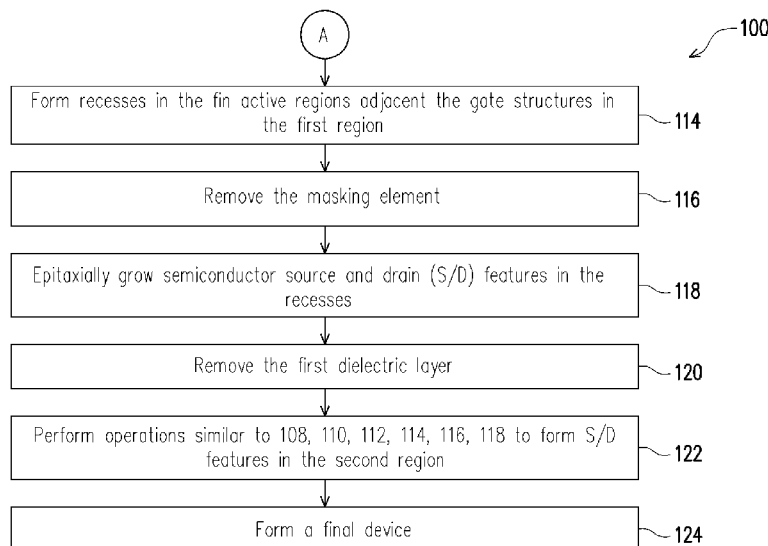
Related U.S. Application Data

(60) Provisional application No. 62/313,430, filed on Mar. 25, 2016.

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(Continued)

20 Claims, 23 Drawing Sheets



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H01L 29/16 (2006.01)
H01L 29/165 (2006.01)
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H01L 27/11 (2006.01)
H01L 21/84 (2006.01)
- (52) **U.S. Cl.**
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 (2013.01); *H01L 29/7851* (2013.01)
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 H01L 29/7851; H01L 29/66636; H01L
 29/161; H01L 29/66795; H01L 29/1608;
 H01L 29/165; H01L 29/084; H01L
 21/845; H01L 21/0262; H01L 27/088;
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See application file for complete search history.

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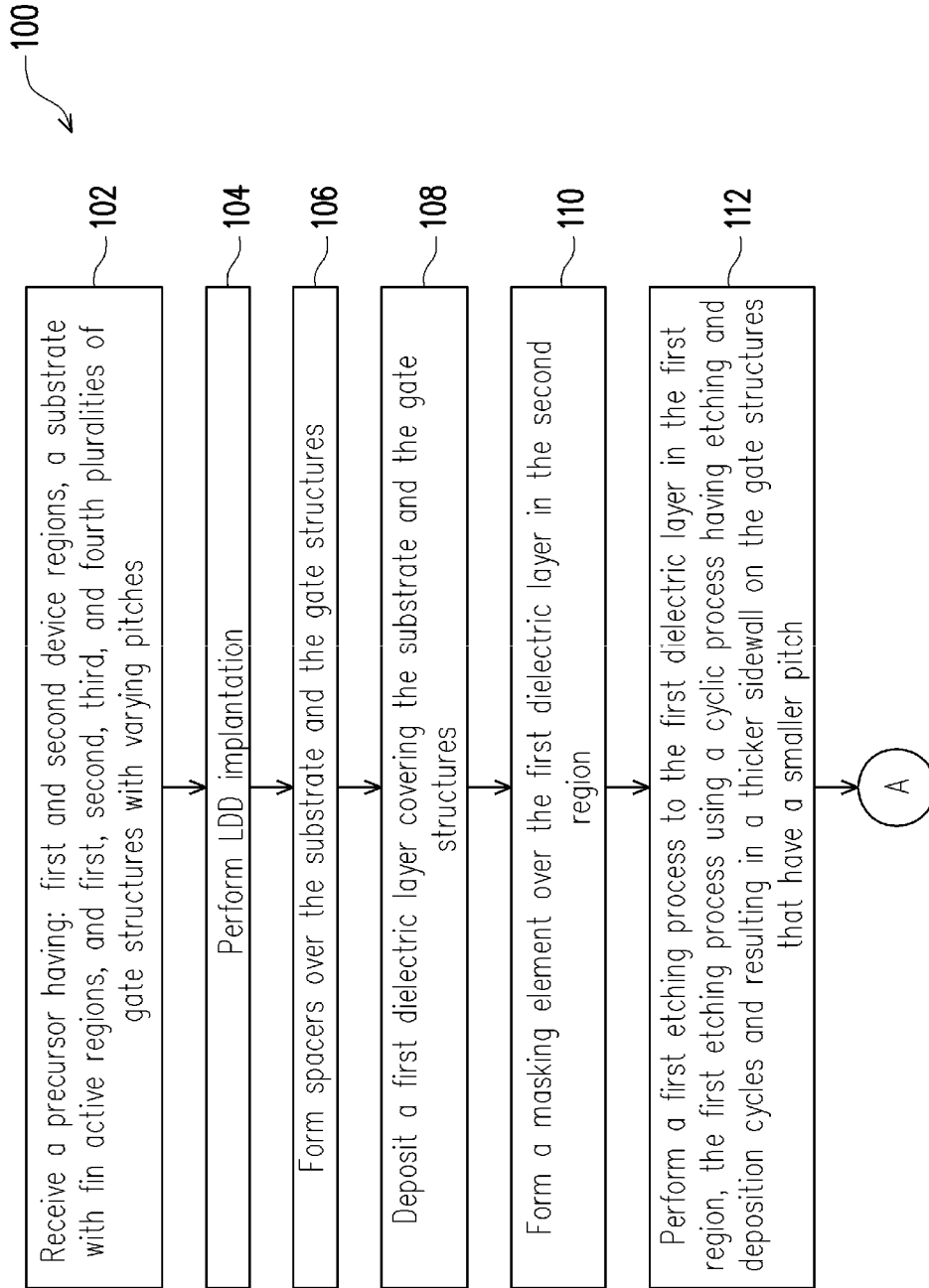


FIG. 1A

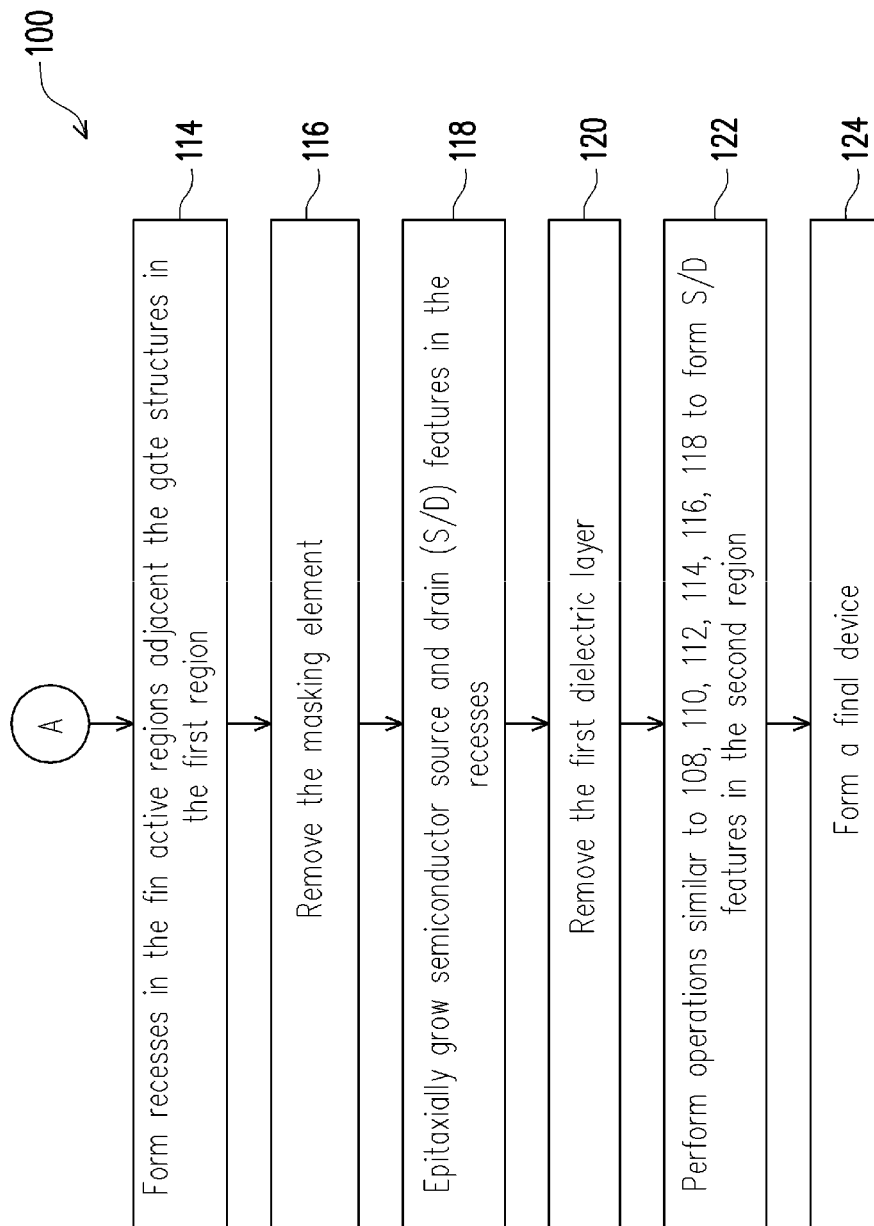


FIG. 1B

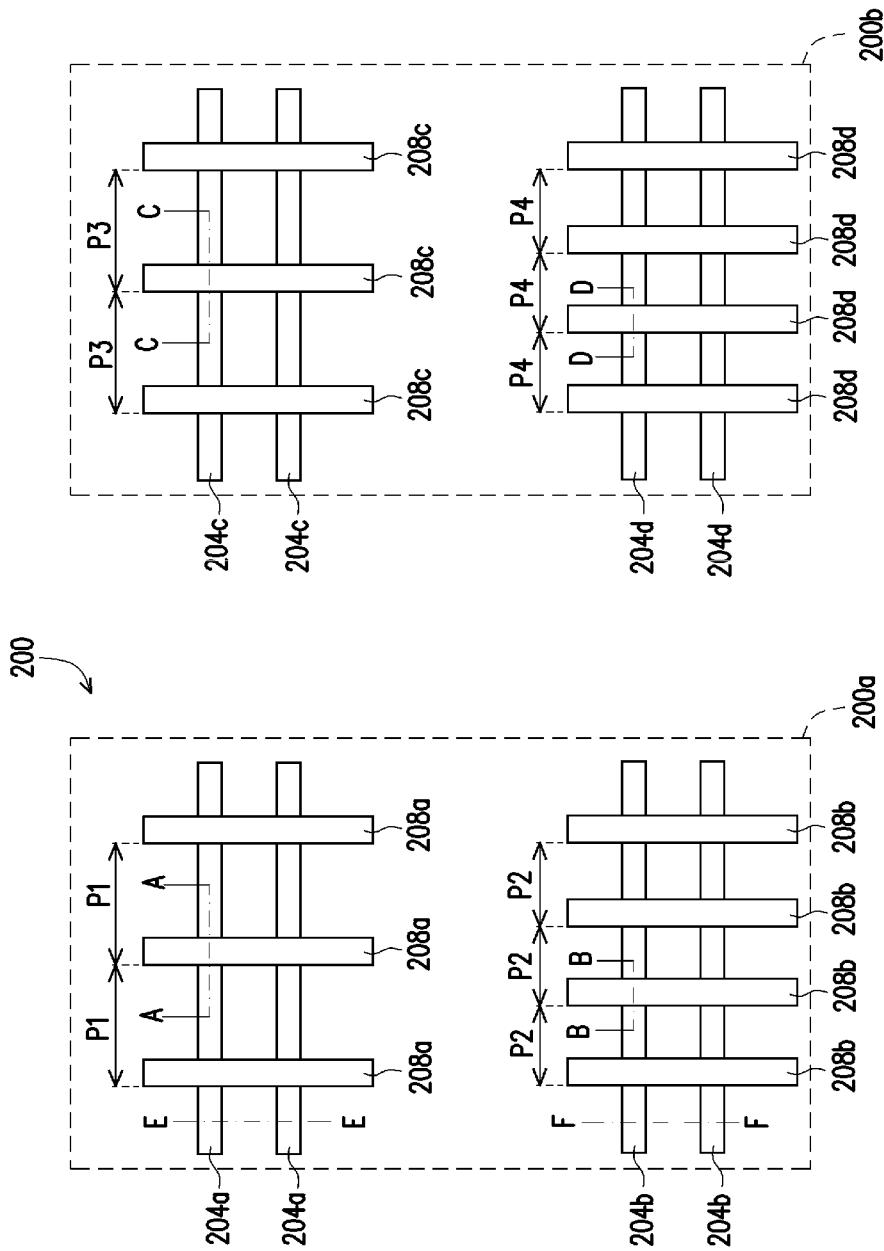


FIG. 2A

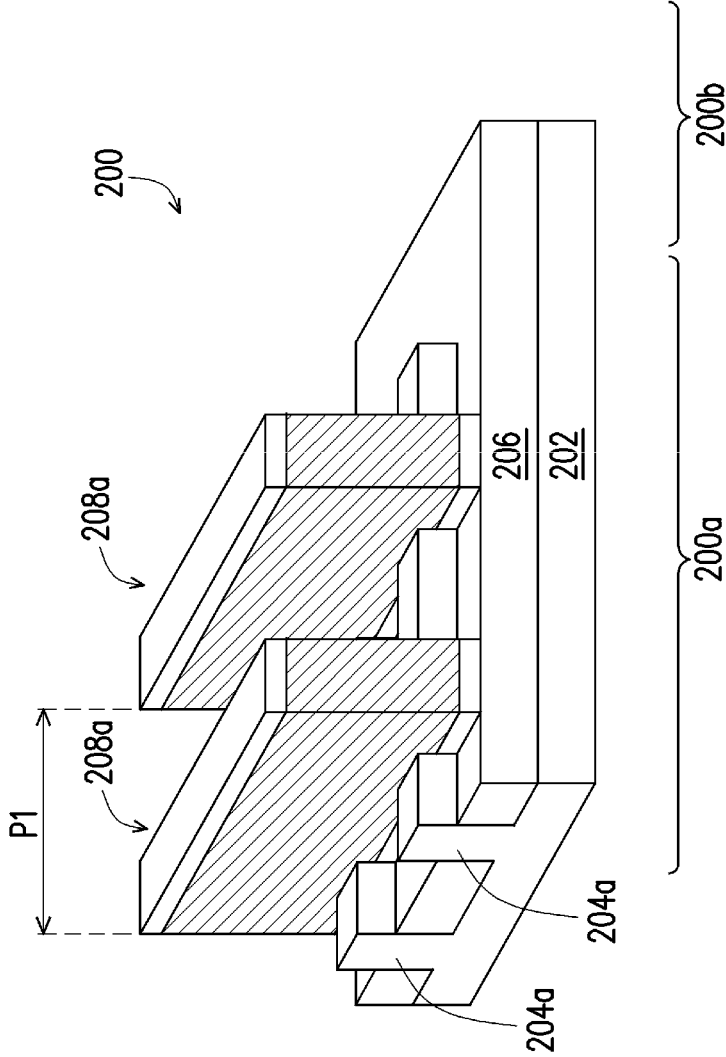


FIG. 2B

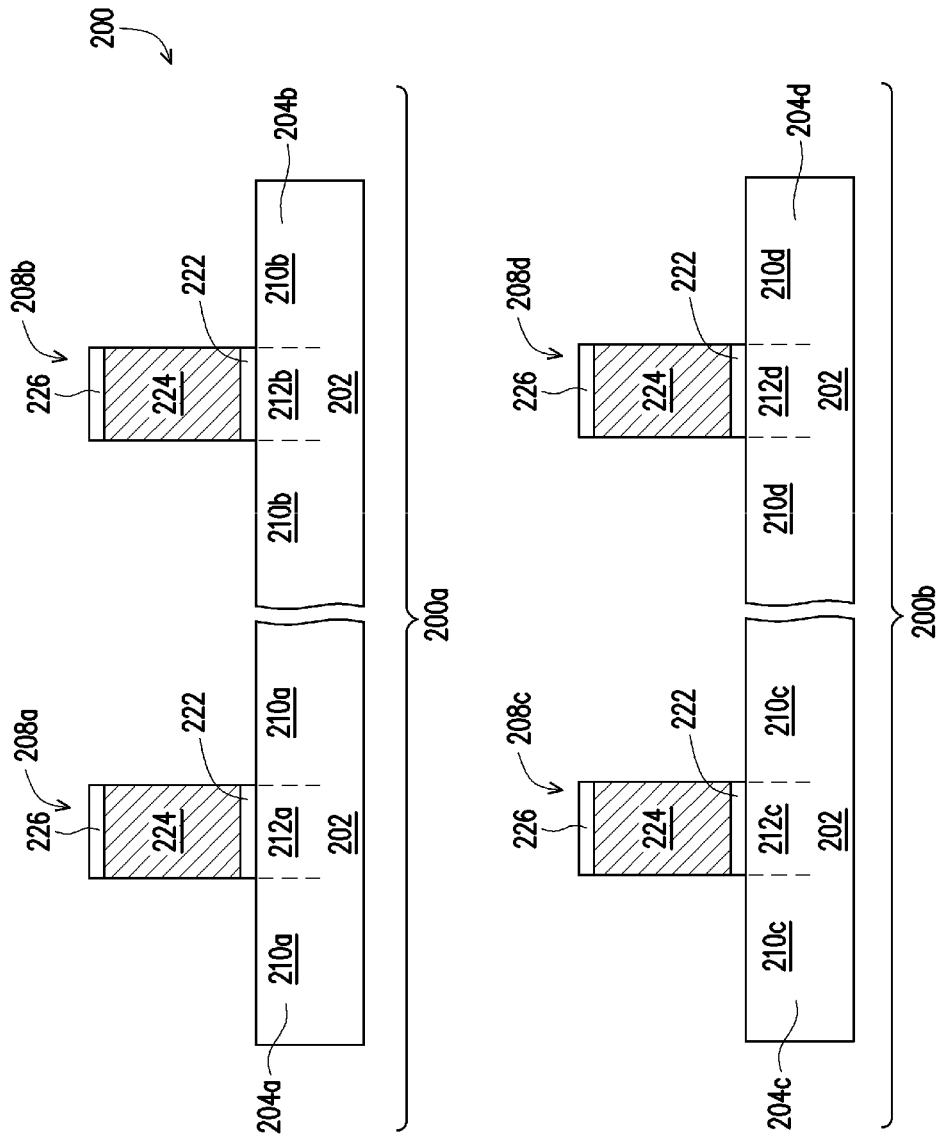


FIG. 2C

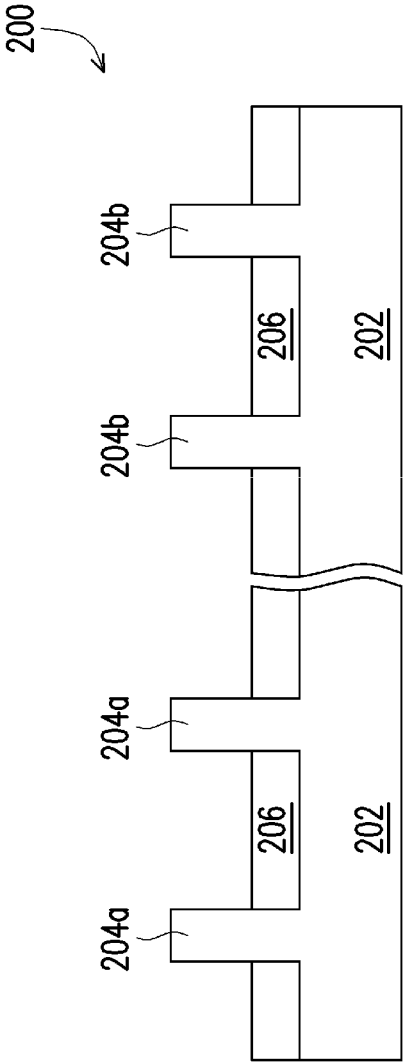


FIG. 2D

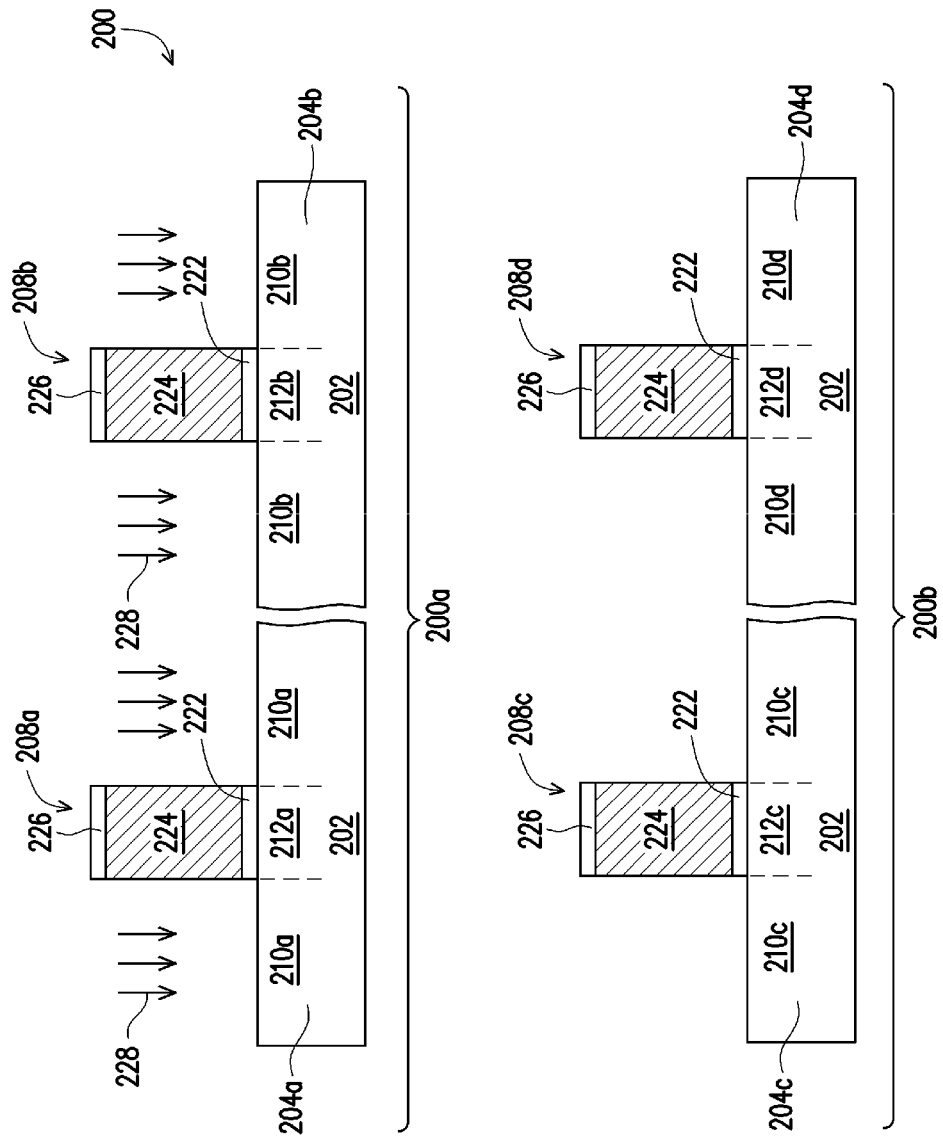


FIG. 3

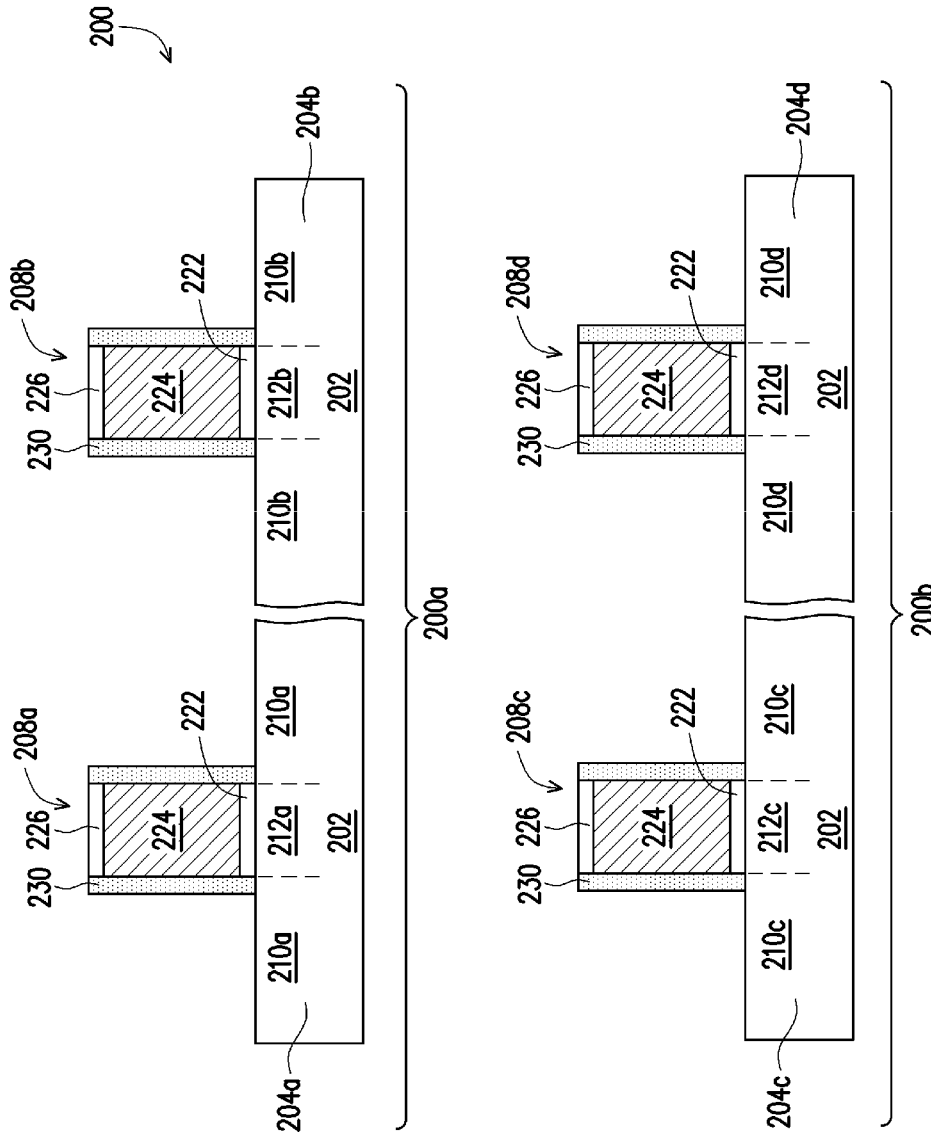


FIG. 4A

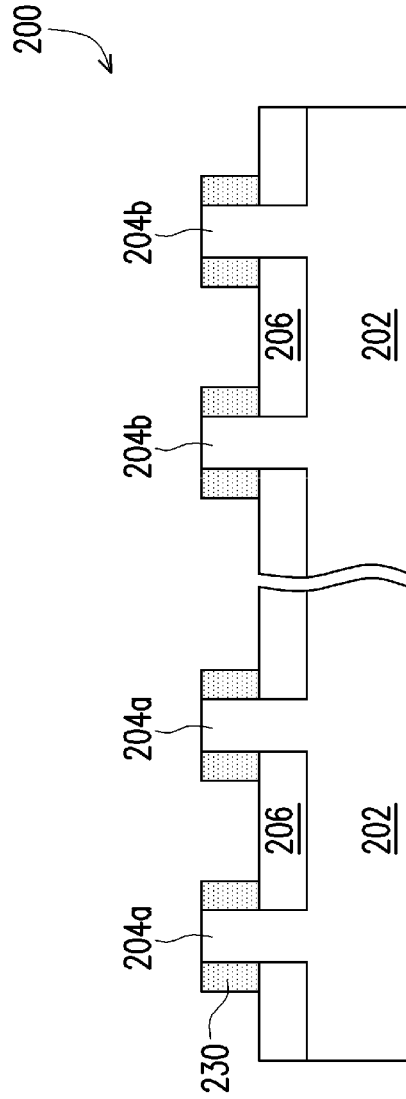


FIG. 4B

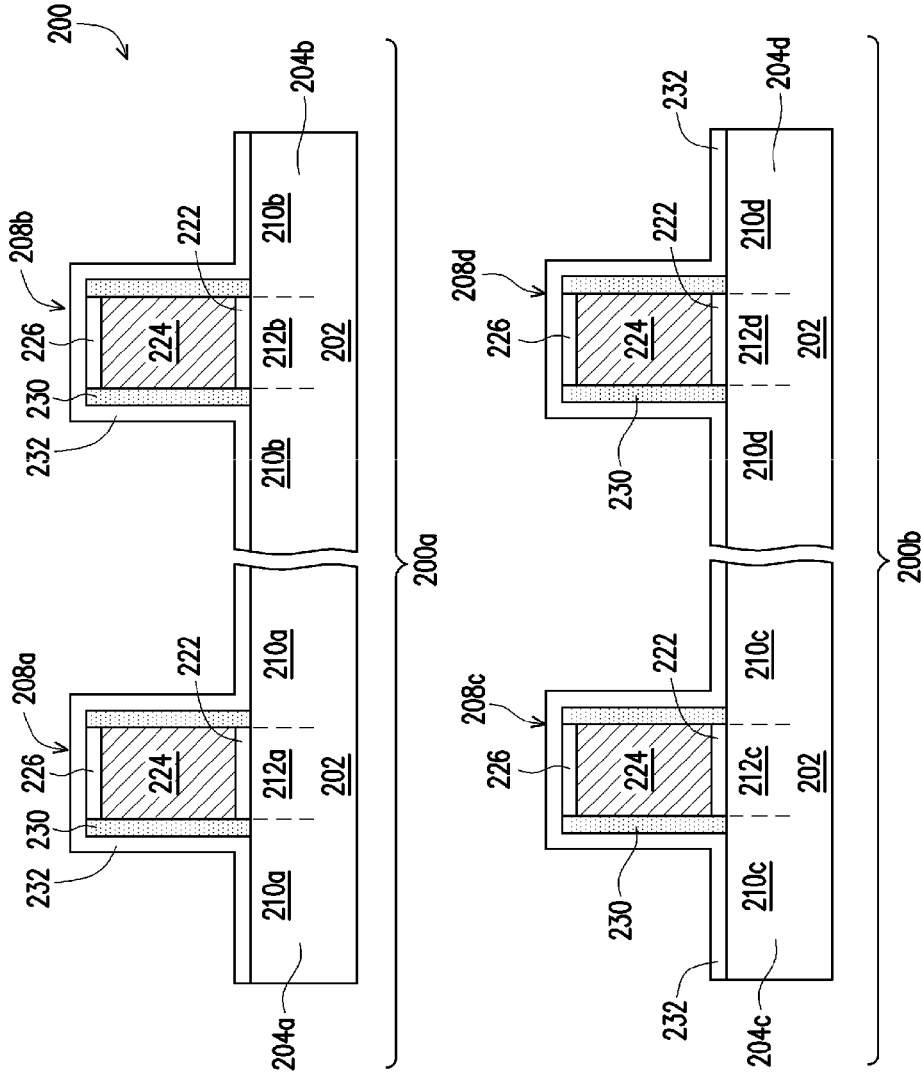


FIG. 5

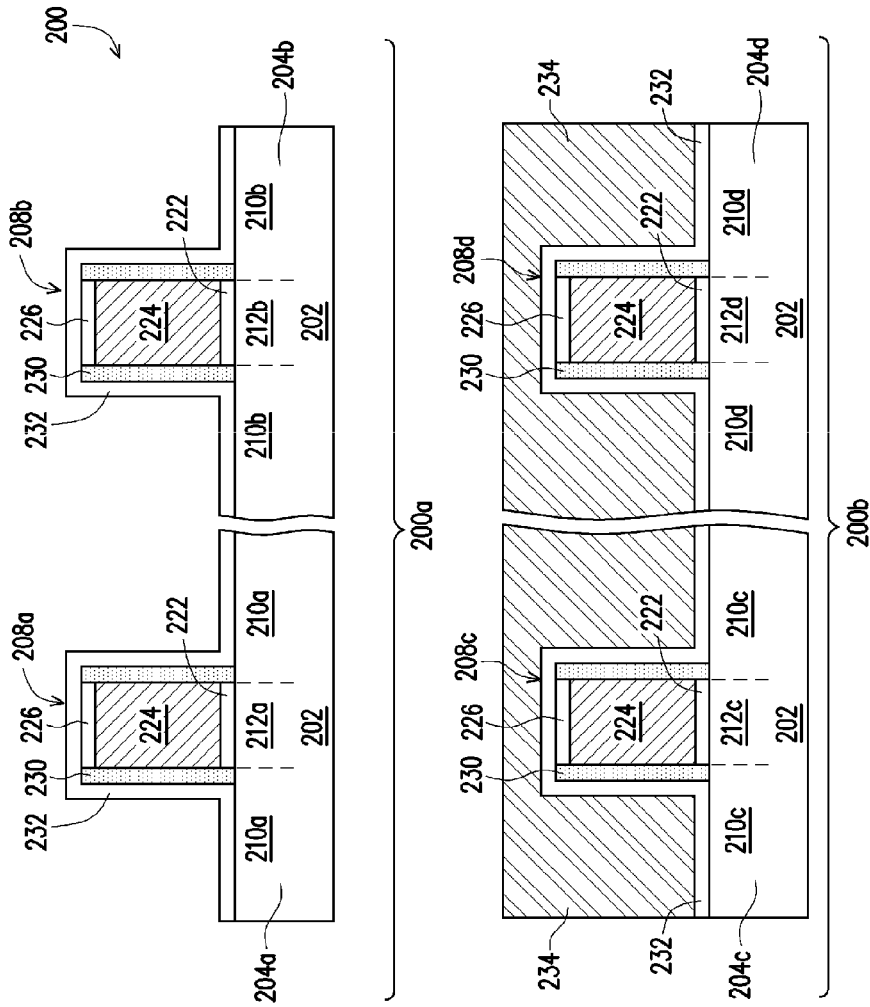


FIG. 6

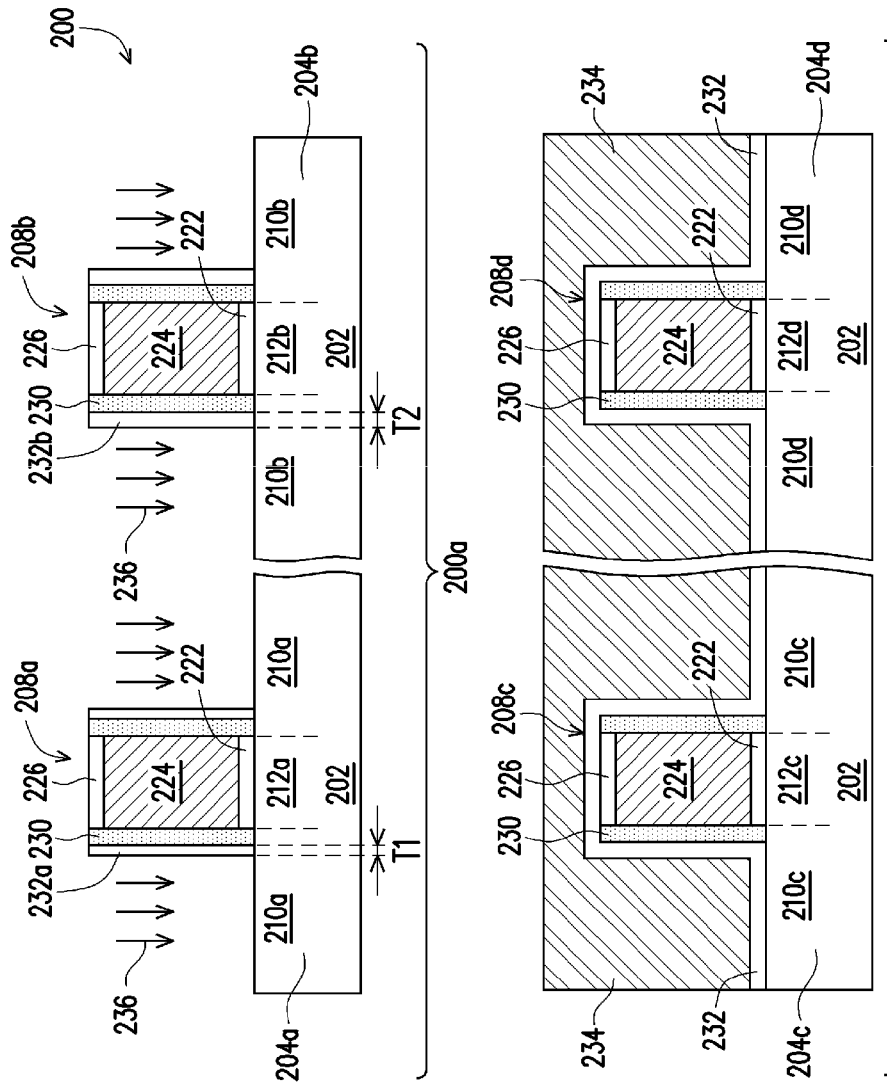


FIG. 7

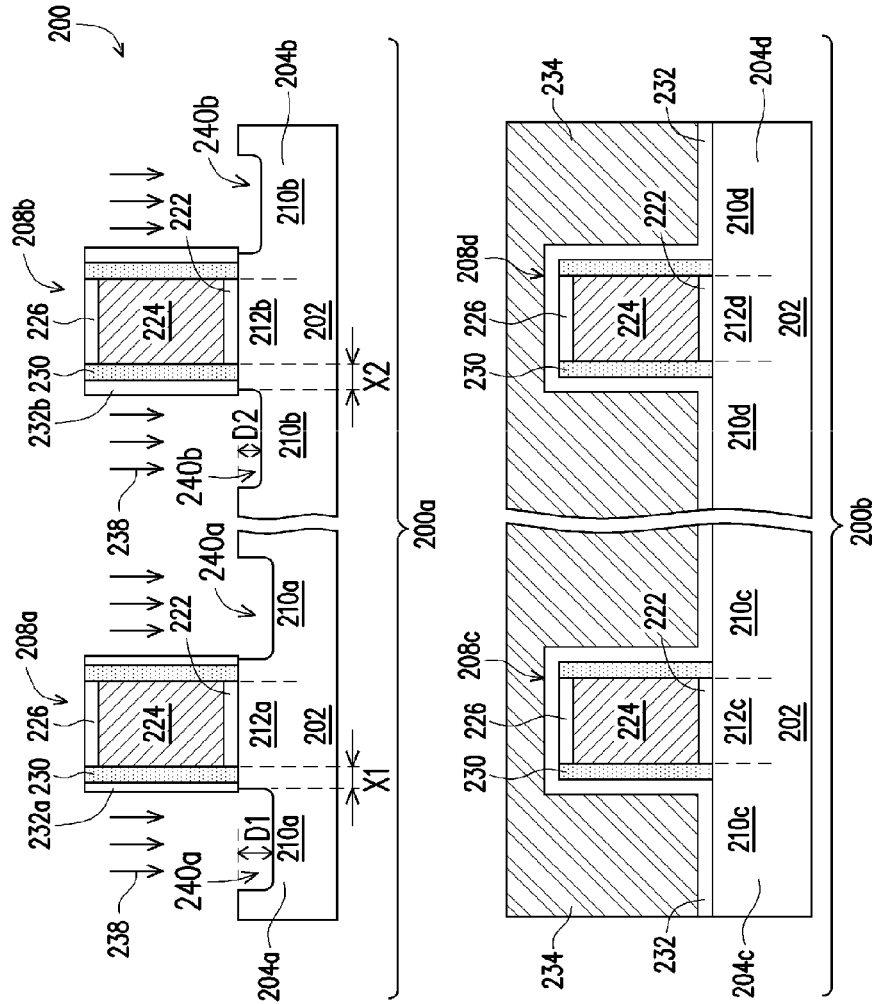


FIG. 8

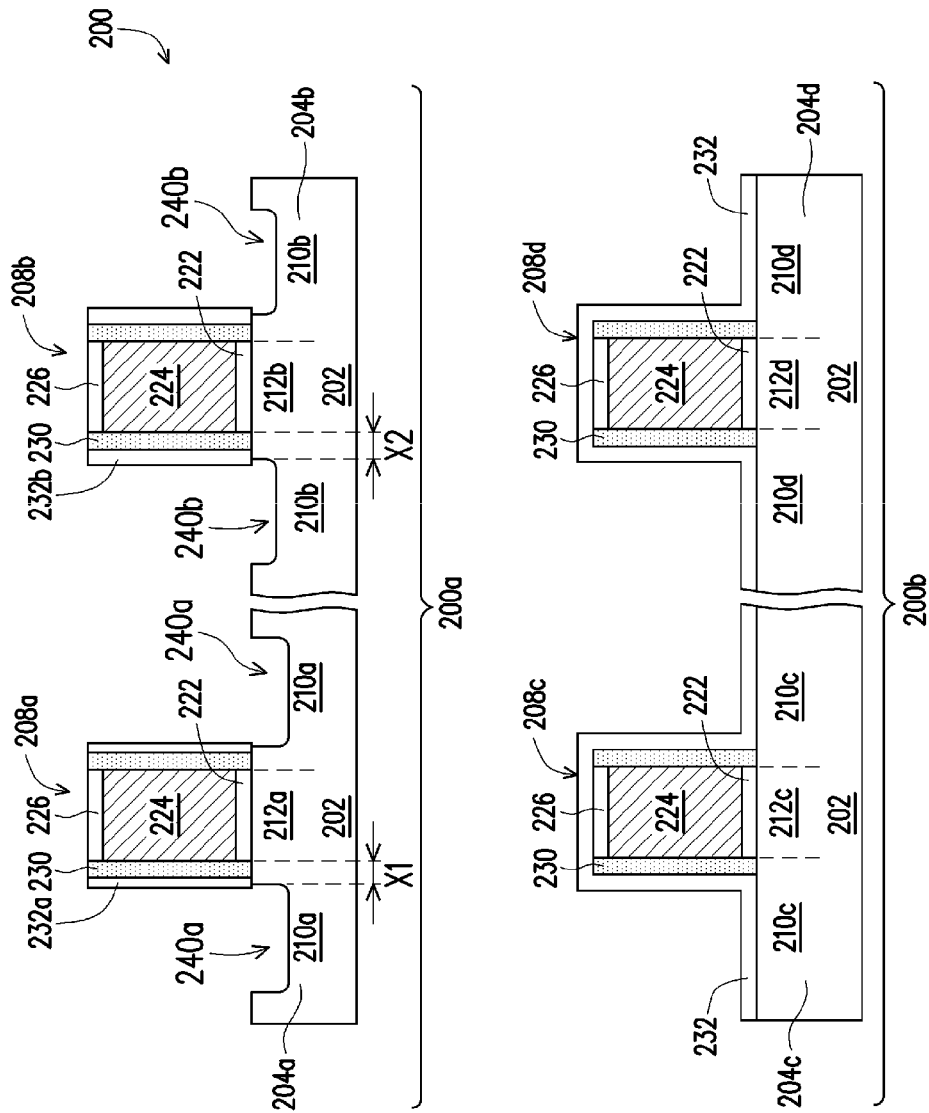


FIG. 9

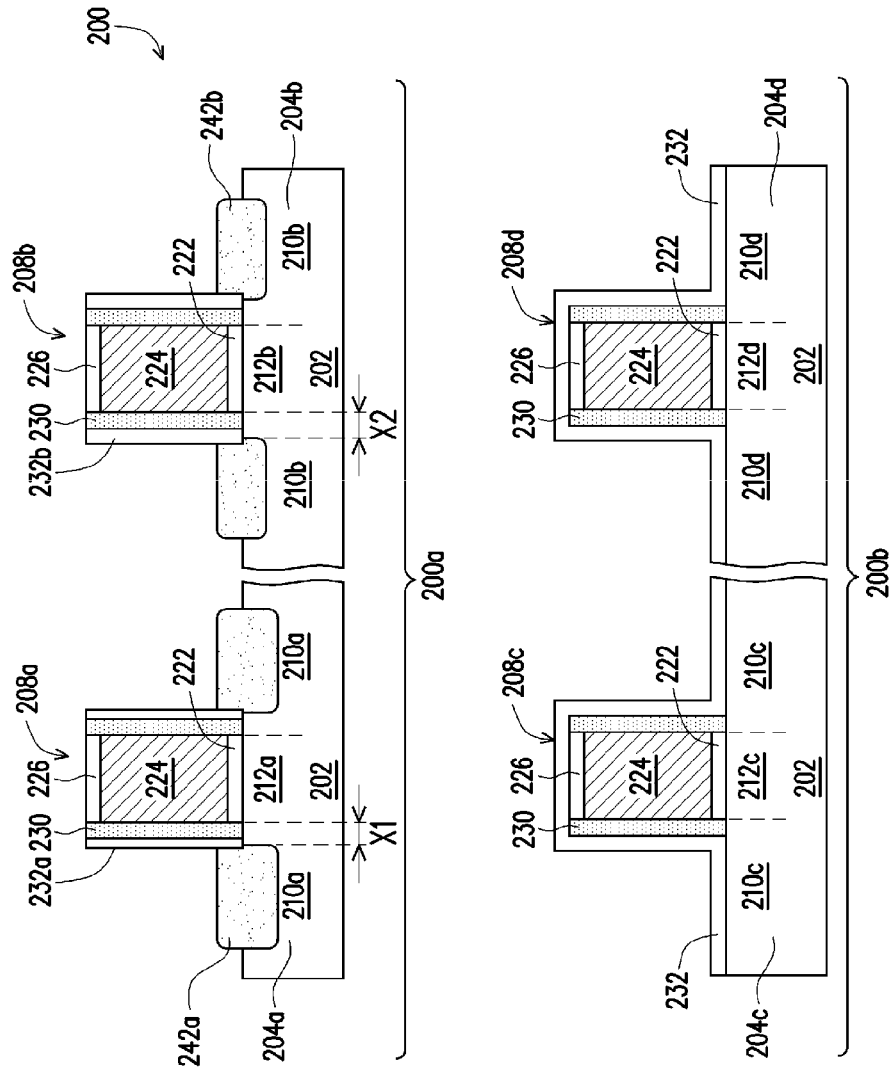


FIG. 10A

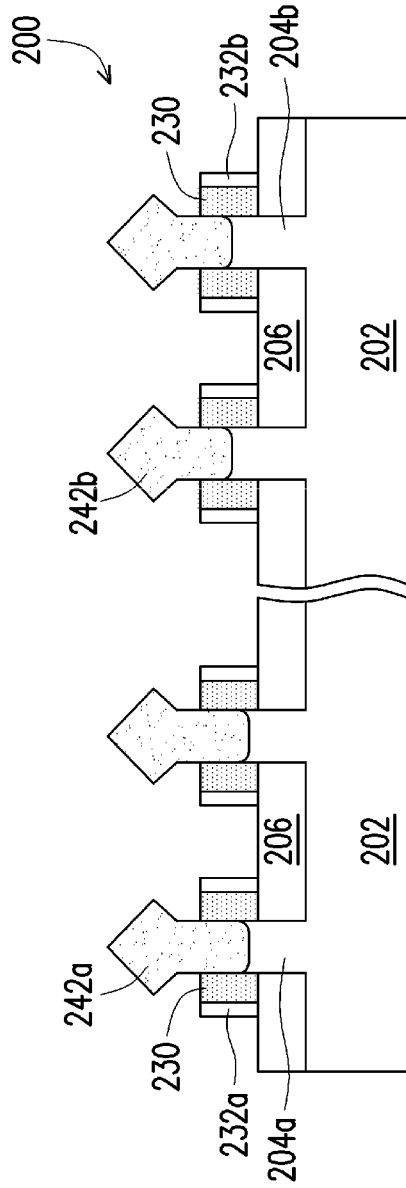


FIG. 10B

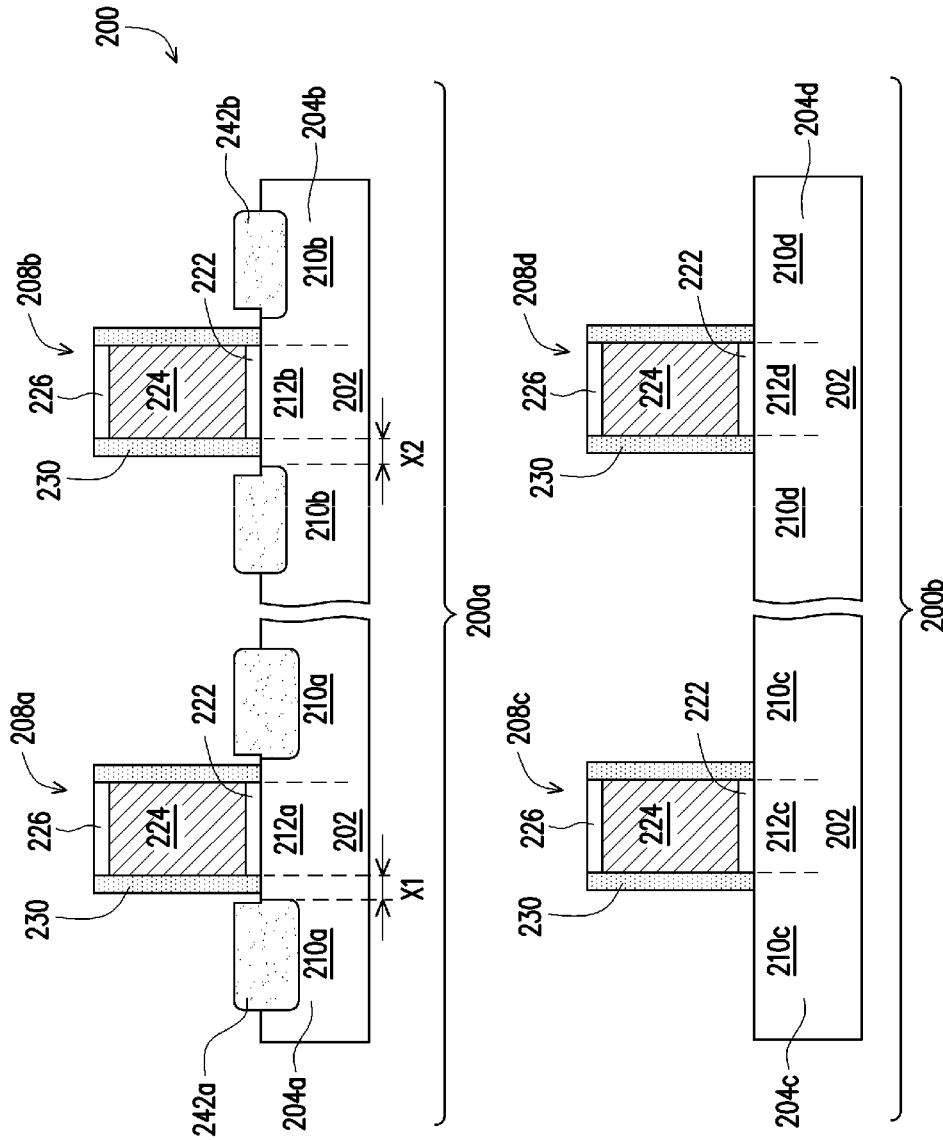


FIG. 11

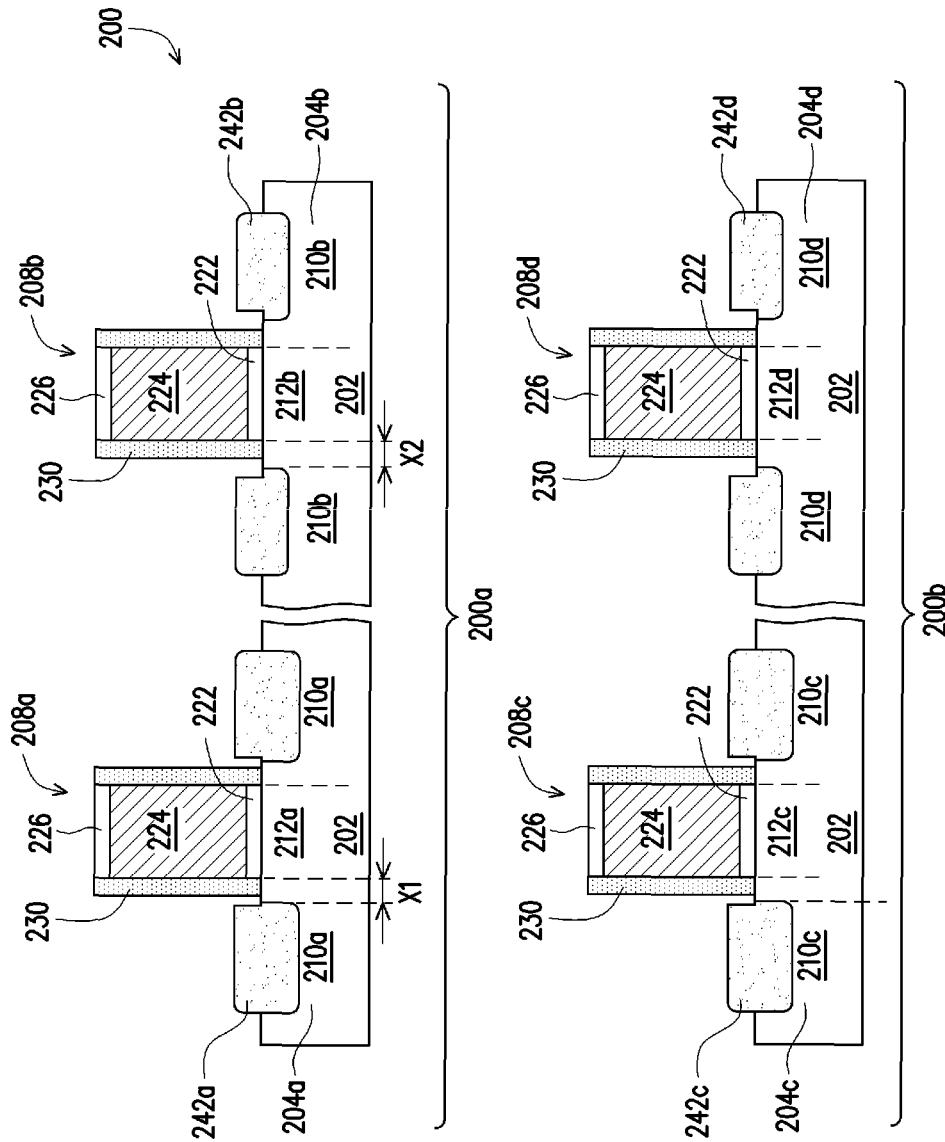


FIG. 12

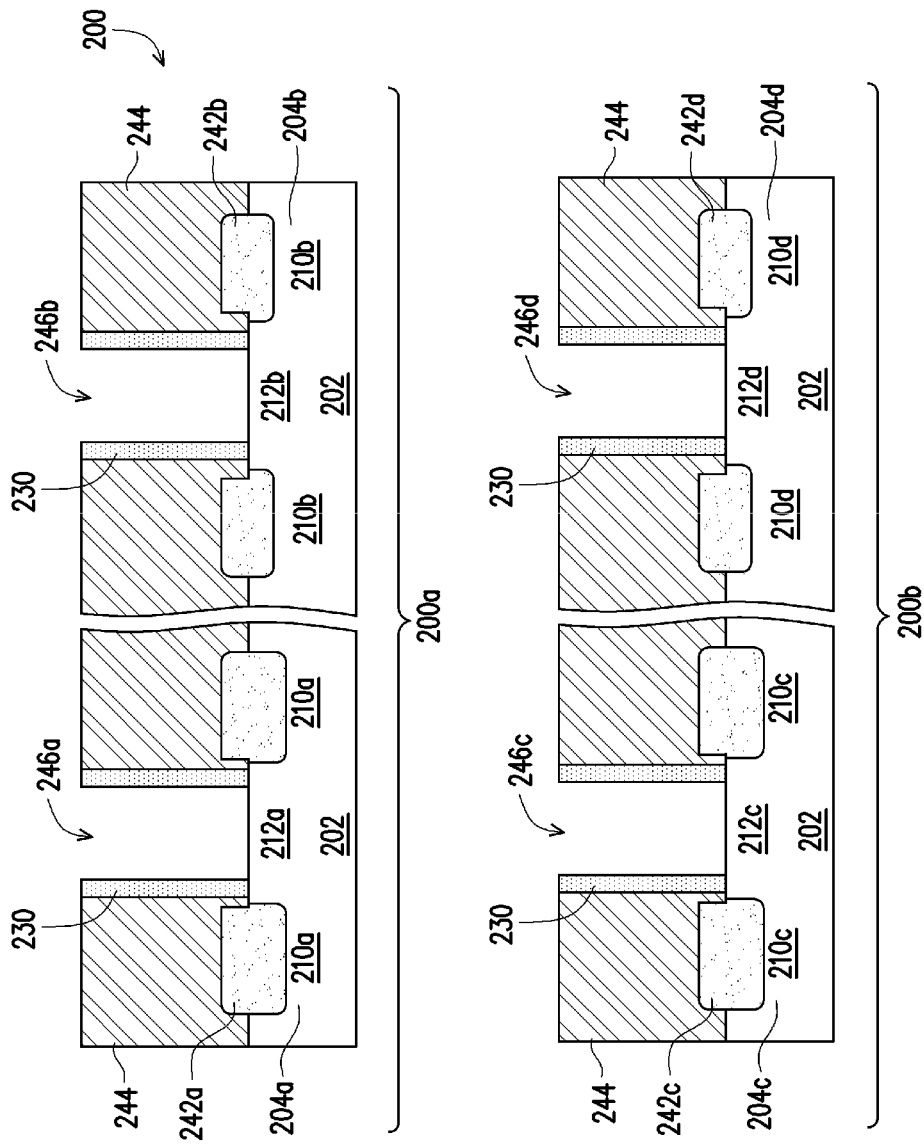


FIG. 13

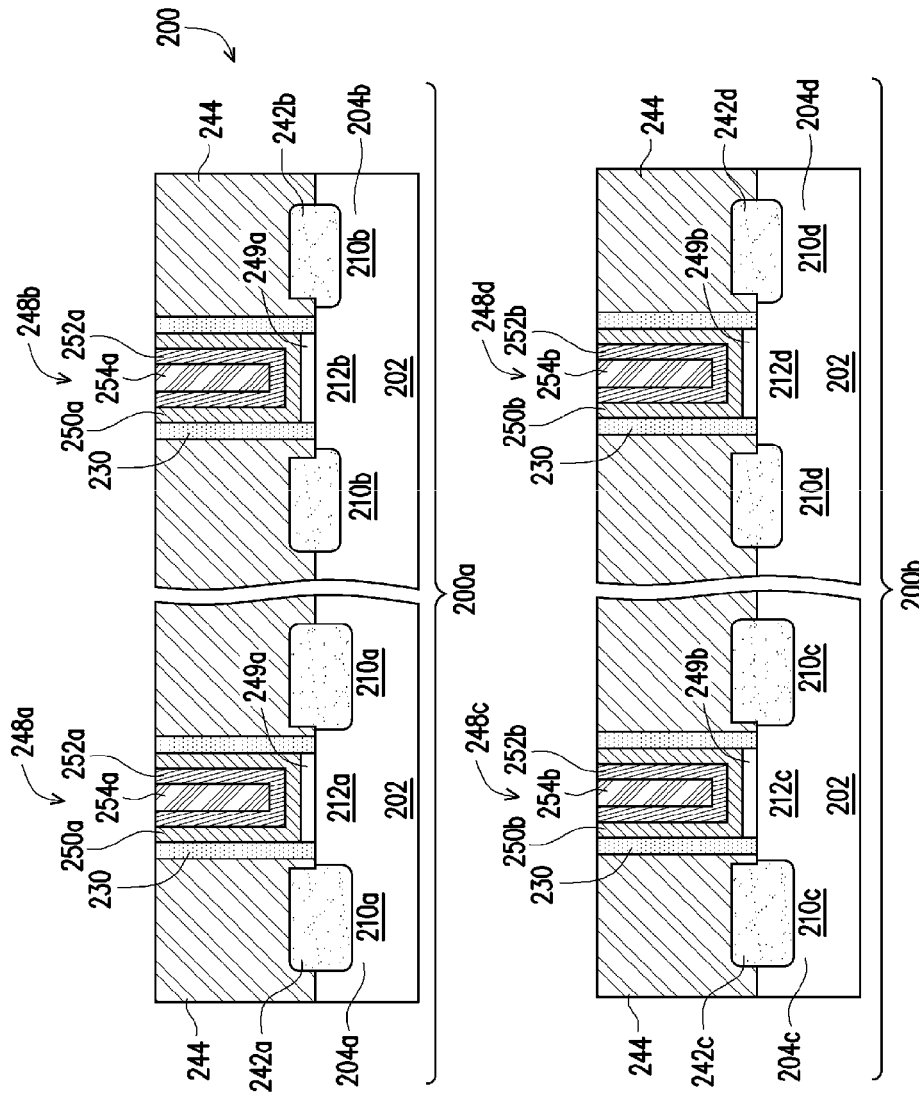


FIG. 14

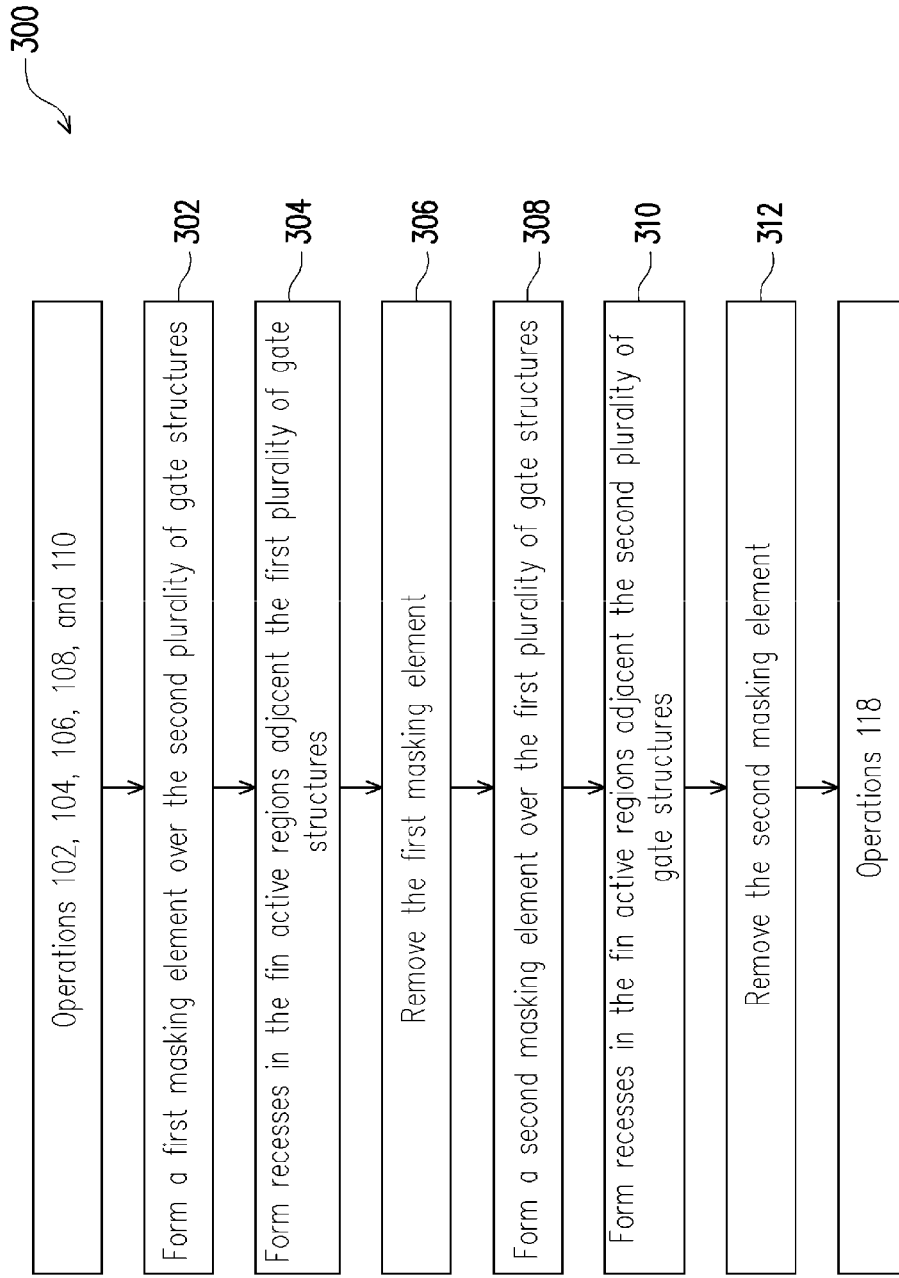


FIG. 15

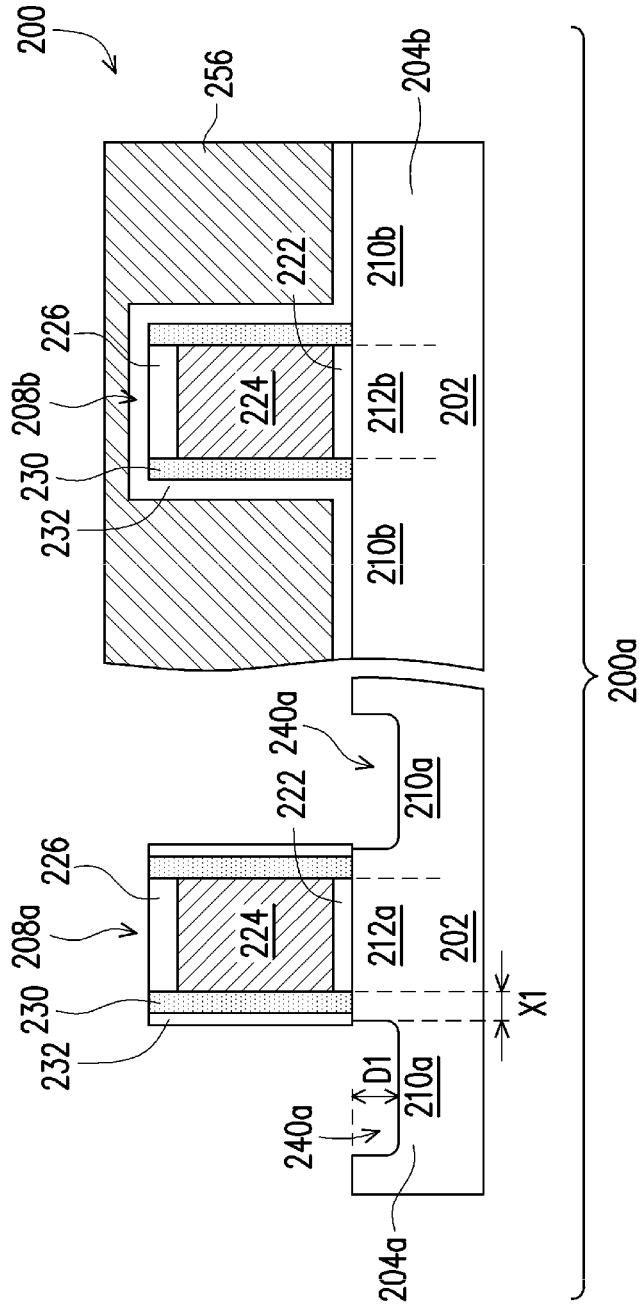


FIG. 16

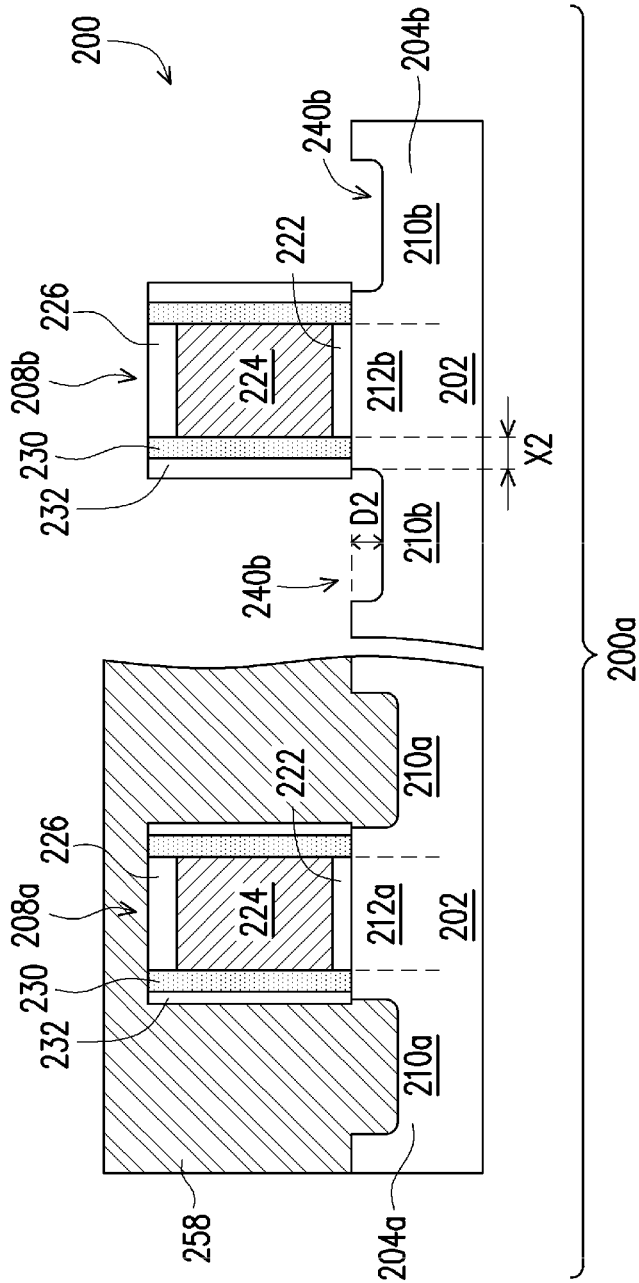


FIG. 17

METHOD FOR SEMICONDUCTOR DEVICE FABRICATION WITH IMPROVED SOURCE DRAIN EPITAXY

PRIORITY

This claims the benefit of U.S. Provisional Application Ser. No. 62/313,430, filed Mar. 25, 2016 and entitled "Method for Semiconductor Device Fabrication with Improved Source Drain Epitaxy," the entire disclosure of which is herein incorporated by reference.

BACKGROUND

The semiconductor integrated circuit (IC) industry has experienced exponential growth. Technological advances in IC materials and design have produced generations of ICs where each generation has smaller and more complex circuits than the previous generation. In the course of IC evolution, functional density (i.e., the number of interconnected devices per chip area) has generally increased while geometry size (i.e., the smallest component (or line) that can be created using a fabrication process) has decreased. This scaling down process generally provides benefits by increasing production efficiency and lowering associated costs. Such scaling down has also increased the complexity of processing and manufacturing ICs.

For example, as semiconductor devices, such as metal-oxide-semiconductor field effect transistors (MOSFETs), are scaled down through various technology nodes, strained source/drain features (e.g., stressor regions) have been implemented using epitaxial (epi) semiconductor materials to enhance carrier mobility and improve device performance. Forming a MOSFET with stressor regions often epitaxially grows silicon (Si) to form raised source and drain (S/D) features for an n-type device, and epitaxially grows silicon germanium (SiGe) to form raised S/D features for a p-type device. Various techniques directed at shapes, configurations, and materials of these S/D features have been implemented to further improve transistor device performance. Although existing approaches have been generally adequate for their intended purposes, they have not been entirely satisfactory in all respects. For example, in a device having memory devices and logic devices, transistor densities are generally higher in the memory device region than in the logic device region, imposing different requirements on the raised S/D features in the two regions and creating challenges in growing the raised S/D features in both regions simultaneously.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale and are used for illustration purposes only. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIGS. 1A and 1B show a block diagram of a method of forming a semiconductor device, according to various aspects of the present disclosure.

FIG. 2A illustrates a top view of a portion of a semiconductor structure at a fabrication stage according to the method of FIGS. 1A and 1B, in accordance with some embodiments.

FIG. 2B illustrates a perspective views of the semiconductor structure of FIG. 2A, in portion, in accordance with some embodiments.

FIGS. 2C and 2D illustrate cross-sectional views of the semiconductor structure of FIG. 2A, in portion, in accordance with some embodiments.

FIGS. 3, 4A, 4B, 5, 6, 7, 8, 9, 10A, 10B, 11, 12, 13, 14 illustrate cross-sectional views of the semiconductor structure of FIG. 2A, in portion, at various fabrication stages according to the method of FIGS. 1A and 1B, in accordance with some embodiments.

FIG. 15 shows a block diagram of another method of forming a semiconductor device, according to various aspects of the present disclosure.

FIGS. 16 and 17 illustrate cross-sectional views of the semiconductor structure of FIG. 2A, in portion, at various fabrication stages according to the method of FIG. 15, in accordance with some embodiments.

DETAILED DESCRIPTION

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

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.

The present disclosure is generally related to methods for semiconductor device fabrication, and more particularly to methods of forming field effect transistors (FETs) having raised epitaxial S/D features in memory devices (e.g., SRAM cells) and logic devices such as input/output (I/O) devices and logic gates including AND, OR, NOR, and inverters. Generally, memory devices and logic devices are in separate regions of an IC. Further, memory devices generally have a higher transistor density (i.e., smaller transistor pitch) than logic devices, for providing increased memory capacity of the IC. This creates some challenges for forming the raised S/D features in both types of devices at the same time. On the one hand, the S/D features in the logic devices are desired to have a large volume so as to stress or strain the devices' channel regions for improved carrier mobility. On the other hand, the S/D features in the memory devices, if grown too tall, might merge where separate S/D features are desired. Methods that fulfill requirements for

both the memory devices and logic devices simultaneously are desired for their improved production efficiency, which are the object of the present disclosure.

Referring to FIGS. 1A and 1B, shown therein is a method **100** of forming a semiconductor device according to various aspects of the present disclosure. The method **100** is an example, and is not intended to limit the present disclosure beyond what is explicitly recited in the claims. Additional operations can be provided before, during, and after the method **100**, and some operations described can be replaced, eliminated, or moved around for additional embodiments of the method. The method **100** is described below in conjunction with FIGS. 2A-14 which are different views of a semiconductor structure **200** according to various aspects of the present disclosure.

As will be shown, the semiconductor structure **200** illustrates various FinFETs in two device regions of a substrate: a first device region for forming p-type FinFETs and a second device region for forming n-type FinFETs. Further, the various FinFETs include FinFETs for memory devices and FinFETs for logic devices in each of the first and second device regions. The number and types of the device regions and the number and types of FinFETs are provided for simplification and ease of understanding and do not necessarily limit the embodiments to any types of devices, any number of devices, any number of regions, or any configuration of structures of regions. For example, the same inventive concept can be applied in fabricating planar FET devices. Furthermore, the semiconductor structure **200** may be an intermediate device fabricated during processing of an IC, or a portion thereof, that may comprise static random access memory (SRAM) and/or other logic circuits, passive components such as resistors, capacitors, and inductors, and active components such as p-type FETs (PFETs), n-type FETs (NFETs), FinFETs, metal-oxide semiconductor field effect transistors (MOSFET), complementary metal-oxide semiconductor (CMOS) transistors, bipolar transistors, high voltage transistors, high frequency transistors, other memory cells, and combinations thereof.

Referring to FIG. 1A, at operation **102**, the method **100** receives or is provided with a precursor of the semiconductor structure **200**. For the convenience of discussion, the precursor is also referred to as the semiconductor structure **200**. Referring to FIG. 2A, in a top view, the semiconductor structure **200** includes a first device region **200a** and a second device region **200b**. The first device region **200a** includes various fin active regions (or fins) **204a** and **204b** (two shown for each), and the second device region **200b** includes various fin active regions (or fins) **204c** and **204d** (two shown for each). In an embodiment, the fins **204a** and **204b** are suitable for forming p-type FinFETs, and the fins **204c** and **204d** are suitable for forming n-type FinFETs. In another embodiment, the fins **204a** and **204b** are suitable for forming n-type FinFETs, and the fins **204c** and **204d** are suitable for forming p-type FinFETs. The semiconductor structure **200** further includes various gate structures **208a**, **208b**, **208c**, and **208d**. The gate structures **208a-d** may have different pitches. A pitch is a distance from a gate structure to an adjacent gate structure. A pitch may be defined as from an edge of a gate structure to a corresponding edge of the adjacent gate structure (such as shown in FIG. 2A) or from a center line of a gate structure to the corresponding center line of an adjacent structure (not shown). Particularly, the gate structures **208a** engage the fins **204a** and have a first pitch **P1**, and the gate structures **208b** engage the fins **204b** and have a second pitch **P2**. In the present embodiment, **P1** is greater than **P2**. In an embodiment, the gate structures

208a (or their derivatives) and the fins **204a** collectively form FinFETs for one or more logic devices, while the gate structures **208b** (or their derivatives) and the fins **204b** collectively form FinFETs for one or more memory devices. Similarly, the gate structures **208c** engage the fins **204c** and have a third pitch **P3**, and the gate structures **208d** engage the fins **204d** and have a fourth pitch **P4**. In the present embodiment, **P3** is greater than **P4**. In an embodiment, the gate structures **208c** (or their derivatives) and the fins **204c** collectively form FinFETs for one or more logic devices, while the gate structures **208d** (or their derivatives) and the fins **204d** collectively form FinFETs for one or more memory devices.

Referring to FIG. 2B, shown therein is a perspective view of the semiconductor structure **200**, in portion, showing two gate structures **208a** over two fins **204a** in the device region **200a**. The semiconductor structure **200** includes a substrate **202** that extends in both the device regions **200a** and **200b**, and an isolation structure **206** over the substrate **202**. The fins **204a** (and the other fins **204b-d**, although not shown here) extend upwardly from the substrate **202** and through the isolation structure **206**. The substrate **202** is a silicon substrate in the present embodiment. Alternatively, the substrate **202** may include another elementary semiconductor, such as germanium; a compound semiconductor including silicon carbide, gallium arsenic, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide; an alloy semiconductor including SiGe, GaAsP, AlInAs, AlGaAs, GaInAs, GaInP, and/or GaInAsP; or combinations thereof. In yet another alternative, the substrate **202** is a semiconductor-on-insulator (SOI), such as a semiconductor substrate having a buried dielectric layer on which the fins **204a-d** stand. The isolation structure **206** may include silicon oxide, silicon nitride, silicon oxynitride, fluoride-doped silicate glass (FSG), a low-k dielectric material, air gap, and/or other suitable insulating material. The isolation structure **206** may be a shallow-trench-isolation (STI), field oxide, and/or other suitable structures. The isolation structure **206** may include a multi-layer structure, for example, having one or more thermal oxide liner layers.

The fins **204a-d** may be fabricated using a suitable procedure that includes photolithography and etch processes. In some embodiments, the fins **204a-d** are formed by a procedure that includes forming shallow trench isolation (STI) features **206**; and epitaxially growing a semiconductor material to form the fins **204a-d**. In some embodiments, the fins **204a-d** are formed by a procedure that includes forming shallow trench isolation (STI) features **206** and recessing the STI features **206** to form the fins **204a-d**. In some examples, the formation of the STI features **206** includes a photolithography process to form a patterned resist layer; etching an underlying hard mask through the openings of the patterned resist layer; etching the substrate **202** through the openings of the mask to form trenches in the substrate **202**; filling in the trenches with one or more dielectric material; and performing a chemical mechanical polishing (CMP) process to form the STI features **206**. The photolithography process may include forming a photoresist (resist) layer over the substrate **202**; exposing the resist layer to a pattern, performing post-exposure baking; and developing the resist layer to form the patterned resist layer. In various examples, the etching process can include dry etching, wet etching, reactive ion etching (RIE), and/or other suitable processes. For example, a dry etching process may implement an oxygen-containing gas, a fluorine-containing gas (e.g., CF₄, SF₆, CH₂F₂, CHF₃, and/or C₂F₆), a chlorine-containing gas (e.g., Cl₂, CHCl₃, CCl₄, and/or BCl₃), a bromine-containing

gas (e.g., HBr and/or CHBR₃), an iodine-containing gas, other suitable gases and/or plasmas, and/or combinations thereof. For example, a wet etching process may comprise etching in diluted hydrofluoric acid (DHF); potassium hydroxide (KOH) solution; ammonia; a solution containing hydrofluoric acid (HF), nitric acid (HNO₃), and/or acetic acid (CH₃COOH); or other suitable wet etchant. Numerous other embodiments of methods to form the fins **204a-d** on the substrate **202** may be suitable.

FIG. 2C shows cross-sectional view of the semiconductor structure **200** along the "AA," "BB," "CC," and "DD" lines of FIG. 2A, while FIG. 2D shows cross-sectional view of the semiconductor structure **200** along the "EE" and "FF" lines of FIG. 2A. Referring to FIGS. 2C and 2D collectively, the fins **204a**, **204b**, **204c**, and **204d** include source and drain (S/D) regions **210a**, **210b**, **210c**, and **210d** and channel regions **212a**, **212b**, **212c**, and **212d**, respectively. The gate structures **208a-d** are disposed over the channel regions **212a-d**, respectively. Each of the gate structures **208a-d** may include a gate dielectric layer **222**, a gate electrode layer **224**, and a hard mask layer **226**. The gate structures **208a-d** may include one or more additional layers. In an embodiment, the gate electrode layer **224** includes polysilicon. In the present embodiment, the gate structures **208a-d** are sacrificial gate structures, i.e., placeholder for final gate stacks.

The gate dielectric layer **222** may include a dielectric material such as silicon oxide, and may be formed by chemical oxidation, thermal oxidation, atomic layer deposition (ALD), chemical vapor deposition (CVD), and/or other suitable methods. The gate electrode layer **224** may include a single layer or multilayer structure. In an embodiment, the gate electrode layer **224** includes polycrystalline silicon (polysilicon) or amorphous silicon. The gate electrode layer **224** may be formed by suitable deposition processes such as low-pressure chemical vapor deposition (LPCVD) and plasma-enhanced CVD (PECVD). In some embodiment, the hard mask layer **226** is a layer of silicon nitride or silicon oxide. In some examples, the hard mask layer **226** may include two or more films, such as a silicon oxide film and a silicon nitride film. The hard mask layer **226** may be formed by deposition and etching processes similar to those forming the gate dielectric layer **222** and the gate electrode layer **224**. In an embodiment, the layers **222**, **224**, and **226** are first deposited as blanket layers over the substrate **202** having the fin active regions **204a-d**. Then the blanket layers are patterned through a process including photolithography processes and etching processes thereby removing portions of the blanket layers and keeping the remaining portions over the substrate **202** as the layers **222**, **224**, and **226**.

At operation **104**, the method **100** (FIG. 1A) performs lightly doped source/drain (LDD) ion implantation **228**. Referring to FIG. 3, the ion implantation **228** is performed to form LDD regions in the substrate **202**. The LDD implantation process **228** may utilize n-type dopants, such as phosphorus (P) or arsenic (As), for the NFETs, or p-type dopants, such as boron (B) or indium (In), for the PFETs. For example, operation **104** may implant n-type dopant(s) into the region **200a** and p-type dopant(s) into the region **200b**, or vice versa. The LDD regions are self-aligned with the gate structures **208a-b**. A mask layer (not shown) may be used to cover the region **200b** when the region **200a** is subject to the ion implantation process **228**. In some embodiments, the mask layer is a patterned photoresist. In some embodiments,

combination thereof. The mask layer is removed after the LDD implantation has completed in the region **200a**. Similarly, although not shown, the operation **104** performs ion implantation in the region **200b** while a mask layer covers the region **200a**. The mask layer is removed after the LDD implantation has completed in the region **200b**.

At operation **106**, the method **100** (FIG. 1A) forms spacers **230** over the substrate **202** and on sidewalls of the gate structures **208a-d** and the fin active regions **204a-d**. Referring to FIG. 4A, the spacers **230** are formed on sidewalls of the gate structures **208a-d**. Referring to FIG. 4B, the spacers **230** are formed on sidewalls of the fin active regions **204a-b**. Although not shown, the spacers **230** are also formed on sidewalls of the fin active regions **204c-d**. The spacers **230** on the sidewalls of the fin active regions **204a-d** are also referred to as fin sidewall (FSW) spacers **230**, while the spacers **230** on the sidewalls of the gate structures **208a-d** are also referred to as gate sidewall (GSW) spacers **230**. The spacers **230** include a dielectric material, such as silicon oxide, silicon nitride, silicon oxynitride, silicon carbon nitride, a low-k nitride, or a combination thereof. The spacers **230** may include multiple films, such as a silicon oxide film and a silicon nitride film. In an embodiment, the spacers **230** have a thickness in a range from about 2 to about 10 nm. The formation of the spacers **230** may include deposition and anisotropic etch. In some examples, the deposition may include CVD, ALD, or other suitable methods. In some examples, the anisotropic etch may include a dry etch, such as a plasma etch with a bias and a suitable etchant, such as CF₄, SF₆, NF₃, CH₂F₂ or a combination thereof. In an embodiment, the FSW spacers **230** are optional, i.e., they may be removed by one or more selective etching process.

At operation **108**, the method **100** (FIG. 1A) deposits a first dielectric layer **232** covering the substrate **202**, the isolation structure **206**, and the gate structures **208a-d**. Referring to FIG. 5, the first dielectric layer **232** is deposited over the top surfaces of the substrate **202** and the gate structures **208a-d**, and over the sidewalls of the fin active regions **204a-d** and the gate structures **208a-d**. Particularly, the first dielectric layer **232** is deposited over both regions **200a** and **200b**. In an embodiment, the first dielectric layer **232** includes a nitride, such as silicon nitride or silicon oxynitride. The first dielectric layer **232** may be deposited as a conformal layer, i.e., having a substantially uniform thickness as a blanket over the various structures. Alternatively, the thickness of the first dielectric layer **232** may be non-uniform. In some embodiments, the thickness of the first dielectric layer **232** is in a range from about 2 nm to about 10 nm, such as about 4 nm. As will be shown later, the thickness of the first dielectric layer **232** on the sidewalls of the gate structure **208a-d** affects proximity of S/D epitaxy to the channel regions **212a-d**. The first dielectric layer **232** may be deposited using CVD, ALD, or other suitable methods.

At operation **110**, the method **100** (FIG. 1A) forms a masking element **234** over the region **200b**. Referring to FIG. 6, the mask element **234** is deposited over the various structures in the region **200b**, while exposing the first dielectric layer **232** in the region **200a**. In an embodiment, the masking element **234** is a patterned resist and is formed by a process including spin-on coating a resist over the device **200**, soft baking the resist, exposing the resist to a pattern, performing post-exposure bake processes, and developing the resist to form the masking element **234** including the resist.

At operation 112, the method 100 (FIG. 1A) performs an etching process 236 to the first dielectric layer 232 in the region 200a while the masking element 234 protects the first dielectric layer 232 in the region 200b. Referring to FIG. 7, the etching process 236 removes the first dielectric layer 232 from the top surfaces of the substrate 202 and the gate structures 208a-d, while leaving a vertical portion 232a and 232b of the first dielectric layer 232 on the sidewalls of the gate structures 208a and 208b, respectively. In an embodiment, the etching process 236 is selective to the material(s) of the first dielectric layer 232. In another word, while etching the first dielectric layer 232, the etching process 236 does not etch (or insignificantly etches) the hard mask layer 226 and the substrate 202. In an embodiment, the etching process 236 is an anisotropic dry etching process that is properly biased to provide a much faster etching rate vertically than laterally.

As discussed with respect to FIG. 2A, the device density is different in memory device regions and in logic device regions in the semiconductor structure 200. The memory device regions generally have a higher device density than the logic device regions. For example, the gate pitch P2 is smaller than the gate pitch P1 in FIG. 2A. Although not shown, the fin pitches (distance from one fin active region to an adjacent fin active region) may also be different in the two regions, with the fin pitch in the memory device regions being smaller than in the logic device regions. The different device density, coupled with the topography of the fin active regions 204a-b and the gate structures 208a-b, create loading effects to the etching process 236. In another word, the etching process 236 may remove the first dielectric layer 232 with slightly different etching rates in the memory device region and in the logic device region. In the present disclosure, the etching process 236 is tuned to have different lateral etching rates to the first dielectric layer 232 while completely removing the first dielectric layer 232 from the top surface of the substrate 202. A net effect is that the first dielectric layers 232a and 232b have different thicknesses, T1 and T2, respectively. The benefits of such tuning will become evident in a later section of the present disclosure.

In an embodiment, the etching process 236 includes a cyclic process having repetitions of an etching cycle and a deposition cycle. For example, it may perform an etching cycle followed by a deposition cycle, and repeats the etching and deposition cycles. During the etching cycle, it introduces an etchant gas such as a gas containing fluorine, chlorine, oxygen, bromine, or iodine for removing the first dielectric layer 232. During the deposition cycle, it introduces a deposition gas such as a carbon-containing gas for forming some polymeric material over the surface of the semiconductor structure 200. The polymeric material deposited during the deposition cycle(s) generally covers both the top surface (horizontal portion) and the sidewalls (vertical portion) of the first dielectric layer 232. The portion of the polymeric material deposited over the sidewalls of the first dielectric layer 232 temporally protects the vertical portions of the first dielectric layer 232 from the next etching cycle. The portion of the polymeric material deposited over the top surface of the first dielectric layer 232 does not provide as much protection to the horizontal portion of the first dielectric layer 232 because the etching is vertically oriented and the polymeric material does not provide much etch resistance. The inventors of the present disclosure have discovered that by tuning the parameters of the etching cycles and the deposition cycles, the etching process 236 can be controlled to produce different thicknesses T1 and T2. In the present embodiment, the etching process 236 is tuned to

result in T1 being less than T2. The parameters to be tuned include, but not limited to, the chemistry of the etching gas and the deposition gas as well as the flow rates thereof, etching pressure, etching cycle duration, deposition cycle duration, and the number of repetitions.

In an embodiment, the first dielectric layer 232 is a layer of silicon nitride of about 4 nm, and the etching process 236 may include more than four repetitions of an etching cycle and a deposition cycle in a cyclic manner. During the etching cycle, the etchant gas may include a fluorine-containing chemical such as CF₄ or CH₃F. The etching cycle may additionally use oxygen as an etching promoter. For example, it may use CH₃F gas and oxygen gas together. During the deposition cycle, a deposition gas containing carbon and hydrogen, such as CH₄, may be used. Each of the etching cycles and the deposition cycles may run for about 10 seconds to 20 seconds and the above etching and deposition gases may be introduced at a flow rate of about 15 to 25 standard cubic centimeters per minute (SCCM). The process pressure may be kept at about 20 mTorr to about 60 mTorr. In this embodiment, when the etching process 236 finishes, T2 is greater than T1, for example, by 1 to 2 nm.

In an embodiment, the etching process 236 includes a main etching process and an over etching process. For example, the main etching process may be used for breaking through, and removing the majority of, the horizontal portion of the first dielectric layer 236. This may be particularly effective in the logic device region. The over etching process may be used for removing any remaining of the horizontal portion of the first dielectric layer 236, particularly in the memory device region. The main etching process may use a lower pressure, higher bias voltage, and stronger etchant gases than the over etching process. The main etching process may run for shorter duration than the over etching process. For example, the main etching process may run for about 10 to 12 seconds, while the over etching process may run 60 seconds or longer. In an embodiment, the above cyclic process is implemented in the over etching process for fine tuning the thicknesses T1 and T2.

At operation 114, the method 100 (FIG. 1B) etches the substrate 202, particularly the fin active regions 204a-b, adjacent the gate structures 208a-b. Referring to FIG. 8, the operation 114 performs an etching process 238 thereby forming recesses 240a and 240b adjacent the gate structures 208a and 208b, respectively. The etching process 238 may be a dry etching process, a wet etching process, or other suitable etching processes. Due to a relatively larger device pitch in the logic device region than in the memory device region, relatively more etchant reaches the fin active regions 204a than the fin active region 204b. Consequently, the recesses 240a are etched deeper than the recesses 240b. In another word, a depth D1 of the recesses 240a is greater than a depth D2 of the recesses 240b. The layers 232a-b further contribute to the difference in the depths of the recesses 240a-b because the thicker layer 232b further limits the amount of etchant reaching the fin active region 204b. In various embodiments, the etching process 238 may be tuned (with the help of the device pitches P1 and P2 and the thicknesses T1 and T2) to produce the depth D1 in a range from about 50 to about 60 nm and the depth D2 in a range from about 35 to about 45 nm. In the present embodiment, D1 is greater than D2 by at least 15 nm to create sufficient depth loading for a subsequent epitaxial growth process.

In the present embodiment, the etching process 238 also laterally etches the fin active regions 204a-b such that the recesses 240a-b laterally expand under the first dielectric layers 232a-b, and even under the GSW spacers 230 in some

embodiments. A proximity X1 is defined to be a horizontal distance from a vertical extension of the gate structure 208a to the nearest edge (or surface) of the recess 240a. A proximity X2 is defined to be a horizontal distance from a vertical extension of the gate structure 208b to the nearest edge (or surface) of the recess 240b. In the present embodiment, X2 is greater than X1. For example, X2 may range from about 5 nm to about 8 nm while X1 may range from about 3 nm to about 6 nm. The difference between X1 and X2 is a result of different device pitches P2 and P1, different thicknesses T1 and T2 of the first dielectric layer 232, among other factors.

At operation 116, the method 100 (FIG. 1B) removes the masking element 234 from the device region 200b (FIG. 9). In an embodiment, the masking element 234 is a patterned resist and may be removed by a resist stripping process or a plasma ashing process. The removal of the masking element 234 is desirable for preventing contamination in a subsequent epitaxial growth process (such as operation 118 to be discussed). Operation 116 may subsequently perform a cleaning process to clean the recesses 240a-b.

At operation 118, the method 100 (FIG. 1B) epitaxially grows source and drain (S/D) features 242a and 242b in the recesses 240a and 240b respectively. Referring to FIGS. 10A and 10B, the S/D features 242a-b fill the recesses 240a-b and further grow above a top surface of the fin active regions 204a-b. In the present embodiment, the S/D features 242a-b are further raised above a top surface of the gate dielectric layer 222. The raised S/D features 242a-b provide stress to the channel region 212a-b for improved device performance. Further, the S/D features 242a are deeper and have a greater volume than the S/D features 242b, which provides a relatively greater stress to the channel region 212a. At the same time, two adjacent S/D features 242b are properly separated from each other (FIG. 10B). Thus, operation 118 satisfies requirements for both logic devices and memory devices simultaneously. One explanation for this phenomenon is as follows. Since the recesses 240b are relatively shallower and smaller, the silicon areas for epitaxial growth are relatively smaller. Therefore, the growth rate of the epitaxial features 242b is relatively slower than the epitaxial features 242a, and when the epitaxial features 242a are properly raised, the epitaxial features 242b still stay separated.

In an embodiment, the epitaxial growth process is a low pressure chemical vapor deposition (LPCVD) process using a silicon-based precursor gas. Further, in the present example, the epitaxial growth process in-situ dopes the grown S/D features 242a-b with an n-type dopant such as P, As, or combinations thereof for forming the source/drain features for NFETs or a p-type dopant such as B for forming the source/drain features for PFETs. In some examples, for PFETs, the S/D features 242a-b include silicon germanium, germanium or a combination. For NFETs, the S/D features 242a-b include silicon carbon, silicon or a combination.

At operation 120, the method 100 (FIG. 1B) removes the first dielectric layer 232 from the semiconductor structure 200 using a selective etching process. In an embodiment, the first dielectric layer 232 includes silicon nitride and operation 120 may use a chemical containing H₃PO₄ to remove the first dielectric layer 232 while keeping various other structures substantially intact, as shown in FIG. 11.

At operation 122, the method 100 (FIG. 1B) may perform steps similar to operations 108, 110, 112, 114, 116, and 118 as discussed above to form S/D features 242c and 242d adjacent the gate structures 208c and 208d respectively as shown in FIG. 12. For example, it may deposit a second

dielectric layer covering the semiconductor structure 200 including the substrate 202 and the gate structures 208a-d. The second dielectric layer may use a material similar to the first dielectric layer 232, such as silicon nitride. Then operation 122 forms a second masking element over the second dielectric layer in the first region 200a and performs a second etching process to the second dielectric layer in the second region 200b. The second etching process may be similar to the first etching process 236. For example, the second etching process may include a cyclic process having repetitions of an etching cycle and a deposition cycle as discussed above. The second etching process results in a thicker portion of the second dielectric layer on the sidewalls of the gate structures 208d than on the sidewalls of the gate structures 208c due to the pitches P3 being greater than P4. Then, operation 122 etches the substrate 202 adjacent the gate structures 208c-d to form recesses. The recesses are deeper adjacent the gate structures 208c than adjacent the gate structures 208d. Also, the recesses are closer to the gate structures 208c than to the gate structures 208d. Next, operation 122 removes the second masking element and epitaxially grows the S/D features 242c-d in the recesses, as shown in FIG. 12.

At operation 124, the method 100 (FIG. 1B) performs further steps to fabricate a final IC device. In an embodiment, the method 100 replaces the gate structure 208a-d with high-k metal gate stacks. Referring to FIG. 13, an inter-layer dielectric (ILD) layer 244 is formed over substrate 202 by a procedure, such as deposition and CMP. In an embodiment, the ILD layer 244 is formed by a flowable CVD (FCVD) process. The FCVD process includes depositing a flowable material (such as a liquid compound) on the substrate 202 to fill the gaps between the various structures and converting the flowable material to a solid material by a suitable technique, such as annealing in one example. Then, a CMP process is performed to the ILD layer 244 to expose the gate structures 208a-d. Subsequently, the gate structures 208a-d are removed by one or more selective etching processes thereby forming first openings 246a, 246b, 246c, and 246d in the regions 200a and 200b. The spacers 230 remain during the etch processes. The openings 246a-d are at least partially surrounded by the corresponding spacers 230. Referring to FIG. 14, one or more material layers are deposited into the openings 246a-d to form high-k metal gates 248a, 248b, 248c, and 248d respectively. In various embodiments, the replacing of the gate structures 208a-b is performed separately from the replacing of the gate structures 208c-d to enable separate n-type and p-type device tuning.

In the example shown in FIG. 14, the final gate stacks 248a-b and 248c-d include interfacial layers 249a and 249b, dielectric layers 250a and 250b, work function metal layers 252a and 252b, and fill layers 254a and 254b, respectively. The interfacial layers 249a-b may include a dielectric material such as silicon oxide or silicon oxynitride, and may be formed by chemical oxidation, thermal oxidation, ALD, CVD, and/or other suitable dielectric. The dielectric layer 250a-b may include a high-k dielectric layer such as hafnium oxide (HfO₂), zirconium oxide (ZrO₂), lanthanum oxide (La₂O₃), titanium oxide (TiO₂), yttrium oxide (Y₂O₃), strontium titanate (SrTiO₃), other suitable metal-oxides, or combinations thereof. The dielectric layers 250a-b may be formed by ALD and/or other suitable methods. The work function metal layers 252a-b may be an n-type work function layer for NFETs or a p-type work function layer for PFETs, and may be deposited by CVD, PVD, and/or other suitable process. The p-type work function layer comprises

a metal with a sufficiently large effective work function, selected from but not limited to the group of titanium nitride (TiN), tantalum nitride (Ta₂N), ruthenium (Ru), molybdenum (Mo), tungsten (W), platinum (Pt), or combinations thereof. The n-type work function layer comprises a metal with sufficiently low effective work function, selected from but not limited to the group of titanium (Ti), aluminum (Al), tantalum carbide (TaC), tantalum carbide nitride (TaCN), tantalum silicon nitride (TaSiN), or combinations thereof. The fill layers **254a-b** may include aluminum (Al), tungsten (W), or copper (Cu) and/or other suitable materials, and may be formed by CVD, PVD, plating, and/or other suitable processes. A CMP process may be performed to remove excess materials from the gate stacks **248a-d** and to planarize a top surface of the semiconductor structure **200**. Further processes, such as contact and via formation, interconnect processing, etc., may be performed subsequently to complete the fabrication of the semiconductor structure **200**.

Referring to FIG. 15, shown therein is a method **300** of forming the semiconductor structure **200** according to various aspects of the present disclosure in some other embodiments. The method **300** is an example, and is not intended to limit the present disclosure beyond what is explicitly recited in the claims. Additional operations can be provided before, during, and after the method **300**, and some operations described can be replaced, eliminated, or moved around for additional embodiments of the method. The method **300** is described below in conjunction with FIGS. 16-17 which show cross-sectional views of the semiconductor structure **200** according to various aspects of the present disclosure.

The method **300** is similar to the method **100** in many respects but differs from the method **100** in the etching of the first dielectric layer **232** and the substrate **202**. Referring to FIG. 15, the method **300** also includes the operations **102**, **104**, **106**, **108**, and **110** as discussed above. From operation **110**, the method **300** proceeds to operation **302** to form a first masking element **256** covering the substrate **202** and the gate structures **208b** in the memory device region as shown in FIG. 16. The first masking element **256** is a patterned resist in an embodiment. Then, the method **300** proceeds to operation **304** to form recesses **240a** adjacent the gate structures **208a**. Operation **304** includes etching the first dielectric layer **232** and etching the substrate **202** in the logic device region. Since operation **304** only etches the logic device region, device density is no longer a concern for etch loading and the etching processes can be tuned to produce a desired profile in the recesses **240a**, including a desired depth **D1** and a desired proximity **X1**. Thereafter, the method **300** removes the first masking element **256** in operation **306** and forms a second masking element **258** covering the substrate **202** and the gate structures **208a** in the logic device region as shown in FIG. 17. Then, the method **300** proceeds to operation **310** to form recesses **240b** adjacent the gate structures **208b**. Operation **310** includes etching the first dielectric layer **232** and etching the substrate **202** in the memory device region. Since operation **310** only etches the memory device region, device density is no longer a concern for etch loading and the etching processes can be tuned to produce a desired profile in the recesses **240b**, including a desired depth **D2** and a desired proximity **X2**. In the present embodiment, the etching processes are controlled such that **D1** is greater than **D2** and **X2** is greater than **X1**. Thereafter, the method **300** removes the second masking element **258** in operation **312** and proceeds to operation **118**, as discussed above.

Although not intended to be limiting, one or more embodiments of the present disclosure provide many benefits to a semiconductor device and the formation thereof. For example, embodiments of the present disclosure provide methods of forming raised epitaxial S/D features for both logic devices and memory devices simultaneously while fulfilling different requirements for the two types of devices. For example, the S/D features in the logic devices have a large volume so as to stress or strain the devices' channel regions for improved carrier mobility while the S/D features in the memory devices may remain separate between adjacent S/D features to avoid unintended circuit shorts. Embodiments of the present disclosure provide the above differences by creating different S/D recess profiles in the two types of devices. A further embodiment creates the different S/D recess profiles using one etching process for the two types of devices rather than separate etching processes. This improves production efficiency.

In one exemplary aspect, the present disclosure is directed to a method of forming a semiconductor structure. The method includes receiving a precursor having a substrate and first and second pluralities of gate structures over the substrate, the first pluralities having a greater pitch than the second pluralities. The method further includes depositing a first dielectric layer covering the substrate and the first and second pluralities; and performing a first etching process to the first dielectric layer. The first etching process removes a first portion of the first dielectric layer over the substrate, while a second portion of the first dielectric layer remains over sidewalls of the first and second pluralities. The second portion of the first dielectric layer is thicker over the sidewalls of the second plurality than over the sidewalls of the first plurality. The method further includes etching the substrate to form third and fourth pluralities of recesses adjacent the first and second pluralities, respectively; and epitaxially growing fifth and sixth pluralities of semiconductor features in the third and fourth pluralities, respectively.

In another exemplary aspect, the present disclosure is directed to a method of forming a semiconductor structure. The method includes receiving a precursor having first and second regions and a substrate extending in the first and second regions. The precursor further has first and second pluralities of gate structures over the substrate in the first region. The first pluralities having a greater pitch than the second pluralities. The precursor further has third and fourth pluralities of gate structures over the substrate in the second region. The third pluralities having a greater pitch than the fourth pluralities. The method further includes depositing a first dielectric layer covering the substrate and the first, second, third, and fourth pluralities; and forming a masking element over the first dielectric layer in the second region. The method further includes performing a first etching process to the first dielectric layer in the first region to expose the substrate, wherein a portion of the first dielectric layer remains over sidewalls of the first and second pluralities. The portion of the first dielectric layer is thicker over the sidewalls of the second plurality than over the sidewalls of the first plurality. The method further includes etching the substrate to form fifth and sixth pluralities of recesses adjacent the first and second pluralities; and epitaxially growing source and drain features in the fifth and sixth pluralities, respectively, using a first semiconductor material.

In yet another exemplary aspect, the present disclosure is directed to a semiconductor structure. The semiconductor structure includes a substrate having fin active regions; and

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first and second pluralities of gate structures over the substrate and engaging the fin active regions. The first pluralities have a greater pitch than the second pluralities. The semiconductor structure further includes third and fourth pluralities of recesses into the fin active regions proximate the first and second pluralities, respectively. A first proximity of the third pluralities to the respective first pluralities is smaller than a second proximity of the fourth pluralities to the respective second pluralities. The semiconductor structure further includes fifth and sixth pluralities of semiconductor features in the third and fourth pluralities, respectively, and raised above a top surface of the fin active regions.

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

What is claimed is:

1. A method of forming a semiconductor device, comprising:

receiving a precursor having a substrate and first and second pluralities of gate structures over the substrate, the first plurality of gate structures having a greater pitch than the second plurality of gate structures;

depositing a first dielectric layer covering the substrate and the first and second pluralities of gate structures;

performing a first etching process to the first dielectric layer, thereby removing a first portion of the first dielectric layer over the substrate, while a second portion of the first dielectric layer remains over sidewalls of the first and second pluralities of gate structures, wherein the second portion of the first dielectric layer is thicker over the sidewalls of the second plurality of gate structures than over the sidewalls of the first plurality of gate structures;

etching the substrate to form third and fourth pluralities of recesses adjacent the first and second pluralities of gate structures, respectively; and

epitaxially growing fifth and sixth pluralities of semiconductor features in the third and fourth pluralities of recesses, respectively.

2. The method of claim 1, wherein the first etching process is a cyclic process having repetitions of an etching cycle and a deposition cycle.

3. The method of claim 2, wherein the deposition cycle deposits a polymer over the second portion of the first dielectric layer.

4. The method of claim 2, wherein:
the first dielectric layer includes silicon nitride; and
the etching cycle uses an etching gas having a fluorine-containing chemical, and the deposition cycle uses a deposition gas having carbon and hydrogen.

5. The method of claim 4, wherein the etching gas includes CH₃F or CF₄, and the deposition gas includes CH₄.

6. The method of claim 2, wherein the first etching process includes more than four repetitions of the etching and deposition cycles.

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7. The method of claim 1, wherein the third plurality of recesses is deeper than the fourth plurality of recesses.

8. The method of claim 7, wherein the third plurality of recesses is deeper than the fourth plurality of recesses by at least 15 nanometers.

9. The method of claim 1, wherein a first proximity of the third plurality of recesses to the respective first plurality of gate structures is smaller than a second proximity of the fourth plurality of recesses to the respective second plurality of gate structures.

10. The method of claim 1, wherein the substrate includes fin active regions, the first and second pluralities of gate structures engage the fin active regions, and the third and fourth pluralities of recesses are etched into the fin active regions.

11. The method of claim 1, wherein the fifth plurality of semiconductor features is source and drain (S/D) features for logic devices and the sixth plurality of semiconductor features is S/D features for memory devices.

12. The method of claim 1, further comprising:

forming gate spacers on sidewalls of the first and second pluralities of gate structures before the depositing of the first dielectric layer.

13. A method of forming a semiconductor device, comprising:

receiving a precursor having first and second regions and a substrate extending in the first and second regions, the precursor further having first and second pluralities of gate structures over the substrate in the first region, the first plurality of gate structures having a greater pitch than the second plurality of gate structures, the precursor further having third and fourth pluralities of gate structures over the substrate in the second region, the third plurality of gate structures having a greater pitch than the fourth plurality of gate structures;

depositing a first dielectric layer covering the substrate and the first, second, third, and fourth pluralities of gate structures;

forming a masking element over the first dielectric layer in the second region;

performing a first etching process to the first dielectric layer in the first region to expose the substrate, wherein a portion of the first dielectric layer remains over sidewalls of the first and second pluralities of gate structures, wherein the portion of the first dielectric layer is thicker over the sidewalls of the second plurality of gate structures than over the sidewalls of the first plurality of gate structures;

etching the substrate to form fifth and sixth pluralities of recesses adjacent the first and second pluralities of gate structures; and

epitaxially growing source and drain features in the fifth and sixth pluralities of recesses, respectively, using a first semiconductor material.

14. The method of claim 13, further comprising:
removing the masking element after the etching of the substrate and before the epitaxially growing of the source and drain features in the fifth and sixth pluralities of recesses.

15. The method of claim 13, further comprising:
removing the first dielectric layer from the first and second regions after the epitaxially growing of the source and drain features in the fifth and sixth pluralities of recesses.

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16. The method of claim 15, further comprising:
 depositing a second dielectric layer covering the substrate
 and the first, second, third, and fourth pluralities of gate
 structures;
 forming another masking element over the second dielec- 5
 tric layer in the first region;
 performing a second etching process to the second dielec-
 tric layer in the second region to expose the substrate,
 wherein a portion of the second dielectric layer remains
 over sidewalls of the third and fourth pluralities of gate 10
 structures, wherein the portion of the second dielectric
 layer is thicker over the sidewalls of the third plurality
 of gate structures than over the sidewalls of the fourth
 plurality of gate structures;
 etching the substrate to form seventh and eighth plurali- 15
 ties of recesses adjacent the third and fourth pluralities
 of gate structures, respectively; and
 epitaxially growing source and drain features in the
 seventh and eighth pluralities of recesses, respectively,
 using a second semiconductor material different from 20
 the first semiconductor material.

17. A semiconductor structure, comprising:
 a substrate having fin active regions;
 first and second pluralities of gate structures over the
 substrate and engaging the fin active regions, the first

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plurality of gate structures having a greater pitch than
 the second plurality of gate structures;
 third and fourth pluralities of recesses into the fin active
 regions proximate the first and second pluralities of
 gate structures, respectively, wherein a first proximity
 of the third plurality of recesses to the respective first
 plurality of gate structures is smaller than a second
 proximity of the fourth plurality of recesses to the
 respective second plurality of gate structures; and
 fifth and sixth pluralities of semiconductor features in the
 third and fourth pluralities of recesses, respectively, and
 raised above a top surface of the fin active regions.

18. The semiconductor structure of claim 17, wherein the
 third plurality of recesses is deeper than the fourth plurality
 of recesses by at least 15 nanometers.

19. The semiconductor structure of claim 17, wherein the
 fifth plurality of semiconductor features is source and drain
 (S/D) features for logic devices and the sixth plurality of
 semiconductor features is S/D features for memory devices.

20. The semiconductor structure of claim 17, wherein the
 fifth and sixth pluralities of semiconductor features include
 silicon doped with an n-type dopant or silicon germanium
 doped with a p-type dopant.

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