

Figure 1

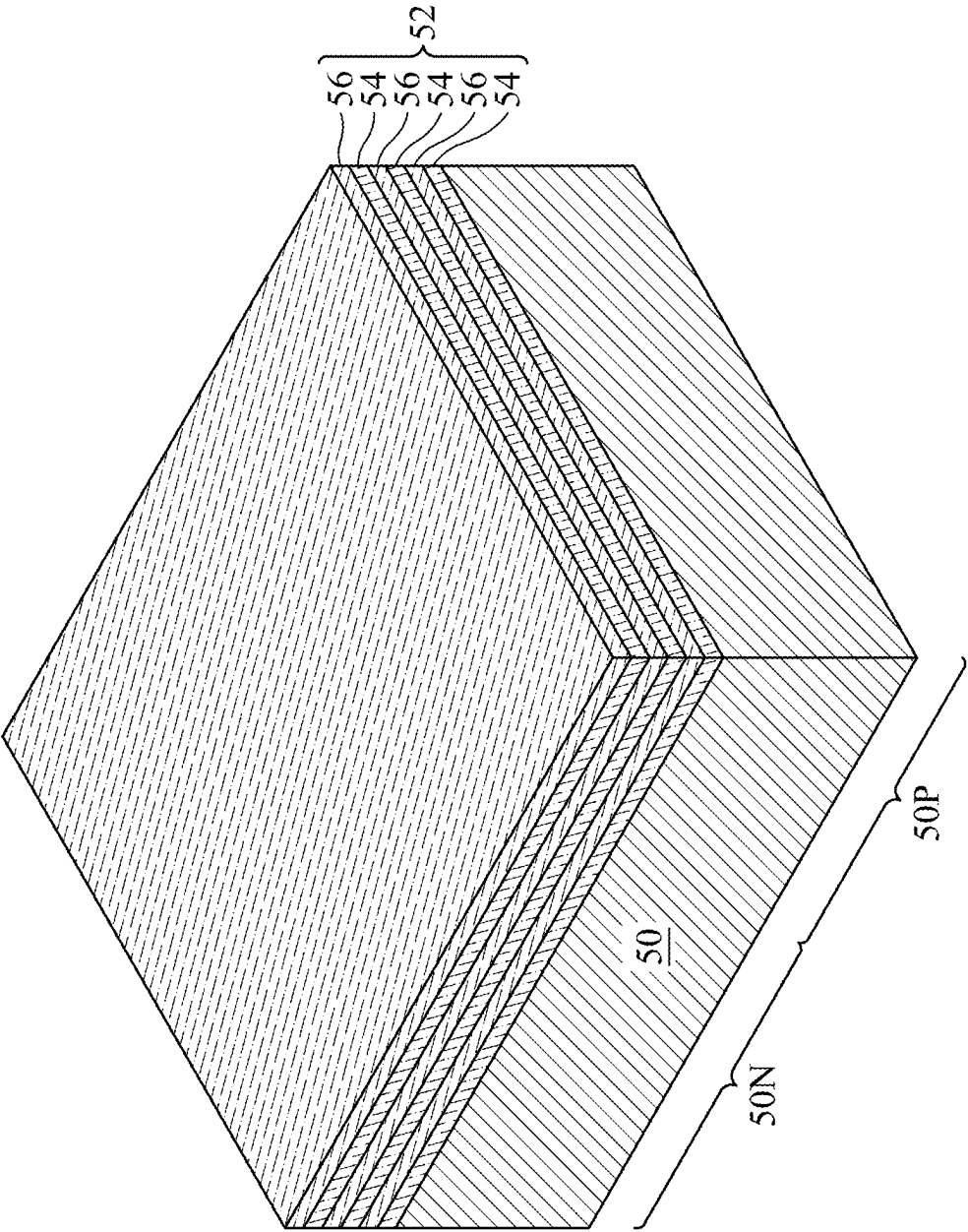


Figure 2

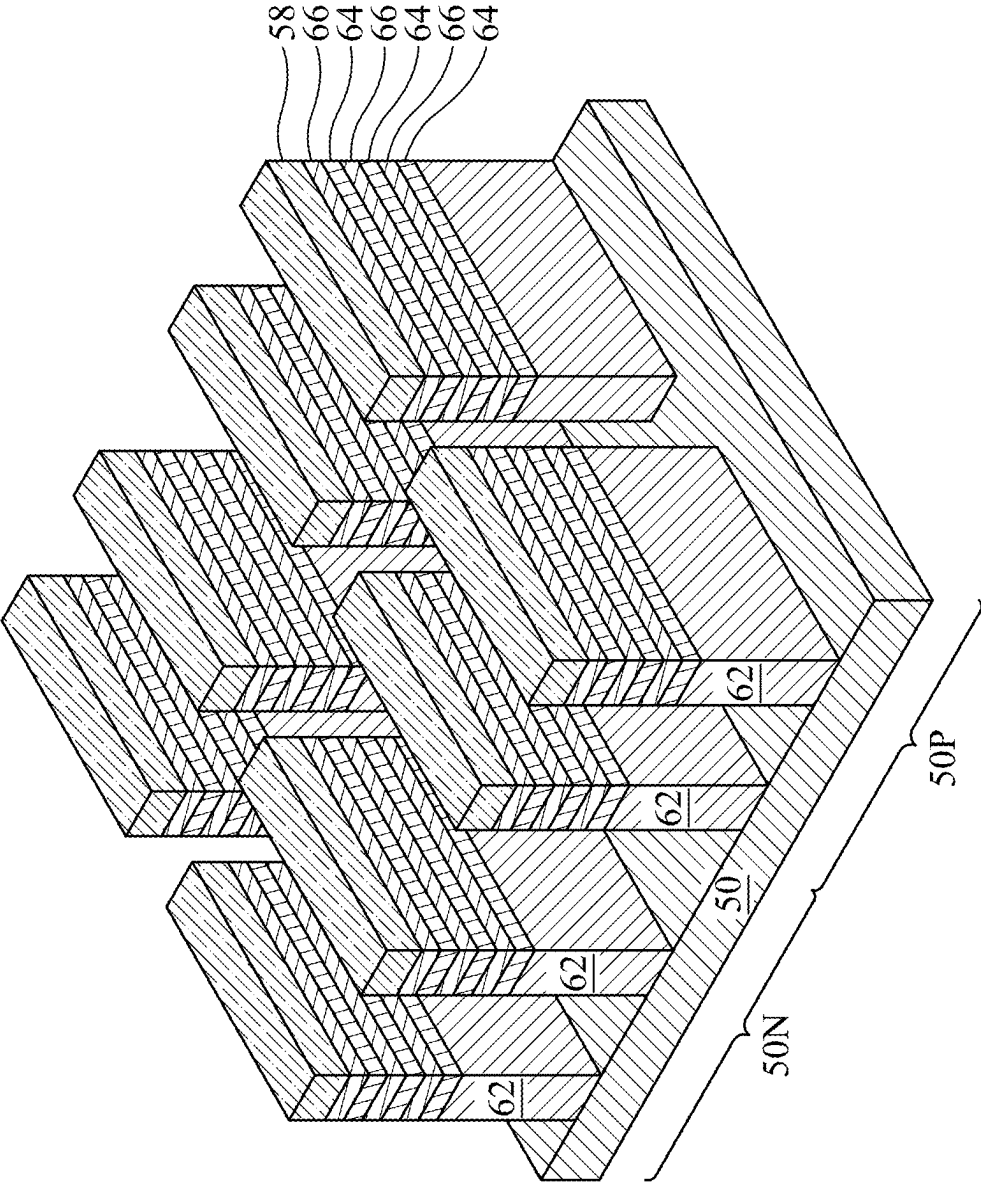


Figure 3

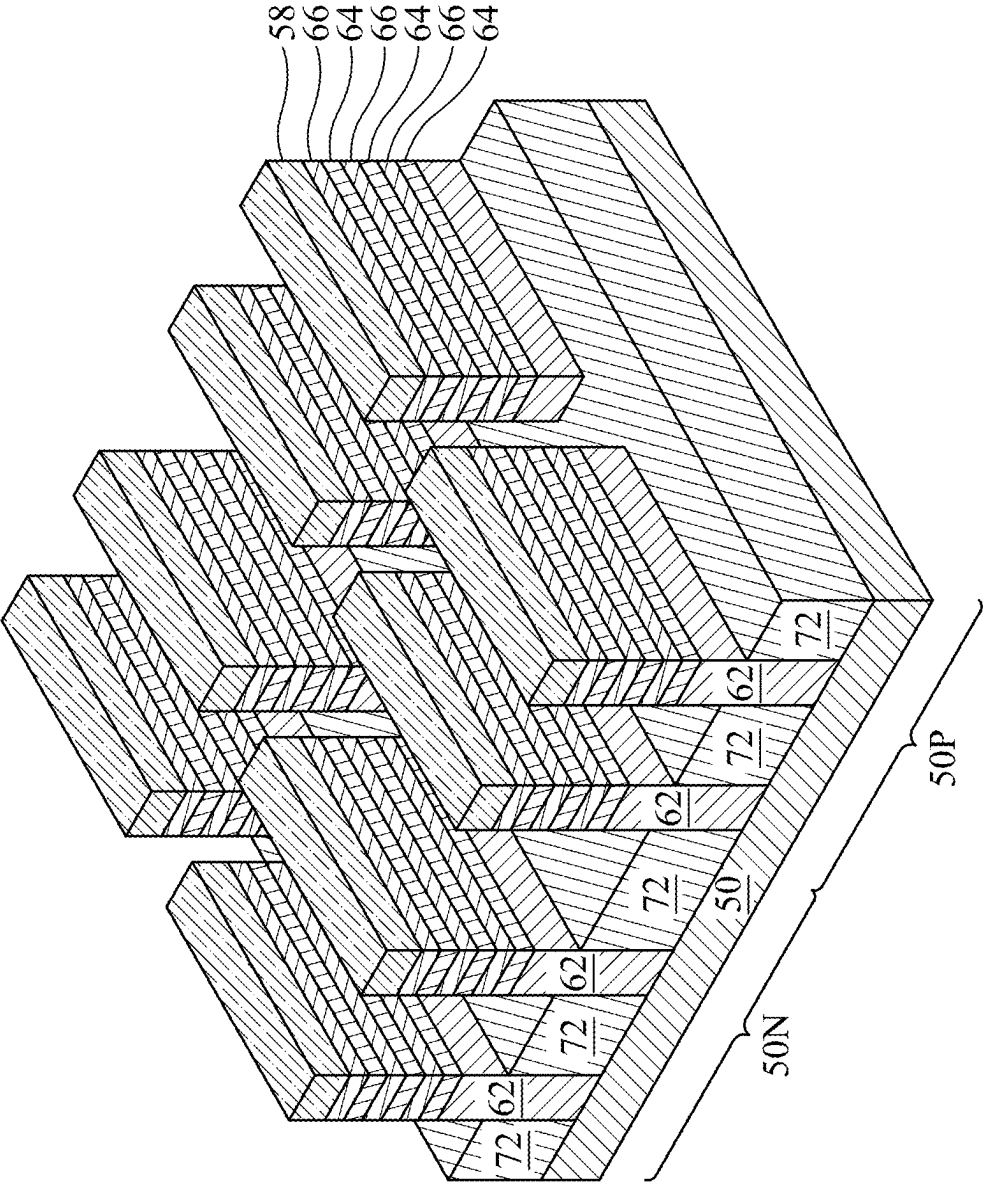


Figure 4

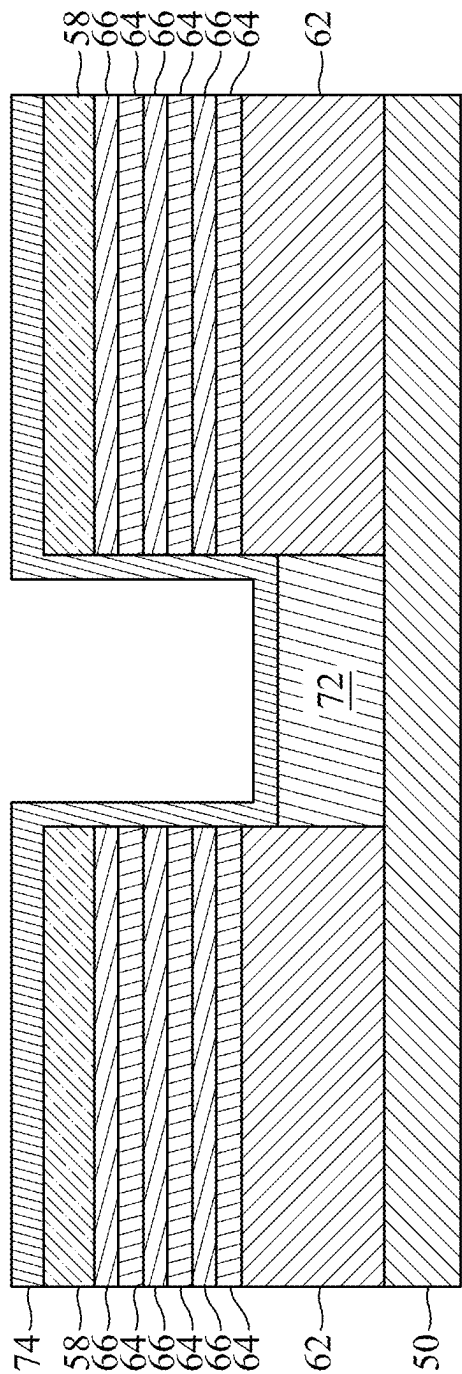


Figure 5A

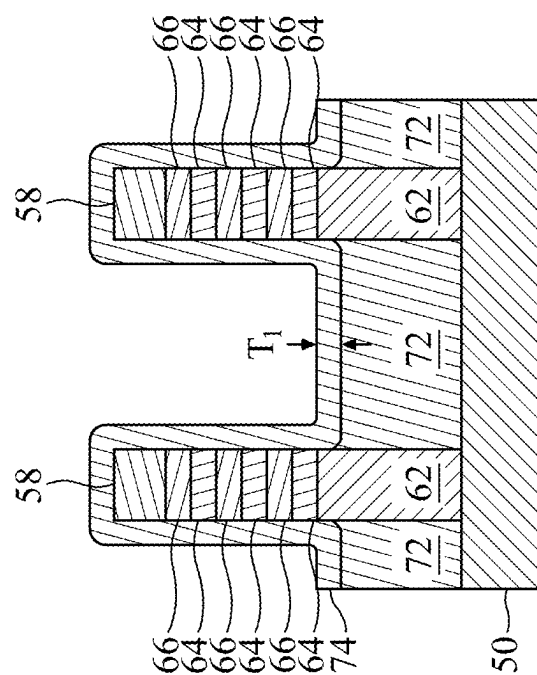


Figure 5B

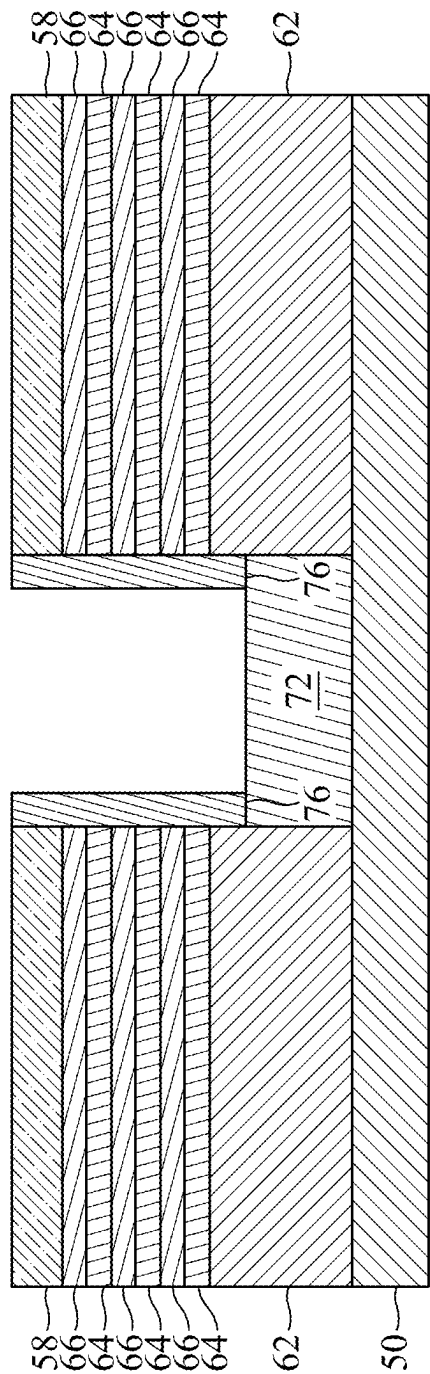


Figure 6A



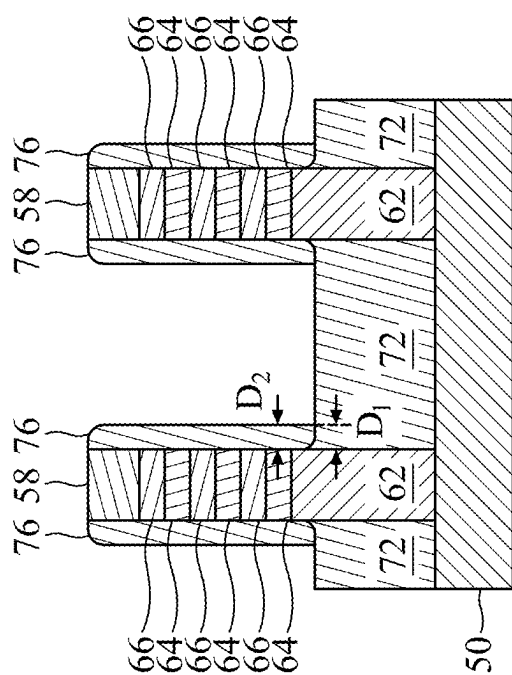


Figure 6B

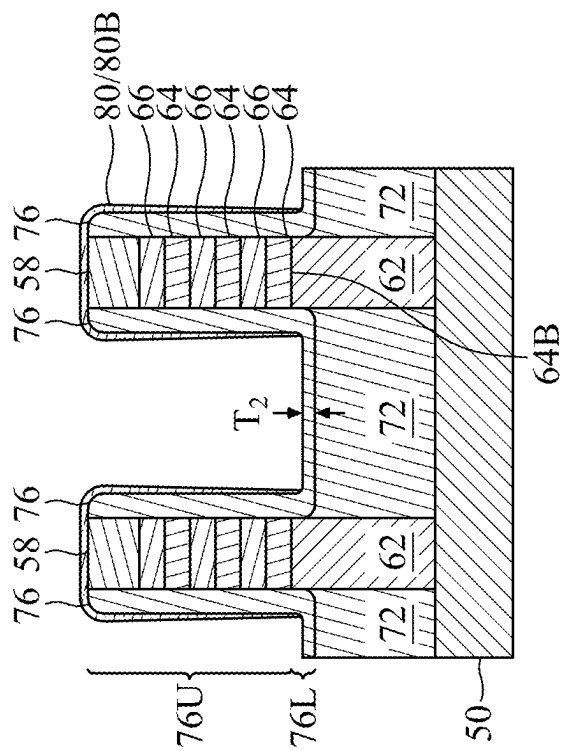


Figure 7B

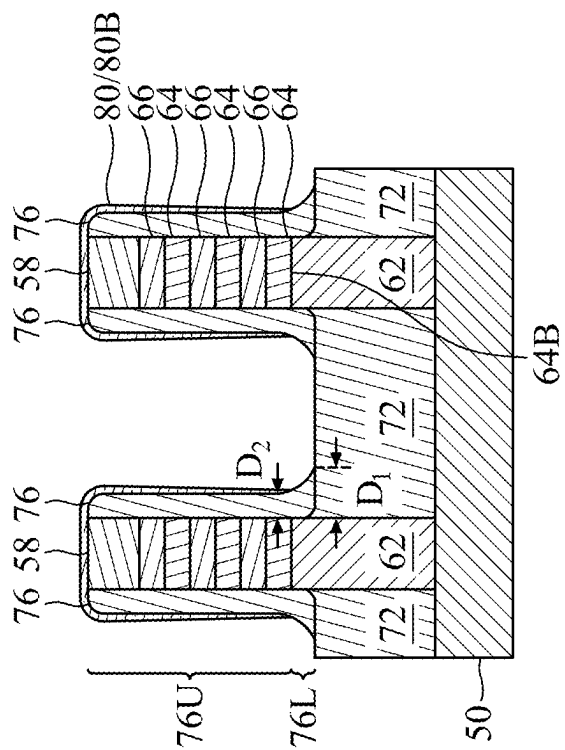


Figure 7A

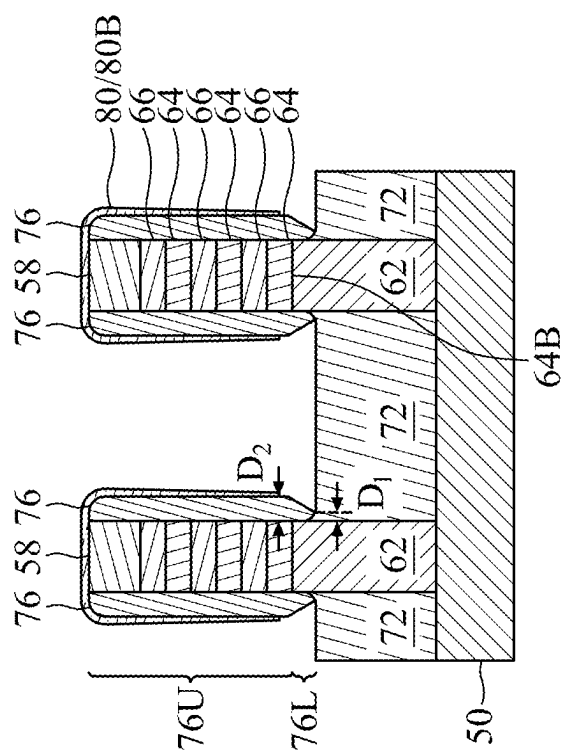


Figure 8B

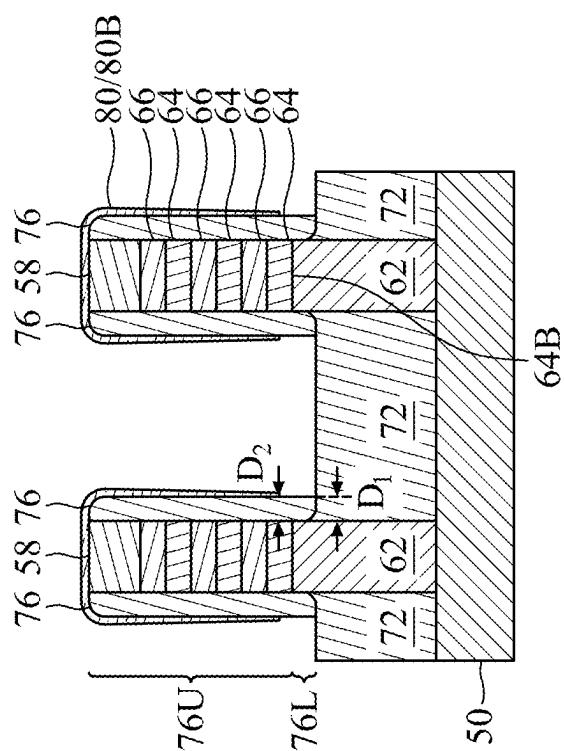


Figure 8A



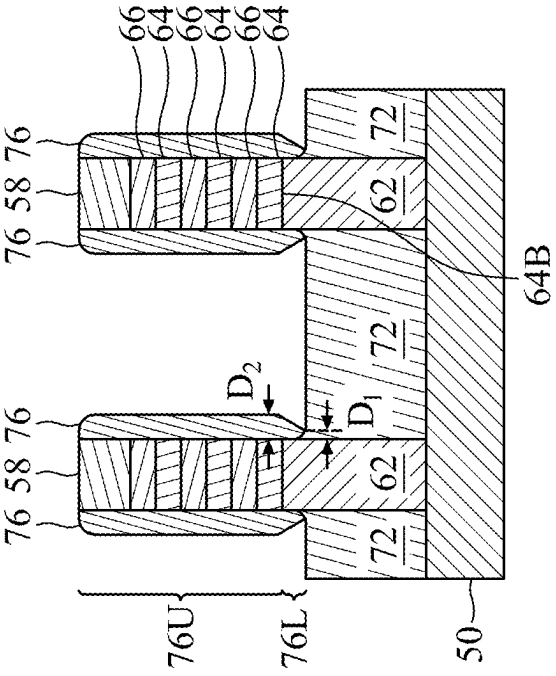


Figure 9B

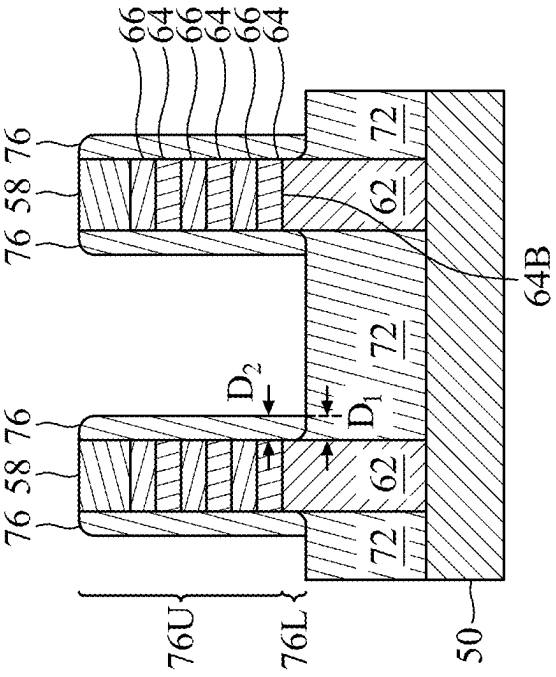


Figure 9A

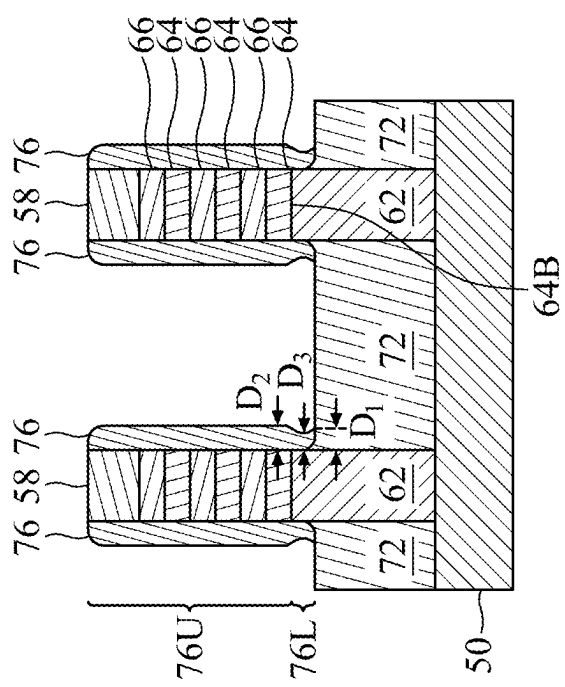


Figure 9C

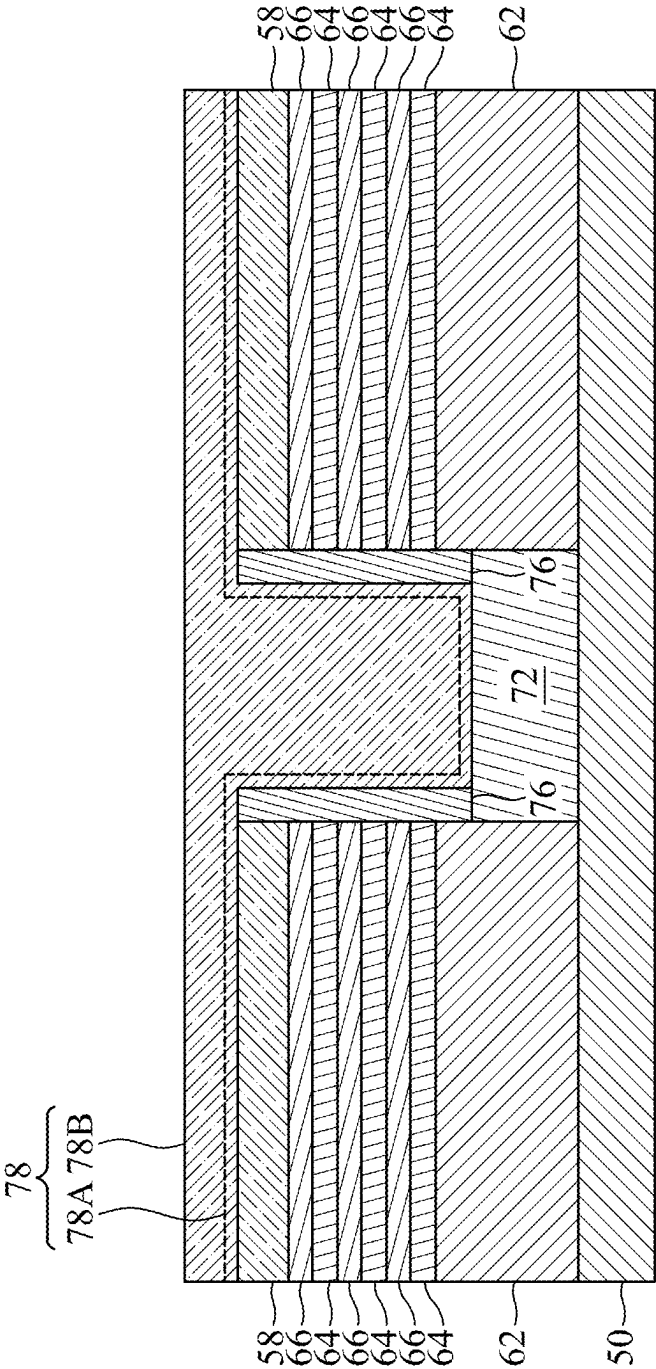


Figure 10A





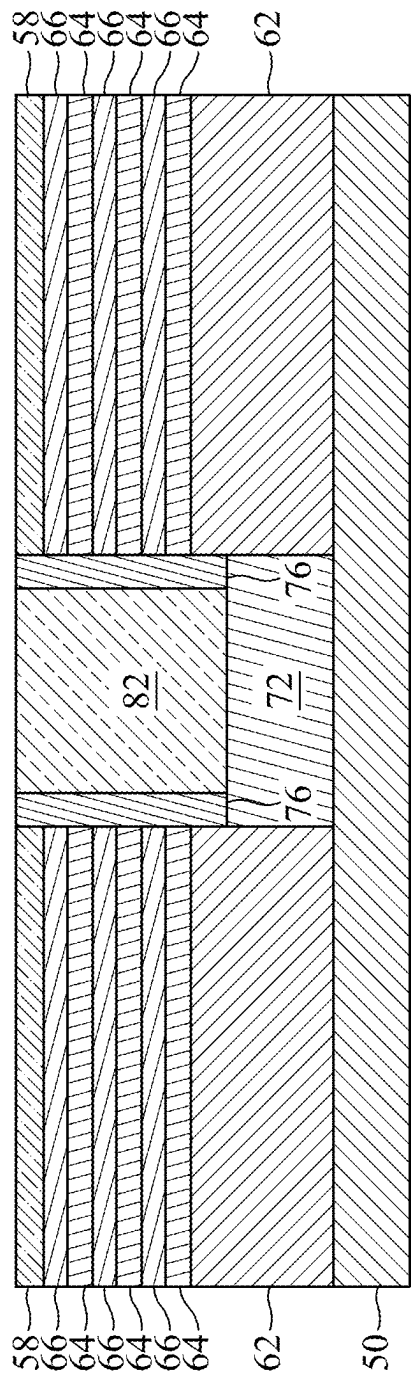


Figure 11A

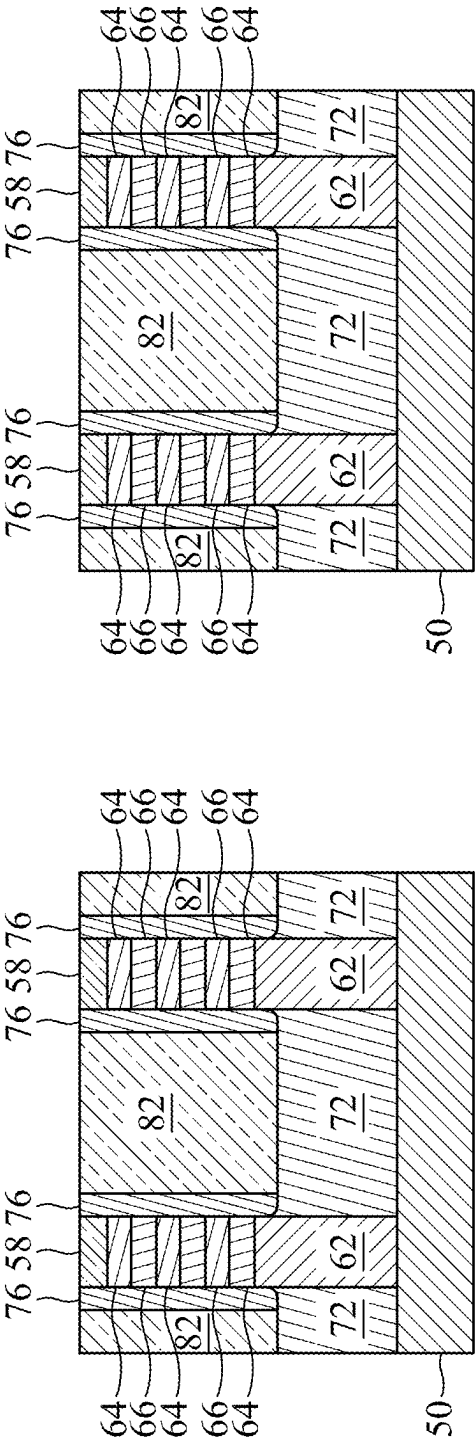


Figure 11C

Figure 11B

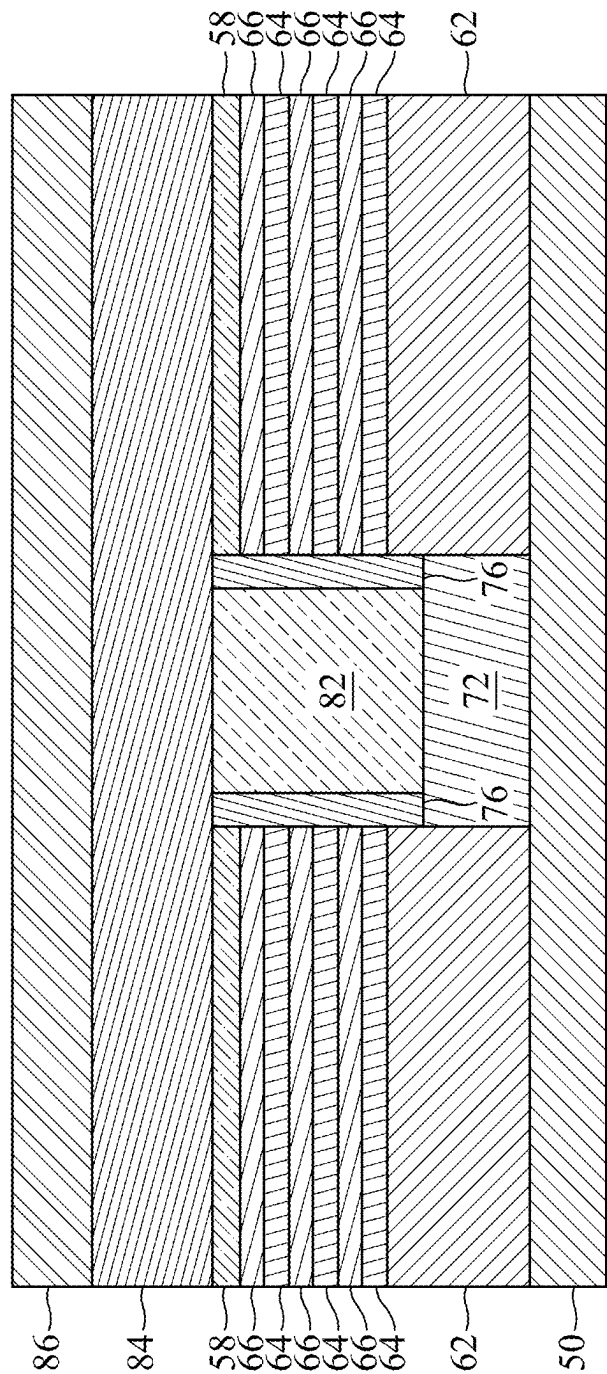


Figure 12A

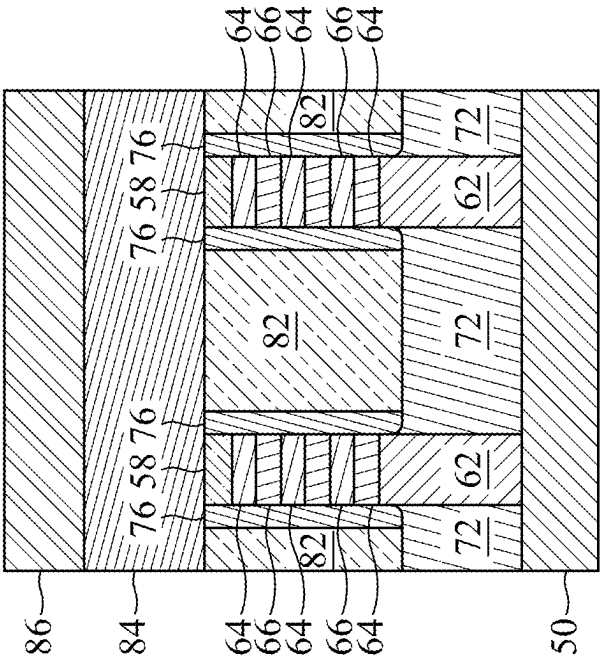


Figure 12C

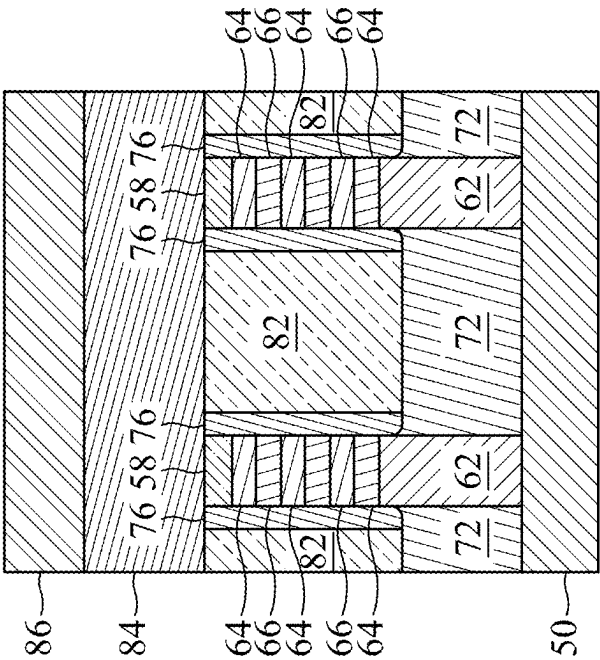


Figure 12B

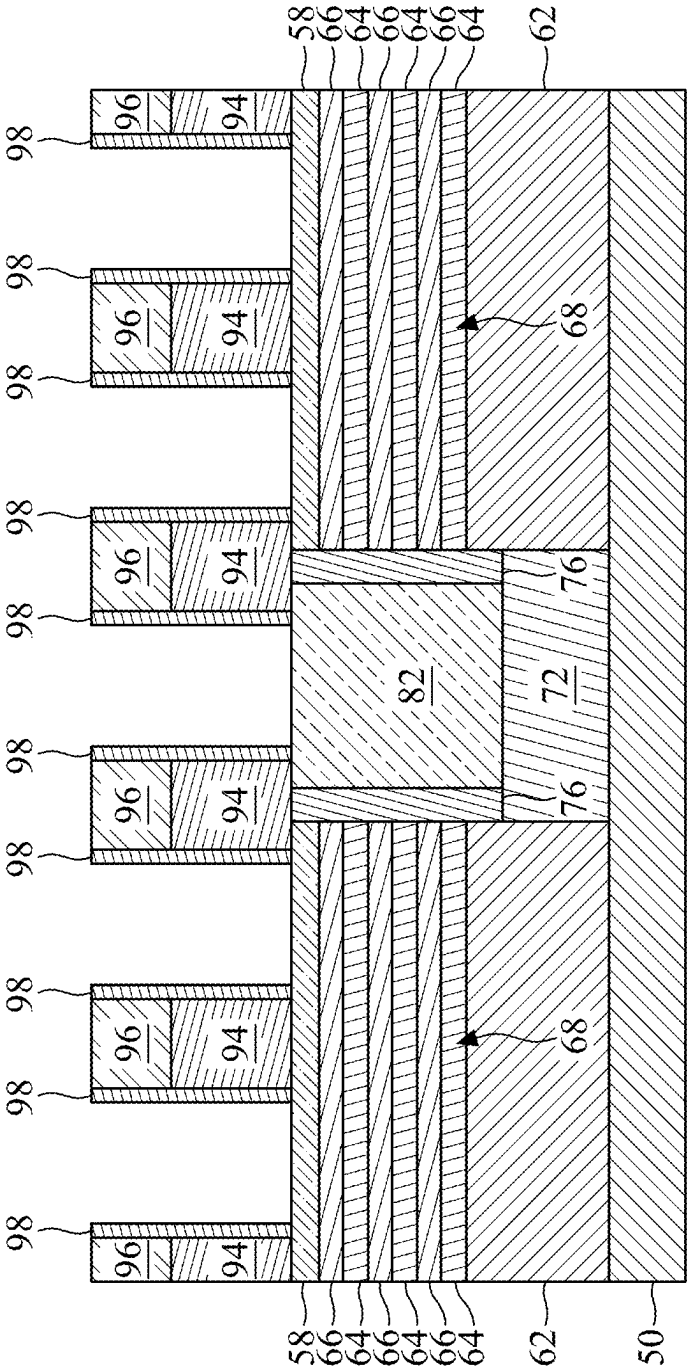


Figure 13A

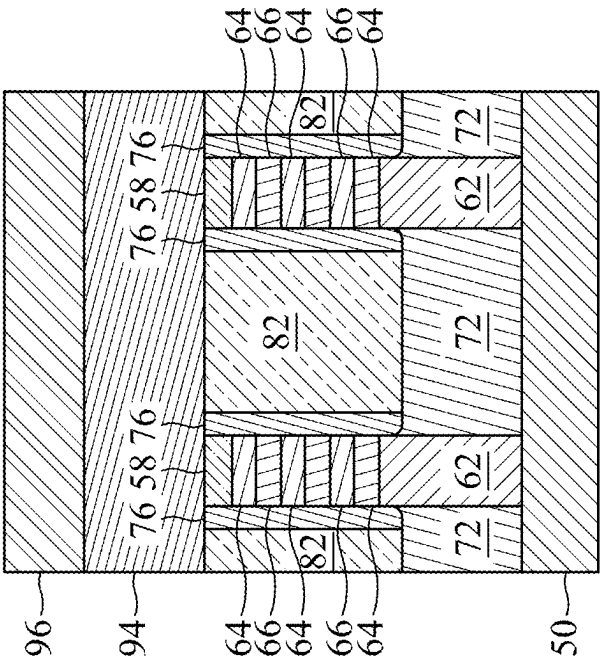


Figure 13B

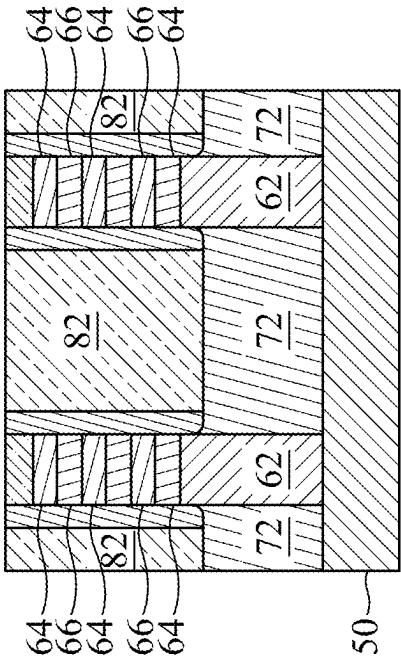


Figure 13C

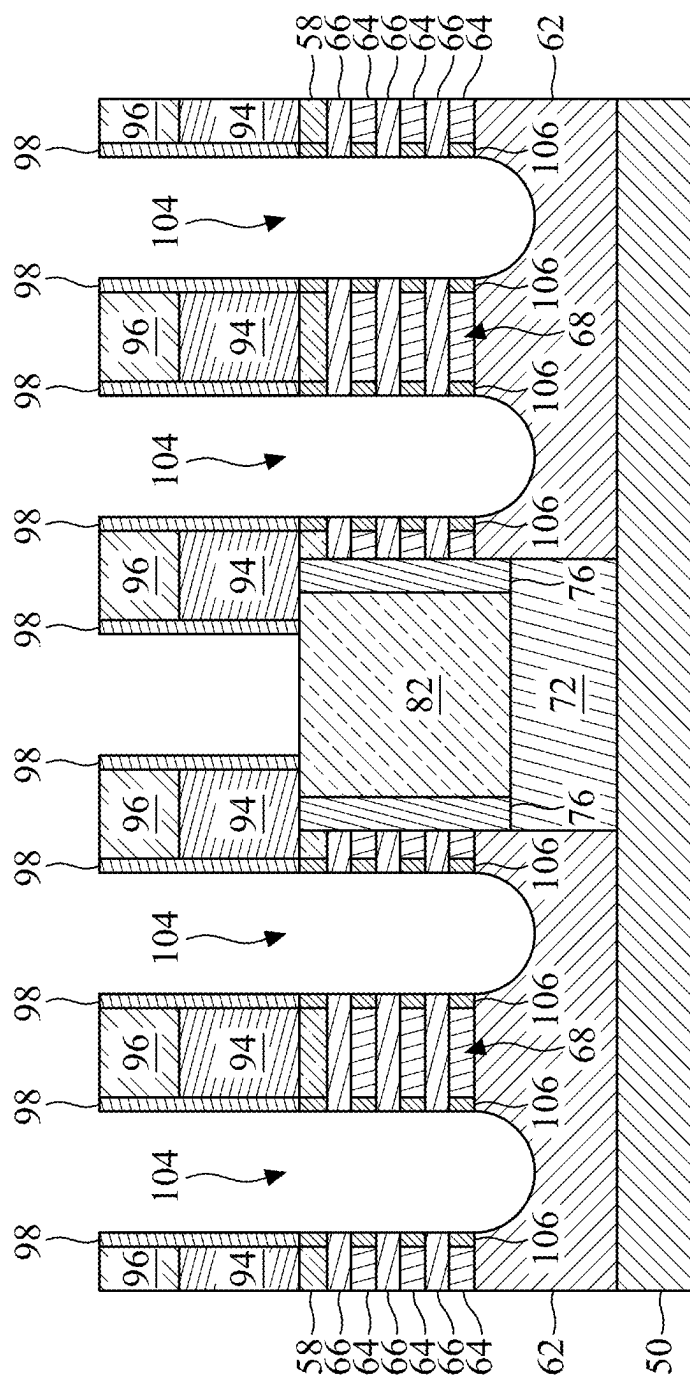


Figure 14A

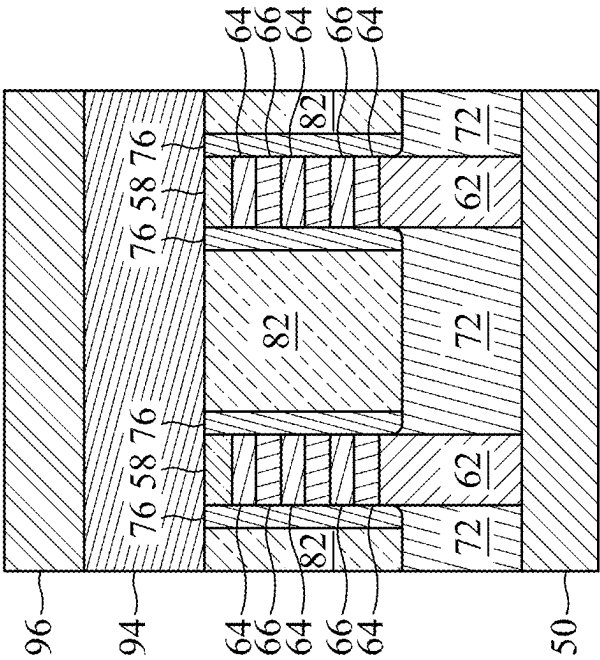


Figure 14B

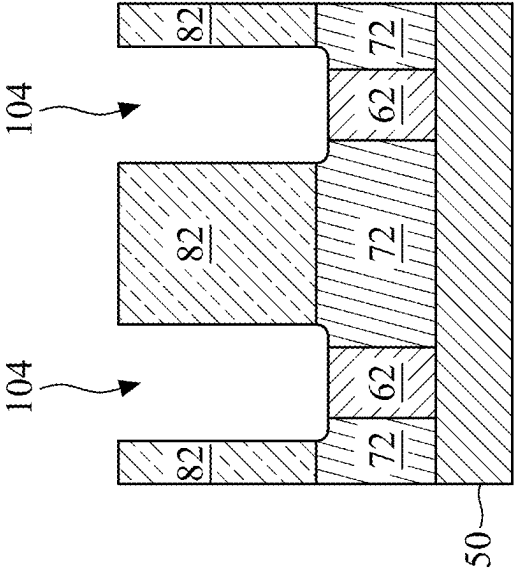


Figure 14C



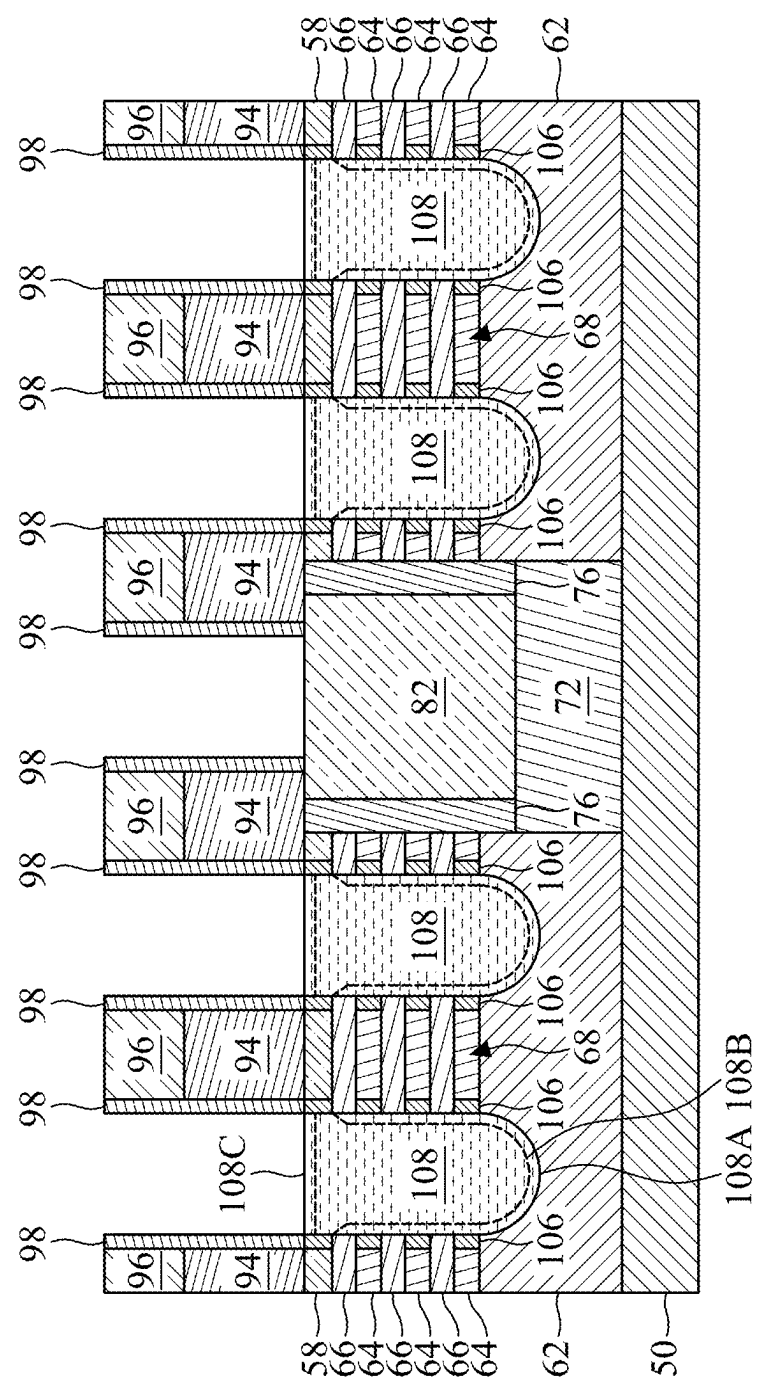


Figure 15A

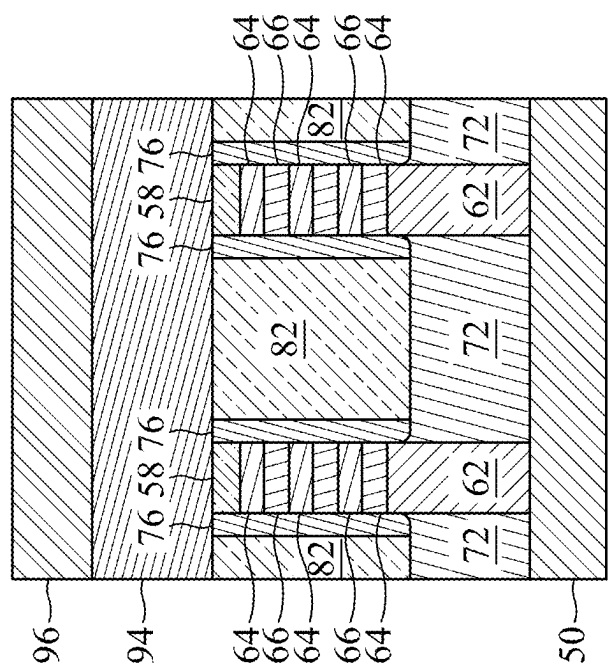


Figure 15B

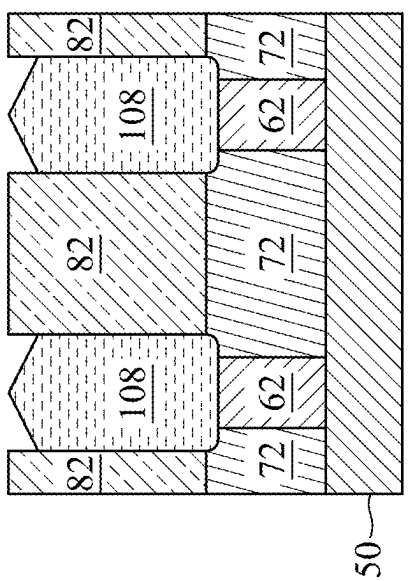


Figure 15C

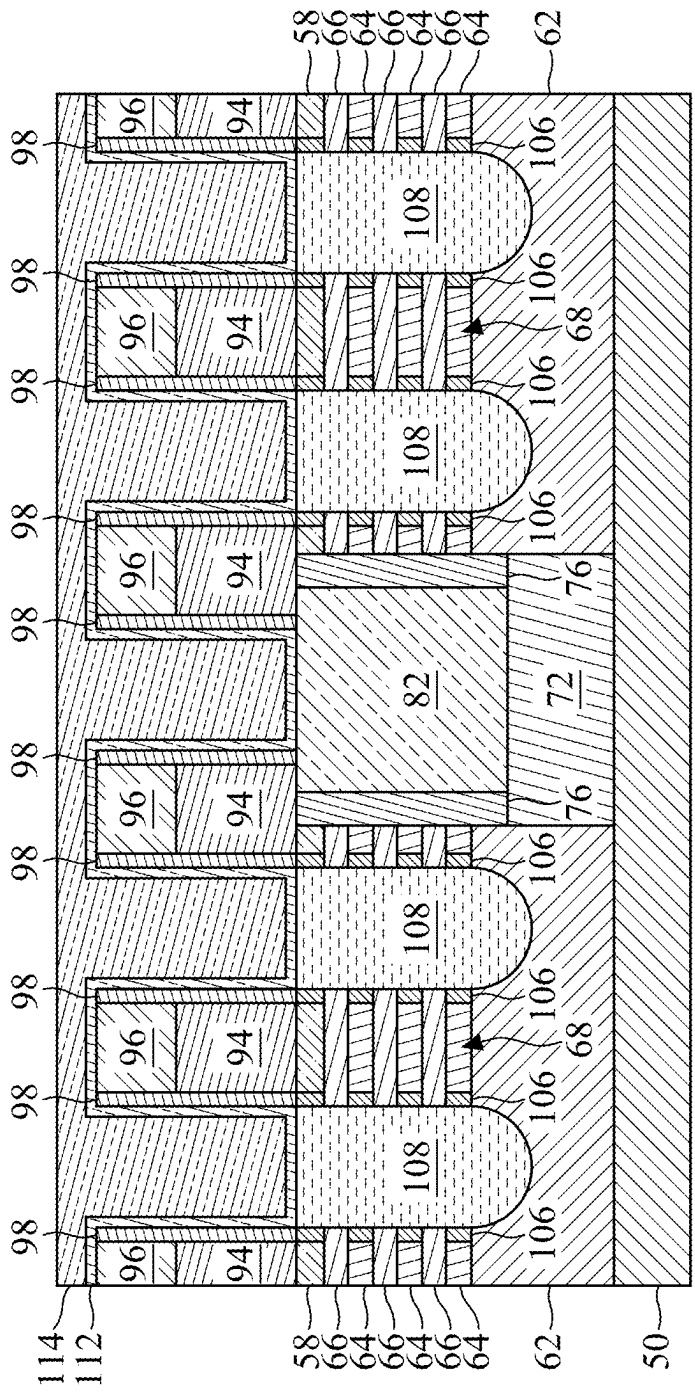


Figure 16A

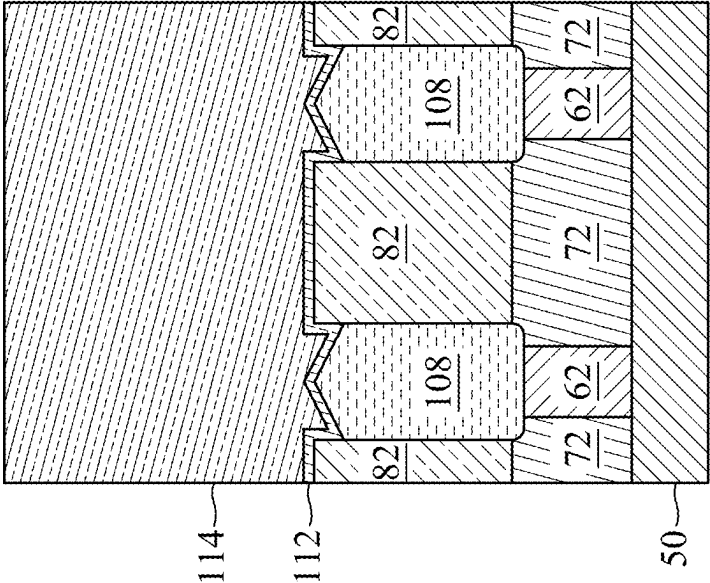


Figure 16C

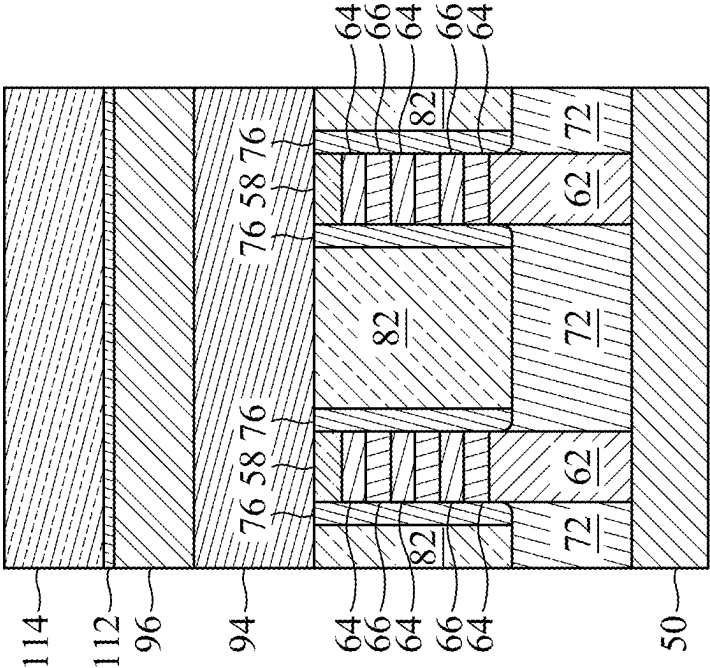


Figure 16B

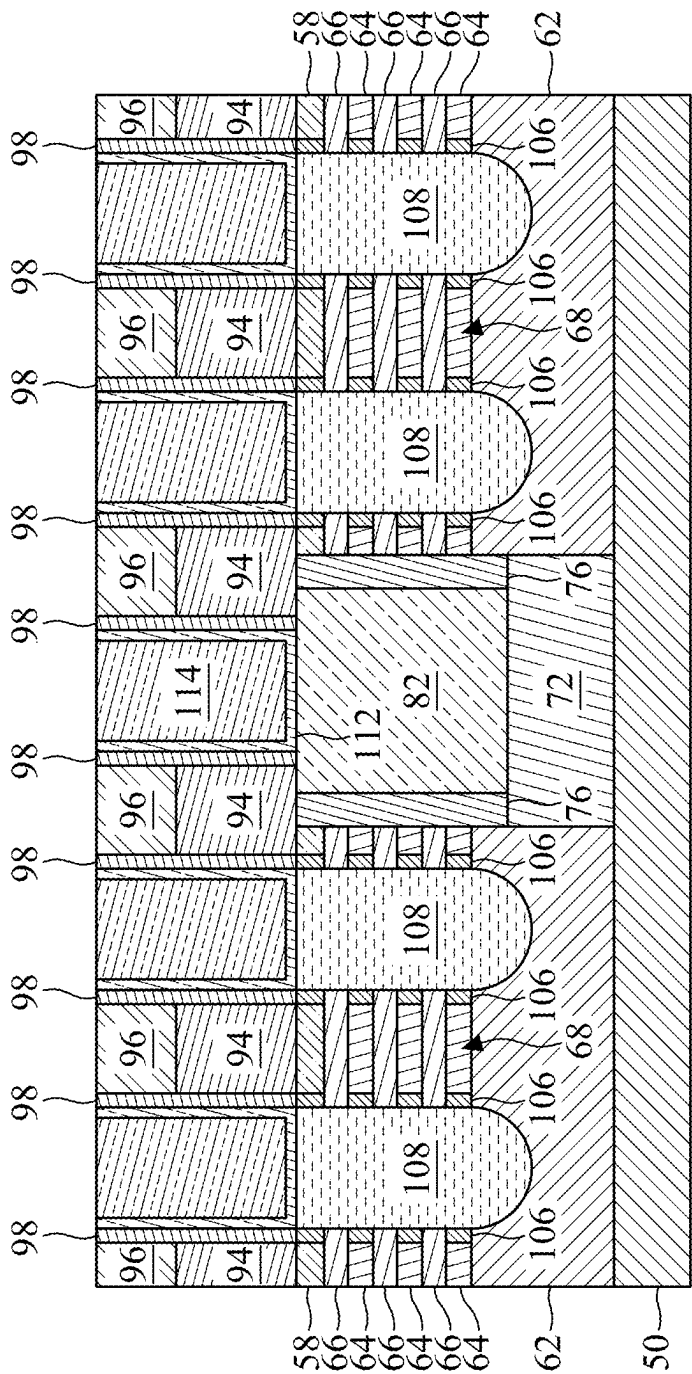


Figure 17A

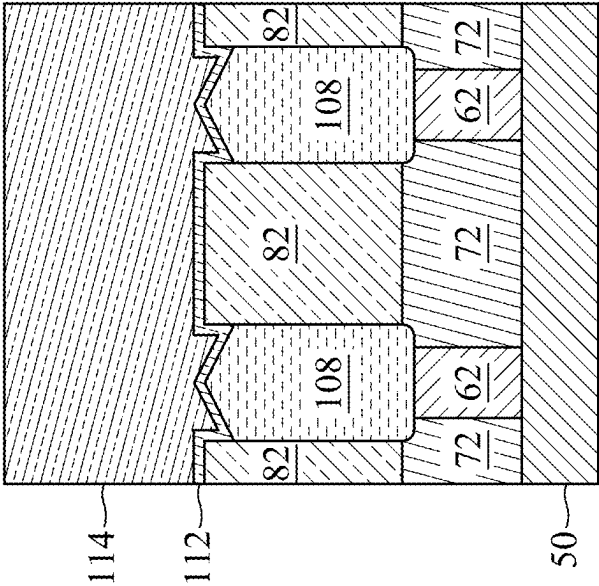


Figure 17C

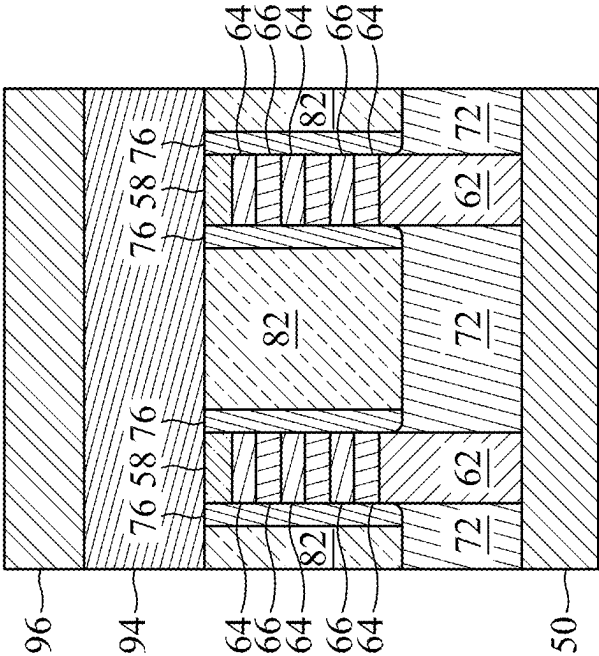


Figure 17B

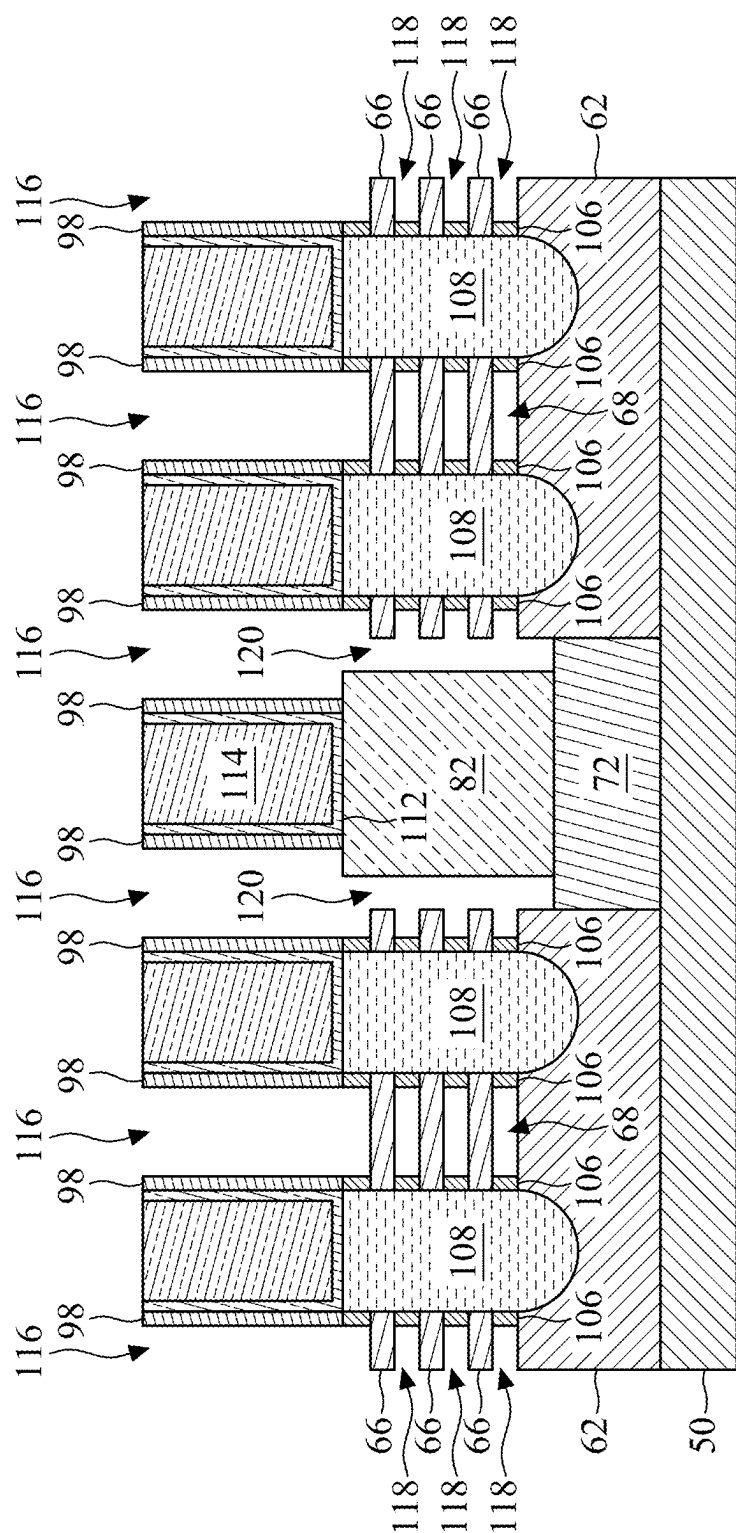


Figure 18A

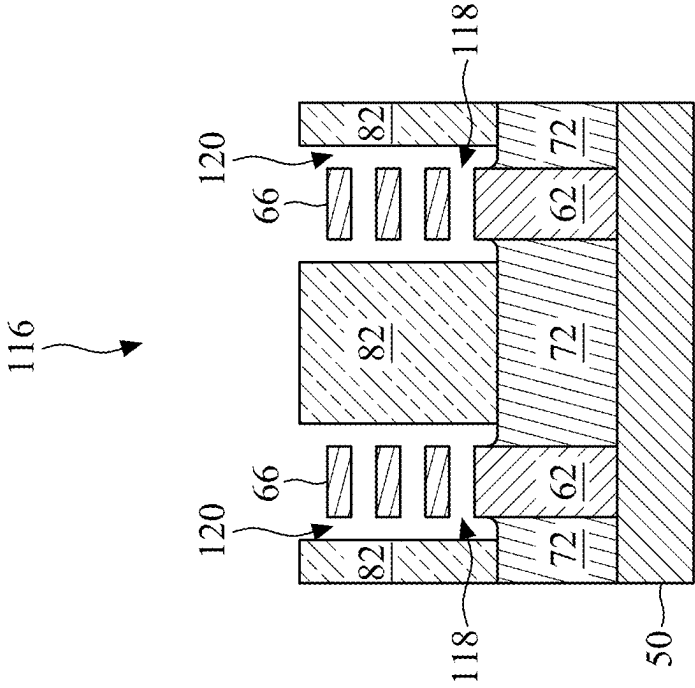


Figure 18B

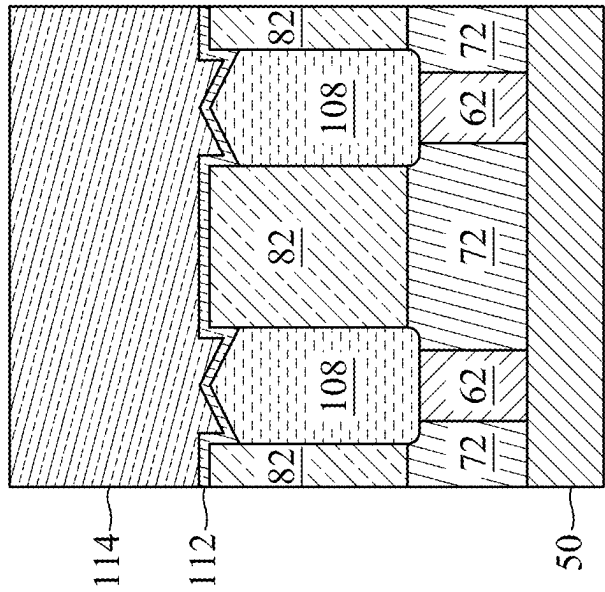


Figure 18C



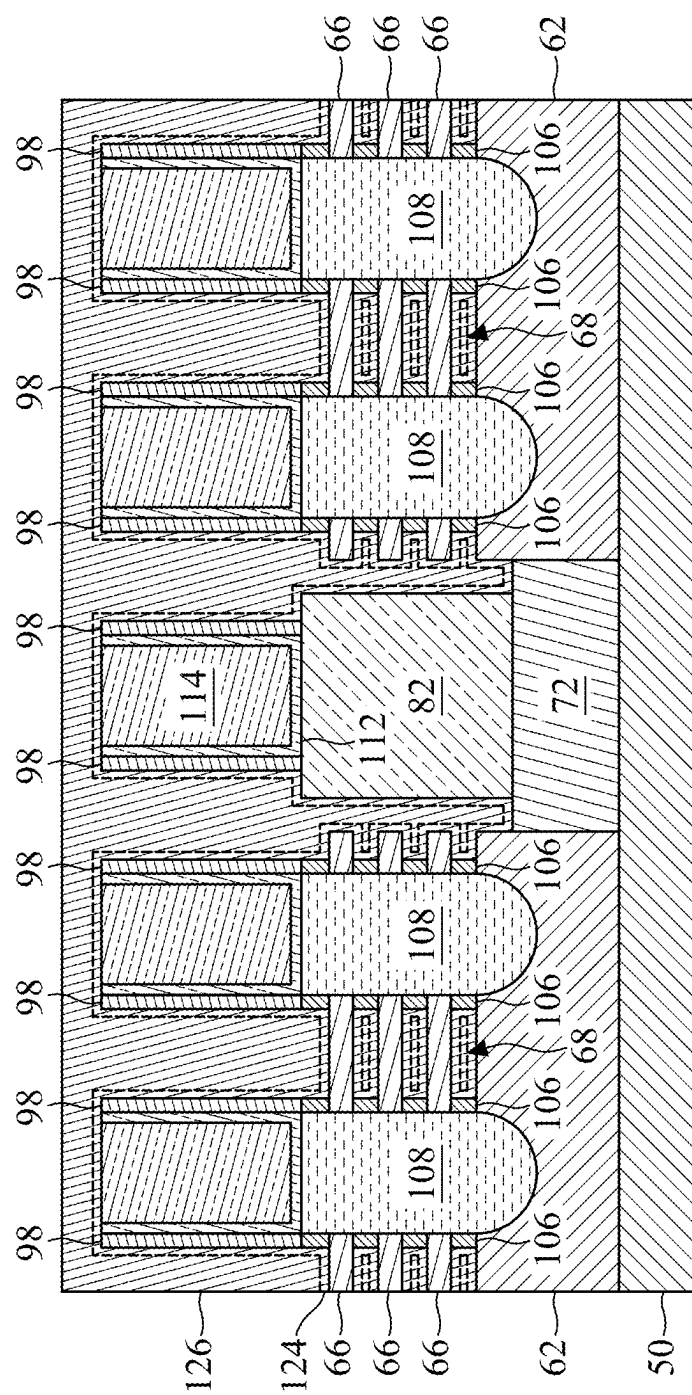


Figure 19A

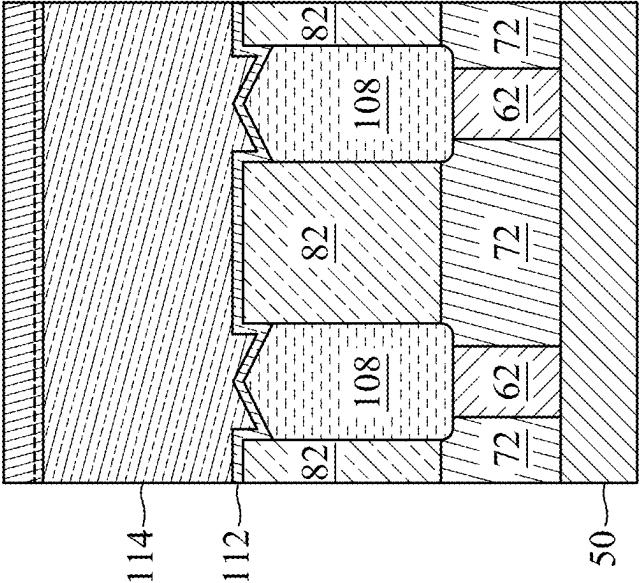


Figure 19C

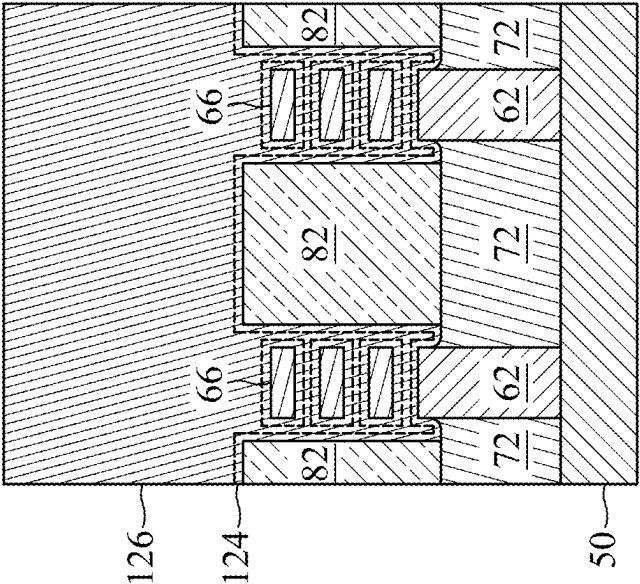


Figure 19B

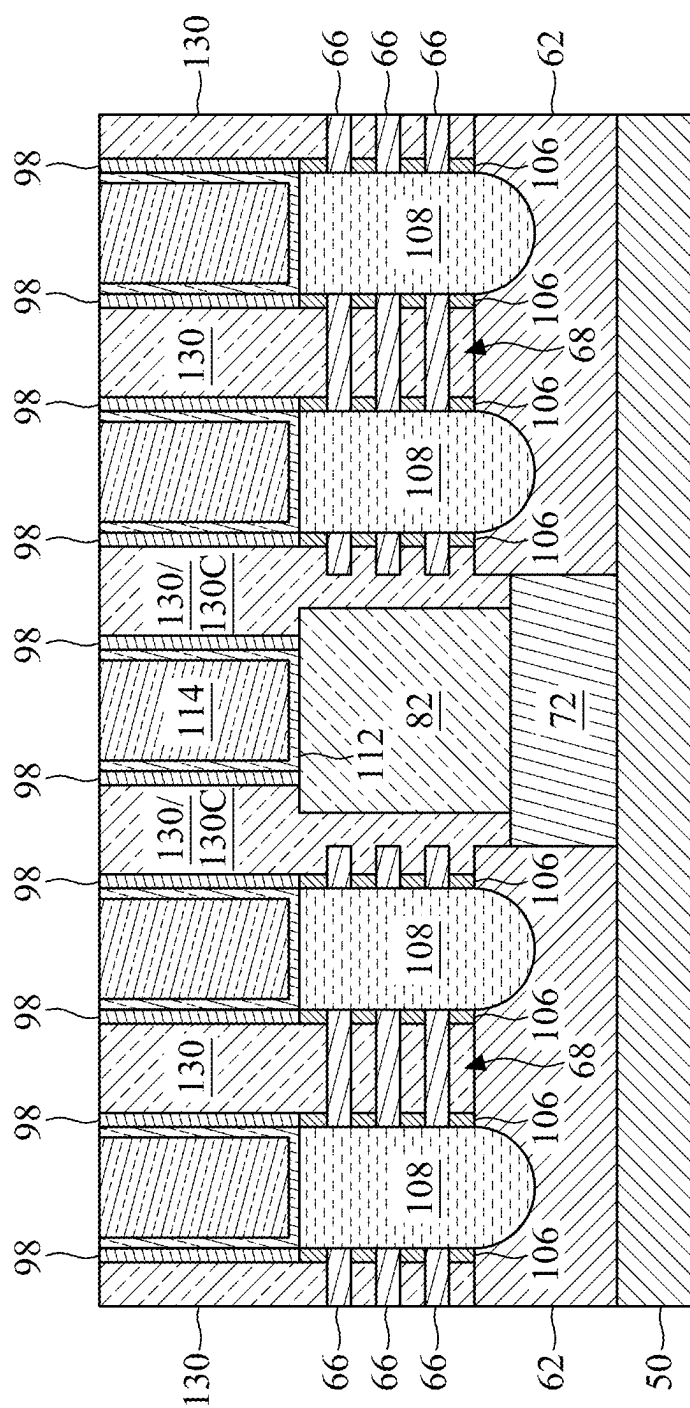


Figure 20A

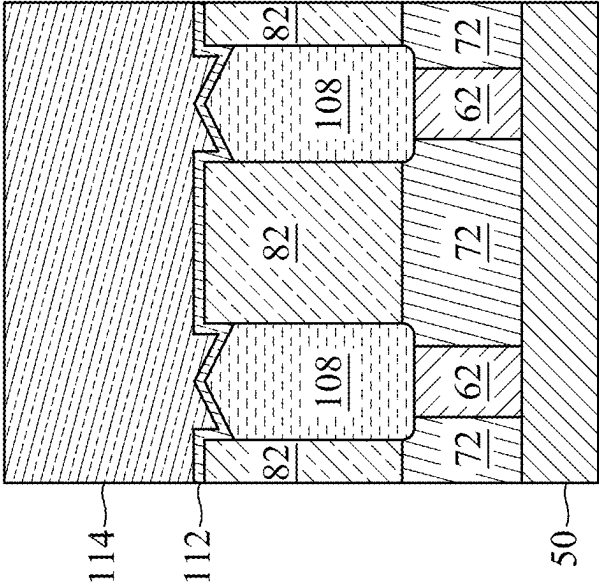


Figure 20C

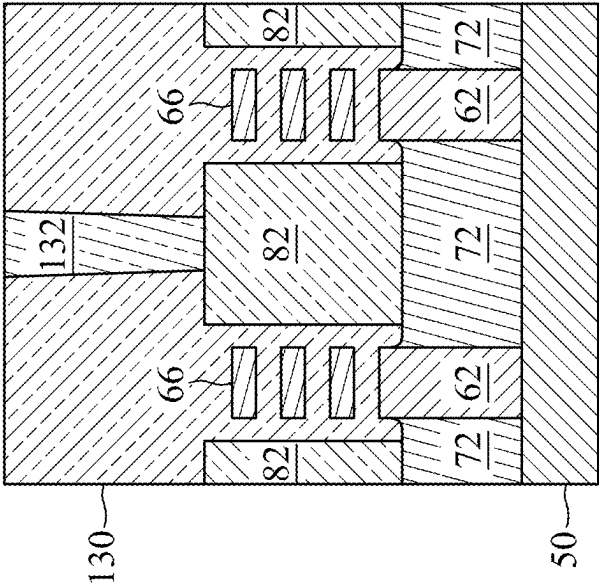


Figure 20B

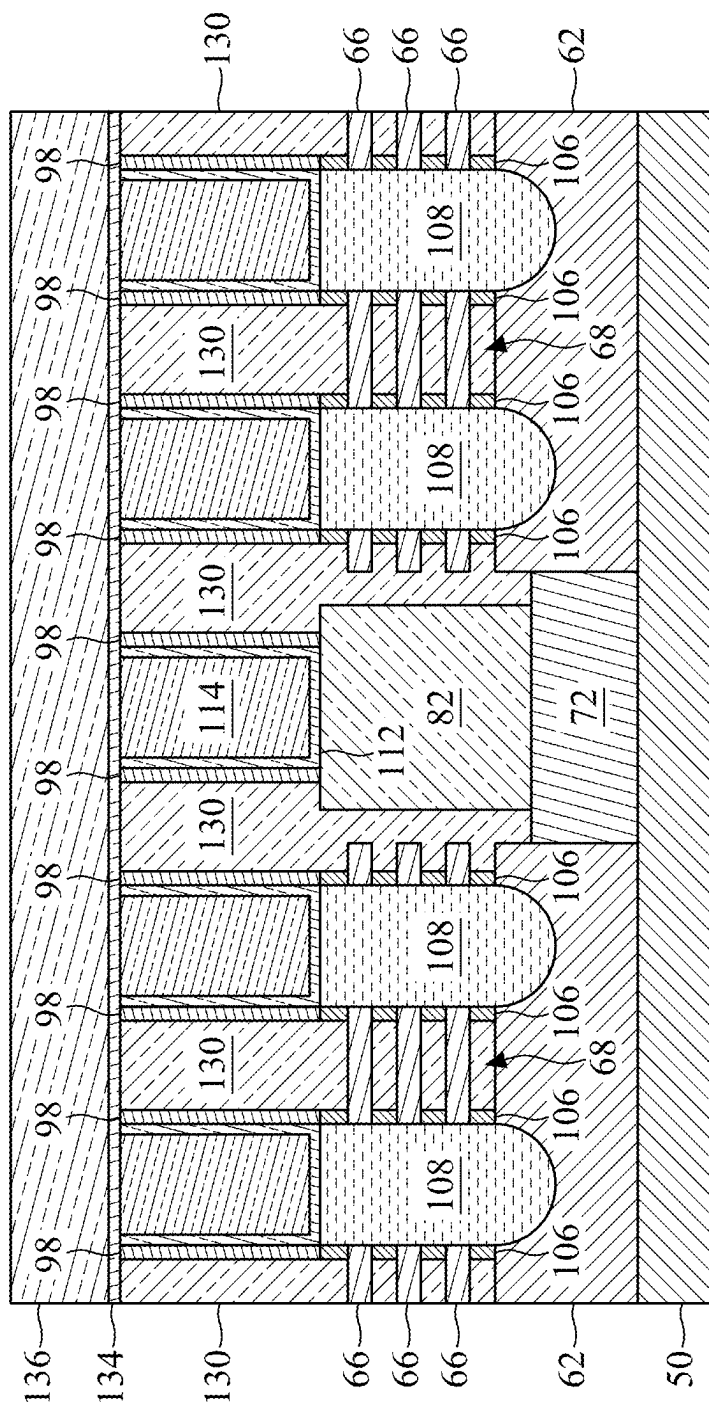


Figure 21A

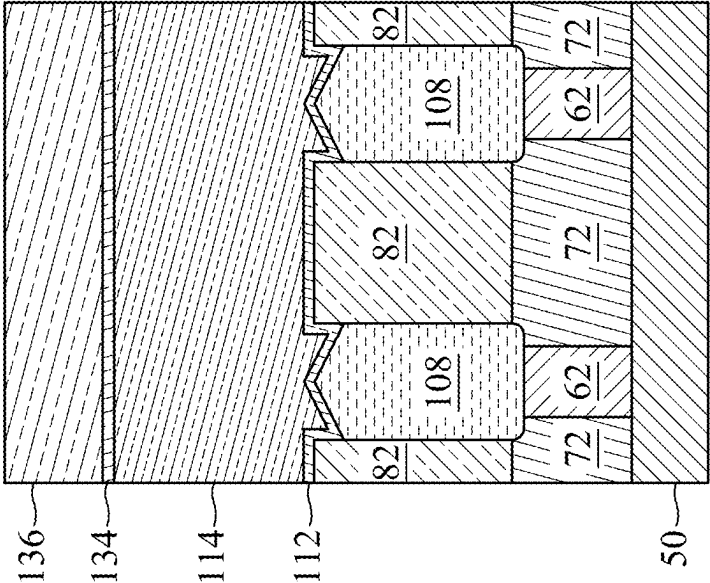


Figure 21C

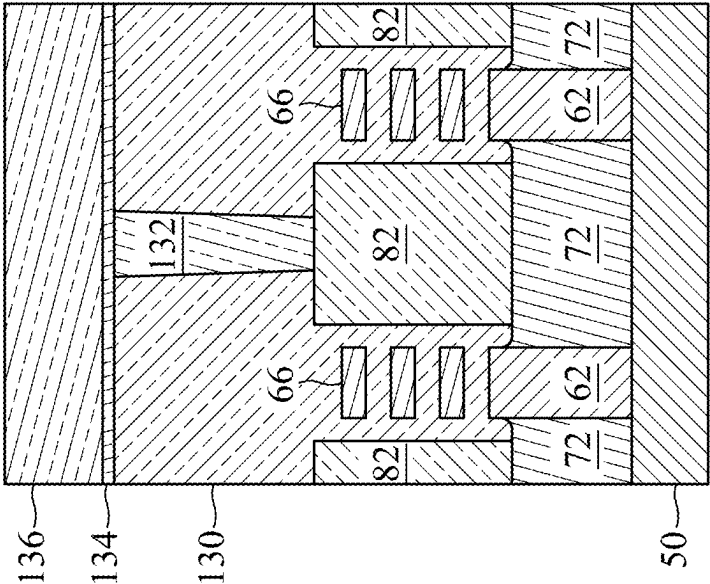


Figure 21B

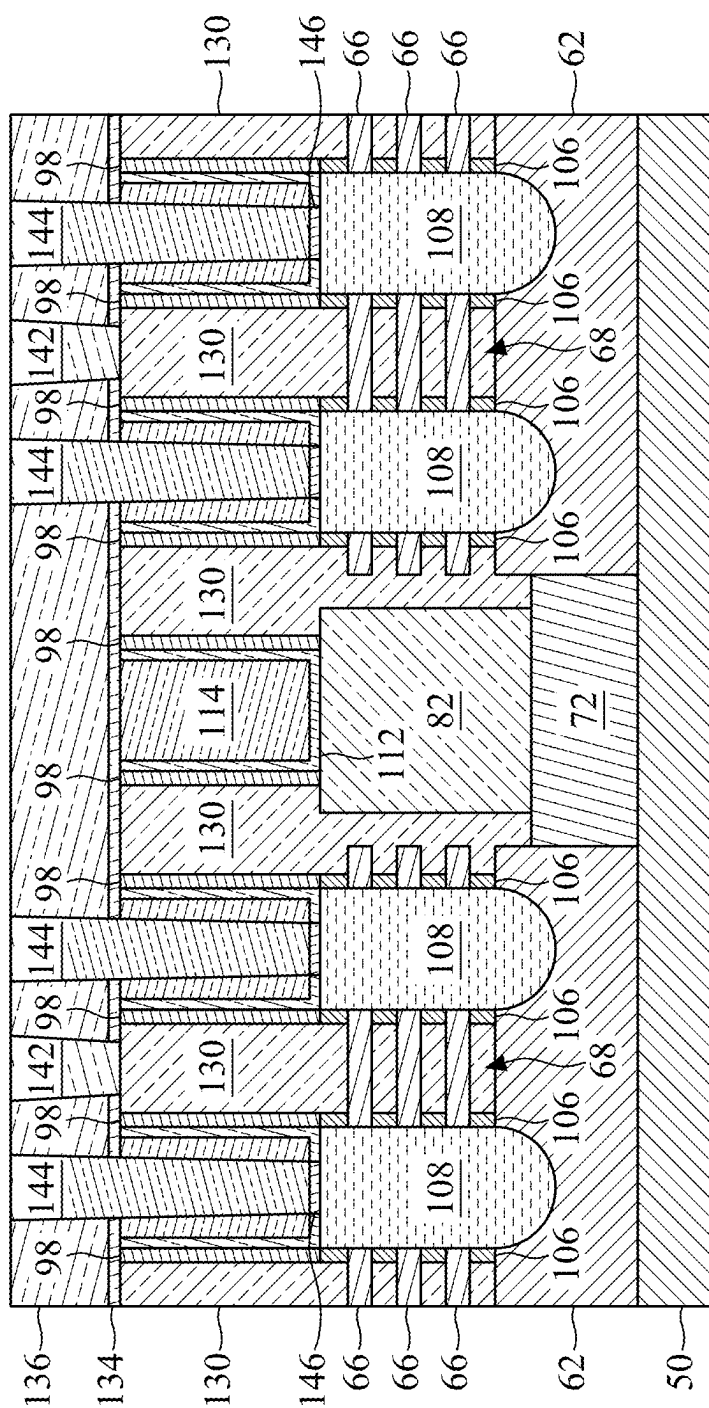


Figure 22A

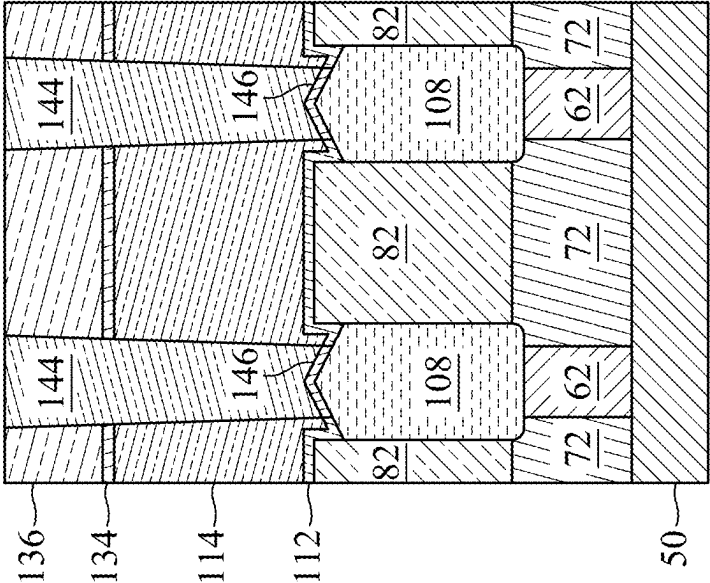


Figure 22C

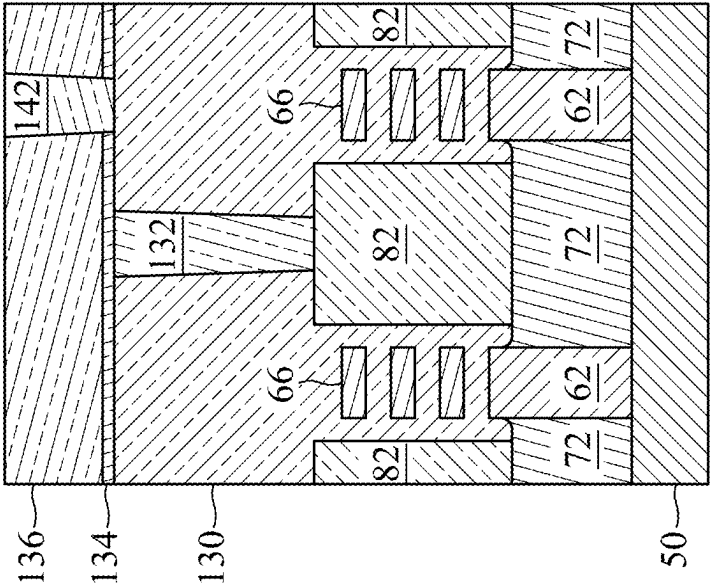


Figure 22B



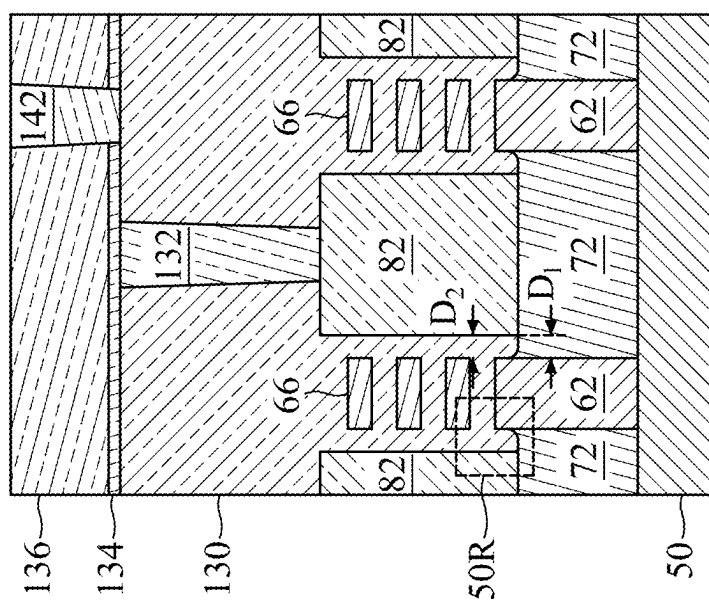


Figure 23A

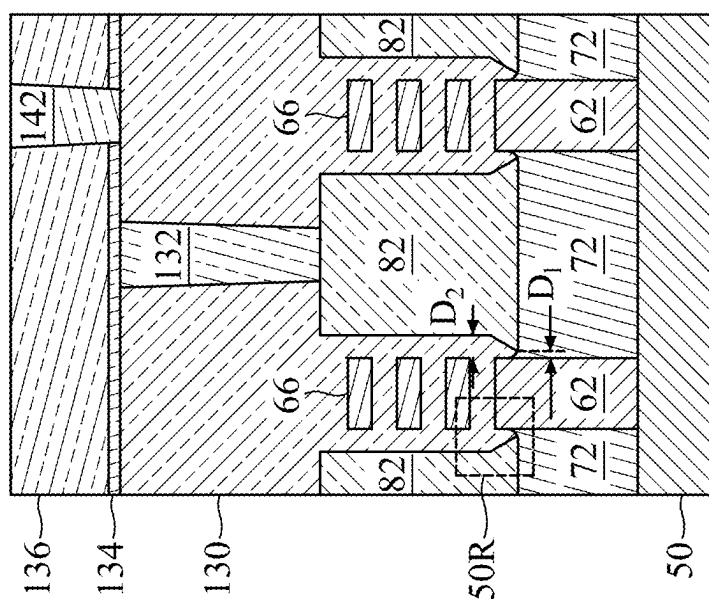


Figure 23B

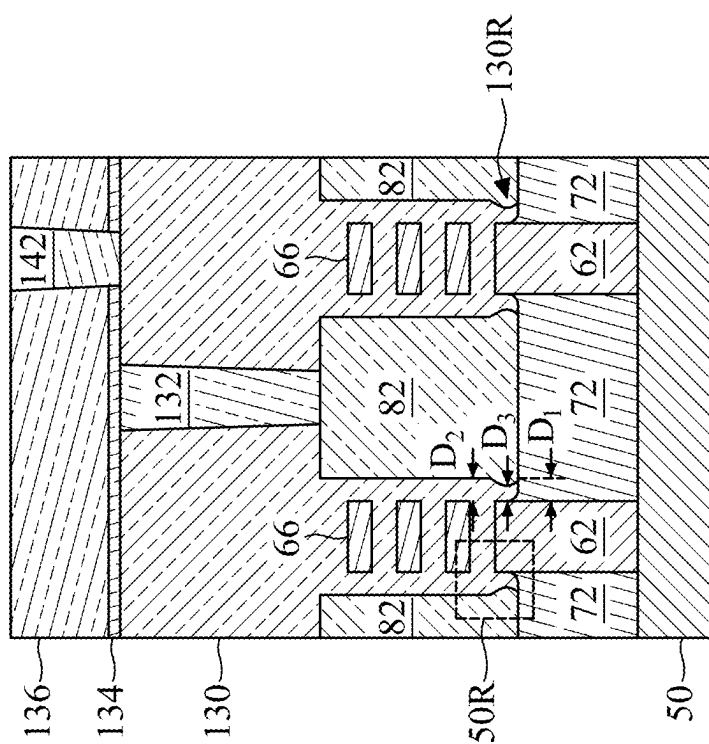


Figure 23C

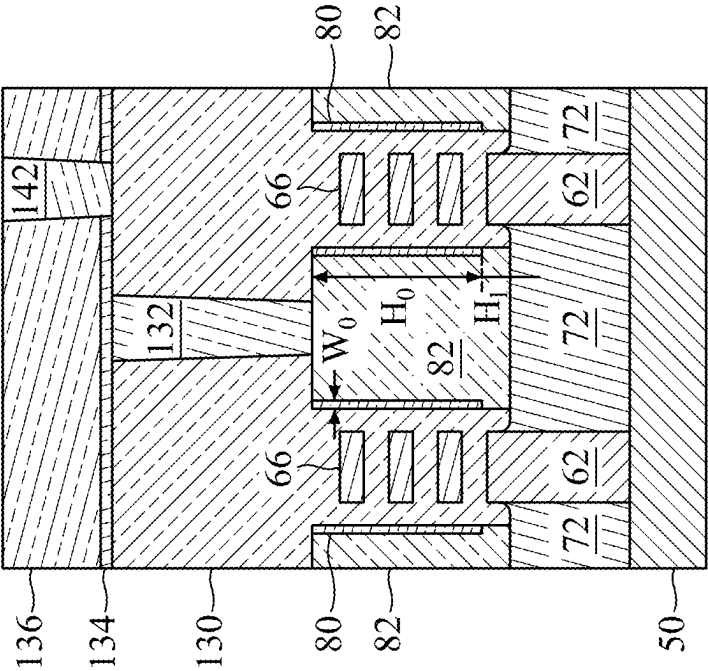


Figure 24A

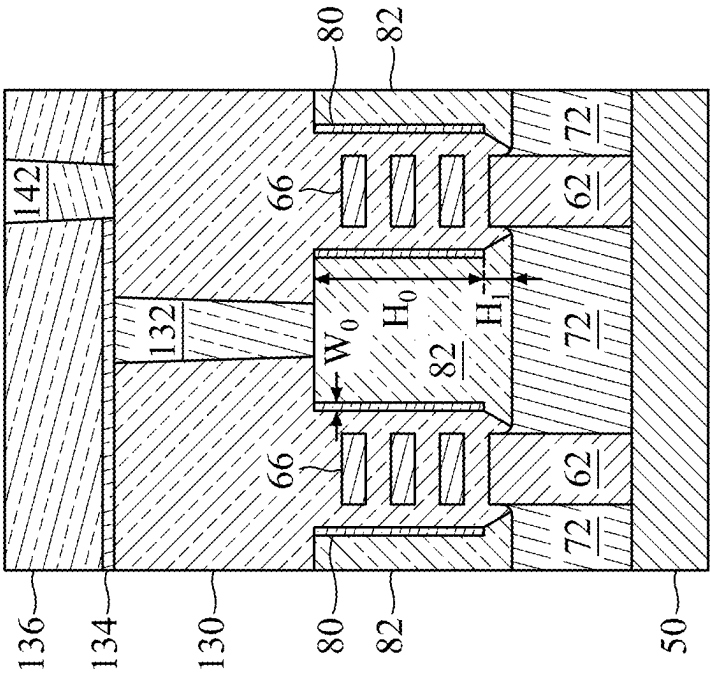


Figure 24B

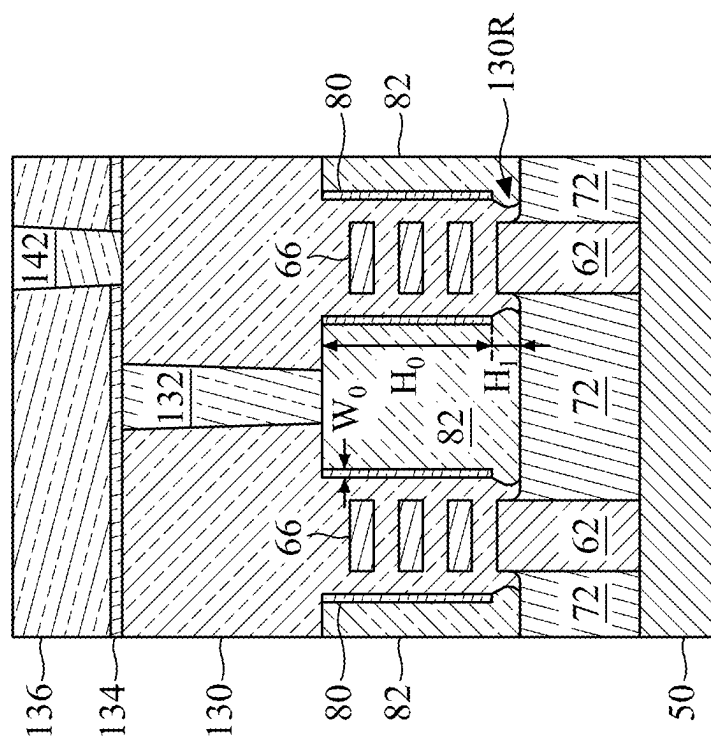


Figure 24C

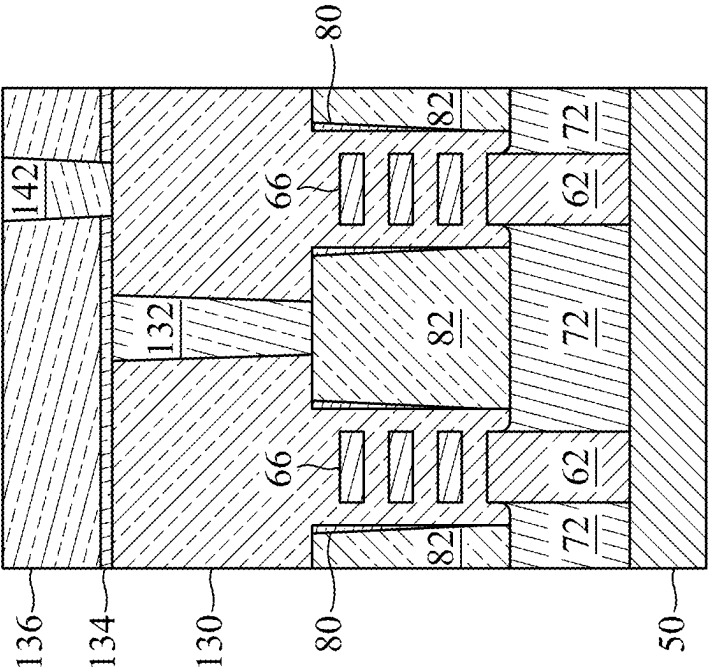


Figure 25A

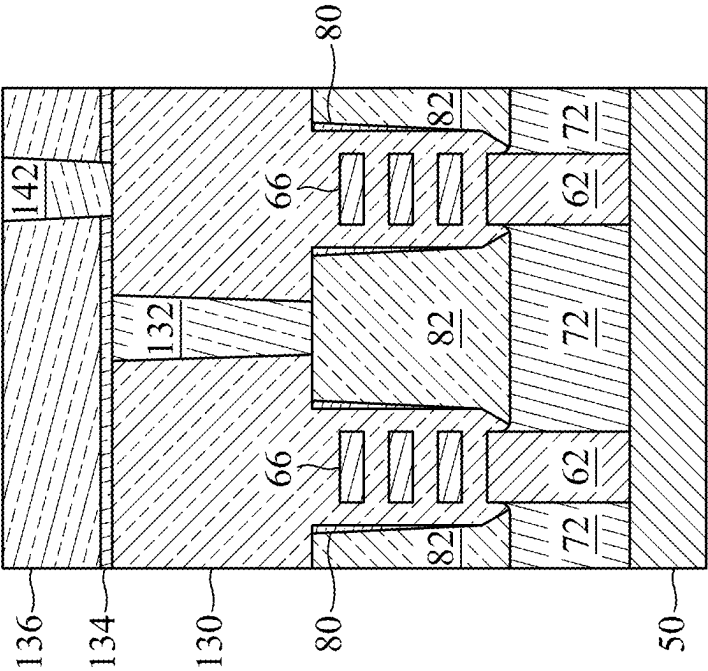


Figure 25B



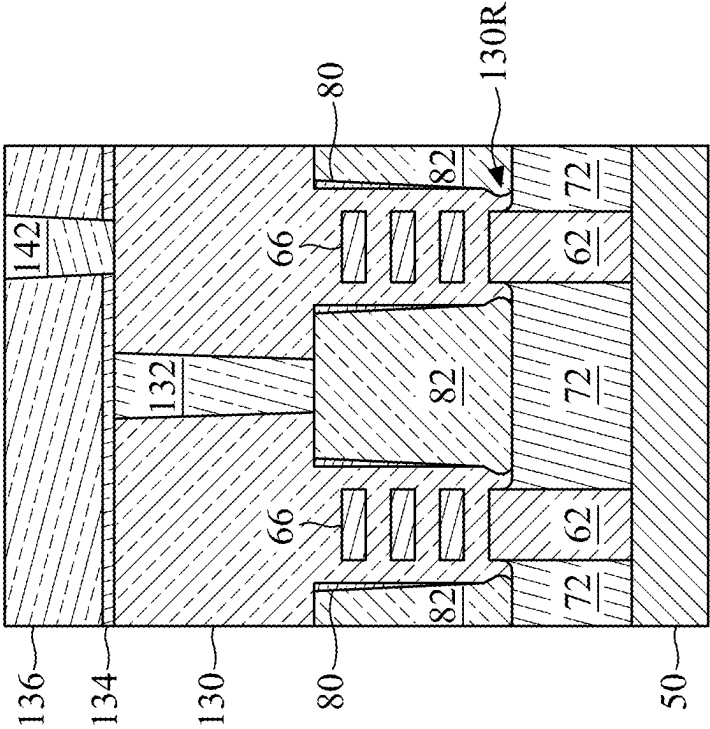


Figure 25C

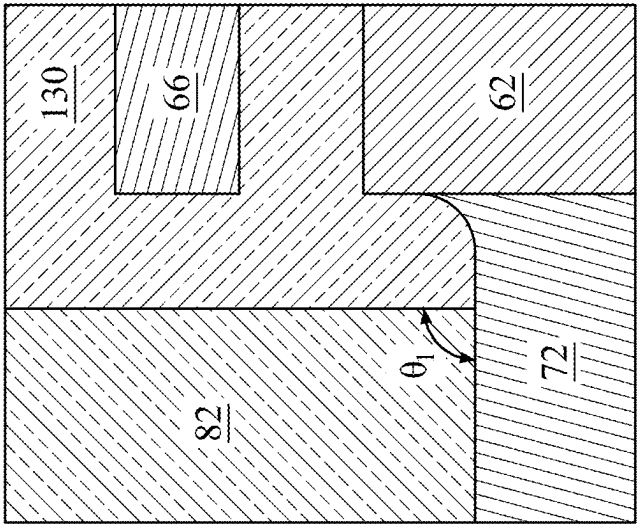


Figure 26A

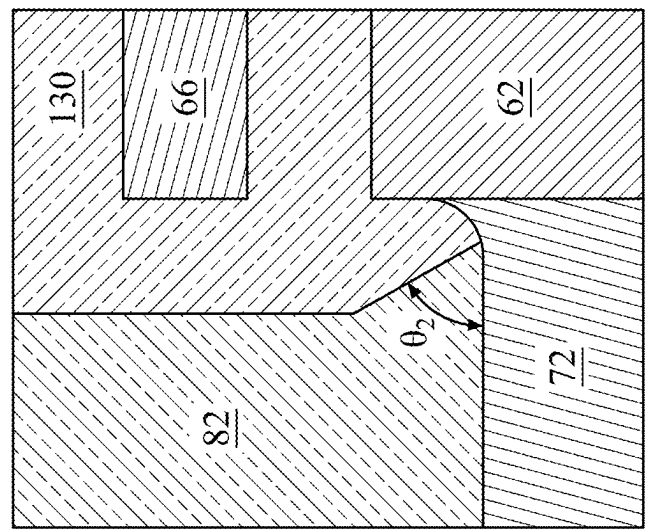


Figure 26B

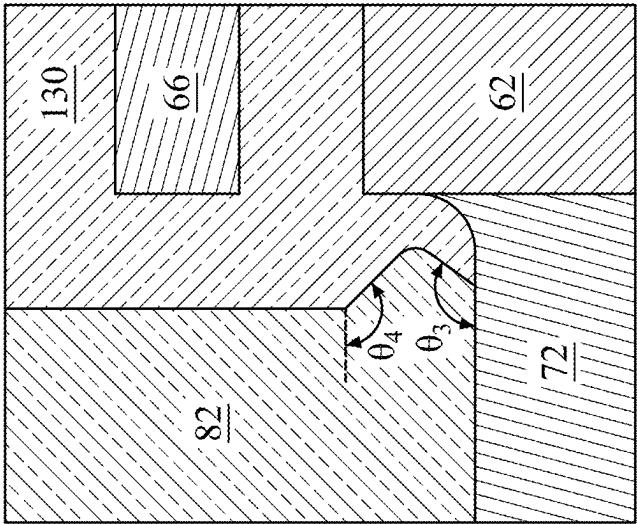


Figure 26C

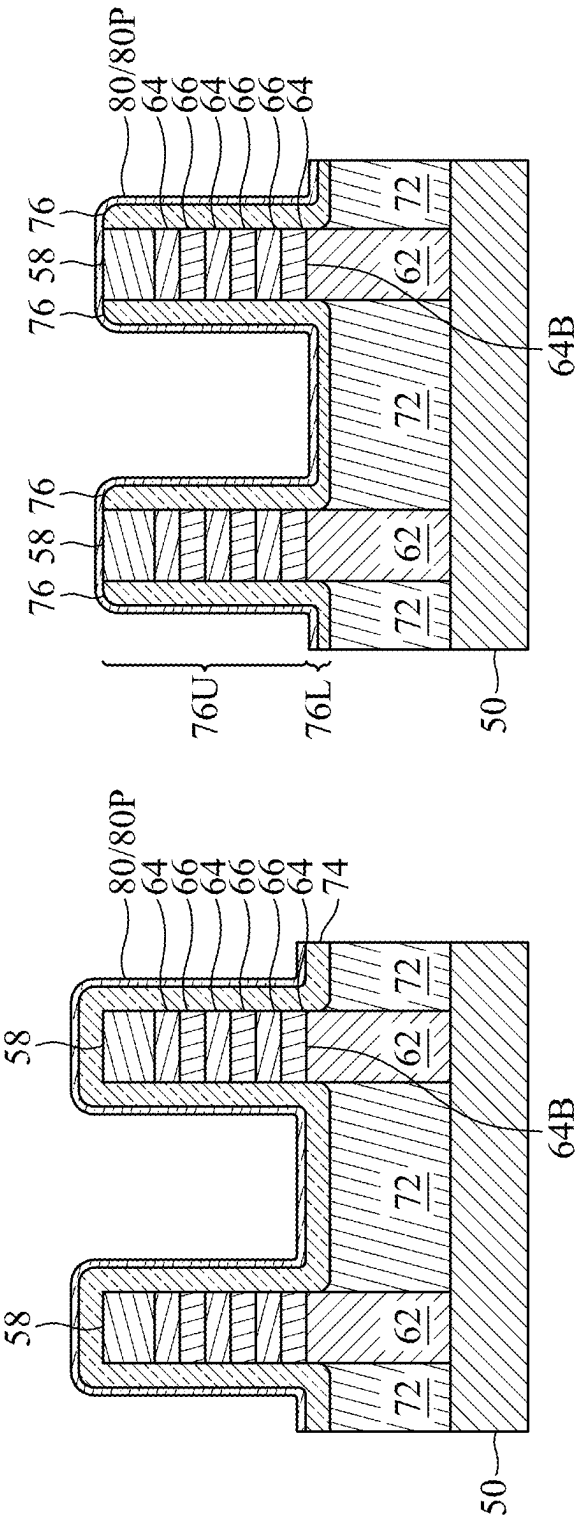


Figure 27B

Figure 27A

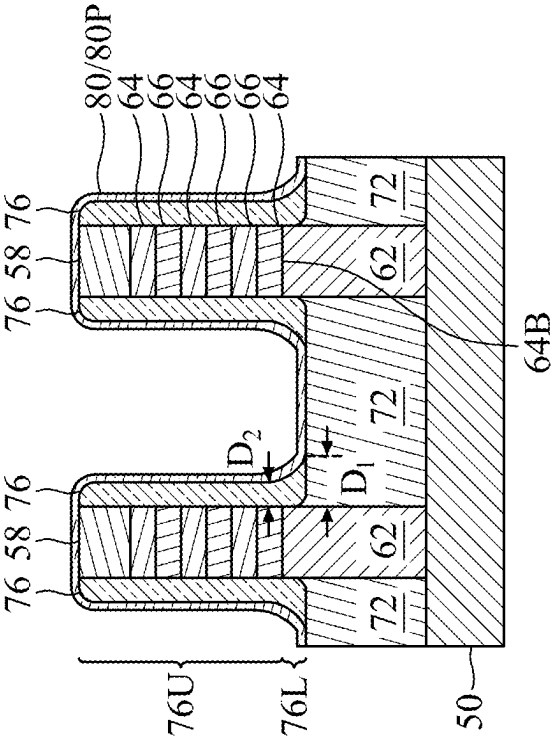


Figure 27D

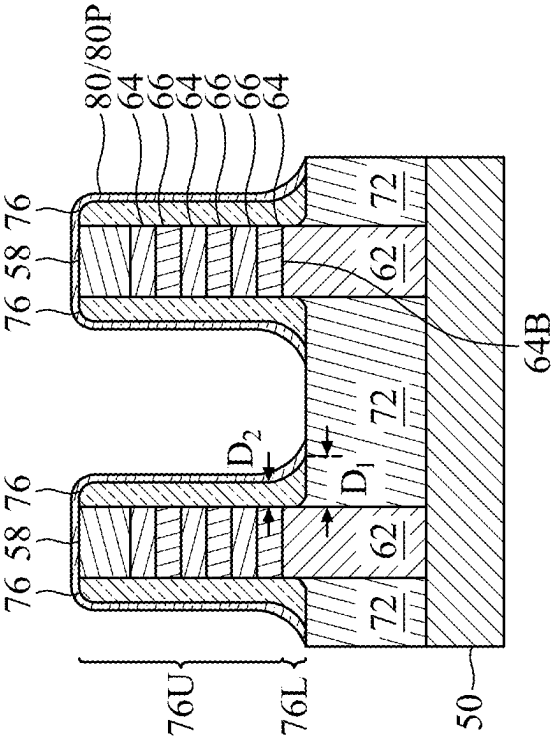


Figure 27C

## TRANSISTOR GATE STRUCTURES

### PRIORITY CLAIM AND CROSS-REFERENCE

**[0001]** This application is a continuation of U.S. patent application Ser. No. 18/363,968, filed on Aug. 2, 2023, entitled “Transistor Gate Structures and Methods of Forming the Same,” which is a divisional of U.S. patent application Ser. No. 17/336,599, filed on Jun. 2, 2021, entitled “Transistor Gate Structures and Methods of Forming the Same,” now U.S. Pat. No. 12,142,655, issued on Nov. 12, 2024, which claims the benefit of U.S. Provisional Application No. 63/059,710, filed on Jul. 31, 2020, which applications are hereby incorporated herein by reference.

### BACKGROUND

**[0002]** Semiconductor devices are used in a variety of electronic applications, such as, for example, personal computers, cell phones, digital cameras, and other electronic equipment. Semiconductor devices are typically fabricated by sequentially depositing insulating or dielectric layers, conductive layers, and semiconductor layers of material over a semiconductor substrate, and patterning the various material layers using lithography to form circuit components and elements thereon.

**[0003]** The semiconductor industry continues to improve the integration density of various electronic components (e.g., transistors, diodes, resistors, capacitors, etc.) by continual reductions in minimum feature size, which allow more components to be integrated into a given area. However, as the minimum features sizes are reduced, additional problems arise that should be addressed.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0004]** Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

**[0005]** FIG. 1 illustrates an example of nanostructure transistors/FETs, in accordance with some embodiments.

**[0006]** FIGS. 2-22C are views of intermediate stages in the manufacturing of nanostructure transistors/FETs, in accordance with some embodiments.

**[0007]** FIGS. 23A-23C are views of nanostructure transistors/FETs, in accordance with various embodiments.

**[0008]** FIGS. 24A-24C are views of nanostructure transistors/FETs, in accordance with various embodiments.

**[0009]** FIGS. 25A-25C are views of nanostructure transistors/FETs, in accordance with various embodiments.

**[0010]** FIGS. 26A-26C are detailed views of nanostructure transistors/FETs, respectively.

**[0011]** FIGS. 27A-27D are views of intermediate stages in the manufacturing of nanostructure transistors/FETs, in accordance with some embodiments.

### DETAILED DESCRIPTION

**[0012]** The following disclosure provides many different embodiments, or examples, for implementing different features of the invention. 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.

**[0013]** 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.

**[0014]** According to various embodiments, dummy gates with a small footing profile are formed around semiconductor fins and nanostructures, which are surrounded by a hybrid fin. The dummy gates are removed in a replacement gate process. Forming the dummy gates with a small footing profile may increase the processing window for subsequent operations, such as the replacement gate process and/or an epitaxial growth process for source/drain regions.

**[0015]** Embodiments are described in a particular context, a die including nanostructure transistors/FETs. Various embodiments may be applied, however, to dies including other types of transistors/FETs (e.g., fin field-effect transistors (finFETs), planar transistors, or the like) in lieu of or in combination with the nanostructure transistors/FETs.

**[0016]** FIG. 1 illustrates an example of nanostructure transistors/FETs (e.g., nanowire FETs, nanosheet FETs, or the like), in accordance with some embodiments. FIG. 1 is a three-dimensional view, where some features of the nanostructure transistors/FETs are omitted for illustration clarity. The nanostructure transistors/FETs may be nanosheet field-effect transistors (NSFETs), nanowire field-effect transistors (NWFETs), gate-all-around field-effect transistors (GAAFETs), or the like.

**[0017]** The nanostructure transistors/FETs include nanostructures 66 (e.g., nanosheets, nanowires, or the like) over semiconductor fins 62 on a substrate 50 (e.g., a semiconductor substrate), with the nanostructures 66 acting as channel regions for the nanostructure transistors/FETs. The nanostructures 66 may include p-type nanostructures, n-type nanostructures, or a combination thereof. Isolation regions 72, such as shallow trench isolation (STI) regions, are disposed between adjacent semiconductor fins 62, which may protrude above and from between adjacent isolation regions 72. Although the isolation regions 72 are described/illustrated as being separate from the substrate 50, as used herein, the term “substrate” may refer to the semiconductor substrate alone or a combination of the semiconductor substrate and the isolation regions. Additionally, although the bottom portions of the semiconductor fins 62 are illustrated as being separate from the substrate 50, the bottom portions of the semiconductor fins 62 may be single, con-

tinuous materials with the substrate **50**. In this context, the semiconductor fins **62** refer to the portion extending above and from between the adjacent isolation regions **72**.

**[0018]** Gate structures **130** are over top surfaces of the semiconductor fins **62** and along top surfaces, sidewalls, and bottom surfaces of the nanostructures **66**. Epitaxial source/drain regions **108** are disposed on the semiconductor fins **62** at opposing sides of the gate structures **130**. The epitaxial source/drain regions **108** may be shared between various semiconductor fins **62**. For example, adjacent epitaxial source/drain regions **108** may be electrically connected, such as through coupling the epitaxial source/drain regions **108** with a same source/drain contact.

**[0019]** Hybrid fins **82** are disposed over the isolation regions **72**, and between adjacent epitaxial source/drain regions **108**. The hybrid fins **82** block epitaxial growth to prevent coalescing of some of the epitaxial source/drain regions **108** during epitaxial growth. For example, the hybrid fins **82** may be formed at cell boundaries to separate the epitaxial source/drain regions **108** of adjacent cells.

**[0020]** FIG. **1** further illustrates reference cross-sections that are used in later figures. Cross-section A-A' is along a longitudinal axis of a semiconductor fin **62** and in a direction of, for example, a current flow between the epitaxial source/drain regions **108** of the nanostructure transistor/FET. Cross-section B-B' is along a longitudinal axis of a gate structure **130** and in a direction, for example, perpendicular to a direction of current flow between the epitaxial source/drain regions **108** of a nanostructure transistor/FET. Cross-section C-C' is parallel to cross-section B-B' and extends through epitaxial source/drain regions **108** of the nanostructure transistors/FETs. Subsequent figures refer to these reference cross-sections for clarity.

**[0021]** FIGS. **2-22C** are views of intermediate stages in the manufacturing of nanostructure transistors/FETs, in accordance with some embodiments. FIGS. **2, 3, and 4** are three-dimensional views. FIGS. **5A, 6A, 10A, 11A, 12A, 13A, 14A, 15A, 16A, 17A, 18A, 19A, 20A, 21A, and 22A** are cross-sectional views illustrated along a similar cross-section as reference cross-section A-A' in FIG. **1**. FIGS. **5B, 6B, 7A-9C, 10B, 11B, 12B, 13B, 14B, 15B, 16B, 17B, 18B, 19B, 20B, 21B, and 22B** are cross-sectional views illustrated along a similar cross-section as reference cross-section B-B' in FIG. **1**. FIGS. **10C, 11C, 12C, 13C, 14C, 15C, 16C, 17C, 18C, 19C, 20C, 21C, and 22C** are cross-sectional views illustrated along a similar cross-section as reference cross-section C-C' in FIG. **1**.

**[0022]** In FIG. **2**, a substrate **50** is provided for forming nanostructure transistors/FETs. The substrate **50** may be a semiconductor substrate, such as a bulk semiconductor, a semiconductor-on-insulator (SOI) substrate, or the like, which may be doped (e.g., with a p-type or an n-type impurity) or undoped. The substrate **50** may be a wafer, such as a silicon wafer. Generally, a SOI substrate is a layer of a semiconductor material formed on an insulator layer. The insulator layer may be, for example, a buried oxide (BOX) layer, a silicon oxide layer, or the like. The insulator layer is provided on a substrate, typically a silicon or glass substrate. Other substrates, such as a multi-layered or gradient substrate may also be used. In some embodiments, the semiconductor material of the substrate **50** may include silicon; germanium; a compound semiconductor including silicon carbide, gallium arsenide, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide; an alloy

semiconductor including silicon germanium, gallium arsenide phosphide, aluminum indium arsenide, aluminum gallium arsenide, gallium indium arsenide, gallium indium phosphide, and/or gallium indium arsenide phosphide; combinations thereof; or the like.

**[0023]** The substrate **50** has an n-type region **50N** and a p-type region **50P**. The n-type region **50N** can be for forming n-type devices, such as NMOS transistors, e.g., n-type nanostructure transistors/FETs, and the p-type region **50P** can be for forming p-type devices, such as PMOS transistors, e.g., p-type nanostructure transistors/FETs. The n-type region **50N** may be physically separated from the p-type region **50P** (not separately illustrated), and any number of device features (e.g., other active devices, doped regions, isolation structures, etc.) may be disposed between the n-type region **50N** and the p-type region **50P**. Although one n-type region **50N** and one p-type region **50P** are illustrated, any number of n-type regions **50N** and p-type regions **50P** may be provided.

**[0024]** The substrate **50** may be lightly doped with a p-type or an n-type impurity. An anti-punch-through (APT) implantation may be performed on an upper portion of the substrate **50** to form an APT region. During the APT implantation, impurities may be implanted in the substrate **50**. The impurities may have a conductivity type opposite from a conductivity type of source/drain regions that will be subsequently formed in each of the n-type region **50N** and the p-type region **50P**. The APT region may extend under the source/drain regions in the nanostructure transistors/FETs. The APT region may be used to reduce the leakage from the source/drain regions to the substrate **50**. In some embodiments, the doping concentration in the APT region is in the range of  $10^{18} \text{ cm}^{-3}$  to  $10^{19} \text{ cm}^{-3}$ .

**[0025]** A multi-layer stack **52** is formed over the substrate **50**. The multi-layer stack **52** includes alternating first semiconductor layers **54** and second semiconductor layers **56**. The first semiconductor layers **54** are formed of a first semiconductor material, and the second semiconductor layers **56** are formed of a second semiconductor material. The semiconductor materials may each be selected from the candidate semiconductor materials of the substrate **50**. In the illustrated embodiment, the multi-layer stack **52** includes three layers of each of the first semiconductor layers **54** and the second semiconductor layers **56**. It should be appreciated that the multi-layer stack **52** may include any number of the first semiconductor layers **54** and the second semiconductor layers **56**. For example, the multi-layer stack **52** may include from one to ten layers of each of the first semiconductor layers **54** and the second semiconductor layers **56**.

**[0026]** In the illustrated embodiment, and as will be subsequently described in greater detail, the first semiconductor layers **54** will be removed and the second semiconductor layers **56** will be patterned to form channel regions for the nanostructure transistors/FETs in both the n-type region **50N** and the p-type region **50P**. The first semiconductor layers **54** are sacrificial layers (or dummy layers), which will be removed in subsequent processing to expose the top surfaces and the bottom surfaces of the second semiconductor layers **56**. The first semiconductor material of the first semiconductor layers **54** is a material that has a high etching selectivity from the etching of the second semiconductor layers **56**, such as silicon germanium. The second semicon-



ductor material of the second semiconductor layers **56** is a material suitable for both n-type and p-type devices, such as silicon.

**[0027]** In another embodiment (not separately illustrated), the first semiconductor layers **54** will be patterned to form channel regions for nanostructure transistors/FETs in one region (e.g., the p-type region **50P**), and the second semiconductor layers **56** will be patterned to form channel regions for nanostructure transistors/FETs in another region (e.g., the n-type region **50N**). The first semiconductor material of the first semiconductor layers **54** may be a material suitable for p-type devices, such as silicon germanium (e.g.,  $\text{Si}_x\text{Ge}_{1-x}$ , where  $x$  can be in the range of 0 to 1), pure germanium, a III-V compound semiconductor, a II-VI compound semiconductor, or the like. The second semiconductor material of the second semiconductor layers **56** may be a material suitable for n-type devices, such as silicon, silicon carbide, a III-V compound semiconductor, a II-VI compound semiconductor, or the like. The first semiconductor material and the second semiconductor material may have a high etching selectivity from the etching of one another, so that the first semiconductor layers **54** may be removed without removing the second semiconductor layers **56** in the n-type region **50N**, and the second semiconductor layers **56** may be removed without removing the first semiconductor layers **54** in the p-type region **50P**.

**[0028]** Each of the layers of the multi-layer stack **52** may be grown by a process such as vapor phase epitaxy (VPE) or molecular beam epitaxy (MBE), deposited by a process such as chemical vapor deposition (CVD) or atomic layer deposition (ALD), or the like. Each of the layers may have a small thickness, such as a thickness in a range of 5 nm to 30 nm. In some embodiments, some layers (e.g., the second semiconductor layers **56**) are formed to be thinner than other layers (e.g., the first semiconductor layers **54**). For example, in embodiments in which the first semiconductor layers **54** are sacrificial layers (or dummy layers) and the second semiconductor layers **56** are patterned to form channel regions for the nanostructure transistors/FETs in both the n-type region **50N** and the p-type region **50P**, the first semiconductor layers **54** can have a first thickness and the second semiconductor layers **56** can have a second thickness, with the second thickness being from 30% to 60% less than the first thickness. Forming the second semiconductor layers **56** to a smaller thickness allows the channel regions to be formed at a greater density.

**[0029]** In FIG. 3, trenches are patterned in the substrate **50** and the multi-layer stack **52** to form semiconductor fins **62**, nanostructures **64**, and nanostructures **66**. The semiconductor fins **62** are semiconductor strips patterned in the substrate **50**. The nanostructures **64** and the nanostructures **66** include the remaining portions of the first semiconductor layers **54** and the second semiconductor layers **56**, respectively. The trenches may be patterned by any acceptable etch process, such as a reactive ion etch (RIE), neutral beam etch (NBE), the like, or a combination thereof. The etching may be anisotropic.

**[0030]** The semiconductor fins **62** and the nanostructures **64**, **66** may be patterned by any suitable method. For example, the semiconductor fins **62** and the nanostructures **64**, **66** may be patterned using one or more photolithography processes, including double-patterning or multi-patterning processes. Generally, double-patterning or multi-patterning processes combine photolithography and self-aligned pro-

cesses, allowing patterns to be created that have, for example, pitches smaller than what is otherwise obtainable using a single, direct photolithography process. For example, in one embodiment, a sacrificial layer is formed over a substrate and patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers may then be used as a mask **58** to pattern the semiconductor fins **62** and the nanostructures **64**, **66**. In some embodiments, the mask **58** (or other layer) may remain on the nanostructures **64**, **66**.

**[0031]** The semiconductor fins **62** and the nanostructures **64**, **66** may each have widths in a range of 8 nm to 40 nm. In the illustrated embodiment, the semiconductor fins **62** and the nanostructures **64**, **66** have substantially equal widths in the n-type region **50N** and the p-type region **50P**. In another embodiment, the semiconductor fins **62** and the nanostructures **64**, **66** in one region (e.g., the n-type region **50N**) are wider or narrower than the semiconductor fins **62** and the nanostructures **64**, **66** in another region (e.g., the p-type region **50P**).

**[0032]** In FIG. 4, STI regions **72** are formed over the substrate **50** and between adjacent semiconductor fins **62**. The STI regions **72** are disposed around at least a portion of the semiconductor fins **62** such that at least a portion of the nanostructures **64**, **66** protrude from between adjacent STI regions **72**. In the illustrated embodiment, the top surfaces of the STI regions **72** are below the top surfaces of the semiconductor fins **62**. In some embodiments, the top surfaces of the STI regions **72** are above or coplanar (within process variations) with the top surfaces of the semiconductor fins **62**.

**[0033]** The STI regions **72** may be formed by any suitable method. For example, an insulation material can be formed over the substrate **50** and the nanostructures **64**, **66**, and between adjacent semiconductor fins **62**. The insulation material may be an oxide, such as silicon oxide, a nitride, such as silicon nitride, the like, or a combination thereof, which may be formed by a chemical vapor deposition (CVD) process, such as high density plasma CVD (HDP-CVD), flowable chemical vapor deposition (FCVD), the like, or a combination thereof. Other insulation materials formed by any acceptable process may be used. In some embodiments, the insulation material is silicon oxide formed by FCVD. An anneal process may be performed once the insulation material is formed. In an embodiment, the insulation material is formed such that excess insulation material covers the nanostructures **64**, **66**. Although the STI regions **72** are each illustrated as a single layer, some embodiments may utilize multiple layers. For example, in some embodiments a liner (not separately illustrated) may first be formed along surfaces of the substrate **50**, the semiconductor fins **62**, and the nanostructures **64**, **66**. Thereafter, an insulation material, such as those previously described may be formed over the liner. A removal process is then applied to the insulation material to remove excess insulation material over the nanostructures **64**, **66**. In some embodiments, a planarization process such as a chemical mechanical polish (CMP), an etch-back process, combinations thereof, or the like may be utilized. In embodiments in which a mask **58** remains on the nanostructures **64**, **66**, the planarization process may expose the mask **58** or remove the mask **58**. After the planarization process, the top surfaces of the insulation material and the mask **58** (if present) or the

nanostructures **64**, **66** are coplanar (within process variations). Accordingly, the top surfaces of the mask **58** (if present) or the nanostructures **64**, **66** are exposed through the insulation material. In the illustrated embodiment, the mask **58** remains on the nanostructures **64**, **66**. The insulation material is then recessed to form the STI regions **72**. The insulation material is recessed such that at least a portion of the nanostructures **64**, **66** protrude from between adjacent portions of the insulation material. Further, the top surfaces of the STI regions **72** may have a flat surface as illustrated, a convex surface, a concave surface (such as dishing), or a combination thereof. In the illustrated embodiment, the top surfaces of the STI regions **72** are concave surfaces, such that portions of the STI regions **72** extend up the sidewalls of the semiconductor fins **62**. The top surfaces of the STI regions **72** may be formed flat, convex, and/or concave by an appropriate etch. The insulation material may be recessed using any acceptable etching process, such as one that is selective to the material of the insulation material (e.g., selectively etches the insulation material of the STI regions **72** at a faster rate than the materials of the semiconductor fins **62** and the nanostructures **64**, **66**). For example, an oxide removal may be performed using dilute hydrofluoric (dHF) acid.

[0034] The process previously described is just one example of how the semiconductor fins **62** and the nanostructures **64**, **66** may be formed. In some embodiments, the semiconductor fins **62** and/or the nanostructures **64**, **66** may be formed using a mask and an epitaxial growth process. For example, a dielectric layer can be formed over a top surface of the substrate **50**, and trenches can be etched through the dielectric layer to expose the underlying substrate **50**. Epitaxial structures can be epitaxially grown in the trenches, and the dielectric layer can be recessed such that the epitaxial structures protrude from the dielectric layer to form the semiconductor fins **62** and/or the nanostructures **64**, **66**. The epitaxial structures may include the alternating semiconductor materials previously described, such as the first semiconductor material and the second semiconductor material. In some embodiments where epitaxial structures are epitaxially grown, the epitaxially grown materials may be in situ doped during growth, which may obviate prior and/or subsequent implantations, although in situ and implantation doping may be used together.

[0035] Further, appropriate wells (not separately illustrated) may be formed in the nanostructures **64**, **66**, the semiconductor fins **62**, and/or the substrate **50**. The wells may have a conductivity type opposite from a conductivity type of source/drain regions that will be subsequently formed in each of the n-type region **50N** and the p-type region **50P**. In some embodiments, a p-type well is formed in the n-type region **50N**, and an n-type well is formed in the p-type region **50P**. In some embodiments, a p-type well or an n-type well is formed in both the n-type region **50N** and the p-type region **50P**.

[0036] In embodiments with different well types, different implant steps for the n-type region **50N** and the p-type region **50P** may be achieved using mask (not separately illustrated) such as a photoresist. For example, a photoresist may be formed over the semiconductor fins **62**, the nanostructures **64**, **66**, and the STI regions **72** in the n-type region **50N**. The photoresist is patterned to expose the p-type region **50P**. The photoresist can be formed by using a spin-on technique and can be patterned using acceptable photoli-

thography techniques. Once the photoresist is patterned, an n-type impurity implant is performed in the p-type region **50P**, and the photoresist may act as a mask to substantially prevent n-type impurities from being implanted into the n-type region **50N**. The n-type impurities may be phosphorus, arsenic, antimony, or the like implanted in the region to a concentration in the range of  $10^{13} \text{ cm}^{-3}$  to  $10^{14} \text{ cm}^{-3}$ . After the implant, the photoresist may be removed, such as by any acceptable ashing process.

[0037] Following or prior to the implanting of the p-type region **50P**, a mask (not separately illustrated) such as a photoresist is formed over the semiconductor fins **62**, the nanostructures **64**, **66**, and the STI regions **72** in the p-type region **50P**. The photoresist is patterned to expose the n-type region **50N**. The photoresist can be formed by using a spin-on technique and can be patterned using acceptable photolithography techniques. Once the photoresist is patterned, a p-type impurity implant may be performed in the n-type region **50N**, and the photoresist may act as a mask to substantially prevent p-type impurities from being implanted into the p-type region **50P**. The p-type impurities may be boron, boron fluoride, indium, or the like implanted in the region to a concentration in the range of  $10^{13} \text{ cm}^{-3}$  to  $10^{14} \text{ cm}^{-3}$ . After the implant, the photoresist may be removed, such as by any acceptable ashing process.

[0038] After the implants of the n-type region **50N** and the p-type region **50P**, an anneal may be performed to repair implant damage and to activate the p-type and/or n-type impurities that were implanted. In some embodiments where epitaxial structures are epitaxially grown for the semiconductor fins **62** and/or the nanostructures **64**, **66**, the grown materials may be in situ doped during growth, which may obviate the implantations, although in situ and implantation doping may be used together.

[0039] FIGS. 5A-22C illustrate various additional steps in the manufacturing of embodiment devices. FIGS. 5A-22C illustrate features in either of the n-type region **50N** and the p-type region **50P**. For example, the structures illustrated may be applicable to both the n-type region **50N** and the p-type region **50P**. Differences (if any) in the structures of the n-type region **50N** and the p-type region **50P** are described in the text accompanying each figure. As will be subsequently described in greater detail, hybrid fins **82** will be formed between the semiconductor fins **62**. FIGS. 5A-22C each illustrate two semiconductor fins **62** and portions of the hybrid fins **82** and the STI regions **72** that are disposed between the two semiconductor fins **62** in the respective cross-sections.

[0040] In FIGS. 5A-5B, a dummy gate layer **74** is conformally formed over the mask **58** (if present), the semiconductor fins **62**, the nanostructures **64**, **66**, and the STI regions **72**. The dummy gate layer **74** may be formed of a semiconductor material (such as one selected from the candidate semiconductor materials of the substrate **50**), which may be grown by a process such as vapor phase epitaxy (VPE) or molecular beam epitaxy (MBE), deposited by a process such as chemical vapor deposition (CVD) or atomic layer deposition (ALD), or the like. For example, the dummy gate layer **74** may be formed of silicon or silicon germanium. The dummy gate layer **74** can be formed to a thickness  $T_1$  over the STI regions **72** in the range of 1 nm to 100 nm. The thickness of the dummy gate layer **74** determines the dimensions of the replacement gate structures for the nanostructure transistors/FETs.

[0041] In FIGS. 6A-6B, the dummy gate layer 74 is patterned to form dummy gates 76 around the mask 58 (if present), the semiconductor fins 62, and the nanostructures 64, 66. The dummy gates 76 are disposed over the STI regions 72. The dummy gate layer 74, when patterned, has portions left on the sidewalls of the mask 58 (if present), the semiconductor fins 62, and the nanostructures 64, 66 (thus forming the dummy gates 76). The dummy gates 76 cover the sidewalls of the nanostructures 64, 66 that will be exposed in subsequent processing to form channel regions. The dummy gates 76 are used as temporary spacers during processing, and will subsequently be removed to expose sidewalls of the portions of the nanostructures 66 that will act as channel regions for the nanostructure transistors/FETs. Specifically, in the illustrated embodiment, the dummy gates 76 and the nanostructures 64 will be subsequently removed and replaced with gate structures that are wrapped around the nanostructures 66. The dummy gates 76 are formed of a material that has a high etching selectivity from the etching of the material of the nanostructures 66. The dummy gates 76 may be formed of the same semiconductor material as the nanostructures 64, or may be formed of a different material.

[0042] As will be subsequently described in greater detail, the dummy gates 76 are formed so that they have a small footing profile. The footing profile of the dummy gates 76 refers to the shape and dimensions of the portions of the dummy gates 76 that extend along the top surfaces of the STI regions 72. Forming the dummy gates 76 with a small footing profile refers to forming the dummy gates 76 so that the portions of the dummy gates 76 on the top surfaces of the STI regions 72 do not flare outward along the concave surfaces of the STI regions 72. As such, the bottom surfaces of the dummy gates 76 extend away from the nanostructures 64, 66 a first distance  $D_1$ , and the outer sidewalls of the dummy gates 76 are disposed a second distance  $D_2$  from the nanostructures 64, 66, with the first distance  $D_1$  being less than or equal to (e.g., not greater than) the second distance  $D_2$ . The first distance  $D_1$  is measured below the top surface of the semiconductor fins 62, and the second distance  $D_2$  between the top surface of the semiconductor fins 62 and the bottom surface of the bottom nanostructure 66. The dimensions of the first distance  $D_1$  and the second distance  $D_2$  will be subsequently described in greater detail. Forming the dummy gates 76 with a small footing profile increases the processing window for subsequent operations, such as a replacement gate process and/or an epitaxial growth process for source/drain regions.

[0043] FIGS. 7A-9C are views of intermediate stages in the patterning of dummy gates 76 with a small footing profile, in accordance with some embodiments. The dummy gates 76 are formed with a small footing profile by patterning the dummy gate layer 74 with multiple etching processes. Specifically, a first etching process is performed to initially pattern the dummy gate layer 74 into the dummy gates 76 (see FIGS. 7A-7B). Protective layers 80 are formed along the upper portions 76U of the dummy gates 76 (see FIGS. 7A-7B), with the lower portions 76L of the dummy gates 76 remaining exposed by the protective layers 80. A second etching process is then performed to trim the lower portions 76L of the dummy gates 76 while the upper portions 76U of the dummy gates 76 are covered by the protective layers 80 (see FIGS. 8A-8C). Trimming the lower portions 76L of the dummy gates 76 reduces the footing

profile of the dummy gates 76 by reducing the widths of the lower portions 76L of the dummy gates 76. The protective layers 80 may optionally be removed (see FIGS. 9A-9C).

[0044] In FIGS. 7A-7B, a first etching process is performed to initially pattern the dummy gate layer 74 (see FIGS. 5A-5B) into the dummy gates 76. The first etching process may be a dry etch, a wet etch, the like, or a combination thereof. The first etching process may be anisotropic. The portions of the dummy gate layer 74 over the mask 58 (if present) or the nanostructures 64, 66 are removed by the first etching process.

[0045] The areal density of the nanostructures 64, 66 determines the outcome of the first etching process, such as by influencing loading during the first etching process. The dummy gates 76 along nanostructures 64, 66 in sparse regions may be patterned so that the STI regions 72 between the nanostructures 64, 66 are exposed, as illustrated by FIG. 7A. The dummy gates 76 along nanostructures 64, 66 in dense regions may be patterned so that the STI regions 72 between the nanostructures 64, 66 are covered, as illustrated by FIG. 7B. In some embodiments, the critical dimension (CD) between the nanostructures 64, 66 is in the range of 2 nm to 2000 nm, where a sparse region refers to a region where the CD is near the lower limit of this range, and a dense region refers to a region where the CD is near the upper limit of this range. A same substrate 50 may have sparse regions and dense regions, such that the first etching process forms the structures of FIGS. 7A and 7B on a same substrate 50.

[0046] The first etching process forms the dummy gates 76 with a large footing profile. Forming the dummy gates 76 with a large footing profile refers to forming the dummy gates 76 so that the portions of the dummy gates 76 on the top surfaces of the STI regions 72 flare outward along the concave surfaces of the STI regions 72. In other words, the sidewalls of the dummy gates 76 are spaced apart by a distance that increases in a direction extending from the top of the dummy gates 76 to the bottom of the dummy gates 76. Referring to FIG. 7A, when the dummy gates 76 are patterned so that the STI regions 72 between the nanostructures 64, 66 are exposed, the first distance  $D_1$  is greater than the second distance  $D_2$ . In this embodiment, the portions of the dummy gate layer 74 over the STI regions 72 are removed. Referring to FIG. 7B, when the dummy gates 76 are patterned so that the STI regions 72 between the nanostructures 64, 66 are covered, the dummy gates 76 extend across the concave surfaces of the STI regions 72. In this embodiment, the portions of the dummy gate layer 74 over the STI regions 72 are thinned. As such, the thickness  $T_1$  of the dummy gates 76 over the STI regions 72 is reduced after the first etching process. After the first etching process, the dummy gate layer 74 can have a thickness  $T_2$  over the STI regions 72 in the range of 0.3 nm to 20 nm, with the thickness  $T_2$  being less than the thickness  $T_1$ .

[0047] Further, protective layers 80 are formed along the upper portions 76U of the dummy gates 76 and over the mask 58 (if present) or the nanostructures 64, 66. In this embodiment, the protective layers 80 are not formed along the lower portions 76L of the dummy gates 76, such that the lower portions 76L of the dummy gates 76 are exposed and can be subsequently trimmed. The protective layers 80 are also not formed along the portions of the dummy gates 76 covering the top surfaces of the STI regions 72 (see FIG. 7B), so that those portions of the dummy gates 76 are

exposed and can be subsequently removed during the trimming. In this context, the upper portions 76U of the dummy gates 76 refers to the portions that have straight sidewalls spaced apart by a constant distance and a rounded top surface, and the lower portions 76L of the dummy gates 76 refers to the portions that flare outward along the STI regions 72. In some embodiments, the lower portion 76L of each dummy gate 76 is disposed beneath the bottom surface 64B of the nanostructure(s) 64/66 that are adjacent that dummy gate 76 and disposed the closest to (and over) the STI regions 72. In some embodiments, the upper portion 76U of each dummy gate 76 is disposed above the bottom surface 64B of the nanostructure(s) 64/66.

[0048] In this embodiment, the protective layers 80 are byproduct layers 80B produced by the first etching process for patterning the dummy gate layer 74. The byproduct layers 80B are formed by including a passivation gas with the etchants used during the first etching process. The passivation gas controls the selectivity of the first etching process and promotes production of etching byproducts, thus leaving behind the byproduct layers 80B after the first etching process. The byproduct layers 80B can have a thickness in the range of 2 Å to 150 Å. The byproduct layers 80B may have an upper thickness that is greater than a lower thickness along the sidewall of the dummy gates 76, such that the byproduct layers 80B have an inverted trapezoid profile shape. Forming the byproduct layers 80B with such a thickness and shape protects the upper portions 76U of the dummy gates 76 when the lower portions 76L of the dummy gates 76 are subsequently trimmed.

[0049] In some embodiments, the first etching process is a dry etch performing with a gas source that includes a main etching gas and a passivation gas. The main etching gas may be  $\text{Cl}_2$ ,  $\text{HBr}$ ,  $\text{CF}_4$ ,  $\text{CHF}_3$ ,  $\text{CH}_2\text{F}_2$ ,  $\text{CH}_3\text{F}$ ,  $\text{C}_4\text{F}_6$ ,  $\text{BCl}_3$ ,  $\text{SF}_6$ ,  $\text{H}_2$ , or the like. The passivation gas may be  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{SiCl}_4$ , or the like. In some embodiments, the gas source also includes a dilute gas such as Ar, He, Ne, or the like. A plasma is generated during the first etching process. In some embodiments, the first etching process is implemented cyclically. For example, first etching process may include cycling between dispensing the main etching gas and dispensing the passivation gas. The etching cycle can be repeated up to 50 times. In some embodiments, the process conditions of the first etching process include: a pressure in the range of 1 mTorr to 800 mTorr; a plasma source power (configured to control the ratio of ions to radicals) in the range of 10 W to 3000 W; a plasma bias power (configured to control the etch direction (e.g., isotropic etch or anisotropic etch)) in the range of 0 W to 3000 W; and a gas source flow rate in the range of 1 sccm to 5000 sccm. Performing the first etching process with parameters in these ranges allows the byproduct layers 80B to be formed with a desired thickness and shape (previously described).

[0050] The composition of the byproduct layers 80B depends on the passivation gas utilized in the first etching process. Continuing the example where the dummy gate layer 74 is formed of silicon or silicon germanium: the byproduct layers 80B may be  $\text{SiO}$  or  $\text{SiGeO}$  byproducts formed when using an oxygen-based passivation gas (e.g.,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}$ , or the like); the byproduct layers 80B

may be  $\text{SiN}$  or  $\text{SiGeN}$  byproducts formed when using a nitrogen-based passivation gas (e.g.,  $\text{N}_2$  or the like); and the byproduct layers 80B may be  $\text{SiS}$  or  $\text{SiGeS}$  byproducts formed when using a sulfur-based passivation gas (e.g.,  $\text{SO}_2$  or the like). In some embodiments, a plurality of passivation gases may be utilized in the first etching process. For example, a mixture of an oxygen-based passivation gas, a nitrogen-based passivation gas, and a sulfur-based passivation gas (e.g.,  $\text{SO}_2$  and  $\text{N}_2$ ) may be utilized in the first etching process, and the byproduct layers 80B may be  $\text{SiGeS}_x\text{O}_y\text{N}_z$  byproducts.

[0051] In FIGS. 8A-8C, a second etching process is performed to trim the lower portions 76L of the dummy gates 76 while the upper portions 76U of the dummy gates 76 are covered by the protective layers 80. The second etching process may be a wet clean, and reduces the footing profile of the dummy gates 76 by reducing the widths of the lower portions 76L of the dummy gates 76. Specifically, the second etching process laterally etches the lower portions 76L of the dummy gates 76 until the dummy gates 76 have a small footing profile. The second etching process can have a greater lateral etch rate than the first etching process, and can have a lesser vertical etch rate than the first etching process, allowing the second etching process to be a trimming process. In embodiments where the dummy gates 76 cover the STI regions 72 between the nanostructures 64, 66 (see FIG. 7B), the second etching process also exposes the top surfaces of the STI regions 72. The protective layers 80 act as etch stop layers during the second etching process, to protect the upper portions 76U of the dummy gates 76 so that they are not trimmed during the second etching process. In other words, the lower portions 76L of the dummy gates 76 are etched during the second etching process, and the upper portions 76U of the dummy gates 76 are not etched (or at least are less etched than the lower portions 76L of the dummy gates 76) during the second etching process. In some embodiments, the first distance  $D_1$  is equal to the second distance  $D_2$  after the second etching process, as illustrated by FIG. 8A. In some embodiments, the first distance  $D_1$  is less than the second distance  $D_2$  after the second etching process, as illustrated by FIGS. 8B and 8C.

[0052] In some embodiments, the second etching process is a wet etch performing with a main etching chemical and an assistant etching chemical in a solvent. The main etching chemical may be  $\text{HF}$ ,  $\text{F}_2$ , or the like. The assistant etching chemical may be  $\text{O}_3$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{HCl}$ ,  $\text{HBr}$ , or the like. The solvent may be deionized (DI) water, alcohol, acetone, or the like.

[0053] The structure of FIG. 8A can be obtained by performing the second etching process on the structure of FIG. 7A, e.g., by patterning the dummy gates 76 so that the STI regions 72 between the nanostructures 64, 66 are exposed, and then by trimming the lower portions 76L of the dummy gates 76. For example, the second etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a lateral direction that is substantially parallel to the major surface of the substrate 50. In this embodiment, the sidewalls of the lower portions 76L of the dummy gates 76 are spaced apart by a distance that is constant in a direction extending from the top of the dummy gates 76 to the bottom of the dummy gates 76. The sidewalls of the lower portions 76L of the dummy gates 76 are thus substantially perpendicular to the major surface of the substrate 50.

[0054] The structure of FIG. 8B can be obtained by performing the second etching process on the structure of FIG. 7A, e.g., by patterning the dummy gates 76 so that the STI regions 72 between the nanostructures 64, 66 are exposed, and then by trimming the lower portions 76L of the dummy gates 76. For example, the second etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a lateral direction that is substantially parallel to the major surface of the substrate 50. The dummy gates 76 in the embodiment of FIG. 8B can be etched more than the embodiment of FIG. 8A, thereby causing them to flare inward along the STI regions 72. In this embodiment, the sidewalls of the lower portions 76L of the dummy gates 76 are spaced apart by a distance that decreases linearly in a direction extending from the top of the dummy gates 76 to the bottom of the dummy gates 76. The sidewalls of the lower portions 76L of the dummy gates 76 thus form acute angles with a plane that is parallel to the major surface of the substrate 50.

[0055] The structure of FIG. 8C can be obtained by performing the second etching process on the structure of FIG. 7B, e.g., by patterning the dummy gates 76 so that the STI regions 72 between the nanostructures 64, 66 are covered, and then by trimming the lower portions 76L of the dummy gates 76 so that the STI regions 72 are exposed. For example, the second etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a diagonal direction that forms an acute angle with a plane that is parallel to the major surface of the substrate 50. In this embodiment, the sidewalls of the lower portions 76L of the dummy gates 76 are spaced apart by a distance that decreases non-linearly in a direction extending from the top of the dummy gates 76 to the bottom of the dummy gates 76, and then also increases non-linearly in that direction. When the dummy gates 76 have portions covering the STI regions 72 (see FIG. 7B), the etching of those portions can reduce the lateral etching of the second etching process. The sidewalls of the lower portions 76L of the dummy gates 76 may thus include sidewall recesses 76R. The bottoms of the sidewall recesses 76R are disposed a third distance  $D_3$  from the nanostructures 64, 66, with the third distance  $D_3$  being less than the second distance  $D_2$  and the first distance  $D_1$ . The third distance  $D_3$  is measured between the points where the second distance  $D_2$  and the first distance  $D_1$  are measured.

[0056] In FIGS. 9A-9C, the protective layers 80 are optionally removed. In some embodiments, the protective layers 80 are removed by a wet clean performed after the lower portions 76L of the dummy gates 76 are trimmed. In some embodiments, the protective layers 80 are removed by the second etching process for trimming the lower portions 76L of the dummy gates 76. In other embodiments (subsequently described), the protective layers 80 are not removed, and remain in the final devices.

[0057] FIGS. 10A-22C are shown for the embodiment of FIG. 9A. Further, the protective layers 80 are removed in the illustrated embodiment. It should be appreciated that a similar process could be performed using the embodiments of FIG. 8A-8C or 9B-9C.

[0058] In FIGS. 10A-10C, a hybrid fin layer 78 is conformally formed over the mask 58 (if present), the semiconductor fins 62, the nanostructures 64, 66, and the dummy gates 76. The hybrid fin layer 78 is formed of one or more dielectric material(s) having a high etching selectivity from

the etching of the semiconductor fins 62, the nanostructures 64, 66, and the dummy gates 76. Acceptable dielectric materials may include silicon oxide, silicon nitride, silicon oxynitride, silicon oxycarbonitride, silicon carbonitride, a metal-based dielectric material, combinations thereof, or the like, which may be formed by a conformal deposition process such as low-pressure chemical vapor deposition (LPCVD), plasma-enhanced chemical vapor deposition (PECVD), flowable chemical vapor deposition (FCVD), or the like. Other insulation materials formed by any acceptable process may be used. In some embodiments, the hybrid fin layer 78 is formed of a low-k dielectric material (e.g., a dielectric material having a k-value less than about 3.5), such as fluorosilicate glass (FSG). The hybrid fin layer 78 fills the remaining area between the semiconductor fins 62 and the nanostructures 64, 66 that is not filled by the dummy gates 76, and may be formed over the top surfaces of the mask 58 (if present) or the nanostructures 64, 66. In some embodiments, the hybrid fin layer 78 includes multiple sub-layers, e.g., a liner layer 78A and a fill layer 78B, which may be formed of different materials.

[0059] In FIGS. 11A-11C, a removal process is performed to remove the excess portions of the material(s) of the hybrid fin layer 78, which excess portions are over the top surfaces of the mask 58 (if present) or the nanostructures 64, 66, thereby forming hybrid fins 82. In some embodiments, a planarization process such as a chemical mechanical polish (CMP), an etch-back process, combinations thereof, or the like may be utilized. The hybrid fin layer 78, when planarized, has portions left in the area between the semiconductor fins 62 and the nanostructures 64, 66 (thus forming the hybrid fins 82). After the planarization process, the top surfaces of the hybrid fins 82, the dummy gates 76, and the mask 58 (if present) or the nanostructures 64, 66 are coplanar (within process variations).

[0060] In embodiments in which a mask 58 remains on the nanostructures 64, 66, the removal process may expose the mask 58 or remove the mask 58. Further, in some embodiments, the mask 58 is removed by a separate process that is performed after the removal process. Any acceptable etch process, such as a dry etch, a wet etch, the like, or a combination thereof, may be performed to remove the mask 58. The etching may be anisotropic. In some embodiments where the mask 58 is removed, the removal process may (or may not) also recess the dummy gates 76.

[0061] In FIG. 12A-12C, a dummy gate layer 84 is formed on the hybrid fins 82, the dummy gates 76, and the mask 58 (if present) or the nanostructures 64, 66. The dummy gate layer 84 may be deposited and then planarized, such as by a CMP. The dummy gate layer 84 may be formed of a conductive or non-conductive material, such as amorphous silicon, polycrystalline-silicon (polysilicon), polycrystalline silicon-germanium (poly-SiGe), a metal, a metallic nitride, a metallic silicide, a metallic oxide, or the like, which may be deposited by physical vapor deposition (PVD), CVD, or the like. The dummy gate layer 84 may also be formed of a semiconductor material (such as one selected from the candidate semiconductor materials of the substrate 50), which may be grown by a process such as vapor phase epitaxy (VPE) or molecular beam epitaxy (MBE), deposited by a process such as chemical vapor deposition (CVD) or atomic layer deposition (ALD), or the like. The dummy gate layer 84 may be formed of material(s) that have a high etching selectivity from the etching of insulation materials,

e.g., the hybrid fins **82**. A mask layer **86** may be deposited over the dummy gate layer **84**. The mask layer **86** may be formed of a dielectric material such as silicon nitride, silicon oxynitride, or the like. In this example, a single dummy gate layer **84** and a single mask layer **86** are formed across the n-type region **50N** and the p-type region **50P**.

[0062] In FIGS. **13A-13C**, the mask layer **86** is patterned using acceptable photolithography and etching techniques to form masks **96**. The pattern of the masks **96** is then transferred to the dummy gate layer **84** by any acceptable etching technique to form dummy gates **94**. The dummy gates **94** cover the top surface of the nanostructures **64**, **66** that will be exposed in subsequent processing to form channel regions. The pattern of the masks **96** may be used to physically separate adjacent dummy gates **94**. The dummy gates **94** may also have lengthwise directions substantially perpendicular (within process variations) to the lengthwise directions of the semiconductor fins **62**. The masks **96** can optionally be removed after patterning, such as by any acceptable etching technique.

[0063] The dummy gates **76** and the dummy gates **94** collectively extend along the portions of the nanostructures **66** that will be patterned to form channel regions **68**. Subsequently formed gate structures will replace the dummy gates **76** and the dummy gates **94**. Forming the dummy gates **94** over the dummy gates **76** allows the subsequently formed gate structures to have a greater height.

[0064] As noted above, the dummy gates **94** may be formed of a semiconductor material. In such embodiments, the nanostructures **64**, the dummy gates **76**, and the dummy gates **94** are each formed of semiconductor materials. In some embodiments, the nanostructures **64** and the dummy gates **76** are formed of a first semiconductor material (e.g., silicon germanium) and the dummy gates **94** are formed of a second semiconductor material (e.g., silicon), so that during a replacement gate process, the dummy gates **94** may be removed in a first etching step, and the nanostructures **64** and the dummy gates **76** may be removed together in a second etching step. When the nanostructures **64** and the dummy gates **76** are formed of silicon germanium: the nanostructures **64** and the dummy gates **76** may have similar germanium concentrations, the nanostructures **64** may have a greater germanium concentration than the dummy gates **76**, or the dummy gates **76** may have a greater germanium concentration than the nanostructures **64**. In some embodiments, the nanostructures **64** are formed of a first semiconductor material (e.g., silicon germanium) and the dummy gates **76** and the dummy gates **94** are formed of a second semiconductor material (e.g., silicon), so that during a replacement gate process, the dummy gates **76** and the dummy gates **94** may be removed together in a first etching step, and the nanostructures **64** may be removed in a second etching step.

[0065] Further, gate spacers **98** are formed over the mask **58** (if present) or the nanostructures **64**, **66**, and on exposed sidewalls of the masks **96** (if present) and the dummy gates **94**. The gate spacers **98** may be formed by conformally depositing one or more dielectric material(s) and subsequently etching the dielectric material(s). Acceptable dielectric materials may include silicon oxide, silicon nitride, silicon oxynitride, silicon oxycarbonitride, or the like, which may be formed by a conformal deposition process such as chemical vapor deposition (CVD), plasma-enhanced chemical vapor deposition (PECVD), atomic layer deposition

(ALD), plasma-enhanced atomic layer deposition (PEALD), or the like. Other insulation materials formed by any acceptable process may be used. Any acceptable etch process, such as a dry etch, a wet etch, the like, or a combination thereof, may be performed to pattern the dielectric material(s). The etching may be anisotropic. The dielectric material(s), when etched, have portions left on the sidewalls of the dummy gates **94** (thus forming the gate spacers **98**). After etching, the gate spacers **98** can have straight sidewalls (as illustrated) or can have curved sidewalls (not separately illustrated).

[0066] Further, implants may be performed to form lightly doped source/drain (LDD) regions (not separately illustrated). In the embodiments with different device types, similar to the implants for the wells previously described, a mask (not separately illustrated) such as a photoresist may be formed over the n-type region **50N**, while exposing the p-type region **50P**, and appropriate type (e.g., p-type) impurities may be implanted into the semiconductor fins **62** and/or the nanostructures **64**, **66** exposed in the p-type region **50P**. The mask may then be removed. Subsequently, a mask (not separately illustrated) such as a photoresist may be formed over the p-type region **50P** while exposing the n-type region **50N**, and appropriate type impurities (e.g., n-type) may be implanted into the semiconductor fins **62** and/or the nanostructures **64**, **66** exposed in the n-type region **50N**. The mask may then be removed. The n-type impurities may be any of the n-type impurities previously described, and the p-type impurities may be any of the p-type impurities previously described. During the implanting, the channel regions **68** remain covered by the dummy gates **94**, so that the channel regions **68** remain substantially free of the impurity implanted to form the LDD regions. The LDD regions may have a concentration of impurities in the range of  $10^{15} \text{ cm}^{-3}$  to  $10^{19} \text{ cm}^{-3}$ . An anneal may be used to repair implant damage and to activate the implanted impurities.

[0067] It is noted that the previous disclosure generally describes a process of forming spacers and LDD regions. Other processes and sequences may be used. For example, fewer or additional spacers may be utilized, different sequence of steps may be utilized, additional spacers may be formed and removed, and/or the like. Furthermore, the n-type devices and the p-type devices may be formed using different structures and steps.

[0068] In FIGS. **14A-14C**, source/drain recesses **104** are formed in the mask **58** (if present), the nanostructures **64**, **66**, and the dummy gates **76**. In the illustrated embodiment, the source/drain recesses **104** extend through the nanostructures **64**, **66** and into the semiconductor fins **62**. The source/drain recesses **104** may also extend into the substrate **50**. In various embodiments, the source/drain recesses **104** may extend to a top surface of the substrate **50** without etching the substrate **50**; the semiconductor fins **62** may be etched such that bottom surfaces of the source/drain recesses **104** are disposed below the top surfaces of the STI regions **72**; or the like. The source/drain recesses **104** may be formed by etching the nanostructures **64**, **66** and the dummy gates **76** using an anisotropic etching processes, such as a RIE, a NBE, or the like. The gate spacers **98** and the dummy gates **94** collectively mask portions of the semiconductor fins **62** and/or the nanostructures **64**, **66** during the etching processes used to form the source/drain recesses **104**. A single etch process may be used to etch each of the nanostructures

64, 66, or multiple etch processes may be used to etch the nanostructures 64, 66. Timed etch processes may be used to stop the etching of the source/drain recesses 104 after the source/drain recesses 104 reach a desired depth. In some embodiments, portions of the STI regions 72 adjacent the hybrid fins 82 may also be etched during the formation of the source/drain recesses 104.

[0069] Because the dummy gates 76 have a small footing profile, they may be more easily removed, without residue of the dummy gates 76 remaining on the top surface of the STI regions 72. More area may thus be available for source/drain regions, and the source/drain regions may be formed so that no residue of the dummy gates 76 remains beneath them. Etching of the subsequently formed source/drain regions during a replacement gate process may thus be avoided, thereby increasing manufacturing yield.

[0070] Optionally, inner spacers 106 are formed on the sidewalls of the remaining portions of the mask 58 (if present) and the nanostructures 64, e.g., those sidewalls exposed by the source/drain recesses 104. As will be subsequently described in greater detail, source/drain regions will be subsequently formed in the source/drain recesses 104, and the nanostructures 64 will be subsequently replaced with corresponding gate structures. The inner spacers 106 act as isolation features between the subsequently formed source/drain regions and the subsequently formed gate structures. Further, the inner spacers 106 may be used to substantially prevent damage to the subsequently formed source/drain regions by subsequent etching processes, such as etching processes used to subsequently remove the nanostructures 64.

[0071] As an example to form the inner spacers 106, the source/drain recesses 104 can be laterally expanded. Specifically, portions of the sidewalls of the nanostructures 64 exposed by the source/drain recesses 104 may be recessed. Although sidewalls of the nanostructures 64 are illustrated as being straight, the sidewalls may be concave or convex. The sidewalls may be recessed by any acceptable etching process, such as one that is selective to the nanostructures 64 (e.g., selectively etches the materials of the nanostructures 64 at a faster rate than the material of the nanostructures 66). The etching may be isotropic. For example, when the nanostructures 66 are formed of silicon and the nanostructures 64 are formed of silicon germanium, the etching process may be a wet etch using tetramethylammonium hydroxide (TMAH), ammonium hydroxide (NH<sub>4</sub>OH), or the like. In another embodiment, the etching process may be a dry etch using a fluorine-based gas such as hydrogen fluoride (HF) gas. In some embodiments, the same etching process may be continually performed to both form the source/drain recesses 104 and recess the sidewalls of the nanostructures 64. The inner spacers 106 are then formed on the recessed sidewalls of the nanostructures 64. The inner spacers 106 can be formed by conformally forming an insulating material and subsequently etching the insulating material. The insulating material may be silicon nitride or silicon oxynitride, although any suitable material, such as a low-k dielectric material, may be utilized. The insulating material may be deposited by a conformal deposition process, such as ALD, CVD, or the like. The etching of the insulating material may be anisotropic. For example, the etching process may be a dry etch such as a RIE, a NBE, or the like. Although outer sidewalls of the inner spacers 106 are illustrated as being flush with respect to the sidewalls of

the gate spacers 98, the outer sidewalls of the inner spacers 106 may extend beyond or be recessed from the sidewalls of the gate spacers 98. In other words, the inner spacers 106 may partially fill, completely fill, or overfill the sidewall recesses. Moreover, although the sidewalls of the inner spacers 106 are illustrated as being straight, the sidewalls of the inner spacers 106 may be concave or convex. Portions of the sidewalls of the mask 58 (if present) may also be recessed, and the inner spacers 106 can also be formed on the recessed sidewalls of the mask 58.

[0072] In FIGS. 15A-15C, epitaxial source/drain regions 108 are formed in the source/drain recesses 104. The epitaxial source/drain regions 108 are formed in the source/drain recesses 104 such that each dummy gate 94 (and corresponding channel region 68) is disposed between respective adjacent pairs of the epitaxial source/drain regions 108. In some embodiments, the gate spacers 98 and the inner spacers 106 are used to separate the epitaxial source/drain regions 108 from, respectively, the dummy gates 94 and the nanostructures 64 by an appropriate lateral distance so that the epitaxial source/drain regions 108 do not short out with subsequently formed gates of the resulting nanostructure transistors/FETs. A material of the epitaxial source/drain regions 108 may be selected to exert stress in the respective channel regions 68, thereby improving performance.

[0073] The epitaxial source/drain regions 108 in the n-type region 50N may be formed by masking the p-type region 50P. Then, the epitaxial source/drain regions 108 in the n-type region 50N are epitaxially grown in the source/drain recesses 104 in the n-type region 50N. The epitaxial source/drain regions 108 may include any acceptable material appropriate for n-type devices. For example, if the nanostructures 66 are silicon, the epitaxial source/drain regions 108 in the n-type region 50N may include materials exerting a tensile strain on the channel regions 68, such as silicon, silicon carbide, phosphorous doped silicon carbide, silicon phosphide, or the like. The epitaxial source/drain regions 108 in the n-type region 50N may be referred to as “n-type source/drain regions.” The epitaxial source/drain regions 108 in the n-type region 50N may have surfaces raised from respective surfaces of the semiconductor fins 62 and the nanostructures 64, 66, and may have facets.

[0074] The epitaxial source/drain regions 108 in the p-type region 50P may be formed by masking the n-type region 50N. Then, the epitaxial source/drain regions 108 in the p-type region 50P are epitaxially grown in the source/drain recesses 104 in the p-type region 50P. The epitaxial source/drain regions 108 may include any acceptable material appropriate for p-type devices. For example, if the nanostructures 66 are silicon, the epitaxial source/drain regions 108 in the p-type region 50P may include materials exerting a compressive strain on the channel regions 68, such as silicon germanium, boron doped silicon germanium, germanium, germanium tin, or the like. The epitaxial source/drain regions 108 in the p-type region 50P may be referred to as “p-type source/drain regions.” The epitaxial source/drain regions 108 in the p-type region 50P may have surfaces raised from respective surfaces of the semiconductor fins 62 and the nanostructures 64, 66, and may have facets.

[0075] The epitaxial source/drain regions 108, the nanostructures 64, 66, and/or the semiconductor fins 62 may be implanted with impurities to form source/drain regions, similar to the process previously described for forming LDD



regions, followed by an anneal. The source/drain regions may have an impurity concentration in the range of  $10^{19}$   $\text{cm}^{-3}$  to  $10^{21}$   $\text{cm}^{-3}$ . The n-type and/or p-type impurities for source/drain regions may be any of the impurities previously described. In some embodiments, the epitaxial source/drain regions **108** may be in situ doped during growth.

**[0076]** The epitaxial source/drain regions **108** may include one or more semiconductor material layers. For example, the epitaxial source/drain regions **108** may each include a liner layer **108A**, a main layer **108B**, and a finishing layer **108C** (or more generally, a first semiconductor material layer, a second semiconductor material layer, and a third semiconductor material layer). Any number of semiconductor material layers may be used for the epitaxial source/drain regions **108**. Each of the liner layer **108A**, the main layer **108B**, and the finishing layer **108C** may be formed of different semiconductor materials and may be doped to different impurity concentrations. In some embodiments, the liner layer **108A** may have a lesser concentration of impurities than the main layer **108B**, and the finishing layer **108C** may have a greater concentration of impurities than the liner layer **108A** and a lesser concentration of impurities than the main layer **108B**. In embodiments in which the epitaxial source/drain regions **108** include three semiconductor material layers, the liner layers **108A** may be grown in the source/drain recesses **104**, the main layers **108B** may be grown on the liner layers **108A**, and the finishing layers **108C** may be grown on the main layers **108B**.

**[0077]** As a result of the epitaxy processes used to form the epitaxial source/drain regions **108**, top surfaces of the epitaxial source/drain regions have facets which expand laterally outward beyond sidewalls of the semiconductor fins **62** and the nanostructures **64**, **66**. However, the hybrid fins **82** block the lateral epitaxial growth. Therefore, adjacent epitaxial source/drain regions **108** remain separated after the epitaxy process is completed as illustrated by FIG. **15C**. The epitaxial source/drain regions **108** contact the sidewalls of the hybrid fins **82**. In the illustrated embodiment, the epitaxial source/drain regions **108** are grown so that the top surfaces of the epitaxial source/drain regions **108** are disposed below the top surfaces of the hybrid fins **82**. In various embodiments, the top surfaces of the epitaxial source/drain regions **108** are disposed above the top surfaces of the hybrid fins **82**; the top surfaces of the epitaxial source/drain regions **108** have portions disposed above and below the top surfaces of the hybrid fins **82**; or the like. Further, in the illustrated embodiment, the epitaxial source/drain regions **108** are grown so that the top surfaces of the epitaxial source/drain regions **108** are coplanar with the top surfaces of the nanostructures **64**, **66**. In another embodiment, the epitaxial source/drain regions **108** are grown so that the top surfaces of the epitaxial source/drain regions **108** are disposed above the top surfaces of the nanostructures **64**, **66**.

**[0078]** In FIGS. **16A-16C**, a first inter-layer dielectric (ILD) **114** is deposited over the epitaxial source/drain regions **108**, the gate spacers **98**, the masks **96** (if present) or the dummy gates **94**. The first ILD **114** may be formed of a dielectric material, which may be deposited by any suitable method, such as CVD, plasma-enhanced CVD (PECVD), FCVD, or the like. Acceptable dielectric materials may include phospho-silicate glass (PSG), boro-silicate glass (BSG), boron-doped phospho-silicate glass (BPSG), undoped silicate glass (USG), or the like. Other insulation materials formed by any acceptable process may be used.

**[0079]** In some embodiments, a contact etch stop layer (CESL) **112** is formed between the first ILD **114** and the epitaxial source/drain regions **108**, the gate spacers **98**, and the masks **96** (if present) or the dummy gates **94**. The CESL **112** may be formed of a dielectric material, such as silicon nitride, silicon oxide, silicon oxynitride, or the like, having a high etching selectivity from the etching of the first ILD **114**. The CESL **112** may be formed by any suitable method, such as CVD, ALD, or the like.

**[0080]** In FIGS. **17A-17C**, a removal process is performed to level the top surfaces of the first ILD **114** with the top surfaces of the masks **96** (if present) or the dummy gates **94**. In some embodiments, a planarization process such as a chemical mechanical polish (CMP), an etch-back process, combinations thereof, or the like may be utilized. The planarization process may also remove the masks **96** on the dummy gates **94**, and portions of the gate spacers **98** along sidewalls of the masks **96**. After the planarization process, the top surfaces of the gate spacers **98**, the first ILD **114**, the CESL **112**, and the masks **96** (if present) or the dummy gates **94** are coplanar (within process variations). Accordingly, the top surfaces of the masks **96** (if present) or the dummy gates **94** are exposed through the first ILD **114**. In the illustrated embodiment, the masks **96** remain, and the planarization process levels the top surfaces of the first ILD **114** with the top surfaces of the masks **96**.

**[0081]** In FIGS. **18A-18C**, the masks **96** (if present) and the dummy gates **94** are removed in an etching process, so that recesses **116** are formed. In some embodiments, the dummy gates **94** are removed by an anisotropic dry etch process. For example, the etching process may include a dry etch process using reaction gas(es) that selectively etch the dummy gates **94** at a faster rate than the first ILD **114** or the gate spacers **98**. Each recess **116** exposes and/or overlies portions of the channel regions **68**. Portions of the nanostructures **66** which act as the channel regions **68** are disposed between adjacent pairs of the epitaxial source/drain regions **108**.

**[0082]** The remaining portions of the nanostructures **64** are then removed to expand the recesses **116**, such that openings **118** are formed in regions between the nanostructures **66**. The remaining portions of the dummy gates **76** are also removed to expand the recesses **116**, such that openings **120** are formed in regions between semiconductor fins **62** and the hybrid fins **82**. The remaining portions of the nanostructures **64** and the dummy gates **76** can be removed by any acceptable etching process that selectively etches the material(s) of the nanostructures **64** and the dummy gates **76** at a faster rate than the material of the nanostructures **66**. The etching may be isotropic. For example, when the nanostructures **64** and the dummy gates **76** are formed of silicon germanium and the nanostructures **66** are formed of silicon, the etching process may be a wet etch using tetramethylammonium hydroxide (TMAH), ammonium hydroxide ( $\text{NH}_4\text{OH}$ ), or the like. The masks **58** (if present) may also be removed. In some embodiments, a trim process (not separately illustrated) is performed to decrease the thicknesses of the exposed portions of the nanostructures **66**.

**[0083]** Because the dummy gates **76** have a small footing profile, they may be more easily removed, without residue of the dummy gates **76** remaining on the top surface of the STI regions **72**. More area may thus be available for replacement gates, and the formation of voids in the replacement gates may be avoided, thereby increasing device performance.



Further, as noted above, the epitaxial source/drain regions **108** are formed so that no residue of the dummy gates **76** remains beneath them. Etching beneath the epitaxial source/drain regions **108** during the formation of the recesses **116** may thus be avoided, reducing the risk of damaging the epitaxial source/drain regions **108**.

**[0084]** In FIGS. **19A-19C**, a gate dielectric layer **124** is formed in the recesses **116**. A gate electrode layer **126** is formed on the gate dielectric layer **124**. The gate dielectric layer **124** and the gate electrode layer **126** are layers for replacement gates, and each wrap around all (e.g., four) sides of the nanostructures **66**. Thus, the gate dielectric layer **124** and the gate electrode layer **126** are formed in the openings **118** and the openings **120** (see FIG. **18B**).

**[0085]** The gate dielectric layer **124** is disposed on the sidewalls and/or the top surfaces of the semiconductor fins **62**; on the top surfaces, the sidewalls, and the bottom surfaces of the nanostructures **66**; on the sidewalls of the gate spacers **98** and the inner spacers **106**; and on the top surfaces and the sidewalls of the hybrid fins **82**. The gate dielectric layer **124** may also be formed on the top surfaces of the first ILD **114** and the gate spacers **98**. The gate dielectric layer **124** may include an oxide such as silicon oxide or a metal oxide, a silicate such as a metal silicate, combinations thereof, multi-layers thereof, or the like. The gate dielectric layer **124** may include a high-k dielectric material (e.g., a dielectric material having a k-value greater than about 7.0), such as a metal oxide or a silicate of hafnium, aluminum, zirconium, lanthanum, manganese, barium, titanium, lead, and combinations thereof. Although a single-layered gate dielectric layer **124** is illustrated in FIGS. **19A-19C**, the gate dielectric layer **124** may include any number of interfacial layers and any number of main layers.

**[0086]** The gate electrode layer **126** may include a metal-containing material such as titanium nitride, titanium oxide, tungsten, cobalt, ruthenium, aluminum, combinations thereof, multi-layers thereof, or the like. Although a single-layered gate electrode layer **126** is illustrated in FIGS. **19A-19C**, the gate electrode layer **126** may include any number of work function tuning layers, any number of barrier layers, any number of glue layers, and a fill material.

**[0087]** The formation of the gate dielectric layers **124** in the n-type region **50N** and the p-type region **50P** may occur simultaneously such that the gate dielectric layers **124** in each region are formed of the same materials, and the formation of the gate electrode layers **126** may occur simultaneously such that the gate electrode layers **126** in each region are formed of the same materials. In some embodiments, the gate dielectric layers **124** in each region may be formed by distinct processes, such that the gate dielectric layers **124** may be different materials and/or have a different number of layers, and/or the gate electrode layers **126** in each region may be formed by distinct processes, such that the gate electrode layers **126** may be different materials and/or have a different number of layers. Various masking steps may be used to mask and expose appropriate regions when using distinct processes.

**[0088]** In FIGS. **20A-20C**, a removal process is performed to remove the excess portions of the materials of the gate dielectric layer **124** and the gate electrode layer **126**, which excess portions are over the top surfaces of the first ILD **114** and the gate spacers **98**, thereby forming gate structures **130**. In some embodiments, a planarization process such as a

chemical mechanical polish (CMP), an etch-back process, combinations thereof, or the like may be utilized. The gate dielectric layer **124**, when planarized, has portions left in the recesses **116** (thus forming gate dielectrics for the gate structures **130**). The gate electrode layer **126**, when planarized, has portions left in the recesses **116** (thus forming gate electrodes for the gate structures **130**). The top surfaces of the gate spacers **98**; the CESL **112**; the first ILD **114**; and the gate structures **130** are coplanar (within process variations). The gate structures **130** are replacement gates of the resulting nanostructure transistors/FETs, and may be referred to as “metal gates.” The gate structures **130** each extend along top surfaces, sidewalls, and bottom surfaces of a channel region **68** of the nanostructures **66**.

**[0089]** Some of the gate structures **130** are capping gate structures **130C**. The capping gate structures **130C** are non-function structures disposed on the ends of the semiconductor fins **62** and over the STI regions **72** between the semiconductor fins **62**. The capping gate structures **130C** are disposed between the hybrid fins **82** and the semiconductor fins **62** in the cross-section of FIG. **20A**.

**[0090]** The gate structures **130** fill the area previously occupied by the nanostructures **64**, the dummy gates **76**, and the dummy gates **94**. After they are formed, the gate structures **130** have the same profile shape as the dummy gates **76**. The profile shapes of the gate structures **130** will be subsequently described in greater detail.

**[0091]** In some embodiments, isolation regions **132** are formed extending through some of the gate structures **130**. An isolation region **132** is formed to divide (or “cut”) a gate structure **130** into multiple gate structures **130**. The isolation region **132** may be formed of a dielectric material, such as silicon nitride, silicon oxide, silicon oxynitride, or the like, which may be formed by a deposition process such as CVD, ALD, or the like. As an example to form the isolation regions **132**, openings can be patterned in the desired gate structures **130**. Any acceptable etch process, such as a dry etch, a wet etch, the like, or a combination thereof, may be performed to pattern the openings. The etching may be anisotropic. One or more layers of dielectric material may be deposited in the openings. A removal process may be performed to remove the excess portions of the dielectric material, which excess portions are over the top surfaces of the gate structures **130**, thereby forming the isolation regions **132**.

**[0092]** In FIGS. **21A-21C**, a second ILD **136** is deposited over the gate spacers **98**, the CESL **112**, the first ILD **114**, and the gate structures **130**. In some embodiments, the second ILD **136** is a flowable film formed by a flowable CVD method. In some embodiments, the second ILD **136** is formed of a dielectric material such as PSG, BSG, BPSG, USG, or the like, which may be deposited by any suitable method, such as CVD, PECVD, or the like.

**[0093]** In some embodiments, an etch stop layer (ESL) **134** is formed between the second ILD **136** and the gate spacers **98**, the CESL **112**, the first ILD **114**, and the gate structures **130**. The ESL **134** may include a dielectric material, such as silicon nitride, silicon oxide, silicon oxynitride, or the like, having a high etching selectivity from the etching of the second ILD **136**.

**[0094]** In FIGS. **22A-22C**, gate contacts **142** and source/drain contacts **144** are formed to contact, respectively, the gate structures **130** and the epitaxial source/drain regions **108**. The gate contacts **142** are physically and electrically

coupled to the gate structures **130**. The source/drain contacts **144** are physically and electrically coupled to the epitaxial source/drain regions **108**.

**[0095]** As an example to form the gate contacts **142** and the source/drain contacts **144**, openings for the gate contacts **142** are formed through the second ILD **136** and the ESL **134**, and openings for the source/drain contacts **144** are formed through the second ILD **136**, the ESL **134**, the first ILD **114**, and the CESL **112**. The openings may be formed using acceptable photolithography and etching techniques. A liner (not separately illustrated), such as a diffusion barrier layer, an adhesion layer, or the like, and a conductive material are formed in the openings. The liner may include titanium, titanium nitride, tantalum, tantalum nitride, or the like. The conductive material may be copper, a copper alloy, silver, gold, tungsten, cobalt, aluminum, nickel, or the like. A planarization process, such as a CMP, may be performed to remove excess material from a surface of the second ILD **136**. The remaining liner and conductive material form the gate contacts **142** and the source/drain contacts **144** in the openings. The gate contacts **142** and the source/drain contacts **144** may be formed in distinct processes, or may be formed in the same process. Although shown as being formed in the same cross-sections, it should be appreciated that each of the gate contacts **142** and the source/drain contacts **144** may be formed in different cross-sections, which may avoid shorting of the contacts.

**[0096]** Optionally, metal-semiconductor alloy regions **146** are formed at the interfaces between the epitaxial source/drain regions **108** and the source/drain contacts **144**. The metal-semiconductor alloy regions **146** can be silicide regions formed of a metal silicide (e.g., titanium silicide, cobalt silicide, nickel silicide, etc.), germanide regions formed of a metal germanide (e.g. titanium germanide, cobalt germanide, nickel germanide, etc.), silicon-germanide regions formed of both a metal silicide and a metal germanide, or the like. The metal-semiconductor alloy regions **146** can be formed before the material(s) of the source/drain contacts **144** by depositing a metal in the openings for the source/drain contacts **144** and then performing a thermal anneal process. The metal can be any metal capable of reacting with the semiconductor materials (e.g., silicon, silicon-germanium, germanium, etc.) of the epitaxial source/drain regions **108** to form a low-resistance metal-semiconductor alloy, such as nickel, cobalt, titanium, tantalum, platinum, tungsten, other noble metals, other refractory metals, rare earth metals or their alloys. The metal can be deposited by a deposition process such as ALD, CVD, PVD, or the like. After the thermal anneal process, a cleaning process, such as a wet clean, may be performed to remove any residual metal from the openings for the source/drain contacts **144**, such as from surfaces of the metal-semiconductor alloy regions **146**. The material(s) of the source/drain contacts **144** can then be formed on the metal-semiconductor alloy regions **146**.

**[0097]** FIGS. 23A-23C are views of nanostructure transistors/FETs, in accordance with various embodiments. FIGS. 23A, 23B, and 23C show the resulting gate structures **130** after a replacement gate process is performed in the embodiments of FIGS. 9A, 9B, and 9C, respectively. As noted above, the gate structures **130** have the same profile shape as the dummy gates **76**. Specifically, the portions of

the gate structures **130** on the top surfaces of the STI regions **72** do not flare outward along the concave surfaces of the STI regions **72**.

**[0098]** In the embodiment of FIG. 23A, after the replacement gate process, the bottom surfaces of the gate structures **130** extend away from the nanostructures **66** a first distance  $D_1$ , and the outer sidewalls of the gate structures **130** are disposed a second distance  $D_2$  from the nanostructures **66**, with the first distance  $D_1$  being equal to the second distance  $D_2$ . Further, the hybrid fins **82** are disposed the first distance  $D_1$  from the semiconductor fins **62** and are disposed the second distance  $D_2$  from the nanostructures **66**. In this embodiment, the sidewalls of the lower portions of the gate structures **130** are spaced apart a constant width. The distance  $D_1$  and the distance  $D_2$  can each be in the range of 0.5 nm to 30 nm.

**[0099]** In the embodiment of FIG. 23B, after the replacement gate process, the bottom surfaces of the gate structures **130** extend away from the nanostructures **66** a first distance  $D_1$ , and the outer sidewalls of the gate structures **130** are disposed a second distance  $D_2$  from the nanostructures **66**, with the first distance  $D_1$  being less than the second distance  $D_2$ . Further, the hybrid fins **82** are disposed the first distance  $D_1$  from the semiconductor fins **62** and are disposed the second distance  $D_2$  from the nanostructures **66**. In this embodiment, the sidewalls of the lower portions of the gate structures **130** are spaced apart by a distance that decreases linearly in a direction extending from the top of the gate structures **130** to the bottom of the gate structures **130**. The distance  $D_1$  and the distance  $D_2$  can each be in the range of 0.5 nm to 30 nm.

**[0100]** In the embodiment of FIG. 23C, after the replacement gate process, the bottom surfaces of the gate structures **130** extend away from the nanostructures **66** a first distance  $D_1$ , and the outer sidewalls of the gate structures **130** are disposed a second distance  $D_2$  from the nanostructures **66**, with the first distance  $D_1$  being less than the second distance  $D_2$ . Further, the hybrid fins **82** are disposed the first distance  $D_1$  from the semiconductor fins **62** and are disposed the second distance  $D_2$  from the nanostructures **66**. In this embodiment, the sidewalls of the lower portions of the gate structures **130** are spaced apart by a distance that decreases non-linearly in a direction extending from the top of the gate structures **130** to the bottom of the gate structures **130**, and then also increases non-linearly in that direction. The sidewalls of those portions of the gate structures **130** include sidewall recesses **130R**. The hybrid fins **82** extend into the sidewall recesses **130R** of the gate structures **130**. The bottoms of the sidewall recesses **130R** are disposed a third distance  $D_3$  from the nanostructures **66**, with the third distance  $D_3$  being less than the second distance  $D_2$  and the first distance  $D_1$ . The distance  $D_1$ , the distance  $D_2$ , and the distance  $D_3$  can each be in the range of 0.5 nm to 30 nm.

**[0101]** FIGS. 24A-24C are views of nanostructure transistors/FETs, in accordance with various embodiments. These embodiments are similar to the embodiments of FIGS. 23A-23C, respectively, except the protective layers **80** are not removed, and remain in the final devices. The protective layers **80** extend along the portions of the sidewall of the gate structures **130** that are adjacent the nanostructures **66**. In these embodiments, the protective layers **80** have a constant width. The protective layers **80** are in contact with the upper portions of the sidewalls of the gate structures **130**. The protective layers **80** can have a height  $H_0$  in the

range of 1 nm to 300 nm and a width  $W_0$  in the range of 0.3 nm to 15 nm. The lower portions of the sidewalls of the gate structures **130** that are not covered by the protective layers **80** can have a height  $H_1$  in the range of 0 nm to 300 nm.

[0102] FIGS. 25A-25C are views of nanostructure transistors/FETs, in accordance with various embodiments. These embodiments are similar to the embodiments of FIGS. 24A-24C, respectively, except the protective layers **80** have a width that decreases in a direction extending from the top of the protective layers **80** to the bottom of the protective layers **80**.

[0103] FIGS. 26A-26C are detailed views of regions **50R** in FIGS. 23A-23C, respectively. Referring to FIG. 26A, the sidewalls of the lower portions of the gate structures **130** are substantially perpendicular with a plane parallel to the major surface of the substrate **50**. For example, the angle  $\theta_1$  between the sidewalls of the gate structures **130** and the top surfaces of the STI regions **72** can be in the range of 80 degrees to 100 degrees. Referring to FIG. 26B, the sidewalls of the lower portions of the gate structures **130** are form an acute angle with a plane parallel to the major surface of the substrate **50**. For example, the angle  $\theta_2$  between the sidewalls of the gate structures **130** and the top surfaces of the STI regions **72** can be in the range of 30 degrees to 85 degrees. Referring to FIG. 26C, the surfaces of the gate structures **130** defining the sidewall recesses **130R** form several angles. Specifically, the surfaces of the gate structures **130** defining the sidewall recesses **130R** form an angle  $\theta_3$  with the top surfaces of the STI regions **72** and an angle  $\theta_4$  with a plane parallel to the major surface of the substrate **50**. The angle  $\theta_3$  and the angle  $\theta_4$  can each be in the range of 95 degrees to 150 degrees.

[0104] FIGS. 27A-27D are views of intermediate stages in the patterning of dummy gates **76** with a small footing profile, in accordance with some other embodiments. The dummy gates **76** are formed with a small footing profile by patterning the dummy gate layer **74** with multiple etching processes, in a similar manner as described for FIGS. 7A-9C. In this embodiment, a different type of protective layers **80** is used. Specifically, the protective layers **80** are passivation layers **80P**. The passivation layers **80P** may be formed by a separate process before or after the dummy gate layer **74** is initially patterned. Advantageously, the passivation layers **80P** may be formed to a more uniform thickness than the byproduct layers **80B**. Further, the passivation gas may be omitted from the first etching process for initially patterning the dummy gates **76**.

[0105] The passivation layers **80P** may be formed by a surface modification process or a deposition process. Generally, surface modification processes are easier to control to reduce damage to the dummy gates **76**, and deposition processes are easier to control the thickness of the resulting passivation layers **80P**. The surface modification process may be a plasma modification process, a chemical modification process, or the like. In some embodiments, the thickness of the passivation layers **80P** is in the range of 2 Å to 150 Å.

[0106] In embodiments where a plasma modification process is used, forming the passivation layers **80P** may include exposing the structure to a passivation gas while generating a plasma. The passivation gas may be  $\text{CH}_4$ ,  $\text{SiCl}_4$ ,  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}$ , or like. In some embodiments, a dilute gas such as Ar, He, Ne, or combinations thereof may be utilized. In some embodiments, the process conditions of the plasma

modification process include: a pressure in the range of 1 mTorr to 10 Torr; a plasma source power (configured to control the ratio of ions to radicals) in the range of 10 W to 3000 W; a plasma bias power (configured to control the plasma direction) in the range of 0 W to 3000 W; and a gas source flow rate in the range of 1 sccm to 5000 sccm. The composition of the passivation layers **80P** formed by the plasma modification process depends on the passivation gas used. Continuing the example where the dummy gate layer **74** is formed of silicon or silicon germanium: the passivation layers **80P** may be formed of  $\text{SiO}$  or  $\text{SiGeO}$  when using an oxygen-based passivation gas (e.g.,  $\text{O}_2$ ,  $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}$ , or the like); the passivation layers **80P** may be formed of  $\text{SiN}$  or  $\text{SiGeN}$  formed when using a nitrogen-based passivation gas (e.g.,  $\text{N}_2$  or the like); and the passivation layers **80P** may be formed of  $\text{SiS}$  or  $\text{SiGeS}$  formed when using a sulfur-based passivation gas (e.g.,  $\text{SO}_2$  or the like). In some embodiments, a plurality of passivation gases may be utilized in the plasma modification process. For example, a mixture of an oxygen-based passivation gas, a nitrogen-based passivation gas, and a sulfur-based passivation gas (e.g.,  $\text{SO}_2$  and  $\text{N}_2$ ) may be utilized in the plasma modification process, and the passivation layers **80P** may be formed of  $\text{SiGeS}_x\text{O}_y\text{N}_z$ .

[0107] In embodiments where a chemical modification process is used, forming the passivation layers **80P** may include exposing the structure to a passivation solution without generating a plasma. The passivation solution may include a main passivation chemical and an assistant passivation chemical in a solvent. The main passivation chemical may be  $\text{O}_3$ ,  $\text{CO}_2$ , or the like. The assistant passivation chemical may be  $\text{H}_2\text{SO}_4$ ,  $\text{NH}_3$ , or the like. The solvent may be deionized (DI) water, alcohol, acetone, or the like.

[0108] In embodiments where a deposition process is used, forming the passivation layers **80P** may include PECVD, CVD, ALD, PVD, or a growth process suitable for depositing a dielectric material. The passivation layers **80P** may be formed of a dielectric material such as  $\text{SiN}$ ,  $\text{SiON}$ ,  $\text{SiCON}$ ,  $\text{SiC}$ ,  $\text{SiOC}$ ,  $\text{SiO}_2$ , or the like.

[0109] In some embodiments, the passivation layers **80P** are formed on the dummy gate layer **74** before the dummy gate layer **74** is patterned, as illustrated by FIG. 27A. After the passivation layers **80P** are formed, the dummy gate layer **74** and the passivation layers **80P** may be simultaneously patterned to form dummy gates **76** with a small footing profile. For example, an etching process can be performed to etch both the dummy gate layer **74** and the passivation layers **80P**. The etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a lateral direction that is substantially parallel to the major surface of the substrate **50**. Portions of the passivation layers **80P** may be removed by the etching process to expose the lower portions of the dummy gate layer **74**, and the lateral direction of the etching process results in etching of the dummy gate layer **74** to form dummy gates **76** with a small footing profile. In some embodiments, portions of the dummy gates **76** can extend over the mask **58** (if present) and the nanostructures **64**, **66**. Those portions of the dummy gates **76** may be removed in a subsequent process, such as the removal process that is performed to remove the portions of the hybrid fin layer **78** over the mask **58** (if present) and the nanostructures **64**, **66** (see FIGS. 11A-11C).

[0110] In some embodiments, the passivation layers **80P** are formed after the dummy gate layer **74** is initially

patterned but before the dummy gates 76 are trimmed, so that the STI regions 72 are covered, as illustrated by FIG. 27B. After the passivation layers 80P are formed, the dummy gates 76 may be trimmed while they are covered by the passivation layers 80P to form dummy gates 76 with a small footing profile, thereby obtaining the structure of FIG. 8C. For example, an etching process can be performed to etch both the dummy gates 76 and the passivation layers 80P. The etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a lateral direction that is substantially parallel to the major surface of the substrate 50. Portions of the passivation layers 80P may be removed by the etching process (thus forming the structure of FIG. 7B), and the lateral direction of the etching process results in etching of the lower portions of the dummy gates 76 to form dummy gates 76 with a small footing profile (thus forming the structure of FIG. 8C).

[0111] In some embodiments, the passivation layers 80P are formed after the dummy gate layer 74 is initially patterned but before the dummy gates 76 are trimmed, so that the STI regions 72 are exposed, as illustrated by FIGS. 27C and 27D. In some embodiments where the passivation layers 80P are formed by a surface modification process, the passivation layers 80P may be selectively formed on the mask 58 (if present) and the dummy gates 76 without being formed on the STI regions 72, as illustrated by FIG. 27C. In some embodiments where the passivation layers 80P are formed by a deposition process, the passivation layers 80P may be conformally formed on the mask 58 (if present), the dummy gates 76, and the STI regions 72, as illustrated by FIG. 27D. After the passivation layers 80P are formed, the dummy gates 76 may be trimmed while they are covered by the passivation layers 80P to form dummy gates 76 with a small footing profile, thereby obtaining the structure of FIG. 8A or 8B. For example, an etching process can be performed to etch both the dummy gates 76 and the passivation layers 80P. The etching process can be controlled (e.g., by adjusting the plasma bias power) so that it etches in a diagonal direction that forms an acute angle with a plane that is parallel to the major surface of the substrate 50. The diagonal direction of the etching process results in etching through the passivation layers 80P at the lower portions of the dummy gates 76 (thus forming the structure of FIG. 7A), and then etching of the lower portions of the dummy gates 76 to form dummy gates 76 with a small footing profile (thus forming the structures of FIG. 8A or 8B).

[0112] As noted above, a same substrate 50 may have sparse regions and dense regions. In such embodiments, the passivation layers 80P can have different thicknesses in different regions. As a result, dummy gates 76 with different footing profiles may be formed from the same initial structure. For example, the structure of FIG. 27A may be formed in a dense region and a sparse region. The passivation layers 80P may be formed over those structures, and then the dummy gates 76 patterned, with the structure of FIG. 8A or 8B resulting in the dense region and the structure of FIG. 8C resulting in the sparse region.

[0113] Embodiments may achieve advantages. Forming the dummy gates 76 with a small footing profile increases the processing window for subsequent operations, such as a replacement gate process and/or an epitaxial growth process for source/drain regions. Specifically, no residue of the dummy gates 76 may remain beneath the epitaxial source/drain regions 108, avoiding damage to the epitaxial source/

drain regions 108 when the dummy gates 76 are removed in a replacement gate process. Further, dummy gates 76 with a small footing profile may be more easily removed in a replacement gate process, avoiding the formation of voids in the replacement gates may be avoided, thereby increasing device performance.

[0114] In an embodiment, a device includes: an isolation region; nanostructures protruding above a top surface of the isolation region; a gate structure wrapped around the nanostructures, the gate structure having a bottom surface contacting the isolation region, the bottom surface of the gate structure extending away from the nanostructures a first distance, the gate structure having a sidewall disposed a second distance from the nanostructures, the first distance less than or equal to the second distance; and a hybrid fin on the sidewall of the gate structure. In some embodiments of the device, the first distance is less than the second distance. In some embodiments of the device, the hybrid fin extends into a sidewall recess of the gate structure. In some embodiments of the device, the first distance is equal to the second distance. In some embodiments of the device, the first distance and the second distance are each in a range of 0.5 nm to 30 nm. In some embodiments, the device further includes: a protective layer disposed between the hybrid fin and the gate structure, the protective layer covering an upper portion of the sidewall of the gate structure, a lower portion of the sidewall of the gate structure uncovered by the protective layer.

[0115] In an embodiment, a device includes: an isolation region; a semiconductor fin protruding above a top surface of the isolation region; nanostructures over the semiconductor fin; a gate structure wrapped around the nanostructures; and a hybrid fin on a sidewall of the gate structure, the hybrid fin disposed a first distance from the semiconductor fin, the hybrid fin disposed a second distance from the nanostructures, the second distance greater than the first distance. In some embodiments, the device further includes: a protective layer between the hybrid fin and the gate structure, the protective layer extending along a portion of the sidewall of the gate structure adjacent the nanostructures. In some embodiments of the device, the protective layer includes  $\text{SiGeS}_x\text{O}_y\text{N}_z$ . In some embodiments of the device, the protective layer includes a dielectric material. In some embodiments of the device, a portion of the hybrid fin extends into a sidewall recess of the gate structure, the portion of the hybrid fin disposed a third distance from the semiconductor fin, the third distance less than the first distance and the second distance.

[0116] In an embodiment, a method includes: depositing a dummy gate layer over an isolation region and alternating first nanostructures and second nanostructures, the first nanostructures and the second nanostructures protruding above a top surface of the isolation region; patterning the dummy gate layer to form a dummy gate on sidewalls of the first nanostructures, sidewalls of the second nanostructures, and the top surface of the isolation region; forming a protective layer on an upper portion of the dummy gate; trimming a lower portion of the dummy gate while the protective layer covers the upper portion of the dummy gate; and replacing the dummy gate and the first nanostructures with a metal gate, the metal gate wrapped around the second nanostructures. In some embodiments of the method, the protective layer is a byproduct layer formed during the patterning the dummy gate layer, and the patterning the

dummy gate layer includes etching the dummy gate layer with a gas source including a main etching gas and a passivation gas. In some embodiments of the method, the dummy gate layer and the first nanostructures include silicon or silicon germanium; and the passivation gas is a mixture of an oxygen-based passivation gas, a nitrogen-based passivation gas, and a sulfur-based passivation gas. In some embodiments of the method, the protective layer is a passivation layer formed after the patterning the dummy gate layer, and forming the protective layer includes exposing the dummy gate to a passivation gas while generating a plasma. In some embodiments of the method, the protective layer is a passivation layer formed after the patterning the dummy gate layer, and forming the protective layer includes exposing the dummy gate to a passivation solution without generating a plasma. In some embodiments of the method, the protective layer is a passivation layer formed after the patterning the dummy gate layer, and forming the protective layer includes depositing a dielectric material on the dummy gate. In some embodiments of the method, the dummy gate has a sidewall and has a bottom surface contacting the isolation region, the sidewall of the dummy gate is disposed a first distance from the second nanostructures, and trimming the lower portion of the dummy gate includes: etching the lower portion of the dummy gate until the bottom surface of the dummy gate extends away from the second nanostructures a second distance less than the first distance. In some embodiments of the method, the dummy gate has a sidewall and has a bottom surface contacting the isolation region, the sidewall of the dummy gate is disposed a first distance from the second nanostructures, and trimming the lower portion of the dummy gate includes: etching the lower portion of the dummy gate until the bottom surface of the dummy gate extends away from the second nanostructures a second distance equal to the first distance. In some embodiments of the method, etching the lower portion of the dummy gate forms a sidewall recess in the lower portion of the dummy gate.

**[0117]** The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

**1.** A device comprising:

- a source/drain region;
- a first channel region adjacent the source/drain region;
- a second channel region adjacent the source/drain region;
- a gate structure over the first channel region and the second channel region; and
- a dielectric fin adjacent the gate structure and the source/drain region, the dielectric fin disposed a first distance from the first channel region, the dielectric fin disposed a second distance from the second channel region, the second distance being greater than the first distance.

- 2.** The device of claim 1, further comprising:
  - a fin comprising the first channel region; and
  - a nanostructure comprising the second channel region, the nanostructure disposed above the fin.
- 3.** The device of claim 1, further comprising:
  - an isolation region adjacent the first channel region and the second channel region, a top surface of the isolation region being non-planar, the dielectric fin disposed on the top surface of the isolation region.
- 4.** The device of claim 1, wherein the gate structure comprises a gate dielectric layer, a k-value of the gate dielectric layer being greater than a k-value of the dielectric fin.
- 5.** The device of claim 1, further comprising:
  - a dielectric layer over the source/drain region;
  - an inter-layer dielectric over the dielectric layer, a material of the inter-layer dielectric being different from a material of the dielectric layer; and
  - a source/drain contact extending through the inter-layer dielectric and the dielectric layer, the source/drain contact surrounded by the inter-layer dielectric.
- 6.** The device of claim 5, wherein the source/drain contact is electrically coupled to the source/drain region through a silicide, and an electrical conductivity of the silicide is between an electrical conductivity of the source/drain region and an electrical conductivity of the source/drain contact.
- 7.** A device comprising:
  - first nanostructures stacked along a first direction;
  - second nanostructures stacked along the first direction;
  - a first isolation region between the first nanostructures and the second nanostructures, a top surface of the first isolation region being non-planar;
  - a dielectric fin on the top surface of the first isolation region, the dielectric fin being disposed between the first nanostructures and the second nanostructures, an upper portion of the dielectric fin having a first width in a second direction that is perpendicular to the first direction, a lower portion of the dielectric fin having a second width in the second direction, the second width being greater than the first width; and
  - a first gate structure extending along the upper portion of the dielectric fin, the lower portion of the dielectric fin, and the top surface of the first isolation region, the first gate structure wrapped around the first nanostructures, the first gate structure comprising a first gate dielectric layer, a k-value of the first gate dielectric layer being greater than a k-value of the dielectric fin.
- 8.** The device of claim 7, wherein the first gate structure is also wrapped around the second nanostructures.
- 9.** The device of claim 7, further comprising:
  - a second gate structure extending along the upper portion of the dielectric fin, the lower portion of the dielectric fin, and the top surface of the first isolation region, the second gate structure wrapped around the second nanostructures, the second gate structure comprising a second gate dielectric layer, a k-value of the second gate dielectric layer being greater than the k-value of the dielectric fin.
- 10.** The device of claim 9, further comprising:
  - a second isolation region on the top surface of the dielectric fin, the second isolation region disposed between the first gate structure and the second gate structure.

11. The device of claim 7, further comprising:  
a protective layer between the first gate structure and the upper portion of the dielectric fin, the lower portion of the dielectric fin being uncovered by the protective layer.
12. The device of claim 7, further comprising:  
a  $\text{SiGeS}_x\text{O}_y\text{N}_z$  layer between the dielectric fin and the first gate structure.
13. The device of claim 7, further comprising:  
a dielectric layer between the dielectric fin and the first gate structure.
14. The device of claim 7, wherein the second width of the lower portion of the dielectric fin increases continuously along the first direction.
15. The device of claim 7, wherein the second width of the lower portion of the dielectric fin decreases and increases along the first direction.
16. A device comprising:  
an isolation region, a top surface of the isolation region being non-planar;  
a dielectric fin on the top surface of the isolation region, an upper portion of the dielectric fin having a first width, a lower portion of the dielectric fin having a second width, the second width being greater than the first width;  
a source/drain region adjacent the dielectric fin;  
a dielectric layer over the source/drain region;  
an inter-layer dielectric over the dielectric layer, a material of the inter-layer dielectric being different from a material of the dielectric layer; and

- a source/drain contact extending through the inter-layer dielectric and the dielectric layer, the source/drain contact surrounded by the inter-layer dielectric, the source/drain contact being electrically coupled to the source/drain region through a silicide, an electrical conductivity of the silicide being between an electrical conductivity of the source/drain region and an electrical conductivity of the source/drain contact.
17. The device of claim 16, further comprising:  
a nanostructure adjacent the source/drain region; and  
a gate structure extending along the upper portion of the dielectric fin, the lower portion of the dielectric fin, and the top surface of the isolation region, the gate structure wrapped around the nanostructure, the gate structure comprising a gate dielectric layer, a k-value of the gate dielectric layer being greater than a k-value of the dielectric fin.
18. The device of claim 17, further comprising:  
a protective layer between the gate structure and the upper portion of the dielectric fin, the lower portion of the dielectric fin physically contacting the gate structure.
19. The device of claim 16, wherein the second width of the lower portion of the dielectric fin decreases continuously along a direction extending away from the top surface of the isolation region.
20. The device of claim 16, wherein the second width of the lower portion of the dielectric fin increases and decreases along a direction extending away from the top surface of the isolation region.

\* \* \* \* \*