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(54) **FIN FIELD-EFFECT TRANSISTOR DEVICE HAVING CONTACT PLUGS WITH RE-ENTRANT PROFILE**

(58) **Field of Classification Search**
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(56) **References Cited**

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U.S. PATENT DOCUMENTS

8,643,122 B2 2/2014 Alptekin et al.
9,685,535 B1 6/2017 Cheng et al.
(Continued)

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FOREIGN PATENT DOCUMENTS

KR 20160136579 A 11/2016
KR 20170091434 A 8/2017
KR 20200037056 A 4/2020

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(57) **ABSTRACT**

A method of forming a semiconductor device includes: forming a gate structure over a fin that protrudes above a substrate; forming source/drain regions over the fin on opposing sides of the gate structure; forming a first dielectric layer and a second dielectric layer successively over the source/drain regions; performing a first etching process to form an opening in the first dielectric layer and in the second dielectric layer, where the opening exposes an underlying electrically conductive feature; after performing the first etching process, performing a second etching process to enlarge a lower portion of the opening proximate to the substrate; and forming a contact plug in the opening after the second etching process.

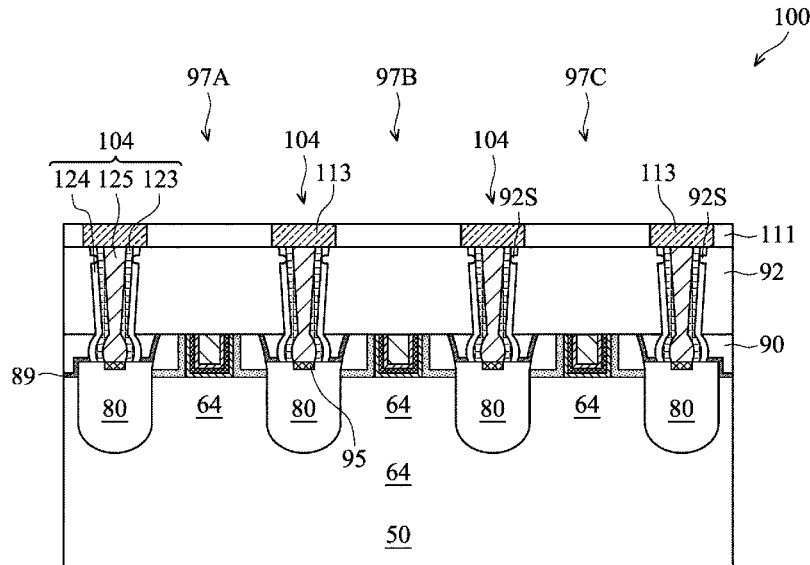
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20 Claims, 21 Drawing Sheets



(51)	Int. Cl.						
	<i>H01L 21/311</i>	(2006.01)	10,714,578	B2	7/2020	Huang	
	<i>H01L 21/3213</i>	(2006.01)	10,734,410	B2	8/2020	Cheng et al.	
	<i>H01L 21/768</i>	(2006.01)	10,825,737	B2	11/2020	Lee et al.	
	<i>H01L 29/165</i>	(2006.01)	10,868,142	B2	12/2020	Chien et al.	
	<i>H01L 29/66</i>	(2006.01)	10,868,181	B2	12/2020	Li et al.	
	<i>H01L 21/223</i>	(2006.01)	10,916,477	B2	2/2021	Hung et al.	
	<i>H01L 21/265</i>	(2006.01)	10,937,877	B2	3/2021	Huang	
	<i>H01L 21/266</i>	(2006.01)	10,937,884	B1	3/2021	Wang et al.	
	<i>H01L 29/08</i>	(2006.01)	10,957,778	B2	3/2021	Cheng et al.	
			10,971,408	B2	4/2021	Yeong et al.	
			11,011,617	B2	5/2021	Lee et al.	
			11,038,060	B2	6/2021	Huang	
(52)	U.S. Cl.		2011/0024801	A1	2/2011	Cheng et al.	
	CPC <i>H01L 21/32139</i>	(2013.01); <i>H01L 21/7682</i>	2012/0164809	A1	6/2012	Yoon et al.	
		(2013.01); <i>H01L 21/76802</i>	2012/0241815	A1	9/2012	Kim et al.	
		(2013.01); <i>H01L 29/165</i>	2013/0171795	A1	7/2013	Pei et al.	
		(2013.01); <i>H01L 29/6653</i>	2015/0243544	A1*	8/2015	Alptekin H01L 21/7682	
		(2013.01); <i>H01L 29/66545</i>				438/586	
		(2013.01); <i>H01L 29/66795</i>	2016/0181383	A1	6/2016	Huang et al.	
		(2013.01); <i>H01L 29/7853</i>	2016/0225667	A1*	8/2016	Zang H01L 21/7682	
		(2013.01); <i>H01L 21/02164</i>	2016/0343825	A1	11/2016	Bae et al.	
		(2013.01); <i>H01L 21/02271</i>	2016/0365426	A1	12/2016	Ching et al.	
		(2013.01); <i>H01L 21/2236</i>	2017/0179241	A1*	6/2017	Chang H01L 29/41775	
		(2013.01); <i>H01L 21/266</i>	2017/0222014	A1	8/2017	Tak et al.	
		(2013.01); <i>H01L 29/0847</i>	2017/0323852	A1	11/2017	Hsu et al.	
		(2013.01); <i>H01L 29/66636</i>	2018/0151445	A1	5/2018	Hsu et al.	
		(2013.01)	2018/0166553	A1*	6/2018	Lee H01L 29/41766	
(58)	Field of Classification Search		2019/0172752	A1	6/2019	Hsu et al.	
	CPC	H01L 21/76831; H01L 21/76843; H01L	2019/0296123	A1	9/2019	Lee et al.	
		21/76897; H01L 21/7682	2019/0333820	A1	10/2019	Chang et al.	
	See application file for complete search history.		2019/0334011	A1	10/2019	Cheng et al.	
			2019/0371898	A1	12/2019	Huang	
(56)	References Cited		2019/0378909	A1	12/2019	Cheng et al.	
	U.S. PATENT DOCUMENTS		2019/0385896	A1	12/2019	Chiang et al.	
	9,859,393	B2	2020/0006228	A1	1/2020	Yang et al.	
	9,876,094	B2	2020/0020776	A1	1/2020	Yang et al.	
	9,899,522	B1	2020/0105867	A1	4/2020	Lee et al.	
	10,177,038	B1	2020/0127109	A1	4/2020	Wang et al.	
	10,199,260	B1	2020/0127110	A1*	4/2020	Lee H01L 29/0649	
	10,388,747	B1	2020/0135591	A1	4/2020	Yeong et al.	
	10,388,770	B1	2021/0050412	A1*	2/2021	Wong H01L 21/76843	
			2021/0066500	A1	3/2021	Liu et al.	

* cited by examiner

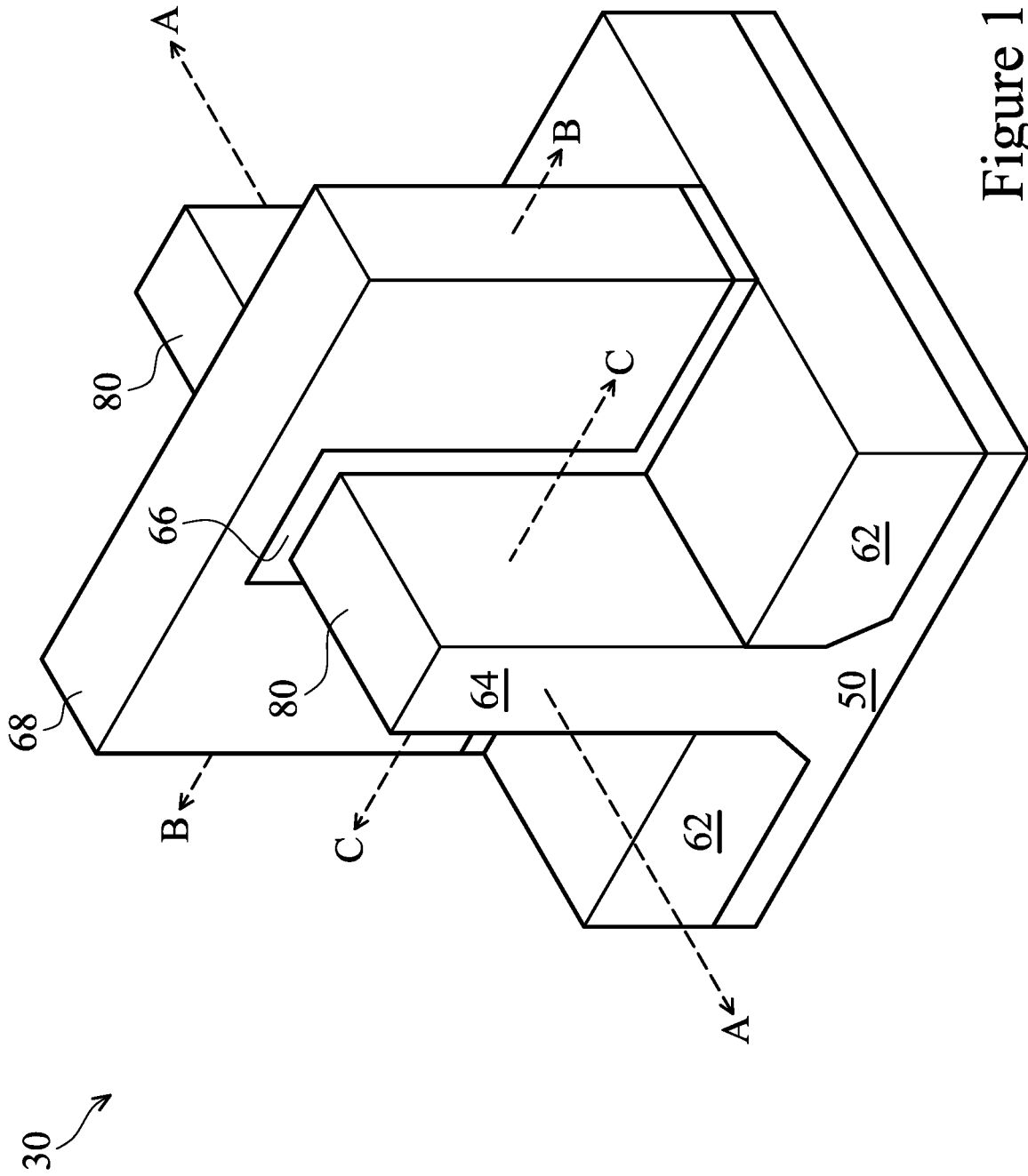
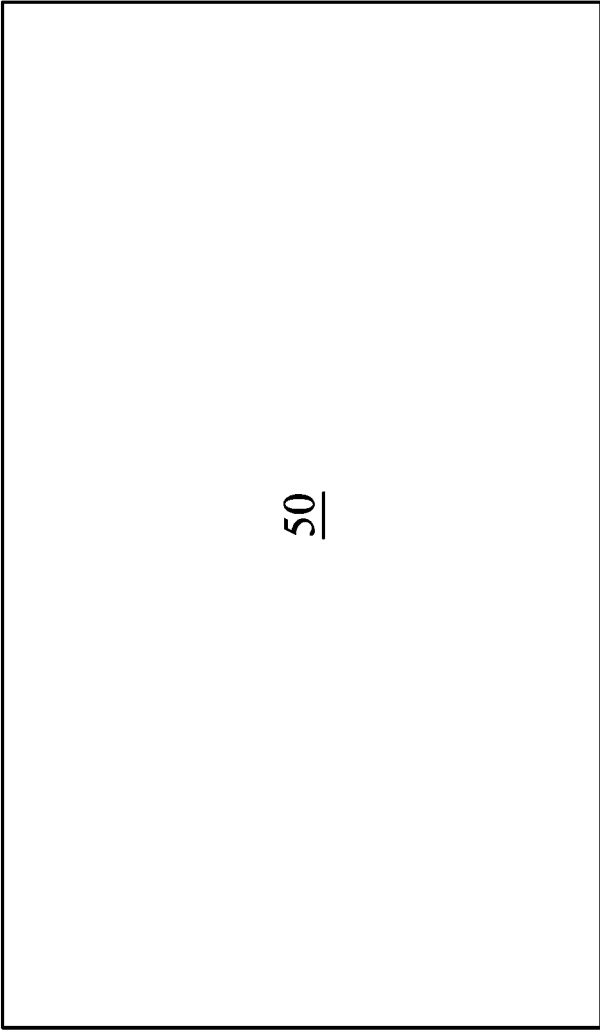


Figure 1

100



50

Figure 2

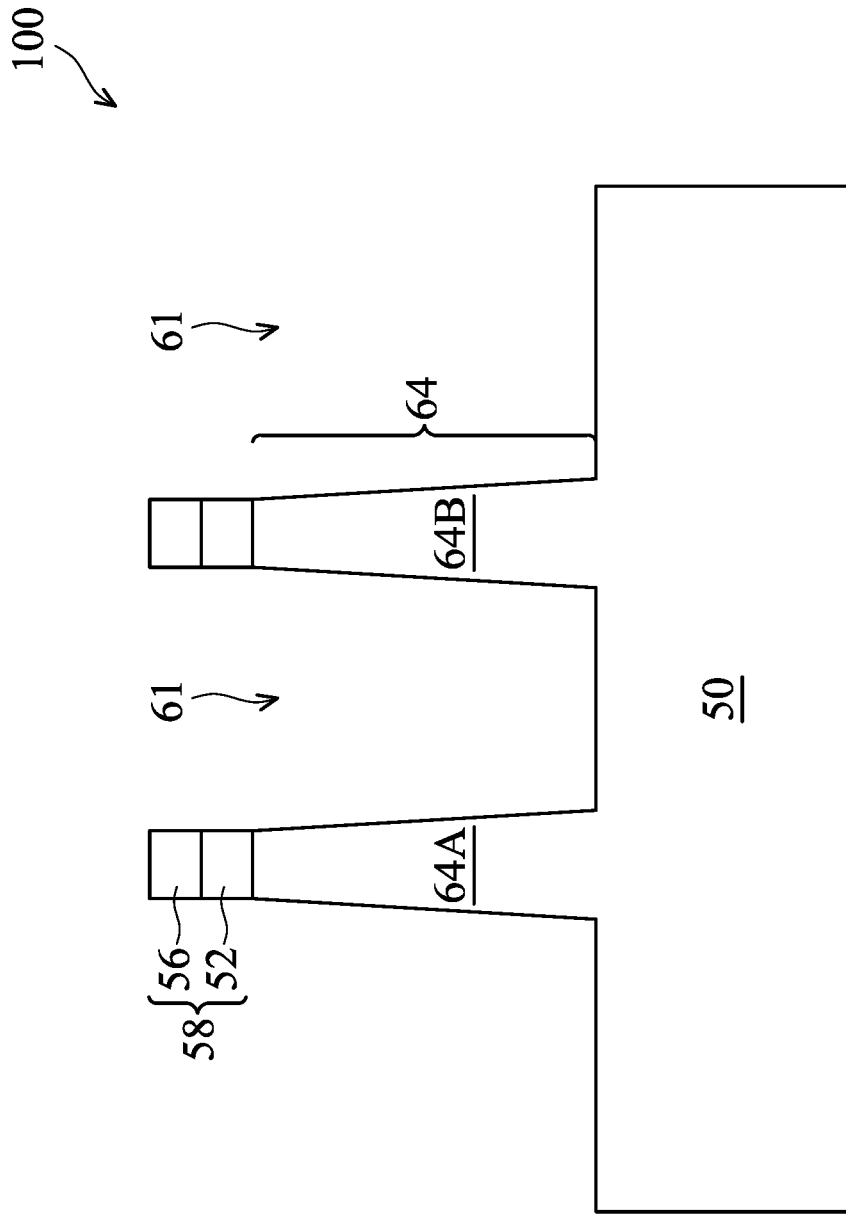


Figure 3

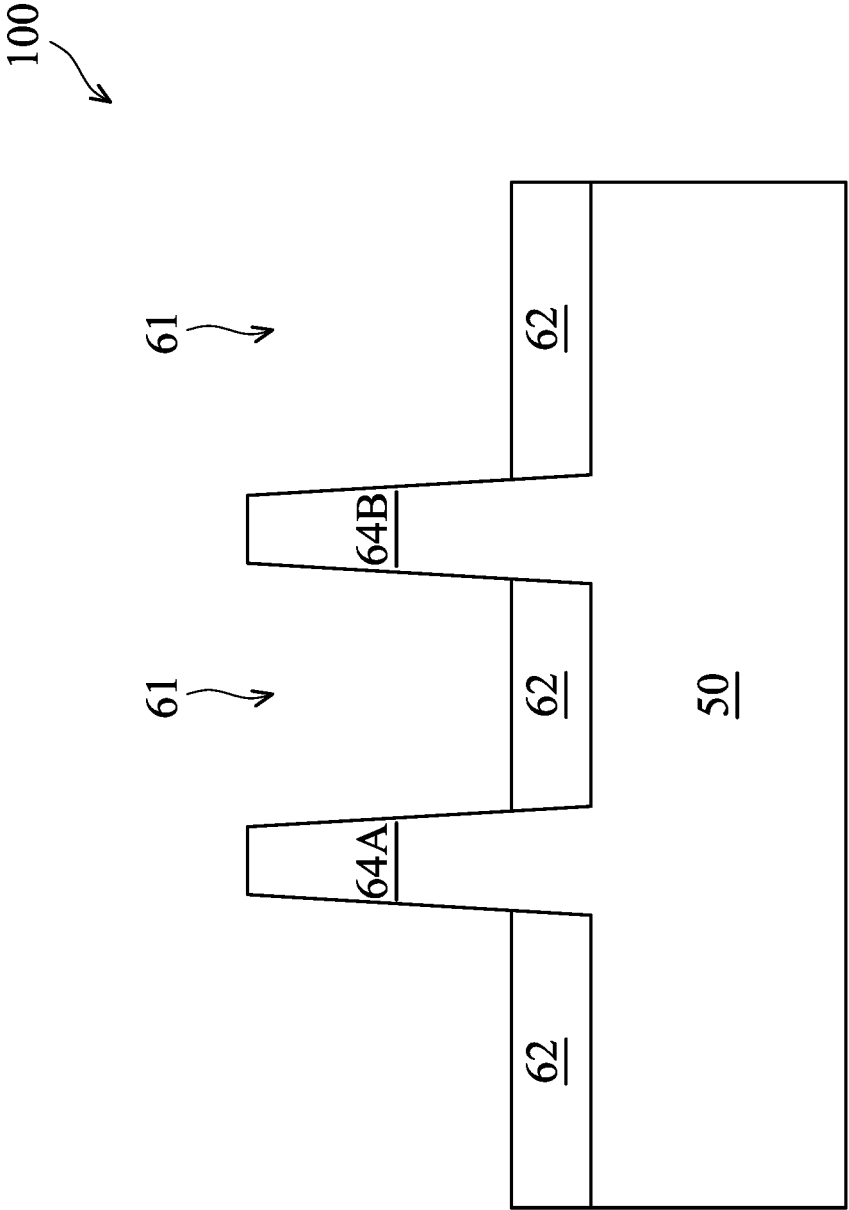


Figure 4

100 ↘

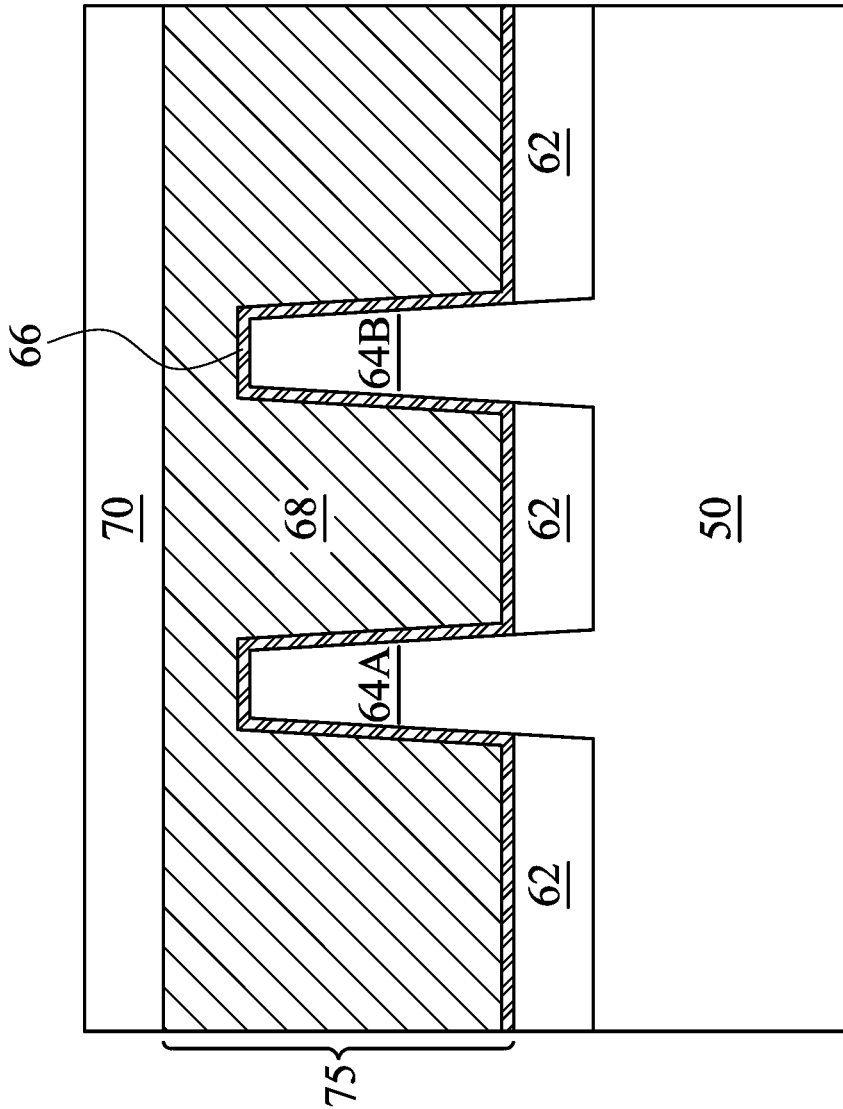


Figure 5

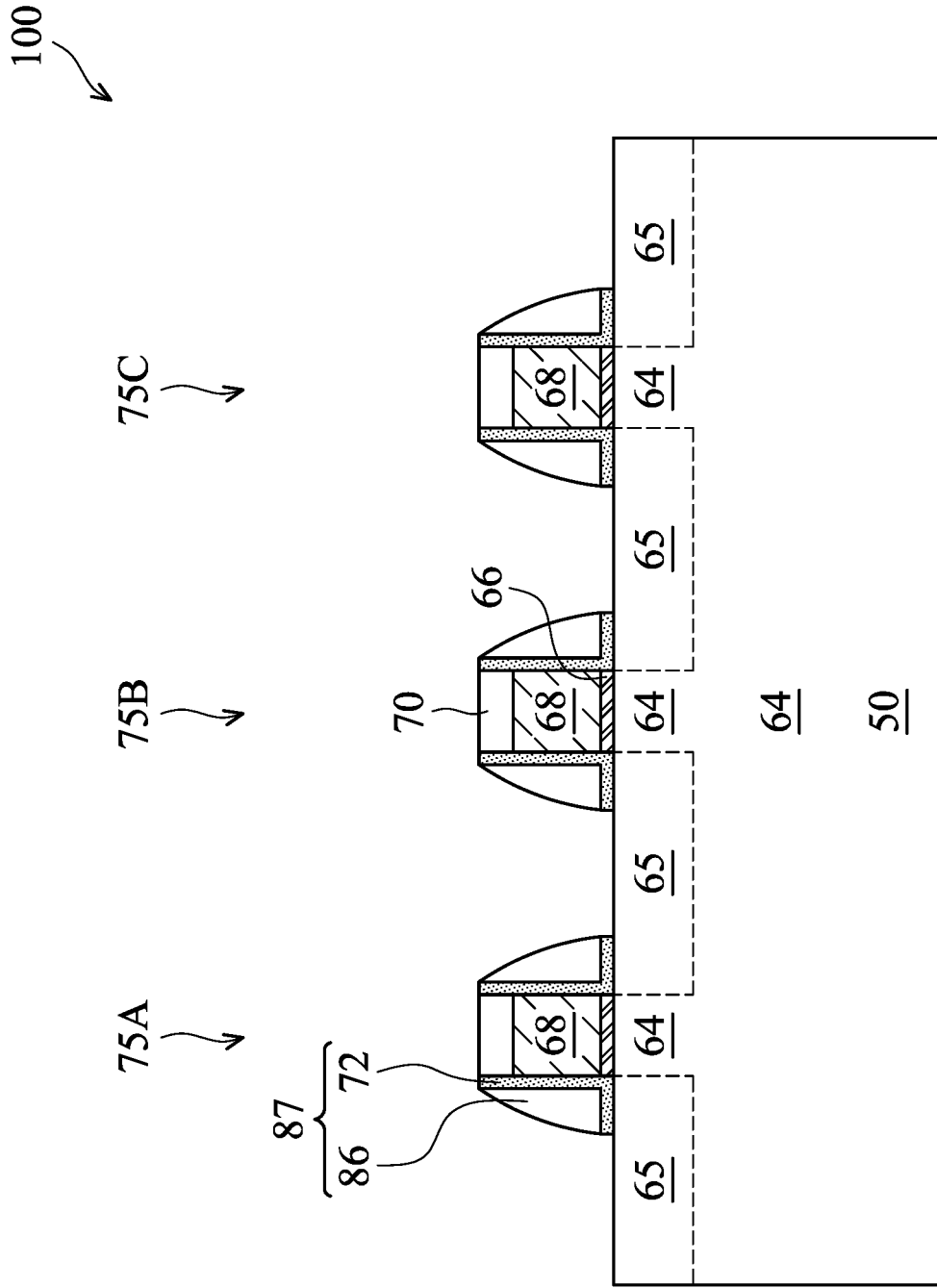


Figure 6

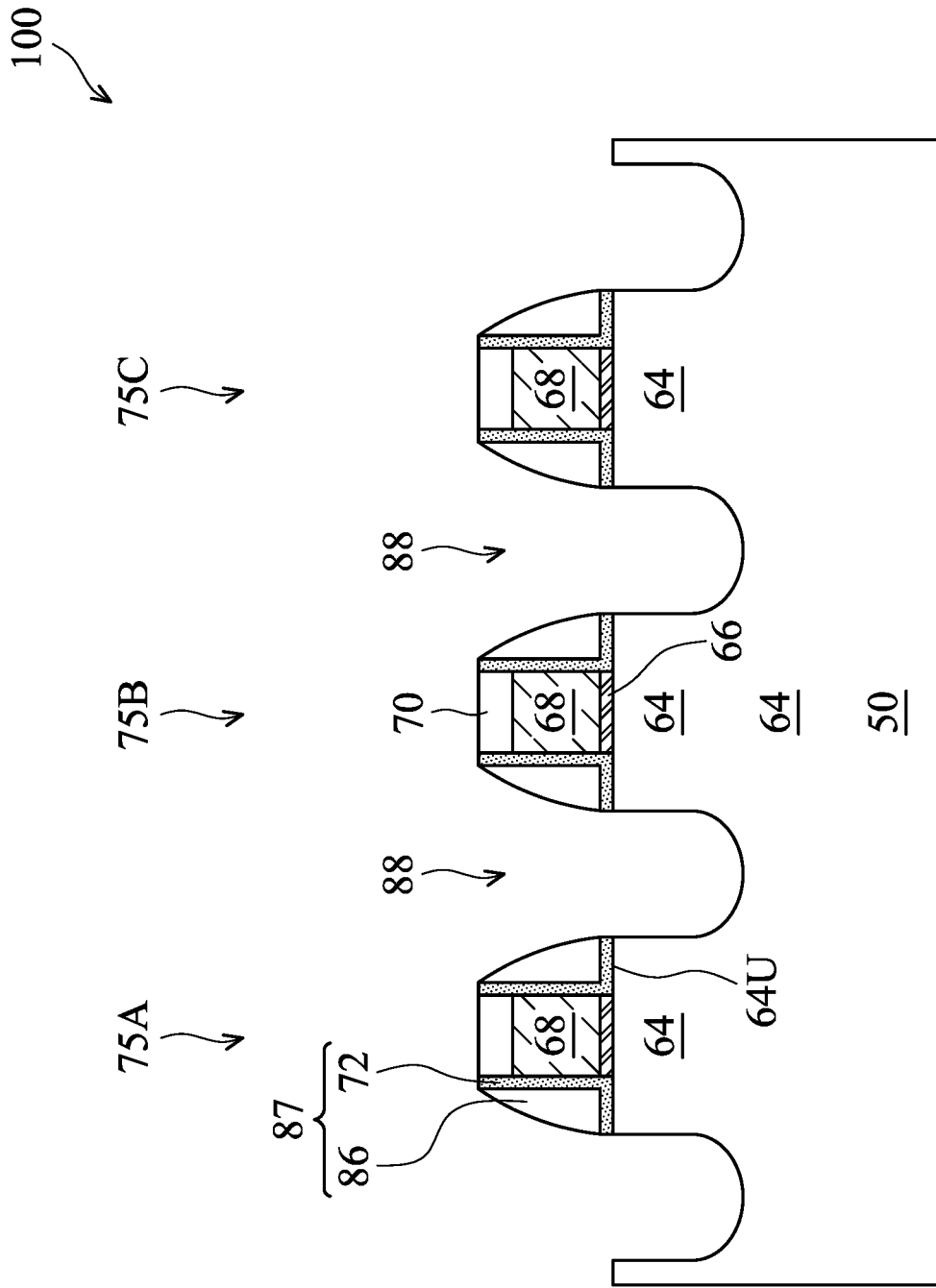


Figure 7

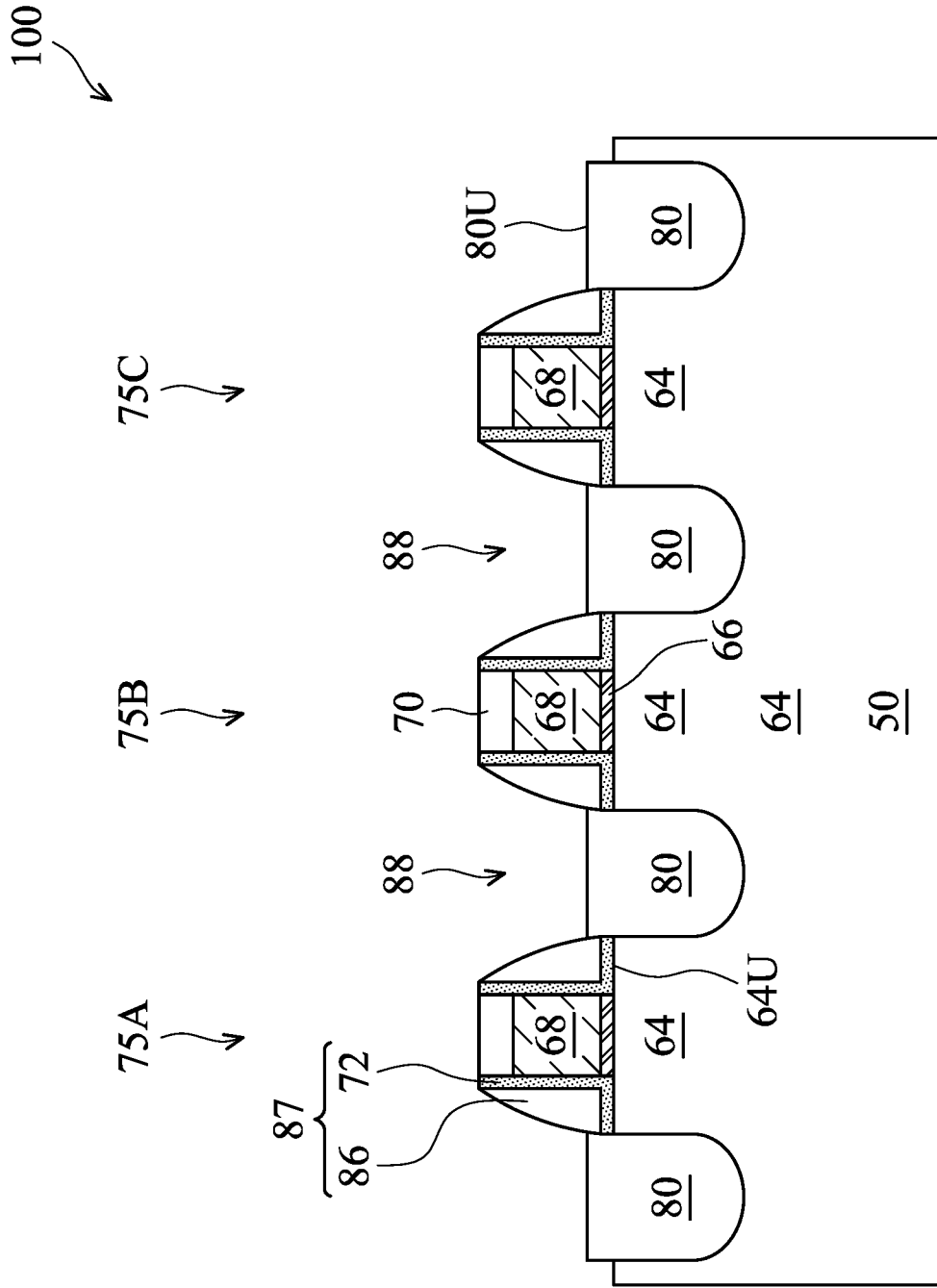


Figure 8A

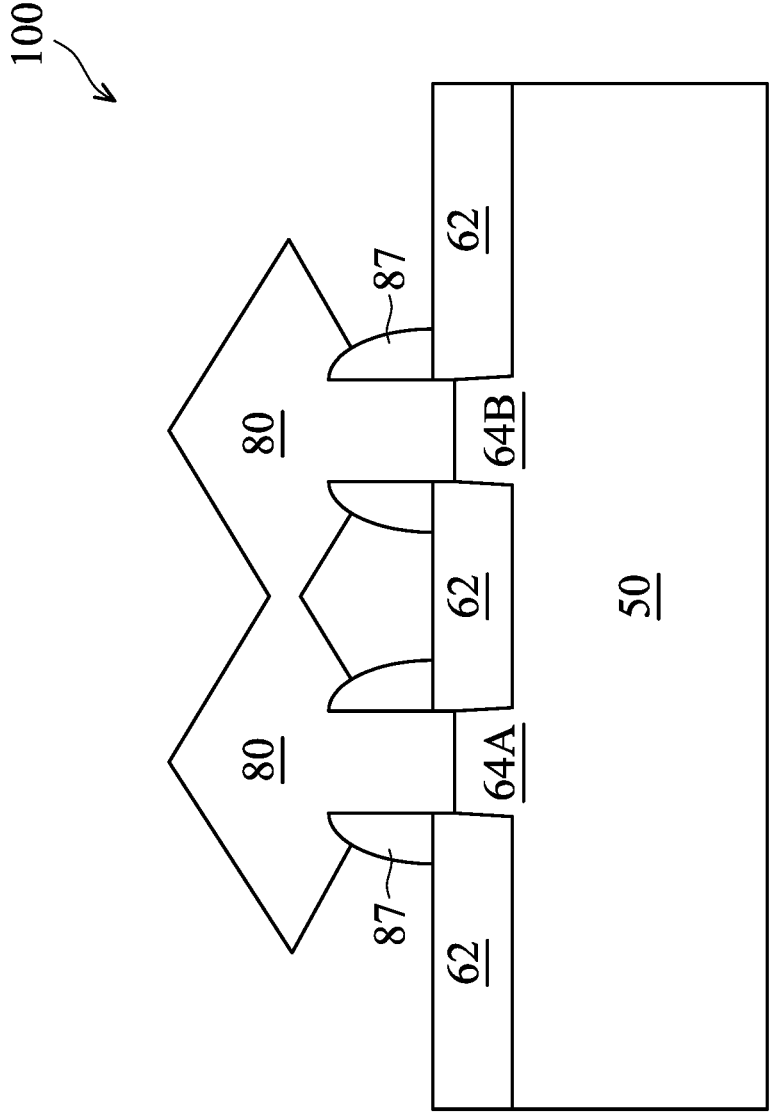


Figure 8B

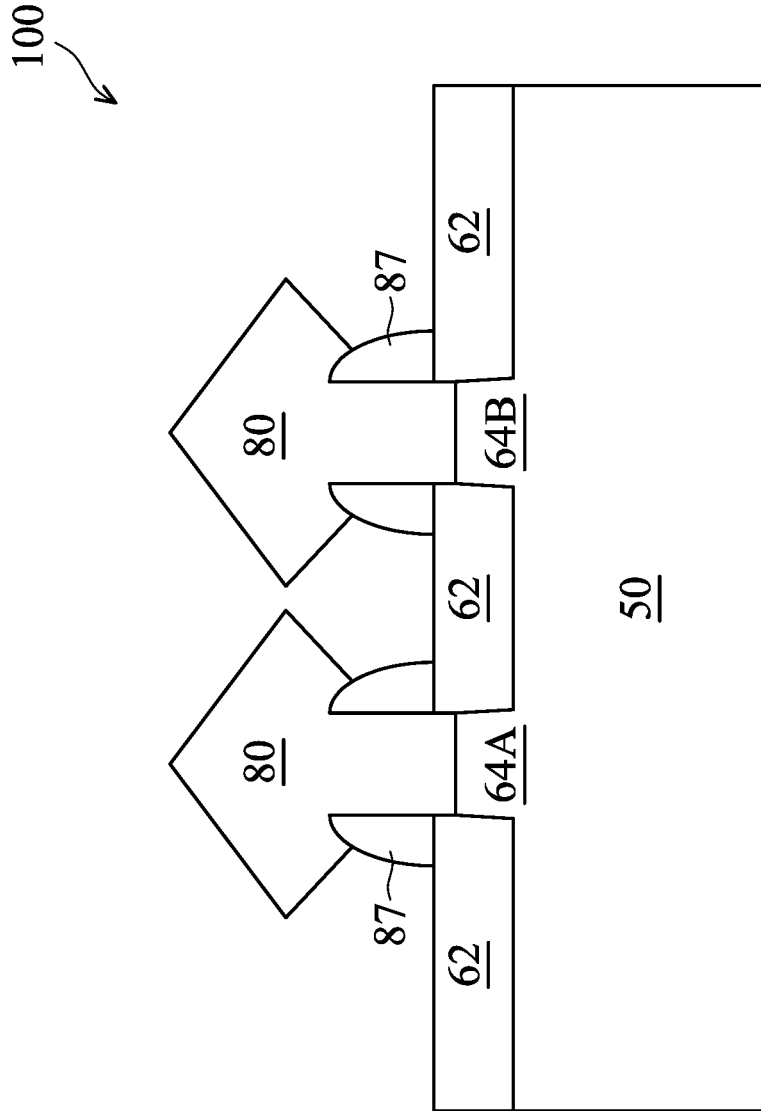


Figure 8C

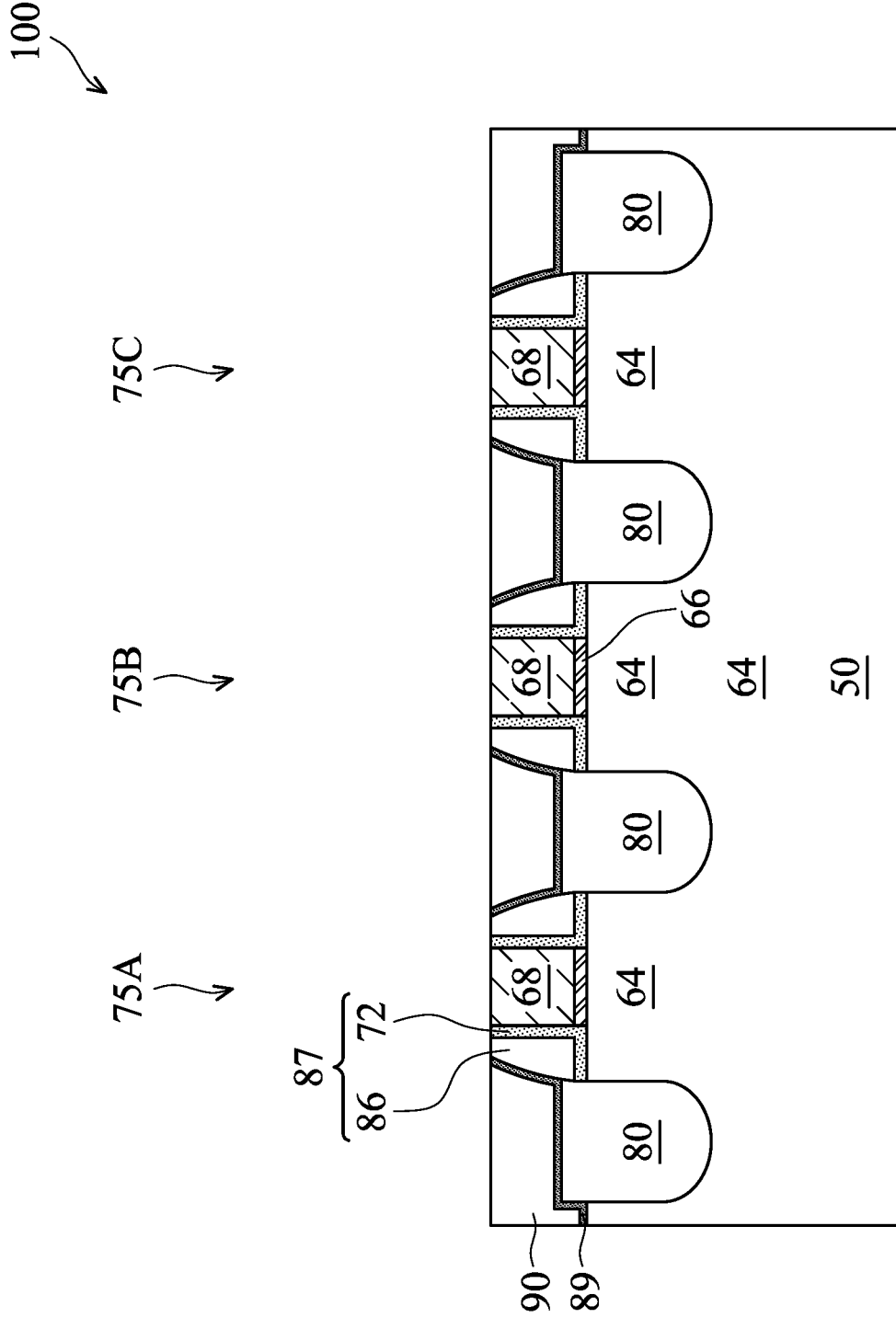


Figure 9

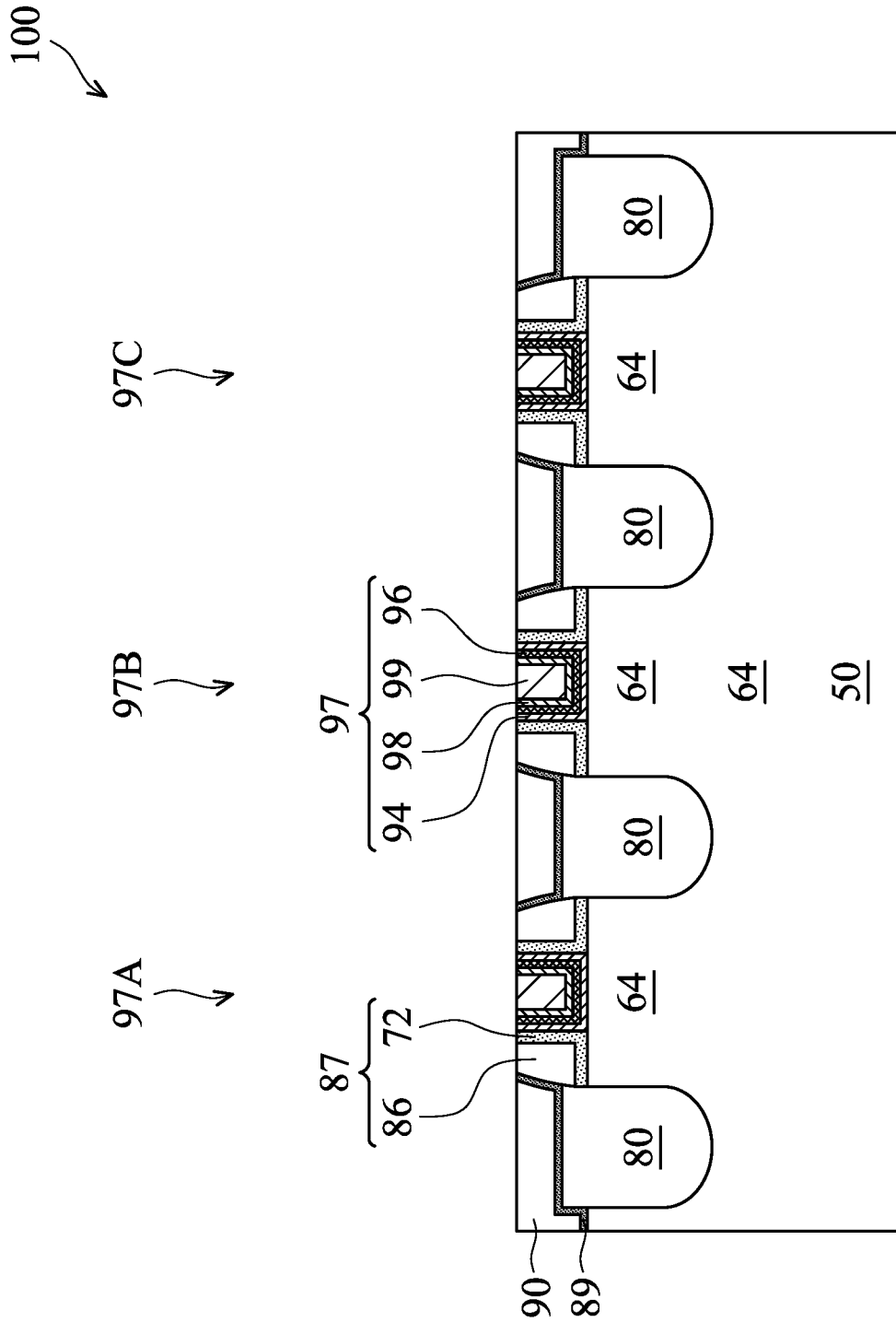


Figure 10

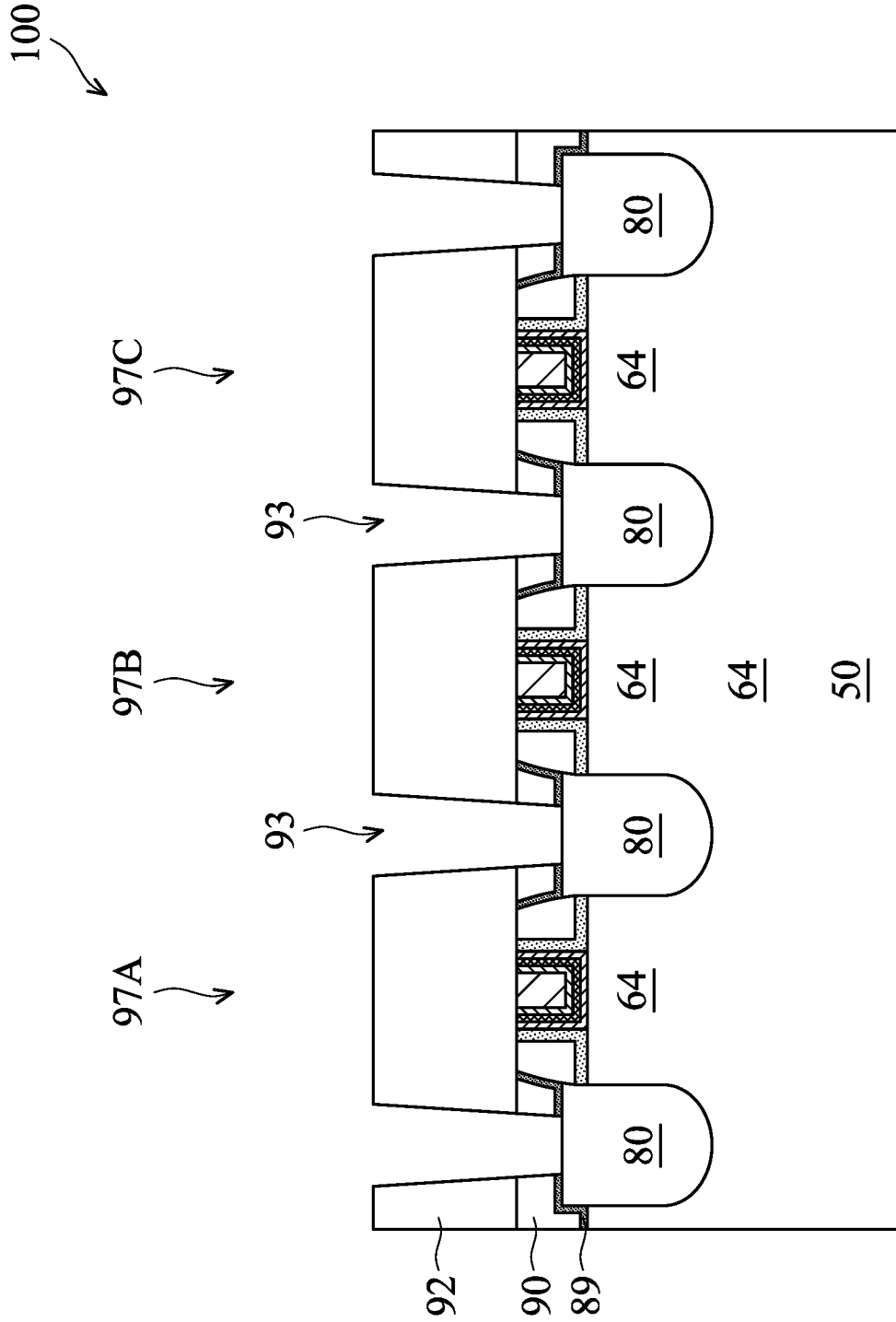


Figure 11

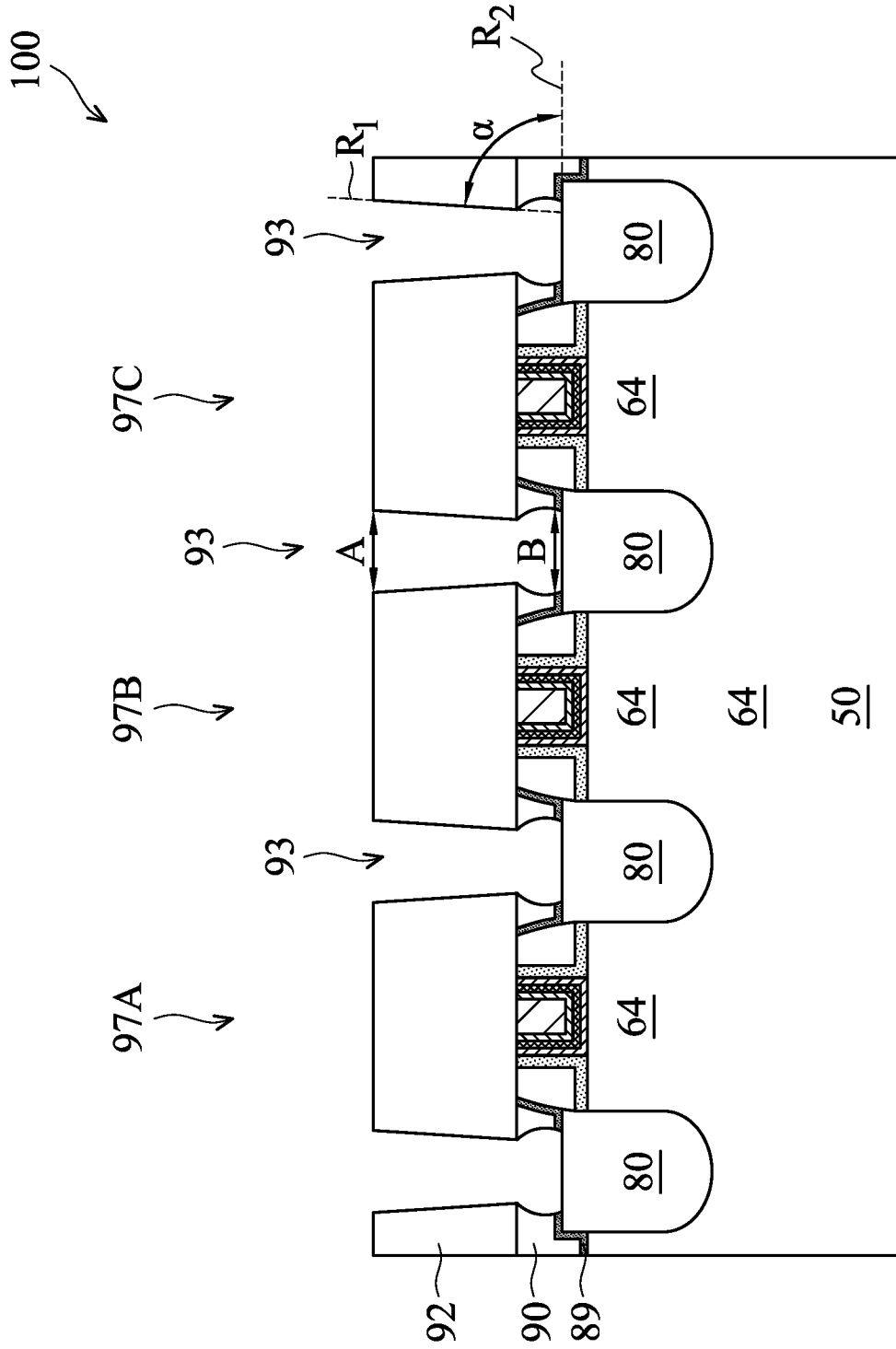


Figure 12

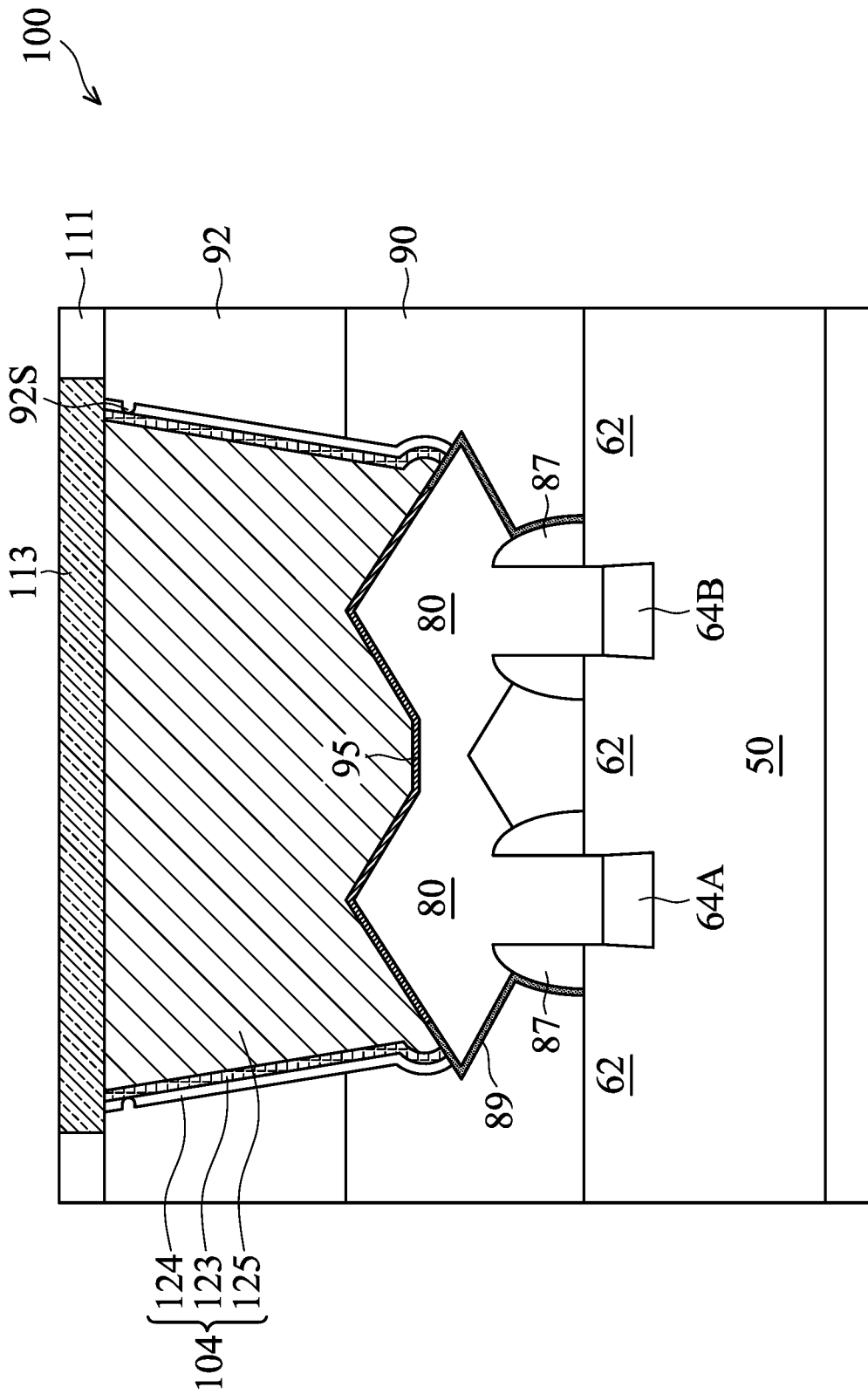


Figure 14B

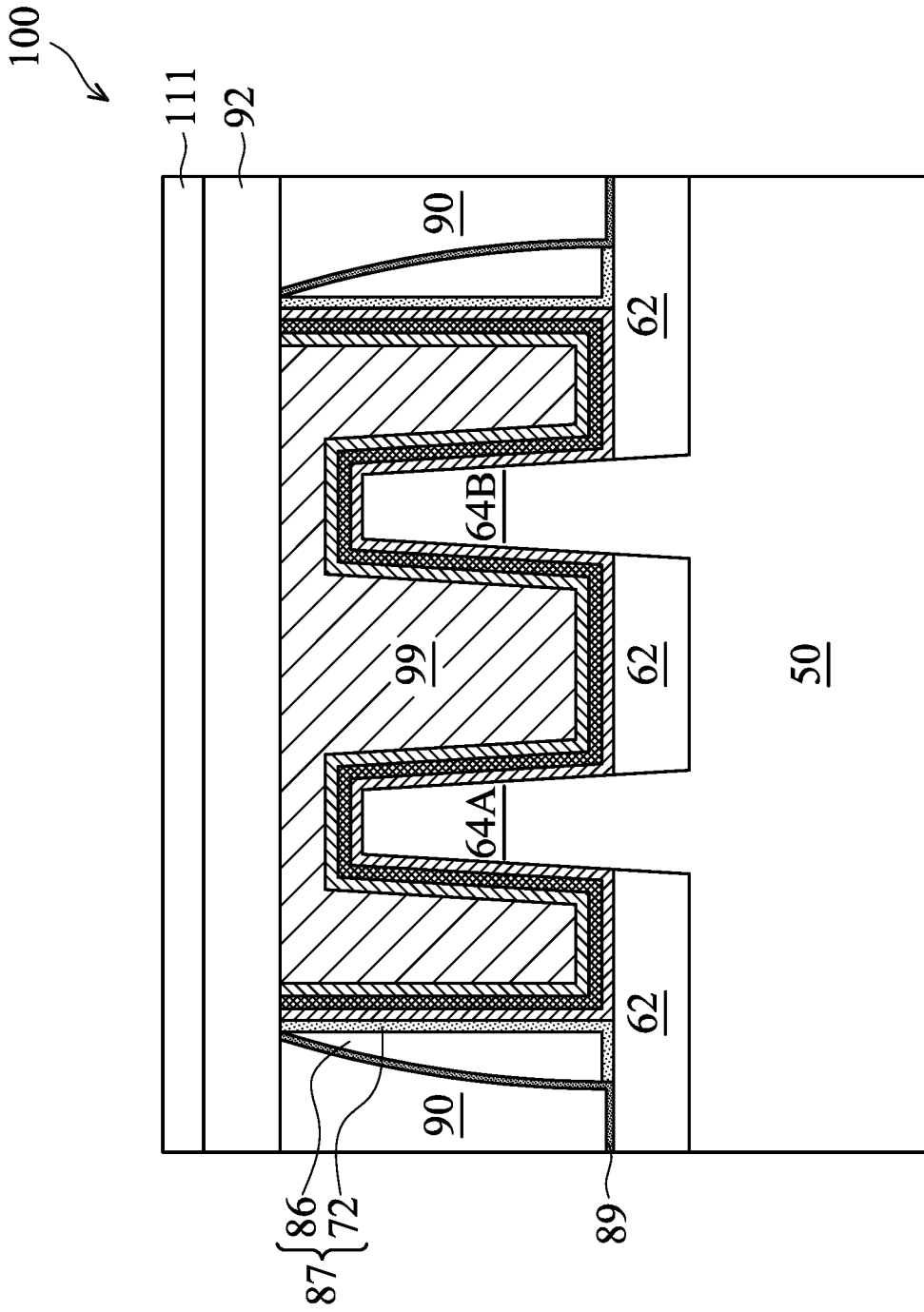


Figure 14C

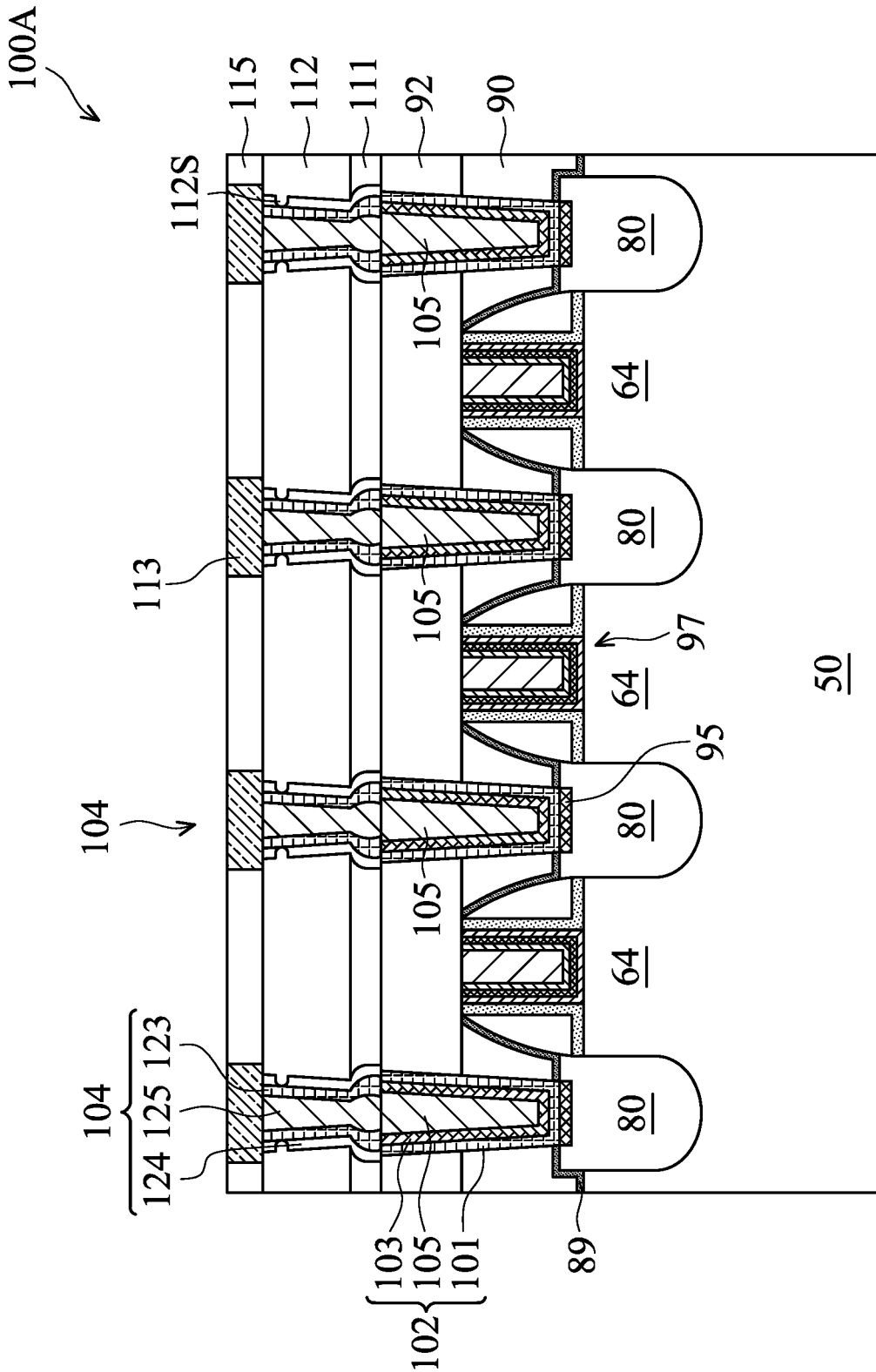


Figure 15

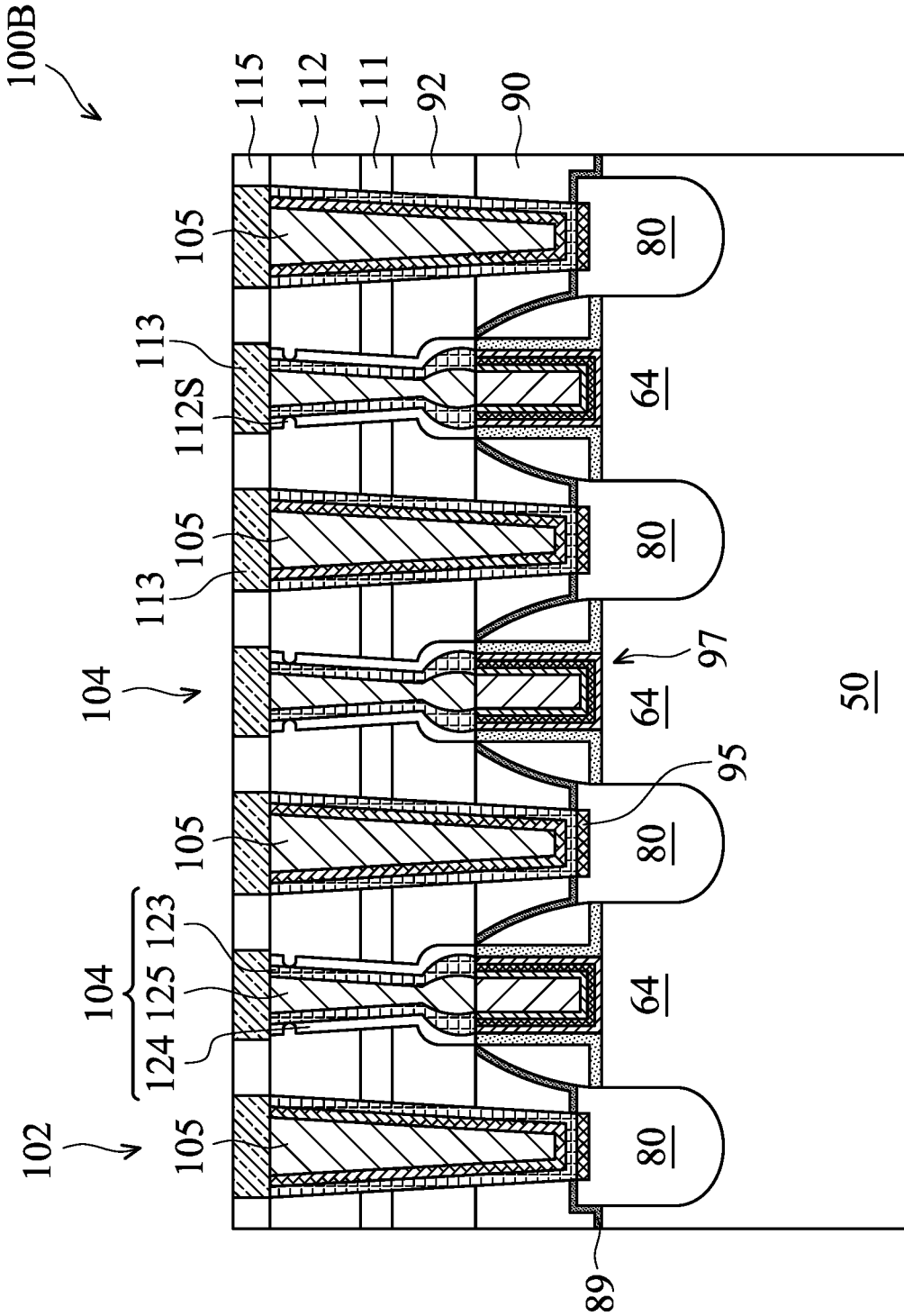


Figure 16

1000

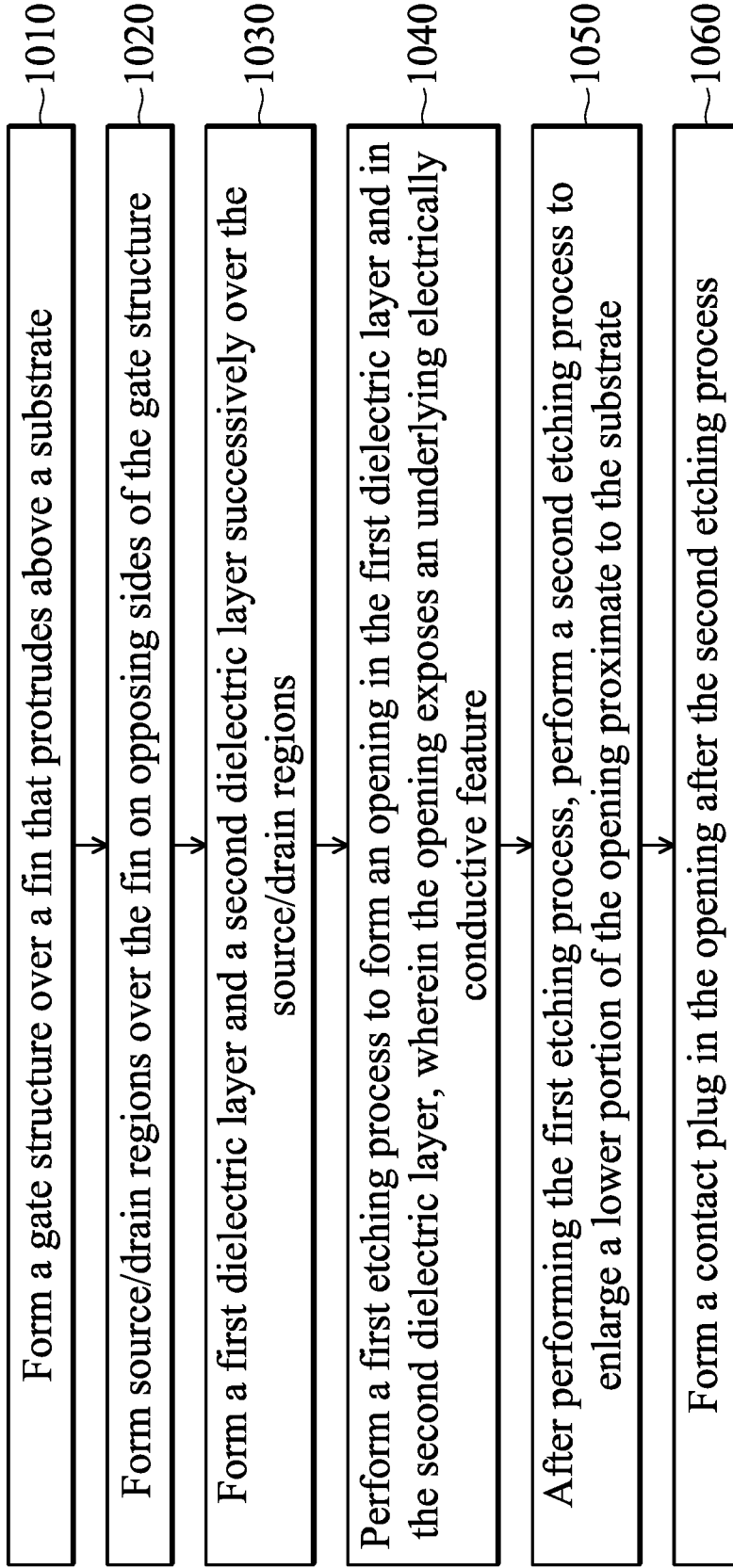


Figure 17

FIN FIELD-EFFECT TRANSISTOR DEVICE HAVING CONTACT PLUGS WITH RE-ENTRANT PROFILE

PRIORITY CLAIM AND CROSS-REFERENCE

This application is a divisional of U.S. patent application Ser. No. 16/870,345, entitled “Fin Field-Effect Transistor Device Having Contact Plugs with Re-Entrant Profile,” filed on May 8, 2020, which application is incorporated herein by reference.

BACKGROUND

The semiconductor industry has experienced rapid growth due to continuous improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, this improvement in integration density has come from repeated reductions in minimum feature size, which allows more components to be integrated into a given area.

Fin Field-Effect Transistor (FinFET) devices are becoming commonly used in integrated circuits. FinFET devices have a three-dimensional structure that comprises a semiconductor fin protruding from a substrate. A gate structure, configured to control the flow of charge carriers within a conductive channel of the FinFET device, wraps around the semiconductor fin. For example, in a tri-gate FinFET device, the gate structure wraps around three sides of the semiconductor fin, thereby forming conductive channels on three sides of the semiconductor fin.

BRIEF DESCRIPTION OF THE DRAWINGS

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.

FIG. 1 illustrates a perspective view of a Fin Field-Effect Transistor (FinFET) device, in accordance with some embodiments.

FIGS. 2-7, 8A, 9-13, and 14A-14C illustrate various cross-sectional views of a FinFET device at various stages of fabrication, in accordance with an embodiment.

FIGS. 8B and 8C illustrate two embodiment cross-sectional views of the FinFET device in FIG. 8A.

FIG. 15 illustrates a cross-sectional view of a FinFET device, in accordance with another embodiment.

FIG. 16 illustrates a cross-sectional view of a FinFET device, in accordance with yet another embodiment.

FIG. 17 illustrates a flow chart of method of forming a semiconductor device, in accordance with some embodiments.

DETAILED DESCRIPTION

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.

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. Throughout the discussion herein, unless otherwise specified, the same numeral in different figures refers to the same or similar component formed by a same or similar method using a same or similar material(s).

Embodiments of the present disclosure are discussed in the context of forming a FinFET device, and in particular, in the context of forming contact plugs with a re-entrant profile for a FinFET device. Although the disclosed embodiments are discussed using FinFET devices as examples, the disclosed methods may also be used in other types of devices, such as planar devices.

In some embodiments, a first dielectric layer and a second dielectric layer are formed over the source/drain regions of a FinFET device. An opening is formed in the first and second dielectric layers using a first etching process (e.g., an anisotropic etching process) to expose an underlying electrically conductive feature, which may be a source/drain region, a via connected to the gate structure of the FinFET device, or a via connected to a source/drain region. Next, a second etching process (e.g., an isotropic etching process) is performed to enlarge a lower portion of the opening, such that the lower portion of the opening has a curved sidewall profile, while the upper portion of the opening has a linear sidewall profile. A contact plug (may also be referred to as a via) is next formed in the opening by: forming a sacrificial layer along sidewalls of the opening; forming a spacer layer over the sacrificial layer; filling the opening with an electrically conductive material; and removing the sacrificial layer after filling the opening. An air gap is formed between the spacer layer and the first and the second dielectric layers after removing the sacrificial layer. The air gap may be sealed by forming another dielectric layer over the second dielectric layer. The enlarged lower portion of the opening results in an enlarged lower portion for the contact plug formed, thereby reducing the electrical resistance of the contact plug. In addition, the air gap advantageously reduces capacitance by reducing the average dielectric constant (K-value) of the dielectric material around the contact plug.

FIG. 1 illustrates an example of a FinFET 30 in a perspective view. The FinFET 30 includes a substrate 50 and a fin 64 protruding above the substrate 50. Isolation regions 62 are formed on opposing sides of the fin 64, with the fin 64 protruding above the isolation regions 62. A gate dielectric 66 is along sidewalls and over a top surface of the fin 64, and a gate electrode 68 is over the gate dielectric 66. Source/drain regions 80 are in the fin 64 and on opposing sides of the gate dielectric 66 and the gate electrode 68. FIG. 1 further illustrates reference cross-sections that are used in later figures. Cross-section B-B extends along a longitudinal axis of the gate electrode 68 of the FinFET 30. Cross-section A-A is perpendicular to cross-section B-B and is along a longitudinal axis of the fin 64 and in a direction of, for example, a current flow between the source/drain regions 80.

Cross-section C-C is parallel to cross-section B-B and is across the source/drain region **80**. Subsequent figures refer to these reference cross-sections for clarity.

FIGS. **2-7**, **8A**, **9-13**, and **14A-14C** are cross-sectional views of a FinFET device **100** at various stages of fabrication in accordance with some embodiments. The FinFET device **100** is similar to the FinFET **30** in FIG. **1**, but with multiple fins and multiple gate structures. FIGS. **2-5** illustrate cross-sectional views of the FinFET device **100** along cross-section B-B. FIGS. **6-7**, **8A**, **9-13**, and **14A** illustrate cross-sectional views of the FinFET device **100** along cross-section A-A. FIGS. **8B** and **8C** illustrate embodiment cross-sectional views of the FinFET device **100** along cross-section C-C. FIGS. **14B** and **14C** illustrates cross-sectional views of the FinFET device **100** along cross-section C-C and B-B, respectively. Throughout the discussion herein, unless otherwise specified, figures with the same number but different alphabets (e.g., FIGS. **14A** and **14B**) refer to different cross-sectional views of a same device at a same stage of fabrication.

FIG. **2** illustrates a cross-sectional view of the substrate **50**. 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 dopant) or undoped. The substrate **50** may be a wafer, such as a silicon wafer. Generally, an SOI substrate includes 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 arsenic, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide; an alloy semiconductor including SiGe, GaAsP, AlInAs, AlGaAs, GaInAs, GaInP, and/or GaInAsP; or combinations thereof.

Referring to FIG. **3**, the substrate **50** shown in FIG. **2** is patterned using, for example, photolithography and etching techniques. For example, a mask layer, such as a pad oxide layer **52** and an overlying pad nitride layer **56**, is formed over the substrate **50**. The pad oxide layer **52** may be a thin film comprising silicon oxide formed, for example, using a thermal oxidation process. The pad oxide layer **52** may act as an adhesion layer between the substrate **50** and the overlying pad nitride layer **56**. In some embodiments, the pad nitride layer **56** is formed of silicon nitride, silicon oxynitride, silicon carbonitride, the like, or a combination thereof, and may be formed using low-pressure chemical vapor deposition (LPCVD) or plasma enhanced chemical vapor deposition (PECVD), as examples.

The mask layer may be patterned using photolithography techniques. Generally, photolithography techniques utilize a photoresist material (not shown) that is deposited, irradiated (exposed), and developed to remove a portion of the photoresist material. The remaining photoresist material protects the underlying material, such as the mask layer in this example, from subsequent processing steps, such as etching. In this example, the photoresist material is used to pattern the pad oxide layer **52** and pad nitride layer **56** to form a patterned mask **58**, as illustrated in FIG. **3**.

The patterned mask **58** is subsequently used to pattern exposed portions of the substrate **50** to form trenches **61**, thereby defining semiconductor fins **64** (e.g., **64A** and **64B**) between adjacent trenches **61** as illustrated in FIG. **3**. In

some embodiments, the semiconductor fins **64** are formed by etching trenches in the substrate **50** using, for example, reactive ion etch (RIE), neutral beam etch (NBE), the like, or a combination thereof. The etching process may be anisotropic. In some embodiments, the trenches **61** may be strips (viewed from in the top) parallel to each other, and closely spaced with respect to each other. In some embodiments, the trenches **61** may be continuous and surround the semiconductor fins **64**. The semiconductor fins **64** may also be referred to as fins **64** hereinafter.

The fins **64** may be patterned by any suitable method. For example, the fins **64** 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 processes, 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, or mandrels, may then be used to pattern the fins.

FIG. **4** illustrates the formation of an insulation material between neighboring semiconductor fins **64** to form isolation regions **62**. The insulation material may be an oxide, such as silicon oxide, a nitride, the like, or a combination thereof, and may be formed by a high density plasma chemical vapor deposition (HDP-CVD), a flowable CVD (FCVD) (e.g., a CVD-based material deposition in a remote plasma system and post curing to make it convert to another material, such as an oxide), the like, or a combination thereof. Other insulation materials and/or other formation processes may be used. In the illustrated embodiment, the insulation material is silicon oxide formed by a FCVD process. An anneal process may be performed once the insulation material is formed. A planarization process, such as a chemical mechanical polish (CMP), may remove any excess insulation material and form top surfaces of the isolation regions **62** and top surfaces of the semiconductor fins **64** that are coplanar (not shown). The patterned mask **58** (see FIG. **3**) may also be removed by the planarization process.

In some embodiments, the isolation regions **62** include a liner, e.g., a liner oxide (not shown), at the interface between the isolation region **62** and the substrate **50**/semiconductor fins **64**. In some embodiments, the liner oxide is formed to reduce crystalline defects at the interface between the substrate **50** and the isolation region **62**. Similarly, the liner oxide may also be used to reduce crystalline defects at the interface between the semiconductor fins **64** and the isolation region **62**. The liner oxide (e.g., silicon oxide) may be a thermal oxide formed through a thermal oxidation of a surface layer of substrate **50**, although other suitable method may also be used to form the liner oxide.

Next, the isolation regions **62** are recessed to form shallow trench isolation (STI) regions **62**. The isolation regions **62** are recessed such that the upper portions of the semiconductor fins **64** protrude from between neighboring STI regions **62**. The top surfaces of the STI regions **62** may have a flat surface (as illustrated), a convex surface, a concave surface (such as dishing), or a combination thereof. The top surfaces of the STI regions **62** may be formed flat, convex, and/or concave by an appropriate etch. The isolation regions **62** may be recessed using an acceptable etching process, such as one that is selective to the material of the isolation

regions **62**. For example, a dry etch, or a wet etch using dilute hydrofluoric (dHF) acid, may be performed to recess the isolation regions **62**.

FIGS. **2** through **4** illustrate an embodiment of forming fins **64**, but fins may be formed in various different processes. For example, a top portion of the substrate **50** may be replaced by a suitable material, such as an epitaxial material suitable for an intended type (e.g., N-type or P-type) of semiconductor devices to be formed. Thereafter, the substrate **50**, with epitaxial material on top, is patterned to form semiconductor fins **64** that comprise the epitaxial material.

As another example, a dielectric layer can be formed over a top surface of a substrate; trenches can be etched through the dielectric layer; homoepitaxial structures can be epitaxially grown in the trenches; and the dielectric layer can be recessed such that the homoepitaxial structures protrude from the dielectric layer to form fins.

In yet another example, a dielectric layer can be formed over a top surface of a substrate; trenches can be etched through the dielectric layer; heteroepitaxial structures can be epitaxially grown in the trenches using a material different from the substrate; and the dielectric layer can be recessed such that the heteroepitaxial structures protrude from the dielectric layer to form fins.

In embodiments where epitaxial material(s) or epitaxial structures (e.g., the heteroepitaxial structures or the homoepitaxial structures) are grown, the grown material(s) or structures may be in situ doped during growth, which may obviate prior and subsequent implantations although in situ and implantation doping may be used together. Still further, it may be advantageous to epitaxially grow a material in an NMOS region different from the material in a PMOS region. In various embodiments, the fins **64** may comprise silicon germanium ($\text{Si}_x\text{Ge}_{1-x}$, where x can be between 0 and 1), silicon carbide, pure or substantially pure germanium, a III-V compound semiconductor, a II-VI compound semiconductor, or the like. For example, the available materials for forming III-V compound semiconductor include, but are not limited to, InAs, AlAs, GaAs, InP, GaN, InGaAs, InAlAs, GaSb, AlSb, AlP, GaP, and the like.

FIG. **5** illustrates the formation of dummy gate structure **75** over the semiconductor fins **64**. Dummy gate structure **75** includes gate dielectric **66** and gate electrode **68**, in some embodiments. A mask **70** may be formed over the dummy gate structure **75**. To form the dummy gate structure **75**, a dielectric layer is formed on the semiconductor fins **64**. The dielectric layer may be, for example, silicon oxide, silicon nitride, multilayers thereof, or the like, and may be deposited or thermally grown.

A gate layer is formed over the dielectric layer, and a mask layer is formed over the gate layer. The gate layer may be deposited over the dielectric layer and then planarized, such as by a CMP. The mask layer may be deposited over the gate layer. The gate layer may be formed of, for example, polysilicon, although other materials may also be used. The mask layer may be formed of, for example, silicon nitride or the like.

After the layers (e.g., the dielectric layer, the gate layer, and the mask layer) are formed, the mask layer may be patterned using acceptable photolithography and etching techniques to form mask **70**. The pattern of the mask **70** then may be transferred to the gate layer and the dielectric layer by an acceptable etching technique to form gate electrode **68** and gate dielectric **66**, respectively. The gate electrode **68** and the gate dielectric **66** cover respective channel regions of the semiconductor fins **64**. The gate electrode **68** may also

have a lengthwise direction substantially perpendicular to the lengthwise direction of respective semiconductor fins **64**.

The gate dielectric **66** is shown to be formed over the fins **64** (e.g., over top surfaces and sidewalls of the fins **64**) and over the STI regions **62** in the example of FIG. **5**. In other embodiments, the gate dielectric **66** may be formed by, e.g., thermal oxidization of a material of the fins **64**, and therefore, may be formed over the fins **64** but not over the STI regions **62**. These and other variations are fully intended to be included within the scope of the present disclosure.

FIGS. **6-7**, **8A**, **9-13**, and **14A** illustrate the cross-sectional views of further processing of the FinFET device **100** along cross-section A-A (along a longitudinal axis of the fin **64**). Note that in FIGS. **6-7**, **8A**, and **9**, three dummy gate structures **75** (e.g., **75A**, **75B**, and **75C**) are formed over the fin **64**. One skilled in the art will appreciate that more or less than three gate structures may be formed over the fin **64**, these and other variations are fully intended to be included within the scope of the present disclosure.

As illustrated in FIG. **6**, lightly doped drain (LDD) regions **65** are formed in the fins **64**. The LDD regions **65** may be formed by a plasma doping process. The plasma doping process may include forming and patterning masks such as a photoresist to cover the regions of the FinFET that are to be protected from the plasma doping process. The plasma doping process may implant N-type or P-type impurities in the fins **64** to form the LDD regions **65**. For example, P-type impurities, such as boron, may be implanted in the fin **64** to form the LDD regions **65** for a P-type device. As another example, N-type impurities, such as phosphorus, may be implanted in the fin **64** to form the LDD regions **65** for an N-type device. In some embodiments, the LDD regions **65** abut the channel region of the FinFET device **100**. Portions of the LDD regions **65** may extend under gate electrode **68** and into the channel region of the FinFET device **100**. FIG. **6** illustrates a non-limiting example of the LDD regions **65**. Other configurations, shapes, and formation methods of the LDD regions **65** are also possible and are fully intended to be included within the scope of the present disclosure. For example, LDD regions **65** may be formed after gate spacers **87** are formed. In some embodiments, the LDD regions **65** are omitted. For simplicity, the LDD regions **65** are not illustrated in subsequent figures, with the understanding the LDD regions **65** may be formed in the fin **64**.

Still referring to FIG. **6**, after the LDD regions **65** are formed, gate spacers **87** are formed around the dummy gate structures **75**. The gate spacer **87** may include a first gate spacer **72** and a second gate spacer **86**. For example, the first gate spacer **72** may be a gate seal spacer and is formed on opposing sidewalls of the gate electrode **68** and on opposing sidewalls of the gate dielectric **66**. The second gate spacer **86** is formed on the first gate spacer **72**. The first gate spacer **72** may be formed of a nitride, such as silicon nitride, silicon oxynitride, silicon carbonitride, the like, or a combination thereof, and may be formed using, e.g., a thermal oxidation, CVD, or other suitable deposition process. The second gate spacer **86** may be formed of silicon nitride, silicon carbonitride, a combination thereof, or the like using a suitable deposition method.

In an embodiment, the gate spacer **87** is formed by first conformally depositing a first gate spacer layer over the FinFET device **100**, then conformally depositing a second gate spacer layer over the deposited first gate spacer layer. Next, an anisotropic etch process, such as a dry etch process, is performed to remove a first portion of the second gate spacer layer disposed on upper surfaces of the FinFET

device **100** (e.g., the upper surface of the mask **70**) while keeping a second portion of the second gate spacer layer disposed along sidewalls of the gate structures. The second portion of the second gate spacer layer remaining after the anisotropic etch process forms the second gate spacer **86**. The anisotropic etch process also removes a portion of the first gate spacer layer disposed outside of the sidewalls of the second gate spacer **86**, and the remaining portion of the first gate spacer layer forms the first gate spacer **72**.

The shapes and formation methods of the gate spacer **87** as illustrated in FIG. **6** are merely non-limiting examples, and other shapes and formation methods are possible. These and other variations are fully intended to be included within the scope of the present disclosure.

Next, as illustrated in FIG. **7**, recesses **88** are formed in the fins **64** adjacent to the dummy gate structures **75**, e.g., between adjacent dummy gate structures **75** and/or next to a dummy gate structure **75**. The recesses **88** are formed by, e.g., an anisotropic etching process using the dummy gate structures **75** and the gate spacers **87** as an etching mask, in some embodiments, although any other suitable etching process may also be used.

Next, as illustrated in FIG. **8A**, the source/drain regions **80** are formed in the recesses **88**. The source/drain regions **80** are formed by epitaxially growing a material in the recesses **88**, using suitable methods such as metal-organic CVD (MOCVD), molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), vapor phase epitaxy (VPE), selective epitaxial growth (SEG), the like, or a combination thereof.

As illustrated in FIG. **8A**, the epitaxial source/drain regions **80** may have surfaces raised from respective surfaces of the fins **64** (e.g. raised above the non-recessed upper surface **64U** of the fins **64**) and may have facets. The source/drain regions **80** of the adjacent fins **64** may merge to form a continuous epitaxial source/drain region **80** (see FIG. **8B**). In some embodiments, the source/drain regions **80** of the adjacent fins **64** do not merge together and remain separate source/drain regions **80** (see FIG. **8C**). In some embodiments, the resulting FinFET is an n-type FinFET, and source/drain regions **80** comprise silicon carbide (SiC), silicon phosphorous (SiP), phosphorous-doped silicon carbon (SiCP), or the like. In some embodiments, the resulting FinFET is a p-type FinFET, and source/drain regions **80** comprise SiGe, and a p-type impurity such as boron or indium.

The epitaxial source/drain regions **80** may be implanted with dopants to form source/drain regions **80** followed by an anneal process. The implanting process may include forming and patterning masks such as a photoresist to cover the regions of the FinFET device **100** that are to be protected from the implanting process. The source/drain regions **80** may have an impurity (e.g., dopant) concentration in a range from about $1E19\text{ cm}^{-3}$ to about $1E21\text{ cm}^{-3}$. P-type impurities, such as boron or indium, may be implanted in the source/drain region **80** of a P-type transistor. N-type impurities, such as phosphorous or arsenide, may be implanted in the source/drain regions **80** of an N-type transistor. In some embodiments, the epitaxial source/drain regions may be in situ doped during growth.

Next, as illustrated in FIG. **9**, a contact etch stop layer (CESL) **89** is formed over the structure illustrated in FIG. **8A**. The CESL **89** functions as an etch stop layer in a subsequent etching process, and may comprise a suitable material such as silicon oxide, silicon nitride, silicon oxynitride, combinations thereof, or the like, and may be formed by a suitable formation method such as CVD, PVD, combinations thereof, or the like.

Next, a first interlayer dielectric (ILD) **90** is formed over the CESL **89** and over the dummy gate structures **75** (e.g., **75A**, **75B**, and **75C**). In some embodiments, the first ILD **90** is formed of a dielectric material such as silicon oxide, phosphosilicate glass (PSG), borosilicate glass (BSG), boron-doped phosphosilicate Glass (BPSG), undoped silicate glass (USG), or the like, and may be deposited by any suitable method, such as CVD, PECVD, or FCVD. A planarization process, such as a CMP process, may be performed to remove the mask **70** and to remove portions of the CESL **89** disposed over the gate electrode **68**. After the planarization process, the top surface of the first ILD **90** is level with the top surface of the gate electrode **68**.

Next, in FIG. **10**, an embodiment gate-last process (sometimes referred to as replacement gate process) is performed to replace the gate electrode **68** and the gate dielectric **66** with an active gate (may also be referred to as a replacement gate or a metal gate) and active gate dielectric material(s), respectively. Therefore, the gate electrode **68** and the gate dielectric **66** may be referred to as dummy gate electrode and dummy gate dielectric, respectively, in a gate-last process. The active gate is a metal gate, in some embodiments.

Referring to FIG. **10**, the dummy gate structures **75A**, **75B**, and **75C** (see FIG. **9**) are replaced by replacement gate structures **97A**, **97B**, and **97C**, respectively. In accordance with some embodiments, to form the replacement gate structures **97** (e.g., **97A**, **97B**, or **97C**), the gate electrode **68** and the gate dielectric **66** directly under the gate electrode **68** are removed in an etching step(s), so that recesses (not shown) are formed between the gate spacers **87**. Each recess exposes the channel region of a respective fin **64**. During the dummy gate removal, the gate dielectric **66** may be used as an etch stop layer when the gate electrode **68** is etched. The gate dielectric **66** may then be removed after the removal of the gate electrode **68**.

Next, a gate dielectric layer **94**, a barrier layer **96**, a work function layer **98**, and a gate electrode **99** are formed in the recesses for the replacement gate structure **97**. The gate dielectric layer **94** is deposited conformally in the recesses, such as on the top surfaces and the sidewalls of the fins **64** and on sidewalls of the gate spacers **87**, and on a top surface of the first ILD **90** (not shown). In accordance with some embodiments, the gate dielectric layer **94** comprises silicon oxide, silicon nitride, or multilayers thereof. In other embodiments, the gate dielectric layer **94** includes a high-k dielectric material, and in these embodiments, the gate dielectric layers **94** may have a k value greater than about 7.0, and may include a metal oxide or a silicate of Hf, Al, Zr, La, Mg, Ba, Ti, Pb, and combinations thereof. The formation methods of gate dielectric layer **94** may include molecular beam deposition (MBD), atomic layer deposition (ALD), PECVD, and the like.

Next, the barrier layer **96** is formed conformally over the gate dielectric layer **94**. The barrier layer **96** may comprise an electrically conductive material such as titanium nitride, although other materials, such as tantalum nitride, titanium, tantalum, or the like, may alternatively be utilized. The barrier layer **96** may be formed using a CVD process, such as PECVD. However, other alternative processes, such as sputtering, metal organic chemical vapor deposition (MOCVD), or ALD, may alternatively be used.

Next, the work function layer **98**, such as a P-type work function layer or an N-type work function layer, may be formed in the recesses over the barrier layers **96** and before the gate electrode **99** is formed, in some embodiments. Exemplary P-type work function metals that may be included in the gate structures for P-type devices include

TiN, TaN, Ru, Mo, Al, WN, ZrSi₂, MoSi₂, TaSi₂, NiSi₂, WN, other suitable P-type work function materials, or combinations thereof. Exemplary N-type work function metals that may be included in the gate structures for N-type devices include Ti, Ag, TaAl, TaAlC, TiAlN, TaC, TaCN, TaSiN, Mn, Zr, other suitable N-type work function materials, or combinations thereof. A work function value is associated with the material composition of the work function layer, and thus, the material of the work function layer is chosen to tune its work function value so that a target threshold voltage V_t is achieved in the device that is to be formed. The work function layer(s) may be deposited by CVD, physical vapor deposition (PVD), and/or other suitable process.

Next, a seed layer (not shown) is formed conformally over the work function layer **98**. The seed layer may include copper, titanium, tantalum, titanium nitride, tantalum nitride, the like, or a combination thereof, and may be deposited by ALD, sputtering, PVD, or the like. In some embodiments, the seed layer is a metal layer, which may be a single layer or a composite layer comprising a plurality of sub-layers formed of different materials. For example, the seed layer comprises a titanium layer and a copper layer over the titanium layer.

Next, the gate electrode **99** is deposited over the seed layer, and fills the remaining portions of the recesses. The gate electrode **99** may be made of a metal-containing material such as Cu, Al, W, the like, combinations thereof, or multi-layers thereof, and may be formed by, e.g., electroplating, electroless plating, or other suitable method. After the formation of the gate electrode **99**, a planarization process, such as a CMP, may be performed to remove the excess portions of the gate dielectric layer **94**, the barrier layer **96**, the work function layer **98**, the seed layer, and the gate electrode **99**, which excess portions are over the top surface of the first ILD **90**. The resulting remaining portions of the gate dielectric layer **94**, the barrier layer **96**, the work function layer **98**, the seed layer, and the gate electrode **99** thus form the replacement gate structure **97** of the resulting FinFET device **100**.

Referring next to FIG. **11**, a second ILD **92** is formed over the first ILD **90**. Openings **93** are formed through the second ILD **92** and the first ILD **90** to expose the source/drain regions **80**.

In an embodiment, the second ILD **92** is a flowable film formed by a flowable CVD method. In some embodiments, the second ILD **92** is formed of a dielectric material such as PSG, BSG, BPSG, USG, or the like, and may be deposited by any suitable method, such as CVD and PECVD. In some embodiments, the second ILD **92** and the first ILD **90** are formed of a same material. In some embodiments, the second ILD **92** and the first ILD **90** are formed of different materials.

In some embodiments, the openings **93** in FIG. **11** are formed using photolithography and etching. The etching process etches through the CESL **89** to expose the source/drain regions **80**. In some embodiments, the openings **93** in FIG. **11** are formed using an anisotropic etching process, such as an anisotropic plasma etching process. The anisotropic plasma etching process uses a gas source that comprises CF₄, C₄F₆, C₄F₈, or combinations thereof, in an embodiment. After the anisotropic etching process, the sidewalls of the openings **93** in FIG. **11** have a linear profile, e.g., each of the sidewalls of the openings **93** extends along a respective straight line (e.g., a slanted straight line).

Next, in FIG. **12**, an isotropic etching process, such as an isotropic plasma etching process, is performed to expand a lower portion of the openings **93**. The isotropic plasma

etching process uses a gas source that comprises Cl₂, HBr, or combinations thereof, in an embodiment. The bias power (or bias voltage) of the plasma etching tool may be adjusted (e.g., reduced) to achieve isotropic plasmas etching, as an example. In some embodiments, the first ILD **90** and the second ILD **92** are formed of a same or similar material (e.g., first ILD **90** is silicon oxide formed by PECVD and the second ILD **92** is silicon oxide formed by FCVD), and the gas source of the isotropic etching process has a high etching selectivity (e.g., higher etching rate) for the first and second ILDs **90/92** over the source/drain regions **80**. During the isotropic etching process, the etching gas in the upper portion of the opening **93** tends to diffuse out of the opening **93**, while the etching gas in the lower portion of the opening **93** remains and removes (e.g., etches) portions of the first ILD **90**, such that lower portions of the openings **93** (e.g., portions inside the first ILD **90**) are enlarge by the isotropic etching process, while upper portions of the openings **93** (e.g., portions in the second ILD **92**) remain substantially unchanged, in some embodiments. Therefore, after the isotropic etching process, the upper portions of the openings **93** have a linear sidewall profile, while the lower portions of the openings **93** have a curved sidewall profile, e.g., sidewalls of the lower portions of each opening **93** are curved. Although an isotropic plasma etching process is used as an example, other suitable isotropic etching process, such as a wet etch process, may also be used.

The isotropic etching process increases the volume of the lower portions of the openings **93**. As illustrated in FIG. **12**, each opening **93** has a first width A at an upper surface of the second ILD **92**, and has a second width B at a bottom of the opening **93**, wherein B is larger than A. In some embodiments, the second width B is larger than the first width A by a value between about 1 nm and about 5 nm (e.g., 5 nm \geq B - A \geq 1 nm), such as about 1 nm. An angle α between line R1 and line R2 is between about 87 degrees and about 91 degrees, such as about 87 degrees, where line R1 extends along the linear sidewall (e.g., a slanted straight sidewall) of the upper portion of the opening **93**, and the line R2 is parallel to a major upper surface of the substrate **50**.

Next, in FIG. **13**, a sacrificial layer **121** is formed (e.g., conformally) in the openings **93** along sidewalls of the first ILD **90** and along sidewalls of the second ILD **92**. A spacer layer **123** is next formed (e.g., conformally) over and along the sacrificial layer **121**. Next, silicide regions **95** are formed at the bottom of the openings **93** over the source/drain regions **80**, and an electrically conductive material **125** is formed to fill the openings **93**. Details are discussed below.

In an embodiment, the sacrificial layer **121** is a semiconductor layer, such as a silicon layer, and is formed by a suitable deposition process such as ALD, CVD, PECVD, or the like. In some embodiments, the as-deposited sacrificial layer **121** extends conformally along sidewalls and bottoms of the openings **93**, and along an upper surface of the second ILD **92**. Next, an etching process (e.g., an anisotropic etching process) is performed to remove portions of the sacrificial layer **121** from the bottoms of the openings **93** to expose the underlying source/drain regions **80**. The etching process may also remove portions of the sacrificial layer **121** from the upper surface of the second ILD **92**. After the etching process, the sacrificial layer **121** is disposed along sidewalls of the openings **93**. In subsequent processing, the sacrificial layer **121** is removed to form an air gap between the first ILD/second ILD **90/92** and the spacer layer **123**. Although silicon is used as an example for the sacrificial layer **121**, any other suitable material (e.g., a material that

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may be selectively removed by a subsequent etching process) may be used as the sacrificial layer **121**.

Next, the spacer layer **123** is formed (e.g., conformally) in the openings **93** and over the sacrificial layer **121**. In an embodiment, the spacer layer **123** is a dielectric layer, such as a silicon nitride layer, and is formed by a suitable deposition process such as ALD, CVD, PECVD, or the like. The spacer layer **123** is formed using a material different from the material of the sacrificial layer **121** to provide etching selectivity, such that in a subsequent etching process to remove the sacrificial layer **121**, the sacrificial layer **121** is removed without substantially attacking the spacer layer **123**.

In some embodiments, the as-deposited spacer layer **123** extends conformally along sidewalls and bottoms of the openings **93**, and along an upper surface of the second ILD **92**. Next, another etching process (e.g., an anisotropic etching process) is performed to remove portions of the spacer layer **123** from the bottoms of the openings **93** to expose the underlying source/drain regions **80**. The another etching process may also remove portions of the spacer layer **123** from the upper surface of the second ILD **92**. After the another etching process, the spacer layer **123** is disposed along sidewalls of the openings **93** over the sacrificial layer **121**.

Next, the silicide regions **95**, which may be optional, are formed in the openings **93** over the source/drain regions **80**. In some embodiments, the silicide regions **95** are formed by first depositing a metal capable of reacting with semiconductor materials (e.g., silicon, germanium) to form silicide or germanide regions, such as nickel, cobalt, titanium, tantalum, platinum, tungsten, other noble metals, other refractory metals, rare earth metals or their alloys, over the exposed portions of the epitaxial source/drain regions **80**, then performing a thermal anneal process to form the silicide regions **95**. The un-reacted portions of the deposited metal are then removed, e.g., by an etching process. Although regions **95** are referred to as silicide regions, regions **95** may also be germanide regions, or silicon germanide regions (e.g., regions comprising silicide and germanide).

Next, a barrier layer (not illustrated) is formed (e.g., conformally) in the openings **93**. The barrier layer may comprise an electrically conductive material such as titanium nitride, although other materials, such as tantalum nitride, titanium, tantalum, or the like, may alternatively be utilized. The barrier layer may be formed using ALD, CVD, PECVD, MOCVD, or the like.

Next, the electrically conductive material **125** is formed in the openings **93** to fill the openings **93**. The electrically conductive material **125** may be made of a metal-containing material such as Cu, Al, W, the like, combinations thereof, or multi-layers thereof, and may be formed by, e.g., electroplating, electroless plating, or other suitable method. A planarization process, such as CMP, may be performed to remove excess portions of the layers (e.g., **121**, **123**, the barrier layer, and **125**) that are disposed over the upper surface of the second ILD **92**. Note that due to the enlarged lower portion of the openings **93**, the electrically conductive material **125** also has enlarged lower portions, which advantageously reduces the electrically resistance of the contact plugs formed. For example, the electrically conductive material **125** in each opening **93** has an upper portion with a linear sidewall profile and a lower portion with a curved sidewall profile, and the lower portion is wider than the upper portion.

Next, in FIG. **14A**, a selective etching process is performed to remove the sacrificial layer **121**. In an embodi-

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ment, sacrificial layer **121** is a silicon layer, and the chemical used in the selective etching process comprises hydrogen (H_2) and nitride fluoride (NF_3). In another embodiment, the sacrificial layer **121** is selectively removed using a chemical comprising ammonium hydroxide (NH_4OH). Note that the selective etching process to remove the sacrificial layer **121** is different from the etching processes to form the openings **93**. After the selective etching process, air gaps **124** are formed between the first ILD/second ILD **90/92** and the spacer layer **123**. The air gaps **124** advantageously reduce the capacitance of the device formed due to the air gaps reducing the average dielectric constant (K-value) of the dielectric material (e.g., first ILD **90** and second ILD **92**) around the contact plugs formed. The air gap **124**, the spacer layer **123**, the barrier layer, and the electrically conductive material **125** in each opening **93** thus form a contact plug **104** that has a re-entrant profile. The contact plugs **104** in FIG. **14A** are electrically coupled to the source/drain regions **80**, thus are also referred to as source/drain contact plugs.

Next, an impurity (e.g., Ge) is implanted into the top portion of the second ILD **92** by an implantation process to seal (at least partially) the air gap **124**, and subsequently, a dielectric layer **111** is formed over the second ILD **92**. In some embodiments, the implantation process implants a suitable impurity, such as germanium, into the top portion of the second ILD **92**. The implantation process causes the top portion of the second ILD **92** to swell (e.g., expand), and therefore, seal (e.g., completely seal or partially seal) the air gap **124**. As illustrated in FIG. **14A**, a portion **92S** (caused by swelling of the top portion of the second ILD **92**), which may comprise the impurity (e.g., Ge), seals the air gap **124**. Electrically conductive features **113**, such as conductive lines, are formed in the dielectric layer **111**. The dielectric layer **111** and/or the electrically conductive feature **113** in the dielectric layer **111** may further seal the air gap **124**. Additional processing may follow the processing of FIG. **14A** to finish the fabrication of the FinFET device **100**, as one skilled in the art readily appreciates, details are not repeated here.

FIG. **14B** illustrate the FinFET device **100** of FIG. **14A**, but along cross-section C-C. FIG. **14C** illustrate the FinFET device **100** of FIG. **14A**, but along cross-section B-B.

FIG. **15** illustrates a cross-sectional view of a FinFET device **100A**, in accordance with another embodiment. The FinFET device **100A** is similar to the FinFET device **100**, but with the contact plugs **104** (also referred to as via-to-contact plugs) formed in dielectric layers **111/112**, which dielectric layers **111/112** are disposed over the second ILD **92**. In other words, the source/drain regions **80** are electrically coupled to contact plugs **102** (which may or may not have the re-entrant profile) first, then the via-to-contact plugs **104** are formed over and electrically coupled to the underlying contact plugs **102**. The contact plugs **102** in the example of FIG. **15** do not have re-entrant profile. In other embodiments, the contact plugs **102** in FIG. **15** may be replaced with contact plugs with re-entrant profile, such as the contact plugs **104**.

In FIG. **15**, the contacts plugs **102** (may also be referred to as contacts) are formed in the first ILD **90** and the second ILD **92**. Each of the contacts **102** includes a barrier layer **101**, a seed layer **103**, and a conductive material **105**, and is electrically coupled to the underlying conductive feature (e.g., a source/drain region **80**). The materials and the formation methods for the barrier layers **101**, the seed layer **103** and the conductive material **105** may be the same as or similar to those discussed above for the barrier layers **96**, the seed layer, and the gate electrode **99** of the replacement gate

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structure 97, respectively, thus details are not repeated. The contact plugs 104 may be formed using a same or similar processing steps as illustrated in FIGS. 11-14A. As illustrated in FIG. 15, an impurity, such as germanium, may be implanted in the top portion of the dielectric layer 112 to cause it to swell, such that a portion 112S of the dielectric layer 112 seals (e.g., completely seals or partially seals) a respective air gap 124. The dielectric layer 115 and/or the electrically conductive feature 113 in the dielectric layer 115 may further seal the air gap 124.

FIG. 16 illustrates a cross-sectional view of a FinFET device 100B, in accordance with another embodiment. The FinFET device 100B is similar to the FinFET device 100, but with the contact plugs 104 (also referred to as via-to-gate plugs) with re-entrant profile formed in dielectric layers 111/112 and in first ILD/second ILD 90/92, and electrically coupled to replacement gate structures 97.

Variations to the disclosed embodiments are possible and are fully intended to be included within the scope of the present disclosure. For example, combination of the via-to-contact plug 104 (with the re-entrant profile) and the underlying contact plug 102 (see, e.g., FIG. 15) may be used to replace contact plug 102 used alone as contacts for electrical connection, such as the contact plug 102 in FIG. 16.

FIG. 17 illustrates a flow chart of a method 1000 of forming a semiconductor device, in accordance with some embodiments. It should be understood that the embodiment method shown in FIG. 17 is merely an example of many possible embodiment methods. One of ordinary skill in the art would recognize many variations, alternatives, and modifications. For example, various steps as illustrated in FIG. 17 may be added, removed, replaced, rearranged and repeated.

Referring to FIG. 17, at step 1010, a gate structure is formed over a fin that protrudes above a substrate. At step 1020, source/drain regions are formed over the fin on opposing sides of the gate structure. At step 1030, a first dielectric layer and a second dielectric layer are formed successively over the source/drain regions. At step 1040, a first etching process is performed to form an opening in the first dielectric layer and in the second dielectric layer, wherein the opening exposes an underlying electrically conductive feature. At step 1050, after performing the first etching process, a second etching process is performed to enlarge a lower portion of the opening proximate to the substrate. At step 1060, a contact plug is formed in the opening after the second etching process.

Embodiments may achieve advantages. For example, the disclosed cleaning method allows the contact plugs formed to have enlarged lower portions, thereby reducing the electrical resistance of the contact plugs formed. In addition, the air gap of the contact plugs helps to prevent or reduce metal diffusion, and may additionally reduce the average dielectric constant value (k-value) of the device formed.

In accordance with an embodiment, a method of forming a semiconductor device includes: forming a gate structure over a fin that protrudes above a substrate; forming source/drain regions over the fin on opposing sides of the gate structure; forming a first dielectric layer and a second dielectric layer successively over the source/drain regions; performing a first etching process to form an opening in the first dielectric layer and in the second dielectric layer, wherein the opening exposes an underlying electrically conductive feature; after performing the first etching process, performing a second etching process to enlarge a lower portion of the opening proximate to the substrate; and forming a contact plug in the opening after the second etching process. In an embodiment, the first etching process

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is an anisotropic etching process. In an embodiment, the second etching process is an isotropic etching process. In an embodiment, after the first etching process and before the second etching process, the opening has a linear sidewall profile, wherein after the second etching process, the lower portion of the opening has a curved sidewall profile, and an upper portion of the opening distal from the substrate has a linear profile. In an embodiment, after the second etching process, the lower portion of the opening has a first width, and an upper portion of the opening distal from the substrate has a second width, wherein the first width is larger than the second width. In an embodiment, the first etching process is an anisotropic plasma etching process performed using a gas source comprising CF_4 , C_4F_6 or C_4F_8 . In an embodiment, the second etching process is an isotropic plasma etching process performed using a gas source comprising Cl_2 , or HBr. In an embodiment, forming the contact plug comprises: forming a sacrificial layer lining sidewalls of the opening; forming a spacer layer over the sacrificial layer; filling the opening with an electrically conductive material; and removing the sacrificial layer after filling the opening, wherein after removing the sacrificial layer, an air gap is formed between the first and second dielectric layers and the spacer layer. In an embodiment, the sacrificial layer is formed along the sidewalls of the opening, and a bottom of the opening is free of the sacrificial layer. In an embodiment, the method further comprises, after removing the sacrificial layer, forming a third dielectric layer over the second dielectric layer, the third dielectric layer sealing the air gap. In an embodiment, the spacer layer is formed using a nitride, and the sacrificial layer is formed using a semiconductor material. In an embodiment, the nitride is silicon nitride, and the semiconductor material is silicon.

In accordance with an embodiment, a method of forming a semiconductor device includes: forming a gate structure over a fin that protrudes above a substrate; forming a source/drain region over the fin adjacent to gate structure; forming a first dielectric layer over the source/drain region and around the gate structure; forming a second dielectric layer over the first dielectric layer; forming an opening that extends into the first dielectric layer and the second dielectric layer using a first etching process, wherein the opening exposes an underlying electrically conductive feature; increasing a volume of the opening in the first dielectric layer using a second etching process; forming a sacrificial layer along sidewalls of the opening; forming a spacer layer along the sacrificial layer; and filling the opening with an electrically conductive material; and removing the sacrificial layer after filling the opening, wherein an air gap is formed between the first and the second dielectric layers and the electrically conductive material after removing the sacrificial layer. In an embodiment, the method further comprises sealing the air gap by forming a third dielectric layer over the second dielectric layer. In an embodiment, the first etching process is an anisotropic etching process, and the second etching process is an isotropic etching process. In an embodiment, the second etching process is performed using an etchant that is selective to a material of the first dielectric layer.

In accordance with an embodiment, a semiconductor device includes: a fin protruding above a substrate; a gate structure over the fin; source/drain regions on opposing sides of the gate structure; dielectric layers over the source/drain regions; and a contact plug extending through the dielectric layers and electrically coupled to an underlying electrically conductive feature, wherein an upper portion of the contact plug has a linear sidewall profile, and a lower portion of the

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contact plug has a curved sidewall profile. In an embodiment, a width of the lower portion of the contact plug proximate to the substrate is larger than a width of the upper portion of the contact plug distal from the substrate. In an embodiment, the contact plug comprises: an electrically conductive material; a spacer layer around the electrically conductive material; and an air gap between the spacer layer and the dielectric layers. In an embodiment, the underlying electrically conductive feature is one of the source/drain regions, the gate structure, or a via connected to the gate structure or connected to one of the source/drain regions.

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 semiconductor device comprising:

a fin protruding above a substrate;

a gate structure over the fin;

source/drain regions on opposing sides of the gate structure;

one or more dielectric layers over the source/drain regions;

a contact plug extending through the one or more dielectric layers and electrically coupled to an underlying electrically conductive feature, wherein an upper surface of the one or more dielectric layers distal from the substrate is level with an upper surface of the contact plug, wherein an upper portion of the contact plug has a linear sidewall profile, and a lower portion of the contact plug has a curved sidewall profile, wherein the contact plug comprises:

an electrically conductive material;

a spacer layer around the electrically conductive material; and

an air gap between the spacer layer and the one or more dielectric layers, wherein the one or more dielectric layers have a protrusion portion that protrudes into the air gap and seals the air gap; and

a second dielectric layer over the contact plug and the one or more dielectric layers, wherein the protrusion portion separates the air gap into a lower air gap and an upper air gap, wherein the lower air gap is between the protrusion portion and the underlying electrically conductive feature, and the upper air gap is between the protrusion portion and the second dielectric layer.

2. The semiconductor device of claim 1, wherein the one or more dielectric layers comprise a dielectric material, wherein the protrusion portion of the one or more dielectric layers is the dielectric material doped with a dopant.

3. The semiconductor device of claim 2, wherein the dopant is germanium.

4. The semiconductor device of claim 2, wherein the protrusion portion is proximate to the upper surface of the one or more dielectric layers, wherein the protrusion portion extends laterally from a sidewall of the one or more dielectric layers exposed by the air gap toward the contact plug, wherein a lower portion of the one or more dielectric layers

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is free of the dopant, the lower portion of the one or more dielectric layers being proximate to the lower portion of the contact plug.

5. The semiconductor device of claim 1, further comprising a conductive line in the second dielectric layer, wherein the conductive line is over and in contact with the contact plug, wherein a lower surface of conductive line facing the substrate is level with a lower surface of the second dielectric layer facing the substrate, wherein the lower surface of the conductive line is exposed to the air gap.

6. The semiconductor device of claim 1, wherein a width of the lower portion of the contact plug is larger than that of the upper portion of the contact plug.

7. The semiconductor device of claim 1, wherein the underlying electrically conductive feature is one of the source/drain regions, the gate structure, or a via that is connected to the gate structure or connected to one of the source/drain regions.

8. The semiconductor device of claim 1, wherein the underlying electrically conductive feature is one of the source/drain regions, wherein the semiconductor device further comprises a silicide region under the contact plug.

9. The semiconductor device of claim 1, wherein the one or more dielectric layers and the spacer layer comprise different dielectric materials.

10. The semiconductor device of claim 1, wherein the lower portion of the contact plug is disposed in the one or more dielectric layers over one of the source/drain regions, wherein the contact plug contacts, but does not extend into, the one of the source/drain regions.

11. A semiconductor device comprising:

a substrate;

a transistor over the substrate, wherein the transistor comprises a gate structure and source/drain regions on opposing sides of the gate structure;

a first dielectric layer over the substrate and around the transistor;

a contact plug extending through the first dielectric layer and electrically coupled to an underlying conductive feature, wherein the contact plug comprises:

an electrically conductive material;

a first dielectric material around the conductive material; and

an air gap between the first dielectric material and first dielectric layer, wherein an upper portion of the first dielectric layer distal from the substrate has a protrusion portion, wherein the protrusion portion extends into the air gap and separates the air gap into a lower air gap below the protrusion portion and an upper air gap over the protrusion portion; and

a second dielectric layer over the contact plug and the first dielectric layer, wherein the upper air gap is between the second dielectric layer and the protrusion portion.

12. The semiconductor device of claim 11, wherein the underlying conductive feature is the gate structure, one of the source/drain regions, or a via that is coupled to the transistor.

13. The semiconductor device of claim 11, wherein the protrusion portion seals the air gap partially, wherein the second dielectric layer seals the air gap completely.

14. The semiconductor device of claim 11, wherein the upper portion of the first dielectric layer and the protrusion portion comprise a second dielectric material doped with a dopant, wherein a lower portion of the first dielectric layer proximate to the substrate comprises the second dielectric material and is free of the dopant.

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15. The semiconductor device of claim 11, wherein an upper portion of the contact plug distal from the substrate has linear sidewalls, and a lower portion of the contact plug proximate to the substrate has curved sidewalls.

16. The semiconductor device of claim 15, wherein a lower surface of the contact plug facing the substrate is a flat surface.

17. The semiconductor device of claim 11, further comprising a conductive line in the second dielectric layer, wherein the protrusion portion seals the air gap partially, wherein the conductive line in the second dielectric layer seals the air gap completely, wherein a lower surface of the conductive line is exposed to the upper air gap.

18. A semiconductor device comprising:

a substrate;

a transistor over the substrate, wherein the transistor comprises a gate structure and source/drain regions on opposing sides of the gate structure;

a first dielectric layer over the substrate;

a conductive plug extending through the first dielectric layer and electrically coupled to a conductive feature of the transistor, wherein an upper portion of the conductive plug has linear sidewalls, and a lower portion of the conductive plug has curved sidewalls;

a spacer layer around the conductive plug;

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an air gap between the spacer layer and the first dielectric layer, wherein the first dielectric layer has a protrusion portion proximate to an upper surface of the first dielectric layer, wherein the protrusion portion extends into the air gap;

a second dielectric layer over the first dielectric layer and the conductive plug; and

a conductive line in the second dielectric layer and over the air gap, wherein the conductive line seals the air gap, wherein a portion of the air gap is disposed between the conductive line and the protrusion portion.

19. The semiconductor device of claim 18, wherein the upper portion of the conductive plug has a first width, and the lower portion of the conductive plug has a second width larger than the first width.

20. The semiconductor device of claim 18, further comprising a third dielectric layer between the first dielectric layer and the substrate, wherein the third dielectric layer surrounds the gate structure, wherein the lower portion of the conductive plug is in the third dielectric layer and over one of the source/drain regions, wherein a lower surface of the conductive plug is a flat surface that contacts, but does not extend into, the one of the source/drain regions.

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