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### METHOD OF MANUFACTURING A SEMICONDUCTOR DEVICE AND A SEMICONDUCTOR DEVICE

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#### Abstract

A method of manufacturing a semiconductor device includes forming a plurality of fin structures extending in a first direction over a semiconductor substrate. Each fin structure includes a first region proximate to the semiconductor substrate and a second region distal to the semiconductor substrate. An electrically conductive layer is formed between the first regions of a first adjacent pair of fin structures. A gate electrode structure is formed extending in a second direction substantially perpendicular to the first direction over the fin structure second region, and a metallization layer including at least one conductive line is formed over the gate electrode structure.

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation application of U.S. patent application Ser. No. 18/504,027, filed Nov. 7, 2023, which is a continuation application of U.S. patent application Ser. No. 17/706,362, filed Mar. 28, 2022, now U.S. Pat. No. 11,848,242, which is a continuation application of U.S. patent application Ser. No. 17/114,347, filed Dec. 7, 2020, now U.S. Pat. No. 11,289,384, which is a divisional application of U.S. patent application Ser. No. 16/281,679, filed Feb. 21, 2019, now U.S. Pat. No. 10,861,750, which claims priority to U.S. Provisional Patent Application No. 62/693,180, filed Jul. 2, 2018, the entire disclosures of each of which are incorporated herein by reference.

### TECHNICAL FIELD

[0002] The disclosure relates to a method of manufacturing semiconductor integrated circuits, and more particularly to method of manufacturing semiconductor devices including fin field effect transistors (FinFETs) and/or gate-all-around (GAA) FETs, and semiconductor devices.

### BACKGROUND

[0003] As the semiconductor industry has progressed into nanometer technology process nodes in pursuit of higher device density, higher performance, and lower costs, challenges from both fabrication and design issues have resulted in the development of three-dimensional designs, such as a multi-gate field effect transistor (FET), including a fin FET (FinFET) and a gate-all-around (GAA) FET. In a FinFET, a gate electrode is adjacent to three side surfaces of a channel region with a gate dielectric layer interposed therebetween. Because the gate structure surrounds (wraps) the fin on three surfaces, the transistor essentially has three gates controlling the current through the fin or channel region. The fourth side, the bottom part of the channel is further away from the gate electrode and thus is not under close gate control. In contrast, in a GAA FET, all side surfaces of the channel region are surrounded by the gate electrode. As transistor dimensions are continually scaled down to sub 10-15 nm technology nodes, further improvements of FinFETs and GAA FETs are required.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in

the industry, various features are not drawn to scale and are used for illustration purposes only. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0005] FIG. 1 shows an isometric view of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure.

[0006] FIG. 2 shows an isometric view of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure.

[0007] FIGS. 3A-3E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 3A is an isometric view. FIG. 3B is a cross-sectional view taken along line A-A' of FIG. 3A. FIG. 3C is a cross-sectional view taken along line B-B' of FIG. 3A. FIG. 3D is a cross-sectional view taken along line C-C' of FIG. 3A. FIG. 3E is a cross-sectional view taken along line D-D' of FIG. 3A.

[0008] FIGS. 4A-4E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 4A is an isometric view. FIG. 4B is a cross-sectional view taken along line A-A' of FIG. 4A. FIG. 4C is a cross-sectional view taken along line B-B' of FIG. 4A. FIG. 4D is a cross-sectional view taken along line C-C' of FIG. 4A. FIG. 4E is a cross-sectional view taken along line D-D' of FIG. 4A.

[0009] FIGS. 5A-5E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 5A is an isometric view. FIG. 5B is a cross-sectional view taken along line A-A' of FIG. 5A. FIG. 5C is a cross-sectional view taken along line B-B' of FIG. 5A. FIG. 5D is a cross-sectional view taken along line C-C' of FIG. 5A. FIG. 5E is a cross-sectional view taken along line D-D' of FIG. 5A.

[0010] FIGS. 6A-6E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 6A is an isometric view. FIG. 6B is a cross-sectional view taken along line A-A' of FIG. 6A. FIG. 6C is a cross-sectional view taken along line B-B' of FIG. 6A. FIG. 6D is a cross-sectional view taken along line C-C' of FIG. 6A. FIG. 6E is a cross-sectional view taken along line D-D' of FIG. 6A.

[0011] FIGS. 7A-7E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 7A is an isometric view. FIG. 7B is a cross-sectional view taken along line A-A' of FIG. 7A. FIG. 7C is a cross-sectional view taken along line B-B' of FIG. 7A. FIG. 7D is a cross-sectional view taken along line C-C' of FIG. 7A. FIG. 7E is a cross-sectional view taken along line D-D' of FIG. 7A.

[0012] FIGS. 8A-8E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 8A is an isometric view. FIG. 8B is a cross-sectional view taken along line A-A' of FIG. 8A. FIG. 8C is a cross-sectional view taken along line B-B' of FIG. 8A. FIG. 8D is a cross-sectional view taken along line C-C' of FIG. 8A. FIG. 8E is a cross-sectional view taken along line D-D' of FIG. 8A.

[0013] FIGS. 9A-9E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 9A is an isometric view. FIG. 9B is a cross-sectional view taken along line A-A' of FIG. 9A. FIG. 9C is a cross-sectional view taken along line B-B' of FIG. 9A. FIG. 9D is a cross-sectional view taken along line C-C' of FIG. 9A. FIG. 9E is a cross-sectional view taken along line D-D' of FIG. 9A.

[0014] FIGS. 10A-10E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 10A is an isometric view. FIG. 10B is a cross-sectional view taken along line A-A' of FIG. 10A. FIG. 10C is a cross-sectional view taken along line B-B' of FIG. 10A. FIG. 10D is a cross-sectional view taken along line C-C' of FIG. 10A. FIG. 10E is a cross-sectional view taken along line D-D' of FIG. 10A.

[0015] FIGS. 11A-11E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 11A is an isometric view. FIG. 11B is a cross-sectional view taken along line A-A' of FIG. 11A. FIG. 11C is a cross-

sectional view taken along line B-B' of FIG. 11A. FIG. 11D is a cross-sectional view taken along line C-C' of FIG. 11A. FIG. 11E is a cross-sectional view taken along line D-D' of FIG. 11A.

[0016] FIGS. 12A-12E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 12A is an isometric view. FIG. 12B is a cross-sectional view taken along line A-A' of FIG. 12A. FIG. 12C is a cross-sectional view taken along line B-B' of FIG. 12A. FIG. 12D is a cross-sectional view taken along line C-C' of FIG. 12A. FIG. 12E is a cross-sectional view taken along line D-D' of FIG. 12A.

[0017] FIGS. 13A-13F show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 13A is an isometric view. FIG. 13B is a cross-sectional view taken along line A-A' of FIG. 13A. FIG. 13C is a cross-sectional view taken along line B-B' of FIG. 13A. FIG. 13D is a cross-sectional view taken along line C-C' of FIG. 13A. FIG. 13E is a cross-sectional view taken along line D-D' of FIG. 13A. FIG. 13F is a cross-sectional view of another embodiment taken along line C-C' of FIG. 13A.

[0018] FIGS. 14A-14F show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 14A is an isometric view. FIG. 14B is a cross-sectional view taken along line A-A' of FIG. 14A. FIG. 14C is a cross-sectional view taken along line B-B' of FIG. 14A. FIG. 14D is a cross-sectional view taken along line C-C' of FIG. 14A. FIG. 14E is a cross-sectional view taken along line D-D' of FIG. 14A. FIG. 13F is a cross-sectional view of another embodiment taken along line C-C' of FIG. 14A.

[0019] FIGS. 15A-15E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 15A is an isometric view. FIG. 15B is a cross-sectional view taken along line A-A' of FIG. 15A. FIG. 15C is a cross-sectional view taken along line B-B' of FIG. 15A. FIG. 15D is a cross-sectional view taken along line C-C' of FIG. 15A. FIG. 15E is a cross-sectional view taken along line D-D' of FIG. 15A.

[0020] FIGS. 16A-16E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 16A is an isometric view. FIG. 16B is a cross-sectional view taken along line A-A' of FIG. 16A. FIG. 16C is a cross-sectional view taken along line B-B' of FIG. 16A. FIG. 16D is a cross-sectional view taken along line C-C' of FIG. 16A. FIG. 16E is a cross-sectional view taken along line D-D' of FIG. 16A.

[0021] FIGS. 17A-17E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 17A is an isometric view. FIG. 17B is a cross-sectional view taken along line A-A' of FIG. 17A. FIG. 17C is a cross-sectional view taken along line B-B' of FIG. 17A. FIG. 17D is a cross-sectional view taken along line C-C' of FIG. 17A. FIG. 17E is a cross-sectional view taken along line D-D' of FIG. 17A.

[0022] FIGS. 18A-18E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 18A is an isometric view. FIG. 18B is a cross-sectional view taken along line A-A' of FIG. 18A. FIG. 18C is a cross-sectional view taken along line B-B' of FIG. 18A. FIG. 18D is a cross-sectional view taken along line C-C' of FIG. 18A. FIG. 18E is a cross-sectional view taken along line D-D' of FIG. 18A.

[0023] FIGS. 19A-19E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 19A is an isometric view. FIG. 19B is a cross-sectional view taken along line A-A' of FIG. 19A. FIG. 19C is a cross-sectional view taken along line B-B' of FIG. 19A. FIG. 19D is a cross-sectional view taken along line C-C' of FIG. 19A. FIG. 19E is a cross-sectional view taken along line D-D' of FIG. 19A.

[0024] FIGS. 20A-20E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 20A is an isometric view. FIG. 20B is a cross-sectional view taken along line A-A' of FIG. 20A. FIG. 20C is a cross-sectional view taken along line B-B' of FIG. 20A. FIG. 20D is a cross-sectional view taken along line C-C' of FIG. 20A. FIG. 20E is a cross-sectional view taken along line D-D' of FIG. 20A.

[0025] FIGS. 21A-21E show views of one of the various stages of manufacturing a GAA FET

[illegible]

semiconductor device according to embodiments of the present disclosure. FIG. 31A is an isometric view. FIG. 31B is a cross-sectional view taken along line A-A' of FIG. 31A. FIG. 31C is a cross-sectional view taken along line B-B' of FIG. 31A. FIG. 31D is a cross-sectional view taken along line C-C' of FIG. 31A. FIG. 31E is a cross-sectional view taken along line D-D' of FIG. 31A. [0036] FIGS. 32A-32E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 32A is an isometric view. FIG. 32B is a cross-sectional view taken along line A-A' of FIG. 32A. FIG. 32C is a cross-sectional view taken along line B-B' of FIG. 32A. FIG. 32D is a cross-sectional view taken along line C-C' of FIG. 32A. FIG. 32E is a cross-sectional view taken along line D-D' of FIG. 32A. [0037] FIGS. 33A-33E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 33A is an isometric view. FIG. 33B is a cross-sectional view taken along line A-A' of FIG. 33A. FIG. 33C is a cross-sectional view taken along line B-B' of FIG. 33A. FIG. 33D is a cross-sectional view taken along line C-C' of FIG. 33A. FIG. 33E is a cross-sectional view taken along line D-D' of FIG. 33A. [0038] FIGS. 34A-34E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 34A is an isometric view. FIG. 34B is a cross-sectional view taken along line A-A' of FIG. 34A. FIG. 34C is a cross-sectional view taken along line B-B' of FIG. 34A. FIG. 34D is a cross-sectional view taken along line C-C' of FIG. 34A. FIG. 34E is a cross-sectional view taken along line D-D' of FIG. 34A. [0039] FIGS. 35A-35E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 35A is an isometric view. FIG. 35B is a cross-sectional view taken along line A-A' of FIG. 35A. FIG. 35C is a cross-sectional view taken along line B-B' of FIG. 35A. FIG. 35D is a cross-sectional view taken along line C-C' of FIG. 35A. FIG. 35E is a cross-sectional view taken along line D-D' of FIG. 35A. [0040] FIGS. 36A-36E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 36A is an isometric view. FIG. 36B is a cross-sectional view taken along line A-A' of FIG. 36A. FIG. 36C is a cross-sectional view taken along line B-B' of FIG. 36A. FIG. 36D is a cross-sectional view taken along line C-C' of FIG. 36A. FIG. 36E is a cross-sectional view taken along line D-D' of FIG. 36A. [0041] FIGS. 37A-37E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 37A is an isometric view. FIG. 37B is a cross-sectional view taken along line A-A' of FIG. 37A. FIG. 37C is a cross-sectional view taken along line B-B' of FIG. 37A. FIG. 37D is a cross-sectional view taken along line C-C' of FIG. 37A. FIG. 37E is a cross-sectional view taken along line D-D' of FIG. 37A. [0042] FIGS. 38A-38F show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 38A is an isometric view. FIG. 38B is a cross-sectional view taken along line A-A' of FIG. 38A. FIG. 38C is a cross-sectional view taken along line B-B' of FIG. 38A. FIG. 38D is a cross-sectional view taken along line C-C' of FIG. 38A. FIG. 38E is a cross-sectional view taken along line D-D' of FIG. 38A. FIG. 38F is a cross-sectional view of another embodiment taken along line C-C' of FIG. 38A. [0043] FIGS. 39A-39F show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 39A is an isometric view. FIG. 39B is a cross-sectional view taken along line A-A' of FIG. 39A. FIG. 39C is a cross-sectional view taken along line B-B' of FIG. 39A. FIG. 39D is a cross-sectional view taken along line C-C' of FIG. 39A. FIG. 39E is a cross-sectional view taken along line D-D' of FIG. 39A. FIG. 39F is a cross-sectional view of another embodiment taken along line C-C' of FIG. 39A. [0044] FIGS. 40A-40E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 40A is an isometric view. FIG. 40B is a cross-sectional view taken along line A-A' of FIG. 40A. FIG. 40C is a cross-sectional view taken along line B-B' of FIG. 40A. FIG. 40D is a cross-sectional view taken

along line C-C' of FIG. 40A. FIG. 40E is a cross-sectional view taken along line D-D' of FIG. 40A. [0045] FIGS. 41A-41E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 41A is an isometric view. FIG. 41B is a cross-sectional view taken along line A-A' of FIG. 41A. FIG. 41C is a cross-sectional view taken along line B-B' of FIG. 41A. FIG. 41D is a cross-sectional view taken along line C-C' of FIG. 41A. FIG. 41E is a cross-sectional view taken along line D-D' of FIG. 41A. [0046] FIGS. 42A-42E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 42A is an isometric view. FIG. 42B is a cross-sectional view taken along line A-A' of FIG. 42A. FIG. 42C is a cross-sectional view taken along line B-B' of FIG. 42A. FIG. 42D is a cross-sectional view taken along line C-C' of FIG. 42A. FIG. 42E is a cross-sectional view taken along line D-D' of FIG. 42A. [0047] FIGS. 43A-43E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 43A is an isometric view. FIG. 43B is a cross-sectional view taken along line A-A' of FIG. 43A. FIG. 43C is a cross-sectional view taken along line B-B' of FIG. 43A. FIG. 43D is a cross-sectional view taken along line C-C' of FIG. 43A. FIG. 43E is a cross-sectional view taken along line D-D' of FIG. 43A. [0048] FIGS. 44A-44E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 44A is an isometric view. FIG. 44B is a cross-sectional view taken along line A-A' of FIG. 44A. FIG. 44C is a cross-sectional view taken along line B-B' of FIG. 44A. FIG. 44D is a cross-sectional view taken along line C-C' of FIG. 44A. FIG. 44E is a cross-sectional view taken along line D-D' of FIG. 44A. [0049] FIGS. 45A-45E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 45A is an isometric view. FIG. 45B is a cross-sectional view taken along line A-A' of FIG. 45A. FIG. 45C is a cross-sectional view taken along line B-B' of FIG. 45A. FIG. 45D is a cross-sectional view taken along line C-C' of FIG. 45A. FIG. 45E is a cross-sectional view taken along line D-D' of FIG. 45A. [0050] FIGS. 46A-46E show views of one of the various stages of manufacturing a GAA FET semiconductor device according to embodiments of the present disclosure. FIG. 46A is an isometric view. FIG. 46B is a cross-sectional view taken along line A-A' of FIG. 46A. FIG. 46C is a cross-sectional view taken along line B-B' of FIG. 46A. FIG. 46D is a cross-sectional view taken along line C-C' of FIG. 46A. FIG. 46E is a cross-sectional view taken along line D-D' of FIG. 46A. [0051] FIG. 47A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 47B is a cross-sectional view taken along line E-E' of FIG. 47A. [0052] FIG. 48A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 48B is a cross-sectional view taken along line F-F' of FIG. 48A. [0053] FIG. 49A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 49B is a cross-sectional view taken along line G-G' of FIG. 49A. [0054] FIG. 50A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 50B is a cross-sectional view taken along line H-H' of FIG. 50A. [0055] FIG. 51A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 51B is a cross-sectional view taken along line J-J' of FIG. 51A.

#### DETAILED DESCRIPTION

[0056] It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of the invention. Specific embodiments or 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, dimensions of elements are not limited to the disclosed range or values, but may depend upon process conditions and/or desired properties of the device. Moreover, 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 interposing the first and second features, such that the first and second features may not be in direct contact. Various features may be arbitrarily drawn in different scales for simplicity and clarity.

[0057] 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. In addition, the term “being made of” may mean either “comprising” or “consisting of.” In the present disclosure, a phrase “one of A, B and C” means “A, B and/or C” (A, B, C, A and B, A and C, B and C, or A, B and C), and does not mean one element from A, one element from B and one element from C, unless otherwise described.

[0058] In the present disclosure, a method for fabricating a GAA FET and a stacked channel FET are provided. It is noted that in the present disclosure, a source and a drain are interchangeably used and the structures thereof are substantially the same.

[0059] Semiconductor devices may include multiple metal tracks, including power rails, such a positive voltage rail (VDD) and a ground rail (GND); and multiple signal lines. Increasing the number of metal tracks can reduce the complexity of placement and routing on a chip, and improve the density of the chip. In some semiconductor devices, the power rails and signal lines are located in the first metallization layer (MO) over the active device. As semiconductor device size shrinks, however, space for metal tracks, such as power rails and signal lines decreases. Thus, it is a challenge to both reduce the semiconductor device size and increase the number of metal tracks.

[0060] FIGS. 1-26E illustrate a method of manufacturing a semiconductor device according to embodiments of the present disclosure. As shown in FIG. 1, impurity ions (dopants) 12 are implanted into a silicon substrate 10 to form a well region. The ion implantation is performed to prevent a punch-through effect. In one embodiment, substrate 10 includes a single crystalline semiconductor layer on at least its surface. The substrate 10 may comprise a single crystalline semiconductor material such as, but not limited to Si, Ge, SiGe, GaAs, InSb, GaP, GaSb, InAlAs, InGaAs, GaSbP, GaAsSb and InP. In one embodiment, the substrate 10 is made of Si.

[0061] The substrate 10 may include in its surface region, one or more buffer layers (not shown). The buffer layers can serve to gradually change the lattice constant from that of the substrate to that of the source/drain regions. The buffer layers may be formed from epitaxially grown single crystalline semiconductor materials such as, but not limited to Si, Ge, GeSn, SiGe, GaAs, InSb, GaP, GaSb, InAlAs, InGaAs, GaSbP, GaAsSb, GaN, GaP, and InP. In a particular embodiment, the substrate 10 includes silicon germanium (SiGe) buffer layers epitaxially grown on the silicon substrate 10. The germanium concentration of the SiGe buffer layers may increase from 30 atomic % germanium for the bottom-most buffer layer to 70 atomic % germanium for the top-most buffer layer. In some embodiments of the present disclosure, the substrate 10 includes various regions that have been suitably doped with impurities (e.g., p-type or n-type conductivity). The dopants 12 are, for example, boron (BF.sub.2) for an n-type FinFET and phosphorus for a p-type FinFET.

[0062] In FIG. 2, an alternating stack of first semiconductor layers 30 and second semiconductor layers 35 made of different materials are formed over the substrate 10. The first semiconductor layers 30 and the second semiconductor layers 35 are formed of materials having different lattice constants, and include one or more layers of Si, Ge, SiGe, GaAs, InSb, GaP, GaSb, InAlAs, InGaAs, GaSbP, GaAsSb or InP in some embodiments of the present disclosure.

[0063] In some embodiments, the first semiconductor layers 30 and the second semiconductor layers 35 are formed of Si, a Si compound, SiGe, Ge or a Ge compound. In one embodiment, the first semiconductor layers 30 are Si.sub.1-xGe.sub.x, where x is more than about 0.3, or Ge (x=1.0) and the second semiconductor layers 35 are Si or Si.sub.1-yGe.sub.y, where y is less than about 0.4



and  $x > y$ . In this disclosure, an “M” compound” or an “M based compound” means the majority of the compound is M.

[0064] In another embodiment, the second semiconductor layers **35** are  $\text{Si.sub.1-yGe.sub.y}$ , where  $y$  is more than about 0.3, or Ge, and the first semiconductor layers **30** are Si or  $\text{Si.sub.1-xGe.sub.x}$ , where  $x$  is less than about 0.4 and  $x < y$ . In yet other embodiments, the first semiconductor layer **30** is made of  $\text{Si.sub.1-xGe.sub.x}$ , where  $x$  is in a range from about 0.3 to about 0.8, and the second semiconductor layer **35** is made of  $\text{Si.sub.1-xGe.sub.x}$ , where  $x$  is in a range from about 0.1 to about 0.4.

[0065] FIG. 2 shows five layers of the first semiconductor layer **30** and second semiconductor layer **35**. However, the number of the layers are not limited to five, and may be as small as 1 (one layer each) in some embodiments, or 2 to 10 layers of each of the first and second semiconductor layers. By adjusting the numbers of the stacked layers, a driving current of the GAA FET device can be adjusted.

[0066] The first semiconductor layers **30** and the second semiconductor layers **35** are epitaxially formed over the substrate **10**. The thickness of the first semiconductor layers **30** may be equal to, greater than, or less than that of the second semiconductor layers **30**, and is in a range from about 2 nm to about 40 nm in some embodiments, in a range from about 3 nm to about 30 nm in other embodiments, and in a range of about 5 nm to about 10 nm in other embodiments. The thickness of the second semiconductor layers **35** is in a range from about 2 nm to about 40 nm in some embodiments, in a range from about 3 nm to about 30 nm in other embodiments, and in a range of about 5 nm to about 10 nm in other embodiments. In some embodiments, the bottom first semiconductor layer **30** (the closest layer to the substrate **10**) is thicker than the remaining first semiconductor layers **30**. The thickness of the bottom first semiconductor layer **30** is in a range from about 10 nm to about 40 nm in some embodiments, or is in a range from about 10 nm to about 30 nm in other embodiments.

[0067] Further, as shown in FIG. 2, a hard mask layer **40** is formed over the stacked first and second semiconductor layers **30**, **35**. In some embodiments, the hard mask layer **40** includes a first mask layer **45** and a second mask layer **50**. The first mask layer **45** is a pad oxide layer made of a silicon oxide in some embodiments. The first mask layer **45** may be formed by thermal oxidation. The second mask layer **50** is made of a silicon nitride in some embodiments. The second mask layer **50** may be formed by chemical vapor deposition (CVD), including low pressure CVD (LPCVD) and plasma enhanced CVD (PECVD); physical vapor deposition (PVD), including sputtering; atomic layer deposition (ALD); or other suitable process.

[0068] The hard mask layer **40** is patterned into a mask pattern by using patterning operations including photolithography and etching. Next, as shown in FIGS. 3A-3E the stacked layers of the first and second semiconductor layers **30**, **35** and the underlying substrate **10** are patterned by using the patterned mask layer, thereby the stacked layers and a portion of the substrate are formed into fin structures **15** extending in the X direction. In FIGS. 3A-3C, four fin structures **15** are arranged in the Y direction. But the number of the fin structures is not limited to four, and may be as small as one or two, or more four. In some embodiments, one or more dummy fin structures are formed on both sides of the fin structures **15** to improve pattern fidelity in the patterning operations. As shown in FIGS. 3A-3E, the fin structures **15** have upper portions **25** constituted by the stacked first and second semiconductor layers **30**, **35**, which will form the channel regions; and lower portions **20**, which are the well regions.

[0069] In FIGS. 3A-26E, the A drawings are isometric views of sequential operations of manufacturing a semiconductor device. The B drawings are cross-sectional views taken along line A-A' of the A drawings. The B drawings are taken along the gate region of the semiconductor device in the Y direction. The C drawings are cross-sectional views taken long line B-B' of the A drawings. The C drawings are taken along the source/drain regions of the semiconductor device in the Y direction. The D drawings are cross-sectional views taken along line C-C' of the A drawings.

The D drawings are taken along the fin structures of the semiconductor device in the X-direction. The E drawings are cross-sectional views taken along line D-D' of the A drawings. The E drawings are cross-sectional views taken along a gate cut in the X direction.

[0070] The width **W1** of the upper portion **25** of the fin structure **15** along the Y direction is in a range from about 4 nm to about 40 nm in some embodiments, in a range from about 5 nm to about 30 nm in other embodiments, and in a range from about 6 nm to about 20 nm in other embodiments. The space **S1** between adjacent fin structures about the bottom part of the upper portion **25** ranges from about 20 nm to about 80 nm in some embodiments, and ranges from about 30 nm to about 60 nm in other embodiments. The height **H1** along the Z direction of the fin structure **15** is in a range from about 75 nm to about 300 nm in some embodiments, and ranges from about 100 nm to about 200 nm in other embodiments.

[0071] The stacked fin structure **15** may be patterned by any suitable method. For example, the structures 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 may then be used to pattern the stacked fin structure **15**.

[0072] An insulating liner layer **55** is subsequently formed over the hard mask layer **40**, fin structures **15**, and substrate **10**, as shown in FIGS. **4A-4E**. The insulating liner layer **55** conformally covers the hard mask layer **40**, fin structures **15**, and substrate in some embodiments. In an embodiment, the insulating liner layer **55** is made of a nitride, such as silicon nitride, a silicon nitride-based material (e.g., SiON, SiCN, or SiOCN), or a carbon nitride. The insulating liner layer **55** may be formed by CVD, LPCVD, PECVD, PVD, ALD, or other suitable process. The thickness of the insulating liner layer **55** ranges from about 1 nm to about 20 nm in some embodiments. In some embodiments, the thickness of insulating liner layer ranges from about 3 nm to about 15 nm. In some embodiments, the insulating liner layer **55** includes two or layers of different material.

[0073] After the insulating liner layer **55** is formed, a first insulating material layer **60** including one or more layers of insulating material is formed over the substrate so that the fin structures are fully embedded in the insulating layer. The insulating material for the first insulating material layer **60** may include silicon oxide, silicon nitride, silicon oxynitride (SiON), SiOCN, SiCN, fluorine-doped silicate glass (FSG), or a low-K dielectric material, formed by LPCVD (low pressure chemical vapor deposition), plasma-CVD or flowable CVD. An anneal operation may be performed after the formation of the insulating layer. Then, a planarization operation, such as a chemical mechanical polishing (CMP) method and/or an etch-back method, is performed such that the upper surface of the insulating liner layer **55** is exposed from the first insulating material layer **60**, as shown in FIGS. **5A-5E**.

[0074] Then, as shown in FIGS. **6A-6E**, a portion of the first insulating material layer **60** is recessed to form first recess openings **65** exposing the insulating liner layer **55** between adjacent fin structures **15**. The present disclosure is not limited to removing portions of the insulating material layer **60** from between every other pair of adjacent fin structures, as shown in FIGS. **6A-6C**. Suitable photolithographic and etching operations are used to remove the portions of the insulating material **60** from between the fin structures **15**.

[0075] Adverting to FIGS. **7A-7E**, the first recess openings **65** are subsequently filled with a first sacrificial material to form a first sacrificial layer **70**. In some embodiments, planarization operation, such as a CMP operation or an etchback operation is performed after the sacrificial material is deposited. In some embodiments, the first sacrificial material is electrically conductive. In some embodiments, the sacrificial material is polycrystalline silicon (polysilicon), amorphous

silicon, polycrystalline germanium, or amorphous germanium.

[0076] The first sacrificial layer **70** and first insulating material layer **60** are subsequently recess-etched to expose the upper channel region of the fin structures **15**. In some embodiments, the first sacrificial layer **70** and first insulating layer **60** are recessed etched to a thickness  $t_1$  in the Z-direction ranging from about 30 nm to about 80 nm. In other embodiments, the thickness  $t_1$  in the Z-direction of the first sacrificial layer **70** and first insulating layer **60** after the recess etch is about 40 nm to about 60 nm. The recessed-etched first insulating layer **60** is also known as an isolation insulating layer. A second insulating material layer is subsequently deposited over the fin structures **15** filling the space between adjacent fin structures **15**. After deposition of the second insulating material layer the device is planarized, such as by CMP or an etchback operation. The hard mask layer **40** is removed, the second insulating material layer is recess-etched to expose the upper channel region **25** of the fin structures **15**, and the insulating liner layer **55** is removed from the upper channel region **25** of the fin structure by suitable etching operations, thereby forming second recess openings **75**. Suitable etching operations include anisotropic or isotropic plasma etching and wet etching techniques. A portion of the second insulating material layer **80** remains over the previously recess-etched sacrificial layer **70**, as shown in FIGS. **8A-8E**. The thickness  $t_2$  of the remaining portion of the second insulating material layer **80** ranges from about 2 nm to about 20 nm in some embodiments. In some embodiments, the thickness  $t_2$  of the remaining portion of the second insulating material layer **80** over the first sacrificial layer **70** ranges from about 5 nm to about 15 nm.

[0077] In some embodiments, the second recess openings **75** are formed by etching the first sacrificial layer **70** to a thickness  $t_1$  and then forming the second insulating material layer **80** fully covering the fin structures **15**. Chemical-mechanical polishing is performed to planarize the device and then the second insulating layer **80** is etched back to a thickness  $t_2$  covering the first sacrificial layer **70**. The hard mask layer **40** and is removed by suitable etching operations and the insulating liner layer **55** is removed from the upper portions **25** of the fin structures **15** by suitable etching operations.

[0078] As shown in FIGS. **9A-9E**, a sacrificial gate dielectric layer **85** is formed over the upper portions **25** of the fin structures **15**. The second recess openings **75** are subsequently filled with a conductive material to form a sacrificial conductive layer **90**. In some embodiments, the second conductive layer **90** is a sacrificial gate electrode layer, which will be subsequently removed.

[0079] The sacrificial gate dielectric layer **85** includes one or more layers of insulating material, such as a silicon oxide-based material. In one embodiment, silicon oxide formed by CVD is used. The thickness of the sacrificial gate dielectric layer **85** is in a range from about 1 nm to about 5 nm in some embodiments.

[0080] The sacrificial gate dielectric layer **85** and sacrificial gate electrode layer **90** form a sacrificial gate structure. The sacrificial gate structure is formed by first blanket depositing the sacrificial gate dielectric layer over the fin structures. A sacrificial gate electrode layer is then blanket deposited on the sacrificial gate dielectric layer and over the fin structures, such that the fin structures are fully embedded in the sacrificial gate electrode layer. The sacrificial gate electrode layer includes silicon such as polycrystalline silicon or amorphous silicon. The thickness of the sacrificial gate electrode layer is in a range from about 100 nm to about 200 nm in some embodiments. In some embodiments, the sacrificial gate electrode layer is subjected to a planarization operation. The sacrificial gate dielectric layer and the sacrificial gate electrode layer are deposited using CVD, including LPCVD and PECVD; PVD; ALD, or other suitable process. Subsequently, a first upper insulating layer **95** is formed over the sacrificial gate electrode layer **90**. The first upper insulating layer **95** may include one or more layers and may be formed by CVD, PVD, ALD, or other suitable process.

[0081] Next, a patterning operation is performed on the upper insulating layer **95** using suitable photolithographic and etching operations. The pattern in the upper insulating layer **95** is

subsequently transferred to the sacrificial gate electrode layer **90** and the sacrificial gate dielectric layer **85** using suitable etching operations, as shown in FIGS. **10A-10E**. The etching operations form openings **100** extending in the Y direction that expose the source/drain regions. The etching operations also form gate cut openings **105** extending in the X direction across the sacrificial gate structures. The etching operations removes the sacrificial gate electrode layer **90** and the sacrificial gate dielectric layer **85** in the exposed areas, thereby leaving a sacrificial gate structure overlying the channel region of the semiconductor device. The sacrificial gate structure includes the sacrificial gate dielectric layer **85** and the remaining sacrificial gate electrode layer **90** (e.g., polysilicon).

[0082] After the sacrificial gate structure is formed, one or more sidewall spacer layers **110** is formed over the exposed fin structures **15** and the sacrificial gate structures **85, 90**. The sidewall spacer layer **110** is deposited in a conformal manner so it is formed to have substantially equal thicknesses on vertical surfaces, such as the sidewalls, horizontal surfaces, and the top of the sacrificial gate structure, respectively. In some embodiments, the sidewall spacer layer **110** has a thickness in a range from about 2 nm to about 20 nm, in other embodiments, the sidewall spacer layer has a thickness in a range from about 5 nm to about 15 nm.

[0083] In some embodiments, the sidewall spacer layer **110** includes a first sidewall spacer layer and a second sidewall spacer layer. The first sidewall spacer layer may include an oxide, such as silicon oxide or any other suitable dielectric material, and the second sidewall spacer layer may include one or more of Si<sub>3</sub>N<sub>4</sub>, SiON, and SiCN or any other suitable dielectric material. The first sidewall spacer layer and the second sidewall spacer layer are made of different materials in some embodiments so they can be selectively etched. The first sidewall spacer layer and the second sidewall spacer layer can be formed by ALD or CVD, or any other suitable method. In some embodiments, the sidewall spacer layer **110** substantially fills the gate cut openings **105**.

[0084] Then, as shown in FIGS. **11A-11E**, the sidewall spacer layer **110** is subjected to anisotropic etching to remove the sidewall spacer layer formed over the upper insulating layer **95** and the source/drain regions of the fin structures **15**, and the second insulating material layer **80**. As shown in FIG. **11D**, the anisotropic etching operation removes a portion of the uppermost first and second semiconductor layers **30, 35** in some embodiments. In some embodiments, the sidewall spacer layer **110** filled in the gate cut openings **105** is not etched and remains in the gate cut openings **105**.

[0085] Next, the first semiconductor layers **30** in the source/drain regions of the fin structures **15** are removed using a suitable etching operation. The first semiconductor layers **30** and the second semiconductor layers **35** are made of different materials having different etch selectivities. Therefore, a suitable etchant for the first semiconductor layer **30** does not substantially etch the second semiconductor layer **35**. For example, when the first semiconductor layers **30** are Si and the second semiconductor layers **35** are Ge or SiGe, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, ammonium hydroxide (NH<sub>4</sub>OH), tetramethylammonium hydroxide (TMAH), ethylenediamine pyrocatechol (EDP), or potassium hydroxide (KOH) solutions. On the other hand, when the first semiconductor layers **30** are SiGe or Ge and the second semiconductor layers **35** Si, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, HF:HNO<sub>3</sub> solution, HF:CH<sub>3</sub>COOH:HNO<sub>3</sub>, or H<sub>2</sub>SO<sub>4</sub> solution and HF:H<sub>2</sub>O:CH<sub>3</sub>COOH. In some embodiments, a combination of dry etching techniques and wet etching techniques are used to remove the first semiconductor layers **30**.

[0086] After removing the first semiconductor layers **30** in the source/drain regions an inner spacer layer **115** is formed over the sidewall spacer layer **110**, second semiconductor layers **35** in the source/drain regions, the upper insulating layer **95**, and the second insulating material layer **80**, as shown in FIGS. **12A-12E**. The inner spacer layer **115** is deposited in a conformal manner, and wraps around the second semiconductor layers **35**. In some embodiments, the inner spacer layer **115** has a thickness in a range from about 3 nm to about 15 nm, in other embodiments, the inner

spacer layer **115** has a thickness in a range from about 5 nm to about 12 nm. In some embodiments, the inner spacer layer **115** substantially fills the space between adjacent second semiconductor layers **35**. In some embodiments, the inner spacer layer **115** includes an oxide, such as silicon oxide or a nitride, such as Si.sub.3N.sub.4, SiON, and SiCN, or any other suitable dielectric material, including aluminum oxide. The inner spacer layer **115** can be formed by ALD or CVD, or any other suitable process.

[0087] Next, the inner spacer layer **115** and second semiconductor layers **35** are recess etched using a suitable etching operation extending the openings **100**, as shown in FIGS. **13A-13E**. As shown in FIG. **13D**, the recess etch extends through the second semiconductor layers **35** in some embodiments. In another embodiment, the second semiconductor layers **35** are not etched, and only the inner spacer layer **115** is etched, as shown in FIG. **13F**. FIG. **13F** is a cross-sectional view taken along line C-C' of FIG. **13A**.

[0088] Subsequently, a source/drain epitaxial layer **120** is formed in the openings **100**, as shown in FIGS. **14A-14E**. The source/drain epitaxial layer **120** includes one or more layers of Si, SiP, SiC and SiCP for an n-channel FET or Si, SiGe, Ge for a p-channel FET. For the P-channel FET, boron (B) may also be contained in the source/drain. The source/drain epitaxial layers **120** are formed by an epitaxial growth method using CVD, ALD or molecular beam epitaxy (MBE). As shown in FIG. **14C**, the source/drain epitaxial layers **120** grow on the fin structures. In another embodiment, the source/drain epitaxial layers **120** wrap around exposed portions of the second semiconductor layers **35**, as shown in FIG. **14F**. FIG. **14F** is a cross-sectional view taken along line C-C' of FIG. **14A**. In some embodiments, the grown source/drain epitaxial layers **120** on adjacent fin structures merge with each other. In some embodiments, the source/drain epitaxial layer **120** has a diamond shape, a hexagonal shape, other polygonal shapes, or a semi-circular shape in cross section.

[0089] Subsequently, a contact etch stop layer (CESL) **125** is formed on the source/drain layer **120** and sidewalls of the openings **100** and then an interlayer dielectric (ILD) layer **130** is formed substantially filling the openings **100** over the source/drain regions, as shown in FIGS. **15A-15E**. The CESL **125** overlying the source/drain regions has a thickness of about 1 nm to about 15 nm in some embodiments. The CESL **125** may include Si.sub.3N.sub.4, SiON, SiCN or any other suitable material, and may be formed by CVD, PVD, or ALD. The materials for the ILD layer **130** include compounds comprising Si, O, C, and/or H, such as silicon oxide, SiCOH and SiOC. Organic materials, such as polymers, may be used for the ILD layer **130**. After the ILD layer **130** is formed, a planarization operation, such as chemical-mechanical polishing (CMP), is performed, so that the top portion of the sacrificial gate electrode layer **90** is exposed. The CMP also removes a portion of the sidewall spacer layer **110**, and the upper insulating layer **95** covering the upper surface of the sacrificial gate electrode layer **90**.

[0090] Then, the sacrificial gate electrode layer **90** is removed, thereby forming a gate space **135**, in which the channel regions of the fin structures **15** are exposed, as shown in FIGS. **16A-16E**. The ILD layer **130** protects the source/drain layers **120** during the removal of the sacrificial gate structures. The sacrificial gate electrode layer **90** can be removed using plasma dry etching and/or wet etching. When the sacrificial gate electrode layer **90** is polysilicon and the ILD layer **130** is silicon oxide, a wet etchant such as a tetramethylammonium hydroxide (TMAH) solution can be used to selectively remove the sacrificial gate electrode layer **90**.

[0091] After the sacrificial gate electrode layer **90** is removed, the device is masked using a patterned photoresist and/or bottom anti-reflective coating (BARC) layer **140**, as shown in FIGS. **17A-17E**. The photoresist and/or BARC is patterned using suitable photolithographic techniques.

[0092] Using the patterned photoresist and/or BARC layer **140** as a mask, the second insulating material layer **80** is selectively etched using a suitable etching operation, as shown in FIGS. **18A-18E**. In some embodiments, a HF-based etchant or a buffered oxide etch (NH.sub.4F:HF solution) is used to selectively etch a silicon oxide second insulating material layer **80**. The second insulating material layer etch undercuts the sidewall spacer layer **110** and the inner spacer layer **115**, as shown

in FIGS. 18A and 18E, to form second insulating material layer recesses 145. The second insulating material layer recesses 145 provide an opening that expose a portion of the first sacrificial layers 70.

[0093] The first sacrificial layers 70 are subsequently removed from under between the well regions 20 of the fin structures by a suitable etching operation, as shown in FIGS. 19A-19E forming voids 150 under the second material insulating layers 80. For example, if the first sacrificial layers 70 are polysilicon a TMAH solution may be used to remove the first sacrificial layers 70. In other embodiments,  $\text{NH}_4\text{OH}$  or KOH solutions are used to remove the first sacrificial layers 70.

[0094] As shown in FIGS. 20A-20E, the patterned photoresist and/or BARC layer 140 is subsequently removed to form a gate space 135'. In some embodiments, the patterned photoresist and/or BARC layer 140 is removed by a suitable photoresist stripping or plasma ashing operation.

[0095] Then, the sacrificial gate dielectric layer 85 is removed from the gate space 135', as shown in FIGS. 21A-21E in some embodiments. The sacrificial gate dielectric layer 85 can be removed by using suitable plasma dry etching and/or wet etching operations.

[0096] Adverting to FIGS. 22A-22E, the first semiconductor layers 30 are removed in the channel regions 25 of the fin structure 15 using a suitable etching operation to form a semiconductor nanowires made of the second semiconductor layers 35. The first semiconductor layers 30 and the second semiconductor layers 35 are made of different materials having different etch selectivities. Therefore, a suitable etchant for the first semiconductor layer 30 does not substantially etch the second semiconductor layer 35. For example, when the first semiconductor layers 30 are Si and the second semiconductor layers 35 are Ge or SiGe, the first semiconductor layers 30 can be selectively removed using a wet etchant such as, but not limited to, ammonium hydroxide ( $\text{NH}_4\text{OH}$ ), tetramethylammonium hydroxide (TMAH), ethylenediamine pyrocatechol (EDP), or potassium hydroxide (KOH) solutions. On the other hand, when the first semiconductor layers 30 are SiGe or Ge and the second semiconductor layers 35 Si, the first semiconductor layers 30 can be selectively removed using a wet etchant such as, but not limited to,  $\text{HF}:\text{HNO}_3$  solution,  $\text{HF}:\text{CH}_3\text{COOH}:\text{HNO}_3$ , or  $\text{H}_2\text{SO}_4$  solution and

$\text{HF}:\text{H}_2\text{O}:\text{CH}_3\text{COOH}$ . In some embodiments, a combination of dry etching techniques and wet etching techniques are used to remove the first semiconductor layers 30.

[0097] The cross sectional shape of the semiconductor nanowires 35 in the channel region 25 are shown as rectangular, but can be any polygonal shape (triangular, diamond, etc.), polygonal shape with rounded corners, circular, or oval (vertically or horizontally).

[0098] After the semiconductor nanowires of the second semiconductor layers 30 are formed, a gate dielectric layer 155 is formed around each of the channel region nanowires 30, as shown in FIGS. 22A-22E. In certain embodiments, the gate dielectric layer 155 includes one or more layers of a dielectric material, such as silicon oxide, silicon nitride, or high-k dielectric material, other suitable dielectric material, and/or combinations thereof. Examples of high-k dielectric material include  $\text{HfO}_2$ ,  $\text{HfSiO}$ ,  $\text{HfSiON}$ ,  $\text{HfTaO}$ ,  $\text{HTiO}$ ,  $\text{HfZrO}$ , zirconium oxide, aluminum oxide, titanium oxide, hafnium dioxide-alumina ( $\text{HfO}_2\text{—Al}_2\text{O}_3$ ) alloy, other suitable high-k dielectric materials, and/or combinations thereof. In some embodiments, the gate dielectric layer 155 includes an interfacial layer formed between the channel layers and the dielectric material. In some embodiments, the gate dielectric layer 155 is also formed on exposed portions of the second insulating material layer 80.

[0099] The gate dielectric layer 155 may be formed by CVD, ALD, or any suitable method. In one embodiment, the gate dielectric layer 155 is formed using a highly conformal deposition process such as ALD in order to ensure the formation of a gate dielectric layer having a uniform thickness around each channel layers. The thickness of the gate dielectric layer 155 is in a range from about 1 nm to about 6 nm in some embodiments.

[0100] After the gate dielectric layer 155 is formed, a gate electrode layer 170 is formed over the

gate dielectric layer **155** in the gate space **135'**, in some embodiments, as shown in FIGS. **23A-23E**. The gate electrode layer **170** is formed on the gate dielectric layer **155** to surround each nanowire **25**. The material used to form the gate electrode layer **170** is also used to form power rails **175** in the void **150** between the well regions **20** of the fin structures **15** in some embodiments. The gate electrode layer **170** and power rails **175** are formed simultaneously in some embodiments. In other embodiments, one of the gate electrode layer **170** and the power rails **175** is formed before the other of the gate electrode layer **170** or power rails **175** are formed.

[0101] The gate electrode layer **170** and power rails **175** include one or more layers of conductive material, such as aluminum, copper, titanium, tantalum, tungsten, cobalt, molybdenum, tantalum nitride, nickel silicide, cobalt silicide, TiN, WN, TiAl, TiAlN, TaCN, TaC, TaSiN, metal alloys, other suitable materials, and/or combinations thereof.

[0102] The gate electrode layer **170** and power rails may be formed by CVD, ALD, electro-plating, or other suitable method. The gate electrode layer **170** is also deposited over the upper surface of the ILD layer **130** in some embodiments, and then the portion of the gate electrode layer formed over the ILD layer **130** is planarized by using, for example, CMP, until the top surface of the ILD layer **130** is revealed.

[0103] In some embodiments of the present disclosure, one or more barrier layers **160** are interposed between the gate dielectric layer **155** and the gate electrode **170**, and between the gate dielectric layer **155** and the insulating liner layer **155**, and the power rail **175**. The barrier layer **160** is made of a conductive material such as a single layer of TiN or TaN or a multilayer of both TiN and TaN.

[0104] In some embodiments of the present disclosure, one or more work function adjustment layers **165** are interposed between the gate dielectric layer **115** or barrier layer **165** and the gate electrode layer **170**, and between the gate dielectric layer **115** or barrier layer and the insulating liner layer and the power rail **175**. The work function adjustment layers are made of a conductive material such as a single layer of TiN, TaN, TaAlC, TiC, TaC, Co, Al, TiAl, HfTi, TiSi, TaSi or TiAlC, or a multilayer of two or more of these materials. For an n-channel FET, one or more of TaN, TaAlC, TiN, TiC, Co, TiAl, HfTi, TiSi and TaSi is used as the work function adjustment layer, and for a p-channel FET, one or more of TiAlC, Al, TiAl, TaN, TaAlC, TiN, TiC and Co is used as the work function adjustment layer. The work function adjustment layer may be formed by ALD, PVD, CVD, e-beam evaporation, or other suitable process. Further, the work function adjustment layer may be formed separately for the n-channel FET and the p-channel FET which may use different metal layers as the gate electrode layer **170**.

[0105] A metal etch stop layer (MESL) **180** and cap insulating layer **185** are subsequently formed over the ILD layer **130** and the gate electrode layer **170**, as shown in FIGS. **24A-24E**. The cap insulating layer **185** is formed over the MESL **180**.

[0106] Contact holes **190** are formed in the cap insulating layer **185** using suitable photolithographic and etching techniques. The contact holes are extended into the MESL **180** and ILD layer **130** by using dry etching. Suitable etching operations are further used to extend the contact holes through the second insulating material layer **80**, and any of the CESL **125**, gate dielectric layer **155**, barrier layer **160**, and work function adjustment layer **165** to expose the power rails **175**. The etching operations also removes the CESL **125** covering the source/drain layers **120**, thereby exposing the source/drain layers **120**. In some embodiments, the upper portion of the source/drain layers **120** is also etched.

[0107] In some embodiments, a metal layer **195** is deposited over the device, including the cap insulating layer **185**, MESL **180**, ILD layer **130**, source/drain layer **120**, and the power rails **175**, as shown FIGS. **25A-25E**. The metal layer **195** is one or more layers of W, Co, Ni, Ti, Mo, and Ta in some embodiments. In some embodiments, the metal layer **195** includes a metal layer selected from W, Co, Ni, Ti, Mo, and Ta; and a metal nitride layer selected from tungsten nitride, cobalt nitride, nickel nitride, titanium nitride, molybdenum nitride, and tantalum nitride. The semiconductor

device is then subjected to a rapid thermal anneal, whereby the portion of the metal layer **195** over the source/drain layer **120** reacts with silicon in the source/drain layer **120** to form a metal silicide layer **200**. In some embodiments, the metal silicide layer **200** formed over the source/drain layer **120** includes one or more of WSi, CoSi, NiSi, TiSi, MoSi, and TaSi. In some embodiments, the metal layer **195** is formed by CVD, PVD, ALD, or other suitable process.

[0108] Then, in some embodiments the unreacted metal layer **195**, including the metal layer and/or the metal nitride layer is removed from the contact holes **190**, and the cap insulating layer **185**. The unreacted metal layer **195** can be removed by a suitable etching operation. After removing the unreacted metal layer **195**, a conductive material is formed in the contact holes **190** to form a conductive contact **205**, as shown in FIGS. **26A-26E**. The conductive material includes one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The conductive contact **205** may be formed by CVD, ALD, electro-plating, or other suitable method. The conductive material is also deposited over the upper surface of the cap insulating layer **185** in some embodiments, and then the portion of the conductive contact **205** formed over the cap insulating layer **185** is planarized by using, for example, CMP, until the top surface of the cap insulating layer **185** is revealed.

[0109] It is understood that the GAA FETs formed according to the disclosed methods undergo further complementary metal oxide semiconductor (CMOS) processes to form various features such as contacts/vias, interconnect metal layers, dielectric layers, passivation layers, metallization layers with signal lines, etc.

[0110] FIGS. **27A-46E** illustrate a method of manufacturing a semiconductor device according to embodiments of the present disclosure. This method employs the same operations previously disclosed herein regarding FIGS. **1** to **5E**. In FIGS. **27A-46E**, the A drawings are isometric views of sequential operations of manufacturing a semiconductor device. The B drawings are cross-sectional views taken along line A-A' of the A drawings. The B drawings are taken along the gate region of the semiconductor device in the Y direction. The C drawings are cross-sectional views taken along line B-B' of the A drawings. The C drawings are taken along the source/drain regions of the semiconductor device in the Y direction. The D drawings are cross-sectional views taken along line C-C' of the A drawings. The D drawings are taken along the fin structures of the semiconductor device in the X-direction. The E drawings are cross-sectional views taken along line D-D' of the A drawings. The E drawings are cross-sectional views taken along a cell edge in the X direction.

[0111] Starting with the structure of FIGS. **5A-5E**, a portion of the first insulating material layer **60** is recessed to form first recess openings **65'** exposing the insulating liner layer **55** between adjacent fin structures **15**. The present disclosure is not limited to the pattern of removing portions of the insulating material layer **60** as illustrated in FIGS. **27A-27E**. Suitable photolithographic and etching operations are used to remove the portions of the insulating material **60** from between the fin structures **15**.

[0112] Referring to FIGS. **28A-28E**, the insulating liner layer **55** is anisotropically etched to remove a portion of the insulating liner layer **55** over the horizontal surfaces of the substrate **10**, thereby exposing the surface of the substrate **10**. The insulating liner layer **55** is also removed from the upper surface of the fin structures during the etching operation. In some embodiments, the anisotropic etching is a plasma etching operation.

[0113] In some embodiments, a metal layer **210** is deposited over the device, including the fin structures **15**, insulating liner layer **55**, and substrate **10**, as shown FIGS. **29A-29E**. The metal layer **210** is one or more layers of W, Co, Ni, Ti, Mo, and Ta in some embodiments. In some embodiments, the metal layer **210** includes a metal layer selected from W, Co, Ni, Ti, Mo, and Ta; and a metal nitride layer selected from tungsten nitride, cobalt nitride, nickel nitride, titanium nitride, molybdenum nitride, and tantalum nitride. The semiconductor device is then subjected to a rapid thermal anneal, whereby the portion of the metal layer **210** over the substrate **10** reacts with silicon in the substrate **10** to form a metal silicide layer **215**. The metal silicide layer **215** provides a seed layer for a subsequent selective deposition of a conductive material. In some embodiments,



the metal silicide layer **215** formed over the substrate **10** includes one or more of WSi, CoSi, NiSi, TiSi, MoSi, and TaSi. In some embodiments, the metal layer **210** is formed by CVD, PVD, ALD, or other suitable process.

[0114] Then, in some embodiments the unreacted metal layer **210**, including the metal layer and/or the metal nitride layer is removed from over the fin structures **15** and first insulating material layer **60**, as shown in FIGS. **30A-30E**. The unreacted metal layer **210** can be removed by as suitable etching operation.

[0115] After removing the unreacted metal layer **210**, a conductive material is formed in the first recess openings **65'** contact holes **190** to form a power rail **175'**, as shown in FIGS. **31A-31E**. The conductive material includes one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The power rail **175'** may be formed by CVD, PVD, ALD, electro-plating, or other suitable method. In some embodiments, the conductive material is deposited over the upper surface of the fin structures **15**, and then the conductive material is planarized by using, for example, CMP. An etchback operation is subsequently performed until the conductive material is reduced to a desired height in between adjacent well regions **20** of adjacent fin structures **15**. In other embodiments, the conductive material is deposited in the first recess openings **65'** until a desired height of the power rail **175'** is achieved.

[0116] As shown in FIGS. **32A-32E**, a second insulating material layer **220** is subsequently deposited over the fin structures **15** filling the second recess openings **65'**. After deposition of the second insulating material layer **220** the device is planarized, such as by CMP or an etchback operation.

[0117] Next, the hard mask layer **40** is removed, the second insulating material layer **220** is recess etched to expose the upper channel region **25** of the fin structures **15**, and the insulating liner layer **55** is removed from the upper channel region **25** of the fin structure by suitable etching operations, thereby forming second recess openings **225**. Suitable etching operations include anisotropic or isotropic plasma etching and wet etching techniques. A portion of the second insulating material layer **220** remains over the previously formed power rails **175'** and first insulating material layer **60**, as shown in FIGS. **33A-33E**. The thickness of the remaining portion of the second insulating material layer **220** over the power rails **175'** ranges from about 2 nm to about 20 nm in some embodiments. In some embodiments, the thickness of the remaining portion of the second insulating material layer **220** ranges from about 5 nm to about 15 nm.

[0118] As shown in FIGS. **34A-34E**, a sacrificial gate dielectric layer **230** is formed over the upper portions **25** of the fin structures. The second recess openings **225** are subsequently filled with a conductive material to form a sacrificial conductive layer **235**. In some embodiments, the second conductive layer **235** is a sacrificial gate electrode layer, which will be subsequently removed.

[0119] The sacrificial gate dielectric layer **230** includes one or more layers of insulating material, such as a silicon oxide-based material. In one embodiment, silicon oxide formed by CVD is used. The thickness of the sacrificial gate dielectric layer **230** is in a range from about 1 nm to about 5 nm in some embodiments.

[0120] The sacrificial gate dielectric layer **230** and sacrificial gate electrode layer **235** form a sacrificial gate structure. The sacrificial gate structure is formed by first blanket depositing the sacrificial gate dielectric layer over the fin structures. A sacrificial gate electrode layer is then blanket deposited on the sacrificial gate dielectric layer and over the fin structures, such that the fin structures are fully embedded in the sacrificial gate electrode layer. The sacrificial gate electrode layer includes silicon such as polycrystalline silicon or amorphous silicon. The thickness of the sacrificial gate electrode layer is in a range from about 100 nm to about 200 nm in some embodiments. In some embodiments, the sacrificial gate electrode layer is subjected to a planarization operation. The sacrificial gate dielectric layer and the sacrificial gate electrode layer are deposited using CVD, including LPCVD and PECVD; PVD; ALD, or other suitable process. Subsequently, a first upper insulating layer **240** is formed over the sacrificial gate electrode layer

**90.** The first upper insulating layer **240** may be formed by CVD, PVD, ALD, or other suitable process.

[0121] Next, a patterning operation is performed on the upper insulating layer **240** using suitable photolithographic and etching operations. The pattern in the upper insulating layer **240** is subsequently transferred to the sacrificial gate electrode layer **235** and the sacrificial gate dielectric layer **230** using suitable etching operations, as shown in FIGS. **35A-35E**. The etching operations form openings **245** extending in the Y direction that expose the source/drain regions. The etching operations also form gate cut openings **250** extending in the X direction across the sacrificial gate structures. The etching operations removes the sacrificial gate electrode layer **235** and the sacrificial gate dielectric layer **230** in the exposed areas, thereby leaving a sacrificial gate structure overlying the channel region of the semiconductor device. The sacrificial gate structure includes the sacrificial gate dielectric layer **230**, the remaining sacrificial gate electrode layer **235** (e.g., polysilicon).

[0122] After the sacrificial gate structure is formed, one or more sidewall spacer layers **255** is formed over the exposed fin structures **15** and the sacrificial gate structures **230**, **235**, as shown in FIGS. **36A-36E**. The sidewall spacer layer **255** is deposited in a conformal manner in some embodiments so as to form to have substantially equal thicknesses on vertical surfaces, such as the sidewalls, horizontal surfaces, and the top of the sacrificial gate structure, respectively. In some embodiments, the sidewall spacer layer **255** has a thickness in a range from about 2 nm to about 20 nm, in other embodiments, the sidewall spacer layer **255** has a thickness in a range from about 5 nm to about 15 nm.

[0123] In some embodiments, the sidewall spacer layer **255** includes a first sidewall spacer layer and a second sidewall spacer layer. The first sidewall spacer layer may include an oxide, such as silicon oxide or any other suitable dielectric material, and the second sidewall spacer layer may include one or more of Si<sub>3</sub>N<sub>4</sub>, SiON, and SiCN or any other suitable dielectric material. The first sidewall spacer layer and the second sidewall spacer layer are made of different materials in some embodiments so they can be selectively etched. The first sidewall spacer layer and the second sidewall spacer layer can be formed by ALD or CVD, or any other suitable method. In some embodiments, the sidewall spacer layer **255** substantially fills the gate cut openings **250**. Then, as shown in FIGS. **36A-36E**, the sidewall spacer layer **225** is subjected to anisotropic etching to remove the sidewall spacer layer formed over the upper insulating layer **240** and the source/drain regions of the fin structures **15**, and the second insulating material layer **220**. In some embodiments, an upper portion of the sidewall spacer layer **255** is removed by a suitable etching operation to expose a portion of the upper insulating layer **240**. In some embodiments, a portion of the uppermost first semiconductor layer **30** and second semiconductor layer **35** may be removed during the etching operations, as shown in FIG. **36D**.

[0124] Next, the first semiconductor layers **30** in the source/drain regions of the fin structures **15** are removed using a suitable etching operation, as shown in FIGS. **37A-37E**. The first semiconductor layers **30** and the second semiconductor layers **35** are made of different materials having different etch selectivities. Therefore, a suitable etchant for the first semiconductor layer **30** does not substantially etch the second semiconductor layer **35**. For example, when the first semiconductor layers **30** are Si and the second semiconductor layers **35** are Ge or SiGe, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, ammonium hydroxide (NH<sub>4</sub>OH), tetramethylammonium hydroxide (TMAH), ethylenediamine pyrocatechol (EDP), or potassium hydroxide (KOH) solutions. On the other hand, when the first semiconductor layers **30** are SiGe or Ge and the second semiconductor layers **35** Si, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, HF:HNO<sub>3</sub> solution, HF:CH<sub>3</sub>COOH:HNO<sub>3</sub>, or H<sub>2</sub>SO<sub>4</sub> solution and HF:H<sub>2</sub>O:CH<sub>3</sub>COOH. In some embodiments, a combination of dry etching techniques and wet etching techniques are used to remove the first semiconductor layers **30**.

[0125] After removing the first semiconductor layers **30** in the source/drain regions an inner spacer layer **260** is formed over the sidewall spacer layer **255**, second semiconductor layers **35** in the source/drain regions, the upper insulating layer **240**, and the second insulating material layer **220**, as shown in FIGS. **37A-37E**. The inner spacer layer **260** is deposited in a conformal manner, and wraps around the second semiconductor layers **35**. In some embodiments, the inner spacer layer **260** has a thickness in a range from about 2 nm to about 20 nm, in other embodiments, the inner spacer layer **260** has a thickness in a range from about 5 nm to about 15 nm. In some embodiments, the inner spacer layer **260** substantially fills the space between adjacent second semiconductor layers **35**. In some embodiments, the inner spacer layer **260** includes an oxide, such as silicon oxide or a nitride, such as Si<sub>3</sub>N<sub>4</sub>, SiON, and SiCN, or any other suitable dielectric material, including aluminum oxide. The inner spacer layer **260** can be formed by ALD or CVD, or any other suitable process.

[0126] Next, the inner spacer layer **260** and second semiconductor layers **35** are recess etched using a suitable etching operation extending the openings **245**, as shown in FIGS. **38A-38E**. As shown in FIG. **38D**, the recess etch extends through the second semiconductor layers **35** in some embodiments. In another embodiment, the second semiconductor layers **35** are not etched, and only the inner spacer layer **260** is etched, as shown in FIG. **38F**. FIG. **38F** is a cross-sectional view taken along line C-C' of the FIG. **38A**.

[0127] Subsequently, a source/drain epitaxial layer **265** is formed in the openings **245**, as shown in FIGS. **39A-39E**. The source/drain epitaxial layer **265** includes one or more layers of Si, SiP, SiC and SiCP for an n-channel FET or Si, SiGe, Ge for a p-channel FET. For the P-channel FET, boron (B) may also be contained in the source/drain. The source/drain epitaxial layers **265** are formed by an epitaxial growth method using CVD, ALD or molecular beam epitaxy (MBE). As shown in FIG. **39C**, the source/drain epitaxial layers **265** grow on the fin structures. In another embodiment, the source/drain epitaxial layers **265** wrap around the second semiconductor layers **25**, as shown in FIG. **39F**. FIG. **39F** is a cross-sectional view taken along line C-C' of FIG. **39A**. In some embodiments, the grown source/drain epitaxial layers **265** on adjacent fin structures merge with each other. In some embodiments, the source/drain epitaxial layer **265** has a diamond shape, a hexagonal shape, other polygonal shapes, or a semi-circular shape in cross section.

[0128] Subsequently, a contact etch stop layer (CESL) **270** is formed on the source/drain layer **265** and sidewalls of the openings **245** and then an interlayer dielectric (ILD) layer **275** is formed substantially filling the openings **245** over the source/drain regions, as shown in FIGS. **40A-40E**. The CESL **270** overlying the source/drain regions has a thickness of about 1 nm to about 15 nm in some embodiments. The CESL **270** may include Si<sub>3</sub>N<sub>4</sub>, SiON, SiCN or any other suitable material, and may be formed by CVD, PVD, or ALD. The materials for the ILD layer **275** include compounds comprising Si, O, C, and/or H, such as silicon oxide, SiCOH and SiOC. Organic materials, such as polymers, may be used for the ILD layer **275**. After the ILD layer **275** is formed, a planarization operation, such as chemical-mechanical polishing (CMP), is performed, so that the top portion of the sacrificial gate electrode layer **235** is exposed. The CMP also removes a portion of the sidewall spacer layer **255**, and the upper insulating layer **240** covering the upper surface of the sacrificial gate electrode layer **235**.

[0129] Then, the sacrificial gate electrode layer **235** and sacrificial gate dielectric layer **230** are removed, thereby forming a gate space **280**, in which the channel regions **25** of the fin structures **15** are exposed, as shown in FIGS. **41A-41E**. The ILD layer **275** protects the source/drain layers **265** during the removal of the sacrificial gate structures. The sacrificial gate electrode layer **235** and sacrificial gate dielectric layer **230** can be removed using plasma dry etching and/or wet etching. When the sacrificial gate electrode layer **235** is polysilicon and the ILD layer **275** is silicon oxide, a wet etchant such as a tetramethylammonium hydroxide (TMAH) solution can be used to selectively remove the sacrificial gate electrode layer **235**.

[0130] Advancing to FIGS. **42A-42E**, the first semiconductor layers **30** are removed in the channel

regions **25** of the fin structure **15** using a suitable etching operation to form a semiconductor nanowires made of the second semiconductor layers **35**. The first semiconductor layers **30** and the second semiconductor layers **35** are made of different materials having different etch selectivities. Therefore, a suitable etchant for the first semiconductor layer **30** does not substantially etch the second semiconductor layer **35**. For example, when the first semiconductor layers **30** are Si and the second semiconductor layers **35** are Ge or SiGe, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, ammonium hydroxide (NH<sub>4</sub>OH), tetramethylammonium hydroxide (TMAH), ethylenediamine pyrocatechol (EDP), or potassium hydroxide (KOH) solutions. On the other hand, when the first semiconductor layers **30** are SiGe or Ge and the second semiconductor layers **35** Si, the first semiconductor layers **30** can be selectively removed using a wet etchant such as, but not limited to, HF:HNO<sub>3</sub> solution, HF:CH<sub>3</sub>COOH:HNO<sub>3</sub>, or H<sub>2</sub>SO<sub>4</sub> solution and HF:H<sub>2</sub>O:CH<sub>3</sub>COOH. In some embodiments, a combination of dry etching techniques and wet etching techniques are used to remove the first semiconductor layers **30**.

[0131] The cross sectional shape of the semiconductor nanowires **35** in the channel region **25** are shown as rectangular, but can be any polygonal shape (triangular, diamond, etc.), polygonal shape with rounded corners, circular, or oval (vertically or horizontally).

[0132] After the semiconductor nanowires of the second semiconductor layers **30** are formed, a gate dielectric layer **285** is formed around each of the channel region nanowires **30**, as shown in FIGS. **42A-42E**. In certain embodiments, the gate dielectric layer **285** includes one or more layers of a dielectric material, such as silicon oxide, silicon nitride, or high-k dielectric material, other suitable dielectric material, and/or combinations thereof. Examples of high-k dielectric material include HfO<sub>2</sub>, HfSiO, HfSiON, HfTaO, HfTiO, HfZrO, zirconium oxide, aluminum oxide, titanium oxide, hafnium dioxide-alumina (HfO<sub>2</sub>—Al<sub>2</sub>O<sub>3</sub>) alloy, other suitable high-k dielectric materials, and/or combinations thereof. In some embodiments, the gate dielectric layer **285** includes an interfacial layer formed between the channel layers and the dielectric material. In some embodiments, the gate dielectric layer **285** is also formed on exposed portions of the second insulating material layer **220**.

[0133] The gate dielectric layer **285** may be formed by CVD, ALD, or any suitable method. In one embodiment, the gate dielectric layer **285** is formed using a highly conformal deposition process such as ALD in order to ensure the formation of a gate dielectric layer having a uniform thickness around each channel layers. The thickness of the gate dielectric layer **285** is in a range from about 1 nm to about 6 nm in some embodiments.

[0134] After the gate dielectric layer **285** is formed, a gate electrode layer **300** is formed over the gate dielectric layer **285** in the gate space **280**, in some embodiments, as shown in FIGS. **43A-43E**. The gate electrode layer **300** is formed on the gate dielectric layer **285** to surround each nanowire **25**. The material used to form the gate electrode layer **300** is the same as the material used to form the power rails **175'** in some embodiments.

[0135] The gate electrode layer **300** includes one or more layers of conductive material, such as aluminum, copper, titanium, tantalum, tungsten, cobalt, molybdenum, tantalum nitride, nickel silicide, cobalt silicide, TiN, WN, TiAl, TiAlN, TaCN, TaC, TaSiN, metal alloys, other suitable materials, and/or combinations thereof.

[0136] The gate electrode layer **300** may be formed by CVD, ALD, electro-plating, or other suitable method. The gate electrode layer **300** is also deposited over the upper surface of the ILD layer **275** in some embodiments, and then the portion of the gate electrode layer formed over the ILD layer **275** is planarized by using, for example, CMP, until the top surface of the ILD layer **275** is revealed.

[0137] In some embodiments of the present disclosure, one or more barrier layers **290** are interposed between the gate dielectric layer **285** and the gate electrode **300**. The barrier layer **290** is made of a conductive material such as a single layer of TiN or TaN or a multilayer of both TiN and

TaN.

[0138] In some embodiments of the present disclosure, one or more work function adjustment layers **295** are interposed between the gate dielectric layer **285** or barrier layer **290** and the gate electrode layer **300**. The work function adjustment layers are made of a conductive material such as a single layer of TiN, TaN, TaAlC, TiC, TaC, Co, Al, TiAl, HfTi, TiSi, TaSi or TiAlC, or a multilayer of two or more of these materials. For an n-channel FET, one or more of TaN, TaAlC, TiN, TiC, Co, TiAl, HfTi, TiSi and TaSi is used as the work function adjustment layer, and for a p-channel FET, one or more of TiAlC, Al, TiAl, TaN, TaAlC, TiN, TiC and Co is used as the work function adjustment layer. The work function adjustment layer may be formed by ALD, PVD, CVD, e-beam evaporation, or other suitable process. Further, the work function adjustment layer may be formed separately for the n-channel FET and the p-channel FET which may use different metal layers as the gate electrode layer **300**.

[0139] A metal etch stop layer (MESL) **305** and cap insulating layer **310** are subsequently formed over the ILD layer **275** and the gate electrode layer **300**, as shown in FIGS. **44A-44E**. The cap insulating layer **310** is formed over the MESL **305**.

[0140] Contact holes **315** are formed in the cap insulating layer **310** using suitable photolithographic and etching techniques. The contact holes **315** are extended into the MESL **305** and ILD layer **275** by using dry etching. Suitable etching operations are further used to extend the contact holes through the second insulating material layer **220**, and any of the CESL **270**, gate dielectric layer **285**, barrier layer **290**, and work function adjustment layer **295** to expose the power rails **175'**. The etching operations also removes the CESL **270** covering the source/drain layers **265**, thereby exposing the source/drain layers **265**. In some embodiments, the upper portion of the source/drain regions **265** is also etched.

[0141] In some embodiments, a metal layer **320** is deposited over the device, including the cap insulating layer **310**, MESL **305**, ILD layer **275**, source/drain layer **265**, and the power rails **175'**, as shown FIGS. **45A-45E**. The metal layer **320** is one or more layer of W, Co, Ni, Ti, Mo, and Ta in some embodiments. In some embodiments, the metal layer **320** includes a metal layer selected from W, Co, Ni, Ti, Mo, and Ta; and a metal nitride layer selected from tungsten nitride, cobalt nitride, nickel nitride, titanium nitride, molybdenum nitride, and tantalum nitride. The semiconductor device is then subjected to a rapid thermal anneal, whereby the portion of the metal layer **320** over the source/drain layer **265** reacts with silicon in the source/drain layer **265** to form a metal silicide layer **340**. In some embodiments, the metal silicide layer **340** formed over the source/drain layer **265** includes one or more of WSi, CoSi, NiSi, TiSi, MoSi, and TaSi.

[0142] Then, in some embodiments the unreacted metal layer **320**, including the metal layer and/or the metal nitride layer is removed from the contact holes **315**, and the cap insulating layer **310**. The unreacted metal layer **320** can be removed by a suitable etching operation. After removing the unreacted metal layer **320**, a conductive material is formed in the contact holes **315** to form a conductive contact **325**, as shown in FIGS. **46A-46E**. The conductive material includes one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The conductive contact **325** may be formed by CVD, ALD, electro-plating, or other suitable method. The conductive material is also deposited over the upper surface of the cap insulating layer **310** in some embodiments, and then the portion of the conductive contact **325** formed over the cap insulating layer **310** is planarized by using, for example, CMP, until the top surface of the cap insulating layer **310** is revealed.

[0143] FIGS. **47A-51B** illustrate several embodiments of semiconductor device structures that can be formed according to the disclosed methods of manufacturing a semiconductor device.

[0144] FIG. **47A** is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. **47B** is a cross-sectional view taken along line E-E' of FIG. **47A**, and showing the placement of signal lines **335** in a metallization layer **355** overlying the active device.

[0145] FIG. **47A** is a schematic plan view of a semiconductor device according to an embodiment of present disclosure showing the relative placement of the power rails **175**, signal lines **335**, gate

electrodes **170**, and fin structures **15**. As shown in FIGS. **47A** and **47B**, a metallization layer **355** including signal lines **335** embedded in an insulating layer **330** is formed overlying the semiconductor device active regions. The metallization layers may be formed by suitable photolithography, etching, and material deposition operations. The insulating layer **330** may be made of silicon oxide, silicon nitride, silicon oxide-based material, or silicon nitride-based material. The insulating layer **330** may be formed by CVD, PVD, ALD, or other suitable method. The signal lines **335** include one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The signal lines **335** may be formed by CVD, ALD, electro-plating, or other suitable method. In some embodiments, the signal lines **335** include W or Cu. As shown in FIG. **47B** the metallization layer **355** is shown directly over the gate electrode layer **170**, however, in some embodiments additional layers are located between the gate electrode **170** layer and the metallization layer **355**.

[0146] Power rails **175** are located between the well regions **20** of adjacent fin structures **15**. One of the power rails **175** is a positive voltage rail (VDD) and the other is a ground rail (GND). By locating the power rails below the active region of the semiconductor device between the lower portions **20** of the fin structures **15**, additional signal lines **335** can be formed overlying the active region of the semiconductor device. For example, if the power rails were located in the same layer as the signal lines there may be room for only three signal lines. However, by locating the power rails below the active region, four signal lines can be provided instead of only three.

[0147] In some embodiments of the disclosure, a complementary metal oxide semiconductor field effect transistor (CMOSFET) is provided with a pFET and nFET formed on the same substrate **10**. As illustrated, the pFET and nFET include a stack of six nanowires **35**, but the disclosure is not limited to stacked structures of six nanowires. The pFET and nFET fin structures **15** are separated by an insulating layer **60**, also known as a shallow trench isolation (STI). The nanowires **35**, are shown as circular in cross section, but the disclosure is not limited to circular cross-section nanowires. The nanowires **35** have thickness (diameter) **D1**, **D2** in a range from about 2 nm to about 40 nm in some embodiments, in a range from about 3 nm to about 30 nm in other embodiments, and in a range of about 5 nm to about 10 nm in other embodiments. The nanowires are spaced apart by distance **S2** of about 2 nm to about 40 nm in some embodiments, in a range from about 3 nm to about 30 nm in other embodiments, and in a range of about 5 nm to about 10 nm in other embodiments. In some embodiments, the height **H2** of the nanowire stacks ranges from about 20 nm to about 100 nm, in other embodiments the height ranges from about 40 to about 80 nm. The space **S4** between adjacent nanowire stacks ranges from about 20 nm to about 80 nm in some embodiments, and from about 30 nm to about 60 nm in other embodiments. In some embodiments, the nanowire stacks are spaced apart from the edge of the gate electrode **170** by a distance **S3** ranging from about 5 nm to about 50 nm, and from about 10 nm to about 40 nm in other embodiments.

[0148] In some embodiments, the bottom of the gate electrode **170** is located at a height **H3** from about 20 nm to about 100 nm from the bottom of the recess in the substrate **10** between adjacent fin structures **15**, in other embodiments, the bottom of the gate electrode **170** is located at a height **H3** of about 40 nm to about 80 nm.

[0149] In some embodiments, the power rails **175** are separated from the gate electrode **170** by an insulating layer **80** having a height **H4** ranging from about 2 nm to about 20 nm, and ranging from about 5 nm to about 15 nm in other embodiments. The power rails **175** are separated from the fin structure **15** sidewalls by an insulating liner layer **55** having a thickness of about 1 nm to about 20 nm in some embodiments and a thickness of about 3 nm to about 15 nm in other embodiments. In some embodiments the thickness of the insulating liner layer **55** between the power rails **175** and the fin structure **15** is about 2 nm to about 5 nm.

[0150] In some embodiments, the signal lines **335** have a height **H5** ranging from about 5 nm to about 50 nm and ranging from about 10 nm to about 25 nm in another embodiment. In some embodiments, the signal lines have a width **W2** ranging from about 3 nm to about 40 nm and

ranging from about 8 nm to about 20 nm in another embodiment. In some embodiments, the signal lines **335** are spaced apart from each other by a distance **S8** ranging from about 5 nm to about 50 nm and ranging from about 10 nm to about 25 nm in another embodiment.

[0151] FIG. **48A** is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. **48B** is a cross-sectional view taken along line F-F' overlying a gate electrode **170** of FIG. **48A**, and showing the placement of signal lines **335** in a metallization layer **355** overlying the active device.

[0152] FIG. **48A** is a schematic plan view of a semiconductor device according to an embodiment of present disclosure showing the relative placement of the power rails **175**, signal lines **335**, gate electrodes **170**, fin structures **15**, and conductive contacts **205**. As shown in FIGS. **48A** and **48B**, a metallization layer including signal lines **335** embedded in an insulating layer **330** are formed overlying the semiconductor device active regions. The metallization layer **355** may be formed by suitable photolithography, etching, and material deposition operations. The insulating layer **330** may be made of silicon oxide, silicon nitride, silicon oxide-based material, or silicon nitride-based material. The insulating layer **330** may be formed by CVD, PVD, ALD, or other suitable method. The signal lines **335** include one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The signal lines **335** may be formed by CVD, ALD, electro-plating, or other suitable method. In some embodiments, the signal lines **335** include W or Cu. As shown in FIG. **48B** the metallization layer **355** is shown directly over the gate electrode layer **170**, however, in some embodiments additional layers are located between the gate electrode **170** layer and the metallization layer **355**.

[0153] Power rails **175** are located between the well regions **20** of adjacent fin structures **15**. One of the power rails **175** is a positive voltage rail (VDD) and the other is a ground rail (GND). By locating the power rails below the active region of the semiconductor device between the lower portions **20** of the fin structures **15**, additional signal lines **335** can be formed overlying the active region of the semiconductor device. For example, if the power rails were located in the same layer as the signal lines there may be room for only three signal lines. However, by locating the power rails below the active region, four signal lines can be provided instead of only three.

[0154] In some embodiments, a CMOSFET is provided where one of the nanowire stacks is a pFET and the other nanowire stack is an nFET formed on the same substrate **10**. The pFET and nFET fin structures **15** are separated by an STI **60** and a gap **350** in the gate electrode **170**, as shown in FIGS. **48A** and **48B**. In some embodiments, the conductive contacts **205** are conductive vias contacting the power rails **175** and the gate electrodes **170**. Thus, in these embodiments the nFET and pFET are normally off. The conductive contacts **205** are formed a conductive material including one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. In some embodiments, the conductive contacts **205** are made of W or Cu. In some embodiments, the conductive contacts **205** are conductive vias connecting the power rails **175** to the metallization layer **355**. In some embodiments, the conductive contacts **205** are conductive vias connecting the power rails **175** to the signal lines **335** in the metallization layer **355**.

[0155] FIG. **49A** is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. **49B** is a cross-sectional view taken along line G-G' overlying a source/drain region of FIG. **49A**, and showing the placement of signal lines **335** in a metallization layer overlying the active device.

[0156] FIG. **49A** is a schematic plan view of a semiconductor device according to an embodiment of present disclosure showing the relative placement of the power rails **175**, signal lines **335**, gate electrodes **170**, fin structures **15**, and conductive contacts **205**. As shown in FIGS. **49A** and **49B**, a metallization layer **355** including signal lines **335** embedded in an insulating layer **330** is formed overlying the semiconductor device active regions. The metallization layer may be formed by suitable photolithography, etching, and material deposition operations. The insulating layer **330** may be made of silicon oxide, silicon nitride, silicon oxide-based material, or silicon nitride-based material. The insulating layer **330** may be formed by CVD, PVD, ALD, or other suitable method.

The signal lines **335** include one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The signal lines **335** may be formed by CVD, ALD, electro-plating, or other suitable method. In some embodiments, the signal lines **335** include W or Cu. In some embodiments additional layers are located between the conductive contacts **205** and the metallization layer **355**.

[0157] Power rails **175** are located between the well regions **20** of adjacent fin structures **15**. One of the power rails **175** is a positive voltage rail (VDD) and the other is a ground rail (GND). By locating the power rails below the active region of the semiconductor device between the lower portions **20** of the fin structures **15**, additional signal lines **335** can be formed overlying the active region of the semiconductor device. By locating the power rails below the active region, four signal lines can be provided instead of only three.

[0158] The conductive contacts **205** are connected to the source/drains **120** via silicide layers **200** in some embodiments. The arrows in FIG. **49B** show the flow of electrons from the source/drains **120** to the power rails **175**. In some embodiments, a dielectric layer is located between the source/drains **120** and conductive contacts and current flows by tunneling. The nanowire stacks of the respective nFET and pFET source/drains are separated by distance **S5** of from about 20 nm to about 80 nm in some embodiments, and from about 30 nm to about 60 nm in other embodiments.

[0159] FIG. **50A** is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. **50B** is a cross-sectional view taken along line H-H' overlying a source/drain of FIG. **50A**, and showing the placement of signal lines **335** in a metallization layer overlying the active device.

[0160] FIG. **50A** is a schematic plan view of a semiconductor device according to an embodiment of present disclosure showing the relative placement of the power rails **175**, signal lines **335**, **335'**, gate electrodes **170**, fin structures **15**, and conductive contacts **205**. As shown in

[0161] FIGS. **50A** and **50B**, a metallization layer **355** including signal lines **335** embedded in an insulating layer **330** are formed overlying the semiconductor device active regions and between well the regions **20** of the fin structures **15**. The metallization layer **355** may be formed by suitable photolithography, etching, and material deposition operations. The insulating layer **330** may be made of silicon oxide, silicon nitride, silicon oxide-based material, or silicon nitride-based material. The insulating layer **330** may be formed by CVD, PVD, ALD, or other suitable method. The signal lines **335**, **335'** include one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The signal lines **335**, **335'** may be formed by CVD, ALD, electro-plating, or other suitable method. In some embodiments, the signal lines **335**, **335'** include W or Cu. In some embodiments additional layers are located between the conductive contacts **205** and the metallization layer **355**.

[0162] Power rails **175** are located between the well regions **20** of adjacent fin structures **15**. One of the power rails **175** is a positive voltage rail (VDD) and the other is a ground rail (GND). By locating the power rails **175** and a signal line **335** below the active region of the semiconductor device between the lower portions **20** of the fin structures **15**, additional signal lines **335** can be formed overlying the active region of the semiconductor device. For example, if the power rails were located in the same layer as the signal lines there may be room for only three signal lines. However, by locating the power rails and an additional signal line **335'** below the active region, five signal lines can be provided instead of only three. The signal line **335'** located between the lower regions **20** of the fin structure **15** are separated from the fin structure by an insulating liner layer **55**.

[0163] In some embodiments, a CMOSFET is provided where one of the nanowire stacks is a pFET and the other nanowire stack is an nFET formed on the same substrate **10**. In some embodiments, the source/drains of the pFET and nFET share a common conductive contact **205**, as shown in FIG. **50B**, where the common conductive contact **205** also contacts the signal line **335** provided between the lower portions **20** of adjacent fin structures **15**. In some embodiments, the nanowire stacks of the respective nFET and pFET source/drains are separated by distance **S6** of from about 20 nm to about 80 nm in some embodiments, and from about 30 nm to about 60 nm in



other embodiments.

[0164] FIG. 51A is a plan view of a semiconductor device according to an embodiment of present disclosure. FIG. 51B is a cross-sectional view taken along line J-J' overlying a source/drain of FIG. 51A, and showing the placement of signal lines 335 in a metallization layer overlying the active device.

[0165] FIG. 51A is a schematic plan view of a semiconductor device according to an embodiment of present disclosure showing the relative placement of the power rails 175, signal lines 335, gate electrodes 170, fin structures 15, and conductive contacts 205. As shown in FIGS. 51A and 51B, a metallization layer 355 comprising signal lines 335 embedded in an insulating layer 330 are formed overlying the semiconductor device active regions and between well the regions 20 of the fin structures 15. The metallization layer may be formed by suitable photolithography, etching, and material deposition operations. The insulating layer 330 may be made of silicon oxide, silicon nitride, silicon oxide-based material, or silicon nitride-based material. The insulating layer 330 may be formed by CVD, PVD, ALD, or other suitable method. The signal lines 335 include one or more of Co, Ni, W, Ti, Ta, Cu, Al, TiN, and TaN. The signal lines 335 may be formed by CVD, ALD, electro-plating, or other suitable method. In some embodiments, the signal lines 335 include W or Cu. In some embodiments additional layers are located between the conductive contacts 205 and the metallization layer 355.

[0166] Power rails 175 are located between the well regions 20 of adjacent fin structures 15. One of the power rails 175 is a positive voltage rail (VDD) and the other is a ground rail (GND). By locating the power rails 175 below the active region of the semiconductor device between the lower portions 20 of the fin structures 15, additional signal lines 335 can be formed overlying the active region of the semiconductor device. For example, if the power rails were located in the same layer as the signal lines there may be room for only three signal lines. However, by locating the power rails 175 below the active region, four signal lines can be provided instead of only three.

[0167] In some embodiments, a CMOSFET is provided where one of the nanowire stacks is a pFET and the other nanowire stack is an nFET formed on the same substrate 10. In some embodiments, a source/drain insulating layer 360 is formed between the lower portion 20 of the fin structure 15 and the source/drains 120 of the nFET and pFET, as shown in FIG. 51B. The source/drain insulating layer 360 is formed of an oxide or nitride in some embodiments to a thickness of about 2 nm to about 20 nm. In other embodiments, the thickness of the source/drain insulating layer 360 ranges from about 5 nm to about 10 nm. In embodiments including the source/drain insulating layer 360, the insulating liner layer 55 between the power rail 175 and the fin structure 15 is not necessary. Thus, the cross sectional area of the power rail 175 can be increased and the overall resistance of the device can be reduced. Reference No. 345 designates CMOSFET well PN junction. In some embodiments, the nanowire stacks of the respective nFET and pFET source/drains are separated by distance S7 of from about 20 nm to about 80 nm in some embodiments, and from about 30 nm to about 60 nm in other embodiments.

[0168] It is understood that the GAA FETs formed according to the disclosed methods undergo further CMOS processes to form various features such as contacts/vias, interconnect metal layers, dielectric layers, passivation layers, metallization layers with signal lines, etc.

[0169] Semiconductor devices and methods of manufacturing semiconductor devices according to the present disclosure provide an increased number metal tracks thereby reducing the complexity of placement and routing on a chip, and improving the density of the chip without increasing the size of semiconductor device. Devices according to the present disclosure about 12% to about 14% increased device density on a chip in some embodiments. Devices and methods of manufacturing according to the present disclosure further provide power rails and signal lines of increased cross sectional area thereby reducing resistance of the device. In addition, devices and methods of manufacturing according to the present disclosure provide direct, low-resistance contact between the power rails and the gate electrodes, between power rails and source/drains, and between signal

lines and source/drains, thereby reducing the resistance of the device.

[0170] An embodiment of the present disclosure is a method of manufacturing a semiconductor device, including forming a plurality of fin structures extending in a first direction over a semiconductor substrate. Each fin structure includes a first region proximate to the semiconductor substrate and a second region distal to the semiconductor substrate. An electrically conductive layer is formed between the first regions of a first adjacent pair of fin structures. A gate electrode structure is formed extending in a second direction substantially perpendicular to the first direction over the fin structure second region, and a metallization layer including at least one conductive line is formed over the gate electrode structure. In an embodiment, the forming a plurality of fin structures includes forming a nanowire structure in the second region of the fin structure. In an embodiment, forming the gate electrode structure includes forming a gate dielectric layer over at least one wire of the nanowire structure; and forming a gate electrode layer over the gate dielectric layer, wherein the gate dielectric layer and the gate electrode layer wrap around the at least one wire of the nanowire structure. In an embodiment, forming an electrically conductive layer includes: forming an insulating material layer between a plurality of adjacent pairs of fin structures, removing the insulating material layer from between at least one pair of adjacent fin structures, and forming the electrically conductive layer between the at least one pair of adjacent fin structures after removing the insulating material layer. In an embodiment, the method includes forming a first insulating layer between the metallization layer and the gate structure and fin structures. In an embodiment, the method includes forming a conductive via in the first insulating layer, wherein the conductive via connects the electrically conductive layer and the metallization layer. In an embodiment, the method includes forming a second insulating layer filling a space between a second adjacent pair of fin structures where no electrically conductive layer is formed. In an embodiment, the method includes forming a third insulating layer between the electrically conductive layer and the first regions of the first pair of adjacent fins. In an embodiment, the method includes forming a fourth insulating layer between the electrically conductive layer and the gate electrode structure.

[0171] Another embodiment of the present disclosure is a method of manufacturing a semiconductor device, including forming a first semiconductor layer having a first composition over a semiconductor substrate and forming a second semiconductor layer having a second composition over the first semiconductor layer. Another first semiconductor layer having the first composition is formed over the second semiconductor layer, and another second semiconductor layer having the second composition is formed over the another first semiconductor layer. The first semiconductor layers, second semiconductor layer, and the semiconductor substrate are patterned to form a plurality of fin structures extending in a first direction. The fin structures include a first region adjacent the semiconductor substrate and a second region including the first semiconductor layers and second semiconductor layers. The second region includes a first portion extending along the first direction between a pair of second portions. An insulating liner layer is formed over the fin structures and an isolation insulating layer is formed between the fin structures. The isolation insulating layer is removed from between a first pair of adjacent fin structures. A first conductive layer is formed between the first pair of adjacent fin structures. The insulating liner layer is removed from the first region of the fin structures. The first semiconductor layer is removed from a first portion of the second region of the fin structures thereby forming nanowires comprising the second semiconductor layer. A dielectric layer and a second conductive layer are formed over the first portion of the fin structures surrounding the nanowires thereby forming a gate electrode structure extending in a second direction substantially perpendicular to the first direction. A metallization layer comprising a plurality of conductive lines is formed over gate electrode structure. In an embodiment, before forming the metallization layer, an interlayer dielectric layer is formed over the gate electrode structure. In an embodiment, the method includes forming a conductive via in the interlayer dielectric layer between the metallization layer and the first

conductive layer. In an embodiment, the method includes before forming the dielectric layer and the second conductive layer over the first portion of the fin structures: forming a sacrificial gate dielectric layer over the first portion of the fin structures surrounding the nanowires, forming a sacrificial gate electrode layer surrounding the sacrificial gate dielectric layer, and removing the sacrificial gate dielectric layer and the sacrificial gate electrode layer.

[0172] Another embodiment of the present disclosure is a method of manufacturing a semiconductor device including forming a plurality of fin structures extending in a first direction over a semiconductor substrate. Each fin structure includes a first region adjacent the semiconductor substrate and a second region overlying the first region, and each fin structure includes a first portion between a pair of second portions extending in the first direction. An isolation insulating region is formed between the first regions of a first adjacent pair of fin structures. An electrically conductive layer is formed between the first regions of a second pair adjacent pair of fin structures. A gate electrode structure extending in a second direction substantially perpendicular to the first direction is formed over the first portion of the fin structure second region. Source/drain regions are formed over the second portions of the fin structure second region. An interlayer dielectric layer over the gate electrode structure, and at least one conductive line is formed over the interlayer dielectric layer. In an embodiment, the method includes forming an insulating liner layer over the fin structures before forming the electrically conductive layer. In an embodiment, the forming a plurality of fin structures includes forming an alternating stack of first semiconductor layers made of a first semiconductor material and second semiconductor layers made of a second semiconductor material, wherein the first semiconductor material and second semiconductor material are different materials. In an embodiment, the method includes removing the first semiconductor layers in the first portion of the fin structures before forming the first gate electrode structure. In an embodiment, the method includes forming conductive vias in interlayer dielectric layer contacting the source/drain regions and the electrically conductive layer. In an embodiment, the method includes forming a contact layer over the source/drain regions. In an embodiment, the method includes forming a source/drain insulating layer over the second portion of the fin structures before forming the source drain/regions.

[0173] Another embodiment of the present disclosure is a semiconductor device including a plurality of fin structures extending in a first direction disposed over a semiconductor substrate. Each fin structure includes a first region proximate to the semiconductor substrate and a second region distal to the semiconductor substrate. At least one first electrically conductive layer is disposed between the first regions of an adjacent pair of fins. At least one gate electrode structure extends in a second direction substantially perpendicular to the first direction disposed over a first portion of the fin structure second region, and a metallization layer including at least one conductive line is disposed over the gate electrode structure. In an embodiment, the fin structure second region includes a nanowire structure including a stack of a plurality of nanowires, each nanowire extending substantially parallel to an adjacent nanowire. In an embodiment, the gate electrode structure includes a gate dielectric layer and gate electrode layer, wherein the gate dielectric layer and gate electrode layer wrap around each nanowire. In an embodiment, the first electrically conductive layer includes a power rail and a ground rail. In an embodiment, a conductive via connects the first electrically conductive layer to the metallization layer. In an embodiment, a first insulating layer is disposed between the first electrically conductive layer and the fin structure. In an embodiment, source/drains are disposed over a second portion of the fin structure second region, and a conductive contact connects the at least one first electrically conductive region and the source/drains. In an embodiment, a second insulating layer fills a space between a pair of adjacent fin structures where no electrically conductive layer is formed. In an embodiment, a third insulating layer is disposed between the electrically conductive layer and the gate electrode structure. In an embodiment, source/drain regions are disposed on opposing sides of the gate electrode structure and over the fin structure first regions. In an embodiment, a contact

layer is disposed on the source/drain regions. In an embodiment, a fourth insulating layer is disposed between the fin structure first region and the source/drain regions. In an embodiment, the metallization layer includes a plurality of signal lines. In an embodiment, a lower signal line is disposed between adjacent fin structure first regions where no first electrically conductive layer is formed. In an embodiment, a conductive via connects the lower signal line with the metallization layer.

[0174] Another embodiment of the present disclosure is a semiconductor device including a plurality of fin structures extending in a first direction disposed over a semiconductor substrate. Each fin structure includes a lower well region and an upper channel region over the well region. The channel region includes one or more nanowires extending substantially parallel to the well region. A gate electrode structure extends in a second direction substantially perpendicular to the first direction disposed over the channel region, and the gate electrode structure wraps around the one or more nanowires. At least one first electrically conductive layer is disposed between the channel regions of adjacent fins extending in the first direction. A plurality of second electrically conductive layers is disposed over the gate electrode structure extending in the first direction. In an embodiment, an insulating liner layer is disposed between the well region and the first conductive layer. In an embodiment, a conductive via is disposed between the first conductive layer and the second conductive layer.

[0175] Another embodiment of the present disclosure is a semiconductor device including a plurality of fin structures extending in a first direction disposed over a semiconductor substrate. Each fin structure includes a well region and a nanowire stack disposed over the well region. The nanowire stack includes a plurality of nanowires extending substantially parallel to each other in the first direction. A gate electrode structure extends in a second direction substantially perpendicular to the first direction disposed over the nanowire stack, and the gate electrode structure wraps around each of the nanowires. A power rail extends in the first direction disposed between the well region of a first pair of adjacent fin structures. A ground rail extends in the first direction disposed between the well region of a second pair of adjacent fin structures, and a plurality of signal lines are disposed over the gate electrode structure extending in the first direction. In an embodiment, an insulating layer is disposed between a third pair of fin structures located between the first pair of fin structures and the second pair of fin structures.

[0176] The foregoing outlines features of several embodiments or examples 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 or examples 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.

[0177] It will be understood that not all advantages have been necessarily discussed herein, no particular advantage is required for all embodiments or examples, and other embodiments or examples may offer different advantages.

## Claims

1. A semiconductor device comprising: first well region and a second well region spaced apart from each other extending in a first direction and arranged in a second direction crossing the first direction; a first stack of spaced-apart channel layers disposed over the first well region and a second stack of spaced-apart channel layers disposed over the second well region, wherein the first stack and the second stack are arranged along a third direction crossing the first direction and the second direction, and the first and second stacks have a height  $H_2$  extending along the third

direction; and an insulating region disposed between the first well region and the second well region, wherein the insulating region has a height H3 extending along the third direction, and wherein a ratio of a height H2 of the first stack and the second stack to a height H3 of the insulating region ( $H2/H3$ ) ranges from 0.2 to 5.0.

2. The semiconductor device of claim 1, further comprising a metal track disposed alongside the first well region on an opposing side from the insulating region as seen in a cross section.

3. The semiconductor device of claim 2, further comprising a gate electrode disposed over the metal track and the insulating region as seen in the cross section.

4. The semiconductor device of claim 3, further comprising a metallization layer disposed over the gate electrode.

5. The semiconductor device of claim 4, further comprising a conductive via connecting the metallization layer to the metal track.

6. The semiconductor device of claim 3, further comprising a gate dielectric layer disposed between each of the channel layers and the gate electrode.

7. The semiconductor device of claim 1, further comprising a ground rail disposed alongside the second well region on an opposing side from the insulating region as seen in a cross section.

8. A semiconductor device comprising: first well region and a second well region spaced apart from each other extending in a first direction and arranged in a second direction perpendicular to the first direction disposed over a substrate; a first stack of spaced-apart semiconductor layers disposed over the first well region and a second stack of spaced-apart semiconductor layers disposed over the second well region, wherein the first stack and the second stack are arranged along a third direction perpendicular to the first direction and the second direction, and wherein a ratio of a height H2 of the first stack to a distance S4 between the first stack and the second stack ( $H2/S4$ ) ranges from 0.25 to 5.0; and a gate electrode wrapping around each of the spaced-apart semiconductor layers.

9. The semiconductor device of claim 8, wherein a metal track is disposed between the first well region and the second well region.

10. The semiconductor device of claim 9, further comprising a metallization layer disposed over the gate electrode.

11. The semiconductor device of claim 10, further comprising a conductive via connecting the metallization layer to the metal track.

12. The semiconductor device of claim 8, further comprising a gate dielectric layer disposed between each of the semiconductor layers and the gate electrode.

13. The semiconductor device of claim 8, further comprising a ground rail disposed between another adjacent pair of well regions.

14. The semiconductor device of claim 8, further comprising a shallow trench isolation filling a space where no electrically conductive layer is formed between a pair of adjacent well regions.

15. The semiconductor device of claim 8, further comprising: source/drains disposed over portions of the well regions on opposing sides of the gate electrode.

16. A semiconductor device, comprising: a first well region extending in a first direction disposed over a substrate; a second well region extending in the first direction disposed over the substrate spaced-apart from the first well region, wherein the first well region and the second well region are separated by a first insulating layer; a first plurality of semiconductor layers arranged along a second direction perpendicular to the first direction disposed over the first well region; a second plurality of semiconductor layers arranged along the second direction disposed over the second well region; a first gate electrode wrapping around the first semiconductor layers; a second gate electrode wrapping around the second semiconductor layers, wherein the first gate electrode and the second gate electrode are separated by a gap along a third direction perpendicular to the first direction and the second direction; and a plurality of spaced-apart signal lines extending in the first direction and arranged along the third direction disposed over the first gate electrode and the second gate electrode, wherein a ratio of a height H5 of each signal line to a width W2 of each

signal line (H5/W2) ranges from 0.13 to 17.0.

**17.** The semiconductor device of claim 16, further comprising: a first metal track extending in the first direction disposed alongside the first well region; and a second metal track extending in the first direction disposed alongside the second well region.

**18.** The semiconductor device of claim 17, further comprising a plurality of signal lines disposed over the first gate electrode and the second gate electrode.

**19.** The semiconductor device of claim 18, further comprising a conductive via connecting the first metal track to the signal lines.

**20.** The semiconductor device of claim 19, further comprising a conductive via connecting the second metal track to the signal lines.

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