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

#### Abstract

In a method of manufacturing a semiconductor device, a fin structure having a channel region protruding from an isolation insulating layer disposed over a semiconductor substrate is formed, a cleaning operation is performed, and an epitaxial semiconductor layer is formed over the channel region. The cleaning operation and the forming the epitaxial semiconductor layer are performed in a same chamber without breaking vacuum.

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## Background/Summary

RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 18/404,638, filed Jan. 4, 2024, which is a continuation of U.S. patent application Ser. No. 17/875,279, filed Jul. 27, 2022, now U.S. Pat. No. 11,901,442, which is a divisional of U.S. patent application Ser. No. 17/109,895, filed Dec. 2, 2020, now U.S. Pat. No. 11,677,015, which claims priority to U.S. Provisional Application No. 63/024,377, filed May 13, 2020, the entire contents of each of which are incorporated herein by reference.

### BACKGROUND

[0002] 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 fin field effect transistor (Fin FET). Fin FET devices typically include semiconductor fins with high aspect ratios and in which channel and source/drain regions of semiconductor transistor devices are formed. A gate is formed over and along the sides of the fin structure (e.g., wrapping) utilizing the advantage of the increased surface area of the channel and source/drain regions to produce faster, more reliable and better-controlled semiconductor transistor devices. In some devices, channel regions of an n-type FET and a p-type FET are made of different materials.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0003] 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.

[0004] FIG. 1 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0005] FIG. 2 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0006] FIG. 3 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0007] FIG. 4 shows one of the various stages of a sequential manufacturing operation of a

semiconductor FET device according to an embodiment of the present disclosure.

[0008] FIG. 5 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0009] FIG. 6 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0010] FIG. 7 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0011] FIG. 8 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0012] FIG. 9 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0013] FIG. 10 shows one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0014] FIGS. 11A and 11B show one of the various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0015] FIGS. 12A, 12B, 12C and 12D show various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0016] FIG. 13 shows a flow chart of forming a cap semiconductor layer according to an embodiment of the present disclosure.

[0017] FIG. 14 shows an apparatus used for manufacturing a semiconductor device according to an embodiment of the present disclosure.

[0018] FIG. 15 shows a condition of cleaning and forming an epitaxial layer according to an embodiment of the present disclosure.

[0019] FIGS. 16A, 16B, 16C, 16D, 16E and 16F show various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure.

[0020] FIGS. 17A and 17B show advantageous effects of the embodiments of the present disclosure.

[0021] FIGS. 18A and 18B show cross sectional views of the semiconductor device according to embodiments of the present disclosure.

#### DETAILED DESCRIPTION

[0022] It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of the disclosure. 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.

[0023] 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 “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. Materials, configurations, processes and/or methods explained with respect to one or more figures and/or embodiments can be applied to other figures and/or embodiments, and detailed description thereof may be omitted for simplicity. [0024] FIGS. **1-11B** show views of various stages of a sequential manufacturing operation of a semiconductor device according to the present disclosure. It is understood that additional operations may be provided before, during, and after the processes shown by FIGS. **1-11B**, and some of the operations described below can be replaced or eliminated for additional embodiments of the method. The order of the operations/processes may be interchangeable.

[0025] As shown in FIG. **1**, a part of a substrate **10** made of a first semiconductor material, in which one or more p-type FETs are subsequently formed, is etched to form a recess by one or more lithography and etching operations, and the recess is filled with a second semiconductor material. In one embodiment, the substrate **10** includes a single crystalline semiconductor layer on at least its surface portion. The substrate **10** may include 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 this embodiment, the substrate **10** is made of Si. The substrate **10** may include various regions that have been suitably doped with impurities (e.g., p-type or n-type conductivity). The dopants are, for example boron (BF.sub.2) for an n-type Fin FET and phosphorus for a p-type Fin FET.

[0026] As shown in FIG. **1**, an epitaxial layer **11** made of the second semiconductor material is formed in the recess. In some embodiments, the epitaxial layer **11** is made of SiGe. In some embodiments, the germanium concentration of the SiGe layer **11** is in a range from about 5 atomic % to about 40 atomic % and in other embodiments, the germanium concentration of the SiGe layer **11** is in a range from about 10 atomic % to about 30 atomic %. In some embodiments, the SiGe layer **11** is doped with a p-type dopant (e.g., boron). In some embodiments, one or more buffer layer having a lower Ge concentration than the epitaxial layer **11** is formed between the epitaxial layer **11** and the substrate **10**. The SiGe layer **11** can be formed by chemical vapor deposition (CVD), such as low pressure CVD (LPCVD) and plasma enhanced CVD (PECVD), molecular beam epitaxy (MBE), atomic layer deposition (ALD), or other suitable process.

[0027] Further, as shown in FIG. **2**, a mask layer **15** is formed over the substrate **10** and the epitaxial layer **11**. In some embodiments, the mask layer **15** includes a first mask layer **15A** and a second mask layer **15B**. The first mask layer **15A** is a pad oxide layer made of a silicon oxide, which can be formed by a thermal oxidation. The second mask layer **15B** is made of a silicon nitride (SiN), which is formed by CVD, PVD, ALD, or other suitable process.

[0028] Next, as shown in FIG. **3**, the mask layer **15**, the substrate **10** and the epitaxial layer **11** in the p-type region are patterned by using the patterned mask layer, thereby forming fin structures **12N** and **12P** (collectively fin structures **12**) extending in the Y direction. In some embodiments, the fin structures **12N** are for an n-type FET, and the fin structures **12P** are for a p-type FET. In FIG. **3**, three n-type fin structures **12N** and two p-type fin structures are arranged in the X direction. However, the number of the fin structures is not limited to two or three, and may be as small as one and four or more. In some embodiments, one or more dummy fin structures **12D** are formed on one or both sides of the fin structures **12** to improve pattern fidelity in the patterning operations.

[0029] The fin structures **12** can be patterned by any suitable method. For example, the fin 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 is patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers, or mandrels, may then be used to pattern the fin structures. The multi-patterning processes combining photolithography and self-aligned processes generally result in forming a pair of fin

structures. The width of the fin structure **12** is in a range of about 5 nm to about 40 nm in some embodiments, and is in a range of about 7 nm to about 15 nm in certain other embodiments. The height of the fin structure **12** is in a range of about 100 nm to about 300 nm in some embodiments, and is in a range of about 50 nm to 100 nm in other embodiments. The space between the fin structures **12** is in a range of about 5 nm to about 80 nm in some embodiments, and may be in a range of about 7 nm to 20 nm in other embodiments. In some embodiments, a pitch of the fin structures is in a range from about 10 nm to 120 nm, and is in a range from about 14 nm to about 35 nm in other embodiments. One skilled in the art will realize, however, that the dimensions and values recited throughout the descriptions are merely examples, and may be changed to suit different scales of integrated circuits.

[0030] In some embodiments, a plurality of fin structures having a constant pitch are formed and then some of the fin structures are removed to obtain the structure shown in FIG. 3. In some embodiments, some of the fin structures are cut into pieces for respective FETs.

[0031] In some embodiments, the p-type fin structures **12P** are arranged with a first pitch **P1**, and three n-type fin structures **12N** are arranged with a second pitch **P2** and a third pitch **P3**. In some embodiments, the first pitch **P1** is a minimum pitch (**P0**) for the fin structures defined by a design rule. In some embodiments, the second pitch **P2** is greater than the first pitch **P1** and is equal to **2P0** or **3P0**. In some embodiments, the third pitch **P3** is greater than the second pitch **P2** and is equal to **3P0**, **4P0** or **5P0**. In some embodiments, the fourth pitch **P4** between the n-type fin structure **12N** and the p-type fin structure **12P** and the fifth pitch **P5** between the p-type fin structure **12P** and the dummy fin structure **12D** are greater than the first pitch **P1** and is equal to **2P0**, **3P0**, **4P0**, **5P0** or more.

[0032] After the fin structures **12** are formed, a first dielectric layer **30** is formed over the fin structures **12** as shown in FIG. 4. The first dielectric layer **30** includes one or more layers of insulating materials such as silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN or SiOCN, formed by LPCVD (low pressure chemical vapor deposition), plasma-CVD or atomic layer deposition (ALD), or any other suitable film formation method. In certain embodiments, silicon oxide is used as the first dielectric layer **30**. In some embodiments, as shown in FIG. 4, the first dielectric layer **30** is conformally formed over the fin structures **12** such that a space is formed between adjacent fin structures **12**, except for the p-type fin structures **12P**. For the p-type fin structures **12P**, since the space between the fin structures is small, the first dielectric layer fully fills the space therebetween as shown in FIG. 4. The thickness of the first dielectric layer **30** is adjusted so that the space between the fin structures (e.g., n-type fin structures with the second pitch) is in a range of about 5 nm to about 40 nm in some embodiments, and is in a range of about 7 nm to about 15 nm in certain embodiments.

[0033] In some embodiments, one or more liner dielectric layers **18** are formed between the first dielectric layer **30** and the fin structures as shown in FIG. 4. In some embodiments, the liner dielectric layer **18** is made of a different material than the first dielectric layer **30** and includes one or more layers of insulating materials such as silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN or SiOCN formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method. The thickness of the liner dielectric layer **18** is in a range from about 1 nm to about 5 nm in some embodiments.

[0034] After the first dielectric layer **30** is formed, a second dielectric layer **35** is formed over the first dielectric layer **30**, as shown in FIG. 5. The material of the second dielectric layer **35** is different from the material of the first dielectric layer **30** and, in some embodiments, is also different from the material of the liner dielectric layer **18**. In some embodiments, the second dielectric layer **35** includes one or more layers of insulating materials such as silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN or SiOCN formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method. In some embodiments, the second dielectric layer **35** is made of silicon nitride. As shown in FIG. 5, the second dielectric layer **35** fully fills the first space in the

n-type fin structures, and covers the top of the first dielectric layer **30**, in some embodiments. As shown in FIG. 5, the second dielectric layer **35** is conformally formed over the first dielectric layer where the pitches of the fin structures are large (e.g., equal to or more than  $4P_0$ ).

[0035] In some embodiments, one or more additional dielectric layers **32** are formed between the first dielectric layer **30** and the second dielectric layer **35** as shown in FIG. 5. In some embodiments, the additional dielectric layer **32** is made of a different material than the second dielectric layer **35** and includes one or more layers of insulating materials such as silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN or SiOCN formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method. In some embodiments, the additional dielectric layer **32** is made of a different material than the first dielectric layer **30**. The thickness of the additional dielectric layer **32** is in a range from about 1 nm to about 5 nm in some embodiments.

[0036] In some embodiments, after the second dielectric layer **35** is formed, a planarization operation, such as an etch-back process or a chemical mechanical polishing (CMP) process, is performed to planarize the upper surface of the second dielectric layer **35**.

[0037] Next, the second dielectric layer **35** is recessed down below the top of the fin structures **12** by using a suitable dry and/or wet etching operation, as shown in FIG. 6. Since the second dielectric layer **35** is made of a different material than the first dielectric layer **30**, the second dielectric layer **35** is selectively etched against the first dielectric layer **30**. In some embodiments, the additional dielectric layer **32** remains on sidewalls of the first dielectric layer **30**. As shown in FIG. 6, a space is formed over the recessed second dielectric layer **35** in relatively narrow spaces (e.g., pitch  $P_2$ ,  $P_3$ ) between fin structures. In relatively wide spaces between fin structures (e.g., pitch  $P_4$ ,  $P_5$ ), the second dielectric layer **35** is fully removed. In some embodiments, the additional dielectric layer **32** is also removed in the relatively wide spaces, and thus, the first dielectric layer **30** is exposed. In some embodiments, the upper surface of the recessed second dielectric layer **35** has a V-shape or a U-shape.

[0038] Further, after the second dielectric layer **35** is recessed, a third dielectric layer **40** is formed over the first dielectric layer **30**, the additional dielectric layer **32**, and the recessed second dielectric layer **35**, as shown in FIG. 7. The material of the third dielectric layer **40** is different from the materials of the first dielectric layer **30**, the additional dielectric layer **32** and the second dielectric layer **35**. In some embodiments, the third dielectric layer **40** includes a material having a lower etching rate than the second dielectric layer **35** against a polysilicon etching. In some embodiments, the third dielectric layer **40** includes a high-k dielectric material. In some embodiments, the third dielectric layer **40** includes a dielectric material having a higher dielectric constant ( $k$ ) than the second dielectric layer **35**, the additional dielectric layer **32** and/or the first dielectric layer **30**. When the upper surface of the recessed second dielectric layer **35** has a V-shape or a U-shape, the bottom of the third dielectric layer **40** has a V-shape or a U-shape.

[0039] In some embodiments, the third dielectric layer **40** includes one or more of non-doped hafnium oxide (e.g.,  $\text{HfO}_{\text{sub.x}}$ ,  $0 < x \leq 2$ ), hafnium oxide doped with one or more other elements (e.g.,  $\text{HfSiO}$ ,  $\text{HfSiON}$ ,  $\text{HfTaO}$ ,  $\text{HfTiO}$  or  $\text{HfZrO}$ ), zirconium oxide, aluminum oxide, titanium oxide, and a hafnium dioxide-alumina ( $\text{HfO}_{\text{sub.2}}$ — $\text{Al}_{\text{sub.2O.sub.3}}$ ) alloy. In certain embodiments, hafnium oxide ( $\text{HfO}_{\text{sub.x}}$ ) is used as the third dielectric layer **40**. The third dielectric layer **40** can be formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method. In some embodiments, the second dielectric layer **35** is made of silicon nitride. As shown in FIG. 7, the third dielectric layer **40** fully fills the relatively narrow spaces and covers the top of the first dielectric layer **30**, in some embodiments. In some embodiments, after the third dielectric layer **40** is formed, a planarization operation, such as an etch-back process or a CMP process, is performed to planarize the upper surface of the third dielectric layer **40**. At the relatively wide spaces between fin structures, the third dielectric layer **40** is conformally formed over the first dielectric layer **30** and the additional dielectric layer **32**, as shown in FIG. 7.

[0040] Next, the third dielectric layer **40** is recessed down below the top of the fin structures **12** by

using a suitable dry and/or wet etching operation, as shown in FIG. 8. Since the third dielectric layer 40 is made of a different material than the additional dielectric layer 32 and the first dielectric layer 30, the third dielectric layer 40 is selectively etched against the additional dielectric layer 32 and the first dielectric layer 30. As shown in FIG. 8, a space is formed over the recessed third dielectric layer 40. In some embodiments, the upper surface of the recessed third dielectric layer 30 has a V-shape or a U-shape. At the relatively wide spaces between fin structures, the third dielectric layer 40 is fully removed and the first dielectric layer 30 is exposed, as shown in FIG. 8.

[0041] Then, in some embodiments, a fourth dielectric layer 45 is formed over the first dielectric layer 30, the additional dielectric layer 32, and the recessed third dielectric layer 40, as shown in FIG. 9. In some embodiments, the fourth dielectric layer 45 includes multiple dielectric layers. In some embodiments, the fourth dielectric layer includes a lower layer 42, a middle layer 44 and an upper layer 46. In some embodiments, the materials for the lower, middle, and upper layers are different from each other, and in other embodiments, the middle layer is made of a different material than the lower and the upper layers. In some embodiments, the fourth dielectric layer 45 is made of a same or a different material than the first, second, and/or third dielectric layers and includes one or more of silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN, or SiOCN formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method. In some embodiments, the thickness of the middle layer 44 is smaller than the thickness of the lower layer 42 and the upper layer 46.

[0042] Further, as shown in FIG. 9, a fifth dielectric layer 48 is formed over the fourth dielectric layer 45, and then a planarization operation, such as a CMP operation, is performed. In some embodiments, the fifth dielectric layer 48 is made of a different material than the fourth dielectric layer (at least the upper layer 46) and includes one or more of silicon oxide, silicon oxynitride, silicon nitride, SiOC, SiCN, or SiOCN formed by LPCVD, plasma-CVD or ALD, or any other suitable film formation method.

[0043] Then, as shown in FIG. 10, a planarization operation is further performed to expose the top of the fin structures 12.

[0044] Next, the first dielectric layer 30 and the liner dielectric layer 18 formed on side walls of the fin structures are recessed to expose channel regions of the fin structures, as shown in FIG. 11A. In some embodiments, the first dielectric layer 30 is recessed to about the level of the bottom of the SiGe layer 11 (e.g.,  $\pm 2$  nm). The recessed first dielectric layer 30 functions as an isolation insulating layer (e.g., shallow trench isolation (STI)) to electrically isolate one fin structure from adjacent fin structures.

[0045] By recessing the first dielectric layer a wall fin 50 (dummy dielectric fin) is formed between relatively narrow spaces of the fin structures. As shown in FIG. 11A, the wall fin 50 includes a part of the lower layer 42 of the fourth dielectric layer, the recessed third dielectric layer 40 formed on the recessed second dielectric layer 35, as a hybrid fin structure. In relatively wide spaces, a wall structure 52 including the fourth dielectric layer 45 and the fifth dielectric layer is formed. In some embodiments, a part of the additional dielectric layer 32 is also included in the wall structure 52 and is embedded in the first dielectric layer 30. In some embodiments, the wall structure 52 does not include the second dielectric layer 35 and the third dielectric layer 40. In some embodiments, depending on the space widths of adjacent fin structures, the widths of the wall fin structures are different. In some embodiments, when the pitch of the adjacent fin structures is more than  $P_0$  (minimum pitch) and equal to or less than  $4P_0$  (or  $3P_0$ ), a wall fin structure is formed, and when the pitch of the adjacent fin structures is more than  $4P_0$  (or  $3P_0$ ), a wall structure is formed. Whether a wall fin structure or a wall structure is formed also depends on a thickness of one or more of the first, second or third dielectric layers. In some embodiments, the pitch  $P_6$  between the n-type fin structure and the wall fin structure 50 is  $1/2P_2$ . In some embodiments, the space between two n-type fin structures is about  $3/2$  of the space between the n-type fin structure and the wall fin structure 50 at the center of the top of the fin structure.

[0046] In some embodiments, when n-type fin structures **12N** are arranged with the pitch **P0**, no wall fin structure **50** is formed between the fin structures as shown in FIG. **11B** similar to the p-type fin structures **12P** with a pitch **P1** ( $=P0$ ), as shown in FIG. **11A**. When the p-type fin structures are arranged with a pitch greater than **P0** (e.g., **P2** or more), a wall fin structure or a wall structure is formed between the p-type fin structures.

[0047] FIGS. **12A**, **12B**, **12C** and **12D** show various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure. It is understood that additional operations may be provided before, during, and after the processes shown by FIGS. **12A-12D**, and some of the operations described below can be replaced or eliminated for additional embodiments of the method. The order of the operations/processes may be interchangeable. FIG. **13** shows a flow chart for forming the cap semiconductor layer **13**.

[0048] FIG. **12A** shows a structure after the channel regions are exposed by recessing the first dielectric layer **30**. For the purpose of illustration, one n-type fin structure **12N** and one p-type fin structure **12P** are shown in FIGS. **12A-12C**.

[0049] In some embodiments, after the isolation insulating layer **30** is formed at **S101** of FIG. **13**, one or more wet cleaning operations are performed in some embodiments. In some embodiments, a thin oxide layer formed on the channel region of the fin structures **12** is removed. In some embodiments, the channel region of the fin structure exposed from the isolation insulating layer is also slightly etched.

[0050] Then, at **S102** of FIG. **13**, in some embodiments, the channel region of the fin structures **12N**, **12P** are trimmed (etched), as shown in FIG. **12B**. In some embodiments, one or more dry etching and/or wet etching are performed. In some embodiments, a wet etching using a tetramethylammonium hydroxide (TMAH) aqueous solution and/or a KOH aqueous solution is used as a wet etchant. In other embodiments, a chemical dry etching using an HCl gas is used to trim the channel region. In some embodiments, a trimming (etching) amount is in a range from about 0.2 nm to about 2.0 nm and is in a range from about 0.5 nm to about 1.0 nm in other embodiments.

[0051] After the trimming etching, in some embodiments, a cap semiconductor layer **13** is formed over the channel region of the n-type fin structure **12N** and the channel region **11** of the p-type fin structure **12P**, as shown in FIG. **12C**.

[0052] In some embodiments, the cap semiconductor layer **13** includes silicon, SiGe or Ge. In certain embodiments, silicon is used. The cap semiconductor layer **13** is formed over the fin structures to adjust dimensions (widths) of the fin structures and also control out-diffusion of Ge from SiGe or Ge layers of the p-type fin structures. In some embodiments, the thickness of the cap semiconductor layer **13** (measured at the 50% height of the channel region) is in a range from about 0.2 nm to about 4 nm and is in a range from about 0.5 nm to about 2 nm in other embodiments, depending on device and/or process requirements.

[0053] In some embodiments, the cap semiconductor layer **13** is epitaxially-grown over the channel regions. In some embodiments, the epitaxial layer is substantially selectively formed on the channel regions. In some embodiments, the cap semiconductor layer **13** is non-doped and in other embodiments, the cap semiconductor layer **13** is appropriately doped for the n-type fin structures **12N** and p-type fin structures **12P**.

[0054] In some embodiments of the present disclosure, just before the cap semiconductor layer **13** is epitaxially formed, a cleaning operation is performed to remove an oxide layer formed in or after the trimming process, at **S103** of FIG. **13**. In some embodiments of the present disclosure, the selectivity of the epitaxial growth of the cap semiconductor layer **13** depends on conditions and/or processes of the cleaning operation.

[0055] In some embodiments of the present disclosure, the cleaning operation and the epitaxial growth operation are performed in a same process chamber (e.g., vacuum chamber or a furnace) (in-situ cleaning). In some embodiments, a furnace shown in FIG. **14** is used for the cleaning



operation and the epitaxial growth operation. As shown in FIG. 14, the furnace includes an outer tube and an inner tube and wafers are arranged vertically inside the inner tube and are supported and moved vertically by pedestal. A reaction gas flows from the bottom of the inner tube and flows down from the top of the inner tube to the exhaust through the space between the inner tube and the outer tube. The furnace is heated by the heaters disposed outside the outer tube. Multiple wafers (e.g., 25-100 wafers) can be processed at the same time in the furnace.

[0056] In some embodiments, the cleaning operation is a chemical dry etching using a mixed gas of HF, NH<sub>3</sub> and N<sub>2</sub>. In some embodiments, a flow rate ratio of HF, NH<sub>3</sub> and N<sub>2</sub> is about 1:1:2.75 to about 5:1:6.5. In some embodiments, no noble gas (He, Ar) is added. In some embodiments, no hydrogen gas is added. The cleaning or removal of silicon oxide by HF and NH<sub>3</sub> proceeds as follows:  $\text{SiO}_2 + 4\text{HF} \rightarrow \text{SiF}_4 + 2\text{H}_2\text{O}$ ;

$\text{SiF}_4 + 2\text{HF} + 2\text{NH}_3 \rightarrow (\text{NH}_4)_2\text{SiF}_6$ ; and

$\text{SiO}_2 + 6\text{HF} + 2\text{NH}_3 \rightarrow (\text{NH}_4)_2\text{SiF}_6$ . Compared to a chemical dry etching using a mixed gas of HF, NH<sub>3</sub> and He, (so called SiCoNi process), the chemical dry etching using a mixed gas of HF, NH<sub>3</sub> and N<sub>2</sub> etches silicon oxide (oxide on the channel region and isolation insulating layer 30) and silicon nitride (liner dielectric layer 18) more equally than the SiCoNi process, which affects the selectivity of the epitaxial growth. In some embodiments, an etching selectivity of the isolation insulating layer 30 (e.g., silicon oxide) to the liner dielectric layer (e.g., silicon nitride) is about 1.4 when using the mixed gas of HF, NH<sub>3</sub> and N<sub>2</sub> etches, while the etching selectivity is about 3.5 when the SiCoNi process is used.

[0057] In some embodiments, the amount of HF and NH<sub>3</sub> (etchant gas) with respect to the total mixed gas is equal to or more than 30 vol % to equal to or less than 80 vol %, and in other embodiments, in a range from about 40 vol % to about 60 vol %. If the amount of etchant gas is smaller than this range, the cleaning effect is insufficient and if the amount of the etchant gas is greater than this range, quartz parts of the furnace may be damaged. In some embodiments, the pressure during the chemical dry etching is about 0.1 Torr to about 0.5 Torr.

[0058] FIG. 15 shows a temperature change from the cleaning operation to the epitaxial growth. In some embodiments, a temperature of the cleaning operation is in a range from about 30° C. to about 100° C., and is in a range from about 40° C. to about 70° C. in other embodiments. If the temperature is lower than the disclosed ranges, the cleaning effect is insufficient and if the temperature is higher than the disclosed ranges, the removal of oxide may decrease (higher selective etching). A time duration of the cleaning operation is in a range from about 1 min to 60 min in some embodiments and is in a range from about 5 min to about 15 min in other embodiments. When the cleaning time is too small, the cleaning effect is insufficient, and when the cleaning time is too long, the dielectric or insulating layers may be etched too much.

[0059] After the cleaning operation by the chemical dry etching, at S104 of FIG. 13, the etching byproduct (e.g., (NH<sub>4</sub>)<sub>2</sub>SiF<sub>6</sub>) is removed by a heating process in a H<sub>2</sub> ambient (e.g., sublimation process:  $(\text{NH}_4)_2\text{SiF}_6 \rightarrow \text{SiF}_4 + 2\text{HF} + 2\text{NH}_3$ ). The temperature of the sublimation process is in a range from about 250° C. to about 350° C. in some embodiments. A time duration of the sublimation process is in a range from about 1 hour to 5 hours in some embodiments.

[0060] After the sublimation process, a pre-baking process is performed in a H<sub>2</sub> ambient at S105 of FIG. 13. In some embodiments, the temperature of the pre-baking process is higher than the sublimation process. In some embodiments, the temperature of the pre-baking process is in a range from about 300° C. to about 650° C., and is in a range from about 350° C. to about 400° C. in other embodiments. In the pre-baking process, fluorine is removed. A time duration of the pre-baking operation is in a range from about 30 min to 3 hours in some embodiments. In some embodiments, the sublimation process and the pre-baking process are performed continuously at the same temperature.

[0061] After the pre-baking process, an epitaxial growth process is performed to form the cap

semiconductor layer **13**, at **S106** of FIG. **13**. In some embodiments, a source gas is one or more of SiH.sub.4 or Si.sub.2H.sub.6. The temperature of the epitaxial growth process is in a range from about 300° C. to about 650° C. in some embodiments and is in a range from about 350° C. to about 400° C. in other embodiments. If the temperature is too high, uniformity of the film thickness decreases, Ge in the SiGe layer diffuses, and selectivity is lower, and if the temperature is too low, the growth rate is too low for mass production. In some embodiments, the temperature of the pre-baking is the same as or different from the temperature of the epitaxial growth.

[0062] FIG. **12D** shows a cross section view after the cap semiconductor layer **13** is formed over the SiGe channel **11**. As shown in FIG. **12D**, the amount of the cap semiconductor layer **13** on the liner dielectric layer **18** (a wing portion) is minimized. In some embodiments, the cap semiconductor layer **13** does not extend over the isolation insulating layer **30**. In some embodiments, the surface area **D3** of the liner dielectric layer **18** not covered by the cap semiconductor layer **13** is about 20% to 90% of the thickness liner dielectric layer **18**, and thus the thickness of the cap semiconductor layer **13** on the liner dielectric layer **18** (the wing portion) is about 10% to about 80% of the thickness **D1** (**D1**, **D2** and **D3** are measured in the horizontal direction (projected onto the horizontal plane)). In other embodiments, **D3** is about 40% to 70% of **D1** (thickness of the cap semiconductor layer **13** on the liner dielectric layer **18** (the wing portion) is about 30% to about 60% of the thickness **D1**). In some embodiments, the dimension **D1** is defined as a distance of e.g., 2.7 nm (the right line defining **D1**) from the outer side face (the left line defining **D1**, interface between the liner dielectric layer **18** and the isolation insulating layer **30**), and the thickness **D2** of the cap semiconductor layer **13** is largest point of the cap semiconductor layer **13** from the right line defining **D1**. In some embodiments, the **D2** (wing width) is about 1.3 nm to about 2.3 nm. When the SiCoNi process and/or ex-situ cleaning process are used, the cap semiconductor layer **13** fully covers the liner dielectric layer and may be formed over the isolation insulating layer beyond the liner dielectric layer **18**. When the wing portion is larger, electrical properties of the FinFET (e.g., drain induced barrier lowering (DIBL)) become worse. In some embodiments, the thickness of the cap semiconductor layer **13** just on the liner dielectric layer **18** is greater than the thickness of the cap semiconductor layer **13** at the middle of the channel region (e.g., 50% of height of the channel region).

[0063] As set forth above, the cleaning operation, the sublimation process, the pre-baking process and the epitaxial growth are continuously performed in the same chamber (furnace) without breaking vacuum. In some embodiments, the operations of FIG. **13** is repeated twice or three times to obtain desired channel shape.

[0064] Although FIG. **12D** shows a p-type fin structure (SiGe channel), the same or similar structure can be obtained for an n-type fin structure (Si channel).

[0065] After the cap semiconductor layer **13** is formed, an annealing operation is performed in some embodiments. In some embodiments, the annealing operation includes rapid thermal annealing at a temperature in a range from about 900° C. to about 1100° C. for about 0.1 sec to 10 sec. In other embodiments, the temperature is in a range from about 950° C. to 1050° C. In other embodiments, the time duration is in a range from about 0.5 sec to 5 sec. In some embodiments, the annealing operation is performed in a mixed gas of N.sub.2 and O.sub.2, where the oxygen concentration is in a range from about 0.1% to 0.5%. The annealing operation is also performed in the same chamber (furnace) in some embodiments.

[0066] FIGS. **16A-16F** show various stages of a sequential manufacturing operation of a semiconductor FET device according to an embodiment of the present disclosure. It is understood that additional operations may be provided before, during, and after the processes shown by FIGS. **16A-16F**, and some of the operations described below can be replaced or eliminated for additional embodiments of the method. The order of the operations/processes may be interchangeable.

[0067] FIG. **16A** shows the structure after the cap semiconductor layer **13** is formed over both p-type fin structures **12P** and n-type fin structures **12N**. Substantially no cap semiconductor layer is

formed over a surface of insulating material, such as the surface of the isolation insulating layer **30** and a wall fin structure **50**.

[0068] After the cap semiconductor layer **13** is formed as shown in FIGS. **12A-12D**, sacrificial gate structures **40** are formed over the fin structures, as shown in FIG. **16B**. In some embodiments, the sacrificial gate structures **40** include a sacrificial dielectric layer, a sacrificial gate electrode layer and a hard mask layer. The sacrificial gate dielectric layer 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 is in a range from about 1 nm to about 5 nm in some embodiments. 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. The hard mask layer is used to form the sacrificial gate electrode layer and includes one or more layers of silicon nitride and silicon oxide. In some embodiments, the sacrificial gate dielectric layer also covers the source/drain region of the fin structures **12P**, **12N**.

[0069] After the sacrificial gate structures **40** are formed, a blanket layer of an insulating material for sidewall spacers is conformally formed by using CVD or other suitable methods. The blanket layer is deposited in a conformal manner so that it has substantially equal thicknesses on vertical surfaces, such as the sidewalls, horizontal surfaces, and the top of the sacrificial gate structure. In some embodiments, the blanket layer is deposited to a thickness in a range from about 2 nm to about 10 nm. In one embodiment, the insulating material of the blanket layer is a silicon nitride-based material, such as SiN, SiON, SiOCN or SiCN and combinations thereof. The sidewall spacers are formed on opposite sidewalls of the sacrificial gate structures **40**.

[0070] In the embodiment of FIG. **16B**, one sacrificial gate structure **40** is disposed over two fin structures **12P** in the p-type region, and one sacrificial gate structure **40** is disposed over three fin structures **12N** and the wall fin structure **50** in the n-type region. However, the number of the fin structures per sacrificial gate structure is not limited, and can be one, two, three or more than four.

[0071] Subsequently, a source/drain epitaxial layer **62** and **64** is formed (see, FIG. **16F**). In some embodiments, the fin structures of source/drain regions are recessed down below the upper surface of the isolation insulating layer **30** by using dry etching and/or wet etching, and then one or more semiconductor layers are epitaxially formed over the recessed fin structures. In other embodiments, one or more semiconductor layers are epitaxially formed over the source/drain region of the non-recessed fin structure. The source/drain epitaxial layer **62** for an n-type FET includes one or more layers of SiC, SiP and SiCP, and the source/drain epitaxial layer **64** for a p-type FET includes one or more layers of SiGe, SiGeSn, which may be doped with B. In at least one embodiment, the epitaxial layers are epitaxially-grown by an LPCVD process, molecular beam epitaxy, atomic layer deposition or any other suitable method. The LPCVD process is performed at a temperature of about 400° C. to about 850° C. and under a pressure of about 1 Torr to about 200 Torr, using a silicon source gas such as SiH<sub>4</sub>, Si<sub>2</sub>H<sub>6</sub>, or Si<sub>3</sub>H<sub>8</sub>; a germanium source gas such as GeH<sub>4</sub> or G<sub>2</sub>H<sub>6</sub>; a carbon source gas such as CH<sub>4</sub> or SiH<sub>3</sub>CH<sub>3</sub>; a phosphorus source gas such as PH<sub>3</sub>; and/or a boron source gas such as B<sub>2</sub>H<sub>6</sub>. In some embodiments, two or more layers with different compositions (e.g., different P, C, Ge and/or B concentrations) are formed as the source/drain epitaxial layers.

[0072] Subsequently, a first interlayer dielectric (ILD) layer **55** is formed over the source/drain epitaxial layers and the sacrificial gate structures **40**, as shown in FIG. **16C**. Then, a planarization operation, such as CMP, is performed, so that the top portion of the sacrificial gate electrode layer is exposed. The materials for the first ILD layer **55** 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 first ILD layer **55**.

[0073] Next, the sacrificial structure **40** including sacrificial gate electrode layer and the sacrificial gate dielectric layer are removed, thereby exposing the upper portions (channel regions) of the fin structures, as shown in FIG. **16D**. The sacrificial gate structures **40** can be removed using plasma dry etching and/or wet etching. When the sacrificial gate electrode layer is polysilicon and the first ILD layer **55** is silicon oxide, a wet etchant such as a TMAH solution can be used to selectively remove the sacrificial gate electrode layer. The sacrificial gate dielectric layer is thereafter removed using plasma dry etching and/or wet etching.

[0074] After the sacrificial gate structures are removed, a gate dielectric layer **82** is formed over channel regions (upper portions of the fin structure above the isolation insulating layer **30**), and a gate electrode layer **84** is formed on the gate dielectric layer **82**, as shown in FIG. **16E**.

[0075] In certain embodiments, the gate dielectric layer **82** 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  $\text{HfO}_2$ ,  $\text{HfSiO}$ ,  $\text{HfSiON}$ ,  $\text{HfTaO}$ ,  $\text{HfTiO}$ ,  $\text{HfZrO}$ , 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 **82** includes an interfacial layer formed between the channel layers and the dielectric material.

[0076] The gate dielectric layer **82** may be formed by CVD, ALD or any suitable method. In one embodiment, the gate dielectric layer **82** 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 over each channel layers. The thickness of the gate dielectric layer **82** is in a range from about 1 nm to about 6 nm in one embodiment.

[0077] The gate electrode layer **84** is formed on the gate dielectric layer **82**. The gate electrode **84** includes one or more layers of conductive material, such as polysilicon, 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.

[0078] The gate electrode layer **84** may be formed by CVD, ALD, electro-plating, or other suitable method. The gate electrode layer is also deposited over the upper surface of the first ILD layer **55**. The gate dielectric layer and the gate electrode layer formed over the first ILD layer **55** are then planarized by using, for example, CMP, until the top surface of the first ILD layer **55** is revealed. In some embodiments, after the planarization operation, the gate electrode layer **84** is recessed and a cap insulating layer is formed over the recessed gate electrode **84**. The cap insulating layer includes one or more layers of a silicon nitride-based material, such as SiN. The cap insulating layer can be formed by depositing an insulating material followed by a planarization operation.

[0079] In certain embodiments of the present disclosure, one or more work function adjustment layers (not shown) are interposed between the gate dielectric layer **82** and the gate electrode **84**. 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 the 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 the 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.

[0080] It is understood that the semiconductor device shown in FIGS. **16E** and **16F** undergoes further CMOS processes to form various features such as contacts/vias, interconnect metal layers, dielectric layers, passivation layers, etc.

[0081] FIGS. **17A** and **17B** show advantageous effects of the present embodiments. FIG. **17A**

shows a Ge concentration from the surface of the cap semiconductor layer in a p-type fin structure. In the present embodiments, a steep slope in the Ge concentration was observed, which means that undesired Ge diffusion from the SiGe layer **11** to the cap semiconductor layer (Si) was effectively suppressed. In some embodiments, the diffusion can be suppressed by about 1.5-2.5 nm. Further, as shown in FIG. **17B**, in the present embodiments, oxygen contamination into the channel region was suppressed. In some embodiments, the concentration of oxygen is smaller than about  $1 \times 10^{18}$  atoms/cm<sup>3</sup>. In some embodiments, the concentration of oxygen is smaller than the detection limit or more than about  $1 \times 10^{16}$  atoms/cm<sup>3</sup>.

[0082] FIGS. **18A** and **18B** show cross sectional views of the semiconductor device according to embodiments of the present disclosure.

[0083] As shown in FIG. **18A**, a wall fin structure **50** is disposed between fin structures where a space therebetween is sufficiently large, while no wall fin structure is disposed between fin structures where a space therebetween is sufficiently small. In some embodiments, the channel region of the fin structure bends and does not have uniform width depending on device performance requirements. In some embodiments, widths of the wall fin structure are greater than the widths of the semiconductor fin structures and different from each other. The height of the top of the third dielectric layer **40** differs from each other depending on space widths between adjacent fin structures. The height of the bottom of the third dielectric layer **40** differs from each other depending on space widths between adjacent fin structures.

[0084] As shown in FIG. **18B**, the wing portions of the cap semiconductor layer **13** are formed asymmetric with respect to the center of the fin structure. In some embodiments, the lateral protruding amounts of the wing portions to the right and the left are different from each other. In some embodiments, the height of the maximum protruding portion of the wing portions are different from each other.

[0085] 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.

[0086] In accordance with one aspect of the present disclosure, in a method of manufacturing a semiconductor device, a fin structure having a channel region protruding from an isolation insulating layer disposed over a semiconductor substrate is formed, a cleaning operation is performed, and an epitaxial semiconductor layer is formed over the channel region. The cleaning operation and the forming the epitaxial semiconductor layer are performed in a same chamber without breaking vacuum. In one or more of the foregoing or the following embodiments, the cleaning operation is a chemical dry etching using a mixed gas of HF, NH<sub>3</sub> and N<sub>2</sub>. In one or more of the foregoing or the following embodiments, the cleaning operation is performed at a temperature in a range from 30° C. to 100° C. In one or more of the foregoing or the following embodiments, the cleaning operation is performed for a time duration in a range from 5 min to about 15 min. In one or more of the foregoing or the following embodiments, a sublimation operation is further performed between the cleaning operation and the forming the epitaxial semiconductor to remove by-products of the cleaning operation. In one or more of the foregoing or the following embodiments, the sublimation operation is performed at a temperature higher than the cleaning operation and lower than the epitaxial growth. In one or more of the foregoing or the following embodiments, the sublimation operation is performed in a H<sub>2</sub> ambient.

[0087] In accordance with another aspect of the present disclosure, in a method of manufacturing a semiconductor device, a fin structure is formed. The fin structure has a channel region protruding from an isolation insulating layer disposed over a semiconductor substrate and a bottom region embedded in the isolation insulating layer. The channel region is made of SiGe and the bottom region is made of Si, a liner dielectric layer is disposed between the bottom region and the isolation insulating layer, and a top of the liner dielectric layer is exposed from the isolation insulating layer. A cleaning operation is performed on the channel region, the isolation insulating layer and the liner

dielectric layer, and an epitaxial semiconductor layer is formed over the channel region. The cleaning operation and the forming the epitaxial semiconductor layer are performed in a same chamber without breaking vacuum. In one or more of the foregoing or the following embodiments, the epitaxial semiconductor layer only partially covers the exposed top of the liner dielectric layer. In one or more of the foregoing or the following embodiments, a thickness of the epitaxial semiconductor on the liner dielectric layer is 10% to 80% of a thickness of the liner dielectric layer at the top of the liner dielectric layer. In one or more of the foregoing or the following embodiments, the epitaxial semiconductor layer is a Si layer. In one or more of the foregoing or the following embodiments, the liner dielectric layer includes silicon nitride, and the isolation insulating layer includes silicon oxide. In one or more of the foregoing or the following embodiments, the forming the epitaxial semiconductor layer is performed at a temperature in a range from 350° C. to 400° C. In one or more of the foregoing or the following embodiments, the cleaning operation is a chemical dry etching using a mixed gas of HF, NH<sub>3</sub> and N<sub>2</sub>, at a temperature in a range from 40° C. to 70° C. In one or more of the foregoing or the following embodiments, no noble gas is added to the mixed gas. In one or more of the foregoing or the following embodiments, the chamber is a furnace in which multiple substrate are processed at the same time.

[0088] In accordance with another aspect of the present disclosure, in a method of manufacturing a semiconductor device, a first dielectric layer is formed over a first pair of semiconductor fins and a second pair of semiconductor fins such that the first dielectric layer fills a space between the second pair of semiconductor fins. A second dielectric layer is formed over the first dielectric layer such that the second dielectric layer fills a space between the first pair of semiconductor fins. The second dielectric layer is recessed below a top of each of the first pair of semiconductor fins. A third dielectric layer is formed over the recessed second dielectric layer. The third dielectric layer is recessed below the top of the first pair of semiconductor fins. A fourth dielectric layer is formed over the recessed third dielectric layer. The fourth dielectric layer and the first dielectric layer are recessed below the top of the first pair of semiconductor fins, thereby forming a wall fin disposed between the first pair of semiconductor fins. A cleaning operation is performed, and an epitaxial semiconductor layer is formed over channel regions of the first and second pairs of semiconductor fins. The cleaning operation and the forming the epitaxial semiconductor layer are performed in a same chamber without breaking vacuum. In one or more of the foregoing or the following embodiments, the wall fin comprises the recessed fourth dielectric layer, the recessed third dielectric layer and the recessed second dielectric layer disposed under the recessed third dielectric layer. In one or more of the foregoing or the following embodiments, no wall fin is formed between the second pair of semiconductor fins. In one or more of the foregoing or the following embodiments, the channel regions of the first pair of semiconductor fins are made of Si, and the channel regions of the second pair of semiconductor fins are made of SiGe.

[0089] In accordance with another aspect of the present disclosure, a semiconductor device includes a semiconductor fin disposed over a semiconductor substrate and extending in a first direction. The semiconductor fin includes a channel region and a bottom region on which the channel region is disposed. The semiconductor device includes a liner dielectric layer disposed on side walls of the bottom region, an isolation insulating layer from which the channel region protrudes and in which the bottom region is embedded, and a gate structure disposed over the channel region of the semiconductor fin and extending in a second direction crossing the first direction. A cap semiconductor layer is disposed on the channel region, and a top of the liner dielectric layer is only partially covered by the cap semiconductor layer. In one or more of the foregoing or the following embodiments, the channel region and the bottom region are made of different semiconductor materials from each other. In one or more of the foregoing or the following embodiments, the channel region is made of SiGe. In one or more of the foregoing or the following embodiments, the cap semiconductor layer is made of Si. In one or more of the foregoing or the

following embodiments, a thickness of the cap semiconductor layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer. In one or more of the foregoing or the following embodiments, the liner dielectric layer includes silicon nitride, and the isolation insulating layer includes silicon oxide. In one or more of the foregoing or the following embodiments, a thickness of the cap semiconductor layer on the liner dielectric layer is greater than a thickness of the cap semiconductor layer at a 50% height of the channel region. In one or more of the foregoing or the following embodiments, the channel region is made of Si, the cap semiconductor layer is made of Si, and a thickness of the cap semiconductor layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer.

[0090] In accordance with another aspect of the present disclosure, a semiconductor device includes a first semiconductor fin and a second semiconductor fin disposed over a semiconductor substrate and extending in a first direction. Each of the first and second semiconductor fins includes a channel region and a bottom region on which the channel region is disposed. The semiconductor device includes a liner dielectric layer disposed on side walls of the bottom region of each of the first and second semiconductor fins, an isolation insulating layer from which the channel region of the first and second semiconductor fins protrudes and in which the bottom region of the first and second semiconductor fins is embedded, and a first gate structure disposed over the channel region of the first semiconductor fin and a second gate structure disposed over the channel region of the second semiconductor fin. A cap semiconductor layer is disposed on the channel region of each of the first and second semiconductor fins, and a top of the liner dielectric layer is only partially covered by the cap semiconductor layer at each of the first and second semiconductor fins. In one or more of the foregoing or the following embodiments, the cap semiconductor layer is made of Si. In one or more of the foregoing or the following embodiments, the channel region of the second semiconductor fin is made of SiGe. In one or more of the foregoing or the following embodiments, the channel region of the first semiconductor fin is made of Si. In one or more of the foregoing or the following embodiments, a thickness of the cap semiconductor layer of on the liner dielectric layer at the second semiconductor fin is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer. In one or more of the foregoing or the following embodiments, the liner dielectric layer includes silicon nitride, and the isolation insulating layer includes silicon oxide. In one or more of the foregoing or the following embodiments, a thickness of the cap semiconductor layer on the liner dielectric layer is greater than a thickness of the cap semiconductor layer at a 50% height of the channel region. In one or more of the foregoing or the following embodiments, a wall fin structure made of at least three different dielectric material is disposed between the first semiconductor fin and the second semiconductor fin.

[0091] In accordance with another aspect of the present disclosure, a semiconductor device includes a first semiconductor fin and a second semiconductor fin disposed over a semiconductor substrate and extending in a first direction, an isolation insulating layer disposed between the first semiconductor fin and the second semiconductor fin, a wall fin extending in the first direction, wherein a lower portion of the wall fin is embedded in the isolation insulating layer and an upper portion of the wall fin protrudes from the isolation insulating layer, and a gate structure disposed over a channel region of the first semiconductor fin and a channel region of the second semiconductor fin and extending in a second direction crossing the first direction. Each of the first semiconductor fin and the second semiconductor fin includes the channel region and a bottom region embedded in the isolation insulating layer and a liner dielectric layer disposed between the isolation insulating layer and the bottom region, the channel region is made of SiGe and further includes a Si cap layer disposed over the SiGe channel region, and a top of the liner dielectric layer is only partially covered by the Si cap layer. In one or more of the foregoing or the following embodiments, a thickness of the Si cap layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer. In one or more of the

foregoing or the following embodiments, the liner dielectric layer includes silicon nitride, and the isolation insulating layer includes silicon oxide. In one or more of the foregoing or the following embodiments, the wall fin includes a lower dielectric layer and an upper dielectric layer disposed over the lower dielectric layer and made of a different material than the lower dielectric layer, and the upper dielectric layer includes at least one selected from the group consisting of  $\text{HfO}_{2.2}$ ,  $\text{HfSiO}$ ,  $\text{HfSiON}$ ,  $\text{HfTaO}$ ,  $\text{HfTiO}$ ,  $\text{HfZrO}$ , zirconium oxide, aluminum oxide, titanium oxide, and a hafnium dioxide-alumina ( $\text{HfO}_{2.2}$ — $\text{Al}_2\text{O}_3$ ) alloy.

[0092] 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.

## Claims

1. A semiconductor device comprising: a first fin structure and a second fin structure disposed over a substrate and extending in a first direction, each of the first and second fin structures including an upper region disposed over a bottom region; a liner dielectric layer disposed on side walls of the bottom region of each of the first fin structure and the second fin structure; an isolation insulating layer disposed between the first fin structure and the second fin structure, wherein a top surface of the isolation insulating layer is coplanar with a top surface of the liner dielectric layer; a cap semiconductor layer disposed over the upper region of each of the first fin structure and the second fin structure and a top of the liner dielectric layer; and a first gate structure extending in a second direction crossing the first direction disposed over the upper region of the first fin structure and a second gate structure extending in the second direction crossing the first direction disposed over the upper region of the second fin structure, wherein a thickness of the cap semiconductor layer on the liner dielectric layer is greater than a thickness of the cap semiconductor layer at a 50% height of the upper region.
2. The semiconductor device of claim 1, wherein the upper region and the bottom region are made of different semiconductor materials from each other.
3. The semiconductor device of claim 1, wherein the upper region is made of  $\text{SiGe}$ .
4. The semiconductor device of claim 1, wherein the cap semiconductor layer is made of  $\text{Si}$ .
5. The semiconductor device of claim 1, wherein a thickness of the cap semiconductor layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer.
6. The semiconductor device of claim 1, wherein the liner dielectric layer includes silicon nitride.
7. The semiconductor device of claim 1, wherein: a portion of the top surface of the liner dielectric layer is covered by the cap semiconductor layer, and a remaining portion of the top surface of the liner dielectric layer is exposed by the cap semiconductor layer.
8. The semiconductor device of claim 1, wherein: the upper region is made of  $\text{Si}$ , the cap semiconductor layer is made of  $\text{Si}$ , and a thickness of the cap semiconductor layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at the top of the liner dielectric layer.
9. A semiconductor device comprising: a first fin structure and a second fin structure disposed over a substrate and extending in a first direction, wherein the first fin structure and the second fin structure comprise a channel region disposed over a bottom region; a first dielectric layer disposed between the bottom regions of the first fin structure and the second fin structure; a gate structure



disposed over a channel region of the first fin structure and a channel region of the second fin structure and extending in a second direction crossing the first direction: a wall fin extending in the first direction disposed over the first dielectric layer between the first fin structure and the second fin structure, wherein the wall fin comprises: a second dielectric layer made of a different material than the first dielectric layer embedded in the first dielectric layer and protruding from the first dielectric layer along a third direction crossing the first and second directions; a third dielectric layer made of a different material than the first dielectric layer and the second dielectric layer disposed over the second dielectric layer; and a fourth dielectric layer disposed over the third dielectric layer; and a liner dielectric layer disposed between the first dielectric layer and the bottom regions of the first fin structure and the second fin structure, wherein a top surface of the first dielectric layer is coplanar with a top surface of the liner dielectric layer, wherein the channel regions of the first fin structure and the second fin structure include a cap layer, the cap layer is in direct contact with the top surface of the liner dielectric layer, covers a portion of the top surface of the liner dielectric layer, and exposes a remaining portion of the top surface of the liner dielectric layer.

**10.** The semiconductor device of claim 9, wherein the cap layer is made of Si.

**11.** The semiconductor device of claim 9, wherein the channel region of the second fin structure is made of SiGe.

**12.** The semiconductor device of claim 9, wherein the channel region of the first fin structure is made of Si.

**13.** The semiconductor device of claim 9, wherein a thickness of the cap layer on the liner dielectric layer at the second fin structure is 30% to 70% of a thickness of the liner dielectric layer at the top surface of the liner dielectric layer.

**14.** The semiconductor device of claim 9, wherein the liner dielectric layer includes silicon nitride.

**15.** The semiconductor device of claim 9, wherein: the fourth dielectric layer includes a lower layer on the third dielectric layer, a middle layer on the lower layer, and an upper layer on the middle layer, and a material of the middle layer is different than a material of the lower layer and a material of the upper layer.

**16.** A semiconductor device comprising: a first fin structure and a second fin structure disposed over a substrate and extending in a first direction; an isolation insulating layer disposed between the first fin structure and the second fin structure; a wall fin extending in the first direction, wherein a lower portion of the wall fin is embedded in the isolation insulating layer and an upper portion of the wall fin protrudes from the isolation insulating layer; and a gate structure disposed over a channel region of the first fin structure and a channel region of the second fin structure and extending in a second direction crossing the first direction, wherein: each of the first fin structure and the second fin structure includes the channel region and a bottom region embedded in the isolation insulating layer and a liner dielectric layer disposed between the isolation insulating layer and the bottom region, wherein: a top surface of the isolation insulating layer is coplanar with a top surface of the liner dielectric layer, the channel regions of the first fin structure and the second fin structure include a cap semiconductor layer disposed over the channel region, a portion of the top surface of the liner dielectric layer is covered by the cap semiconductor layer, and a remaining portion of the top surface of the liner dielectric layer is exposed by the cap semiconductor layer, and a thickness of the cap semiconductor layer on the liner dielectric layer is greater than a thickness of the cap semiconductor layer at a 50% height of the channel region.

**17.** The semiconductor device of claim 16, wherein the cap semiconductor layer is made of Si.

**18.** The semiconductor device of claim 16, wherein a thickness of the cap semiconductor layer on the liner dielectric layer is 30% to 70% of a thickness of the liner dielectric layer at a top of the liner dielectric layer.

**19.** The semiconductor device of claim 16, wherein the liner dielectric layer includes silicon nitride, and the isolation insulating layer includes silicon oxide.

**20.** The semiconductor device of claim 16, wherein the upper portion of the wall fin includes at least one selected from the group consisting of HfO.sub.2, HfSiO, HfSiON, and HfTaO.

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