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Semiconductor devices and methods of manufacturing thereof

Abstract

A semiconductor device in a first area includes first non-planar semiconductor structures separated with a first distance, and a first isolation region including a first layer and a second layer that collectively embed a lower portion of each of the first non-planar semiconductor structures. At least one of the first layer or second layer of the first isolation region is in a cured state. The semiconductor device in a second area includes second non-planar semiconductor structures separated with a second distance, and a second isolation region including a first layer and a second layer that collectively embed a lower portion of each of the second non-planar semiconductor structures. At least one of the first or second layer of the second isolation region is in a cured state.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation application of U.S. Utility application Ser. No. 18/066,777, filed Dec. 15, 2022, which is a divisional application of U.S. Utility application Ser. No. 17/230,414, filed Apr. 14, 2021, the entire contents of each of which are incorporated herein by reference for all purposes.

BACKGROUND

(1) The semiconductor industry has experienced rapid growth due to continuous improvements in the integration density of a variety of electronic components (e.g., transistors, diodes, resistors, capacitors, etc.). For the most part, this improvement in integration density has come from repeated

reductions in minimum feature size, which allows more components to be integrated into a given area.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
- (2) FIG. 1 illustrates a perspective view of a fin-based field-effect-transistor (FinFET) device, in accordance with some embodiments.
- (3) FIG. 2 illustrates a flow chart of an example method for making a FinFET device, in accordance with some embodiments.
- (4) FIGS. 3, 4, 5, 6, 7, 8, 9, 10, and 11 illustrate cross-sectional views of an example FinFET device (or a portion of the example FinFET device) during various fabrication stages, made by the method of FIG. 2, in accordance with some embodiments.
- (5) FIGS. 12A, 12B, 13A, 13B, 14A, 14B, 15A, and 15B illustrate cross-sectional views of the example FinFET device of FIGS. 3-11, in accordance with some other embodiments.
- (6) FIG. 16 illustrates a cross-sectional views of an example gate-all-around (GAA) FET device, in accordance with some other embodiments.

DETAILED DESCRIPTION

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

(8) 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.

(9) In general, an integrated circuit includes various types of transistors formed on a substrate. Some of the transistors are configured to conduct a higher current, while some of the transistors are configured to conduct a lower current. For the transistor that can generate the higher current, its corresponding active gate structure can straddle a number of channels that may be disposed more closer to each other (e.g., in a higher density). For the transistor that can generate the lower current, its corresponding active gate structure can straddle a number of channels that may be disposed less closer to each other (e.g., in a lower density). After defining the channels, an insulation material may be disposed between the channels to form a shallow trench isolation (STI) region/structure such as to expose respective upper portions of the channels. Such an insulation material can be

further densified by various curing techniques.

(10) However, due to the different densities of channels, the portion of the insulation material being densified may have different thickness (or heights). This can cause the following etching back process, which is applied on the insulation material that has a mixture of cured and uncured states, to form the STI structure in different heights between the channels in different densities. For example, the STI structure formed over the high density channels may have a lower height (i.e., exposing a higher height of the channels), and the STI structure formed over the low density channels may have a lower height (i.e., exposing a lower height of the channels). Consequently, active gate structures later formed over such channels have different gate heights, which may disadvantageously affect performance of some transistors that have the lower gate heights.

(11) Embodiments of the present disclosure are discussed in the context of forming a non-planar field-effect-transistor (FET) device (e.g., a fin-based FET device, a gate-all-around (GAA) FET device, etc.), and in particular, in the context of forming STI structures for a number of non-planar transistors. Unlike the existing technologies that cures only the upper portion of an insulation material, the present disclosure provides various embodiments of methods to form at least a first insulation layer/film in a cured state below a second insulation layer/film that is later converted into a cured state. As such, a thick enough cured insulation material (e.g., constituted by a stack of the first and second insulation layers) can be formed between the channels in different densities, which allows the later etching back process to have a unified etching rate on such a thick, cured insulation material. Consequently, portions of the channels, exposed by the STI structures, can be controlled to have a similar height, which can allow the later formed active gate structures to have a similar gate height.

(12) FIG. 1 illustrates a perspective view of an example FinFET device **100**, in accordance with various embodiments. The FinFET device **100** includes a substrate **102** and a fin **104** protruding above the substrate **102**. Isolation regions **106** are formed on opposing sides of the fin **104**, with the fin **104** protruding above the isolation regions **106**. A gate dielectric **108** is along sidewalls and over a top surface of the fin **104**, and a gate **110** is over the gate dielectric **108**. Source region **112S** and drain region **112D** are in (or extended from) the fin **104** and on opposing sides of the gate dielectric **108** and the gate **110**. FIG. 1 is provided as a reference to illustrate a number of cross-sections in subsequent figures. For example, cross-section A-A extends along a longitudinal axis of the gate **110**. Subsequent figures refer to this reference cross-section for clarity.

(13) FIG. 2 illustrates a flowchart of a method **200** to form a non-planar transistor device, according to one or more embodiments of the present disclosure. For example, at least some of the operations (or steps) of the method **200** can be used to form a FinFET device (e.g., FinFET device **100**), a nanosheet transistor device, a nanowire transistor device, a vertical transistor device, or the like. It is noted that the method **200** is merely an example, and is not intended to limit the present disclosure. Accordingly, it is understood that additional operations may be provided before, during, and after the method **200** of FIG. 2, and that some other operations may only be briefly described herein. In some embodiments, operations of the method **200** may be associated with cross-sectional views of an example FinFET device at various fabrication stages as shown in FIGS. 3, 4, 5, 6, 7, 8, 9, 10, and 11, respectively, which will be discussed in further detail below.

(14) In brief overview, the method **200** starts with operation **202** of providing a substrate. The method **200** continues to operation **204** of forming a number of semiconductor fin structures. The method **200** continues to operation **206** of filling trenches between the semiconductor fin structures with a first insulation material. The method **200** continues to operation **208** of recessing the first insulation material. The method **200** continues to operation **210** of curing the first insulation material. The method **200** continues to operation **212** of filling the trenches with a second insulation material. The method **200** continues to operation **214** of curing at least the second insulation material. The method **200** continues to operation **216** of recessing a cured insulation stack. The method **200** continues to operation **218** of forming active gate structures.

(15) As mentioned above, FIGS. 3-11 each illustrate, in a cross-sectional view, a portion of a transistor device **300** at various fabrication stages of the method **200** of FIG. 2. The transistor device **300** is similar to the FinFET device **100** shown in FIG. 1, but with multiple gate structures and multiple fins. Although FIGS. 3-11 illustrate the transistor device **300**, it is understood the transistor device **300** may include a number of other devices such as inductors, fuses, capacitors, coils, etc., which are not shown in FIGS. 3-11, for purposes of clarity of illustration.

(16) Corresponding to operation **202** of FIG. 2, FIG. 3 is a cross-sectional view of the transistor device **300** including a semiconductor substrate **302** at one of the various stages of fabrication, in some embodiments. The cross-sectional view of the transistor device **300** in FIG. 3 is cut along the lengthwise direction of a gate structure, e.g., cross-section A-A (as indicated in FIG. 1).

(17) The substrate **302** may be a semiconductor substrate, such as a bulk semiconductor, a semiconductor-on-insulator (SOI) substrate, or the like, which may be doped (e.g., with a p-type or an n-type dopant) or undoped. The substrate **302** may be a wafer, such as a silicon wafer. Generally, an SOI substrate includes a layer of a semiconductor material formed on an insulator layer. The insulator layer may be, for example, a buried oxide (BOX) layer, a silicon oxide layer, or the like. The insulator layer is provided on a substrate, typically a silicon or glass substrate. Other substrates, such as a multi-layered or gradient substrate may also be used. In some embodiments, the semiconductor material of the substrate **302** may include silicon; germanium; a compound semiconductor including silicon carbide, gallium arsenic, gallium phosphide, indium phosphide, indium arsenide, and/or indium antimonide; an alloy semiconductor including SiGe, GaAsP, AlInAs, AlGaAs, GaInAs, GaInP, and/or GaInAsP; or combinations thereof.

(18) In some embodiments, the transistor device **300** can include areas **302A** and **302B**. The area **302A** can be configured to form a number of first channels (e.g., a semiconductor fin structure, a stack of nanostructures/channel layers) in a relatively higher density; and the area **302B** can be configured to form a number of second channels (e.g., a semiconductor fin structure, a stack of nanostructures/channel layers) in a relatively lower density. The areas **302A** and **302B** may sometimes be referred to as “high density area **302A**” and “low density area **302B**,” respectively. As shown in FIG. 3 (and the following figures), the high density area **302A** and low density area **302B** are separated from each other by a symbolic divider **303**, which can include additional features/components/devices that are omitted for simplicity. It should be appreciated that some of the operations of the method **200** may be concurrently performed in the areas **302A** and **302B**. For purposes of illustration, some of the feature(s) formed in the areas **302A** and **302B** are hereinafter shown in the same figure that corresponds to one of the operations of the method **200**.

(19) Corresponding to operation **204** of FIG. 2, FIG. 4 is a cross-sectional view of the transistor device **300** including semiconductor fin structures **402**, **404**, and **406** in the area **302A** and semiconductor fin structures **412** and **414** in the area **302B** at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 4 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(20) The term “semiconductor fin structure” may refer to a non-planar semiconductor structure that vertically protrudes from the top surface of a planar surface. Although in the illustrated example of FIG. 4, the semiconductor fin structures **402** to **406** and **412** to **414** are each formed as a continuous one-piece structure protruding from a top surface of the substrate **302**, it should be understood that the semiconductor fin structures **402** to **406** and **412** to **414** may each be formed as a structure protruding from the top surface, while remaining within the scope of the present disclosure. For example, the semiconductor fin structures **402** to **406** and **412** to **414** can each include a number of first semiconductor layers and a number of second semiconductor layers alternately stacked on top of one another.

(21) In the high density area **302A**, the semiconductor fin structures **402-406**, each of which has a width, $W_{sub.A}$, are laterally separated from one another with a first distance (or spacing), $S_{sub.A}$;

and in the low density area **302B**, the semiconductor fin structures **412-414**, each of which has a width, $W_{sub.B}$, are laterally separated from one another with a second distance (spacing), $S_{sub.B}$. The widths $W_{sub.A}$ and $W_{sub.B}$ may each range between about 3 nanometers (nm) and about 200 nm. The spacings $S_{sub.A}$ and $S_{sub.B}$ may each range between about 3 nm and about 1000 nm. Although three and two semiconductor fin structures are shown in the area **302A** and area **302B**, respectively, it should be appreciated that the transistor device **300** can include any number of semiconductor fin structures in each of the areas **302A** and **302B**, while remaining within the scope of the present disclosure.

(22) A density of the semiconductor fin structures in the area **302A**, $D_{sub.A}$, can be characterized by the following formula: $\Sigma W_{sub.A} + \Sigma S_{sub.A}$; and a density of the semiconductor fin structures in the area **302B**, $D_{sub.B}$, can be characterized by the following formula: $\Sigma W_{sub.B} / \Sigma W_{sub.B} + \Sigma S_{sub.B}$. In some embodiments, $D_{sub.A}$ may be substantially greater than $D_{sub.B}$. In some embodiments, a ratio of $D_{sub.A}$ to $D_{sub.B}$ may be at least 1.05.

(23) The semiconductor fin structures **402** to **406** and **412** to **414** are formed by patterning the substrate **302** using, for example, photolithography and etching techniques. For example, a mask layer, such as a pad oxide layer and an overlying pad nitride layer, is formed over the substrate **302**. The pad oxide layer may be a thin film comprising silicon oxide formed, for example, using a thermal oxidation process. The pad oxide layer may act as an adhesion layer between the substrate **302** and the overlying pad nitride layer. In some embodiments, the pad nitride layer is formed of silicon nitride, silicon oxynitride, silicon carbonitride, the like, or combinations thereof. It should be understood that the pad nitride layer can include a multilayer structure (e.g., a layer of silicon oxide on a layer of silicon nitride). The pad nitride layer may be formed using low-pressure chemical vapor deposition (LPCVD) or plasma enhanced chemical vapor deposition (PECVD), for example.

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

(25) The patterned mask is subsequently used to pattern exposed portions of the substrate **302** to form trenches (or openings) **409** and **417** between adjacent ones of the semiconductor fin structures **402** to **406** and **412** to **414**, as illustrated in FIG. 4. When multiple semiconductor fin structures are formed, such a trench may be disposed between any adjacent ones of the semiconductor fin structures. In some embodiments, the semiconductor fin structures **402** to **406** and **412** to **414** are formed by etching trenches **409** and **417** in the substrate **302** using, for example, reactive ion etch (RIE), neutral beam etch (NBE), the like, or combinations thereof. The etch may be anisotropic. In some embodiments, the trenches **409** and **417** may be strips (viewed from the top) parallel to each other, and closely spaced with respect to each other. In some embodiments, the trenches **409** and **417** may be continuous and surround the semiconductor fin structures.

(26) The semiconductor fin structures **402** to **406** and **412** to **414** may be patterned by any suitable method. For example, the semiconductor fin structures **402** to **406** and **412** to **414** may be patterned using one or more photolithography processes, including double-patterning or multi-patterning processes. Generally, double-patterning or multi-patterning processes combine photolithography and self-aligned processes, allowing patterns to be created that have, for example, pitches smaller than what is otherwise obtainable using a single, direct photolithography process. For example, in one embodiment, a sacrificial layer is formed over a substrate and patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers, or mandrels, may then be used to pattern the fin.

(27) FIGS. 3 and 4 illustrate an embodiment of forming the semiconductor fin structures **402** to **406** and **412** to **414**, but a fin structure may be formed in various different processes. For example, a top portion of the substrate **302** may be replaced by a suitable material, such as an epitaxial material suitable for an intended type (e.g., N-type or P-type) of semiconductor devices to be formed. Thereafter, the substrate **302**, with epitaxial material on top, is patterned to form the semiconductor fin structures **402** to **406** and **412** to **414** that include the epitaxial material.

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

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

(30) In embodiments where epitaxial material(s) or epitaxial structures (e.g., the heteroepitaxial structures or the homoepitaxial structures) are grown, the grown material(s) or structures may be in situ doped during growth, which may obviate prior and subsequent implantations although in situ and implantation doping may be used together. Still further, it may be advantageous to epitaxially grow a material in an NMOS region different from the material in a PMOS region. In various embodiments, the semiconductor fin structures **404A-D** may include silicon germanium ($\text{Si.sub.xGe.sub.1-x}$, where x can be between 0 and 1), silicon carbide, pure or pure germanium, a III-V compound semiconductor, a II-VI compound semiconductor, or the like. For example, the available materials for forming III-V compound semiconductor include, but are not limited to, InAs, AlAs, GaAs, InP, GaN, InGaAs, InAlAs, GaSb, AlSb, AlP, GaP, and the like.

(31) Corresponding to operation **206** of FIG. 2, FIG. 5 is a cross-sectional view of the transistor device **300** including an insulation (isolation) material **502** at least partially filling the trenches **409** and **417** (FIG. 4) at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 5 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(32) The insulation material **502** can be formed as a flowable insulation layer, hereinafter “flowable insulation layer **502**.” For example, the flowable insulation layer **502** can overfill the trenches **409** and **417** and the semiconductor fin structures **402-406** and **412-414**, optionally followed by a chemical mechanical polishing (CMP) process. In another example, the flowable insulation layer **502** can partially fill the trenches **409** and **417** (i.e., with a certain amount of upper portions of the semiconductor fin structures **402-406** and **412-414** protruding from the flowable insulation layer **502**). Further, it should be understood that the trenches **409** and **417** can be filled with the insulation material **502** that is formed through a deposition-based process, for example, a chemical vapor deposition (CVD) process, a low-pressure chemical vapor deposition (LPCVD) process, a plasma enhanced chemical vapor deposition (PECVD) process, or the like, while remaining within the scope of the present disclosure.

(33) The flowable insulation layer **502** can include a flowable dielectric material such as, for example, a silicon oxide material, a silicon nitride material, or combinations thereof. The flowable insulation layer **502** is formed by using a spin on dielectric (SOD) such as a silicate, a siloxane, a methyl SilsesQuioxane (MSQ), a hydrogen SisesQuioxane (HSQ), an MSQ/HSQ, a perhydrosilazane (TCPS) or a perhydro-polysilazane (PSZ). Alternatively, the flowable insulation layer **502** can be formed by using a low temperature plasma chemical vapor deposition at a temperature less than about 100° C. under a pressure ranging from about 100 mTorr to about 10 Torr. A reaction source uses a gaseous environment containing Si.sub.3H.sub.9N and NH.sub.3 . In one embodiment, the flow rates of Si.sub.3H.sub.9N and NH.sub.3 should be in the range of about

100 standard cubic centimeters per minute (sccm) to about 1000 sccm, and of about 100 sccm to about 2000 sccm, respectively. The flowable insulation layer **502** can fill the narrow and deep gaps and prevent voids and discontinuities in an STI structure.

(34) In accordance with various embodiments, an insulation layer as-formed (e.g., through a flowable process, a deposition process, etc.) may be in an uncured state. When in the uncured state, the insulation layer may have less or nearly no bonding between its molecules/atoms. In one or more later processes (which will be discussed in further detail below), such an uncured insulation layer may be cured or otherwise converted to be in a cured state, which can cause the molecules/atoms to bond to one another. Alternatively stated, the uncured insulation layer can be densified to become the cured insulation layer.

(35) Corresponding to operation **208** of FIG. 2, FIG. 6 is a cross-sectional view of the transistor device **300** in which the flowable insulation layer **502** is recessed at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 6 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(36) An upper portion of the flowable insulation layer **502** is removed such that respective upper portions of the semiconductor fin structures **402-406** and **412-414** protrude from between neighboring remaining flowable insulation layer **502**. Respective top surfaces of the remaining flowable insulation layer **502** may have a flat surface (as illustrated in FIG. 6), a convex surface, a concave surface (such as dishing), or combinations thereof. The top surfaces of the flowable insulation layer **502** may be formed flat, convex, and/or concave by an appropriate etch. The flowable insulation layer **502** may be recessed using an acceptable dry or wet etching process, such as one that is selective to the material of the flowable insulation layer **502**.

(37) For example, a wet etching process may be used to remove the upper portion of the flowable insulation layer **502**. The wet etching process can involve exposing the workpiece having the uncured flowable insulation layer **502** thereon to an etching solution. The etching solution may be a hydrochloric acid-hydrogen peroxide mixture (HPM), sulfuric acid-hydrogen peroxide mixture (SPM), or ammonium hydroxide-hydrogen peroxide mixture (APM). In certain embodiments, the etching solution is a dilute hydrofluoric acid solution. An amount of the flowable insulation layer **502** removed is controlled by the duration of exposure and the etchant.

(38) In another example, a dry (e.g., plasma) etching process may be used to remove the upper portion of the flowable insulation layer **502**. In such a plasma etching process (including radical plasma etching, remote plasma etching, and other suitable plasma etching processes), gaseous etchants such as chlorine (Cl.sub.2), hydrogen bromide (HBr), carbon tetrafluoride (CF.sub.4), fluoroform (CHF.sub.3), difluoromethane (CH.sub.2F.sub.2), fluoromethane (CH.sub.3F), hexafluoro-1,3-butadiene (C.sub.4F.sub.6), boron trichloride (BCl.sub.3), sulfur hexafluoride (SF.sub.6), hydrogen (H.sub.2), nitrogen trifluoride (NF.sub.3), and other suitable gaseous etchants and combinations thereof can be used with passivation gases. The passivation gases can include nitrogen (N.sub.2), oxygen (O.sub.2), carbon dioxide (CO.sub.2), sulfur dioxide (SO.sub.2), carbon monoxide (CO), methane (CH.sub.4), silicon tetrachloride (SiCl.sub.4), and other suitable passivation gases and combinations thereof. Moreover, for the plasma etching process, the etchants and/or the passivation gases can be diluted with gases such as argon (Ar), helium (He), neon (Ne), and other suitable dilutive gases and combinations thereof.

(39) Corresponding to operation **210** of FIG. 2, FIG. 7 is a cross-sectional view of the transistor device **300** in which the (remaining) flowable insulation layer **502** is cured through a curing process **701** at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 7 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(40) Upon being cured, at least a portion of the flowable insulation layer **502** may be converted from the uncured state to the cured state. In the illustrated example of FIG. 7, the flowable

insulation layer **502** includes an uncured (e.g., lower) portion **502UA** and a cured (e.g., upper) portion **502CA** in the high density area **302A**; and the flowable insulation layer **502** includes an uncured (e.g., lower) portion **502UB** and a cured (e.g., upper) portion **502CB** in the low density area **302B**. In particular, the cured portion **502CA** in the high density area **302A** may have a depth (height), D.sub.a, and the cured portion **502CB** in the low density area **302B** may have a depth (height), D.sub.b. The depths D.sub.a and D.sub.b may be equal to or different from each other. (41) In various embodiments, the curing process **701** can include a radiation cure process, an oxidation cure process, a nitridization cure process, a thermal cure process, an electron beam cure process, an ion beam cure process, a plasma cure process, a microwave cure process, or combinations thereof. For example, the radiation cure process may include applying a radiation source over the uncured insulation layer **502**, in which the radiation source can include an infrared (IR) radiation source, a visible radiation source, an ultra-violet (UV) radiation source, a vacuum-ultra-violet (VUV) radiation source, or combinations thereof. In another example, the oxidation cure process may include flowing at least one of O.sub.2, CO, CO.sub.2, or SO.sub.2 to oxidize ligands of the uncured flowable insulation layer **502**. In yet another example, the nitridization cure process may include flowing at least one of N.sub.2 or NH.sub.3 to nitridize ligands of the uncured flowable insulation layer **502**.

(42) Corresponding to operation **212** of FIG. 2, FIG. 8 is a cross-sectional view of the transistor device **300** including an insulation material **802** at least partially filling the trenches **409** and **417** (FIG. 4) at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 8 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(43) The insulation material **802** can be formed as a flowable insulation layer, hereinafter referred to as “flowable insulation layer **802**.” For example, the flowable insulation layer **802** can overfill the (remaining) trenches **409** and **417** and the semiconductor fin structures **402-406** and **412-414**, optionally followed by a chemical mechanical polishing (CMP) process. In another example, the flowable insulation layer **802** can partially fill the trenches **409** and **417** (i.e., with a certain amount of upper portions of the semiconductor fin structures **402-406** and **412-414** protruding from the flowable insulation layer **802**). Moreover, it should be understood that the trenches **409** and **417** can be filled with the insulation material **502** that is formed through a deposition-based process, for example, a chemical vapor deposition (CVD) process, a low-pressure chemical vapor deposition (LPCVD) process, a plasma enhanced chemical vapor deposition (PECVD) process, or the like, while remaining within the scope of the present disclosure.

(44) The flowable insulation layer **802** can include a flowable silicon oxide or silicon nitride dielectric material, hereinafter referred to as “flowable insulation layer **802**.” The flowable insulation layer **802** is formed by using a spin on dielectric (SOD) such as a silicate, a siloxane, a methyl SilsesQuioxane (MSQ), a hydrogen SilesQuioxane (HSQ), an MSQ/HSQ, a perhydrosilazane (TCPS) or a perhydro-polysilazane (PSZ). Alternatively, the flowable insulation layer **802** can be formed by using a low temperature plasma chemical vapor deposition at a temperature less than about 100° C. under a pressure ranging from about 100 mTorr to about 10 Torr. A reaction source uses a gaseous environment containing Si.sub.3H.sub.9N and NH.sub.3. In one embodiment, the flow rates of Si.sub.3H.sub.9N and NH.sub.3 should be in the range of about 100 standard cubic centimeters per minute (sccm) to about 1000 sccm, and of about 100 sccm to about 2000 sccm, respectively. The flowable insulation layer **802** can fill the narrow and deep gaps and prevents voids and discontinuities in an STI structure.

(45) Corresponding to operation **214** of FIG. 2, FIG. 9 is a cross-sectional view of the transistor device **300** in which the at least the flowable insulation layer **802** is cured through a curing process **901** at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 9 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(46) In various embodiments, at least the flowable insulation layer **802** may be converted from the uncured state to the cured state. For example, the cured insulation layer **802** includes a portion **802CA** in the area **302A** and a portion **802CB** in the area **302B**, respectively. In various embodiments, the cured portion **802CA** can contact the cure portion **502CA** to form a thick enough cured insulation stack, hereinafter cured insulation stack **902A**, in the area **302A**. Similarly, the cured portion **802CB** can contact the cure portion **502CB** to form a thick enough cured insulation stack, hereinafter cured insulation stack **902B**, in the area **302B**. Such a sequence of etching, curing, deposition, and curing processes can be iteratively performed to form a cured insulation stack that includes a number of cured insulation layers in both of the high density and low density areas.

(47) By forming such a thick enough cured insulation stack across the areas with different densities, an etching process can be universally applied on the areas, while forming the STI structures in the areas with similar heights. When the cured insulation stacks in the trenches of the areas with different densities are thick enough, an etchant of the universal etching process can etch the cured insulation stacks in similar etching rates, while not reacting with any uncured insulation layer disposed therebelow. As such, the recessed depths across the different areas can still be controlled as being similar, which allows the semiconductor fin structures in the different areas to expose with a similar height.

(48) In various embodiments, the curing process **901** can include a radiation cure process, an oxidation cure process, a nitridization cure process, a thermal cure process, an electron beam cure process, an ion beam cure process, a plasma cure process, a microwave cure process, or combinations thereof. For example, the radiation cure process may include applying a radiation source over the uncured insulation layer **802**, in which the radiation source can include an infrared (IR) radiation source, a visible radiation source, an ultra-violet (UV) radiation source, a vacuum-ultra-violet (VUV) radiation source, or combinations thereof. In another example, the oxidation cure process may include flowing at least one of O.sub.2, CO, CO.sub.2, or SO.sub.2 to oxidize ligands of the uncured flowable insulation layer **802**. In yet another example, the nitridization cure process may include flowing at least one of N.sub.2 or NH.sub.3 to nitridize ligands of the uncured flowable insulation layer **802**.

(49) Corresponding to operation **216** of FIG. 2, FIG. 10 is a cross-sectional view of the transistor device **300** in which the cured insulation stacks **902A** and **902B** (FIG. 9) are recessed at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 10 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(50) In various embodiments, respective upper portions of the cured insulation stack **902A** in the area **302A** and the cured insulation stack **902B** in the area **302B** can be concurrently removed. As discussed above, by forming the cured insulation stacks **902A** and **902B** in thick enough thicknesses (which may be similar to or different from each other), amounts of the removed upper portions of the cured insulation stacks **902A** and **902B** can be similar, which allows a height (H.sub.A) of the semiconductor fin structures **402-406** in the area **302A** and a height (H.sub.B) of the semiconductor fin structures **412-414** in the area **302B** to be approximately the same (i.e., with a difference between H.sub.A and H.sub.B equal to about 0 nanometers (nm)). Alternatively, the difference between H.sub.A and H.sub.B may be greater than 0 nm but less than about 15 nm, while remaining within the scope of the present disclosure. As a non-limiting example, the heights H.sub.A and H.sub.B may each range between about 40 nm and about 300 nm. In various embodiments, the remaining cured insulation stack **902A** and the underlying insulation layer (e.g., the uncured insulation portion **502UA**) can collectively form a STI structure **1002A** that embeds respective lower portions of the semiconductor fin structures **402-406**; and the remaining cured insulation stack **902B** and the underlying insulation layer (e.g., the uncured insulation portion **502UB**) can collectively form a STI structure **1002B** that embeds respective lower portions of the

semiconductor fin structures **412-414**.

(51) In various embodiments, the remaining cured insulation stack **902A** may be characterized with a depth (height), D.sub.A; and the remaining cured insulation stack **902B** may be characterized with a depth (height), D.sub.B. The depths D.sub.A and D.sub.B may be equal to or different from each other. For example, when the cured depths D.sub.a and D.sub.b (FIG. 7) are about the same, the depths D.sub.A and D.sub.B may be similar to each other. In another example, when the cured depth D.sub.a is less than D.sub.b (FIG. 7), the depth D.sub.B in the low density area **302B** may be greater than the depth D.sub.A in the high density area **302A**. The depths D.sub.A and D.sub.B may each range between about 1 nm and about 500 nm.

(52) Respective top surfaces of the STI structures **1002A-B** may have a flat surface (as illustrated in FIG. 10), a convex surface, a concave surface (such as dishing), or combinations thereof. The top surfaces of the STI structures **1002A-B** may be formed flat, convex, and/or concave by an appropriate etch. The STI structures **1002A-B** may be formed by recessing the cured insulation stacks **902A-B** using an acceptable dry or wet etching process, such as one that is selective to the material of the cured insulation stack **902A-B**.

(53) For example, a wet etching process may be used to remove the upper portion of the cured insulation stack **902A-B**. The wet etching process can involve exposing the workpiece having the cured insulation stack **902A-B** thereon to an etching solution. The etching solution may be a hydrochloric acid-hydrogen peroxide mixture (HPM), sulfuric acid-hydrogen peroxide mixture (SPM), or ammonium hydroxide-hydrogen peroxide mixture (APM). In certain embodiments, the etching solution is a dilute hydrofluoric acid solution. An amount of the cured insulation stack **902A-B** removed is controlled by the duration of exposure and the etchant.

(54) In another example, a dry (e.g., plasma) etching process may be used to remove the upper portion of the cured insulation stack **902A-B**. In such a plasma etching process (including radical plasma etching, remote plasma etching, and other suitable plasma etching processes), gaseous etchants such as chlorine (Cl.sub.2), hydrogen bromide (HBr), carbon tetrafluoride (CF.sub.4), fluoroform (CHF.sub.3), difluoromethane (CH.sub.2F.sub.2), fluoromethane (CH.sub.3F), hexafluoro-1,3-butadiene (C.sub.4F.sub.6), boron trichloride (BCl.sub.3), sulfur hexafluoride (SF.sub.6), hydrogen (H.sub.2), nitrogen trifluoride (NF.sub.3), and other suitable gaseous etchants and combinations thereof can be used with passivation gases. The passivation gases can include nitrogen (N.sub.2), oxygen (O.sub.2), carbon dioxide (CO.sub.2), sulfur dioxide (SO.sub.2), carbon monoxide (CO), methane (CH.sub.4), silicon tetrachloride (SiCl.sub.4), and other suitable passivation gases and combinations thereof. Moreover, for the plasma etching process, the etchants and/or the passivation gases can be diluted with gases such as argon (Ar), helium (He), neon (Ne), and other suitable dilutive gases and combinations thereof.

(55) Corresponding to operation **218** of FIG. 2, FIG. 11 is a cross-sectional view of the transistor device **300** including an active gate structure **1102A** in the area **302A** and an active gate structure **1102B** in the area **302B** at one of the various stages of fabrication, in some embodiments. The cross-sectional view of FIG. 11 is cut along the lengthwise direction of an active/dummy gate structure of the transistor device **300** (e.g., cross-section A-A indicated in FIG. 1).

(56) As shown, the active gate structure **1102A** may straddle (e.g., respective central portions) of the semiconductor fin structures **402-406**, with its bottom surface contacting the STI structure **1002A**; and the active gate structure **1102B** may straddle (e.g., respective central portions) of the semiconductor fin structures **412-414**, with its bottom surface contacting the STI structure **1002B**. The semiconductor fin structures **402-406** and **412-414** protrude from the STI structures **1002A** and **1002B**, respectively, with the similar height. Thus, even over the semiconductor fin structures disposed in different densities, the active gate structures **1102A** and **1102B** can be formed with a similar gate height.

(57) It should be understood that prior to forming the active gate structures **1102A-B**, a number of features may have been formed in the transistor device **300**, which will be briefly described as

follows. For example, following the formation of the STI structures, dummy gate structures can be formed to straddle the semiconductor fin structures **402-406** and **412-414**, respectively. Next, on opposite sides of each of the dummy gate structures, one or more source/drain structures can be epitaxially grown in each of the semiconductor fin structures, followed by forming an interlayer dielectric (ILD) overlaying the source/drain structures. Next, the dummy gate structures may be replaced with the active gate structures, as illustrated in FIG. **11**.

(58) The active gate structures **1102A-B** can each include a gate dielectric layer, a metal gate layer, and one or more other layers that are not shown for clarity. For example, each of the active gate structures **1102A-B** may further include a capping layer and a glue layer. The capping layer can protect the underlying work function layer from being oxidized. In some embodiments, the capping layer may be a silicon-containing layer, such as a layer of silicon, a layer of silicon oxide, or a layer of silicon nitride. The glue layer can function as an adhesion layer between the underlying layer and a subsequently formed gate electrode material (e.g., tungsten) over the glue layer. The glue layer may be formed of a suitable material, such as titanium nitride.

(59) The gate dielectric layers each include silicon oxide, silicon nitride, or multilayers thereof. In example embodiments, the gate dielectric layers each include a high-k dielectric material, and in these embodiments, the gate dielectric layers may each have a k value greater than about 7.0, and may include a metal oxide or a silicate of Hf, Al, Zr, La, Mg, Ba, Ti, Pb, or combinations thereof. The formation methods of the gate dielectric layers **1802** and **1822** may include molecular beam deposition (MBD), atomic layer deposition (ALD), PECVD, and the like. A thickness of each of the gate dielectric layers may be between about 8 angstroms (Å) and about 20 Å, as an example.

(60) The metal gate layers may each be a P-type work function layer, an N-type work function layer, multi-layers thereof, or combinations thereof, in some embodiments. Accordingly, the metal gate layers may each be referred to as a work function layer, in some embodiments. In the discussion herein, a work function layer may also be referred to as a work function metal. Example P-type work function metals that may be included in the gate structures for P-type devices include TiN, TaN, Ru, Mo, Al, WN, ZrSi.sub.2, MoSi.sub.2, TaSi.sub.2, NiSi.sub.2, WN, other suitable P-type work function materials, or combinations thereof. Example N-type work function metals that may be included in the gate structures for N-type devices include Ti, Ag, TaAl, TaAlC, TiAlN, TaC, TaCN, TaSiN, Mn, Zr, other suitable N-type work function materials, or combinations thereof.

(61) A work function value is associated with the material composition of the work function layer, and thus, the material of the work function layer is chosen to tune its work function value so that a target threshold voltage $V_{sub.t}$ is achieved in the device that is to be formed. The work function layer(s) may be deposited by CVD, physical vapor deposition (PVD), ALD, and/or other suitable process. The thickness of a P-type work function layer may be between about 8 Å and about 15 Å, and the thickness of an N-type work function layer may be between about 15 Å and about 30 Å, as an example.

(62) FIGS. **12A**, **12B**, **13A**, **13B**, **14A**, **14B**, **15A**, and **15B** respectively illustrate cross-sectional views of the transistor device **300**, in various other embodiments. For example in FIGS. **12A-B**, each of the STI structures **1002A** and **1002B** may include a stack of a number of cured insulation layers, which are formed of a similar insulation material; in FIGS. **13A-B**, each of the STI structures **1002A** and **1002B** may include a stack of a number of cured insulation layers, which are formed of respective different insulation materials; in FIGS. **14A-B**, each of the STI structures **1002A** and **1002B** may include a stack of a number of uncured and cured insulation layers, which are formed of a similar insulation material; and in FIGS. **15A-B**, each of the STI structures **1002A** and **1002B** may include a stack of a number of uncured and cured insulation layers, some of which are formed of a similar insulation material and some of which are formed of respective different insulation materials.

(63) To form the STI structures **1002A-B** shown in FIG. **12A**, some of the operations of the method **200** can be again performed with minor changes. For example, when recessing first flowable

insulation layers **1202A-B** (e.g., operation **208**), the flowable insulation layers **1202A-B** may be formed shorter, followed by curing almost all the remaining flowable insulation layers **1202A-B** (e.g., operation **210**). Next, operations **212-218** can be again performed with no changes to form second flowable insulation layers **1204A-B** (in the cured state), thereby forming the STI structures **1002A-B** of FIG. **12A**. The first and second flowable insulation layers may be formed of a similar dielectric material. The first insulation layer **1202A**, second insulation layer **1204A**, first insulation layer **1202B**, and second insulation layer **1204B** may have their heights (depths), $D_{sub.A2}$, $D_{sub.A1}$, $D_{sub.B2}$, and $D_{sub.B1}$, respectively. $D_{sub.A2}$ and $D_{sub.B2}$ may be similar to or different from each other; and $D_{sub.A1}$ and $D_{sub.B1}$ may be similar to or different from each other.

(64) In some other embodiments, when recessing an insulation layer, the top surface may present a curvature-based profile (e.g., a concave surface, a convex surface, or combinations thereof). For example, the STI structures **1002A-B** shown in FIG. **12B** present a curvature-based intermediate surface at an interface between the first and second flowable insulation layers. Such a curvature-based intermediate interface can be characterized with one or more non-right angles. For example, angles, $\theta_{sub.A}$ and $\theta_{sub.B}$, exist between a relatively flat middle portion and a relatively curved (or otherwise bent) end portion of the interface between the insulation layers **1202A** and **1204A**, and between the insulation layers **1202B** and **1204B**. The angles $\theta_{sub.A}$ and $\theta_{sub.B}$ may each be an obtuse angle between about 95 degrees and about 140 degrees. The curvature-based intermediate interface may be formed during the recessing of the first flowable insulation layers **1202A-B**.

(65) To form the STI structures **1002A-B** shown in FIG. **13A**, some of the operations of the method **200** can be again performed with minor changes. For example, when recessing first flowable insulation layers **1302A-B** (e.g., operation **208**), the flowable insulation layers **1302A-B** may be formed shorter, followed by curing almost all the remaining flowable insulation layers **1302A-B** (e.g., operation **210**). Next, operations **212-218** can be again performed with no changes to form second flowable insulation layers **1304A-B** (in the cured state), thereby forming the STI structures **1002A-B** of FIG. **13A**. The first and second flowable insulation layers may be formed of respective different dielectric materials. The first insulation layer **1302A**, second insulation layer **1304A**, first insulation layer **1302B**, and second insulation layer **1304B** may have their heights (depths), $D_{sub.A2}$, $D_{sub.A1}$, $D_{sub.B2}$, and $D_{sub.B1}$, respectively. $D_{sub.A2}$ and $D_{sub.B2}$ may be similar to or different from each other; and $D_{sub.A1}$ and $D_{sub.B1}$ may be similar to or different from each other.

(66) In some other embodiments, when recessing an insulation layer, the top surface may present a curvature-based profile (e.g., a concave surface, a convex surface, or combinations thereof). For example, the STI structures **1002A-B** shown in FIG. **13B** present a curvature-based intermediate surface at an interface between the first and second flowable insulation layers. Such a curvature-based intermediate interface can be characterized with one or more non-right angles. For example, angles, $\theta_{sub.A}$ and $\theta_{sub.B}$, exist between a relatively flat middle portion and a relatively curved (or otherwise bent) end portion of the interface between the insulation layers **1302A** and **1304A**, and between the insulation layers **1302B** and **1304B**. The angles $\theta_{sub.A}$ and $\theta_{sub.B}$ may each be an obtuse angle between about 95 degrees and about 140 degrees. The curvature-based intermediate interface may be formed during the recessing of the first flowable insulation layers **1302A-B**.

(67) To form the STI structures **1002A-B** shown in FIG. **14A**, some of the operations of the method **200** can be iteratively performed. For example, after curing second insulation layers **1404A-B** disposed above first insulation layers **1402A-B** which may or may not remain in the uncured state (e.g., operations up to **214**), operations **212** and **214** may be again performed to form third insulation layers **1406A-B** (in the cured state). Operations **212** and **214** can be performed more than once. As such, the STI structures **1002A-B** of FIG. **14A**, each of which includes a stack of two or

more cured insulation layers disposed above an uncured insulation layer, can be formed. In some embodiments, the number of iterations of operations **212** to **214** may correspond to the number of cured insulation layers of the stack. The first, second, and third flowable insulation layers may be formed of a similar dielectric material. The first insulation layer **1402A**, second insulation layer **1404A**, third insulation layer **1406A**, first insulation layer **1402B**, second insulation layer **1404B**, and third insulation layer **1406B** may have their heights (depths), D.sub.A3, D.sub.A2, D.sub.A1, D.sub.B3, D.sub.B2, D.sub.B1, respectively. D.sub.A3 and D.sub.B3 may be similar to or different from each other; D.sub.A2 and D.sub.B2 may be similar to or different from each other; and D.sub.A1 and D.sub.B1 may be similar to or different from each other.

(68) In some other embodiments, when recessing an insulation layer, the top surface may present a curvature-based profile (e.g., a concave surface, a convex surface, or combinations thereof). For example, the STI structures **1002A-B** shown in FIG. **14B** present at least one of a curvature-based intermediate surface at an interface between the first and second flowable insulation layers, or a curvature-based intermediate surface at an interface between the second and third flowable insulation layers. Such a curvature-based intermediate interface can be characterized with one or more non-right angles. For example, angles, $\theta_{\text{sub.A}}$ and $\theta_{\text{sub.B}}$, exist between a relatively flat middle portion and a relatively curved (or otherwise bent) end portion of the interface between the insulation layers **1404A** and **1406A**, and between the insulation layers **1404B** and **1406B**. The angles $\theta_{\text{sub.A}}$ and $\theta_{\text{sub.B}}$ may each be an obtuse angle between about 95 degrees and about 140 degrees. The curvature-based intermediate interfaces may be formed during the recessing of the first flowable insulation layers **1402A-B** and/or the second flowable insulation layers **1404A-B**.

(69) To form the STI structures **1002A-B** shown in FIG. **15A**, some of the operations of the method **200** can be iteratively performed. For example, after curing second insulation layers **1504A-B** disposed above first insulation layers **1502A-B** which may or may not remain in the uncured state (e.g., operations up to **214**), operations **212** and **214** may be again performed to form third insulation layers **1506A-B** (in the cured state). Operations **212** and **214** can be performed more than once. As such, the STI structures **1002A-B** of FIG. **15A**, each of which includes a stack of two or more cured insulation layers disposed above an uncured insulation layer, can be formed. In some embodiments, the number of iterations of operations **212** to **214** may correspond to the number of cured insulation layers of the stack. Some of the first, second, and third flowable insulation layers may be formed of respective different dielectric materials. The first insulation layer **1502A**, second insulation layer **1504A**, third insulation layer **1506A**, first insulation layer **1502B**, second insulation layer **1504B**, and third insulation layer **1506B** may have their heights (depths), D.sub.A3, D.sub.A2, D.sub.A1, D.sub.B3, D.sub.B2, D.sub.B1, respectively. D.sub.A3 and D.sub.B3 may be similar to or different from each other; D.sub.A2 and D.sub.B2 may be similar to or different from each other; and D.sub.A1 and D.sub.B1 may be similar to or different from each other.

(70) In some other embodiments, when recessing an insulation layer, the top surface may present a curvature-based profile (e.g., a concave surface, a convex surface, or combinations thereof). For example, the STI structures **1002A-B** shown in FIG. **15B** present at least one of a curvature-based intermediate surface at an interface between the first and second flowable insulation layers, or a curvature-based intermediate surface at an interface between the second and third flowable insulation layers. Such a curvature-based intermediate interface can be characterized with one or more non-right angles. For example, angles, $\theta_{\text{sub.A}}$ and $\theta_{\text{sub.B}}$, exist between a relatively flat middle portion and a relatively curved (or otherwise bent) end portion of the interface between the insulation layers **1504A** and **1506A**, and between the insulation layers **1404B** and **1406B**. The angles $\theta_{\text{sub.A}}$ and $\theta_{\text{sub.B}}$ may each be an obtuse angle between about 95 degrees and about 140 degrees. The curvature-based intermediate interfaces may be formed during the recessing of the first flowable insulation layers **1502A-B** and/or the second flowable insulation layers **1504A-B**.

(71) FIG. **16** illustrates a cross-sectional view of the transistor device **300** where each of the semiconductor fin structures (channels) **402** to **406** and **412** to **414** includes a number of

semiconductor layers, in some embodiments. The cross-sectional view of the transistor device **300** in FIG. **16** is cut along the lengthwise direction of a gate structure, e.g., cross-section A-A (as indicated in FIG. **1**).

(72) Such semiconductor layers may be vertically separated with each other, and each of the semiconductor layers may be wrapped around by an active gate structure. As shown, the active gate structure **1102A** can wrap around each of the semiconductor layers of the fin structure **402**, each of the semiconductor layers of the fin structure **404**, and each of the semiconductor layers of the fin structure **406**; and the active gate structure **1102B** can wrap around each of the semiconductor layers of the fin structure **412** and each of the semiconductor layers of the fin structure **414**. The cross-sectional view of FIG. **16** illustrates the transistor device **300** that includes the STI structures **1002A-B** shown in FIG. **11**, but it should be appreciated that the transistor device **300** (with it channel having one or more vertically separated semiconductor layers) can include other embodiments of the STI structures as shown in FIGS. **12A-15B**, while remaining within the scope of present disclosure.

(73) In one aspect of the present disclosure, a semiconductor device is disclosed. The semiconductor device includes a substrate including a first area and a second area. The semiconductor device in the first area includes: a plurality of first non-planar semiconductor structures, wherein the first non-planar semiconductor structures, parallel with one another, are separated with a first distance; and a first isolation region comprising a first layer and a second layer that collectively embed a lower portion of each of the first non-planar semiconductor structures, wherein at least one of the first layer or second layer is in a cured state. The semiconductor device in the second area includes: a plurality of second non-planar semiconductor structures, wherein the second non-planar semiconductor structures, parallel with one another, are separated with a second distance; and a second isolation region comprising a first layer and a second layer that collectively embed a lower portion of each of the second non-planar semiconductor structures, wherein at least one of the first or second layer is in a cured state.

(74) In another aspect of the present disclosure, a method for making a semiconductor device is disclosed. The method includes forming a plurality of fin structures over a substrate. The method includes filling trenches between adjacent one of the fin structures with a first insulation material. The method includes recessing the first insulation material. The method includes densifying at least an upper portion of the first insulation material. The method includes filling the trenches with a second insulation material. The method includes densifying the second insulation material, thereby causing the densified second insulation material to be in contact with the densified upper portion of the first insulation material. The method includes removing at least a portion of the densified second insulation material to form a shallow trench isolation between the adjacent fin structures.

(75) In yet another aspect of the present disclosure, a method for making a semiconductor device is disclosed. The method includes forming a plurality of first fin structures and a plurality of second fin structures over respective areas of a substrate. The method includes filling trenches between the first fin structures and trenches between the second fin structures with a first insulation material, respectively. The method includes recessing the first insulation material disposed in the trenches between the first fin structures and the first insulation material disposed in the trenches between the second fin structures, respectively. The method includes curing an upper portion of the recessed first insulation material disposed in the trenches between the first fin structures and an upper portion of the recessed first insulation material disposed in the trenches between the second fin structures, respectively.

(76) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such

equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

Claims

1. A semiconductor device, comprising: a plurality of first non-planar semiconductor structures disposed in a first area of a substrate, wherein the first non-planar semiconductor structures, parallel with one another, are separated with a first distance; and a first isolation region collectively embedding a lower portion of each of the first non-planar semiconductor structures and comprising a first layer and a second layer, wherein the second layer is disposed above the first layer, and wherein at least the second layer of the first isolation region is in a cured state.
2. The semiconductor device of claim 1, further comprising: a plurality of second non-planar semiconductor structures disposed in a second area of the substrate, wherein the second non-planar semiconductor structures, parallel with one another, are separated with a second distance; and a second isolation region collectively embedding a lower portion of each of the second non-planar semiconductor structures and comprising a first layer and a second layer, wherein the second layer is disposed above the first layer, and wherein at least the second layer of the second isolation region is in a cured state.
3. The semiconductor device of claim 2, wherein the first distance is less than the second distance.
4. The semiconductor device of claim 2, wherein a first height of a non-embedded, upper portion of each of the first non-planar semiconductor structures is equal to a second height of a non-embedded, upper portion of each of the second non-planar semiconductor structures.
5. The semiconductor device of claim 1, wherein each of the first non-planar semiconductor structures comprises a plurality of first channel layers vertically separated from one another.
6. The semiconductor device of claim 1, wherein the one of the first and second layers of the first isolation region that is in the cured state is disposed above the other one of first and second layers of the first isolation region that is in an uncured state.
7. The semiconductor device of claim 1, further comprising: a first gate structure over a non-embedded, upper portion of each of the first non-planar semiconductor structures.
8. The semiconductor device of claim 1, wherein the one of the first and second layers of the first isolation region that is in the cured state has a higher density than the other one of first and second layers of the first isolation region that is in an uncured state.
9. The semiconductor device of claim 1, wherein the first isolation region further comprises a third layer, together with the first and second layers of the first isolation region, that collectively embed the lower portion of each of the first non-planar semiconductor structures.
10. The semiconductor device of claim 9, wherein the third layer of the first isolation region is in an uncured state and disposed below the first and second layers of the first isolation region.
11. The semiconductor device of claim 9, wherein the third layer of the first isolation region is in the cured state and disposed above one of the first and second layers of the first isolation region that is in an uncured state.
12. A semiconductor device, comprising: a plurality of non-planar semiconductor structures, wherein the non-planar semiconductor structures, parallel with one another, are separated with a distance; and an isolation region collectively embedding a lower portion of each of the non-planar semiconductor structures and comprising at least a first layer and a second layer; wherein the second layer is disposed above the first layer, and wherein at the second layer of the isolation region is in a cured state and the first layer of the isolation region is in an uncured state.
13. The semiconductor device of claim 12, wherein each of the non-planar semiconductor structures comprises a plurality of channel layers vertically separated from one another.
14. The semiconductor device of claim 12, further comprising a gate structure over a non-

embedded, upper portion of each of the non-planar semiconductor structures.

15. The semiconductor device of claim 12, wherein the first layer of the isolation region has a first density and the second layer of the isolation region has a second density, and wherein the second density is higher than the first density.

16. The semiconductor device of claim 12, wherein the isolation region further comprises a third layer, together with the first and second layers of the isolation region, that collectively embed the lower portion of each of the non-planar semiconductor structures.

17. The semiconductor device of claim 16, wherein the third layer of the isolation region is in an uncured state and disposed below the first and second layers of the isolation region.

18. The semiconductor device of claim 16, wherein the third layer of the isolation region is in the cured state and disposed between the first and second layers of the isolation region.

19. A semiconductor device, comprising: a plurality of non-planar semiconductor structures, wherein the non-planar semiconductor structures, parallel with one another, are separated with a distance; and an isolation region collectively embedding a lower portion of each of the non-planar semiconductor structures and comprising at least a first layer and a second layer; wherein the second layer is disposed above the first layer, wherein at the second layer of the isolation region is in a cured state and the first layer of the isolation region is in an uncured state, and wherein the first layer of the isolation region has a first density and the second layer of the isolation region has a second density, and wherein the second density is higher than the first density.

20. The semiconductor device of claim 19, wherein the isolation region further comprises a third layer, together with the first and second layers of the isolation region, that collectively embed the lower portion of each of the non-planar semiconductor structures.
