METHODS OF FORMING CARBON-CONTAINING SILICON EPITAXIAL LAYERS

The present application claims priority to U.S. Provisional Patent Application Serial No. 60/834,773 filed July 31, 2006, and entitled "METHODS OF FORMING CARBON-CONTAINING SILICON EPITAXIAL LAYERS" (Attorney Docket No. 10595/L) which is hereby incorporated herein by reference in its entirety for all purposes.

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is related to the following co-pending applications, each of which is hereby incorporated by reference herein in its entirety:

U.S. Patent Application Serial No. 11/001,774, filed December 1, 2004 (Docket No. 9618); and

U.S. Patent Application Serial No. 11/227,974, filed September 14, 2005 (Docket No. 9618/P01).

FIELD OF THE INVENTION

The present invention relates to semiconductor device manufacturing, and more specifically to methods of forming carbon-containing silicon epitaxial layers.

BACKGROUND

As smaller transistors are manufactured, ultra shallow source/drain junctions are becoming more challenging to produce. Generally, sub-100 nm CMOS (complementary metal-oxide semiconductor) devices require a junction depth to be less than 30 nm. Selective epitaxial deposition is often utilized to form epilayers of silicon-containing materials (*e.g.*, Si, SiGe and SiC) into the junctions. Generally, selective epitaxial deposition permits growth of epilayers on silicon moats with no growth on dielectric areas. Selective epitaxy can be used within semiconductor

devices, such as elevated source/drains, source/drain extensions, contact plugs or base layer deposition of bipolar devices.

Generally, a selective epitaxy process involves a deposition reaction and an etch reaction. The deposition and etch reactions occur simultaneously with relatively different reaction rates to an epitaxial layer and to a polycrystalline layer. During the deposition process, the epitaxial layer is formed on a monocrystalline surface while a polycrystalline layer is deposited on at least a second layer, such as an existing polycrystalline layer and/or an amorphous layer. However, the deposited polycrystalline layer is generally etched at a faster rate than the epitaxial layer. Therefore, by changing the concentration of an etchant gas, the net selective process results in deposition of epitaxy material and limited, or no, deposition of polycrystalline material. For example, a selective epitaxy process may result in the formation of an epilayer of silicon-containing material on a monocrystalline silicon surface while no deposition is left on a spacer.

Selective epitaxy deposition of silicon-containing materials has become a useful technique during formation of elevated source/drain and source/drain extension features, for example, during the formation of silicon-containing MOSFET (metal oxide semiconductor field effect transistor) devices. Source/drain extension features are manufactured by etching a silicon surface to make a recessed source/drain feature and subsequently filling the etched surface with a selectively grown epilayer, such as a silicon germanium (SiGe) material. Selective epitaxy permits near complete dopant activation with *in-situ* doping, so that the post annealing process is omitted. Therefore, junction depth can be defined accurately by silicon etching and selective epitaxy. On the other hand, the ultra shallow source/drain junction inevitably results in increased series resistance.

Also, junction consumption during silicide formation increases the series resistance even further. In order to compensate for junction consumption, an elevated source/drain is epitaxially and selectively grown on the junction. Typically, the elevated source/drain layer is undoped silicon.

However, current selective epitaxy processes have some drawbacks. In order to maintain selectivity during present epitaxy processes, chemical concentrations of the precursors, as well as reaction temperatures must be regulated and adjusted throughout the deposition process. If not enough silicon precursor is administered, then the etching reaction may dominate and the overall process is slowed down. Also, harmful over etching of substrate features may occur. If not enough etchant precursor is administered, then the deposition reaction may dominate reducing the selectivity to form monocrystalline and polycrystalline materials across the substrate surface. Also, current selective epitaxy processes usually require a high reaction temperature, such as about 800°C, 1,000°C or higher. Such high temperatures are not desirable during a fabrication process due to thermal budget considerations and possible uncontrolled nitridation reactions to the substrate surface. Furthermore, some epitaxial films and/or processes are prone to morphological deficiencies such as pitting or surface roughness in the films.

Therefore, there is a need to have a process for selectively and epitaxially depositing silicon and silicon-containing compounds. Furthermore, the process should be versatile to form silicon-containing compounds with varied elemental concentrations while having a fast deposition rate and maintaining a process temperature, such as about 800°C or less. Finally, the process should result in a low defect film or film stack (e.g., with little pitting, dislocations, roughness, point defects, etc.).

SUMMARY OF THE INVENTION

In a first aspect of the invention, a method is provided for forming an epitaxial layer stack on a substrate. The method includes (1) selecting a target carbon concentration for the epitaxial layer stack; (2) forming a carbon-containing silicon layer on the substrate, the carbon-containing silicon layer having at least one of an initial carbon concentration, a thickness and a deposition time selected based on the selected target carbon concentration; and (3) forming a non-carbon-containing silicon layer on the carbon-containing silicon layer prior to etching.

In a second aspect of the invention, a method is provided for forming an epitaxial layer stack. The method includes (1) selecting a target carbon concentration for the epitaxial layer stack; and (2) forming the epitaxial layer stack by depositing alternating carbon-containing silicon layers and non-carbon-containing silicon layers. The target carbon concentration is achieved based on at least one of a total thickness, an initial carbon concentration, and a deposition time for the carbon-containing silicon layers.

In a third aspect of the invention, a method is provided for controlling carbon concentration in an epitaxial layer stack formed on a substrate. The method includes (1) determining a desired carbon concentration for the epitaxial layer stack; and (2) forming the epitaxial layer stack by (a) forming a carbon-containing epitaxial layer on the substrate; and (b) forming a non-carbon-containing cap layer on the carbon-containing epitaxial layer. A thickness of the carbon-containing epitaxial layer is selected based on the desired carbon concentration for the epitaxial layer stack. Numerous other aspects are provided.

Other features and aspects of the present

invention will become more fully apparent from the following detailed description, the appended claims and the accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

FIGS. 1A-1D illustrate cross-sectional views of a substrate during formation of an epitaxial layer stack in accordance with the present invention.

FIG. 2 is a graph illustrating a concentration of carbon throughout stacked layers of a non-carbon-containing seed epitaxial layer, a carbon-containing epitaxial layer and a non-carbon-containing cap epitaxial layer formed in accordance with the present invention.

FIG. 3 is a graph illustrating the dependence of substitutional carbon (SC) concentration on the deposition time of a carbon-containing epitaxial layer for fixed deposition times of seed and cap epitaxial layers in accordance with the present invention.

FIG. 4 is a flowchart of an exemplary method for forming an epitaxial layer stack having a target carbon concentration in accordance with the present invention.

DETAILED DESCRIPTION

During a selective epitaxial growth process on a silicon substrate patterned with dielectric films, formation of single-crystal semiconductor occurs only on exposed silicon surfaces (e.g., not on dielectric surfaces). Selective epitaxial growth processes may include simultaneous etch-deposition processes as well as alternating gas supply processes. In a simultaneous etch-deposition process, both etchant species and deposition species are flowed simultaneously. As such, an epitaxial layer is simultaneously deposited and etched during its formation.

In contrast, previously incorporated U.S. Patent

Application Serial No. 11/001,774, filed December 1, 2004 (Docket No. 9618), describes an alternating gas supply (AGS) process for forming epitaxial layers on a substrate. During an AGS process, an epitaxial deposition process is conducted on a substrate, and then an etching process is conducted on the substrate. The cycle of an epitaxial deposition process followed by an etching process is repeated until a desired thickness of an epitaxial layer is formed.

A deposition process may include exposing the substrate surface to a deposition gas containing at least a silicon source and a carrier gas. The deposition gas may also include a germanium source and/or a carbon source, as well as a dopant source. Common dopants may include arsenic, boron, phosphorus, antimony, gallium, aluminum and other elements.

During the deposition process, an epitaxial layer is formed on the monocrystalline surface(s) of the substrate while a polycrystalline layer is formed on secondary surfaces, such as amorphous and/or polycrystalline surfaces. Subsequently, the substrate is exposed to an etching gas. The etching gas includes a carrier gas and an etchant. The etching gas removes silicon-containing materials deposited during the deposition process. During the etching process, the polycrystalline layer is removed at a faster rate than the epitaxial layer. Therefore, the net result of the deposition and etching processes forms epitaxially grown silicon-containing material on monocrystalline surfaces while minimizing growth, if any, of polycrystalline silicon-containing material on the secondary surfaces. Exemplary silicon-containing materials which can be deposited include silicon, silicon germanium, silicon carbon, silicon germanium carbon, dopant variants thereof and the like.

Conventional silicon epitaxial film formation processes employ hydrogen (H_2), hydrogen chloride (HCl) and a silicon source such as dichlorosilane and are performed at a

substrate temperature above about 700 degrees Celsius (e.g., to dissociate HCl and/or the silicon source). One approach to reduce the epitaxial film formation temperature is to employ chlorine (Cl_2) in place of HCl, as Cl_2 dissociates efficiently at lower temperatures (e.g., about 600 degrees Celsius or less). Because of incompatibility between hydrogen and Cl_2, a carrier gas other than hydrogen, such as nitrogen, may be employed with Cl_2. Similarly, a silicon source having a lower dissociation temperature may be employed (e.g., silane (SiH_4), disilane (Si_2H_6), etc.).

The use of Cl_2 as the etchant gas for a silicon epitaxial film formation process may lead to poor surface morphology of the resultant silicon epitaxial film. While not wishing to be bound by any particular theory, it is believed that Cl_2 may over aggressively attack a silicon epitaxial film surface, producing pitting or the like. The use of Cl_2 has been found to be particularly problematic when the silicon epitaxial film contains carbon.

The present invention provides methods for employing Cl_2 as an etchant gas during a silicon epitaxial film formation process that may improve epitaxial film surface morphology. The inventive methods may be used, for example, with the alternating gas supply (AGS) process described in U.S. Patent Application Serial No. 11/001,774, filed December 1, 2004 (Docket No. 9618).

In some embodiments, any carbon-containing silicon epitaxial films may be "encapsulated" prior to being exposed to Cl_2 during an etch phase. A carbon-containing silicon epitaxial film may be encapsulated, for example, via a silicon epitaxial film formed without a carbon source (a "non-carbon-containing silicon epitaxial film").

As an example, formation of a carbon-containing silicon epitaxial layer stack in accordance with the present invention, and employing an AGS process, is described below with reference to FIGS. 1A-1D. With reference to FIG. 1A, a

cross-sectional view of a substrate 100 is illustrated having a seed epitaxial layer 102 (*e.g.*, a silicon (Si) epitaxial layer) formed on the substrate 100. In some embodiments, the seed epitaxial layer 102 may be eliminated.

To form the seed epitaxial layer 102, the substrate 100 may be placed in a processing chamber, and heated to a desired substrate and/or process temperature. An exemplary epitaxial film chamber may be found in the Epi Centura® system and the Poly Gen® system available from Applied Materials, Inc., located in Santa Clara, California, although other epitaxial film chambers and/or systems may be used. In at least one embodiment of the invention, a substrate and/or process temperature of less than about 700 degrees Celsius may be employed to improve carbon incorporation within any silicon epitaxial layer formed within the process chamber. In a particular embodiment, a substrate and/or process temperature range of between about 550 to 650 degrees Celsius may be used, and in yet another embodiment, a substrate and/or process temperature of less than about 600 degrees Celsius may be used. Other substrate and/or process temperatures may be used, including substrate and/or process temperatures above 700 degrees Celsius.

After the desired substrate and/or process temperature has been reached, the substrate 100 is exposed to at least a silicon source (without a carbon source) so as to form the seed epitaxial layer 102. For example, the substrate 100 may be exposed to a silicon source such as silane or disilane, and a carrier gas such as nitrogen. A dopant source such as phosphorous or boron, a germanium source or the like also may be used (as may any other suitable sources and/or gasses). During the epitaxial film formation process, the epitaxial layer 102 may be formed on any monocrystalline surface of the substrate 100 while a polycrystalline layer may be formed on any polycrystalline

layer and/or any amorphous layer present on the substrate 100 (as previously described).

The seed epitaxial layer 102 may be formed, for example, by flowing a silicon source at a flow rate of about 50-150 sccm for silane (or a flow rate of about 10 - 40 sccm for disilane) and a nitrogen carrier gas at a flow rate of about 20 - 25 slm (although larger or smaller silicon source and/or carrier gas flow rates may be used). HCl may also be flowed if desired.

In at least one embodiment, the seed epitaxial layer 102 may have a thickness of about 2 angstroms to about 100 angstroms, although other thicknesses may be used. For example, a deposition time of about 1 second to about 100 seconds, and in one or more embodiments about 5 seconds, may be used.

After the seed epitaxial layer 102 is formed (if used at all), the substrate 100 is exposed to at least a silicon source and a carbon source so as to form a carbon-containing silicon epitaxial layer 104 (FIG. 1B) on the substrate 100 over the seed epitaxial layer 102. For example, the substrate 100 may be exposed to a silicon source such as silane or disilane, a carbon source such as methane, and a carrier gas such as nitrogen. A dopant source such as phosphorous or boron, a germanium source or the like also may be used (as may any other suitable sources and/or gasses). During the epitaxial film formation process, a carbon-containing epitaxial layer may be formed on any monocrystalline surface of the substrate 100 while a polycrystalline layer may be formed on any polycrystalline layer and/or any amorphous layer present on the substrate 100 (as previously described).

In at least one embodiment, a carbon source flow rate of approximately 1 - 5 sccm for methane may be used

with a silicon source at a flow rate of about 50 - 150 sccm for silane (or of about 10 - 40 sccm for disilane) and a nitrogen carrier gas at a flow rate of about 20 - 25 slm (although larger or smaller silicon source and/or carrier gas flow rates may be used). HCl may also be flowed if desired.

The carbon-containing epitaxial layer 104 may have, for example, a thickness of about 2 angstroms to about 100 angstroms, although other thicknesses may be used. For example, a deposition time of about 1 second to about 50 seconds, and in one or more embodiments about 10 seconds, may be used.

After the carbon-containing silicon epitaxial layer 104 is formed, the substrate 100 is exposed to at least a silicon source (without a carbon source) so as to form a second silicon epitaxial layer 106 (e.g., a capping layer as shown in FIG. 1C) on the substrate 100 over the carbon-containing silicon epitaxial layer 104. For example, the substrate 100 may be exposed to a silicon source such as silane or disilane, and a carrier gas such as nitrogen. A dopant source such as phosphorous or boron, a germanium source or the like also may be used (as may any other suitable sources and/or gasses). The presence of the second silicon epitaxial layer 106 over the carbon-containing silicon epitaxial layer 104 may diminish the interaction of chlorine with carbon (and/or hydrogen) in the carbon-containing silicon epitaxial layer 104. HCl may also be flowed as described previously.

The second silicon epitaxial layer 106 may be formed, for example, by flowing a silicon source at a flow rate of about 50-150 sccm for silane (or a flow rate of about 10 - 40 sccm for disilane) and a nitrogen carrier gas at a flow rate of about 20 to 25 slm (although larger or

smaller silicon source and/or carrier gas flow rates may be used). HCl may also be flowed.

In at least one embodiment, the second silicon epitaxial layer 106 may have a thickness of about 2 angstroms to about 100 angstroms, although other thicknesses may be used. For example, a deposition time of about 1 second to about 100 seconds, and in one or more embodiments about 5 seconds, may be used.

An epitaxial layer stack 108 thereby is formed, in which the carbon-containing epitaxial layer 104 is encapsulated between non-carbon-containing epitaxial layers 102, 106 (e.g., epitaxial layers that are formed without an intentional carbon source).

After formation of the second silicon epitaxial layer 106, the substrate 100 may be exposed to Cl2 and/or another etchant so as to etch at least the second silicon epitaxial layer 106, and/or any other films formed on the substrate 100 (e.g., polycrystalline silicon formed on polycrystalline and/or amorphous layers present on the substrate 100 and/or monocrystalline silicon formed on the carbon-containing silicon epitaxial layer 104). For example, in at least one embodiment, the substrate 100 may be exposed to a Cl2 flow rate of about 30-50 sccm and a nitrogen carrier gas flow rate of 20 slm (although larger or smaller Cl2 and/or nitrogen carrier gas flow rates may be used). HCl may also be flowed.

Following etching, the process chamber being employed may be purged (e.g., with nitrogen and/or another inert gas for about 20 seconds or for some other suitable time period) to remove any Cl2 and/or any other unwanted species/by-products from the chamber.

The cap epitaxial layer 106 and/or seed layer 102 prevent a reaction from occurring between an etchant and carbon in the carbon-containing epitaxial layer 104. As such, Cl_2 may be employed as the etchant because the underlying carbon-containing layer is not exposed to the Cl_2 during etching. Accordingly, the carbon-containing epitaxial layer 102 will not have a pitted surface morphology, but rather a smooth surface morphology.

Deposition and etching sequences may be repeated until the desired total epitaxial layer stack thickness is achieved as shown, for example, in FIG. 1D. For example, the sequence of non-carbon-containing silicon layer deposition/carbon-containing silicon layer deposition/non-carbon-containing silicon layer deposition/etching may be repeated about 80 times to yield a total epitaxial layer stack thickness of about 600 Å. In other embodiments, deposition of an underlying seed layer may be eliminated, so that the formation sequence may be carbon-containing silicon layer deposition/non-carbon-containing silicon layer deposition/etching repeated a number of times to yield the desired total epitaxial layer stack thickness.

While the above examples illustrate particular embodiments, in general, the epitaxial layer stack (which includes carbon-containing epitaxial layers and non-carbon-containing epitaxial layers) may have a thickness in a range from about 10 Å to about 2,000 Å, preferably from about 100 Å to about 1,500 Å, and more preferably from about 300 Å to about 1,000 Å. In one particular embodiment, a layer stack of about 600 Å may be used.

By controlling the (1) film thickness of the encapsulated carbon-containing epitaxial layer(s) relative to the non-carbon-containing epitaxial material; and (2) carbon concentration in the carbon-containing epitaxial layer(s), average carbon concentration of the final epitaxial layer stack may be controlled and/or determined.

For example, in some embodiments, the carbon in the carbon-containing epitaxial layer(s) may quickly and uniformly diffuse along a depth of the stacked layers (e.g., the seed layer, carbon-containing layer and cap layer), even though carbon is only deposited during the carbon-containing epitaxial layer formation step.

FIG. 2 is a graph 200 illustrating a concentration of carbon throughout stacked layers of a non-carbon-containing seed epitaxial layer, a carbon-containing epitaxial layer and a non-carbon-containing cap epitaxial layer formed in accordance with the present invention (such as in FIG. 1C). As may be seen with reference to FIG. 2, a concentration of carbon, generally indicated by a line 202, is uniformly distributed throughout a depth of the stacked layers, (where the X-axis represents a depth of the stacked layers and the Y-axis represents carbon distribution throughout the stacked layers). As such, according to some embodiments of the present invention, the concentration of carbon within the stacked layers may be controlled by controlling the relative thicknesses of the carbon-containing layer and/or of the seed and/or cap layers, as well as initial carbon concentration within the carbon-containing layer.

In some embodiments, final carbon concentration can be estimated from the relative thickness of the carbon-containing epitaxial layer to the non-carbon-containing epitaxial layer(s). For example, FIG. 3 is a graph 300 illustrating the dependence of substitutional carbon (SC) concentration on the deposition time of the carbon-containing epitaxial layer for fixed deposition times of the seed and cap layers (e.g., in FIG. 1C). As may be seen with reference to line 302 in FIG. 3, the concentration of carbon within the stack layers is proportional to the deposition time of the carbon-containing epitaxial layer. Thus, according to some embodiments of the present invention, the

concentration of carbon within a seed layer/carbon-containing layer/cap layer stack or "sandwich" may be controlled by controlling the deposition time of the carbon-containing epitaxial layer.

In one or more embodiments, the target carbon concentration of an epitaxial layer stack may be in the range from about 200 parts per million (ppm) to about 5 atomic percent (at%), preferably from about 0.5 at% to about 2 at%, for example about 1.5 at%. Other target concentrations may be used. In some embodiments, the carbon concentration may be graded within an epitaxial layer (such as layer 104 in FIGS. 1A-1D).

Carbon incorporated in carbon-containing silicon layers is generally located in interstitial sites of the crystalline lattice immediately following the deposition of the silicon-containing layer. The initial carbon concentration, or in other words, the as-deposited carbon content in a carbon-containing layer may be about 10 at% or less, preferably less than about 5 at% and more preferably from about 0.5 at% to about 3 at%, for example, about 2 at%. Either by annealing (described below) or by natural diffusion during (subsequent) process steps, an epitaxial layer may incorporate at least a portion, if not all of the interstitial carbon into substitutional sites of the crystalline lattice. The total carbon concentration of the epitaxial layer stack includes all carbon, whether interstitially or substitutionally incorporated in the stack. High resolution X-ray diffraction (XRD) may be used to determine substitutional carbon concentration and thickness. Secondary Ion Mass Spectroscopy (SIMS) may be used to determine the total (substitutional and interstitial) carbon concentration in the epitaxial layer stack. Substitutional carbon concentration may be equal to or lower than the total carbon concentration. A suitable annealing process may include a spike anneal, such as a rapid thermal process

(RTP), laser annealing or thermal annealing with an atmosphere of gas, such as oxygen, nitrogen, hydrogen, argon, helium or combinations thereof. In some embodiments, an annealing process may be conducted at a temperature from about 800°C to about 1,200°C, preferably from about 1,050°C to about 1,100°C. Such an annealing process may occur immediately after the capping non-carbon-containing layer 106 is deposited or after a variety of other process steps (e.g., such as after the entire film stack is deposited).

FIG. 4 is a flowchart of an exemplary method 400 for forming an epitaxial layer stack having a target carbon concentration in accordance with the present invention. With reference to FIG. 4, in step 401, a substrate is loaded into a process chamber and is heated to a temperature of about 800 °C or less. In some embodiments, a lower temperature range may be used during epitaxial film formation, such as less than 750°C, less than 700°C or less than 650°C.

In step 402, a carbon-containing epitaxial layer is formed on the substrate. The initial carbon concentration, thickness and/or deposition time of the carbon-containing epitaxial layer may be selected based on the target carbon concentration for the epitaxial layer stack. Thereafter, in step 403 a non-carbon-containing epitaxial layer is formed on the carbon-containing epitaxial layer. In some embodiments, the non-carbon-containing epitaxial layer is thick enough to protect the underlying carbon-containing layer from subsequent etching.

In step 404, the substrate is etched using an etchant gas such as HCl and/or Cl_2. As stated, the non-carbon-containing epitaxial layer protects the underlying carbon-containing epitaxial layer from the etchant gas. A purge step (not shown) may be employed following etching so as to remove any etchant gas and/or other undesirable gases from the process chamber being employed.

In step 405, a determination is made whether the desired epitaxial layer stack thickness has been reached. If so, the process ends in step 406; otherwise, the process returns to step 402 to deposit additional epitaxial material on the substrate.

In another exemplary embodiment, a process cycle may include (1) a non-carbon-containing silicon (Si) layer deposition step; (2) a carbon-containing silicon (Si:C) layer deposition step; (3) a non-carbon-containing silicon (Si) layer deposition step; (4) an etch step; and (5) a purge step. The process cycle may be repeated numerous times to achieve an overall epitaxial layer stack thickness. In one particular embodiment, the process cycle may be repeated about 80 times to obtain about 600 angstroms of epitaxial material for an epitaxial layer stack. In this case, each deposition of Si or Si:C may result in about 5 to 30 angstroms of epitaxial material, a portion of which is etched away by a subsequent etch step (e.g., about 15-25 angstroms). After about 80 repetitions, the remaining epitaxial material (e.g., on a Si moat) may be about 600 angstroms (with little or no deposition on dielectric regions of the substrate). In other embodiments, an epitaxial layer stack thickness range of about 30 to 100 nanometers may be used.

In some embodiments, a substitutional carbon concentration range for an epitaxial layer stack and/or for an as-deposited Si:C layer may be about 0.5-2.0 at%. When the Si:C layer is sandwiched within Si layers, the total stack carbon concentration is reduced depending on the thickness of the Si layers compared to thickness of the Si:C layer. Depending on process conditions, substitutional carbon concentration may be equal to or lower than total carbon concentration.

Exemplary gas flow ranges include silicon source flow rates of about 5-500 sccm for dichlorosilane, silane,

disilane, or high order silane, carbon source flow rates of about 1-30 sccm for mono methylsilane, and carrier gas flow rates of about 3-30 slm for H2 or N2. During etching, an exemplary flow rate for HCl is about 20-1000 sccm and for Cl2 is about 10-500 sccm.

In one particular embodiment, HCl may be flowed during each process step (except the purge step) at approximately the same flow rate (e.g., about 300 sccm or another suitable rate), and Cl2 may be flowed only during the etching step (e.g., at about 30 sccm or another suitable rate). Disilane may be flowed during each deposition step (e.g., at about 7 sccm or another suitable rate), and methylsilane may be flowed during the Si:C deposition step (e.g., at about 2.2 sccm or another suitable rate). N2 carrier gas may be flowed at about 20 slm or another suitable rate during each process cycle step, and increased to about 30 slm or another suitable rate during each purge step. In some embodiments, about 5 angstroms of Si may be deposited during the first Si deposition step (e.g., about a 4 second deposition), about 9 angstroms of Si:C may be deposited during the Si:C deposition step (e.g., about a 7 second deposition), about 13 angstroms of Si may be deposited during the second Si deposition step (e.g., about a 10 second deposition), and about 19 angstroms of epitaxial material may be removed during the etching step (e.g., about a 13 second etch). A suitable purge time may be used (e.g., about 10 seconds). A process temperature of about 600 °C and a chamber pressure of about 10 Torr during deposition and purging, and about 13 Torr during etching may be employed. As stated, other process conditions may be used.

The foregoing description discloses only exemplary embodiments of the invention. Modifications of the above disclosed apparatus and methods which fall within the scope of the invention will be readily apparent to those of ordinary skill in the art. Accordingly, while the present

invention has been disclosed in connection with exemplary embodiments thereof, it should be understood that other embodiments may fall within the spirit and scope of the invention, as defined by the following claims.

THE INVENTION CLAIMED IS:

1. A method of forming an epitaxial layer stack on a substrate comprising:

selecting a target carbon concentration for the epitaxial layer stack;

forming a carbon-containing silicon layer on the substrate, the carbon-containing silicon layer having at least one of an initial carbon concentration, a thickness and a deposition time selected based on the selected target carbon concentration; and

forming a non-carbon-containing silicon layer on the carbon-containing silicon layer prior to etching.

2. The method of claim 1 wherein the target carbon concentration is between about 200 ppm and 5 at%.

3. The method of claim 1 wherein the initial carbon concentration is between about 0.5 at% and 10 at%.

4. The method of claim 1 further comprising forming a non-carbon-containing epitaxial layer between the carbon-containing silicon layer and the substrate.

5. The method of claim 1 wherein the epitaxial layer stack has a thickness of between about 10 Å and 2000 Å.

6. The method of claim 1 wherein the initial carbon concentration is greater than or equal to the target carbon concentration.

7. The method of claim 1 further comprising etching the epitaxial layer stack after forming the non-carbon-containing silicon layer on the carbon-containing silicon layer.

8. The method of claim 7 wherein etching the epitaxial layer stack includes etching the epitaxial layer stack in an etchant gas that includes Cl_2.

9. The method of claim 7 wherein the non-carbon-containing silicon layer has a thickness that prevents a reaction from occurring between the etchant gas and the carbon-containing silicon layer.

10. The method of claim 1 wherein forming at least one of the carbon-containing silicon layer and the non-carbon-containing silicon layer is performed at a temperature less than or about 700 °C.

11. A method of forming an epitaxial layer stack comprising:

selecting a target carbon concentration for the epitaxial layer stack; and

forming the epitaxial layer stack by depositing alternating carbon-containing silicon layers and non-carbon-containing silicon layers;

wherein the target carbon concentration is achieved based on at least one of a total thickness, an initial carbon concentration, and a deposition time for the carbon-containing silicon layers.

12. The method of claim 11 wherein the target carbon concentration is between about 200 ppm and 5 at%.

13. The method of claim 11 wherein the initial carbon concentration of each carbon-containing silicon layer is between about 0.5 at% and 10 at%.

14. The method of claim 11 further comprising forming a non-carbon-containing epitaxial layer between a first

carbon-containing silicon layer and the substrate.

15. The method of claim 11 wherein a thickness of the epitaxial layer stack is between about 10 Å and 2000 Å.

16. A method of controlling carbon concentration in an epitaxial layer stack formed on a substrate comprising:

determining a desired carbon concentration for the epitaxial layer stack; and

forming the epitaxial layer stack by:

forming a carbon-containing epitaxial layer on the substrate; and

forming a non-carbon-containing cap layer on the carbon-containing epitaxial layer;

wherein a thickness of the carbon-containing epitaxial layer is selected based on the desired carbon concentration for the epitaxial layer stack.

17. The method of claim 16 further comprising forming a seed epitaxial layer between the carbon-containing epitaxial layer and the substrate.

18. The method of claim 16 wherein the target carbon concentration is between about 200 ppm and 5 at%.

19. The method of claim 16 wherein the carbon-containing epitaxial layer has a thickness of between about 2 angstroms and 100 angstroms.

20. The method of claim 16 further comprising etching the epitaxial layer stack using Cl_2.

21. The method of claim 16 further comprising forming additional, alternating carbon-containing layers and non-carbon-containing layers for the epitaxial layer stack.