

METHOD FOR FORMING HIGH-QUALITY FILM BY MEANS OF CVD METHOD

Technical Field

The present application relates to the field of semiconductor device manufacturing, particularly to a method for forming high-quality films by chemical vapor deposition (CVD) method.

Background

When manufacturing semiconductor devices, shallow trench isolation structures are typically used to isolate components. In the isolation regions of a semiconductor substrate, shallow trench isolation structures comprise trenches or gaps, which can be filled with dielectric materials to prevent electrical coupling of nearby device structures (e.g., transistors, diodes, etc.). With the development of technology, the size of semiconductor devices is getting smaller and smaller, but more and more components (such as transistors, capacitors, diodes, etc.) are needed on semiconductor devices, which puts higher demands on the manufacturing of semiconductors. One problem with existing manufacturing technology is that it is difficult to fill the trenches or gaps of shallow trench isolation structures without creating holes or gaps. The presence of holes or gaps can have adverse effects on the subsequent manufacturing of semiconductor devices, such as causing non-uniform etching, polishing, annealing, etc. If there are holes or gaps in the finished semiconductor device, it will have adverse effects on the performance of the semiconductor device, such as dielectric quality, electrical crosstalk, charge leakage, and short circuits.

Some techniques have been developed to reduce the formation of holes or gaps, such as reducing the deposition rate of dielectric materials, but these methods can lower production efficiency and yield. Another method of controlling the formation of holes or gaps is to increase the flowability of the deposited dielectric material. Materials with greater flowability are beneficial

for quickly filling holes or gaps, preventing them from forming permanent defects. However, commonly used flowable films, such as Spin-On Glass coating, have lower density and are unstable.

In view of this, it is necessary to provide an improved method for forming flowable films by CVD method, in order to form high-quality films.

Summary

The present application attempts to solve at least one problem existing in the relevant field to some extent by providing a method for depositing a film on a substrate.

According to one aspect of the present application, the present application provides a method for depositing a flowable film on a substrate, wherein the method comprises:

introducing an organosilicon precursor into a deposition chamber, wherein the deposition chamber comprising a substrate;

generating at least one nitrogen-containing radical in a remote plasma;

introducing the nitrogen-containing radical into the deposition chamber;

reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on a surface of the substrate, forming the flowable film.

According to the embodiments of the present application, the polysilazane chain comprises Si-N bonds.

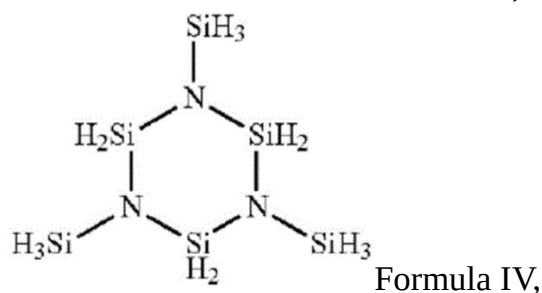
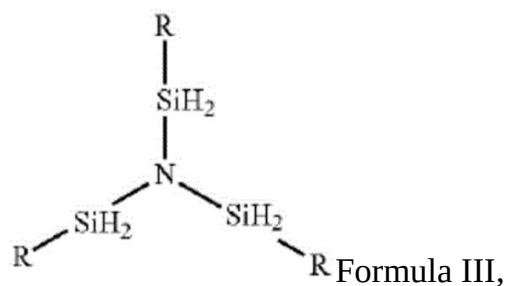
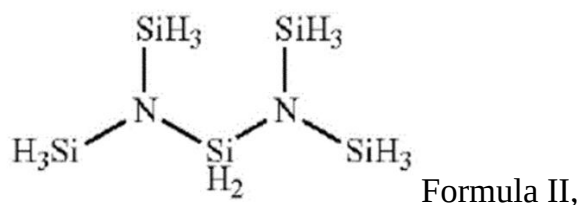
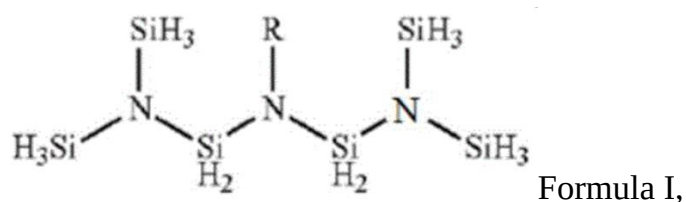
According to the embodiments of the present application, the organosilicon precursor reacts with the nitrogen-containing radical to form silicon-nitrogen radicals, which polymerize to form the polysilazane chain.

According to the embodiments of the present application, the polysilazane chain comprises repeating units of $\text{-(Si-N)}_n\text{-}$, wherein n is 2-50.

According to the embodiments of the present application, a number-average molecular weight of the polysilazane chain is 40-1000 g/mol.

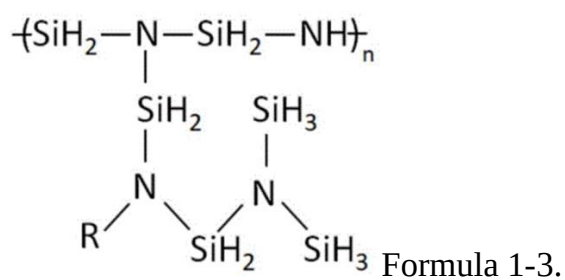
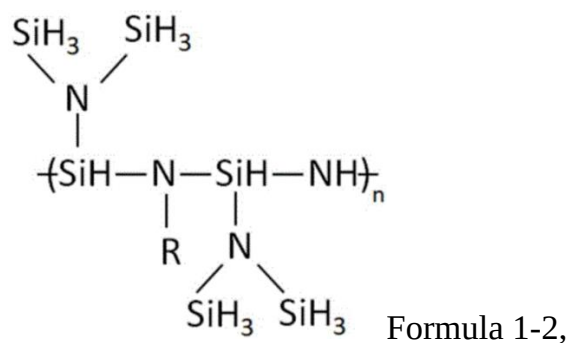
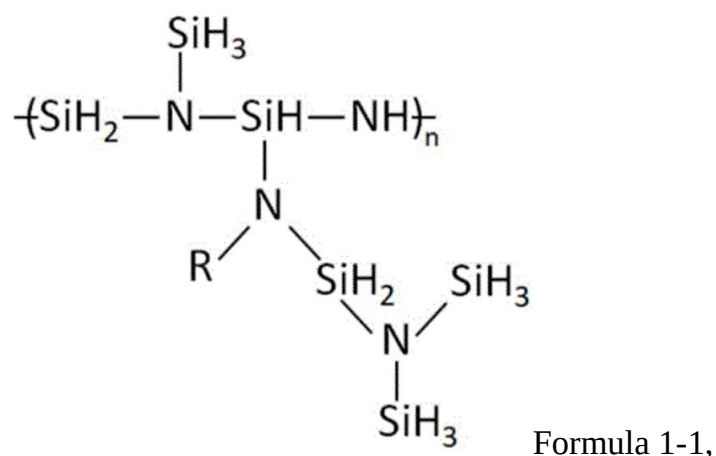
According to the embodiments of the present application, the organosilicon precursor comprises at least one of Formula I, Formula II,

Formula III, and Formula IV:

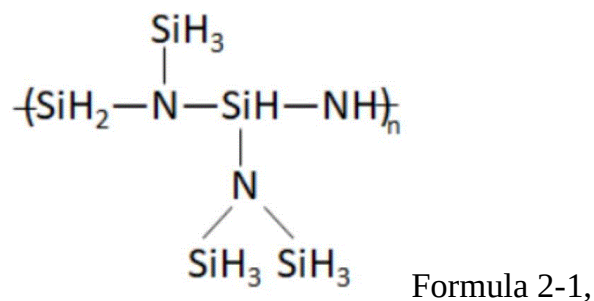


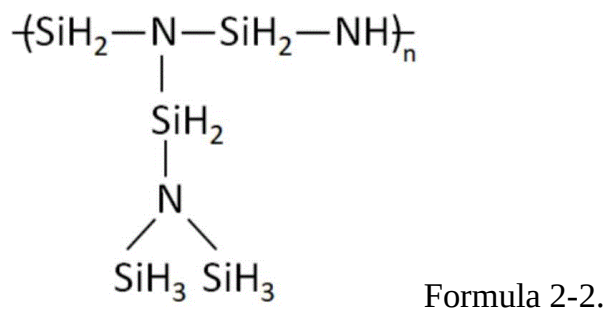
wherein, R is each independently selected from hydrogen, halogen, C₁-C₁₀ alkyl with straight chain, C₃-C₁₀ alkyl with branched chain, C₃-C₁₂ alkenyl with straight chain or branched chain, C₃-C₁₂ alkynyl with straight chain or branched chain, C₄-C₁₀ cycloalkyl, or C₆-C₁₀ aryl.

According to the embodiments of the present application, when the organosilicon precursor comprises Formula I, the polysilazane chain comprises at least one of Formula 1-1, Formula 1-2, and Formula 1-3:

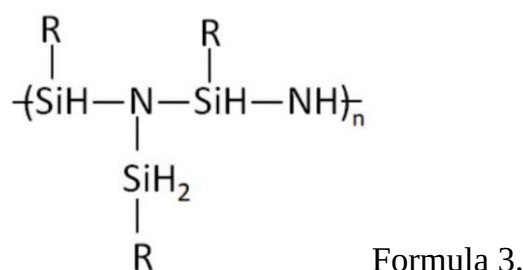


According to the embodiments of the present application, when the organosilicon precursor comprises Formula II, the polysilazane chain comprises at least one of Formula 2-1 and Formula 2-2:

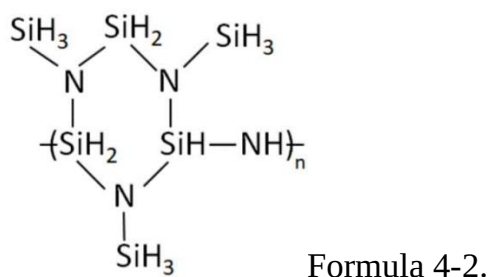
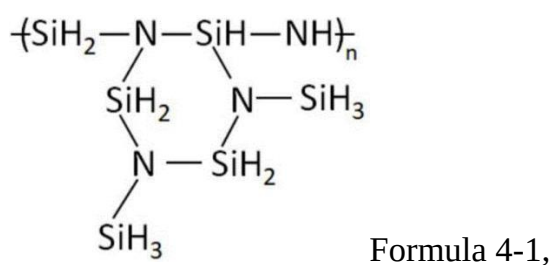




According to the embodiments of the present application, when the organosilicon precursor comprises Formula III, the polysilazane chain comprises Formula 3:



According to the embodiments of the present application, when the organosilicon precursor comprises Formula IV, the polysilazane chain comprises at least one of Formula 4-1 and Formula 4-2:



According to the embodiments of the present application, the method further comprises exposing ammonia in the remote plasma to generate the nitrogen-containing radical.

According to the embodiments of the present application, the nitrogen-containing radical has a chemical formula NH_x , where x is 0, 1, or 2.

According to another aspect of the present application, the present application provides a method for forming a film on a substrate, wherein the method comprises:

introducing an organosilicon precursor into a deposition chamber comprising a substrate;

generating at least one nitrogen-containing radical in a remote plasma;

introducing the nitrogen-containing radical into the deposition chamber;

reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on a surface of the substrate, forming a flowable film;

curing the flowable film; and

annealing the cured flowable film to form the film, which comprises a plurality of Si-O-Si bonds.

According to the embodiments of the present application, the flowable film is formed by the method described in the present application.

According to the embodiments of the present application, curing the flowable film comprises at least one of the following:

(a) exposing the flowable film to ozone and water; and

(b) exposing the flowable film to ozone and ultraviolet.

According to the embodiments of the present application, curing the flowable film comprises exposing the flowable film to ozone and water at a temperature of 150 °C to 450 °C and a pressure of 400 Torr to 800 Torr.

According to the embodiments of the present application, curing the flowable film comprises exposing the flowable film to ozone at a temperature below 100 °C and a pressure of 400 Torr to 800 Torr, followed by exposure to ultraviolet at a pressure below 150 Torr.

According to the embodiments of the present application, annealing the cured flowable film comprises performing the annealing at a temperature of 1050 °C in a nitrogen atmosphere.

According to the embodiments of the present application, annealing the

cured flowable film comprises performing the annealing at a temperature of 200 °C to 600 °C in a steam atmosphere.

According to the embodiments of the present application, the steam comprises at least one of water vapor and acidic vapor.

According to the embodiments of the present application, the method comprises performing the annealing in an atmosphere of water vapor to form at least a first portion of the Si-O-Si bonds.

According to the embodiments of the present application, the method comprises performing the annealing in an atmosphere of acidic vapor to form at least a second portion of the Si-O-Si bonds.

According to the embodiments of the present application, the acidic vapor comprises hydrochloric acid or acetic acid.

According to the embodiments of the present application, the film is a silicon oxide film.

According to the embodiments of the present application, the density of the film is greater than that of the flowable film.

The method described in this application can generate polysilazane chains by CVD method, which are flowable on the surface of a substrate, forming a flowable film. This flowable film can rapidly fill holes or gaps, preventing the holes or gaps from forming permanent defects. Through curing and annealing processes, the flowable film can be transformed into a high-quality film.

The additional aspects and advantages of this application will be partially described, displayed, or illustrated through the implementation of the embodiments of this application in the subsequent description

Description of drawings

In the following text, the necessary drawings for describing the examples of the present application or the prior art will be briefly explained to facilitate the description of the examples of the present application. Obviously, the drawings in the following description are only partial examples of the present invention. For those skilled in the art, other drawings of different examples

may be obtained from the illustrated structures in these drawings without creative effort.

Figure 1 shows a simplified flowchart of a method for depositing a film on a substrate according to an embodiment of the present application.

Figure 2 shows another simplified flowchart of a method for depositing a film on a substrate according to an embodiment of the present application.

Figure 3 shows the chemical reaction mechanism for forming a polysilazane chain from trisilylamine (TSA) precursor and the nitrogen-containing radical generated by decomposing ammonia in a remote plasma, according to an embodiment of the present application.

Figure 4 shows a reaction flowchart of a method for depositing a silicon oxide film on a substrate according to an embodiment of the present application.

Detailed Description

The embodiments of the present application will be described in detail below. These examples should not be construed as limiting the scope of the present application.

In the detailed description and claims, a list of items connected by the term "at least one of" may mean any combination of the listed items. For example, if items A and B are listed, the phrase "at least one of A and B" means only A, only B, or both A and B. In another example, if items A, B, and C are listed, the phrase "at least one of A, B, and C" means only A, only B, only C, A and B (excluding C), A and C (excluding B), B and C (excluding A), or all of A, B, and C. Item A may comprise a single element or multiple elements. Item B may comprise a single element or multiple elements. Item C may comprise a single element or multiple elements.

The term "alkyl" refers to a straight-chain saturated hydrocarbon structure with 1 to 10 carbon atoms. "Alkyl" also refers to branched or cyclic hydrocarbon structures with 3 to 10 carbon atoms. When an alkyl group with a specific number of carbons is specified, all geometric isomers with that number

of carbons are encompassed. For example, "butyl" comprises n-butyl, sec-butyl, isobutyl, tert-butyl, and cyclobutyl; "propyl" comprises n-propyl, isopropyl, and cyclopropyl. Examples of alkyl groups comprise, but are not limited to, methyl, ethyl, n-propyl, isopropyl, cyclopropyl, n-butyl, isobutyl, sec-butyl, tert-butyl, cyclobutyl, n-pentyl, isopentyl, neopentyl, cyclopentyl, methylcyclopentyl, ethylcyclopentyl, n-hexyl, isohexyl, cyclohexyl, n-heptyl, octyl, cyclopropyl, cyclobutyl, norbornyl, and the like.

The term "alkenyl" refers to a monovalent unsaturated hydrocarbon group that can be straight or branched and has at least one and typically one, two, or three carbon-carbon double bonds. Unless otherwise defined, the alkenyl group generally comprises 3 to 12 carbon atoms and includes, for example, -C₂₋₄ alkenyl, -C₂₋₆ alkenyl, and -C₂₋₁₀ alkenyl. Representative alkenyl groups include, for example, vinyl, n-propenyl, isopropenyl, n-but-2-enyl, but-3-enyl, n-hex-3-enyl, and the like.

The term "alkynyl" refers to a monovalent unsaturated hydrocarbon group that can be straight or branched and has at least one and typically one, two, or three carbon-carbon triple bonds. Unless otherwise defined, the alkynyl group generally comprises 3 to 12 carbon atoms and includes, for example, -C₂₋₄ alkynyl, -C₃₋₆ alkynyl, and -C₃₋₁₀ alkynyl. Representative alkynyl groups include, for example, ethynyl, prop-2-ynyl (n-propynyl), n-but-2-ynyl, n-hex-3-ynyl, and the like.

The term "cycloalkyl" refers to a non-aromatic monocyclic or polycyclic hydrocarbon group consisting solely of carbon and hydrogen atoms, which may include fused or bridged ring systems, and may contain 3 to 15 carbon atoms, preferably 4 to 10 carbon atoms, and may be saturated or unsaturated. Monocyclic groups include, for example, cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl, cycloheptyl, cyclooctyl, and the like. Polycyclic groups include, for example, adamantane, norbornane, decahydronaphthyl, 7,7-dimethyl-bicyclo[2.2.1]heptyl, and the like.

The term "aryl" refers to a monovalent aromatic hydrocarbon group with a single ring (e.g., phenyl) or fused rings. Fused ring systems include those that

are fully unsaturated (e.g., naphthalene) as well as those that are partially unsaturated (e.g., 1,2,3,4-tetrahydronaphthalene). Unless otherwise defined, the aryl group generally contains 6 to 10 ring carbon atoms and includes, for example, -C₆₋₁₀ aryl. Representative aryl groups include, for example, phenyl, methylphenyl, propylphenyl, isopropylphenyl, benzyl, naphthalen-1-yl, naphthalen-2-yl, and the like.

The present application provides a method for depositing a flowable film on a substrate, wherein the method comprises:

introducing an organosilicon precursor into a deposition chamber comprising a substrate;

generating at least one nitrogen-containing radical in a remote plasma;

introducing the nitrogen-containing radical into the deposition chamber;

reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on the surface of the substrate, forming the flowable film.

In some embodiments, the polysilazane chain comprises Si-N bonds.

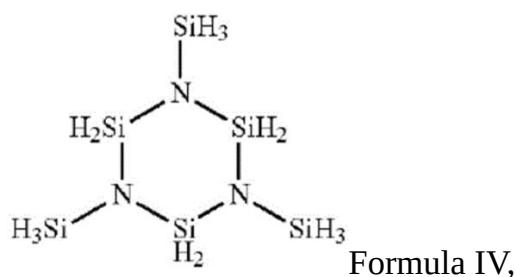
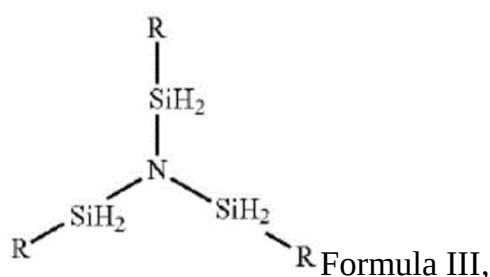
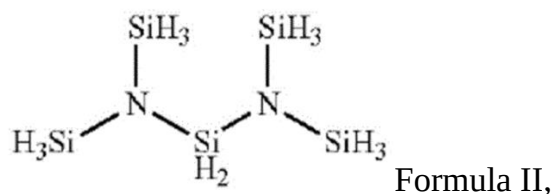
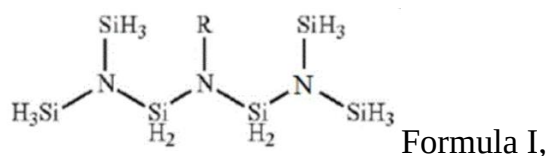
In some embodiments, the organosilicon precursor reacts with the nitrogen-containing radical to form silicon-nitrogen radicals, which polymerize to form the polysilazane chain. The nitrogen-containing radical may act as polymerization chain initiators, reacting with the organosilicon precursor to form silicon-nitrogen small-molecule radical. The silicon-nitrogen small-molecule radical continuously reacts with the nitrogen-containing radical, enabling chain propagation and ultimately forming the polysilazane chain.

In some embodiments, the polysilazane chain comprises repeating units of -(Si-N)_n , wherein n is 2-50. In some embodiments, n is 5-40. In some embodiments, n is 10-30. In some embodiments, n is 10-20.

In some embodiments, a number-average molecular weight of the polysilazane chain is 40-1000 g/mol. In some embodiments, a number-average molecular weight of the polysilazane chain is 50-800 g/mol. In some embodiments, a number-average molecular weight of the polysilazane chain is 100-500 g/mol. In some embodiments, a number-average molecular weight of

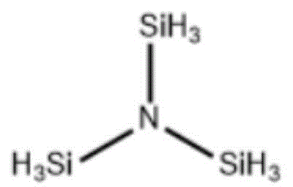
the polysilazane chain is 200-400 g/mol.

In some embodiments, the organosilicon precursor comprises at least one of Formula I, Formula II, Formula III, and Formula IV:



wherein, R is each independently selected from hydrogen, halogen, C₁-C₁₀ alkyl with straight chain, C₃-C₁₀ alkyl with branched chain, C₃-C₁₂ alkenyl with straight chain or branched chain, C₃-C₁₂ alkynyl with straight chain or branched chain, C₄-C₁₀ cycloalkyl, or C₆-C₁₀ aryl.

In some embodiments, the organosilicon precursor is trisilylamine (TSA):

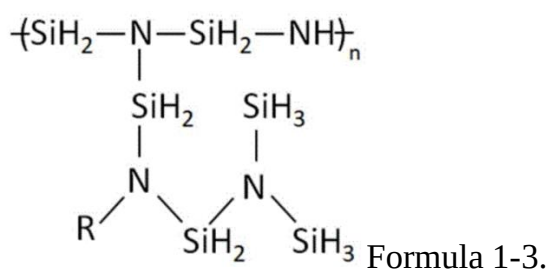
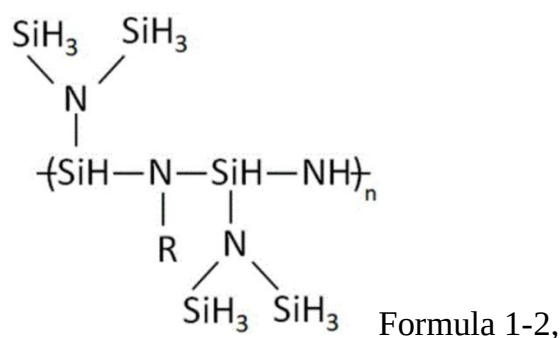
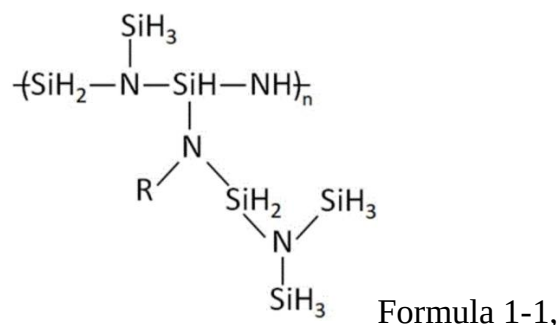


In some embodiments, the method further comprises exposing ammonia in the remote plasma to generate the nitrogen-containing radical. Plasma conditions for decomposing ammonia into the nitrogen-containing radical

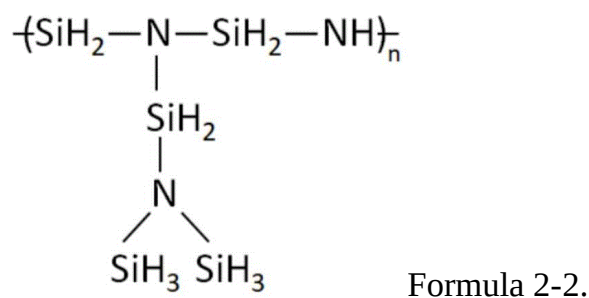
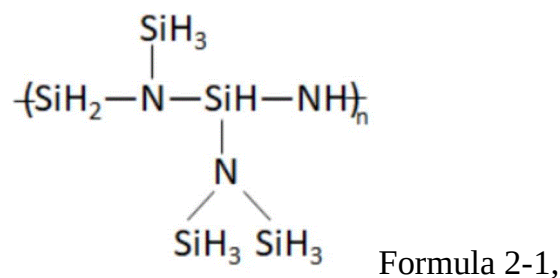
comprise: using RF power in the range of 3 kW to 15 kW to generate plasma at a chamber pressure from 1 Torr to 10 Torr and a chamber temperature from room temperature to about 200°C.

In some embodiments, the nitrogen-containing radical has a chemical formula NH_x , wherein x is 0, 1, or 2. Decomposition of ammonia in a remote plasma system can generate the nitrogen-containing radical comprising N, NH, or NH_2 .

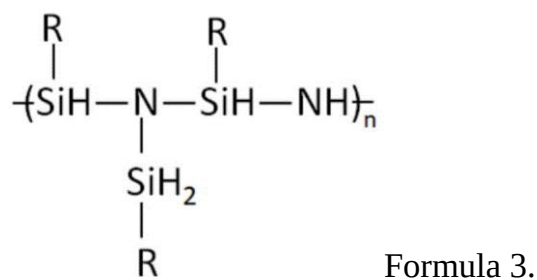
In some embodiments, when the organosilicon precursor comprises Formula I, the polysilazane chain comprises at least one of Formula 1-1, Formula 1-2, and Formula 1-3:



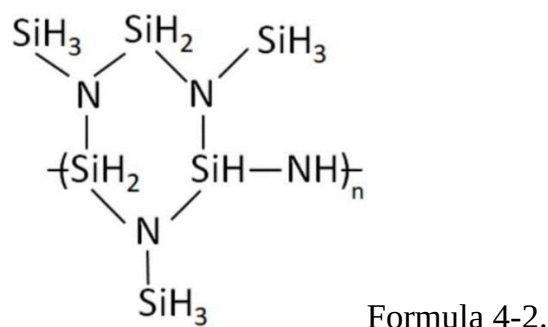
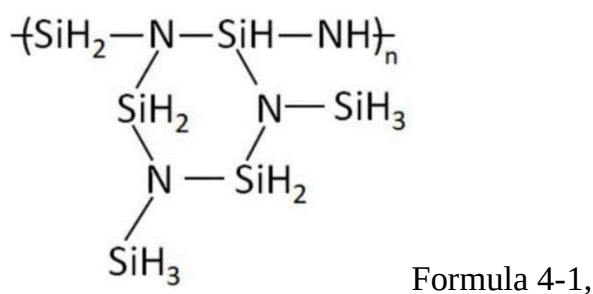
In some embodiments, when the organosilicon precursor comprises Formula II, the polysilazane chain comprises at least one of Formula 2-1 and Formula 2-2:



In some embodiments, when the organosilicon precursor comprises Formula III, the polysilazane chain comprises Formula 3:



In some embodiments, when the organosilicon precursor comprises Formula IV, the polysilazane chain comprises at least one of Formula 4-1 and Formula 4-2:



This application employs a chemical vapor deposition (CVD) method to react an organosilicon precursor with at least one nitrogen-containing radical (e.g. -N, -NH, -NH₂) generated in a remote plasma, producing a polysilazane chain containing Si-N bonds. The polysilazane chain has repeating units of -(Si-N)_n . The main chain of the polysilazane chain does not comprise carbon and oxygen atoms, which helps to improve the flowability of the formed film on a substrate, allowing for rapid and effective filling of trenches or gaps on the substrate.

The order in which the organosilicon precursor and the nitrogen-containing radical are introduced into the deposition chamber is not limited. Figure 1 shows a simplified flowchart of a method for depositing a film on a substrate according to an embodiment of the present application, wherein after providing a substrate in a deposition chamber, an organosilicon precursor is first introduced into the deposition chamber, and then at least one nitrogen-containing radical generated in a remote plasma is introduced into the deposition chamber, and the two react to produce a polysilazane chain, forming a flowable film.

Figure 2 shows another simplified flowchart of a method for depositing a film on a substrate according to an embodiment of the present application, wherein after providing a substrate in a deposition chamber, at least one nitrogen-containing radical generated in a remote plasma is first introduced into the deposition chamber, and then an organosilicon precursor is introduced into the deposition chamber, and the two react to produce a polysilazane chain, forming a flowable film.

Figure 3 shows the chemical reaction steps for forming a polysilazane chain from trisilylamine (TSA) precursor and a nitrogen-containing radical generated by decomposing ammonia in a remote plasma, according to an embodiment of the present application. As shown in the figure, TSA and the radicals N, NH, and NH₂ generated by ammonia decomposition meet in the deposition chamber to form silicon-nitrogen (-Si-N-) radicals, which undergo polymerization reactions to form a polysilazane chain and form a flowable film.

Other types of silicon-containing precursors can react with the nitrogen-containing radical according to a similar mechanism to generate the polysilazane chain.

The CVD method can be performed under the following processing conditions: a flow rate of a precursor is set to 100-1000 sccm; the deposition chamber is maintained at a pressure ranging from approximately 1 mTorr to about 600 Torr; and a temperature of the chamber is controlled between approximately 0°C and 400°C.

The present application also provides a method for forming a film on a substrate, wherein the method comprising:

- introducing an organosilicon precursor into a deposition chamber comprising a substrate;

- generating at least one nitrogen-containing radical in a remote plasma;

- introducing the nitrogen-containing radical into the deposition chamber;

- reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on the surface of the substrate, forming the flowable film;

- curing the flowable film; and

- annealing the cured flowable film to form the film, which comprises a plurality of Si-O-Si bonds.

Figure 4 shows a reaction flowchart of a method for depositing a silicon oxide film on a substrate according to an embodiment of the present application, wherein step 401 shows the formation process of a polysilazane chain, which exhibit high flowability; step 402 shows the curing process, during which the N atoms in the polysilazane chain are replaced by O atoms, increasing the stability of the film and forming a structurally stable, non-flowing film; step 403 shows the annealing process, during which the H atoms in the film are removed, forming a silicon oxide film. The method of the present application can obtain high-quality films, including but not limited to silicon oxide films, silicon nitride films, silicon oxynitride films, carbon-doped silicon nitride films, or carbon-doped silicon oxide films, etc. Therefore, it can be widely used in the

manufacture of various semiconductor devices.

In some embodiments, the flowable film is formed by the method described in this application.

In some embodiments, curing the flowable film comprises at least one of the following:

(a) exposing the flowable film to ozone and water; and

(b) exposing the flowable film to ozone and ultraviolet.

In some embodiments, curing the flowable film comprises exposing the flowable film to ozone and water at a temperature of 150 °C to 450 °C and a pressure of 400 Torr to 800 Torr.

In some embodiments, curing the flowable film comprises exposing the flowable film to ozone and water at a temperature of 150 °C and a pressure of 600 Torr.

In some embodiments, curing the flowable film comprises exposing the flowable film to ozone at a temperature below 100 °C and a pressure of 400 Torr to 800 Torr, followed by exposure to ultraviolet at a pressure below 150 Torr. In some embodiments, curing the flowable film comprises exposing the flowable film to ozone at a temperature of 25 °C to 100 °C and a pressure of 600 Torr, followed by exposure to ultraviolet at a pressure of 50 Torr to 150 Torr.

In some embodiments, annealing the cured flowable film comprises performing the annealing at a temperature of 1050 °C in a nitrogen atmosphere.

In some embodiments, annealing the cured flowable film comprises performing the annealing at a temperature of 200 °C to 600 °C in a steam atmosphere.

In some embodiments, the steam comprises at least one of water vapor and acidic vapor.

In some embodiments, the method comprises performing the annealing in

an atmosphere of water vapor to form at least a first portion of the Si-O-Si bonds.

In some embodiments, the method comprises performing the annealing in an atmosphere of acidic vapor to form at least a second portion of the Si-O-Si bonds.

After two annealing steps, the H in the cured flowable film can be basically completely removed, further improving the quality of the film.

In some embodiments, the acidic vapor comprises hydrochloric acid or acetic acid.

In some embodiments, the film is a silicon oxide film.

In some embodiments, the density of the film is greater than that of the flowable film.

The following will only take a silicon oxide film as an example and explain its formation method in conjunction with specific examples. Technicians in the art will understand that the method and film described in this application are only examples, and any other suitable methods and films may be applicable.

Example

Firstly, a substrate is provided in a deposition chamber and trisilylamine (TSA) is introduced into the deposition chamber. Then, a remote plasma source is used and RF power in the range of 3kW to 15kW is used to generate plasma at a chamber pressure ranging from 1 Torr to 10 Torr and at a chamber temperature ranging from room temperature to approximately 200 °C .

Ammonia is decomposed in the plasma, producing radicals H, NH, and NH₂, which are introduced into the deposition chamber. In the deposition chamber, TSA undergoes polymerization reaction with the radicals, producing a polysilazane chain in the gas-phase environment and condensing into a thin film on the substrate. The thin film is flowable on a surface of the substrate, forming a flowable film. Subsequently, the flowable film is exposed to ozone and ultraviolet to get cured. Next, annealing is carried out at a temperature

ranging from 20 °C to 900 °C to obtain a silicon oxide film.

The reference to "embodiments," "partial embodiments," "one embodiment," "another example," "examples," "specific examples," or "partial examples" throughout the entire specification means that at least one embodiment or example in this application comprises specific features, structures, materials, or characteristics described in that embodiment or example. Therefore, the descriptions that appear throughout the entire specification, such as "in some embodiments", "in embodiments", "in one embodiment", "in another example", "in one example", "in a specific example" or "example", do not necessarily refer to the same embodiments or examples in this application. In addition, specific features, structures, materials, or characteristics described herein may be combined in any suitable manner in one or more embodiments or examples.

Although illustrative embodiments have been demonstrated and described, those skilled in the art should understand that the above embodiments should not be construed as limiting the present application, and that changes, substitutions, and modifications may be made to the embodiments without departing from the spirit, principles, and scope of the present application.

What is claimed is:

1. A method for depositing a flowable film on a substrate, wherein the method comprises:

introducing an organosilicon precursor into a deposition chamber comprising a substrate;

generating at least one nitrogen-containing radical in a remote plasma;

introducing the nitrogen-containing radical into the deposition chamber;

reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on the surface of the substrate, forming the flowable film.

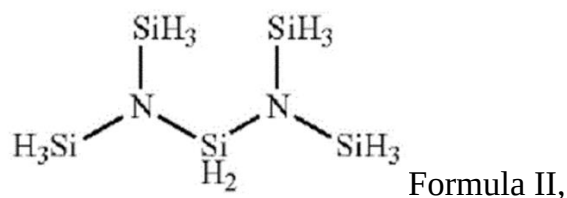
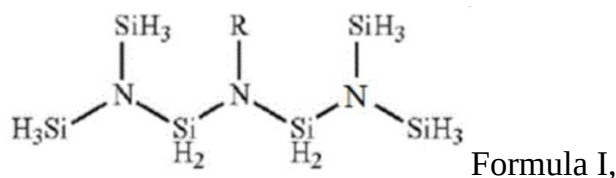
2. The method of claim 1, wherein the polysilazane chain comprises Si-N bonds.

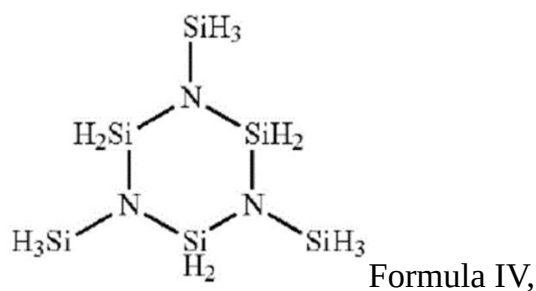
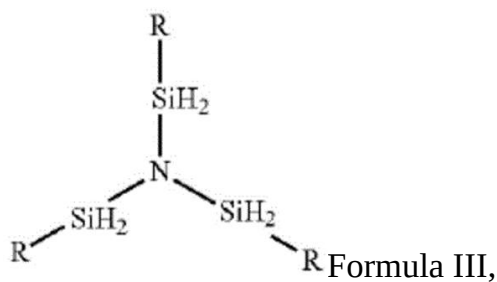
3. The method of claim 1, wherein the organosilicon precursor reacts with the nitrogen-containing radical to form silicon-nitrogen radicals, which polymerize to form the polysilazane chain.

4. The method of claim 1, wherein the polysilazane chain comprises repeating units of -(Si-N)_n , wherein n is 2-50.

5. The method of claim 1, wherein a number-average molecular weight of the polysilazane chain is 40-1000 g/mol.

6. The method of claim 1, wherein the organosilicon precursor comprises at least one of Formula I, Formula II, Formula III, and Formula IV:

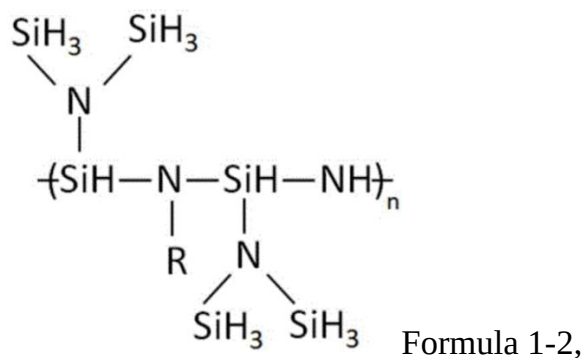
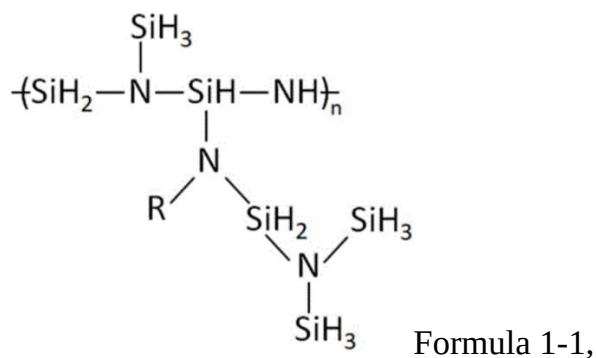


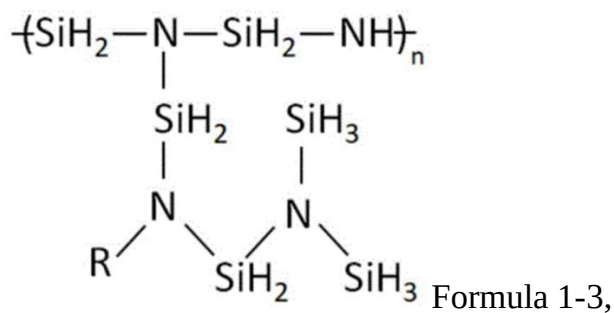


wherein, R is each independently selected from hydrogen, halogen, C₁-C₁₀ alkyl with straight chain, C₃-C₁₀ alkyl with branched chain, C₃-C₁₂ alkenyl with straight chain or branched chain, C₃-C₁₂ alkynyl with straight chain or branched chain, C₄-C₁₀ cycloalkyl, or C₆-C₁₀ aryl.

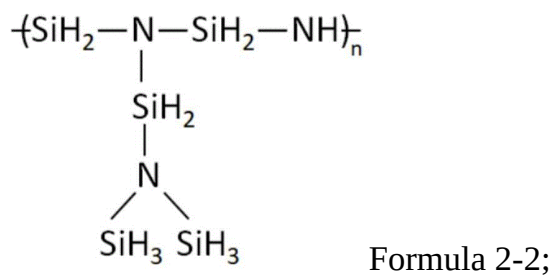
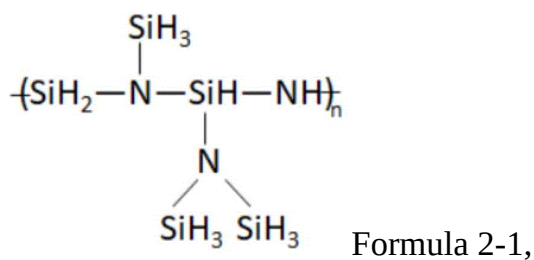
7. The method of claim 6, wherein:

(i) when the organosilicon precursor comprises Formula I, the polysilazane chain comprises at least one of Formula 1-1, Formula 1-2, and Formula 1-3:

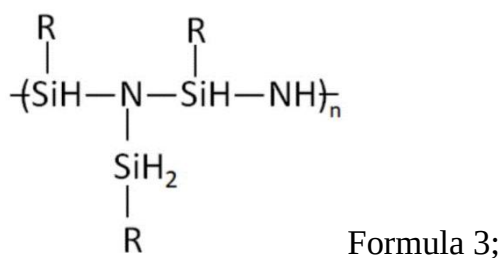




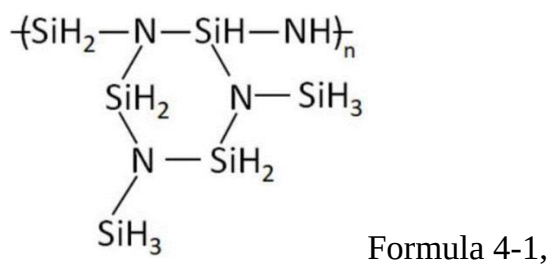
(ii) when the organosilicon precursor comprises Formula II, the polysilazane chain comprises at least one of Formula 2-1 and Formula 2-2:

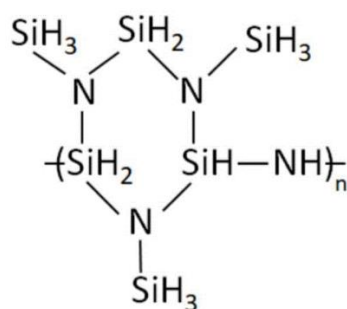


(iii) when the organosilicon precursor comprises Formula III, the polysilazane chain comprises Formula 3:



(iv) when the organosilicon precursor comprises Formula IV, the polysilazane chain comprises at least one of Formula 4-1 and Formula 4-2:





Formula 4-2.

8. The method of claim 1, wherein the method further comprises exposing ammonia in the remote plasma to generate the nitrogen-containing radical.

9. The method of claim 1, wherein the nitrogen-containing radical has a chemical formula NH_x , wherein x is 0, 1, or 2.

10. A method for forming a film on a substrate, wherein the method comprises:

introducing an organosilicon precursor into a deposition chamber comprising a substrate;

generating at least one nitrogen-containing radical in a remote plasma;

introducing the nitrogen-containing radical into the deposition chamber;

reacting the nitrogen-containing radical with the organosilicon precursor to produce a polysilazane chain, which is deposited on the substrate and is flowable on the surface of the substrate, forming the flowable film;

curing the flowable film; and

annealing the cured flowable film to form the film, which comprises a plurality of Si-O-Si bonds.

11. The method of claim 10, wherein the flowable film is formed by the method of any one of claims 1-9.

12. The method of claim 10, wherein curing the flowable film comprises at least one of the following:

(a) exposing the flowable film to ozone and water; and

(b) exposing the flowable film to ozone and ultraviolet.

13. The method of claim 12, wherein curing the flowable film comprises exposing the flowable film to ozone and water at a temperature of 150 °C to 450 °C and a pressure of 400 Torr to 800 Torr.

14. The method of claim 12, wherein curing the flowable film comprises exposing the flowable film to ozone at a temperature below 100 °C and a pressure of 400 Torr to 800 Torr, followed by exposure to ultraviolet at a pressure below 150 Torr.

15. The method of claim 10, wherein annealing the cured flowable film comprises performing the annealing at a temperature of 1050 °C in a nitrogen atmosphere.

16. The method of claim 10, wherein annealing the cured flowable film comprises performing the annealing at a temperature of 200 °C to 600 °C in a steam atmosphere.

17. The method of claim 16, wherein the steam comprises at least one of water vapor and acidic vapor.

18. The method of claim 17, wherein the method comprises performing the annealing in an atmosphere of water vapor to form at least a first portion of the Si-O-Si bonds.

19. The method of claim 18, wherein the method comprises performing the annealing in an atmosphere of acidic vapor to form at least a second portion of the Si-O-Si bonds.

20. The method of claim 17, wherein the acidic vapor comprises hydrochloric acid or acetic acid.

21. The method of claim 10, wherein the film is a silicon oxide film.

22. The method of claim 10, wherein the density of the film is greater than that of the flowable film.