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### METHOD OF INTEGRATED COPPER OXIDE REMOVAL AND LOW K REPAIR PROCESS

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#### Abstract

A method for repairing copper and low-k dielectric films on a substrate is provided. In some embodiments, the method includes positioning the substrate within a process chamber, introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate, removing the reducing agent from the process chamber, and introducing a recovery precursor into the process chamber to decrease a k value of a low-k film on the substrate.

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## Background/Summary

RELATED APPLICATIONS [0001] This application claims benefit of and priority to U.S. Provisional Application No. 63/552,472 filed Feb. 12, 2024 which is herein incorporated in its entirety by reference for all purposes.

### BACKGROUND

#### Field

[0002] Embodiments described herein generally relate to processes for processing low-k dielectric films. More specifically, embodiments described herein relate to processes for repairing copper and low-k dielectric films.

#### Description of the Related Art

[0003] The dielectric constant (k) of dielectric films in semiconductor fabrication is continually decreasing as device scaling continues. Minimizing integration damage on low dielectric constant (low-k) films is important to be able to continue decreasing feature sizes. However, as feature sizes shrink, improvement in the resistive capacitance and reliability of dielectric films becomes a serious challenge.

[0004] Porous low-k dielectric films suffer significant damages after going through back end of line (BEOL) integration due to the contamination in the exposed pores, which leads to larger resistive-capacitive (RC) delay. In order to maintain the integrity of the low-k dielectric films and to minimize the oxidization on the copper, a method of restoring the copper and the low-k film is needed.

### SUMMARY

[0005] Embodiments described herein generally relate to processes for processing low-k dielectric films. More specifically, embodiments described herein relate to processes for repairing copper and low-k dielectric films.

[0006] In one embodiment, a method for repairing copper and low-k dielectric films is provided. The method includes positioning a substrate within a process chamber, and introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate. After the copper oxide is removed, the method further includes removing the reducing agent from the process chamber and introducing a recovery precursor into the process chamber to decrease a k-value of a low-k film on the substrate.

[0007] In another embodiment, a method for repairing copper and low-k dielectric films is provided. The method includes positioning a substrate within a process chamber and introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate. In some embodiments, the reducing agent comprises ammonia (NH<sub>3</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), ethanol (C<sub>2</sub>H<sub>5</sub>OH), methane (CH<sub>4</sub>), or ethene (C<sub>2</sub>H<sub>4</sub>). The method also includes turning on a UV light source to expose the substrate to UV light. After the copper oxide is removed, the method further includes removing the reducing agent from the process chamber and introducing a recovery precursor into the process chamber to decrease a k-value of a low-k film on the substrate.

[0008] In a further embodiment, a non-transitory computer-readable medium is provided. The non-transitory computer-readable medium comprises instructions that, when executed by a processor, cause a computer system to perform the steps of: positioning a substrate within a process chamber, introducing a reducing agent into the process chamber to remove copper oxide from a copper layer

on the substrate, removing the reducing agent from the process chamber, and introducing a recovery precursor into the process chamber to decrease a k value of a low-k film on the substrate.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective embodiments.

[0010] FIG. 1 is a schematic cross-sectional view of a process chamber, according to one or more embodiments.

[0011] FIG. 2 is a schematic block diagram view of a method of substrate processing, according to one or more embodiments.

[0012] FIGS. 3A-3C are molecular views of a low-k film during a method, according to one or more embodiments.

[0013] FIGS. 4A-4D are partial schematic side cross-sectional views of a semiconductor device during a method, according to one or more embodiments.

### DETAILED DESCRIPTION

[0014] Embodiments described herein generally relate to processes for processing low-k dielectric films. More specifically, embodiments described herein relate to processes for repairing copper and low-k dielectric films.

[0015] During back end of line processing operations, processing steps may damage copper layers by oxidizing the copper. Additionally, the processing steps may cause damage to low-k dielectric films through carbon loss (causing higher k values) and introducing undesirable Si-OH bonds (making the low-k surface hydrophilic). Accordingly, the techniques for repairing copper and low-k dielectric films described herein reverse the copper oxidation, decrease the k dielectric constant on the low-k films, and increase the hydrophobicity of the low-k films.

[0016] FIG. 1 is a schematic cross-sectional view of a process chamber **100**, according to one or more embodiments. The process chamber **100** may be a vapor deposition chamber that includes UV radiation for assisting a silylation reaction. In one or more embodiments, the process chamber **100** may be the ONYX® or the SILENA® process chamber available from Applied Materials, Inc., of Santa Clara, California. The process chamber **100** may include a chamber body **102** and a chamber lid **104** disposed over the chamber body **102**. The chamber body **102** and the chamber lid **104** may form an inner volume **106**. A substrate support assembly **108** may be disposed in the inner volume **106**. The substrate support assembly **108** may receive and support a substrate **110** thereon for processing.

[0017] A first UV transparent gas distribution showerhead **116** may be hung in the inner volume **106** through a central opening **112** of the chamber lid **104** by an upper clamping member **118** and a lower clamping member **120**. The UV transparent glass distribution showerhead **116** may be positioned facing the substrate support assembly **108** to distribute one or more processing gases across a distribution volume **122** which is below the first UV transparent gas distribution showerhead **116**. A second UV transparent showerhead **124** may be hung in the inner volume **106** through the central opening **112** of the chamber lid **104** below the first UV transparent gas distribution showerhead **116**. Each of the UV transparent gas distribution showerheads **116**, **124** may be disposed in a recess formed in the chamber lid **104**. A first recess **126** may be an annular recess around an internal surface of the chamber lid **104**, and the first UV transparent gas

distribution showerhead **116** fits into the first recess **126**. Likewise, a second recess **128** may receive the second UV transparent gas distribution showerhead **124**.

[0018] A UV transparent window **114** may be disposed above the first UV transparent gas distribution showerhead **116**. The UV transparent window **114** may be positioned above the first UV transparent gas distribution showerhead **116** forming a gas volume **130** between the UV transparent window **114** and the first UV transparent gas distribution showerhead **116**. The UV transparent window **114** may be secured to the chamber lid **104** by any means, such as clamps, screws, bolts, etc.

[0019] The UV transparent window **114** and the first and second UV transparent gas distribution showerheads **116**, **124** may be at least partially transparent to thermal or radiant energy within the UV wavelengths. The UV transparent window **114** may be quartz or another UV transparent material, such as sapphire, CaF.sub.2, MgF.sub.2, AlON, a silicon oxide material, a silicon oxynitride material, or another transparent material.

[0020] A UV source **150** may be disposed above the UV transparent window **114**. The UV source **150** may be configured to generate UV energy and project the UV energy towards the substrate support assembly **108** through the UV transparent window **114**, the first UV transparent gas distribution showerhead **116**, and the second UV transparent gas distribution showerhead **124**, thereby exposing the substrate **110** on the substrate support assembly **108** to UV light. A cover (not shown) may be disposed above the UV source **150**. In one or more embodiments, the cover may be shaped to assist the projection of the UV energy from the UV source **150** towards the substrate support.

[0021] In one or more embodiment, the UV source **150** may include one or more UV lights **152** to generate UV radiation. The UV lights **152** may be lamps, LED emitters, or other UV emitters. In one or more embodiments, the UV lights **152** may be argon lamps discharging radiation at 126 nm, krypton lamps discharging at 146 nm, xenon lamps discharging at 172 nm, krypton chloride lamps discharging at 222 nm, xenon chloride lamps discharging at 308 nm, mercury lamps discharging at 254 nm or 365 nm, metal vapor lamps such as zinc discharging at 214 nm, rare earth near-UV lamps such as europium-doped strontium borate or fluoroborate lamps discharging at 368-371 nm, to name a few examples.

[0022] The process chamber **100** may include flow channels **132**, **134**, **136** configured to supply one or more processing gases across the substrate support assembly **108** to process a substrate **110** disposed thereon. A first flow channel **132** provides a flow pathway for gas to enter the gas volume **130** and to be exposed to UV radiation from the UV source **150**. The gas from the gas volume **130** may flow through the first UV transparent gas distribution showerhead **116** into the distribution volume **122**. A second flow channel **134** may provide a flow pathway for precursor compounds and gases to enter the distribution volume **122** directly without passing through the first UV transparent gas distribution showerhead **116** to mix with the gas that was previously exposed to UV radiation in the gas volume **130**. The mixed gases in the distribution volume **122** may be further exposed to UV radiation through the first UV transparent gas distribution showerhead **116** before flowing through the second UV transparent gas distribution showerhead **124** into a space proximate the substrate support assembly **108**. The gas proximate the substrate support assembly **108**, and a substrate disposed on the substrate support assembly **108**, is further exposed to the UV radiation through the second UV transparent gas distribution showerhead **124**. Purge gases may be provided through an opening **138** in the bottom of the process chamber **100** such that the purge gas flow around the substrate support assembly **108**, preventing intrusion of processing gases into the space under the substrate support assembly **108**. One or more gases may be exhausted through the opening **138**.

[0023] The first UV transparent gas distribution showerhead **116** may include a plurality of holes **140** that allow processing gas to flow from the gas volume **130** to the distribution volume **122**. The second UV transparent gas distribution showerhead **124** may also include a plurality of holes **142** that allow processing gas to flow from the distribution volume **122** into the processing space

proximate the substrate support assembly **108**. The holes **140**, **142** in the first and second UV transparent gas distribution showerheads **116**, **124** may be evenly distributed or irregularly spaced. [0024] A purge gas or carrier gas source **154** may be coupled to the first flow channel **132** through a conduit **156**. Purge gas from the purge gas source **154** may be provided through the first flow channel **132** during substrate processing to prevent intrusion of process gases into the gas volume **130**. A cleaning gas source **174** may also be coupled to the first flow channel **132** through the conduit **156** to provide cleaning of the conduit **156**, the first flow channel **132**, the gas volume **130**, and the rest of the chamber body **102** when not processing substrates.

[0025] A process gas or precursor compound source **158** may be coupled to the second flow channel **134** through a conduit **160** to provide a mixture, as described above, to the chamber body **102**. The process gas source **158** may also be coupled to a third flow channel **136**. Appropriate valves may allow selection of one or both of the flow channels **134**, **136** for flowing the process gas mixture into the chamber body **202**.

[0026] Substrate temperature may be controlled by providing heating and cooling features in the substrate support assembly **108**. A coolant conduit **164** may be coupled to a coolant source **170** to provide a coolant to a cooling plenum **162** disposed in the substrate support assembly **108**. One example of a coolant that may be used is a mixture of 50% ethylene glycol in water, by volume. The coolant flow is controlled to maintain temperature of the substrate at or below a desired level to promote deposition of UV-activated oligomers or fragments on the substrate. A heating element **166** may also be provided in the substrate support assembly **108**. The heating element **166** may be a resistive heater, and may be coupled to a heating source **172**, such as a power supply, by a conduit **168**. The heating element **166** may be used to heat the substrate during the hardening process described above.

[0027] FIG. **2** is a schematic block diagram of a method **200** of substrate processing, according to one or more embodiments. FIGS. **3A-3C** are molecular views of a low-k film **310a**, **310b**, **310c** during the method **200**, according to one or more embodiments. FIGS. **4A-4D** are partial schematic side cross-sectional views of an interconnect structure **400** during the method **200**, according to one or more embodiments.

[0028] At operation **210**, a substrate, such as an interconnect structure **400** shown in FIG. **4A**, is transferred into a process chamber. The process chamber may be a deposition process chamber such as the process chamber **100** depicted in FIG. **1**. At operation **210**, the interconnect structure **400** is post deposition, according to certain embodiments. The interconnect structure **400**, shown in FIG. **4A** may include a low-k film **310a** on an etch stop layer **430**, a metal barrier **432** between the etch stop layer **430** and a copper layer **420**, a metal barrier **432** between the copper layer and a substrate **434**, residue **422** on the copper layer **420**, and residue **424** on the low-k film **310a**. In some embodiments, an interconnect structure **400** with a different configuration may be utilized in method **200**.

[0029] FIG. **3A** is a molecular view of the low-k film **310a** at operation **210**. In FIG. **3A**, the low-k film **310a** has Si—O bonds, Si—CH<sub>sub.3</sub> bonds, and Si—H bonds.

[0030] In some embodiments, the metal barrier **432** may comprise tantalum nitride (TaN).

[0031] At operation **220**, the interconnect structure **400** is processed in the process chamber **100**. As a result of operation **220**, the copper layer **420** of the interconnect structure **400** is damaged. As shown in FIG. **4B**, a copper oxide **426** may form on the copper layer **420**, and the residue **422** on the copper oxide **426** may decrease. Operation **220** may also damage the low-k film **310b** of the interconnect structure **400**. As shown in FIG. **3B**, the overall number of Si—CH<sub>sub.3</sub> bonds in the low-k film **310b** may be decreased, and Si—OH bonds may be formed. With the increase of Si—OH bonds, the low-k film **310b** becomes more hydrophilic, which is undesirable. The decrease in Si—CH<sub>sub.3</sub> bonds in the low-k film **310** results in an increased k value of the low-k film **310b**. In some embodiments, the processing operations of operation **220** may include etching, ash, wet cleaning operations, or combinations thereof.

[0032] At operation 230, the copper oxide 426 on the interconnect structure 400 is removed from the copper layer 420, as shown in FIG. 4C. Operation 230 may be performed in the process chamber 100 utilizing a reducing agent and UV light. In some embodiments, the interconnect structure 400 may be exposed to UV light during operation 230. In some embodiments, the reducing agent may be a reducing gas such as ammonia (NH<sub>3</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), ethanol (C<sub>2</sub>H<sub>5</sub>OH), methane (CH<sub>4</sub>), or ethene (C<sub>2</sub>H<sub>4</sub>). As shown in FIG. 4C, the low-k film 310b may remain damaged after operation 230.

[0033] In some embodiments, operation 230 may be performed at a temperature between about 75° C. and about 500° C. In some embodiments, operation 230 may be performed for a period ranging from about 1 minute to about 10 minutes. In some embodiments, operation 230 may be performed at a pressure between about 3 Torr and about 100 Torr. In some embodiments, operation 230 may be performed with a reducing gas flow ranging from about 100 sccm to about 2000 sccm. In some embodiments, operation 230 may be performed with RF power ranging from 0 W to about 1000 W. In some embodiments, operation 230 may be performed with a UV power percentage between 0% and about 90%.

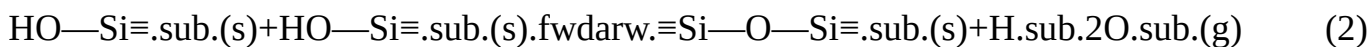
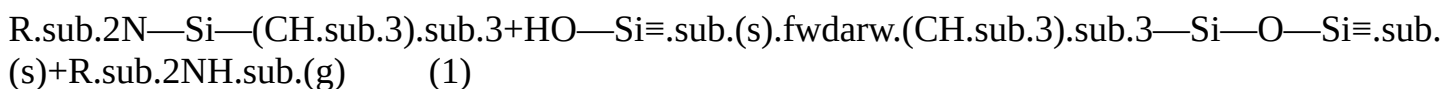
[0034] After the completion of operation 230, the reducing gas may be removed from the process chamber.

TABLE-US-00001 TABLE 1 Cu Reflectivity at 480 nm Process Parameters After After NH<sub>3</sub> Pressure NH<sub>3</sub> Flow Oxidation UV/NH<sub>3</sub> (Torr) (sccm) Cu Recovery 0.122 0.630 20-50 500-2000 100% 0.168 0.645 6.5-9.5 500-2000 100%

[0035] In Table 1, the ability of UV and NH<sub>3</sub> to remove copper oxide 426 from the copper layer 420 is demonstrated. Copper reflectivity is utilized as an indication of the oxidation state of the copper layer 420. As shown in Table 1, the pressure of the NH<sub>3</sub> has little to no effect on the recovery of the copper layer 420. Additionally, by utilizing UV and NH<sub>3</sub> in operation 230, the copper layer 420 may be fully recovered.

[0036] At operation 240, as shown in FIG. 4D, the low-k film 310c is repaired. As shown in FIG. 3C, the low-k film 310c has fewer to no Si-OH bonds and a greater percentage of Si-CH<sub>3</sub> bonds than the low-k films 310a, 310b shown in FIG. 3A and FIG. 3B, respectively.

[0037] In some embodiments, operation 240 may be performed utilizing a recovery precursor. In some embodiments, operation 240 may also be performed utilizing UV light, for example, the interconnect structure 400 may be exposed to UV light during operation 240. In some embodiments, operation 240 may be performed via the chemical reactions (1) and (2) shown below. Chemical reactions (1) and (2) illustrate the removal of the Si-OH bonds and the formation of the Si-CH<sub>3</sub> bonds when the low-k film 310b is exposed to the recovery precursor



[0038] The recovery precursor may include a molecule selected from Group 1. In Group 1, R may be independently selected from Me, Et, iPr, tBu, and H. R' may be independently selected from an alkane, an alkene, and an alkyne. R' may include between one and twenty carbon atoms.

##STR00001##

[0039] In one or more embodiments, the recovery precursor may be one of the molecules pictured in Group 1 Examples below.

##STR00002##

[0040] In certain embodiments, the recovery precursor may include a molecule selected from Group 2. In Group 2, R may be independently selected from Me, Et, iPr, and tBu. R' may be independently selected from an alkane, an alkene, and an alkyne. R' may include between one and twenty carbon atoms.

##STR00003##

[0041] In certain embodiments, the recovery precursor may include a molecule selected from Group 3. In Group 3, X may be Cl, Br, or I. R' may be independently selected from an alkane, an alkene, and an alkyne. R' may include between one and twenty carbon atoms.

##STR00004##

[0042] In certain embodiments, the recovery precursor may include a molecule selected from Group 4. In Group 4, R' may be independently selected from an alkane, an alkene, and an alkyne. R' may include between one and twenty carbon atoms.

##STR00005##

[0043] In certain embodiments, the recovery precursor may include a molecule selected from Group 5. In Group 5, R and R' may be independently selected from hydrogen, an alkane, an alkene, an alkyne, and an aryl. In embodiments where R and/or R' contain carbon, R and R' may include between one and twenty carbon atoms each.

##STR00006##

[0044] In certain embodiments, the recovery precursor may include a molecule selected from Group 6. In Group 6, R, R', and R'' may be independently selected from hydrogen, an alkane, an alkene, an alkyne, and an aryl. In embodiments where R, R', and/or R'' contain carbon, R, R', and R'' may include between one and twenty carbon atoms each.

##STR00007##

[0045] In some embodiments, operation **240** may be performed at a temperature between about 75° C. and about 500° C. In some embodiments, operation **240** may be performed for a period ranging from about 1 minute to about 10 minutes. In some embodiments, operation **240** may be performed at a pressure between about 3 Torr and about 100 Torr. In some embodiments, operation **240** may be performed with a gas flow of the recovery precursor ranging from about 100 mgm to about 2000 mgm.

[0046] It may be advantageous to perform operation **230** prior to operation **240** because recovery precursors are prone to be scavenged by copper oxide (CuO.sub.x), leading to Si residue on the copper layer **420**, affecting via resistance.

[0047] The following non-limiting examples are provided to further illustrate embodiments described herein. However, the examples are not intended to be all inclusive and are not intended to limit the scope of the embodiments described herein.

TABLE-US-00002

TABLE 2	First	1.sup.st	2.sup.nd	Test	Substrate	Layer	Treatment	Treatment	Si
Si Cu	Operation	None	0.53	230 + UV	2	Si Cu	Operation	Operation 240 (no UV)	1.90
Si Cu	Operation	None	6.82	240 (no UV)	4	Si Cu	Operation	Operation 240 + UV 60s	11.46
Si Cu	Operation	Operation 240 + UV 60s	5.11	230 + UV					

[0048] As shown in Table 2, copper oxide has an increased amount of silicon residue than reduced copper after operation **240**. Additionally, performing operation **240** without UV may be desirable for minimizing the silicon residue on the copper surface.

TABLE-US-00003

TABLE 3	Water	Contact	Angle	(Center)	(Degrees)	k	Low	k	film	at	Operation
99.2	2.46	210	(FIG. 4A)	Post	Operation	220	<10	2.74	Damage	(FIG. 4B)	Post
89	2.61	UV	(FIG. 4D)	Post	Operation	240	with	93.7	2.59	UV 60s	(FIG. 4D)
79.3	2.60	followed	by	UV 60s	after	operation	240	(FIG. 4D)			

[0049] As shown in Table 3, the low-k film **310a** had a high water contact angle and thus was hydrophobic. After the operation **220** damage, the low-k film **310b** had a low water contact angle and thus was hydrophilic. Then, after operation **240**, the low-k film **310c** had a higher water contact angle and was thus hydrophobic. Operation **220** increased the k value, but k value was then partially recovered by operation **240**. In some embodiments, UV exposure may be performed during operation **240** or sequentially after the recovery precursor process in operation **240**. When UV exposure was performed after operation **240**, the low-k film **310b** had a lower water contact angle as compared to operation **240** without UV or operation **240** simultaneously with UV.

[0050] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

## Claims

1. A method, comprising: positioning a substrate within a process chamber; introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate; removing the reducing agent from the process chamber; and introducing a recovery precursor into the process chamber to decrease a k-value of a low-k film on the substrate.
2. The method of claim 1, further comprising: exposing the substrate to UV light during at least a portion of a time when the reducing agent is within the process chamber.
3. The method of claim 2, wherein the reducing agent is ammonia.
4. The method of claim 1, further comprising: exposing the substrate to UV light during at least a portion of a time when the recovery precursor is within the process chamber.
5. The method of claim 1, wherein the recovery precursor is introduced to the process chamber after the reducing agent is removed from the process chamber.
6. The method of claim 1, wherein the recovery precursor comprises a molecule selected from a group consisting of: ##STR00008## wherein R is independently selected from Me, Et, iPr, tBu, and H, and R' is an alkane, alkene, or an alkyne.
7. The method of claim 1, wherein the recovery precursor comprises a molecule selected from a group consisting of ##STR00009##
8. The method of claim 1, wherein the recovery precursor comprises a molecule selected from a group consisting of ##STR00010## wherein R is independently selected from Me, Et, iPr, and tBu, and R' is an alkane, alkene, or an alkyne.
9. The method of claim 1, wherein the recovery precursor comprises a molecule selected from a group consisting of ##STR00011## wherein X is Cl, Br, or I, and R' is an alkane, alkene, or an alkyne.
10. The method of claim 1, wherein the recovery precursor comprises a molecule with a formula: ##STR00012## wherein R' is an alkane, alkene, or an alkyne.
11. The method of claim 1, wherein the recovery precursor comprises a molecule with a formula: ##STR00013## wherein R is hydrogen, an alkane, an alkene, an alkyne, or an aryl, and R' is hydrogen, an alkane, an alkene, an alkyne, or an aryl.
12. The method of claim 1, wherein the recovery precursor comprises a molecule with a formula: ##STR00014## wherein R is hydrogen, an alkane, an alkene, an alkyne, or an aryl, R' is hydrogen, an alkane, an alkene, an alkyne, or an aryl, and R'' is hydrogen, an alkane, an alkene, an alkyne, or an aryl.
13. The method of claim 1, wherein the reducing agent comprises ammonia (NH<sub>3</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), ethanol (C<sub>2</sub>H<sub>5</sub>OH), methane (CH<sub>4</sub>), or ethene (C<sub>2</sub>H<sub>4</sub>).
14. A method, comprising: positioning a substrate within a process chamber; introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate, wherein the reducing agent comprises ammonia (NH<sub>3</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), ethanol (C<sub>2</sub>H<sub>5</sub>OH), methane (CH<sub>4</sub>), or ethene (C<sub>2</sub>H<sub>4</sub>); turning on a UV light source to expose the substrate to UV light; removing the reducing agent from the process chamber; and introducing a recovery precursor into the process chamber to decrease a k value of a low-k film on the substrate.
15. The method of claim 14, further comprising: turning off the UV light source prior to introducing the recovery precursor into the process chamber.
16. A non-transitory computer-readable medium storing instructions that, when executed by a



processor, cause a computer system to perform the steps of: positioning a substrate within a process chamber; introducing a reducing agent into the process chamber to remove copper oxide from a copper layer on the substrate; removing the reducing agent from the process chamber; and introducing a recovery precursor into the process chamber to decrease a k value of a low-k film on the substrate.

**17.** The non-transitory computer-readable medium of claim 16, further comprising: turning on a UV light source to expose the substrate to UV light.

**18.** The non-transitory computer-readable medium of claim 17, further comprising: turning off the UV light source prior to introducing the recovery precursor into the process chamber.

**19.** The non-transitory computer-readable medium of claim 16, further comprising: adjusting a flow rate of the recovery precursor to be between 100 mgm and 2000 mgm.

**20.** The non-transitory computer-readable medium of claim 16, further comprising: adjusting a pressure inside the process chamber to be between 3 Torr and 100 Torr; and adjusting a temperature inside the process chamber to be between 75° C. and 500° C.

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