OXYGEN DOPED SiC FOR Cu BARRIER AND ETCH STOP LAYER IN DUAL DAMASCENE FABRICATION

FIELD OF THE INVENTION

The invention relates to the field of fabricating integrated circuits and other electronic devices and in particular to a dual damascene structure with high performance and improved reliability and a method for forming the same.

BACKGROUND OF THE INVENTION

The manufacture of an integrated circuit in a semiconductor device involves the formation of a metal layer that typically contains a wiring pattern which is overlaid on another conductive pattern. This process is repeated several times to produce a stack of metal layers. Metal interconnects which form horizontal and vertical electrical pathways in the device are separated by insulating or dielectric materials to prevent crosstalk between the metal wiring that can degrade device performance by slowing circuit speed. A popular method of forming an interconnect structure is a dual damascene process in which vias and trenches are filled with metal in the same step. A single damascene process is also commonly employed to form a metal pattern in one or more dielectric layers. The most frequently used dual damascene approach is a via first process in which a via is formed in a stack of dielectric layers and then a trench is formed above the via. Recent improvements in dual damascene processing include lowering the resistivity of the metal interconnect by switching from aluminum to copper and reducing the dielectric constant (k) of insulating materials to avoid capacitance coupling between the metal interconnects.

Current manufacturing practices involve forming vias and trenches that have sub-micron dimensions which can be less than 0.25 microns in width. One of the more promising low k dielectric materials is organosilicate glass (OSG) also known as SiCOH which is a silicon oxide that is doped with carbon and hydrogen atoms. Silicon oxide which has been traditionally used as a dielectric material has a dielectric constant of about 4. SiCOH has a k value between about 2 and 3 and thereby provides a much needed reduction in capacitance coupling between wiring. SiCOH is available as Black Diamond™ from Applied Materials, CORAL™ from Novellus, or can be obtained by different trade names from other manufacturers. The composition and properties of SiCOH may vary depending on the deposition conditions and source gases.

One concern with using SiCOH in a damascene structure is that the material as deposited is porous. A porous structure will allow moisture uptake which increases the dielectric constant and defeats the purpose of depositing a low k dielectric material. An organosilicate glass layer is employed as a thick dielectric layer in U.S. Patent 6,472,333. A SiC cap layer is formed on the organosilicate glass (SiCOH) layer to provide increased hardness for a subsequent chemical mechanical polish (CMP) step and then the SiCOH layer is annealed for improved mechanical properties and a lower k value. An amorphous carbon cap layer on a low k dielectric layer is described in U.S. Patent 6,541,397 and serves as an etch mask and as a CMP stop layer.

In some cases, densification after annealing is desirable. A well known method of densifying a porous SiCOH layer is to perform a plasma treatment such as the N_2/NH_3 plasma process described in U.S. Patent 6,436,808. Besides stabilizing the dielectric constant, the densification also improves SiCOH resistance to etchants such as O_2

plasma during removal of a photoresist mask that is used to transfer a trench pattern into the damascene stack.

The integration of amorphous silicon carbide (α-SiC:H) as a barrier/etch stop layer in a copper damascene fabrication scheme has been suggested as a possible solution to the problems of parasitic capacitance and RC delay in ultra-large scale integration. Although the α-SiC:H film has a lower dielectric constant (k ~ 4.5) than silicon nitride (k ~ 7), α-SiC:H has a higher current leakage level under high bias and a lower breakdown field than silicon nitride. Nitrogen doped SiC (SiCN) has been used as a barrier layer in a damascene structure as mentioned in U.S. Patent 6,436,824. While SiCN can improve the leakage performance, trace amounts of amines in SiCN have a tendency to poison a photoresist layer in a via hole during patterning of a trench opening in a via first dual damascene scheme. As a result, photoresist residue remains in the via after exposed regions are developed in an aqueous base solution which leads to an expensive rework process. In addition, the dielectric constant of SiCN (k ~ 4.9) is higher than the desired value of less than 4 and preferably less than 3 for a low k dielectric material. Therefore, an improved barrier layer or etch stop layer is required for new technologies which has a higher breakdown field and lower dielectric constant than current materials and which does not contain nitrogen that can have a deleterious effect on photoresist patterning.

One prior art method that mitigates the poisoning effect of a SiCN etch stop layer is described in U.S. Patent 6,455,417 where a composite etch stop comprised of an upper carbon doped oxide (SiCOH) is formed over a lower SiCN layer on a substrate. The lower layer acts as a buffer to keep the oxide layer from oxidizing the underlying

conductive metal while the SiCOH layer prevents the photoresist poisoning issue. However, this prior art does not address the issue of a relatively high k value for SiCN and a thick SiCOH layer may be necessary to prevent amines in SiCN from diffusing through the porous upper layer.

Other low k dielectric materials such as benzocyclobutene or hydrogen silsesquioxane (HSQ) are employed as an etch stop layer in a damascene structure in U.S. Patent 6,417,090. However, there is no provision to form a buffer layer between the oxygen containing HSQ layer and an underlying copper pattern.

A carbon doped silicon oxide layer is formed on a substrate in U.S. Patent 6,410,462 and uses silane, an oxygen source, and a mixture of CH_4 and acetylene for the deposition step. The introduction of methane and acetylene into the CVD process is claimed to promote a lower film density by forming more Si-O network terminating species. In this case, the composition of the SiCOH film appears to be less crosslinked than is normally desired and may result in a less mechanically sturdy structure. Low density also implies a higher porosity that can lead to water absorption and higher k value in subsequent processing steps.

An oxygen or nitrogen doped SiC layer is employed as an etch stop layer in U.S. Patent 6,486,082. However, the concentration of the dopant is not described.

A method of incorporating a SiCOH layer with a low oxygen content, hereafter referred to as oxygen doped silicon carbide, as an etch stop or barrier layer in a dual damascene scheme is desirable so that a reduction in dielectric constant and a higher breakdown field can be achieved without compromising Cu barrier capability or a photoresist processing step. An oxygen doped silicon carbide etch stop layer should

have good etch selectivity to other low k dielectric layers including SiCOH layers like Black Diamond™ from Applied Materials or CORAL™ available from Novellus.

SUMMARY OF THE INVENTION

An objective of the present invention is to provide a method of forming a dual damascene structure with a barrier/etch stop layer comprised of oxygen doped silicon carbide that has a dielectric constant of about 4 or less.

A further objective of the present invention is to provide an oxygen doped silicon carbide barrier/etch stop layer that has a better breakdown field than a silicon carbide layer.

A still further objective of the present invention is to integrate an oxygen doped silicon carbide barrier/etch stop layer into a damascene structure so that oxidation of an underlying metal layer is avoided.

Yet another objective of the present invention is to provide an oxygen doped silicon carbide layer that has good etch selectivity to other low k dielectric films including Black Diamond™ and CORAL™ and that has good copper barrier capability.

These objectives are achieved by providing a substrate having a first metal layer with an exposed top surface. The first metal layer may be formed in an opening that is lined with a diffusion barrier layer. In one embodiment, the first metal layer and diffusion barrier layer are contained in a first dielectric layer that has an overlying silicon carbide (SiC) cap layer which is coplanar with the first metal layer. A second SiC layer may be formed on the substrate to form a protective etch stop barrier over the first metal layer. Next, a first oxygen doped SiC layer is deposited on the SiC barrier layer by a plasma

enhanced chemical vapor deposition (PECVD) process and also functions as a barrier/etch stop layer. The first oxygen doped SiC layer may be further processed by treating with a plasma comprised of an inert gas such as He, Ar, or N_2 to densify the layer and prevent any increase in dielectric constant. A second dielectric layer is deposited on the first oxygen doped SiC layer followed by formation of a second oxygen doped SiC layer on the second dielectric layer. The second oxygen doped SiC layer serves as a second etch stop layer and is deposited in a manner similar to the first oxygen doped SiC layer. The second oxygen doped SiC layer may also be densified with a plasma treatment. A third dielectric layer is deposited on the second oxygen doped SiC layer followed by formation of a cap layer on the third dielectric layer to complete the damascene stack

A conventional process flow then follows and involves formation of a via pattern in the damascene stack by a photoresist patterning and etch sequence. Similar steps are taken to form a trench pattern in the cap layer and third dielectric layer that is aligned above the via pattern. The exposed first etch stop layer comprised of the second SiC layer and first oxygen doped SiC layer is removed to expose a portion of the surface of the first metal layer. A second diffusion barrier metal layer is deposited on the sidewalls and bottom of the trenches and via holes. Next, a second metal layer is deposited to fill the via and trench openings to a level above the cap layer. A planarization method such as a chemical mechanical polish (CMP) process is then employed to lower the second metal layer to a level that is coplanar with the cap layer on the damascene stack to complete the damascene sequence.

The invention is also a damascene structure that is formed on a substrate that may contain a first metal layer with an exposed top surface. The damascene structure has a first barrier/etch stop layer that is a composite of a lower SiC layer and a first oxygen doped SiC layer on the SiC layer. There is sequentially formed on the first oxygen doped SiC layer a second low k dielectric layer, a second oxygen doped etch stop layer, a third low k dielectric layer, and a cap layer on top of the damascene stack. The damascene stack has a trench in the cap layer and third dielectric layer which is aligned over a via that extends from the second etch stop layer through the second dielectric layer and first barrier/etch stop layer. There is a conformal diffusion barrier layer on the sidewalls and bottoms of the trench and via openings and a second metal layer formed on the diffusion barrier layer that is coplanar with the cap layer.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1 - 5 are cross-sectional views depicting a method of employing an oxygen doped SiC layer as a barrier and etch stop layer in a dual damascene process.

FIG. 6 is a plot showing density vs. sputter time during an ESCA analysis of an oxygen doped SiC layer that was deposited by a method of the present invention.

FIG. 7 is a plot showing breakdown field vs. oxygen flow rate for oxygen doped SiC layers that were deposited using different conditions by a method of the present invention.

FIG. 8 is a plot showing dielectric constant as a function of oxygen flow rate for oxygen doped SiC layers that were deposited using different conditions according to a method of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention is particularly useful in forming a dual damascene structure with high performance and good reliability. Although a via first dual damascene process is described, the method of incorporating an oxygen doped SiC etch stop layer into a damascene stack is equally effective for other damascene approaches including a single damascene method and a trench first dual damascene process. A first embodiment is depicted in FIGS. 1 – 5. The drawings are used for illustrative purposes and are not intended to limit the scope of the invention.

Referring to FIG. 1, a substrate **8** is provided that is typically monocrystalline silicon but optionally may be comprised of silicon-germanium, silicon-on-insulator, or other semiconductor materials used in the art. The substrate **8** may further include active and passive devices (not shown). In the exemplary embodiment, a first conductive layer comprised of three conductive lines is formed on the substrate **8**. Alternatively, a first conductive layer may be formed with a different pattern. However, the conductive layer should have an exposed top surface.

A first dielectric layer **10** that is preferably comprised of a low k dielectric material selected from a group including fluorine doped SiO_2, carbon doped SiO_2, hydrogen silsesquioxane (HSQ), methyl silsesquioxane (MSQ), fluorinated polyimide, poly(arylether), or benzocyclobutene is deposited by a chemical vapor deposition (CVD), plasma enhanced CVD (PECVD), or a spin-on method. Two popular forms of carbon doped SiO_2 are Black Diamond^{TM} from Applied Materials and COREL^{TM} from Novellus. Additional processing of the first dielectric layer **10** may include a high temperature cure or anneal at temperatures of up to 600^{O}C. A passivation layer **11**

preferably comprised of silicon carbide is deposited by a CVD or PECVD technique and has a thickness between about 0 and 1000 Angstroms.

A conventional method is used to form openings in first dielectric layer **10** and is typically comprised of patterning a photoresist layer (not shown) on the passivation layer **11** and using the photoresist as a mask while transferring the pattern through the passivation layer **11** and first dielectric layer **10** by a plasma etch process. A conformal diffusion barrier layer **12** such as Ta, TaN, TaSiN, Ti, TiN, W, or WN having a thickness between 50 and 300 Angstroms is deposited on the sidewalls and bottom of openings in first dielectric layer **10**. A first conductive layer that is preferably comprised of copper is deposited on the diffusion barrier layer **12** to form the conductive lines **13a**, **13b**, **13c**. A planarization step is employed to lower the first conductive layer so that the conductive lines **13a** – **13c** are coplanar with the passivation layer **11**. For example, a chemical mechanical polish (CMP) process may be used. It is understood that the widths of the conductive lines **13a** – **13c** are not necessarily equal in size. Similarly, the width of the first dielectric layer **10** between conductive lines **13a** and **13b** and between conductive lines **13b** and **13c** is not necessarily drawn to scale and could be larger or smaller in width than the width of the conductive lines **13a** – **13c**.

Referring to FIG. 2, a damascene stack of layers is fabricated by initially depositing a second SiC layer **14** having a thickness from about 50 to 150 Angstroms on the passivation layer **11** and on the conductive lines **13a** – **13c** by a CVD or PECVD method. In the preferred embodiment where the passivation layer **11** is SiC, the second SiC layer **14** is not distinguishable from first SiC layer **11** and the combined SiC layers **11**, **14** in FIGS. 3 - 5 will be referred to as SiC barrier layer **15**.

Returning to FIG. 2, a first oxygen doped SiC etch stop layer **16** is preferably formed on the second SiC layer **14** by a PECVD process that includes O_2 with a flow rate from about 20 to 200 standard cubic centimeters per minute (sccm), a trimethylsilane or tetramethylsilane flow rate of 280 to 350 sccm, a helium flow rate of from 700 to 1000 sccm with a chamber pressure of from 2 to 8 torr, a RF power of from 100 to 1000 Watts and preferably 200 to 600 watts generated with a RF frequency of 13.56 MHz, and a substrate temperature between 300^{O}C and 400^{O}C and preferably 350^{O}C. The helium is used to help transport the trimethylsilane or tetramethylsilane into the chamber. The process is preferably carried out using an inductively coupled plasma (ICP) source or a transformer coupled plasma (TCP) source to enable a higher degree of control and uniformity during the deposition. Under these conditions, the resulting oxygen doped SiC layer **16** typically has a lower oxygen content than Black Diamond^{TM} or COREL^{TM} films.

The thickness of the first oxygen doped SiC layer **16** is from 50 to 1000 Angstroms and preferably from 150 to 350 Angstroms. In one embodiment, the first oxygen doped SiC layer **16** is subjected to a plasma treatment known to those skilled in the art to stabilize the dielectric constant and prevent water uptake. For example, the first oxygen doped SiC layer **16** may be subjected to a plasma generated from N_2, He, or Ar to densify the layer. The plasma treatment is preferably performed in the same process chamber in which the previous PECVD process was carried out.

A second dielectric layer **17** having a thickness of from 2000 to 10000 Angstroms is deposited on the first oxygen doped SiC layer **16** by a CVD, PECVD or spin-on method. The second dielectric layer **17** is preferably comprised of a low k dielectric material and

is selected from the same group of materials previously described for the first dielectric layer **10**. A conventional cure or anneal process is typically performed to remove trace amounts of solvents and other low molecular weight compounds from the second dielectric layer **17**. In one embodiment, the damascene stack is completed at this point.

In the exemplary embodiment, a second oxygen doped SiC layer **18** that functions as an etch stop is preferably formed on the second dielectric layer **17** by the same method employed to form first oxygen doped SiC layer **16** and has a thickness in the range of 50 to 1000 Angstroms. In one embodiment, the second oxygen doped SiC layer **18** is treated with a N_2, He, or Ar plasma to densify the layer and stabilize its dielectric constant during subsequent processes.

A third dielectric layer **19** having a thickness from 1000 to 10000 Angstroms is deposited on second oxygen doped SiC layer **18** by a CVD, PECVD, or spin-on method. The third dielectric layer **19** is preferably comprised of the same low k dielectric material used in the second dielectric layer **17** and is typically cured or annealed to drive off trace amounts of solvent and low molecular weight compounds. The damascene stack may be completed by deposition of a cap layer **20** with a thickness between 0 and 1000 Angstroms. The cap layer **20** is comprised of a material such as SiC, silicon nitride, silicon oxide, fluorine doped SiO_2, or silicon oxynitride which is deposited by a CVD or PECVD technique. The cap layer **20** is selected for its low removal rate in a subsequent CMP step and for its resistance to scratch and dishing defects during the polishing process.

Referring to FIG. 3, a via pattern comprised of vias **21a** – **21c** is formed in the damascene stack. Vias **21a**, **21b**, **21c** are aligned above the conductive lines **13a**, **13b**,

13c, respectively, in the first conductive layer. The patterning method typically involves forming via openings in a photoresist layer (not shown) on the cap layer **20** or on the top layer of the damascene stack and employing the photoresist as a mask to transfer the pattern through the underlying layers by a plasma etch process that can have multiple steps. Note that the etch process stops on the first oxygen doped SiC layer **16** and the width of the vias **21a** – **21c** should not be larger than the width of an underlying conductive line.

In a preferred embodiment, the first oxygen doped SiC layer **16** has enough selectivity to the second dielectric layer **17** so that a minimum amount of the first oxygen doped SiC layer **16** thickness is lost as the etch transfer step removes the last portion of the second dielectric layer **17** from the bottom of the vias **21a** – **21c**. The etch process is usually not completely uniform and the second dielectric layer **17** may be removed from some vias faster than from others. For example, the etch rate of the second dielectric layer **17** in the vias **21a** – **21c** that are in a dense array may be different than in an isolated via (not shown) in the same via pattern. The first oxygen doped SiC layer **16** is deposited in the preferred embodiment so that it has good selectivity towards carbon doped SiO_2 materials in the second dielectric layer **17** such as Black Diamond™ and COREL™ when a plasma etch generated from C_4F_8 and Ar gases is employed. Optionally, other fluorocarbons may be used in place of C_4F_8. Those skilled in the art will appreciate that the gas composition of the plasma etch through the second and third dielectric layers **17**, **19** may be different than in the plasma etch through the cap layer **20** and through the second oxygen doped SiC layer **18**.

In one embodiment, the first and second oxygen doped SiC layers **16**, **18** are formed with a carbon content of from 17 to 25% and an oxygen content of from 5 to 15%. In comparison, Black Diamond™ or other SiCOH films generally have a carbon content of 10 to 15% and an oxygen content of 25 to 35%. As a result, an etch rate selectivity of between 6:1 and 10:1 is achieved for SiCOH relative to the oxygen doped SiC layers **16**, **18** in an etch process having a plasma chemistry based on C_4F_8 and Ar.

Referring to FIG. 4, a trench pattern that includes trenches **22a**, **22b** is formed in cap layer **20** and in the third dielectric layer **19**. The trench **22a** is aligned above the via **21a** and may be formed above one or more other vias (not shown) while the trench **22b** is aligned above via **21c** and may be formed above one or more vias in an adjacent region of the pattern that is not pictured. This is only one possible embodiment for a dual damascene scheme and other designs in which a trench pattern is overlaid on a via hole pattern are equally useful in the present invention as appreciated by those skilled in the art. The trenches **22a**, **22b** are formed by a conventional sequence that normally involves patterning a photoresist layer (not shown) on the cap layer **20** and employing the photoresist as a mask while the trench openings are plasma etch transferred through the cap layer **20** and third dielectric layer **19**. The photoresist remaining on the cap layer **20** and any organic material in vias **21a** – **21c** including the first oxygen doped SiC layer **16** and second SiC layer **15** are then removed by a plasma etch so that conductive lines **13a** – **13c** are exposed. Preferably, the SiC layer **15** is removed by a soft etch known to those skilled in the art that does not damage the underlying conductive lines **13a** – **13c** and does not deform the sidewalls of the second

and third dielectric layers **17**, **19** or the sidewalls of the first and second oxygen doped SiC layers **16**, **18**.

Alternatively, when the second dielectric layer **17** is the top layer in the damascene stack, then a trench pattern is formed in the second dielectric layer and is aligned over the via pattern as appreciated by those skilled in the art.

Referring to FIG. 5, a completed dual damascene structure is shown. Preferably, a second diffusion barrier layer **23** selected from the same group as described for first diffusion barrier layer **12** is deposited to a thickness of from 50 to 300 Angstroms on the sidewalls and bottoms of the trenches **22a**, **22b** and vias **21a** – **21c**. Next, a metal layer **24** that is copper, Al, Al/Cu or W is deposited by an electroplating method or physical vapor deposition (PVD), for example, on the second diffusion barrier layer **23** to a level that is above the top of cap layer **20**, or optionally, above the top layer in the damascene stack. The metal layer **24** is preferably planarized by a CMP process to a level that is coplanar with the cap layer **20** or the top of the damascene stack.

An advantage of the damascene method of the present invention is that the first and second oxygen doped SiC layers **16**, **18** have a lower dielectric constant (k ~ 3.7 to 4.3) than convention etch stops such as SiC (k ~ 4.5) or SiCN (k ~ 4.9). Furthermore, there is no nitrogen content in the oxygen doped SiC etch stop layers **16**, **18** which eliminates any concern about contamination of photoresist in via holes during the trench definition step. Other performance advantages are realized because the oxygen doped SiC layer of the present invention has a higher breakdown field (6 mV/cm) than SiC (3.7 mV/cm) while exhibiting a similar Cu barrier capability to SiC and SiCN. The relationship between breakdown field and O_2 flow rate during the deposition of oxygen doped SiC

layers **16**, **18** is depicted in FIG. 7. Representative values for dielectric constants of the oxygen doped SiC layer **16**, **18** formed at various O_2 flow rates are shown in FIG. 8.

The present invention is also a damascene structure comprised of one or more oxygen doped SiC etch stop layers as depicted in FIG. 5 and formed by a method of the first embodiment. Although a dual damascene structure is shown, other damascene schemes including a single damascene structure and a second dual damascene structure stacked on a first dual damascene structure are also compatible with the integration of oxygen doped SiC layers in a damascene stack in this invention. Moreover, the present invention anticipates a variety of damascene structures that include various combinations of a trench pattern overlaid on a via pattern. Additionally, the damascene stack may include only the first oxygen doped SiC and a second dielectric layer as the top layer.

A substrate **8** is provided that is preferably monocrystalline silicon but optionally may be based on silicon-germanium, silicon-on-insulator, or other semiconductor materials used in the art. There is a first dielectric layer **10** on the substrate **8** that is comprised of a low k dielectric material such as fluorine doped SiO_2, carbon doped SiO_2, hydrogen silsesquioxane (HSQ), methyl silsesquioxane (MSQ), fluorinated polyimide, poly(arylether), or benzocyclobutene having a thickness in the range of 1000 to 10000 Angstroms. Within the first dielectric layer **10** there is a first conductive layer comprised of the conductive lines **13a** – **13c**. The first conductive layer is formed on a conformal diffusion barrier layer **12** that is Ta, TaN, TaSiN, Ti, TiN, W, or WN, for example, that lines the sidewalls and bottoms of the openings in the dielectric stack. The conductive

lines **13a** – **13c** are preferably comprised of copper and are coplanar with the top of the openings in the first dielectric layer **10**.

The damascene structure includes a first barrier/etch stop layer that is a composite of a lower SiC layer **15** with a thickness between 50 and 150 Angstroms and an upper oxygen doped SiC layer **16** having a thickness from 50 to 1000 Angstroms. The oxygen doped SiC layer **16** has the following composition: 25 to 35 atomic %Si; 17 to 25 atomic % C; 5 to 15 atomic % O; and 20 to 40 atomic % H. In one embodiment, the bottom of the SiC layer **15** is at a level on the first dielectric layer **10** that is below the top of the conductive lines **13a** – **13c**. Alternatively, the SiC layer **15** is formed on a first dielectric layer **10** that is coplanar with the conductive lines **13a** – **13c**. A succession of layers is formed on the first oxygen doped SiC layer **16** and includes in order a second dielectric layer **17**, a second oxygen doped SiC etch stop layer **18** with a thickness and composition similar to first oxygen doped SiC layer **16**, a third dielectric layer **19**, and a cap layer **20** on top of the damascene stack. Second and third dielectric layers **17**, **19** are selected from the same group of materials as described for the first dielectric layer **10** and have a thickness in a range of 2000 to 10000 Angstroms. The cap layer **20** is from 0 to 1000 Angstroms thick and is SiC, silicon nitride, silicon oxide, fluorine doped SiO_2, or silicon oxynitride.

In the exemplary embodiment, the damascene stack has trenches **22a**, **22b** in the cap layer **20** and third dielectric layer **19** that are aligned over the vias **21a** and **21c**, respectively, which extend through the first and second oxygen doped SiC layers **16**, **18**, the second dielectric layer **17**, and through SiC layer **15**. The via **21a** is aligned over the conductive line **13a** while the via **21c** is aligned over the conductive line **13c**. A

third via **21b** extends through the cap layer **20**, second and third dielectric layers **17**, **19**, and through SiC layer **15** and first and second oxygen doped SiC layers **16**, **18** above conductive line **13b**. Other trenches and vias may be present in the damascene stack above substrate **8** but are not shown. For example, the trench **22a** may be formed over other vias besides via **21a** and the trench **22b** may be formed over other vias in addition to via **21c**. Moreover, other designs in which a trench pattern is overlaid on a via pattern is anticipated as described previously.

There is a second diffusion barrier layer **23** with a thickness of 50 to 300 Angstroms formed on the sidewalls and bottoms of the trenches **22a**, **22b** and vias **21a** – **21c** that is selected from the same group of materials as mentioned earlier for the first diffusion barrier layer **12**. A metal layer **24** is formed that fills the trenches **22a**, **22b** and vias **21a** – **21c** and is coplanar with the cap layer **20** and with the top of second diffusion barrier layer **23**. The metal layer **24** is preferably comprised of copper but optionally may be Al/Cu, Al, or W Although the invention is not limited to a specific size of width for the first conductive layer and metal layers, the invention is especially effective in improving the performance of a device where the width of the first conductive layer and metal layer is less than about 0.25 microns.

An advantage of the damascene structure of the present invention is that the first and second oxygen doped SiC layers **16**, **18** have a lower dielectric constant (k ~ 3.7 to 4.3) than conventional etch stops including SiC (k ~ 4.5) or SiCN (k ~ 4.9). Other performance advantages are realized because the oxygen doped SiC layer of the present invention has a higher breakdown field (6 mV/cm) than SiC (3.7 mV/cm) while exhibiting a similar Cu barrier capability to SiC and SiCN. The relationship between

breakdown field and O_2 flow rate during the deposition of oxygen doped SiC layers **16**, **18** is depicted in FIG. 7. Representative values for dielectric constants of the oxygen doped SiC layer **16**, **18** formed at various O_2 flow rates are shown in FIG. 8.

An example in which an oxygen doped SiC layer is deposited on a substrate according to the present invention is provided in Example 1.

EXAMPLE 1

A 1 micron thick copper film was deposited on 200 mm silicon wafers by an ECP method. Next, a series of oxygen doped SiC films with a thickness of 500 Angstroms were deposited on the copper coated wafers in a Producer tool available from Applied Materials (AMAT) by a PECVD process involving an oxygen flow rate of from 0 to 200 sccm, a helium flow rate of 800 sccm, a trimethylsilane flow rate of 320 sccm at a substrate temperature of 350^{O}C with a RF power of 460 Watts generated with a RF frequency of 13.56 MHz and with a chamber pressure of 3.5 Torr. The deposition rate is about 900 Angstroms per minute. The films were annealed by baking at 400^{O}C for four hours in a nitrogen ambient.

As shown in FIG. 6, a SIMS analysis of the resulting films was plotted as copper concentration or density in terms of atoms/cm^3 vs. sputter time during the analysis. Curve **40** represents a SiC film deposited with no oxygen flow rate. Curve **41** represents an oxygen doped SiC film deposited with a 40 sccm flow rate of O_2 while curves **42** and **43** show the results from oxygen doped SiC films deposited with O_2 flow rates of 75 sccm and 200 sccm, respectively. The films deposited at the three lower O_2 flow rates (curves **40**, **41**, **42**) tend to have a fairly low copper out-diffusion into the

oxygen doped films. However, the oxygen doped SiC layer formed with a 200 sccm O_2 flow rate exhibits a much lower resistance to block the copper out-diffusion. The inventors have determined that an oxygen flow rate of 20 to 75 sccm is preferred at these conditions because the resulting films have a high enough resistance to block the copper out-diffusion.

The breakdown field (Mv/cm) of the oxygen doped SiC films as a function of O_2 flow rate during deposition was determined by an Al dot I-V measurement at 150^{O}C which is well known to those skilled in the art. FIG. 7 shows that the breakdown field improves rapidly while increasing the O_2 flow rate to 75 sccm and then has a further slight improvement at a 200 sccm O_2 flow rate. At O_2 flow rates between 20 and 75 sccm, the oxygen doped SiC films have a breakdown field of greater than 4 mV/cm which is better than a pure SiC film.

Referring to FIG. 8, the dielectric constants of the various films were measured at 1 MHz (Curve **51**) by an Al dot I–V test at room temperature which indicates that the dielectric constant becomes lower as the oxygen flow rate increases and changes from about 4.3 at 0 sccm O_2 to 3.7 for a 75 sccm O_2 flow rate.

The results obtained from the three different types of analyses demonstrate that an oxygen doped SiC film deposited at O_2 flow rates between about 20 and 75 sccm has an advantage over a conventional SiC layer (0 O_2 flow rate) in terms of a lower dielectric constant and a higher breakdown field. Furthermore, the oxygen doped SiC film of the present invention has an equivalent capacity to function as a copper out-diffusion barrier.

While this invention has been particularly shown and described with reference to, the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of this invention.

We claim:

1. A damascene method, comprising:

(a) providing a substrate;

(b) depositing a composite barrier/etch stop layer comprised of a lower silicon carbide (SiC) layer and an upper oxygen doped SiC layer on said substrate;

(c) forming a first dielectric layer on said oxygen doped SiC layer;

(d) forming an opening with sidewalls and a bottom in said first dielectric layer;

(e) removing said composite barrier/etch stop layer that is exposed at the bottom of said opening;

(f) depositing a conformal diffusion barrier layer on the sidewalls and bottom of said opening; and

(g) depositing a metal layer on the conformal diffusion barrier layer that fills said opening.

2. The method of claim **1** wherein the substrate is comprised of a conductive layer with a top surface and said opening exposes a portion of the top surface of the conductive layer.

3. The method of claim **2** wherein the conductive layer and the metal layer are comprised of copper.

4. The method of claim **1** wherein the diffusion barrier layer is comprised of Ta, TaN, TaSiN, Ti, TiN, W, or WN and has a thickness in the range of about 50 to 300 Angstroms.

5. The method of claim **1** wherein said first dielectric layer is comprised of Black Diamond™, CORAL™, fluorine doped SiO_2, hydrogen silsesquioxane (HSQ), methyl silsesquioxane (MSQ), a fluorinated polyimide, a polyarylether, or benzocyclobutene.

6. The method of claim **1** wherein the lower SiC layer has a thickness from about 50 to 150 Angstroms and the oxygen doped SiC layer has a thickness between about 50 and 1000 Angstroms.

7. The method of claim **1** wherein the oxygen doped SiC layer is deposited by a PECVD process that includes an oxygen flow rate from about 20 to 200 standard cubic centimeters per minute (sccm), a helium flow rate of about 700 to 1000 sccm, a trimethylsilane or tetramethylsilane flow rate of about 280 to 350 sccm, a substrate temperature of from 300^{O}C to 400^{O}C, a chamber pressure of 2 to 8 Torr, and a RF power of about 100 to 1000 Watts that is generated with a RF frequency of 13.56 MHz.

8. The method of claim **7** wherein the substrate temperature is 350^{O}C, the RF power is 460 Watts, chamber pressure is 3.5 Torr, the O_2 flow rate is about 30 sccm, the He flow rate is about 800 sccm, and the trimethylsilane flow rate is about 320 sccm to give an oxygen doped SiC deposition rate in the range of 850 to 950 Angstroms per minute.

9. The method of claim **7** wherein the oxygen doped SiC layer has a silicon content from about 25 to 35 atomic weight %, a carbon content of about 17 to 25 atomic wt. %, an oxygen content of about 5 to 15 atomic wt. %, and a hydrogen content from about 20 to 40 atomic wt. %.

10. The method of claim **7** wherein the oxygen doped SiC layer has a good etch selectivity to Black Diamond^{TM} or CORAL^{TM} of about 1:6 to 1:10 in a plasma etch comprised of C_4F_8 and Ar gases.

11. The method of claim **1** further comprised of treating said oxygen doped SiC layer with a N_2, He, or Ar plasma before said first dielectric layer is formed.

12. The method of claim **1** further comprised of a chemical mechanical polish process to planarize said metal layer.

13. A dual damascene method, comprising:

(a) providing a substrate with a conductive layer formed within a first dielectric layer, said conductive layer has an exposed top surface that is coplanar with the top surface of said substrate;

(b) depositing a barrier/etch stop layer comprised of a lower silicon carbide (SiC) layer and an upper first oxygen doped SiC layer on said substrate;

(c) forming a second dielectric layer on said first oxygen doped SiC layer;

(d) depositing a second oxygen doped SiC etch stop layer on said second dielectric layer;

(e) forming a third dielectric layer on said second oxygen doped SiC layer;

(f) forming an opening comprised of a via that exposes said conductive layer and a trench aligned above said via wherein the via has sidewalls and a bottom and extends through said second and third dielectric layers, second oxygen doped SiC layer, and through the composite barrier/etch stop layer and wherein the trench has sidewalls and a bottom and is formed in the third dielectric layer; and

(g) depositing a conformal diffusion barrier layer on the sidewalls and bottom of said trench and via and depositing a metal layer on said conformal diffusion barrier layer that fills said trench and via.

14. The method of claim **13** further comprised of forming a cap layer on the third dielectric layer and wherein the trench is aligned above a via that exposes the conductive layer and said trench is formed in the cap layer and third dielectric layer.

15. The method of claim **13** wherein said conductive layer and metal layer are comprised of copper.

16. The method of claim **13** wherein the diffusion barrier layer is comprised of Ta, TaN, TaSiN, Ti, TiN, W, or WN and has a thickness in the range of about 50 to 300 Angstroms.

17. The method of claim **13** wherein said first, second, and third dielectric layers are a low k dielectric material comprised of Black Diamond^{TM}, CORAL^{TM}, fluorine doped SiO_2, hydrogen silsesquioxane (HSQ), methyl silsesquioxane (MSQ),a fluorinated polyimide, a polyarylether, or benzocyclobutene.

18. The method of claim **13** wherein said second and third dielectric layers have a thickness in the range of about 1000 to 10000 Angstroms.

19. The method of claim **14** wherein the SiC in said barrier/etch stop layer has a thickness from about 50 to 150 Angstroms and the first and second oxygen doped SiC layers have a thickness between about 50 and 1000 Angstroms.

20. The method of claim **13** wherein said first and second oxygen doped SiC layers are deposited by a PECVD process that includes an oxygen flow rate from about 20 to 200 sccm, a helium flow rate of about 700 to 1000 sccm, a trimethylsilane or

tetramethylsilane flow rate of about 280 to 350 sccm, a substrate temperature of from 300^{O}C to 400^{O}C, a chamber pressure of 2 to 8 Torr, and a RF power of about 100 to 1000 Watts that is generated with a RF frequency of 13.56 MHz.

21. The method of claim **20** wherein the substrate temperature is 350^{O}C, the RF power is 460 Watts, chamber pressure is 3.5 torr, the O_2 flow rate is 30 sccm, the He flow rate is 800 sccm, and the trimethylsilane flow rate is 320 sccm to give an oxygen doped SiC deposition rate in the range of 850 to 950 Angstroms per minute.

22. The method of claim **20** wherein the first and second oxygen doped SiC layers have an etch selectivity to Black Diamond^{TM} or CORAL^{TM} of about 1:6 to 1:10 in a plasma etch comprised of C_4F_8 and Ar gases.

23. The method of claim **21** wherein the composition of the first and second oxygen doped SiC layers has a silicon content from about 25 to 35 atomic weight %, a carbon content of about 17 to 25 atomic wt. %, an oxygen content of about 5 to 15 atomic wt. %, and a hydrogen content from about 20 to 40 atomic wt. %.

24. The method of claim **13** further comprised of treating the first oxygen doped SiC layer with a N_2, Ar, or He plasma prior to depositing the second dielectric layer and treating the second oxygen doped SiC layer with a N_2, Ar, or He plasma prior to depositing the third dielectric layer.

25. A dual damascene structure comprising:

(a) a semiconductor substrate;

(b) a silicon carbide barrier layer formed on said substrate;

(c) a first oxygen doped SiC etch stop layer formed on said silicon carbide layer;

(d) a first dielectric layer formed on said first oxygen doped SiC layer;

(e) a second oxygen doped SiC etch stop layer formed on said first dielectric layer;

(f) a second dielectric layer formed on said second oxygen doped SiC layer;

(g) an opening comprised of a via with sidewalls and a bottom that exposes a portion of said substrate and a trench aligned above said via, said trench has sidewalls and a bottom and is formed in said second dielectric layer; and

(h) a conformal diffusion barrier on the sidewalls and bottoms of said via and trench and a metal layer on said diffusion barrier layer that fills said opening and is coplanar with the second dielectric layer.

26. The dual damascene structure of claim **25** wherein the substrate is comprised of a conductive layer with an exposed top surface and the bottom of the via exposes a portion of the top surface of said conductive layer.

27. The dual damascene structure of claim **26** wherein said conductive layer and metal layers are comprised of copper.

28. The dual damascene structure of claim **25** wherein the metal layer has a width that is less than about 0.25 microns.

29. The dual damascene structure of claim **25** wherein the diffusion barrier layer is comprised of Ta, TaN, TaSiN, Ti, TiN, W, or WN and have a thickness in the range of about 50 to 300 Angstroms.

30. The dual damascene structure of claim **25** wherein said first and second dielectric layers are comprised of Black Diamond^{TM}, CORAL^{TM}, fluorine doped SiO_2, hydrogen silsesquioxane (HSQ), methyl silsesquioxane (MSQ), a fluorinated polyimide, a polyarylether, or benzocyclobutene.

31. The dual damascene structure of claim **25** wherein said first and second dielectric layers have a thickness in the range of about 1000 to 10000 Angstroms.

32. The dual damascene structure of claim **25** wherein the SiC barrier layer has a thickness in the range of about 50 to 150 Angstroms.

33. The dual damascene structure of claim **25** wherein said first and second oxygen doped SiC layers have a thickness between about 50 and 1000 Angstroms.

34. The dual damascene structure of claim **25** wherein the first and second oxygen doped SiC layers have a silicon content from about 25 to 35 atomic weight %, a carbon content of about 17 to 25 atomic wt. %, an oxygen content of about 5 to 15 atomic wt. %, and a hydrogen content from about 20 to 40 atomic wt. %.

35. The dual damascene structure of claim **25** wherein the dielectric constant of said first and second oxygen doped SiC layers is between about 3.7 and 4.3.

36. The dual damascene structure of claim **25** wherein the breakdown field of said first and second oxygen doped SiC layers is greater than about 4 milliVolts/cm.

37. The damascene structure of claim **25** which is repeated a plurality of times to form a stack of metal layers on said substrate.