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(54) **POLISHING SLURRIES FOR CHEMICAL-MECHANICAL POLISHING**

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(57) **ABSTRACT**

The aqueous slurries according to the present invention include soluble salts of molybdenum dissolved in an oxidizing agent and deionized water. Other aqueous polishing slurries include dissolved and undissolved nanoparticles of MoO_3 in a solution of deionized water and an oxidizing agent.

POLISHING SLURRIES FOR CHEMICAL-MECHANICAL POLISHING

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application is a continuation of co-pending U.S. patent application Ser. No. 11/540,297, filed Sep. 9, 2006, allowed, which is a division of Ser. No. 11/032,717, filed Jan. 11, 2005, now U.S. Pat. No. 7,186,653, which is a continuation-in-part of co-pending U.S. patent application Ser. No. 10/846,718, filed on May 13, 2004, which is a continuation-in-part of co-pending U.S. patent application Ser. No. 10/631,698, filed on Jul. 30, 2003, all of which are hereby incorporated by reference for all that they disclose.

FIELD OF THE INVENTION

[0002] This invention relates to chemical-mechanical planarization processes in general and more specifically to slurries for chemical-mechanical planarization.

BACKGROUND OF THE INVENTION

[0003] Chemical-mechanical polishing (CMP) is the term used to refer to a process that is used in semiconductor manufacture. As its name implies, the CMP process is typically used in semiconductor processing to polish (e.g., planarize) the surface of the semiconductor wafer. The CMP process is relatively new in that, until recently, conventional processes were sufficient with the comparatively low circuit densities involved. However, increases in circuit densities (e.g., the transition from wafers having 0.25 micron features to 0.18 micron features, and even to 0.045 micron features) have forced the need to develop new processes for planarizing the wafer, of which CMP has become favored. Similarly, the more recent shift away from aluminum interconnect technology to copper interconnect technology has further favored the use of CMP to polish (e.g., planarize) semiconductor wafers.

[0004] Briefly, the chemical-mechanical polishing (CMP) process involves scrubbing a semiconductor wafer with a pad in the presence of a chemically reactive slurry that contains abrasive particles. As its name implies, the polishing action of the chemical-mechanical polishing (CMP) process is both chemical and mechanical. Chemicals aid in material removal by modifying the surface film while abrasion between the surface particles, pad, and the modified film facilitates mechanical removal. It is believed that this synergistic interplay between the chemical and mechanical components in the process is the key to effective polishing of the CMP process.

[0005] While the CMP process is being increasingly used in semiconductor manufacturing processes, the CMP process remains poorly understood, and the exact mechanisms though which the process works have not been determined. For example, while certain parameters for the CMP process have been developed that are satisfactory for wafers utilizing aluminum interconnect technology, those same process parameters have not proven to be particularly satisfactory for use with wafers utilizing copper interconnect technology. One important requirement of a successful CMP slurry for copper is a high polish rate. High polish rates lead to shorter copper overburden polishing times.

BRIEF SUMMARY OF THE INVENTION

[0006] The following summary is provided as a brief overview of the claimed product and process. It shall not limit the invention in any respect, with a detailed and fully-enabling disclosure being set forth in the Detailed Description of Preferred Embodiments section. Likewise, the invention shall not be restricted to any numerical parameters, processing equipment, chemical reagents, operational conditions, and other variables unless otherwise stated herein.

[0007] The claimed invention involves novel aqueous slurries which exhibit high polish rates for copper when used in the CMP process at low pressures. One embodiment of aqueous slurries according to the present invention comprises a solution of deionized water and an oxidizing agent, the oxidizing agent being in a first amount; a soluble salt of molybdenum dissolved in the solution, the soluble salt of molybdenum being in a second amount; and at least two complexing agents, the complexing agents each being in the second amount. In another embodiment, the first amount is in a range from about 0.1 weight percent to about 1.0 weight percent of the slurry.

[0008] Complexing agents of the present invention are selected from the group consisting of glycine ($C_2H_5NO_2$), alanine ($C_3H_7NO_2$), amino butyric acid ($C_4H_9NO_2$) ethylene diamine ($C_2H_8N_2$), ethylene diamine tetra acetic acid (EDTA), citric acid ($C_6H_8O_7$), phthalic acid ($C_6H_4(COOH)_2$), oxalic acid ($C_2H_2O_4$), acetic acid ($C_2H_4O_2$), and succinic acid ($C_4H_6O_4$).

[0009] In another embodiment, the aqueous slurry for polishing copper of the present invention comprises MoO_3 in an aqueous oxidizing agent solution, the MoO_3 consisting of dissolved and undissolved nanoparticles, and the dissolved nanoparticles of MoO_3 comprising molybdic acid. Further, the aqueous slurry exhibits chemical reactivity with copper and may include supplemental ceramic/metallic nanoparticles.

[0010] In still another embodiment, the aqueous slurry comprises molybdic acid powder dissolved in a solution of deionized water and an oxidizing agent, the molybdic acid powder comprising one or more selected from the group consisting of phosphotungstomolybdic acid and vanadiomolybdic acid. The slurry may include about 0.1% to about 10% by weight of the molybdic acid powder.

[0011] In yet another embodiment the slurry of the present invention comprises ions selected from the group consisting of per-molybdate ions and peroxy-molybdate ions, the ions being in a solution comprising deionized water and an oxidizing agent.

[0012] The oxidizing agents may oxidize the copper as well as react with molybdate ions present in the slurry. The new per-molybdate or peroxy-molybdate ions are expected to further oxidize and complex with copper, thereby providing high polish rates. Similar high polishing action may also occur by use of tungstates, vanadates, chromates and similar transition metal oxide ions or peroxy ions with or without the molybdate ions.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0013] Broadly described, embodiments of aqueous slurries according to the present invention may comprise a molybdenum oxide (MoO_2) polishing material and an oxidizing agent. The MoO_2 polishing material may be present in an amount of about 0.5 to about 10 wt. %, such as about 1 to about 3 wt. %, and more preferably in an amount of about 3 wt. %. The molybdenum oxide polishing material may comprise fine particles of MoO_2 having a mean particle size in the

range of about 25 nanometers (nm) to about 1 micron, such as about 25 nanometers to about 560 nm, and more preferably about 50 to 200 nm, as measured by a Horiba laser scattering analyzer.

[0014] The MoO_2 particles may be produced from a variety of molybdenum-containing precursor materials, such as, for example, ammonium molybdates and related compounds, as well as molybdenum oxides prepared from a variety of processes known in the art, wherein molybdenum precursors and products can be made into particles within the size ranges specified herein. Alternatively particles of MoO_2 may be reduced in size to the ranges specified herein by any of a variety of milling methods known in the art, such as attrition milling assisted by the use of appropriate reagents.

[0015] By way of example, embodiments of slurries according to the present invention may utilize particles of MoO_2 produced from a precursor material comprising nano-particles of MoO_3. Nano-particles of MoO_3 are commercially available from the Climax Molybdenum Company of Ft. Madison, Iowa (US). Alternatively, nano-particles of MoO_3 may be produced in accordance with the teachings provided in U.S. Pat. No. 6,468,497 B1, entitled "Method for Producing Nano-Particles of Molybdenum Oxide," which is incorporated herein by reference for all that it discloses.

[0016] Regardless of whether the nano-particles of MoO_3 are obtained commercially or manufactured in accordance with the teachings provided in U.S. Pat. No. 6,468,497 B1, identified above, the MoO_2 particles comprising the polishing material may be produced by heating nano-particles of MoO_3 for a time sufficient to convert substantially all of the MoO_3 to MoO_2. More specifically, the nano-particles of MoO_3 may be heated in a reducing atmosphere (e.g., hydrogen) to a temperature in the range of about 400° C. to about 700° C. (550° C. preferred). Times may be in the range of about 30 to about 180 minutes, as may be required to reduce MoO_3 to MoO_2 in sufficient quantities. Heating may be accomplished in a rotary furnace, although other types of furnaces may be used. If necessary, the resulting MoO_2 product may then be ground to produce an MoO_2 polishing material having a mean particle diameter within the ranges specified herein. A particle classification step may optionally be used to ensure that the resulting MoO_2 polishing material lacks particles that may cause damage during polishing.

[0017] The oxidizing agent may comprise any one or a mixture of ferric nitrate ($Fe(NO_3)_3$), nitric acid (HNO_3), potassium iodide (KI), and potassium iodate (KIO_3). Ferric nitrate oxidizing agent may be present in concentrations ranging from about 0.05 to about 0.2 molar (M) $Fe(NO_3)_3$, such as about 0.1 to about 0.2M $Fe(NO_3)_3$, and more preferably in a concentration of about 0.2 M $Fe(NO_3)_3$. Nitric acid oxidizing agent may be present in amounts ranging from about 0.5 to about 2 wt. % HNO_3, such as about 1 to about 2 wt. % HNO_3, and more preferably in an amount of about 2 wt. % HNO_3. Potassium iodide oxidizing agent may be present in amounts ranging from about 0.5 to about 5 wt. % KI, such as about 1 to about 5 wt. % KI, and more preferably in an amount of about 3 wt. % KI. Potassium iodate oxidizing agent may be present in amounts ranging from about 1 to about 5 wt. % KIO_3, such as about 1 to about 3 wt. % KIO_3, and more preferably in an amount of about 3 wt. % KIO_3.

[0018] Additional oxidizing agents may comprise any one or a mixture of hydroxylamine hydrochloride ($(NH_2OH)Cl$) and potassium permanganate ($KMnO_4$). Hydroxylamine hydrochloride oxidizing agent may be present in amounts ranging from about 1 to about 5 wt. % $(NH_2OH)Cl$, such as about 2 to about 4 wt. % $(NH_2OH)Cl$, and more preferably in an amount of about 3 wt. % $(NH_2OH)Cl$. Potassium permanganate oxidizing agent may be present in amounts ranging from about 1 to about 5 wt. % $KMnO_4$, such as about 2 to about 4 wt. % $KMnO_4$, and more preferably in an amount of about 3 wt. % $KMnO_4$. However, the polishing rates with slurries containing hydroxylamine hydrochloride and potassium permanganate are generally lower than with the other oxidizing agents identified herein.

[0019] Embodiments of slurries according to the present invention may also be provided with an anionic surfactant or a cationic surfactant. The anionic surfactant used in the aqueous slurry may comprise any one or a mixture of polyacrylic acid (PAA), a carboxylic acid or its salt, a sulfuric ester or its salt, a sulfonic acid or its salt, a phosphoric acid or its salt, and a sulfosuccinic acid or its salt. The cationic surfactant used in the aqueous slurry may comprise any one or a mixture of a primary amine or its salt, a secondary amine or its salt, a tertiary amine or its salt, and a quaternary amine or its salt. Optionally, the aqueous slurry may be provided with a copper corrosion inhibitor which may comprise any one or a mixture of heterocyclic organic compounds including benzotriazole (BTA), triazole, and benzimidazole. Further, the slurry may contain any combination of these surfactants and corrosion inhibitors.

[0020] A preferred anionic surfactant is polyacrylic acid (PAA). A preferred cationic surfactant is cetyl pyridinium chloride (CPC). A preferred copper corrosion inhibitor is benzotriazole (BTA). The addition of PAA improved slurry dispersability and surface quality. It is believed that the addition of PAA modifies the surface charge of the molybdenum oxide particles such that interaction between the molybdenum oxide particles and copper is favorable, leading to an increase in the polish rate. Polyacrylic acid (PAA) surfactant may be present in amounts ranging from about 0.1 to about 4 wt. % PAA, such as about 0.5 to about 1 wt. % PAA, and more preferably in an amount of about 1 wt. % PAA. The cationic surfactant cetyl pyridinium chloride (CPC) may be present in amounts ranging from about 0.01 to about 1 wt. % CPC, such as about 0.05 to about 0.5 wt. % CPC, and more preferably in an amount of about 0.1 wt. % CPC. Benzotriazole (BTA) copper corrosion inhibitor may be present in concentrations ranging from about 0.5 to about 10 milli-molar (mM) BTA, such as about 1 to about 5 mM BTA, and more preferably in a concentration of about 1 mM BTA.

[0021] Embodiments of slurries according to the present invention may also be provided with amounts of molybdenum sulfide (MoS_2) as a lubricant. It has been found that the addition of molybdenum sulfide particles increases the polish rate of copper for slurries containing KIO_3 and PAA. Molybdenum sulfide particles may have mean diameters in the range of about 0.01 to about 1 micron. Molybdenum sulfide particles may be present in amounts ranging from about 0.1 to about 10 wt. % MoS_2, such as about 0.5 to about 5 wt. % MoS_2, and more preferably in an amount of about 1 wt. % MoS_2. Molybdenum sulfide particles having the size ranges herein are commercially available from the Climax Molybdenum Company of Ft. Madison, Iowa (US).

[0022] The pH of embodiments of slurries according to the present invention may be in the range of about 1 to about 14, such as a pH in the range of about 3 to about 7, and preferably having a pH of 4. The pH of embodiments of slurries according to the present invention may be adjusted by the addition of

suitable acids (e.g., hydrochloric acid (HCl)) or bases (e.g., potassium hydroxide (KOH)), as would be known by persons having ordinary skill in the art.

[0023] Yet additional embodiments of planarizing slurries according to the invention may also be provided with supplemental ceramic/metal oxide particles. Such supplemental ceramic/metal oxide particles used in the aqueous slurry may comprise any one or a mixture of silica, ceria, alumina, zirconia, titania, magnesia, iron oxide, tin oxide, and germania. Embodiments of slurries according to the present invention exhibit high polish rates for copper when used in the CMP process. More particularly, when potassium iodate (KIO_3) was used as an oxidizing agent in the molybdenum oxide slurries very high copper disk and copper film polish rates (e.g., up to 1000 and 470 nm/min, respectively, were obtained, as detailed in the following examples. Addition of PAA enhanced the film polish rate to about 667 nm/min. Further, when molybdenum sulfide particles were added to slurries containing KIO_3 and PAA, copper film polish rates of about 750 nm/min were obtained.

[0024] While polish rates with the KIO_3-based slurries of the present invention are high for copper, the post-polish surface of the copper tended to be covered with a thick, uneven misty layer with roughness values as high as about 150 nm as measured by a non-contact optical profilometer. If the post-polish surface quality is desired to be higher, the CMP polishing step may be followed by a buffing step. In one embodiment, the buffing step involved additionally polishing the copper surface with a dilute suspension of H_2O_2, glycine, BTA, and colloidal silica in deionized water at a pH of 4. The advantage of using an H_2O_2-based buffing step is that H_2O_2 reacts spontaneously with molybdenum oxide, thus removing residual amounts of molybdenum oxide that may remain on the surface. Very clean and smooth copper surfaces were obtained after subsequent buffing, some with roughness values as low as 0.35 nm as measured by a non-contact optical profilometer.

[0025] Polishing selectivity of one embodiment of a slurry of the present invention between Cu, Ta, and silicon oxide (SiO_2) was determined to be 235:1:1 for Cu:Ta:SiO_2, as presented in Example 24.

[0026] Examples 25 and 26 involve the addition of ethylene diamine tetra acetic acid (EDTA) to test the complexing ability of EDTA with copper ions. The polish rates for the two specified slurry compositions are presented in Table 5.

[0027] In order to provide further information regarding the invention, the following examples are provided. The examples presented below are representative only and are not intended to limit the invention in any respect.

Examples 1-15

[0028] Slurries of examples 1-15 were used to polish a copper disk having a diameter of 1.25 inches. The CMP polisher was a Struers DAP® with an IC-1400, k-groove polishing pad. The carrier remained stationary (i.e., was not rotated). The rotation rate of the platen was 90 revolutions per minute (rpm). The down-force placed on the copper disk was 6.3 pounds per square inch (psi). The slurry flow rate was 60 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the weight difference of the copper disk both before and after polishing, taking into consideration the density of the Cu material, the area of the disk that was polished, and the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0029] The slurries of examples 1-10 all contained 3 wt. % molybdenum oxide (MoO_2) in deionized water. The mean particle size of molybdenum oxide for examples 1-10 was 1 micron (1000 nm). The mean particle size of molybdenum oxide for examples 11-15 was 150 nm. Various amounts and types of oxidizing agents were added, as identified in Table 1. Example 11 contained 1.5 wt. % MoO_2 with 3 wt. % hydroxylamine hydrochloride ($(NH_2OH)Cl$) as an oxidizing agent. Example 12 contained 1.5 wt. % MoO_2 with 3 wt. % potassium permanganate ($KMnO_4$) as the oxidizing agent. Examples 13-15 all contain 3 wt. % KIO_3 with varying amounts of MoO_2, as noted. The pH of slurries for examples 1-15 was adjusted to 4.0 by the addition of hydrochloric acid (HCl) or potassium hydroxide (KOH). The slurry compositions and polishing rates for the copper disk are presented in Table 1.

TABLE 1

Example	Slurry Composition	Mean Particle Size (nm)	pH	Polish Rate (nm/min)
1	3% MoO_2 + 0.05M $Fe(NO_3)_3$	1000	4	69
2	3% MoO_2 + 0.1M $Fe(NO_3)_3$	1000	4	88
3	3% MoO_2 + 0.2M $Fe(NO_3)_3$	1000	4	230
4	3% MoO_2 + 0.5% HNO_3	1000	4	348
5	3% MoO_2 + 1% HNO_3	1000	4	221
6	3% MoO_2 + 2% HNO_3	1000	4	353
7	3% MoO_2 + 3% KI	1000	4	157
8	3% MoO_2 + 1% KIO_3	1000	4	123
9	3% MoO_2 + 2% KIO_3	1000	4	345
10	3% MoO_2 + 3% KIO_3	1000	4	1014
11	1.5% MoO_2 + 3%$(NH_2OH)Cl$	150	4	68
12	1.5% MoO_2 + 3% $KMnO_4$	150	4	31
13	1% MoO_2 + 3% KIO_3	150	4	169
14	2% MoO_2 + 3% KIO_3	150	4	524
15	3% MoO_2 + 3% KIO_3	150	4	862

Examples 16-18

[0030] Slurries of examples 16-18 were used to polish a copper film deposited on a silicon substrate by sputter deposition. The copper film had a diameter of 6 inches. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 40 rpm. The platen was rotated at 40 rpm. The down-force placed on the copper film was 6 pounds per square inch (psi). The slurry flow rate was set at 200 ml/min.

[0031] The amount of copper removed from the surface of the silicon substrate by CMP was determined by measuring the sheet resistance of the Cu film both before and after polishing at 17 points spread across the film utilizing a homemade paper mask and a 4-point probe. Sheet resistance was measured at the same points on the film before and after polishing. The measured sheet resistances both before and after polishing were then converted to respective film thicknesses before and after polishing based on the resistivity of the Cu material, the current applied, and the voltage across the 4-point probe. The difference between the starting and final thicknesses as 17 points were calculated, an average thickness loss was obtained which was then divided by the polish time to give the polish rate in nm/min.

[0032] The slurries all contained 3 wt. % molybdenum oxide (MoO_2) in deionized water and with potassium iodate (KIO_3) oxidizing agent present in an amount of 3 wt. %. The mean particle size of the molybdenum oxide for examples 16-18 was 1 micron (1000 nm). Example 17 added 1 wt. % PAA to the slurry. Example 18 added 1 wt. % PAA and 1 wt. % molybdenum sulfide (MoS_2) to the slurry. The pH of the slurries of examples 16-18 was adjusted to 4.0 by the addition of hydrochloric acid (HCl) or potassium hydroxide (KOH). The slurry compositions and polishing rates for the copper film are presented in Table 2.

TABLE 2

Example	Slurry Composition	Mean Particle Size (nm)	pH	Polish Rate (nm/min)
16	3% MoO_2 + 3% KIO_3	1000	4	471
17	3% MoO_2 + 3% KIO_3 + 1% PAA	1000	4	667
18	3% MoO_2 + 3% KIO_3 + 1% PAA + 1% MoS_2	1000	4	750

Examples 19-23

[0033] Slurries of examples 19-23 were used to polish a copper film deposited on a silicon substrate by sputter deposition. The copper film had a diameter of 6 inches. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 75 rpm. The platen was also rotated at 75 rpm. The down-force placed on the copper film was 4 pounds per square inch (psi). The slurry flow rate was set at 200 ml/min.

[0034] The amount of copper removed from the surface of the silicon substrate by CMP was determined by measuring the sheet resistance of the Cu film both before and after polishing at 17 points spread across the film utilizing a home-made paper mask and a 4-point probe. Sheet resistance was measured at the same points on the film before and after polishing. The measured sheet resistances both before and after polishing were then converted to respective film thicknesses before and after polishing based on the resistivity of the Cu material, the current applied, and the voltage across the 4-point probe. The difference between the starting and final thicknesses as 17 points were calculated, an average thickness loss was obtained which was then divided by the polish time to give the polish rate in nm/min.

[0035] The slurries all contained 3 wt. % molybdenum oxide (MoO_2) in deionized water and with a potassium iodate (KIO_3) oxidizing agent present in an amount of 3 wt. %. The mean particle diameter of the molybdenum oxide for examples 19-23 was 150 nm. Example 20 added 1 mM benzotriazole (BTA) to the slurry. Example 21 added 1 wt. % polyacrylic acid (PAA) to the slurry. Example 22 added 0.1 wt. % cetyl pyridinium chloride (CPC) to the slurry. Example 23 added 2 wt. % PAA and 1 mM BTA to the slurry. The pH of the slurries of examples 19-23 was adjusted to 4.0 by the addition of hydrochloric acid (HCl) or potassium hydroxide (KOH). The slurry compositions and polishing rates for the copper film are presented in Table 3.

TABLE 3

Example	Slurry Composition	Mean Particle Size (nm)	pH	Polish Rate (nm/min)
19	3% MoO_2 + 3% KIO_3	150	4	695
20	3% MoO_2 + 3% KIO_3 + 1 mM BTA	150	4	471
21	3% MoO_2 + 3% KIO_3 + 1% PAA	150	4	997
22	3% MoO_2 + 3% KIO_3 + 0.1% CPC	150	4	913
23	3% MoO_2 + 3% KIO_3 + 2% PAA + 1 mM BTA	150	4	660

Example 24

[0036] Silicon wafers (6 inch diameter) having a 0.3 micron Ta layer deposited by sputter deposition and wafers having a 1 micron SiO_2 layer applied by thermal oxidation were separately polished with a polishing slurry. The amount of copper and Ta removed was determined using a four-point probe, and SiO_2 removed from the surface of the silicon wafer by CMP was measured using an optical interferometer, in order to determine the rate of removal in terms of nm of material removed per minute.

[0037] The slurry utilized comprised 3 wt % molybdenum oxide (MoO_2) in deionized water with potassium iodate (KIO_3) oxidizing agent present in an amount of 3 wt. %. The mean particle size of the molybdenum oxide for example 24 was 1 micron (1000 nm). The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 40 rpm. The platen was also rotated at 40 rpm. The down-force placed on the copper film was 6 pounds per square inch (psi). The slurry flow rate was 200 ml/min. The slurry composition and polishing rates for Cu, Ta, and SiO_2 are presented in Table 4.

TABLE 4

Example	Slurry Composition	Cu Polish Rate (nm/min)	Ta Polish Rate (nm/min)	SiO_2 Polish Rate (nm/min)
24	3% MoO_2 + 3% KIO_3	471	2	2

Examples 25 and 26

[0038] Slurries of examples 25 and 26 were used to polish a copper disk having a diameter of 1.25 inches. The CMP polisher was a Struers DAP® with an IC-1400, k-groove polishing pad. The carrier remained stationary (i.e., was not rotated). The rotation rate of the platen was 90 revolutions per minute (rpm). The down-force placed on the copper disk was 6.3 pounds per square inch (psi). The slurry flow rate was 60 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the weight difference of the copper disk both before and after polishing, taking into consideration the density of the Cu material, the area of the disk that was polished, and the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0039] The slurries of examples 25 and 26 all contained 3 wt. % molybdenum oxide (MoO_2) in deionized water. The mean particle size of molybdenum oxide for both examples 25 and 26 was 1 micron (1000 nm). Various amounts and

types of oxidizing agents were added, as identified in Table 5. Slurries of both examples included the addition of 1 wt. % ethylene diamine tetra acetic acid (EDTA) to test the complexing ability of EDTA with copper ions. The slurry compositions and polishing rates for the copper disk are presented in Table 5.

TABLE 5

Example	Slurry Composition	Mean Particle Size (nm)	pH	Polish Rate (nm/min)
25	3% MoO_2 + 3% KI + 1% EDTA	1000	4	146
26	3% MoO_2 + 3% KI + 1% $KMnO_4$ + 1% EDTA	1000	4	259

[0040] Another embodiment of an aqueous slurry may comprise molybdenum trioxide (MoO_3) and an oxidizing agent. The MoO_3 may be present in an amount of about 0.1 to about 10 wt. %, such as about 0.5 to about 10 wt. %, and more preferably in an amount of about 0.5 to about 5 wt. %. The molybdenum trioxide (MoO_3) may be provided in powder form such that the molybdenum trioxide (MoO_3) visibly dissolves or substantially visibly dissolves in the oxidizing agent. The molybdenum trioxide powder may have a mean particle size of about 10,000 nm (10 microns) and more preferably less than about 1,000 nm (1 micron), as measured by a Horiba laser scattering analyzer. Generally speaking molybdenum trioxide (MoO_3) powders having these sizes are visibly dissolved in an aqueous solution of deionized water and the oxidizing agent. As used herein, the terms "dissolved" and "visibly dissolved," refer to solutions wherein the particles of MoO_3 are at least partially, although not necessarily completely, dissolved. Stated another way, solutions containing particles of MoO_3 may appear substantially clear or "visibly dissolved" to the naked eye, even though the particles of MoO_3 may not be completely dissolved.

[0041] An alternative embodiment of an aqueous slurry may comprise molybdic acid. The dissolution of molybdenum trioxide in an aqueous solution of deionized water and an oxidizing agent may form molybdic acid. In addition, molybdic acid may be formed by dissolving molybdenum metal, molybdenum oxides, or molybdates in an oxidizing medium. The term "molybdic acid" as used herein refers to any compound containing molybdenum and capable of transferring a hydrogen ion in solution. Embodiments of the aqueous slurry of the present invention utilizing molybdic acid may comprise the same oxidizing agents, complexing agents, surfactants, corrosion inhibitors, acids or bases, and supplemental ceramic/metal oxide particles as are listed below for the molybdenum trioxide aqueous slurry.

[0042] The MoO_3 particles may be produced from a variety of molybdenum-containing precursor materials, such as, for example, ammonium molybdates and related compounds, as well as molybdenum oxides prepared from a variety of processes known in the art, wherein molybdenum precursors and products can be made into particles of varying sizes. Molybdenum trioxide particles suitable for use in the present invention are commercially available from a wide variety of sources, including the Climax Molybdenum Company of Ft. Madison, Iowa (US).

[0043] The oxidizing agent used with molybdenum trioxide (MoO_3) may comprise any one or a mixture of hydrogen peroxide (H_2O_2), ferric nitrate ($Fe(NO_3)_3$), potassium iodate (KIO_3), nitric acid (HNO_3), potassium permanganate ($KMnO_4$), potassium persulfate ($K_2S_2O_8$), ammonium persulfate ($(NH_4)_2S_2O_8$), potassium periodate (KIO_4), and hydroxylamine (NH_2OH). Hydrogen peroxide oxidizing agent may be present in concentrations ranging from about 0.5 to about 20 wt % H_2O_2, such as about 1 to about 10 wt % H_2O_2, and more preferably in a concentration of about 5 wt % H_2O_2. Ferric nitrate oxidizing agent may be present in concentrations ranging from about 0.05 to about 0.2 molar (M) $Fe(NO_3)_3$, such as about 0.1 to about 0.2 M $Fe(NO_3)_3$, and more preferably in a concentration of about 0.2 M $Fe(NO_3)_3$. Potassium iodate oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % KIO_3, such as about 1 to about 3 wt % KIO_3, and more preferably in a concentration of about 3 wt % KIO_3. Nitric acid oxidizing agent may be present in concentrations ranging from about 0.5 to about 2 wt % HNO_3, such as about 1 to about 2 wt % HNO_3, and more preferably in a concentration of about 2 wt % HNO_3. Potassium permanganate oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % $KMnO_4$, such as about 2 to about 4 wt % $KMnO_4$, and more preferably in a concentration of about 3 wt % $KMnO_4$. Potassium persulfate oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % $K_2S_2O_8$, such as about 2 to about 4 wt % $K_2S_2O_8$, and more preferably in a concentration of about 3 wt % $K_2S_2O_8$. Ammonium persulfate oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % $(NH_4)_2S_2O_8$, such as about 2 to about 4 wt % $(NH_4)_2S_2O_8$, and more preferably in a concentration of about 3 wt % $(NH_4)_2S_2O_8$. Potassium periodate oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % KIO_4, such as about 2 to about 4 wt % KIO_4, and more preferably in a concentration of about 3 wt % KIO_4. Hydroxylamine oxidizing agent may be present in concentrations ranging from about 1 to about 5 wt % NH_2OH, such as about 2 to about 4 wt % NH_2OH, and more preferably in a concentration of about 3 wt % NH_2OH.

[0044] Additionally, complexing agents may be used in the molybdenum trioxide (MoO_3) aqueous slurry. Complexing agents may comprise any one or a mixture of glycine ($C_2H_5NO_2$), alanine ($C_3H_7NO_2$), amino butyric acids ($C_4H_9NO_2$), ethylene diamine ($C_2H_8N_2$), ethylene diamine tetra acetic acid (EDTA), ammonia (NH_3), family of mono, di, and tri-carboxylic acids like citric acid ($C_6H_8O_7$), phthalic acid ($C_6H_4(COOH)_2$), oxalic acid ($C_2H_2O_4$), acetic acid ($C_2H_4O_2$), and succinic acid ($C_4H_6O_4$) and family of amino benzoic acids ($C_7H_7NO_2$).

[0045] Glycine complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_2H_5NO_2$, such as about 0.1 to about 3 wt. % $C_2H_5NO_2$, and more preferably in an amount of about 0.5 wt. % $C_2H_5NO_2$. Alanine complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_3H_7NO_2$, such as about 0.1 to about 3 wt. % $C_3H_7NO_2$, and more preferably in an amount of about 0.5 wt. % $C_3H_7NO_2$. Amino butyric acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_4H_9NO_2$, such as about 0.1 to about 3 wt. % $C_4H_9NO_2$, and more preferably in an amount of about 0.5 wt. % $C_4H_9NO_2$. Ethylene diamine complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_2H_8N_2$, such as about 0.1 to about 3 wt. % $C_2H_8N_2$, and more preferably in an amount of about 0.5 wt. % $C_2H_8N_2$. Ethylene diamine tetra acetic acid complexing agent may be

present in amounts ranging from about 0.1 to about 5 wt. % EDTA, such as about 0.1 to about 3 wt. % EDTA, and more preferably in an amount of about 0.5 wt. % EDTA. Ammonia complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % NH_3, such as about 0.1 to about 3 wt. % NH_3, and more preferably in an amount of about 0.5 wt. % NH_3. Citric acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_6H_8O_7$ such as about 0.1 to about 3 wt. % $C_6H_8O_7$, and more preferably in an amount of about 0.5 wt. % $C_6H_8O_7$. Phthalic acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_6H_4(COOH)_2$ such as about 0.1 to about 3 wt. % $C_6H_4(COOH)_2$, and more preferably in an amount of about 0.5 wt. % $C_6H_4(COOH)_2$. Oxalic acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_2H_2O_4$ such as about 0.1 to about 3 wt. % $C_2H_2O_4$, and more preferably in an amount of about 0.5 wt. % $C_2H_2O_4$. Acetic acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_2H_4O_2$ such as about 0.1 to about 3 wt. % $C_2H_4O_2$, and more preferably in an amount of about 0.5 wt. % $C_2H_4O_2$. Succinic acid complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_4H_6O_4$ such as about 0.1 to about 3 wt. % $C_4H_6O_4$, and more preferably in an amount of about 0.5 wt. % $C_4H_6O_4$. Amino benzoic acids as a complexing agent may be present in amounts ranging from about 0.1 to about 5 wt. % $C_7H_7NO_2$ such as about 0.1 to about 3 wt. % $C_7H_7NO_2$, and more preferably in an amount of about 0.5 wt. % $C_7H_7NO_2$.

[0046] Embodiments of slurries containing molybdenum trioxide (MoO_3) may also be provided with a nonionic surfactant, an anionic surfactant, or a cationic surfactant. The anionic surfactant used in the aqueous slurry may comprise any one or a mixture of polyacrylic acid (PAA), a carboxylic acid or its salt, a sulfuric ester or its salt, a sulfonic acid or its salt, a phosphoric acid or its salt, and a sulfosuccinic acid or its salt. The cationic surfactant used in the aqueous slurry may comprise any one or a mixture of a primary amine or its salt, a secondary amine or its salt, a tertiary amine or its salt, and a quaternary amine or its salt. The nonionic surfactant may be one or a mixture of one of the family of polyethylene glycols.

[0047] Optionally, the molybdenum trioxide (MoO_3) aqueous slurry may also be provided with a copper corrosion inhibitor which may comprise any one or a mixture of heterocyclic organic compounds including benzotriazole (BTA), benzimidazole, poly triazole, phenyl triazole, thion and their derivatives. Further, the slurry may contain any combination of these surfactants and corrosion inhibitors.

[0048] A preferred anionic surfactant used in the MoO_3 slurry is a salt of dodecyl benzene sulfonic acid. The addition of a small amount of the dodecyl benzene sulfonic acid (DBSA) anionic surfactant to the slurry drastically reduced copper coupon dissolution rates to about 0 nm/minute and blanket copper wafer polish rates of about 750 nm/minute were obtained. See Example 34. This low copper coupon dissolution rate indicates low dishing of copper lines during pattern wafer polishing. Dodecyl benzene sulfonic acid surfactant and salts thereof (DBSA) may be present in amounts ranging from about 0.00001 to about 1 wt. % (DBSA), such as about 0.0001 to about 0.5 wt. % (DBSA), and more preferably in an amount of about 0.001 wt. % (DBSA).

[0049] A preferred copper corrosion inhibitor used in the MoO_3 slurry is benzotriazole (BTA). The addition of BTA to the slurry brought down the dissolution rates drastically, to less than 50 nm/minute. See Examples 30-33. Benzotriazole (BTA) copper corrosion inhibitor may be present in concentrations ranging from about 1 to about 20 milli-molar (mM) BTA, such as about 1 to about 10 mM BTA, and more preferably in a concentration of about 10 mM BTA.

[0050] The pH of embodiments of MoO_3 slurries according to the present invention may be in the range of about 1 to about 14, such as a pH in the range of about 1 to about 5, and preferably having a pH of about 2.6. The pH of embodiments of slurries according to the present invention may be adjusted by the addition of suitable acids (e.g., acetic acid) or bases (e.g., potassium hydroxide), as would be known by persons having ordinary skill in the art.

[0051] Yet additional embodiments of MoO_3 polishing slurries according to the invention may also be provided with supplemental ceramic/metal oxide particles. Such supplemental ceramic/metal oxide particles used in the aqueous slurry may comprise any one or a mixture of silica, ceria, zirconia, titania, magnesia, iron oxide, tin oxide, and germania. A preferred supplemental ceramic/metal oxide used in the MoO_3 slurry is colloidal silicon dioxide (SiO_2). Colloidal silicon dioxide (SiO_2) may have an average particle size of about 20 nm.

[0052] Embodiments of MoO_3 slurries according to the present invention exhibit high polish rates for copper when used in the CMP process. More particularly, when molybdenum trioxide MoO_3 particles were dispersed and dissolved in an aqueous solution containing hydrogen peroxide and glycine and used as a copper CMP slurry, high disk polish rates (e.g., about 2150 nm/minute) were obtained. However, the copper coupon dissolution rates in this slurry were also high (e.g., about 1150 nm/minute). See Example 28. These high dissolution and disk polish rates indicate the active chemical nature of the slurry chemicals. One of the reasons why this slurry exhibits such a high chemical reactivity is due to the partial dissolution of the molybdenum trioxide MoO_3 nanoparticles, which form molybdic acid. The copper dissolution rate gives an indication of the rate at which copper would be removed in those regions of the wafer that are not subject to mechanical abrasion. With proper choice of the concentrations of the additives and by inclusion of a corrosion inhibitor, polish rates can be tuned according to a user's requirements and dissolution rates can be minimized.

[0053] As shown in Examples 29 and 30, blanket copper wafer polishing rates of one embodiment of an MoO_3 slurry of the present invention were determined to be as high as about 1200 nm/minute with post CMP surface roughness of about 1 nm. The slurries of Examples 29 and 30 were filtered to remove particles above 1,000 nm (1 micron) in size and 1.0 wt % of 20 nm colloidal SiO_2 abrasives were added.

[0054] The post-polish surface of the copper was good with post CMP surface roughness values of about 1 nm as measured by a non-contact optical profilometer. If higher post-polish surface quality is desired, the CMP polishing step may be followed by a buffing step. In one embodiment, the buffing step may involve additionally polishing the copper surface with deionized water for about five to about fifteen seconds at a pH in the range of about 5 to about 7. The advantage of using a deionized water rinse buffing step is the removal of reactive chemicals from the wafer-pad interface, which removes residual amounts of molybdenum oxide that may remain on the surface of the wafer-pad. Clean and smooth copper surfaces were obtained after subsequent buffing using a deion-

ized water rinse, some with roughness values as low as about 0.5 to 0.6 nm as measured by a non-contact optical profilometer.

[0055] With proper adjustment of the concentrations of the chemicals added and with a deionized water rinse for about five seconds at the end of the wafer polishing, very high polish rates (e.g., about 900 nm/minute) and very low post CMP roughness (e.g., about 0.5 to 0.6 nm) were obtained. Copper coupon dissolution rate in this slurry was low (e.g., about 40 nm/minute). When a small amount of an anionic surfactant, such as sodium dodecyl benzene sulfonate (SDBS), was added to the MoO_3 polishing slurry, copper coupon dissolution rates became about 0 nm/minute, indicating low dishing of copper lines during pattern wafer polishing, and blanket copper wafer polish rates of about 750 nm/minute were obtained. See Example 34.

[0056] The general methodology for pattern wafer copper polishing is to polish the bulk copper initially at a high polish rate and then, as planarization is achieved, the copper polish rate is reduced in order to minimize dishing of copper lines. With proper adjustment of the slurry constituent composition and process parameters, the slurry of the present invention can be tuned for this general methodology of polishing at higher rates and then lower rates.

Examples 27 and 28

[0057] Slurries of examples 27 and 28 were used to polish a copper disk having a diameter of 32 millimeters (mm). The CMP polisher was a Struers DAP® with an IC-1400, k-groove polishing pad. The carrier remained stationary (i.e., was not rotated). The rotation rate of the platen was 90 revolutions per minute (rpm). The down-force placed on the copper disk was 6.3 pounds per square inch (psi). The slurry flow rate was 60 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the weight difference of the copper disk both before and after polishing, taking into consideration the density of the copper material, the area of the disk that was polished, and the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0058] Copper coupon dissolution experiments were performed in a 500 ml. glass beaker containing 400 ml. of the chemical solution. A copper coupon (i.e. 99.99% pure) of dimensions 25×25×1 mm was used as the experimental sample. The copper coupon was hand polished with 1500 grit sandpaper, washed with dilute hydrochloric acid (HCl) to remove copper oxides from the surface, dried in an air stream, and then weighed. The copper coupon was then immersed in the solution for three minutes while continuously stirring the solution. After the experiment, the copper coupon was washed repeatedly with a deionized water rinse, dried in an air stream, and weighed. Weight loss was used to calculate the dissolution rate.

[0059] Example 27 contained 1.0 wt. % MoO_3 in deionized (DI) water and Example 28 contained 1.0 wt. % MoO_3 in deionized (DI) water with 5.0% H_2O_2 and 1.0% glycine as an oxidizing agent and complexing agent, respectively. The natural pH of the Example 27 slurry was about 1.8. The natural pH of the Example 28 slurry was about 2.6. The remaining percentages not specified in the below table for the slurry compositions is the percentage of deionized water. In Example 27, the MoO_3 comprises 1% of the slurry composition and the deionized water comprises the remaining 99% of the slurry composition. The slurry compositions, copper coupon dissolution rates and polishing rates for the copper disk of Examples 27 and 28 are presented in Table 6.

TABLE 6

Example	Slurry Composition	pH	Polish Rate (nm/min)	Dissolution Rate (nm/min)
27	1.0% MoO_3 in DI Water	1.8	60	20
28	1.0% MoO_3 + 5.0% H_2O_2 + 1.0% glycine in DI water	2.6	2150	1140

Examples 29-34

[0060] Slurries of examples 29-34 were used to polish a copper film deposited on a silicon substrate by sputter deposition. The copper film had a diameter of 6 inches. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 75 rpm. The platen was rotated at 75 rpm. The down-force placed on the copper film was 4 pounds per square inch (psi). The slurry flow rate was set at 200 ml/min.

[0061] The amount of copper removed from the surface of the silicon substrate by CMP was determined by measuring the sheet resistance of the copper film both before and after polishing at 17 points spread across the film utilizing a home-made paper mask and a 4-point probe. Sheet resistance was measured at the same points on the film before and after polishing. The measured sheet resistances both before and after polishing were then converted to respective film thicknesses before and after polishing based on the resistivity of the copper material, the current applied, and the voltage across the 4-point probe. The difference between the starting and final thicknesses as 17 points were calculated, an average thickness loss was obtained which was then divided by the polish time to give the polish rate in nm/mm.

[0062] Copper coupon dissolution experiments were performed in a 500 ml. glass beaker containing 400 ml. of the chemical solution. A copper coupon (i.e. 99.99% pure) having dimensions of 25 mm×25 mm×1 mm was used as the experimental sample. The copper coupon was hand polished with 1500 grit sandpaper, washed with dilute hydrochloric acid (HCl) to remove any copper oxide from the surface, dried in an air stream, and then weighed. The copper coupon was then immersed in the solution for three minutes while continuously stirring the solution. After the experiment, the copper coupon was washed repeatedly with a deionized (DI) water rinse, dried in an air stream, and weighed. Weight loss was used to calculate the dissolution rate.

[0063] The slurries of Examples 29-34 contained 0.5 wt. % molybdenum trioxide (MoO_3) in deionized water. At the end of the wafer polishing a deionized (DI) water rinse was applied for five seconds. Example 29 contained 0.5% MoO_3+5.0% H_2O_2+1.0% glycine+5 mM BTA–filtered with 100 nm filter+1.0% SiO_2. The natural pH of the Example 29 slurry was about 2.9. Example 30 contained 0.5% MoO_3+5.0% H_2O_2+1.0% glycine+10 mM BTA–filtered with 100 nm filter+1.0% SiO_2. The natural pH of the Example 30 slurry was about 2.9. Example 31 contained 0.5% MoO_3+5% H_2O_2+0.5% glycine+10 mM BTA–filtered with 100 nm filter+0.1% SiO_2. The natural pH of the Example 31 slurry was about 2.6. Example 32 contained 0.5% MoO_3+5% H_2O_2+0.5% glycine+10 mM BTA–filtered with 100 nm filter+0.5% SiO_2.

The natural pH of the Example 32 slurry was 2.6. Example 33 contained 0.5% MoO_3+5% H_2O_2+0.5% glycine+10 mM BTA–filtered with 100 nm filter+1.0% SiO_2. The natural pH of the Example 33 slurry was about 2.6. Example 34 contained 0.5% MoO_3+5% H_2O_2+0.5% glycine+10 mM BTA+0.001% SDBS–filtered with 100 nm filter+1.0% SiO_2. The natural pH for the slurry of Example 34 was about 2.6. The average size of the particles of SiO_2 in the slurries of Examples 29-34 was about 20 nm. The remaining percentages not specified in the below table for the slurry compositions is the percentage of deionized water in the slurry. The slurry compositions and polishing rates for the copper wafer along with the copper coupon dissolution rates for Examples 29-34 are presented in Table 7.

TABLE 7

Example	Slurry Composition	Mean Particle Size of SiO_2 (nm)	pH	Polish Rate (nm/min)	Dissolution Rate (nm/min)
29	0.5% MoO_3 + 5.0% H_2O_2 + 1.0% glycine + 5 mM BTA − filtered + 1.0% SiO_2	20	2.9	1250	70
30	0.5% MoO_3 + 5.0% H_2O_2 + 1.0% glycine + 10 mM BTA − filtered + 1.0% SiO_2	20	2.9	1225	40
31	0.5% MoO_3 + 5% H_2O_2 + 0.5% glycine + 10 mM BTA − filtered + 0.1% SiO_2	20	2.6	600	35
32	0.5% MoO_3 + 5% H_2O_2 + 0.5% glycine + 10 mM BTA − filtered + 0.5% SiO_2	20	2.6	775	35
33	0.5% MoO_3 + 5% H_2O_2 + 0.5% glycine + 10 mM BTA − filtered + 1.0% SiO_2	20	2.6	925	35
34	0.5% MoO_3 + 5% H_2O_2 + 0.5% glycine + 10 mM BTA + 0.001% SDBS − filtered + 1.0% SiO_2	20	2.6	750	0

Examples 35-37

[0064] Slurries of Examples 35-37 were used to polish six inch copper blanket films. The CMP polisher was a Westech 372 Wafer Polisher with an IC-1400, k-groove polishing pad. The rotation rate of the carrier was 75 revolutions per minute (rpm). The rotation rate of the platen was also 75 revolutions per minute (rpm). The down-force placed on the copper blanket film was 4.0 pounds per square inch (psi). The slurry flow rate was 200 ml/min.

[0065] The amount of copper removed from the surface of the silicon substrate by CMP was determined by measuring the sheet resistance of the copper film both before and after polishing at 17 points spread across the film utilizing a home-made paper mask and a 4-point probe. Sheet resistance was measured at the same points on the film before and after polishing. The measured sheet resistances both before and after polishing were then converted to respective film thicknesses before and after polishing based on the resistivity of the copper material, the current applied, and the voltage across the 4-point probe. The difference between the starting and final thicknesses as 17 points were calculated, an average thickness loss was obtained which was then divided by the polish time to give the polish rate in nm/min.

[0066] Copper coupon dissolution experiments were performed in a 500 ml. glass beaker containing 400 ml. of the chemical solution. A copper coupon (i.e. 99.99% pure) having dimensions of 25 mm×25 mm×1 mm was used as the experimental sample. The copper coupon was hand polished with 1500 grit sandpaper, washed with dilute hydrochloric acid (HCl) to remove copper oxides from the surface, dried in an air stream and weighed. The copper coupon was then immersed in the solution for three minutes while continuously stirring the solution. After the experiment, the copper coupon was washed repeatedly with deionized (DI) water, dried in an air stream, and weighed. Weight loss was used to calculate the dissolution rate.

[0067] Example 35 contained 1% MoO_3+5.0% H_2O_2+1.0% glycine+5 mM BTA–filtered with 100 nm filter+1.0% SiO_2. The natural pH of the Example 35 slurry was about 2.6. Example 36 contained 1% MoO_3+5.0% H_2O_2+1.0% glycine+10 mM BTA–filtered with 100 nm filter+10.0% SiO_2. The natural pH of the Example 36 slurry was about 2.6. Example 37 contained 1% MoO_3+5.0% H_2O_2+1.0% glycine+15 mM BTA–filtered with 100 min filter+1.0% SiO_2. The natural pH of the Example 37 slurry was about 2.6. The remaining percentages not specified in the below table for the slurry compositions is the percentage of deionized water in the slurry. The slurry compositions and polishing rates for the copper wafer along with the copper coupon dissolution rates for Examples 35-37 are presented in Table 8.

TABLE 8

Example	Slurry Composition	Mean Particle Size of SiO_2 (nm)	pH	Polish Rate (nm/min)	Dissolution Rate (nm/min)
35	1% MoO_3 + 5.0% H_2O_2 + 1.0% glycine + 5 mM BTA - filtered + 1.0% SiO_2	20	2.6	1230	55
36	1% MoO_3 + 5.0% H_2O_2 + 1.0% glycine + 10 mM BTA - filtered + 1.0% SiO_2	20	2.6	1120	50
37	1% MoO_3 + 5.0% H_2O_2 + 1.0% glycine + 15 mM BTA - filtered + 1.0% SiO_2	20	2.6	760	35

[0068] The open circuit potential of a copper coupon in the MoO_3 slurry was noble to that of a tantalum coupon indicating that galvanic corrosion of copper will not be a problem during pattern wafer polishing which will minimize the dishing of copper lines. The details of the experimental procedure in obtaining these results are as follows. EG&G model 273A Potentiostat/Galvanostat was used to perform potentiodynamic polarization experiments. A three-electrode configu-

ration consisting of a working electrode (Cu/Ta coupon), platinum counter electrode, and a saturated calomel electrode (SCE) as a reference electrode was used. The three electrodes are immersed in a 250 ml of the chemical solution and the potential of the working electrode was scanned from −750 mV to about 1000 mV with respect to open circuit potential (OCP) and the resulting current density was monitored using a EG&G Princeton Applied Research model 352 softcorr TM II corrosion software.

[0069] The general method for pattern wafer polishing is to polish the bulk copper initially at a high rate and as planarization is achieved, the copper is removed at a lower rate in order to minimize dishing of copper lines. With proper adjustment of the MoO_3 slurry constituent composition and process parameters, the MoO_3 slurry of the present invention may be tuned for this general method of polishing at a higher rate and then a lower rate. Tantalum dissolution and disk polish rates with the same MoO_3 slurry were both less than 5 nm/minute. High copper blanket wafer removal rates, high selectivity to tantalum, good post CMP surface finish and low abrasive content, leading to a reduced number of post CMP defects and easier post CMP cleaning, make this slurry an attractive candidate for the first step of copper CMP process.

[0070] Another embodiment of an aqueous slurry may comprise one or more soluble salts of molybdenum dissolved in deionized water and an oxidizing agent. Molybdenum forms salts with valencies of 3, 4, or 6, but the hexavalent salts are the most stable. Soluble salts of molybdenum may be recovered from primary or secondary sources of molybdenum and may include ammonium molybdates such as ammonium dimolybdate $(NH_4)_2Mo_2O_7$ (ADM), ammonium heptamolybdate $(NH_4)_6Mo_7O_{24}$ (AHM), and ammonium octamolybdate $(NH_4)_4Mo_8O_{26}$ (AOM). In addition, molybdate salts of sodium, potassium, iron, and other transition metal elements may be used.

[0071] The soluble salt (or salts) of molybdenum may be present in an amount of about 0.1 to about 10 wt. %, and more preferably in an amount of about 0.5 to about 10 wt. %. The soluble salt of molybdenum may be provided in powder form such that the soluble salt of molybdenum dissolves in the solution of deionized water and an oxidizing agent. Generally speaking, soluble salts of molybdenum powders are completely visibly dissolved in an aqueous solution of deionized water and the oxidizing agent. As used herein, the terms "completely dissolved" and "visibly dissolved," refer to solutions wherein the majority of the particles of soluble salt of molybdenum are completely dissolved, and preferably wherein all of the particles of soluble salt of molybdenum are completely dissolved.

[0072] The oxidizing agent used with the soluble salt of molybdenum may comprise any one or a mixture of the oxidizing agents already described and present in the amounts specified earlier. Additionally, complexing agents may be used in the soluble salt of molybdenum aqueous slurry. Complexing agents may comprise any one or a mixture of the complexing agents already described and present in the amounts specified above.

[0073] Embodiments of slurries containing the soluble salt of molybdenum may also be provided with a nonionic surfactant, an anionic surfactant, or a cationic surfactant. The anionic surfactant used in the aqueous slurry may comprise any one or a mixture of polyacrylic acid (PAA), a carboxylic acid or its salt, a sulfuric ester or its salt, a sulfonic acid or its salt, a phosphoric acid or its salt, and a sulfosuccinic acid or its salt. The cationic surfactant used in the aqueous slurry may comprise any one or a mixture of a primary amine or its salt, a secondary amine or its salt, a tertiary amine or its salt, and a quaternary amine or its salt. The nonionic surfactant may be one or a mixture of one of the family of polyethylene glycols.

[0074] Optionally, the aqueous slurry comprising the soluble salt of molybdenum may also be provided with a copper corrosion inhibitor which may comprise any one or a mixture of heterocyclic organic compounds including benzotriazole (BTA), benzimidazole, poly triazole, phenyl triazole, thion and their derivatives. Further, the slurry may contain any combination of these surfactants and corrosion inhibitors.

[0075] A preferred anionic surfactant used in the soluble salt of molybdenum slurry is a salt of dodecyl benzene sulfonic acid. Dodecyl benzene sulfonic acid surfactant and salts thereof (DBSA) may be present in amounts ranging from about 0.00001 to about 1 wt. % (DBSA), such as about 0.0001 to about 0.5 wt. % (DBSA), and more preferably in an amount of about 0.001 wt. % (DBSA).

[0076] A preferred copper corrosion inhibitor used in the slurry comprising the soluble salt of molybdenum is benzotriazole (BTA). Benzotriazole (BTA) copper corrosion inhibitor may be present in concentrations ranging from about 1 to about 20 milli-molar (mM) BTA, such as about 1 to about 10 mM BTA, and more preferably in a concentration of about 10 mM BTA.

[0077] The pH of embodiments of slurries comprising the soluble salt of molybdenum according to the present invention may be in the range of about 1 to about 14, such as a pH in the range of about 1 to about 7, and preferably having a pH of in the range of about 4 to about 6. The pH of embodiments of slurries according to the present invention may be adjusted by the addition of suitable acids (e.g., acetic acid) or bases (e.g., potassium or ammonium hydroxide), as would be readily recognized by persons having ordinary skill in the art after having become familiar with the teachings provided herein.

[0078] Yet additional embodiments of polishing slurries comprising the soluble salt of molybdenum according to the invention may also be provided with supplemental ceramic/metal oxide particles. Such supplemental ceramic/metal oxide particles may be added to the aqueous slurry as colloidal particles or as fumed particles. Such supplemental ceramic/metal oxide particles used in the aqueous slurry may comprise any one or a mixture of silica, ceria, zirconia, titania, magnesia, iron oxide, tin oxide, and germania. A preferred supplemental ceramic/metal oxide used in the slurry is colloidal silicon dioxide (SiO_2). Colloidal silicon dioxide (SiO_2) may have an average particle size of between about 10 nm and about 100 nm, and more preferably of about 20 nm to about 50 nm.

[0079] Polishing slurries comprising the soluble salt of molybdenum may be utilized in a method for polishing copper by chemical-mechanical planarization. The method comprises providing an aqueous slurry comprising dissolved soluble salt of molybdenum and an oxidizing agent and polishing copper with the aqueous slurry using a polishing pad and a pressure between the copper and the polishing pad of about 0.5 psi and about 6.0 psi and more preferably between about 0.5 psi and about 2.0 psi.

[0080] Embodiments of soluble salt of molybdenum slurries according to the present invention exhibit high polish rates for copper when used in the CMP process, even when the CMP process is carried out at very low pressures (i.e.,

down forces) between the copper and the polishing pad. CMP processes carried out at high pressures (i.e., down forces) may cause undesirable delamination of lower-k dielectric layers. Accordingly, slurries according to the teachings provided herein allow copper CMP processes to be carried out at low pressures (i.e., down forces), such as pressures in a range of about 0.5-6.0 psi, and more preferably as low as 0.5-2.0 psi. Use of such low pressures minimizes the shear forces that act on the low-k layers of dielectric materials during the CMP process. Thus, the slurries described herein are desirable so that the copper CMP processes can be carried out at high throughput rates while minimizing defects such as micro-scratches, corrosion, dishing, erosion, as well as enabling high cleanability of the polished surface that has been exposed to a variety of chemicals and particles.

[0081] The high disk polish rates obtained from CMP processes carried out at low pressures (i.e., down forces), such as, for example, pressures in the range of about 0.5 to about 2.0 psi, indicates the active chemical nature of the slurry chemicals. With proper choice of the concentrations of the additives, surfactants, complexing agents, and by inclusion of a corrosion inhibitor and an abrasive, polish rates can be selected or "tuned" as desired or required (e.g., to manage the productivity of the copper CMP process).

Examples 38-42

[0082] Slurries of examples 38-42 were used to polish a copper disk having a diameter of 6 inches. The CMP polisher was a Struers DAP® with an IC-1400, k-groove polishing pad. The carrier remained stationary (i.e., was not rotated). The rotation rate of the platen was 90 revolutions per minute (rpm). The pressure (i.e., down-force) placed between the copper disk and polishing pad was 5 pounds per square inch (psi). The slurry flow rate was 60 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the weight difference of the copper disk both before and after polishing, taking into consideration the density of the Cu material, the area of the disk that was polished, and the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0083] The slurries of Examples 38-42 are all the same except that the weight percentage of the oxidizing agent, i.e. hydrogen peroxide H_2O_2, was varied for each example. Examples 38-42 all contained 0.5 wt. % ADM+0.5% glycine+0.5% amino butyric acid,

[0084] 5 mM BTA+1% SiO_2 particles. Example 38 contained 0.125% H_2O_2. Example 39 contained 0.35% H_2O_2. Example 40 contained 0.50% H_2O_2. Example 41 contained 0.75% H_2O_2. Example 42 contained 1.0% H_2O_2. The remaining percentages of each of the slurry compositions, which were not specified above, represent the percentage of deionized water. The weight percentage of H_2O_2 and the disk polishing rates for the copper disk of Examples 38-42 are presented in Table 9.

TABLE 9

Example	Slurry Composition	% wt. H_2O_2	Polish Rate (nm/min)
38	0.5 wt. % ADM + 0.5% glycine + 0.5% amino butyric acid, 5 mM BTA + 1% SiO_2	0.125%	478
39	0.5 wt. % ADM + 0.5% glycine + 0.5% amino butyric acid, 5 mM BTA + 1% SiO_2	0.35%	1244
40	0.5 wt. % ADM + 0.5% glycine + 0.5% amino butyric acid, 5 mM BTA + 1% SiO_2	0.50%	1177
41	0.5 wt. % ADM + 0.5% glycine + 0.5% amino butyric acid, 5 mM BTA + 1% SiO_2	0.75%	862
42	0.5 wt. % ADM + 0.5% glycine + 0.5% amino butyric acid, 5 mM BTA + 1% SiO_2	1.0%	504

Example 43

[0085] The slurry of Example 43 was used to polish an 8 inch silicon wafer having a copper layer deposited thereon by electroplating. The CMP polisher was a Westech 372 Wafer Polisher with an IC-1400, k-groove polishing pad. The rotation rate of the carrier was 75 revolutions per minute (rpm). The rotation rate of the platen was also 75 revolutions per minute (rpm). The pressure (i.e., down-force) placed between the copper and the polishing pad was 2 pounds per square inch (psi). The slurry flow rate was 200 ml/min. The amount of copper removed from the surface of the wafer by CMP was determined by measuring the thickness of the copper layer on the wafer both before and after polishing and taking into consideration the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0086] Examples 43 contained 0.5 wt. % ADM+0.5% glycine+0.5% amino butyric acid, 5 mM BTA+1% SiO_2 particles+0.125% H_2O_2. The remaining percentage of the slurry composition, which are not specified above, represent the percentage of deionized water. The copper film polishing rate for Example 43 was 1130 nm/min.

[0087] Another embodiment of an aqueous slurry may comprise other molybdic acids dissolved in deionized water and an oxidizing agent. Such other molybdic acids may include, but are not limited to, phosphomolybdic acid (PMA), phosphotungstomolybdic acid and vanadiomolybdic acid, for example, and are readily commercially available.

[0088] The molybdic acid may be present in an amount of about 0.1 to about 10 wt. %, and more preferably in an amount of about 0.5 to about 10 wt. %. The molybdic acid may be provided in powder form such that the molybdic acid dissolves in the solution of deionized water and an oxidizing agent. Generally speaking molybdic acids are completely visibly dissolved in an aqueous solution of deionized water and the oxidizing agent.

[0089] The oxidizing agent used with the molybdic acid may comprise any one or a mixture of the oxidizing agents already described and present in the amounts described earlier. Additionally, complexing agents may be used in the molybdic acid aqueous slurry. Complexing agents may comprise any of the complexing agents and provided in the amounts already described herein.

[0090] The oxidizing agents may oxidize the copper as well as react with molybdate ions present in the slurry. The new per-molybdate or peroxy-molybdate ions are expected to further oxidize and complex with copper, thereby providing high polish rates. Similar high polishing action may also occur by use of tungstates, vanadates, chromates and similar transition metal oxide ions or peroxy ions with or without the molybdate ions.

[0091] Embodiments of slurries containing the molybdic acid may also be provided with a nonionic surfactant, an anionic surfactant, or a cationic surfactant. The anionic surfactant used in the aqueous slurry may comprise any one or a mixture of the anionic surfactants described herein and provided in the amounts previously described. Similarly, the cationic surfactant used in the aqueous slurry may comprise any one or a mixture of the cationic surfactants and present in the amounts already described. The nonionic surfactant may be one or a mixture of one of the family of polyethylene glycols already described.

[0092] Optionally, the aqueous slurry comprising the molybdic acid may also be provided with a copper corrosion inhibitor which may comprise any one or a mixture of heterocyclic organic compounds including benzotriazole (BTA), benzimidazole, poly triazole, phenyl triazole, thion and their derivatives. Further, the slurry may contain any combination of these surfactants and corrosion inhibitors.

[0093] A preferred anionic surfactant used in the molybdic acid slurry is a salt of dodecyl benzene sulfonic acid. Dodecyl benzene sulfonic acid surfactant and salts thereof (DBSA) may be present in amounts ranging from about 0.00001 to about 1 wt. % (DBSA), such as about 0.0001 to about 0.5 wt. % (DBSA), and more preferably in an amount of about 0.001 wt. % (DBSA).

[0094] A preferred copper corrosion inhibitor used in the slurry comprising the molybdic acid is benzotriazole (BTA). Benzotriazole (BTA) copper corrosion inhibitor may be present in concentrations ranging from about 1 to about 20 milli-molar (mM) BTA, such as about 1 to about 10 mM BTA, and more preferably in a concentration of about 10 mM BTA.

[0095] The pH of embodiments of slurries comprising the molybdic acid according to the present invention may be in the range of about 1 to about 14, such as a pH in the range of about 1 to about 6, and preferably having a pH in the of about 4 to about 6. The pH of embodiments of slurries according to the present invention may be adjusted by the addition of suitable acids (e.g., acetic acid) or bases (e.g., potassium or ammonium hydroxide), as would be known by persons having ordinary skill in the art.

[0096] Yet additional embodiments of polishing slurries comprising the molybdic acid according to the invention may also be provided with supplemental ceramic/metal oxide particles. Such supplemental ceramic/metal oxide particles may be added to the aqueous slurry as colloidal particles or as fumed particles. Such supplemental ceramic/metal oxide particles used in the aqueous slurry may comprise any one or a mixture of silica, ceria, zirconia, titania, magnesia, iron oxide, tin oxide, and germania. A preferred supplemental ceramic/metal oxide used in the slurry is colloidal silicon dioxide (SiO_2). Colloidal silicon dioxide (SiO_2) may have an average particle size of between about 10 nm and about 100 nm, and preferably of about 20 nm to about 50 nm.

[0097] Polishing slurries comprising the molybdic acid may be utilized in a method for polishing copper by chemical-mechanical planarization. The method comprises providing an aqueous slurry comprising molybdic acid dissolved in deionized water and an oxidizing agent and polishing copper with the aqueous slurry using a polishing pad and a pressure between the copper and the polishing pad of between about 0.5 psi and about 6.0 psi and more preferably between about 0.5 psi and about 2.0 psi.

Examples 44-49

[0098] Slurries of examples 44-49 were used to polish a copper disk having a diameter of 6 inches. The CMP polisher was a Struers DAP® with an IC-1400, k-groove polishing pad. The carrier remained stationary (i.e., was not rotated). The rotation rate of the platen was 90 revolutions per minute (rpm). The pressure placed between the copper and the polishing pad was about 5 pounds per square inch (psi). The slurry flow rate was 60 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the weight difference of the copper disk both before and after polishing, taking into consideration the density of the Cu material, the area of the disk that was polished, and the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0099] The slurries of Examples 44-49 are all the same except that the weight percentage of the oxidizing agent, i.e. hydrogen peroxide (H_2O_2), was varied for each Example. Examples 44-49 all contained 1 wt. % phosphomolybdic acid (PMA)+10 mM BTA+1% glycine, 1% amino butyric acid+1% SiO_2 particles. Example 44 contained 0% H_2O_2. Example 45 contained 0.25% H_2O_2. Example 46 contained 0.50% H_2O_2. Example 47 contained 0.75% H_2O_2. Example 48 contained 1.0% H_2O_2. Example 49 contained 2.0% H_2O_2. The remaining percentages of each of the slurry compositions, which were not specified above, represent the percentage of deionized water. The weight percentage of H_2O_2 and the disk polishing rates for the copper disk of Examples 44-49 are presented in Table 10.

TABLE 10

Example	Slurry Composition	% wt. H_2O_2	Polish Rate (nm/min)
44	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	0%	698
45	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	0.25%	1670
46	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	0.50%	4424
47	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	0.75%	9233
48	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	1.00%	13978
49	10 wt. % PMA + 1 mM BTA + 1% glycine + 1% amino butyric acid + 1% SiO_2	2.00%	11087

[0100] Yet another embodiment of an aqueous slurry may comprise molybdenum trioxide (MoO_3) dissolved in deionized water and an oxidizing agent. To this mixture is added supplemental ceramic/metal oxide particles as already described herein, but which may be added as colloidal particles or as fumed particles. As previously described above with regard to the molybdenum trioxide (MoO_3) slurry, the

same oxidizing agents, complexing agents, surfactants, corrosion inhibitors, acids, and bases may be used in various combinations in accordance with the teachings provided herein.

[0101] The MoO_3 may be utilized in a method for polishing copper by chemical-mechanical planarization. The method comprises providing an aqueous slurry comprising dissolved MoO_3 and an oxidizing agent and polishing copper with the aqueous slurry using a polishing pad and a pressure between the copper and the pad of between about 0.5 psi and about 6.0 psi, and more preferably between about 0.5 psi and about 2.0 psi.

[0102] Embodiments of MoO_3 slurries according to the present invention exhibit high polish rates for copper when used in the CMP process, even when the CMP process is carried out at very low pressures. More particularly, when molybdenum trioxide MoO_3 particles were dispersed and completely dissolved in an aqueous solution containing deionized water, hydrogen peroxide, and BTA and used as a copper CMP slurry, high disk polish rates (e.g., about 1200 nm/minute) were obtained with a nominal pressure (e.g., about 0.5 to about 2.0 psi). As mentioned, CMP processes carried out at high pressures may cause undesirable delamination of lower-k dielectric layers provided on the copper. Accordingly, copper CMP should be carried out at low pressures, such as, for example, pressures in a range of about 0.5-6.0 psi, and more preferably pressures as low as 0.5-2.0 psi, to minimize the shear forces that act on the low-k layers of dielectric materials during the CMP process. Thus, the slurries described herein may be used to advantage in copper CMP processes described herein, allowing the processes to be carried out at high throughput rates while minimizing defects such as micro-scratches, corrosion, dishing, erosion, as well as enabling high cleanability of the polished surface that has been exposed to a variety of chemicals and particles.

[0103] The high disk polish rates obtained from CMP processes described herein carried out at such minimal pressures (e.g., in a range of about 0.5 to about 2.0 psi) indicates the active chemical nature of the slurry. One of the reasons why this slurry exhibits such a high chemical reactivity is due to the complete dissolution of the molybdenum trioxide particles. With proper choice of the concentrations of the additives and by inclusion of a corrosion inhibitor and an abrasive, polish rates can be tuned according to a user's requirements and delamination of the low-k dielectric layers can be minimized.

[0104] As shown in Example 54, blanket copper wafer polishing rates of one embodiment of an MoO_3 slurry of the present invention were determined to be as high as about 1200 nm/minute. The slurries of Examples 50-54 were filtered to remove any undissolved particles above 1,000 nm (1 micron) in size and 1.0 wt % of 20 nm colloidal SiO_2 abrasives were added.

[0105] The post-polish surface of the copper was good with post CMP surface roughness values of about 1 nm as measured by a non-contact optical profilometer. If higher post-polish surface quality is desired, the CMP polishing step may be followed by a buffing step. In one embodiment, the buffing step may involve additionally polishing the copper surface with deionized water for about five to about fifteen seconds at a pH in the range of about 5 to about 7. The advantage of using a deionized water rinse buffing step is the removal of reactive chemicals from the wafer-pad interface, which removes residual amounts of molybdenum oxide that may remain on the surface of the wafer-pad. Clean and smooth copper surfaces may be obtained after subsequent buffing using a deionized water rinse.

[0106] The general methodology for pattern wafer copper polishing is to polish the bulk copper initially at a high polish rate and then, as planarization is achieved, the copper polish rate is reduced in order to minimize dishing of copper lines. With proper adjustment of the slurry constituent composition and process parameters, the slurry of the present invention can be tuned for this general methodology of polishing at higher rates and then lower rates.

Examples 50-54

[0107] Slurries of examples 50-54 were used to polish copper deposited on a silicon wafer disk having a diameter of 6 inches. The copper was deposited by electroplating. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 75 rpm. The pressure placed on the copper disk was 4 pounds per square inch (psi). The slurry flow rate was 200 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the thickness of the copper film both before and after polishing, taking into consideration the polishing time. This was then converted into the rate of removal in terms of nm of copper layer removed per minute.

[0108] The slurries of Examples 50-54 are all the same except that the weight percentage of molybdenum trioxide was varied for each example. Examples 50-54 all contained 5% H_2O_2+0.5% glycine+10 mM BTA−filtered+1% SiO_2 particles. Example 50 contained 0 wt. % MoO_3. Example 51 contained 0.5 wt. % MoO_3. Example 52 contained 1.0 wt. % MoO_3. Example 53 contained 3.0 wt. % MoO_3. Example 54 contained 5.0 wt. % MoO_3. The remaining percentages not specified above represent the percentage of deionized water. The weight % of molybdenum and polishing rates for the copper disks of Examples 50-54 are presented in Table 11.

TABLE 11

Example	Slurry Composition	% wt. MoO_3	Polish Rate (nm/min)
50	5.0% H_2O_2 + 0.5% glycine + 10 mM BTA + filtered + 1% SiO_2	0%	350
51	5.0% H_2O_2 + 0.5% glycine + 10 mM BTA + filtered + 1% SiO_2	0.5%	900
52	5.0% H_2O_2 + 0.5% glycine + 10 mM BTA + filtered + 1% SiO_2	1.0%	900
53	5.0% H_2O_2 + 0.5% glycine + 10 mM BTA + filtered + 1% SiO_2	3.0%	1000
54	5.0% H_2O_2 + 0.5% glycine + 10 mM BTA + filtered + 1% SiO_2	5.0%	1200

Examples 55-58

[0109] Slurries of examples 55-58 were used to polish a copper film deposited on a silicon substrate wafer having a diameter of 6 inches. The copper film was deposited by electroplating. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 75 rpm. The platen was rotated at 75 rpm. The pressure (i.e., down-force) between the copper and the polishing pad was about 4 pounds per square inch (psi). The slurry flow rate was set at 200 ml/min. The amount of copper removed from the surface of the disk by CMP was determined

by measuring the thickness of the copper film both before and after polishing, taking into consideration the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0110] The slurries of Examples 55-58 are all the same except that the type of abrasive was varied for each Example. Examples 55-58 all contained 0.5 wt. % MoO_3+5.0% H_2O_2+1.0% glycine+10 mM BTA. Example 55 contained no abrasives. Example 56 contained colloidal alumina (AlO_2) particles, having a mean particle size of 50 nm, as an abrasive. Example 57 contained Aerosol® 200 fumed silica particles as an abrasive. Example 58 contained colloidal silica (SiO_2) particles, having a mean particle size of 20 nm, as an abrasive. The remaining percentages not specified above represent the percentage of deionized water. The effect of the various types of abrasives on the polish rate of a slurry containing 0.5 wt. % molybdenum trioxide is shown in Table 12.

TABLE 12

Example	Slurry Composition	Abrasive (1% wt.)	Polish Rate (nm/min)
55	0.5% MoO_3 + 5.0% H_2O_2 + 10 mM BTA	No Abrasive	360
56	0.5% MoO_3 + 5.0% H_2O_2 + 10 mM BTA	50 nM colloidal alumina (AlO_2)	495
57	0.5% MoO_3 + 5.0% H_2O_2 + 10 mM BTA	Aerosil ® 200 fumed silica (SiO_2)	495
58	0.5% MoO_3 + 5.0% H_2O_2 + 10 mM BTA	20 nm colloidal silica (SiO_2)	740

[0111] Yet another embodiment of an aqueous slurry may comprise molybdenum dioxide (MoO_2) dissolved in deionized water, an oxidizing agent, as previously described above. To this mixture is added supplemental ceramic/metal oxide particles as already described herein, but which may be added as colloidal particles or as fumed particles. As previously described above with regard to the molybdenum dioxide (MoO_2) slurry, the same oxidizing agents, complexing agents, surfactants, corrosion inhibitors, acids, and bases may be used in various combinations in accordance with the teachings provided herein.

[0112] The MoO_2 may be utilized in a method for polishing copper by chemical-mechanical planarization. The method comprises providing an aqueous slurry comprising dissolved MoO_2 and an oxidizing agent and polishing copper with the aqueous slurry using a polishing pad and a pressure (i.e., down-force) of between about 0.5 psi and about 6.0 psi, and more preferably between about 0.5 psi and about 2.0 psi.

Examples 59-62

[0113] Slurries of examples 59-62 were used to polish a copper coated silicon wafer having a diameter of 6 inches. The copper was coated on the wafer by electroplating. The CMP polisher was a Westech Model 372 with an IC-1400, k-groove polishing pad. The carrier was rotated at a rate of 75 rpm. The pressure placed on the copper disk was 4 pounds per square inch (psi). The slurry flow rate was 200 ml/min. The amount of copper removed from the surface of the disk by CMP was determined by measuring the thickness of the copper film both before and after polishing, taking into consideration the polishing time. This was then converted into the rate of removal in terms of nm of copper removed per minute.

[0114] The slurries of Examples 59-62 show the effect of different abrasives on the polish rates of copper disks. The pH of Examples 59-62 was maintained at approximately 4. Example 59 contained 3 wt % KIO_3. Example 60 contained filtrate from a solution comprising 3 wt % MoO_2+3 wt % KIO_3. Example 61 contained filtrate from a solution comprising 3 wt % MoO_2+3 wt % KIO_3+3 wt % silica. Example 62 contained filtrate from a solution comprising 3 wt % MoO_2+3 wt % KIO_3+3 wt % alumina. The remaining percentages of the slurry composition which were not specified represent the percentage of deionized water. The weight percentage and type of abrasives and the disk polishing rates for the copper disks of Examples 59-62 are presented in Table 13.

TABLE 13

Example	Slurry Composition	Abrasive	Polish Rate (nm/min)
59	3% KIO_3	none	30 ± 3
60	3% MoO_2 + 3% KIO_3	none	268 ± 10
61	3% MoO_2 + 3% KIO_3	3% wt. silica (SiO_2)	353 ± 15
62	3% MoO_2 + 3% KIO_3	3% wt. alumina (AlO_2)	840 ± 17

[0115] In conclusion, the claimed product and process collectively represent an important development in CMP technology. The product and process discussed above are novel, distinctive, and highly beneficial from a technical and utilitarian standpoint. Having herein set forth preferred embodiments of the present invention, it is anticipated that suitable modifications can be made thereto which will nonetheless remain within the scope of the invention. The invention shall therefore only be construed in accordance with the following claims:

What is claimed is:

1. A slurry for chemical mechanical planarization of a copper layer on a semiconductor substrate, comprising:
- a solution of deionized water and an oxidizing agent, the oxidizing agent being in a first amount;
- a soluble salt of molybdenum dissolved in the solution, the soluble salt of molybdenum being in a second amount; and
- at least two complexing agents, the complexing agents each being in the second amount.

2. The slurry of claim **1**, wherein the second amount is not more than the first amount.

3. The slurry of claim **1**, wherein the first amount is in a range from about 0.1 weight percent to about 1.0 weight percent of the total weight percent of the slurry.

4. The slurry of claim **1**, wherein the complexing agents are selected from the group consisting of glycine ($C_2H_5NO_2$), alanine ($C_3H_7NO_2$), amino butyric acid ($C_4H_9NO_2$) ethylene diamine ($C_2H_8N_2$), ethylene diamine tetra acetic acid (EDTA), citric acid ($C_6H_8O_7$), phthalic acid ($C_6H_4(COOH)_2$), oxalic acid ($C_2H_2O_4$), acetic acid ($C_2H_4O_2$), and succinic acid ($C_4H_6O_4$).

5. The slurry of claim **1**, further comprising ceramic/metallic nanoparticles, the ceramic/metallic nanoparticles being in an amount greater than the first amount.

6. An aqueous slurry for polishing copper, comprising MoO_3 in an aqueous oxidizing agent solution, the MoO_3 consisting of dissolved and undissolved nanoparticles, the dissolved nanoparticles of MoO_3 comprising molybdic acid.

7. The aqueous slurry of claim **6**, wherein the aqueous slurry exhibits chemical reactivity with copper.

8. The aqueous slurry of claim **6**, further comprising supplemental ceramic/metallic nanoparticles.

9. The aqueous slurry of claim **6**, wherein the supplemental ceramic/metallic nanoparticles have a mean particle size of about 20 nanometers.

10. The aqueous slurry of claim **6**, further comprising a mixture of at least two complexing agents.

11. The aqueous slurry of claim **10** wherein the mixture of the at least two complexing agents comprises at least two complexing agents selected from the group consisting of glycine ($C_2H_5NO_2$), alanine ($C_3H_7NO_2$), amino butyric acid ($C_4H_9NO_2$) ethylene diamine ($C_2H_8N_2$), ethylene diamine tetra acetic acid (EDTA), citric acid ($C_6H_8O_7$), phthalic acid ($C_6H_4(COOH)_2$), oxalic acid ($C_2H_2O_4$), acetic acid ($C_2H_4O_2$), and succinic acid ($C_4H_6O_4$).

12. An aqueous slurry for chemical mechanical planarization of copper, comprising molybdic acid powder dissolved in a solution of deionized water and an oxidizing agent, the molybdic acid powder comprising one or more selected from the group consisting of phosphotungstomolybdic acid and vanadiomolybdic acid.

13. The aqueous slurry of claim **12**, wherein the slurry comprises about 0.1% to about 10% by weight of the molybdic acid powder.

14. The aqueous slurry of claim **12**, wherein the oxidizing agent comprises one or more selected from the group consisting of hydrogen peroxide, ferric nitrate, potassium iodate, nitric acid, potassium permanganate, potassium persulfate, ammonium persulfate, potassium periodate, and hydroxylamine.

15. The aqueous slurry of claim **12**, further comprising ceramic/metallic oxide particles.

16. The aqueous slurry of claim **12**, wherein the oxidizing agent comprises at least one selected from the group consisting of potassium iodate, potassium permanganate, potassium persulfate, and potassium periodate.

17. An aqueous slurry for chemical mechanical planarization of a copper layer on a semiconductor substrate, comprising a soluble salt of molybdenum visibly dissolved in a solution of deionized water and an oxidizing agent, the soluble salt of molybdenum comprising one or more selected from the group consisting of a potassium molybdate and an iron molybdate.

18. A slurry for chemical mechanical polishing of copper, comprising ions selected from the group consisting of permolybdate ions and peroxy-molybdate ions, the ions being in a solution comprising deionized water and an oxidizing agent.

19. The slurry of claim **18**, further comprising at least two complexing agents.

20. The slurry of claim **18**, further comprising a copper corrosion inhibitor.

21. An aqueous slurry for chemical mechanical planarization of copper comprising about 0.1 to less than one weight percent of MoO_3 dissolved in an oxidizing agent.

22. The aqueous slurry of claim **21**, wherein the about 0.1 to less than one weight percent of MoO_3 is about 0.1 to about 0.5 weight percent of MoO_3.

23. The aqueous slurry of claim **21**, wherein the oxidizing agent comprises at least one selected from the group consisting of potassium iodate, potassium permanganate, potassium persulfate, and potassium periodate.

24. The aqueous slurry of claim **21**, wherein the oxidizing agent is ferric nitrate.

25. The aqueous slurry of claim **21**, further comprising at least one surfactant selected from the group consisting of polyacrylic acid, a carboxylic acid and its salt, a sulfuric ester and its salt, a sulfonic acid and its salt, a phosphoric acid and its salt, a sulfosuccinic acid and its salt, and cetyl trimethyl ammonium tosylate (CTAT).

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