SILICON CARBIDE POLISHING METHOD UTILIZING WATER-SOLUBLE OXIDIZERS

BACKGROUND OF THE INVENTION

[0001] Semiconductors with the ability to operate more efficiently in order to achieve a significant reduction in power consumption are highly desirable. Typically, silicon substrates are used in the manufacture of such devices, however, further development is limited due to the inherent characteristics of silicon. Development of the next generation of semiconductor devices has emphasized the use of materials having a greater hardness and other unique properties. For example, silicon carbide, when compared with silicon oxide, has a higher thermal conductivity, a greater tolerance for radiation, a higher dielectric strength, and is able to withstand greater temperatures, which makes it suitable for a variety of applications. The use of silicon carbide has been limited, however, by semiconductor fabrication technology.

[0002] In order to produce silicon carbide semiconductors, the surfaces of the silicon carbide substrates must be polished in order to provide smooth surfaces and to obtain precise dimensions for the surfaces. The properties which make silicon carbide such a useful substrate provide unique challenges in the polishing process. Due to the hardness of silicon carbide, diamond grit is typically used to mechanically polish silicon carbide substrates.

[0003] Chemical-mechanical polishing (CMP) techniques are widely used throughout the semiconductor industry in order to polish the current generation of silicon devices. CMP involves the use of a polishing composition (also known as a polishing slurry) containing an abrasive and an aqueous material, which is applied to a surface by contacting the surface with a polishing pad saturated with the polishing composition. The polishing composition may also contain an oxidizing agent, which allows for less aggressive mechanical abrasion of the substrate, thus reducing mechanical damage to the substrate caused by the abrading process. The use of such techniques to polish silicon carbide substrates could greatly reduce the costs of manufacturing semiconductors by decreasing polish time and reducing damage to the substrate.

[0004] Adaptation of CMP techniques for silicon carbide polishing has been relatively unsuccessful. Polishing compositions containing colloidal silica resulted in low silicon carbide removal rates, thus requiring a lengthy polishing cycle lasting several hours at temperatures of around 50° C, which is likely to result in damage to the silicon carbide substrate. Zhou, et al., *J. Electrochemical Soc.*, 144, p. L161-L163 (1997); Neslen, et al., *J. Electronic Materials*, 30, p. 1271-1275 (2001). The long polishing cycle adds considerable cost to the process and is a barrier preventing widespread use of silicon carbide within the semiconductor industry. Thus, there remains a need for alternative polishing systems and methods of polishing substrates comprising silicon carbide.

BRIEF SUMMARY OF THE INVENTION

[0005] The invention provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, wherein the abrasive is substantially spherical silica particles having an average particle size of 40 nm to 130 nm, and (c) an oxidizing agent selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, iodates, persulfates, and mixtures thereof, (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

[0006] The invention further provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, wherein the abrasive is alumina and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and (c) an oxidizing agent, wherein the oxidizing agent is present in an amount of 0.001 wt.% to 0.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, and is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, iodates, persulfates, and mixtures thereof, and (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

[0007] The invention also provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, and (c) an oxidizing agent, wherein the oxidizing agent is present in an amount of 0.001 wt.% to 0.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, and is selected from the group consisting of oxone, potassium persulfate, and mixtures thereof (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

[0008] The invention additionally provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, wherein the abrasive is alumina

and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and (c) an oxidizing agent, wherein the oxidizing agent is present in an amount of 0.001 wt.% to 2.5 wt.% based on the weight of the liquid carrier and any component dissolved or suspended therein, wherein the oxidizing agent is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, periodic acid, iodates, persulfates, chromates, permanganates, bromates, perbromates, ferrates, perrhenates, perruthenates, and mixtures thereof, and (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

[0009] The invention further provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, wherein the abrasive is selected from the group consisting of alumina, titania, ceria, and zirconia, and wherein the abrasive is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and (c) a permanganate salt, wherein the permanganate salt is present in an amount of 0.001 wt.% to 2.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein,
(ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

[0010] The invention also provides a method of chemically-mechanically polishing a substrate, which method comprises (i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, wherein the abrasive is selected from the group consisting of alumina, titania, ceria, and zirconia, and wherein the abrasive is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and (c) periodic acid or periodates, wherein the periodic acid or periodates is present in an amount of 0.001 wt.% to 1 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

DETAILED DESCRIPTION OF THE INVENTION

[0011] The invention provides a method of chemically-mechanically polishing a substrate comprising silicon carbide. The method comprises (i) contacting a substrate comprising at least

one layer of single crystal silicon carbide, (ii) moving the polishing composition relative to the substrate, and (iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate. The polishing composition comprises, consists essentially of, or consists of (a) a liquid carrier, (b) an abrasive suspended in the liquid carrier, and (c) an oxidizing agent.

[0012] In a first embodiment, the abrasive is substantially spherical silica particles having an average particle size of 40 nm to 130 nm, and the oxidizing agent is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, iodates, persulfates, and mixtures thereof. In a second embodiment, the abrasive is alumina and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and the oxidizing agent is present in an amount of 0.001 wt.% to 0.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, and is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, iodates, persulfates, and mixtures thereof. In a third embodiment, the oxidizing agent is present in an amount of 0.001 wt.% to 0.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, and is selected from the group consisting of oxone, potassium persulfate, and mixtures thereof. In a fourth embodiment, the abrasive is alumina and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and the oxidizing agent is present in an amount of 0.001 wt.% to 0.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein, and is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, periodic acid, iodates, persulfates, chromates, permanganates, bromates, perbromates, ferrates, perrhenates, perruthenates, and mixtures thereof. In a fifth embodiment, the abrasive is alumina, titania, ceria, or zirconia, and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and the oxidizing agent is a permanganate salt, wherein the permanganate salt is present in an amount of 0.001 wt.% to 2.5 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein. In a sixth embodiment, the abrasive is alumina, titania, ceria, or zirconia, and is present in an amount of 3 wt.% or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and the oxidizing agent is periodic acid, wherein the periodic acid is present in an amount of 0.001 wt.% to 1 wt.% based on the weight of the liquid carrier and any components dissolved or suspended therein.

[0013] The substrate to be polished using the method of the invention can be any suitable substrate which comprises at least one layer of silicon carbide. Suitable substrates include, but

are not limited to, flat panel displays, integrated circuits, memory or rigid disks, metals, interlayer dielectric (ILD) devices, semiconductors, micro-electro-mechanical systems, ferroelectrics, and magnetic heads. The silicon carbide can comprise, consist essentially of, or consist of any suitable silicon carbide, many of which are known in the art. The silicon carbide can be single crystal or polycrystalline. Silicon carbide has many different types of crystal structures, each having its own distinct set of electronic properties. Only a small number of these polytypes, however, can be reproduced in a form acceptable for use as semiconductors. Such polytypes can be either cubic (e.g., 3C silicon carbide) or non-cubic (e.g., 4H silicon carbide, 6H silicon carbide). The properties of these polytypes are well known in the art.

[0014] The polishing pad can be any suitable polishing pad, many of which are known in the art. Suitable polishing pads include, for example, woven and non-woven polishing pads. Moreover, suitable polishing pads can comprise any suitable polymer of varying density, hardness, thickness, compressibility, ability to rebound upon compression, and compression modulus. Suitable polymers include, for example, polyvinylchloride, polyvinylfluoride, nylon, fluorocarbon, polycarbonate, polyester, polyacrylate, polyether, polyethylene, polyamide, polyurethane, polystyrene, polypropylene, coformed products thereof, and mixtures thereof.

[0015] The polishing pad can comprise fixed abrasive particles on or within the polishing surface of the polishing pad, or the polishing pad can be substantially free of fixed abrasive particles. Fixed abrasive polishing pads include pads having abrasive particles affixed to the polishing surface of the polishing pad by way of an adhesive, binder, ceramer, resin, or the like or abrasives that have been impregnated within a polishing pad so as to form an integral part of the polishing pad, such as, for example, a fibrous batt impregnated with an abrasive-containing polyurethane dispersion.

[0016] The polishing pad can have any suitable configuration. For example, the polishing pad can be circular and, when in use, typically will have a rotational motion about an axis perpendicular to the plane defined by the surface of the pad. The polishing pad can be cylindrical, the surface of which acts as the polishing surface, and, when in use, typically will have a rotational motion about the central axis of the cylinder. The polishing pad can be in the form of an endless belt, which, when in use, typically will have a linear motion with respect to the cutting edge being polished. The polishing pad can have any suitable shape and, when in use, have a reciprocating or orbital motion along a plane or a semicircle. Many other variations will be readily apparent to the skilled artisan.

[0017] The polishing composition comprises an abrasive, which desirably is suspended in the liquid carrier (e.g., water). The abrasive typically is in particulate form. Any suitable

abrasive can be used, many of which are well known in the art. Preferably, the abrasive comprises, consists essentially of, or consists of one or more metal oxides. The metal oxide desirably is selected from the group consisting of alumina, ceria, germania, magnesia, silica, titania, zirconia, co-formed products thereof, and combinations thereof.

[0018] In particular, the abrasive comprises, consists essentially of, or consists of substantially spherical silica, alumina, ceria, zirconia, or titania. Substantially spherical silica is also referred to as colloidal silica by those of ordinary skill in the art. Preferably, the substantially spherical silica is precipitated or condensation-polymerized silica, which is prepared using the sol-gel process. Condensation-polymerized silica particles typically are prepared by condensing $Si(OH)_4$ to form substantially spherical particles. The precursor $Si(OH)_4$ can be obtained, for example, by hydrolysis of high purity alkoxysilanes, or by acidification of aqueous silicate solutions. Such abrasive particles can be prepared in accordance with U. S. Patent 5,230,833 or can be obtained as any of various commercially available products such as Bindzil from EKA Chemicals, the Fuso PL-1, PL-2, and PL-3 products, and the Nalco 1034A, 1050, 2327, and 2329 products, as well as other similar products available from DuPont, Bayer, Applied Research, Nissan Chemical, and Clariant. Preferably, the alumina is seeded gel process alpha alumina, which is available from manufactures such as Saint Gobain (alpha alumina). The substantially spherical silica, alumina, ceria, zirconia, and titania particles can have any suitable particle size. For example, the substantially spherical silica, alumina, ceria, zirconia, and titania particles can have an average particle size of 10 nm or more (e.g., 20 nm or more, 30 nm or more, 40 nm or more, or 50 nm or more). The substantially spherical silica, alumina, ceria, zirconia, and titania particles can have an average particle size of 200 nm or less (e.g., 180 nm or less, 170 nm or less, 160 nm or less, 150 nm or less, 130 nm or less, 110 nm or less, or 100 nm or less). Accordingly, the substantially spherical silica, alumina, ceria, zirconia, and titania particles can have an average particle size of 40 nm to 130 nm (e.g., 45 nm to 125 nm, 50 nm to 120 nm, 55 nm to 115 nm, or 60 nm to 110 nm). The particle size of a particle is the diameter of the smallest sphere that encompasses the particle.

[0019] Any suitable amount of abrasive can be present in the polishing composition. Typically, 0.01 wt.% or more (e.g., 0.05 wt.% or more) abrasive will be present in the polishing composition. More typically, 0.1 wt.% or more (e.g., 1 wt.% or more, 5 wt.% or more, 7 wt.% or more, 10 wt.% or more, or 12 wt.% or more) abrasive will be present in the polishing composition. The amount of abrasive in the polishing composition typically will be 50 wt.% or less, more typically will be 40 wt.% or less (e.g., 15 wt.% or less, 10 wt.% or less, 5 wt.% or less, 3 wt.% or less, 1 wt.% or less, 0.6 wt.% or less, or 0.3 wt.% or less). Accordingly, the

amount of abrasive in the polishing composition can be 2 wt.% to 50 wt.%, and more preferably 5 wt.% to 40 wt.% (e.g., 10 wt.% to 35 wt.%, 15 wt.% to 35 wt.%, or 20 wt.% to 35 wt.%). The amount of abrasive in the polishing composition also can be 0.01 wt.% to 3 wt.% (e.g., 0.05 wt.% to 1 wt.% or 0.1 wt.% to 0.6 wt.%).

[0020] A liquid carrier is used to facilitate the application of the abrasive and any optional additives to the surface of a suitable substrate to be polished (e.g., planarized). The liquid carrier can be any suitable liquid, e.g., solvent, including lower alcohols (e.g., methanol, ethanol, etc.), ethers (e.g., dioxane, tetrahydrofuran, etc.), water, and mixtures thereof. Preferably, the liquid carrier comprises, consists essentially of, or consists of water, more preferably deionized water.

[0021] The polishing composition comprises an oxidizing agent, which can be any suitable oxidizing agent for one or more materials of the substrate to be polished with the polishing composition. Preferably, the oxidizing agent is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, iodates, persulfates, chlorates, chromates, permanganates, bromates, perbromates, ferrates, perrhenates, perruthenates, and mixtures thereof. The permanganates, periodiates, and persulfates can be any periodate, iodate, persulfate or combination of periodates, iodates, and persulfates, such as, for example, potassium periodate, periodic acid, ammonium persulfate, potassium persulfate, or potassium permanganate. More preferably, the oxidizing agent is oxone, potassium persulfate, potassium permanganate, or periodic acid. The oxidizing agent can be present in the polishing composition in any suitable amount. Typically, the polishing composition comprises 0.001 wt.% or more (e.g., 0.005 wt.% or more, 0.01 wt.% or more, 0.05 wt.% or more, or 0.1 wt.% or more) oxidizing agent. The polishing composition preferably comprises 20 wt.% or less (e.g., 15 wt.% or less, 10 wt.% or less, 5 wt.% or less, 2.5 wt.% or less, 2 wt.% or less, 1 wt.% or less, or 0.5 wt.% or less) oxidizing agent. Preferably, the polishing composition comprises 0.001 wt.% to 20 wt.% (e.g., 0.001 wt.% to 15 wt.%, 0.001 wt.% to 2.5 wt.%, 0.005 wt.% to 10 wt.%, 0.01 wt.% to 5 wt.%, 0.05 wt.% to 2 wt.%, or 0.1 wt.% to 0.5 wt.%) oxidizing agent. More preferably, the polishing composition comprises 0.001 wt.% to 0.05 wt.%, 0.001 wt.% to 0.1 wt.%, 0.001 wt.% to 0.5 wt.%, or 0.001 wt.% to 2 wt.% oxidizing agent.

[0022] The polishing composition, specifically the liquid carrier with any components dissolved or suspended therein, can have any suitable pH. The actual pH of the polishing composition will depend, in part, on the type of substrate being polished. The polishing composition can have a pH of 11 or less (e.g., 9 or less, 7 or less, 6 or less, 5 or less, 4 or less, 3 or less, or 2 or less). The polishing composition can have a pH of 1 or more (e.g., 2 or more, 3

or more, 4 or more, 6 or more, 8 or more, or 9 or more). The pH can be, for example, from 1 to 11 (e.g., from 2 to 10, from 2 to 6, from 3 to 9, from 4 to 8, from 5 to 7, or from 3 to 5).

[0023] The pH of the polishing composition can be achieved and/or maintained by any suitable means. More specifically, the polishing composition can further comprise a pH adjustor, a pH buffering agent, or a combination thereof. The pH adjustor can comprise, consist essentially of, or consist of any suitable pH-adjusting compound. For example, the pH adjustor can be any suitable acid, such as an inorganic or an organic acid, or combination thereof. For example, the acid can be nitric acid. The pH buffering agent can be any suitable buffering agent, for example, phosphates, acetates, borates, sulfonates, carboxylates, and the like. The polishing composition can comprise any suitable amount of a pH adjustor and/or a pH buffering agent, provided such amount is sufficient to achieve and/or maintain the desired pH of the polishing composition, e.g., within the ranges set forth herein.

[0024] It will be appreciated that many of the aforementioned compounds can exist in the form of a salt, an acid, or as a partial salt. Furthermore, certain compounds or reagents may perform more than one function. For example, some compounds can function both as a chelating agent and an oxidizing agent.

[0025] The polishing composition can comprise a surfactant and/or rheological control agent, including viscosity enhancing agents and coagulants (e.g., polymeric rheological control agents, such as, for example, urethane polymers). Suitable surfactants can include, for example, cationic surfactants, anionic surfactants, nonionic surfactants, amphoteric surfactants, mixtures thereof, and the like. The amount of surfactant in the polishing composition typically is 0.0001 wt.% to 1 wt.% (preferably 0.001 wt.% to 0.1 wt.% and more preferably 0.005 wt.% to 0.05 wt.%).

[0026] The polishing composition can comprise an antifoaming agent. The antifoaming agent can be any suitable anti-foaming agent. Suitable antifoaming agents include, but are not limited to, silicon-based and acetylenic diol-based antifoaming agents. The amount of anti-foaming agent in the polishing composition typically is 10 ppm to 140 ppm.

[0027] The polishing composition can comprise a biocide. The biocide can be any suitable biocide, for example, an isothiazolinone biocide. The amount of biocide in the polishing composition typically is 1 to 50 ppm, preferably 10 to 20 ppm.

[0028] The polishing composition can be prepared by any suitable technique, many of which are known to those skilled in the art. The polishing composition can be prepared in a batch or continuous process. Generally, the polishing composition can be prepared by combining the components thereof in any order. The term "component" as used herein includes individual

ingredients (e.g., oxidizing agent, abrasive, etc.) as well as any combination of ingredients (e.g., water, halogen anion, surfactants, etc.).

[0029] The polishing composition can be supplied as a one-package system comprising the liquid carrier, the abrasive, the oxidizing agent, and optionally other additives. Alternatively, some of the components, such as an oxidizing agent, can be supplied in a first container, either in dry form, or as a solution or dispersion in the liquid carrier, and the remaining components, such as the abrasive and other additives, can be supplied in a second container or multiple other containers. Other two container, or three or more container combinations of the components of the polishing composition are within the knowledge of one of ordinary skill in the art.

[0030] Solid components, such as the abrasive, can be placed in one or more containers either in dry form or as a solution in the liquid carrier. Moreover, it is suitable for the components in the first, second, or other containers to have different pH values, or alternatively to have substantially similar, or even equal, pH values. The components of the polishing composition can be partially or entirely supplied separately from each other and can be combined, e.g., by the end-user, shortly before use (e.g., 1 week or less prior to use, 1 day or less prior to use, 1 hour or less prior to use, 10 minutes or less prior to use, or 1 minute or less prior to use).

[0031] The polishing composition also can be provided as a concentrate which is intended to be diluted with an appropriate amount of liquid carrier prior to use. In such an embodiment, the polishing composition concentrate can comprise a liquid carrier and optionally other components in amounts such that, upon dilution of the concentrate with an appropriate amount of liquid carrier, each component will be present in the polishing composition in an amount within the appropriate range recited above for each component. For example, each component can be present in the concentrate in an amount that is 2 times (e.g., 3 times, 4 times, or 5 times) greater than the concentration recited above for each component in the polishing composition so that, when the concentrate is diluted with an appropriate volume of liquid carrier (e.g., an equal volume of liquid carrier, 2 equal volumes of liquid carrier, 3 equal volumes of liquid carrier, or 4 equal volumes of liquid carrier, respectively), each component will be present in the polishing composition in an amount within the ranges set forth above for each component. Furthermore, as will be understood by those of ordinary skill in the art, the concentrate can contain an appropriate fraction of the liquid carrier present in the final polishing composition in order to ensure that the other components of the polishing composition are at least partially or fully dissolved or suspended in the concentrate.

[0032] The inventive method of polishing a substrate is particularly suited for use in conjunction with a chemical-mechanical polishing (CMP) apparatus. Typically, the apparatus comprises a platen, which, when in use, is in motion and has a velocity that results from orbital, linear, or circular motion, a polishing pad in contact with the platen and moving with the platen when in motion, and a carrier that holds a substrate to be polished by contacting and moving relative to the surface of the polishing pad. The polishing of the substrate takes place by the substrate being placed in contact with the polishing pad and the polishing composition (which generally is disposed between the substrate and the polishing pad), with the polishing pad moving relative to the substrate, so as to abrade at least a portion of the substrate to polish the substrate.

[0033] Desirably, the polishing end-point is determined by monitoring the weight of the silicon carbide substrate, which is used to compute the amount silicon carbide removed from the substrate. Such techniques are well known in the art.

[0034] Polishing refers to the removal of at least a portion of a surface to polish the surface. Polishing can be performed to provide a surface having reduced surface roughness by removing gouges, crates, pits, and the like, but polishing also can be performed to introduce or restore a surface geometry characterized by an intersection of planar segments.

[0035] The method of the invention can be used to polish any suitable substrate comprising at least one layer of silicon carbide. The silicon carbide can be removed at any suitable rate to effect polishing of the substrate. For example, silicon carbide can be removed at a rate of 5 nm/hr or more (e.g., 10 nm/hr or more, 20 nm/hr or more, 50 nm/hr or more, 70 nm/hr or more, 100 nm/hr or more, or 200 nm/hr or more). The silicon carbide can be removed at a rate of 800 nm/hr or less (e.g., 500 nm/hr or less, 300 nm/hr or less, 250 nm/hr or less, or 200 nm/hr or less). Accordingly, the silicon carbide can be removed from the substrate at a rate of 5 nm/hr to 1500 nm/hr (e.g., 10 nm/hr to 1000 nm/hr, 20 nm/hr to 800 nm/hr, 30 nm/hr to 500 nm/hr, 40 nm/hr to 300 nm/hr, or 50 nm/hr to 180 nm/hr). More preferably, the silicon carbide can be removed from the substrate at a rate of 20 nm/hr to 180 nm/hr, 70 nm/hr to 180 nm/hr, 100 nm/hr to 180 nm/hr, 30 nm/hr to 2700 nm/hr, 30 nm/hr to 1000 nm/hr, 100 nm/hr to 500 nm/hr, or 200 nm/hr to 400 nm/hr.

[0036] The following examples further illustrate the invention but, of course, should not be construed as in any way limiting its scope.

EXAMPLE 1

[0037] This example demonstrates the effect on the removal rate of silicon carbide by the presence of substantially spherical silica and an oxidizer in a polishing composition.

[0038] A 6H semi-insulating single crystal silicon carbide wafer was polished with ten different polishing compositions. The contents and pH of each of the polishing compositions are indicated in Table 1. The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 1.

TABLE 1

Polishing Composition	Abrasive Concentration	Oxidizer Concentration	pH	Silicon Carbide Removal Rate (nm/hr)
1A (comparative)	30 wt.% fumed silica	N/A	10-10.5	0
1B (comparative)	30 wt.% fumed silica	0.5 wt.% H_2O_2	10-10.5	46.5
1C (comparative)	30 wt.% fumed silica	1.0 wt.% H_2O_2	10-10.5	77.5
1D (comparative)	30 wt.% fumed silica	2.0 wt.% H_2O_2	10-10.5	69.75
1E (comparative)	30 wt.% substantially spherical silica	N/A	10	0
1F (invention)	30 wt.% substantially spherical silica	1 wt.% ammonium persulfate	10	77.5
1G (invention)	30 wt.% substantially spherical silica	1 wt.% ammonium persulfate	10	93
1H (invention)	30 wt.% substantially spherical silica	1 wt.% KIO_3	11	124
1I (invention)	30 wt.% substantially spherical silica	2 wt.% ammonium persulfate	10	124
1J (invention)	30 wt.% substantially spherical silica	2 wt.% oxone	10	93

[0039] As is apparent from the data presented in Table 1, the silicon carbide removal rate increases when the polishing composition comprises substantially spherical silica particles in combination with an oxidizing agent such as ammonium persulfate, potassium iodate, or oxone.

EXAMPLE 2

[0040] This example demonstrates the effect on the removal rate of silicon carbide by the presence of different oxidizing agents in the polishing composition of the invention.

[0041] A 4HN single crystal silicon carbide wafer was polished with seven different polishing compositions. Each of the polishing compositions contained 30 wt.% substantially

spherical silica. Six of the polishing compositions were further modified by the addition of either ammonium persulfate or ammonium cerium nitrates as indicated in Table 2.

[0042] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 2.

TABLE 2

Polishing Composition	Oxidizer Concentration	pH	Silicon Carbide Removal Rate (nm/hr)
2A (comparative)	N/A	10	0
2B (invention)	1 wt.% ammonium persulfate	10	105
2C (invention)	1 wt.% ammonium persulfate	10	87.5
2D (invention)	1 wt.% ammonium persulfate	10	126
2E (invention)	1 wt.% ammonium persulfate	10	182
2F (invention)	2 wt.% ammonium persulfate	10	105
2G (invention)	1 wt.% ammonium cerium nitrate	1.7	126

[0043] As is apparent from the data presented in Table 2, the presence of either ammonium persulfate or ammonium cerium nitrate in the polishing composition increased the silicon carbide removal rate from 0 to as high as 182 nm/hr.

EXAMPLE 3

[0044] This example demonstrates the effect on the removal rate of silicon carbide by the presence of an oxidizer in a polishing composition.

[0045] A 4H semi-insulating single crystal silicon carbide wafer was polished with three different polishing compositions. Each of the polishing compositions contained 30 wt.% substantially spherical silica and was adjusted to a pH of 10. Two of the polishing compositions were further modified by the addition of ammonium persulfate as indicated in Table 3.

[0046] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 3.

TABLE 3

Polishing Composition	Oxidizer Concentration	Silicon Carbide Removal Rate (nm/hr)
3A (comparative)	N/A	0
3B (invention)	1 wt.% ammonium persulfate	22.75
3C (invention)	1 wt.% ammonium persulfate	21

[0047] As is apparent from the data presented in Table 3, the silicon carbide removal rate increases when the polishing composition comprises ammonium persulfate.

EXAMPLE 4

[0048] This example demonstrates the effect on the removal rate of silicon carbide by the presence of an oxidizer and an abrasive in a polishing composition.

[0049] A 4H single crystal silicon carbide wafer was polished with fifteen different polishing compositions. The contents and pH of each of the polishing compositions are indicated below in Table 4. The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 4.

TABLE 4

Polishing Composition	Abrasive Concentration	pH	Oxidizer Concentration	Silicon Carbide Removal Rate (nm/hr)
4A (comparative)	20 wt.% substantially spherical silica (Bindzil)	10	N/A	76
4B (invention)	20 wt.% substantially spherical silica (Bindzil)	10	0.5 wt.% H_2O_2	105

4C (invention)	20 wt.% substantially spherical silica (Bindzil)	10	0.5 wt.% potassium periodate	102
4D (invention)	20 wt.% substantially spherical silica (Bindzil)	10	0.5 wt.% potassium persulfate	104
4E (comparative)	20 wt.% substantially spherical silica (Nalco 1034)	2	N/A	97
4F (comparative)	20 wt.% substantially spherical silica (Nalco 1034)	2	0.5 wt.% H_2O_2	96
4G (invention)	20 wt.% substantially spherical silica (Nalco 1034)	2	0.5 wt.% potassium periodate	122
4H (invention)	20 wt.% substantially spherical silica (Nalco 1034)	2	0.5 wt.% potassium persulfate	116
4I (comparative)	0.5 wt.% ceria	5	N/A	0
4K (comparative)	0.5 wt.% ceria	5	3000 ppm potassium periodate	0
4L (invention)	0.5 wt.% ceria	5	3000 ppm potassium persulfate	64
4M (comparative)	7.5 wt.% g seeded gel process alpha alumina	3	N/A	0
4N (invention)	7.5 wt.% seeded gel process alpha alumina	3	0.5 wt.% H_2O_2	37
4O (invention)	7.5 wt.% seeded gel process alpha alumina	3	0.5 wt.% potassium periodate	59
4P (invention)	7.5 wt.% seeded gel process alpha alumina	3	0.5 wt.% potassium persulfate	350

[0050] As is apparent from the data presented in Table 4, the silicon carbide removal rate typically increases upon the addition of an oxidizer to the polishing composition. The combination of seeded gel process alpha alumina with potassium persulfate was particularly effective in increasing the removal rate of silicon carbide.

EXAMPLE 5

[0051] This example demonstrates the effect on the removal rate of silicon carbide by the presence of different types of alumina abrasive in a polishing composition.

[0052] A 4H single crystal silicon carbide wafer was polished with six different polishing compositions. Each of the polishing compositions contained 3 wt.% abrasive and 1.0 wt.% potassium persulfate, and was adjusted to a pH of 3. The type of alumina abrasive used in each of the polishing compositions is indicated below in Table 5.

[0053] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 5.

TABLE 5

Polishing Composition	Alumina Type	Alumina Manufacturer	Average Particle Size (nm)	Silicon Carbide Removal Rate (nm/hr)
5A (invention)	seeded gel process alpha	Saint Gobain (alpha)	<100	315
5B (invention)	fumed	Degussa (RMU3-11)	120	109
5C (invention)	fumed	Cabot (RMWA-11)	120	129
5D (invention)	polymer coated alumina	Cabot Microelectronics (TPA6)	120	58
5E (invention)	alpha	Saint Gobain PN 7955.35	350	121
5F (invention)	alpha	Saint Gobain PN 7955.80	800	151

[0054] As is apparent from the data presented in Table 5, use of the seeded gel process alpha alumina resulted in a silicon carbide removal rate which was significantly larger than the rates achieved with the compositions containing other types of alumina.

EXAMPLE 6

[0055] This example demonstrates the effect on the removal rate of silicon carbide by the concentration of potassium persulfate in a polishing composition.

[0056] A 4HN single crystal silicon carbide wafer was polished with five different polishing compositions. Each of the polishing compositions contained 3 wt.% seeded gel process alpha alumina and was adjusted to a pH of 4. Four of the polishing compositions were further modified by the addition of potassium persulfate.

[0057] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 6.

TABLE 6

Polishing Composition	Potassium Persulfate Concentration (wt.%)	Colloidal Stability	Silicon Carbide Removal Rate (nm/hr)
6A (comparative)	0	stable	15
6B (invention)	0.002	stable	290
6C (invention)	0.005	stable	336
6D (invention)	0.03	stable	270
6E (invention)	0.1	unstable	288

[0058] As is apparent from the data presented in Table 6, the silicon carbide removal rate continued to increase as the concentration of potassium persulfate increased up to a concentration between 0.005 wt.% and 0.03 wt. % potassium persulfate.

EXAMPLE 7

[0059] This example demonstrates the effect on the removal rate of silicon carbide by the concentration of seeded gel process alpha alumina in a polishing composition.

[0060] A 4HN single crystal silicon carbide wafer was polished with two different polishing compositions. Each of the polishing compositions contained 0.1 wt.% potassium persulfate and was adjusted to a pH of 4. The polishing compositions also contained seeded gel process alpha alumina at a concentration of either 0.1 wt.% or 0.5 wt.%.

[0061] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 7.

TABLE 7

Polishing Composition	Alumina Concentration (wt.%)	Silicon Carbide Removal Rate (nm/hr)
7A (invention)	0.1	213
7B (invention)	0.5	288

[0062] As is apparent from the data presented in Table 7, although both compositions were effective in polishing the silicon carbide wafer, the composition containing the higher concentration of alumina achieved a higher silicon carbide polishing rate.

EXAMPLE 8

[0063] This example demonstrates the effect on the removal rate of several different types of silicon carbide wafers by a polishing composition.

[0064] Nine different types of single crystal silicon carbide wafers were polished with a polishing composition containing 0.6 wt.% seeded gel process alpha alumina and 0.03 wt.% potassium persulfate, adjusted to a pH of 4.

[0065] The silicon carbide removal rate (nm/hr) was determined for each type of wafer, and the results are shown in Table 8.

TABLE 8

Silicon Carbide Wafer Type	Silicon Carbide Removal Rate (nm/hr)
4HN single crystal	282
6H semi-insulating	235
6H semi-insulating	222
6H semi-insulating	241
4HN single crystal	322
6H semi-insulating	341
6H semi-insulating	358
6H semi-insulating	345
4HN single crystal	316

[0066] As is apparent from the data presented in Table 8, the inventive polishing composition was able to successfully polish each type of silicon carbide wafer tested.

EXAMPLE 9

[0067] This example demonstrates the effect on the removal rate of silicon carbide by polishing a silicon carbide substrate using different polish tool parameters with a polishing composition.

[0068] Five different sets of polishing tool parameters were used to polish a chemical vapor deposition (CVD) polycrystalline silicon carbide wafer with a polishing composition containing 1 wt.% seeded gel process alpha alumina and 0.3 wt.% potassium persulfate, adjusted to a pH of 4.

[0069] The silicon carbide removal rate (nm/hr) was determined for each set of polishing conditions, and the results are shown in Table 9.

TABLE 9

Polishing Conditions	Platen Speed (rpm)	Down Force (kPa) [psi]	Silicon Carbide Removal Rate (nm/hr)
9A (invention)	60	6.62 [0.96]	63
9B (invention)	60	19.97 [2.87]	221
9C (invention)	100	19.97 [2.87]	655
9D (invention)	120	32.96 [4.78]	978
9E (invention)	120	32.96 [4.78]	982

[0070] As is apparent from the data presented in Table 9, the silicon carbide removal rate increased as the platen rotational speed of the polishing pad and the down force pressure of the substrate against the polishing pad were increased.

EXAMPLE 10

[0071] This example demonstrates the effect on the removal rate of silicon carbide by the presence of different oxidizing agents in the polishing composition of the invention.

[0072] A 4H semi-insulating single crystal silicon carbide wafer was polished with 12 different polishing compositions. Each of the polishing compositions contained 0.6 wt.% seeded gel process alpha alumina and was adjusted to a pH of 4.

[0073] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 10.

TABLE 10

Polishing Composition	Oxidizer Concentration	Silicon Carbide Removal Rate (nm/hr)
10A (invention)	0.3 wt.% potassium persulfate	280-313
10B (invention)	0.12 wt.% potassium permanganate	1682
10C (invention)	0.27 wt.% potassium chlorate	152
10D (comparative)	0.48 wt.% cerium perchlorate	<10
10E (invention)	0.43 wt.% potassium chromate	492
10F (invention)	0.43 wt.% ammonium iodate	20
10G (invention)	0.25 wt.% periodic acid	694
10H (invention)	0.37 wt.% potassium bromate	236
10I (comparative)	Iodine	<10
10J (invention)	0.3 wt.% potassium persulfate and 0.12 wt.% potassium permanganate	473
10K (comparative)	0.37 wt.% sodium tungstate dehydrate	<10
10L (comparative)	0.26 wt.% potassium molybdate	<10

[0074] As is apparent from the data presented in Table 10, the silicon carbide removal rate increases when the polishing composition comprises alumina particles in combination with an

oxidizing agent such as potassium persulfate, potassium permanganate, potassium chlorate, potassium chromate, periodic acid, or potassium bromate.

EXAMPLE 11

[0075] This example demonstrates the effect on the removal rate of silicon carbide by the concentration of potassium permanganate in a polishing composition.

[0076] A 4H semi-insulating single crystal silicon carbide wafer was polished with 11 different polishing compositions. Each of the polishing compositions contained 0.6 wt.% seeded gel process alpha alumina.

[0077] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 11.

TABLE 11

Polishing Composition	Potassium Permangante Concentration (wt.%)	pH	Silicon Carbide Removal Rate (nm/hr)
11A (invention)	0.1	4	1660
11B (invention)	0.12	4	1682
11C (invention)	0.14	4	1722
11D (invention)	0.18	4	1591
11E (invention)	0.2	4	1712
11F (invention)	0.3	4	1747
11G (invention)	0.5	4	1922
11H (invention)	1.0	4	1958
11I (invention)	1.5	4	1812
11J (invention)	2.5	4	1913
11K (invention)	0.14	10	164

[0078] As is apparent from the data presented in Table 11, polishing compositions comprising potassium permanganate over a concentration range of 14 wt.% to 2.5 wt.% and at pH of 4 resulted in a significant silicon carbide removal rate.

EXAMPLE 12

[0079] This example demonstrates the effect on the removal rate of silicon carbide by the concentration of periodic acid and abrasive in a polishing composition and the pH of the polishing composition.

[0080] A 4H semi-insulating single crystal silicon carbide wafer was polished with 12 different polishing compositions.

[0081] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 12.

TABLE 12

Polishing Composition	pH	Periodic Acid Concentration (wt.%)	Alumina Concentration (wt.%)	Silicon Carbide Removal Rate (nm/hr)
12A (invention)	2	0.15	0.1	504
12B (invention)	2	0.05	0.6	335
12C (invention)	2	0.25	0.6	671
12D (invention)	2	0.15	1.1	761
12E (invention)	4	0.05	0.1	374
12F (invention)	4	0.25	0.1	573
12G (invention)	4	0.15	0.6	717
12H (invention)	4	0.25	1.1	761
12I (invention)	6	0.15	0.1	487
12J (invention)	6	0.05	0.6	586
12K (invention)	6	0.25	0.6	656
12L (invention)	6	0.15	1.1	688

[0082] As is apparent from the data presented in Table 12, polishing compositions comprising periodic acid over a concentration range of 0.05 wt.% to 0.25 wt.%, and alpha-alumina over a concentration range of 0.1 to 1.1 wt.%, at pH of 2 to 6, resulted in a significant silicon carbide removal rate.

EXAMPLE 13

[0083] This example demonstrates the effect on the removal rate of silicon carbide by the presence of different types of abrasives in a polishing composition.

[0084] A 4H semi-insulating single crystal silicon carbide wafer was polished with 7 different polishing compositions. Each of the polishing compositions contained an abrasive and potassium permanganate, and was adjusted to a pH of 4. The type of abrasive used in each of the polishing compositions and the amount of potassium permanganate are indicated below in Table 13.

[0085] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 13.

TABLE 13

Polishing Composition	Potassium Permangante Concentration (wt.%)	Abrasive Type	Abrasive Concentration (wt.%)	Silicon Carbide Removal Rate (nm/hr)
13A (invention)	0.12	alpha-alumina	0.6	2069
13B (invention)	0.12	titania	0.6	1032
13C (comparative)	0.12	substantially spherical silica (25 nm)	10	<10
13D (invention)	0.14	zirconia	0.6	389
13E (invention)	0.14	ceria	0.6	480
13F (comparative)	0.14	substantially spherical silica (80 nm)	10	70
13G (comparative)	0.14	fumed silica	10	26

[0086] As is apparent from the data presented in Table 13, the use of alpha-alumina, titania, zirconia, and ceria resulted in a silicon carbide removal rate which was significantly larger than the rates achieved with the compositions containing silica.

EXAMPLE 14

[0087] This example demonstrates the effect on the removal rate of silicon carbide by the pH of the polishing composition and the concentration of potassium permanganate in the polishing composition.

[0088] A 4H semi-insulating single crystal silicon carbide wafer was polished with 5 different polishing compositions. Each of the polishing compositions contained 0.6 wt. % ceria and potassium permanganate. The pH and the amount of potassium permanganate are indicated in Table 14.

[0089] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 14.

TABLE 14

Polishing Composition	Potassium Permangante Concentration (wt.%)	pH	Silicon Carbide Removal Rate (nm/hr)
14A (invention)	0.06	2	233
14B (invention)	0.25	2	1202
14C (invention)	0.155	4	915
14D (invention)	0.06	6	690
14E (invention))	0.25	6	1907

[0090] As is apparent from the data presented in Table 14, the use of ceria over a pH range of 2 to 6 at a variety of potassium permanganate concentrations resulted in a significant silicon carbide removal rate.

EXAMPLE 15

[0091] This example demonstrates the effect on the removal rate of silicon carbide by the pH and concentration of potassium permanganate.

[0092] A 4H semi-insulating single crystal silicon carbide wafer was polished with 6 different polishing compositions. Each of the polishing compositions contained 0.6 wt. % titania and potassium permanganate. The pH and the amount of potassium permanganate are indicated below in Table 15.

[0093] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 15.

TABLE 15

Polishing Composition	Potassium Permangante Concentration (wt.%)	pH	Silicon Carbide Removal Rate (nm/hr)
15A (invention)	0.05	2	485
15B (invention)	0.45	2	1236
15C (invention)	0.05	4	289
15D (invention)	0.14	4	389
15E (invention)	0.05	6	69
15F (invention)	0.45	6	129

[0094] As is apparent from the data presented in Table 15, use of titania over a pH of 2 to 6 at a variety of potassium permanganate concentrations resulted in a significant silicon carbide removal rate.

EXAMPLE 16

[0095] This example demonstrates the effect on the removal rate of 4HN single crystal silicon carbide by a polishing composition.

[0096] 4HN single crystal silicon carbide wafers were polished with three polishing composition containing seeded gel process alpha alumina and either potassium permanganate, potassium persulfate, or periodic acid, adjusted to a pH of 4. The amount of abrasive and the amount of oxidizing agent are indicated in Table 16.

[0097] The silicon carbide removal rate (nm/hr) was determined for each polishing composition, and the results are shown in Table 16.

TABLE 16

Polishing Composition	Oxidizer Concentration (wt.%)	Alumina Concentration (wt. %)	Silicon Carbide Removal Rate (nm/hr)
16A (invention)	0.3 wt.% potassium persulfate	0.6	341
16B (invention)	0.4 wt.% potassium permanganate	0.6	2055
16C (invention)	0.2 wt % periodic acid	0.2	698

[0098] As is apparent from the data presented in Table 16, the inventive polishing compositions were able to successfully polish 4HN single crystal silicon carbide wafers.

EXAMPLE 17

[0099] This example demonstrates the stability of potassium permanganate in an accelerated heating test to simulate the decomposition of oxidizing agents at room temperature.

[00100] The silicon carbide removal rate, pH, conductivity, and % oxidizer of a polishing composition containing potassium persulfate and a polishing composition containing potassium permanganate were measured initially and after heating to 62° C for 16 hours. The results are shown in Table 17.

TABLE 17

Oxidizing Agent	Potassium Persulfate (initial)	Potassium Persulfate (16 hours at 62° C)	Potassium Permanganate (initial)	Potassium Permanganate (16 hours at 62° C)
Removal rate (nm/hr)	251	164	1148	1139
pH	3.75	1.90	3.84	3.88
Conductivity (μS/cm)	5520	11,350	1198	1185
% oxidizider	0.598	0.297	0.170	0.170

[00101] As is apparent from the data presented in Table 17, potassium permanganate does not decompose but rather remains stable under the accelerated heating test.

CLAIMS

1. A method of chemically-mechanically polishing a substrate, which method comprises:

(i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising:

(a) a liquid carrier,

(b) an abrasive suspended in the liquid carrier, wherein the abrasive is alumina and is present in an amount of about 3 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and

(c) an oxidizing agent, wherein the oxidizing agent is present in an amount of about 0.001 wt. % to about 2.5 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein, and wherein the oxidizing agent is selected from the group consisting of hydrogen peroxide, oxone, ammonium cerium nitrate, periodates, periodic acid, iodates, persulfates, chromates, chlorates, permanganates, bromates, perbromates, ferrates, perrhenates, perruthenates, and mixtures thereof, and

(ii) moving the polishing composition relative to the substrate, and

(iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

2. The method of claim 1, wherein the abrasive is present in an amount about 1 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein.

3. The method of claim 1, wherein the oxidizing agent is present in an amount of about 0.1 wt. % to about 0.5 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein.

4. The method of claim 1, wherein the liquid carrier with any components dissolved or suspended therein has a pH of about 2 to about 6.

5. The method of claim 1, wherein the oxidizing agent is potassium permanganate.

6. The method of claim 1, wherein the oxidizing agent is periodic acid.

7. The method of claim 1, wherein the silicon carbide is removed from the substrate at a rate of about 30 nm/hr to about 2700 nm/hr.

8. A method of chemically-mechanically polishing a substrate, which method comprises:

(i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising:

(a) a liquid carrier,

(b) an abrasive suspended in the liquid carrier, wherein the abrasive is selected from the group consisting of alumina, titania, ceria, and zirconia, and wherein the abrasive is present in an amount of about 3 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and

(c) a permanganate salt, wherein the permanganate salt is present in an amount of about 0.001 wt. % to about 2.5 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein,

(ii) moving the polishing composition relative to the substrate, and

(iii) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

9. The method of claim 8, wherein the abrasive is present in amount of about 1 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein.

10. The method of claim 8, wherein the abrasive is alumina.

11. The method of claim 8, wherein the permanganate salt is present in an amount of amount of about 0.1 wt. % to about 1 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein.

12. The method of claim 8, wherein the liquid carrier with any components dissolved or suspended therein has a pH of about 2 to about 6.

13. A method of chemically-mechanically polishing a substrate, which method comprises:

(i) contacting a substrate comprising at least one layer of single crystal silicon carbide with a chemical-mechanical polishing composition comprising:

(a) a liquid carrier,

(b) an abrasive suspended in the liquid carrier, wherein the abrasive is selected from the group consisting of alumina, titania, ceria, and zirconia, and wherein the abrasive is present in an amount of about 3 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein, and

(c) periodic acid or periodates, wherein the periodic acid or periodates are present in an amount of about 0.001 wt. % to about 1 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein,

(ii) moving the polishing composition relative to the substrate, and

(iv) abrading at least a portion of the silicon carbide of the substrate to polish the substrate.

14. The method of claim 13, wherein the abrasive is present in amount of about 1 wt. % or less based on the weight of the liquid carrier and any components dissolved or suspended therein.

15. The method of claim 13, wherein the abrasive is alumina.

16. The method of claim 13, wherein the permanganate salt is present in an amount of amount of about 0.1 wt. % to about 0.5 wt. % based on the weight of the liquid carrier and any components dissolved or suspended therein.

17. The method of claim 13, wherein the liquid carrier with any components dissolved or suspended therein has a pH of about 2 to about 6.