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(54) POLISHING PAD COMPRISING MAGNETICALLY SENSITIVE PARTICLES AND METHOD FOR THE USE THEREOF

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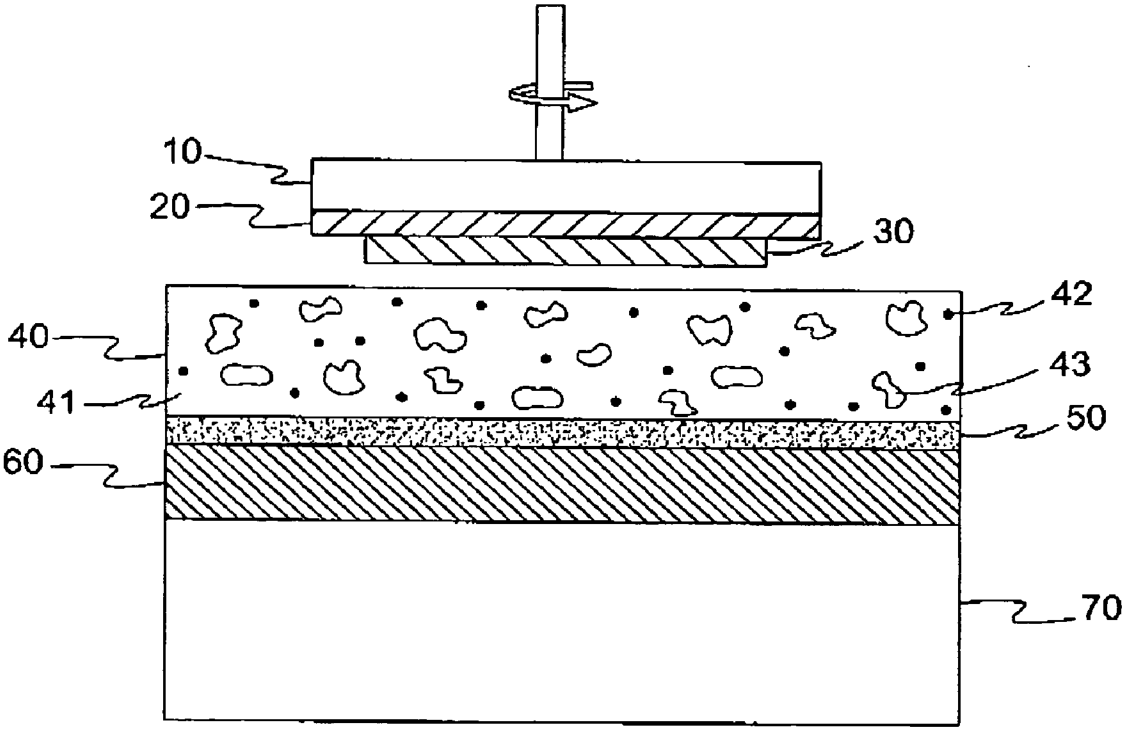
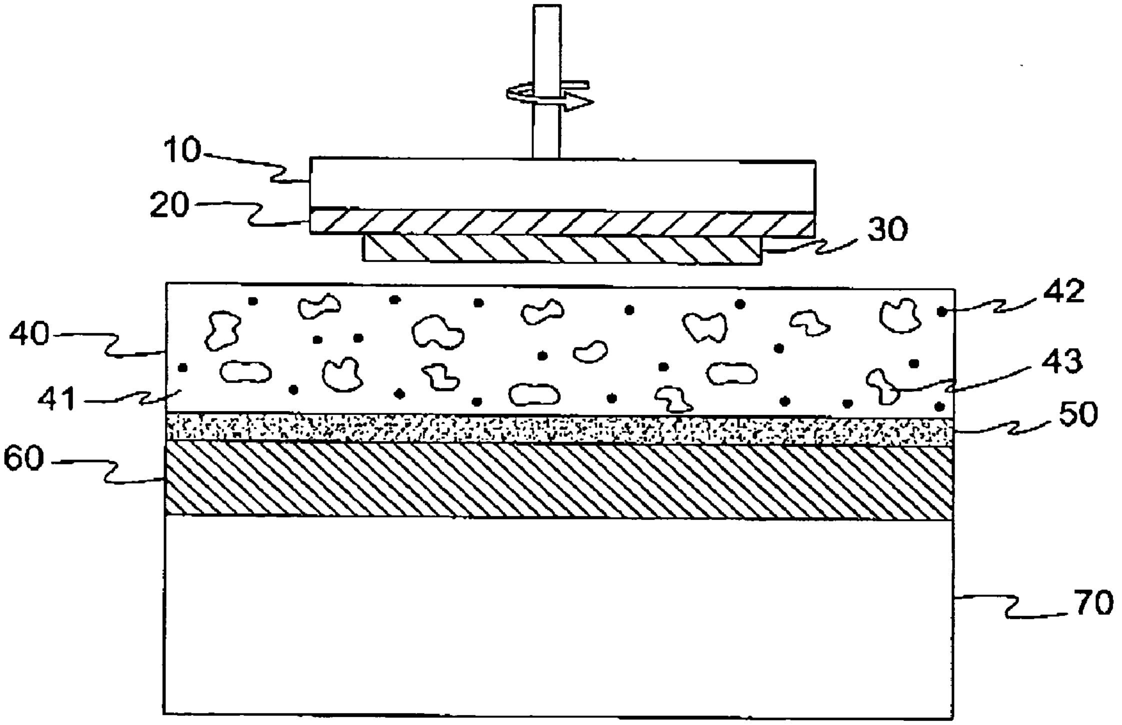
(57) ABSTRACT

The invention provides polishing pads comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field. The invention further provides a polishing system and a method for polishing a substrate involving such a polishing pad.

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POLISHING PAD COMPRISING MAGNETICALLY SENSITIVE PARTICLES AND METHOD FOR THE USE THEREOF

FIELD OF THE INVENTION

[0001] This invention pertains to a polishing pad that is useful for chemical-mechanical polishing.

BACKGROUND OF THE INVENTION

[0002] Chemical-mechanical polishing ("CMP") processes are used in the manufacturing of microelectronic devices to form flat surfaces on semiconductor wafers, integrated circuits, field emission displays, and many other microelectronic substrates. For example, the manufacture of semiconductor devices generally involves the formation of various process layers, selective removal or patterning of portions of those layers, and deposition of yet additional process layers above the surface of a semiconducting substrate to form an integrated circuit. The process layers can include, by way of example, insulation layers, gate oxide layers, conductive layers, and layers of metal or glass, etc. It is generally desirable in certain steps of the process that the uppermost surface of the process layers be planar, i.e., flat, for the deposition of subsequent layers. CMP is used to planarize process layers wherein a deposited material, such as a conductive or insulating material, is polished to planarize the wafer for subsequent process steps.

[0003] In a typical CMP process, a wafer is mounted upside down on a carrier in a CMP tool. A force pushes the carrier and the wafer downward toward a polishing pad. The carrier and the wafer are rotated above the rotating polishing pad on the CMP tool's polishing table. A polishing composition (also referred to as a polishing slurry) generally is introduced between the rotating wafer and the rotating polishing pad during the polishing process. The polishing composition typically contains a chemical that interacts with or dissolves portions of the uppermost wafer layer(s) and an abrasive material that physically removes portions of the layer(s). The wafer and the polishing pad can be rotated in the same direction or in opposite directions, whichever is desirable for the particular polishing process being carried out. The carrier can also oscillate across the polishing pad on the polishing table.

[0004] Polishing pads used in chemical-mechanical polishing processes are manufactured using both soft and rigid pad materials, which include polymer-impregnated fabrics, microporous films, cellular polymer foams, non-porous polymer sheets, and sintered thermoplastic particles. A pad containing a polyurethane resin impregnated into a polyester non-woven fabric is illustrative of a polymer-impregnated fabric polishing pad.

[0005] Despite the attention that has been directed towards improvement of polishing pads for CMP, the polishing pads are typically fixed elements in the CMP process. That is, once a polishing pad has been selected and placed into use, the physical characteristics of the polishing pad cannot be altered during the course of chemical-mechanical polishing operations. However, the surface characteristics of the polishing substrate undergo changes as the surface is polished and approaches planarity. Consequently, there remains a need for a polishing pad, a polishing system, and a polishing method that allows for control of the polishing pad characteristics during the polishing operation.

[0006] The invention provides such a polishing pad, system, and method. These and other advantages of the invention, as well as additional inventive features, will be apparent from the description of the invention provided herein.

BRIEF SUMMARY OF THE INVENTION

[0007] The invention provides a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field. The invention also provides a polishing system comprising (a) a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field, and (b) an adjustable-strength magnetic field positioned proximate to the polishing pad. The invention further provides a method of polishing a substrate comprising (a) providing a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field, (b) contacting the polishing pad with a substrate, (c) applying a magnetic field to the polishing pad, and (d) moving the polishing pad relative to the substrate, thereby polishing the substrate.

DETAILED DESCRIPTION OF THE INVENTION

[0008] The invention provides a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field. When a magnetic field is applied to the polishing pad of the invention, the magnetically sensitive particles contained within the deformable polishing pad body are repulsed by or attracted to the magnetic field and exert a force upon the deformable polishing pad body. This force causes the polishing pad body to deform (e.g., expand or contract in one or more dimensions), which alters one or more properties of the polishing pad comprising the deformable polishing pad body. The polishing pad of the invention, thus, allows a user to customize the properties of the polishing pad during use by applying a magnetic field to the polishing pad.

[0009] The term "applied magnetic field," as used herein, refers to a magnetic field applied to the polishing pad of the invention in addition to any natural magnetic field (e.g., the earth's magnetic field) that may be present at the particular location in which the polishing pad is used. The term "magnetically sensitive particles," as used herein, refers to any particle that is attracted to, or repulsed by, the applied magnetic field.

[0010] The magnetically sensitive particles can comprise inorganic particles, organic particles, or a mixture of inorganic and organic particles. Inorganic magnetically sensitive particles are well known in the art, and include Fe_3O_4, Nd—Fe—B, Ba—Sr ferrite, Ni—Zn—Cu ferrite, $SmCo_5$, Sm_2Co_{17}, iron, steel, and mixtures thereof. Organic (or metal-organic) magnetically sensitive particles useful in accordance with the present invention include those described in "Metal-Organic and Organic Molecular Magnets", editors P. Day and A. F. Underhill (The Royal Society of Chemistry, Cambridge, 1999) and "Organic Conductors, Superconductors and Magnets: From Synthesis to Molecular Electronics", editors Lahcene Ouahab and Eduard Yagubskii (Kluwer Academic Publishers, 2004). Preferably, the organic or metal-organic particles are selected from the group consisting of $V[\text{tetracyanoethylene}]_{\sim 2}$, $V[Cr(CN)]_{\sim 0.9}$, $Cr(\text{tetracyanoethylene})_2$, $KV[Cr(CN)_6]$, and C-60 fullerene, any of which can further comprise molecules of salvation depending upon the method of synthesis (e.g., $V[Cr(CN)]_{\sim 0.9}.2.8H_2O$, $KV[Cr(CN)_6].2H_2O$, and the like).

[0011] While the magnetically sensitive particles may be used without any particular treatment, in some instances it may be desirable to coat the particles, for example, to improve the dispersibility or adherence of the magnetically sensitive particles in the material of the deformable polishing pad. Any suitable coating can be used provided that the coating does not substantially interfere with or eliminate the magnetic sensitivity of the particles. Useful coatings include polymer coatings, such as coatings comprising polyurethane, nylon, polyethylene, or any other polymer that imparts a desired property to the particles.

[0012] The deformable polishing pad body can comprise any suitable amount of magnetically sensitive particles. The amount of magnetically sensitive particles will affect the degree to which the deformable polishing pad body responds to an applied magnetic field. Increasing the amount of magnetically sensitive particles will typically increase the degree to which the deformable polishing pad body deforms in the presence of an applied magnetic field and, thereby, increase the degree to which the properties of the polishing pad are altered. Decreasing the amount of magnetically sensitive particles generally has the opposite effect. The inventive polishing pad can comprise about 0.1 wt. % or more (e.g., about 5 wt. % or more, or about 10 wt. % or more) of the magnetically sensitive particles, such as about 20 wt. % or more (e.g., about 30 wt. % or more), or about 40 wt. % or more (e.g., about 60 wt % or more) of the magnetically sensitive particles. Typically, the inventive polishing pad will comprise about 60 wt % or less of the magnetically sensitive particles, and can comprise about 40 wt. % or less, such as about 20 wt. % or less (e.g., about 10 wt % or less, or about 5 wt % or less) of the magnetically sensitive particles.

[0013] The magnetically sensitive particles can have any suitable average particle diameter. As used herein, the term "average particle diameter" refers to the average diameter on a number basis. Typically, the magnetically sensitive particles have an average particle diameter of about 5 μm or less, such as about 3 μm or less, or even about 1 μm or less. The average particle diameter of the magnetically sensitive particles is generally within the range of about 0.1 to about 5 μm, such as about 0.3 to about 3 μm, or even about 0.5 to about 1 μm. The magnetically sensitive particles can have any suitable shape including spheres, rectangular solids, cubes, flakes, acicular shapes, and mixtures thereof.

[0014] The deformable polishing pad body comprising the magnetically sensitive particles can be made from any suitable material provided that it allows the properties of the polishing pad to be altered when a magnetic field is applied as compared to the properties of the polishing pad in the absence of the magnetic field. The effect of an applied magnetic field on the properties of the polishing pad will, of course, depend not only upon the material of the polishing pad, but also upon the concentration of magnetically sensitive particles present in the polishing pad and the strength of the applied magnetic field. Accordingly, the choice of the particular material used will depend upon the particular pad configuration and the desired application.

[0015] In general, the deformable polishing pad body will comprise an elastomeric material, such as a natural or synthetic elastomeric polymer. Suitable polymers include elastomers, polyurethanes, polyolefins, polycarbonates, polyvinylalcohols, nylons, natural and synthetic rubbers, styrenic polymers, polyaromatics, fluoropolymers, polyimides, cross-linked polyurethanes, thermoset polyurethanes, cross-linked polyolefins, polyethers, polyesters, polyacrylates, elastomeric polyethylenes, copolymers and block copolymers thereof, and mixtures and blends thereof.

[0016] The polishing pad comprising the deformable polishing pad body and magnetically sensitive particles can have any suitable storage modulus. In the absence of an applied magnetic field, the storage modulus of the polishing pad typically will be about 100-1000 MPa, such as about 400-900 MPa or even about 450-800 MPa (e.g. about 500-700 MPa). The polishing pad can be configured with a lower storage modulus, as may be appropriate for certain applications. Thus, the polishing pad of the invention can have a storage modulus of 350 MPa or less (e.g., about 0.1 MPa to about 350 MPa, such as about 1 MPa to about 350 MPa, or about 10 MPa to about 350 MPa, or even about 100 MPa to about 350 MPa). The storage modulus of the polishing pad can be determined according to the protocol reported in ASTM D790.

[0017] The polishing pad comprising the deformable polishing pad body and magnetically sensitive particles can have any suitable compressibility. The compressibility is generally stated as a percent-change in the thickness of the polishing pad under a given load (e.g., the thickness of the polishing pad under a given load over the original polishing pad thickness (no load) stated as a percent). A preferred method for determining the compressibility of the polishing pad comprises: (a) determining the thickness of the polishing pad without any load applied (D1), (b) applying a given load (e.g., about 32 kPa (about 4.7 psi)) to the polishing pad for about one minute to compress the polishing pad, (c) determining the thickness of the compressed polishing pad (D2), and (d) determining the percent-compressibility according to the following relationship:

$$\text{percent-compressibility}(\%)=[(D1-D2)/D1]\times 100.$$

The compressibility of the polishing pad can be determined with the assistance of commercially available instruments (e.g., "Ames Meter" model BG2500-1-04 manufactured by B.C. Ames Inc.). In the absence of an applied magnetic field, the average percent compressibility of the polishing pad under a load of about 32 kPa will generally be about 2% or more, such as about 4% or more, or even about 10% or more (e.g., about 15% or more, or even about 20% or more). The compressibility will generally be within the range of about 2-50%, such as about 4-40%, or about 10-30%.

[0018] The polishing pad comprising the deformable polishing pad body and magnetically sensitive particles can have any suitable resilience. Resilience is typically recited as percent-rebound capacity. A preferred method for determining the percent-rebound capacity of a polishing pad comprises: (a) determining the thickness of the polishing pad without any load applied (D1), (b) applying a given load (e.g., about 32 kPa (about 4.7 psi)) to the polishing pad for about one minute to compress the polishing pad, (c) determining the thickness of the compressed polishing pad (D2), (d) removing the load from the polishing pad and allowing the polishing pad to rebound for about one minute, (e) determining the thickness of the rebounded polishing pad (D3), and (f) determining the percent-rebound capacity of the polishing pad according to the following relationship:

$$\text{percent-rebound}(\%)=[(D3-D2)/(D1-D2)]\times 100.$$

As with compressibility, the percent-rebound of the polishing pad can be determined with the assistance of commercially available instruments, such as the aforementioned "Ames Meter." For most applications, it is desirable that the polishing pad has a high percent-rebound capacity in the absence of an applied magnetic field. Thus, the polishing pad preferably has a percent-rebound capacity, after application of a load of about 32 kPa (about 4.7 psi), of about 50% or more, such as about 60% or more, or even about 85% or more. Of course, lower percent-rebound capacities of about 25% or more (e.g., about 30% or more, or about 40% or more) may be suitable for some applications.

[0019] The polishing pad comprising the deformable polishing pad body and magnetically sensitive particles can have any suitable hardness. Hardness can be measured according to the Shore method using a durometer, for example, according to ASTM D-2240-95. Thus, the polishing pad of the invention can have a Shore hardness of about 40 A to about 90 D. Generally, the Shore hardness of the polishing pad in the absence of an applied magnetic field will be about 90 D or less, such as about 70 D or less, or even about 50 D or less (wherein the "D" designation represents the hardness on the Shore "D" scale), and will be within the range of about 40 D-90 D, such as about 50 D-80 D. For applications in which softer polishing pads are needed, the polishing pad of the invention can be configured with a Shore hardness of about 40 A or more (e.g., about 40 A to about 90 A) or about 60 A or more (e.g., about 60 A to about 90 A) or even about 70 A or more (e.g., about 70 A to about 90 A).

[0020] The polishing pad comprising the deformable polishing pad body and magnetically sensitive particles can be produced by any suitable method. Many such methods are known in the art. Suitable methods include casting, cutting, reaction injection molding, injection blow molding, compression molding, sintering, thermoforming, or pressing the chosen material into a desired shape. The polymer typically is a pre-formed polymer; however, the polymer also can be formed in situ according to any suitable method, many of which are known in the art (see, for example, *Szycher's Handbook of Polyurethanes* CRC Press: New York, 1999, Chapter 3). For example, thermoplastic polyurethane can be formed in situ by reaction of urethane prepolymers, such as isocyanate, di-isocyanate, and tri-isocyanate prepolymers, with a prepolymer containing an isocyanate-reactive moiety. Suitable isocyanate-reactive moieties include amines and polyols. Foam polymers, such as polyurethane foam polymers, comprising primarily open-cells or closed-cells, or a mixture of open and closed cells, also can be used. Techniques for the use of foam polymers are described in the art and include the mucell process, phase inversion process, spinodal or bimodal decomposition process, and pressurized gas injection process. Preferably, the polishing pads are produced using a mucell process or a pressurized gas injection process.

[0021] The polishing pad and deformable polishing pad body comprising the magnetically sensitive particles can have any suitable shape. Typically, the polishing pad and deformable polishing pad body will have the shape of a belt, a disc or a flat polygonal solid shape (e.g., rectangular solid) comprising two broad surfaces providing front and rear "faces" and one or more edge surfaces on the perimeter of the polishing pad and deformable polishing pad body. When used in an apparatus that rotates the polishing pad and deformable polishing pad body, the polishing pad and deformable polishing pad body will have an axis of rotation perpendicular to the faces.

[0022] The magnetically sensitive particles are generally distributed in the material of the deformable polishing pad body during the production of the pad. The distribution of the magnetically sensitive particles can be effected in any suitable manner. For example, the magnetically sensitive particles can be combined with the material of the deformable polishing pad by mixing or blending prior to forming the material into the desired shape.

[0023] The magnetically sensitive particles can be distributed in the material of the deformable polishing pad body evenly to provide a uniform distribution of magnetically sensitive particles, or they can be distributed in a non-uniform manner. For example, the magnetically sensitive particles can be concentrated in a particular thickness of the deformable polishing pad body, such as at or near one or both faces of the deformable polishing pad, or at the center of the thickness of the deformable polishing pad body. The magnetically sensitive particles can also be concentrated at one or more distances from the axis of rotation of the deformable polishing pad body, such as at or near the perimeter of the deformable polishing pad body, or closer to the axis of rotation. Alternatively, the magnetically sensitive particles can be distributed in selected areas of the polishing pad. Preferably, the magnetically sensitive particles are distributed in the polishing pad in a manner that reduces the edge effect during polishing (e.g., reduces the tendency of the edges of a substrate to polish at a different rate from the rest of the substrate).

[0024] When distributed in a non-uniform manner, the magnetically sensitive particles can be distributed in distinct concentrated areas, or can be distributed along a concentration gradient. For example, the magnetically sensitive particles can be present in highest concentration at the perimeter of the deformable polishing pad body with a decreasing concentration gradient towards the axis of rotation, or vice versa (e.g., the concentration being highest at the center of the pad and decreasing towards the axis of rotation). The same types of gradients can be established through the thickness of the pad as well. For example, concentrations of magnetic particles can be highest at the faces and decrease towards the center thickness, or vice versa. Alternatively, the concentration of magnetic particles can steadily increase or decrease from one face to the opposite face. The gradients of magnetically sensitive particle concentration in the deformable polishing pad body can be linear or non-linear.

[0025] A non-uniform distribution of the magnetically sensitive particles in the deformable polishing pad body can be accomplished by any suitable method. For example, the settling properties of different types or sizes of magnetically sensitive particles can be used to establish concentration gradients in the material of the deformable polishing pad prior to formation. Also, the deformable polishing pad body can be formed using layers or sections having different concentrations of magnetically sensitive particles. Alternatively, magnetically sensitive particles can be embedded into the surface of a formed polishing pad in any suitable pattern or gradient, followed by heating the material of the deformable polishing pad body to its flow temperature, with the optional application of pressure, to incorporate the particles into the material. Other methods for the non-uniform distribution of particles in the deformable polishing pad body will be readily apparent to those of ordinary skill in the art.

[0026] The polishing pad of the invention can be configured as a top-pad or a subpad. In many polishing processes, the top-pad is the polishing pad that actually makes contact with the surface of the substrate being polished. Thus, the top-pad comprises a polishing surface. The subpad underlies and supports the top-pad. When configured as a top pad, the polishing pad of the invention is typically used in conjunction with a subpad. Alternatively, when configured as a top pad, the polishing pad of the invention is typically used in conjunction with a subpad.

[0027] The invention also encompasses a polishing pad configured as a top pad in combination with a subpad, wherein either or both the subpad or top pad can comprise the magnetically sensitive particles. In accordance with this aspect of the invention, the top pad and subpad can be provided by different layers of a single polymer sheet, or by separate polymer sheets associated or bonded together. When the top pad and subpad are provided by separate polymer sheets, the top pad polymer sheet and subpad polymer sheet desirably are associated without the use of an adhesive (e.g., without an intervening adhesive layer). For example, the top-pad sheet and subpad sheet can be joined by welding (e.g., ultrasonic welding), thermal bonding, radiation-activated bonding, lamination, or coextrusion. Alternatively, the top pad and subpad can be provided by different layers or parts of a single polymer sheet. For instance, a single-layer polymer sheet can by subjected to a process that alters the physical properties of one or both faces of the single-layer polymer sheet to provide a two-layer polymer sheet, wherein one layer serves as the top-pad and the other layer serves as the subpad. For example, a solid polymer sheet can be selectively foamed such that porosity is introduced into one face of the polymer sheet, resulting in a two-layer polymer sheet (e.g., two-layer polishing pad) having a porous layer that is attached to a solid layer without the use of an adhesive. One of the layers provides the top pad, and the other provides the subpad. One or both layers of the polishing pad can comprise the magnetically sensitive particles. According to any of the above configurations, the subpad is preferably provided by a porous layer comprising the magnetically sensitive particles.

[0028] When configured as a top-pad/subpad combination, or as a one-piece polishing pad, the polishing pad of the invention can further comprise a polishing surface. The polishing surface can be provided by a separate layer of material adhered or welded to the surface of the deformable polishing pad body, or it can be provided by a surface of the deformable polishing pad body. When the polishing surface is provided by a separate layer of material, it can be adhered or welded to a surface of the deformable polishing pad body by any suitable method, such as by way of friction (e.g., no intervening layer), hook-loop type interlocking fabrics, vacuum, magnetic forces, various adhesive compounds and tapes, "welding" the layers using chemicals, heat, and/or pressure, or other various methods. Typically, an intermediate backing layer such as a polyethyleneterephthalate film is disposed between the polishing layer and the subpad. This configuration of the polishing pad of the invention can, optionally, be used in conjunction with a subpad.

[0029] Whether provided by a surface of the deformable polishing pad body, or by a separate layer of material, the polishing surface can comprise any suitable material, such as one or more of any of the polymers previously identified with respect to the deformable polishing pad body. The material can be the same as or different from the material of the deformable polishing pad body. Typically, the polishing surface comprises a non-porous polyurethane.

[0030] The polishing surface can further comprise grooves, channels, and/or perforations, which facilitate the lateral transport of polishing compositions across the surface of the polishing pad. Such grooves, channels, or perforations can be in any suitable pattern and can have any suitable depth and width. The polishing surface can have two or more different groove patterns, such as a combination of large grooves and small grooves as described in U.S. Pat. No. 5,489,233. Examples of suitable groove patterns include slanted grooves, concentric grooves, spiral or circular grooves, and XY crosshatch patterns, which can be continuous or non-continuous in connectivity. Preferably, the polishing surface comprises at least small grooves produced by standard pad-conditioning methods.

[0031] The polishing surface can be free of magnetically sensitive particles, or can comprise magnetically sensitive particles in any suitable amount. The concentration and distribution of magnetically sensitive particles in the polishing surface can be configured in the same manner previously described with respect to the deformable polishing pad body. In a given polishing pad according to the invention, the concentration and distribution of magnetically sensitive particles in the polishing surface can be the same as or different from that of the deformable polishing pad body.

[0032] When the polishing surface comprises magnetically sensitive particles, the particles are preferably coated to prevent any particles that become exposed during polishing from scratching the surface of the substrate. Alternatively, the magnetically sensitive particles used in the polishing surface can be made of a material that will not scratch the surface of a substrate being polished, such as non-abrasive metal-organic or organic particles. Whether a given type of non-abrasive particle is abrasive or non-abrasive must be determined with respect to the particular type of substrate being polished. The magnetically sensitive particles will typically be positioned in the polishing pad such that they do not protrude from the surface of the polishing pad during polishing. However, the magnetically sensitive particles can be positioned in the polishing pad such that they do protrude from the surface in order to provide an abrasive polishing surface. When in the presence of a magnetic field, the magnetically sensitive particles protruding from the surface of the polishing pad serve the dual purposes of providing a fixed abrasive in the polishing pad and providing for the alteration of the properties of the polishing pad as described herein.

[0033] The polishing pad of the invention can be configured for use in conjunction with an in situ polishing endpoint detection system. In situ endpoint detection generally involves analyzing the surface of a substrate during polishing through the use of light or other form of radiation, so as to determine the end-point of the polishing process. Desirably, the polishing pad of the invention comprises a port or aperture that provides a path through which light or other form of radiation can travel to reach the substrate surface. The port or aperture can be provided by a hole formed through the thickness of the deformable polishing pad body, polishing surface, subpad, and any other layer which the polishing pad comprises. Alternatively, the polishing pad can comprise a “window” of a suitable polymer or other material that is translucent or transparent to the light or other radiation used in the detection technique. The particular type of port or aperture used will depend upon the specific endpoint detection technique chosen and the type of radiation employed for that purpose. Techniques for inspecting and monitoring the polishing process by analyzing light or other radiation reflected from a surface of the workpiece are known in the art. Such methods are described, for example, in U.S. Pat. No. 5,196,353, U.S. Pat. No. 5,433,651, U.S. Pat. No. 5,609,511, U.S. Pat. No. 5,643,046, U.S. Pat. No. 5,658,183, U.S. Pat. No. 5,730,642, U.S. Pat. No. 5,838,447, U.S. Pat. No. 5,872,633, U.S. Pat. No. 5,893,796, U.S. Pat. No. 5,949,927, and U.S. Pat. No. 5,964,643.

[0034] When a magnetic field is applied to the polishing pad comprising the deformable polishing pad body, one or more properties of the deformable polishing pad body (or the polishing pad comprising the deformable polishing pad body) are altered, desirably to a degree sufficient to affect the polishing performance of the polishing pad. The properties that are altered can be any of the properties of the polishing pad, including the storage modulus, compressibility, resilience, and hardness. Preferred configurations of the polishing pad comprise a deformable polishing pad body comprising magnetically sensitive particles in an amount such that, when in the presence of an applied magnetic field of about 1-1000 Gauss (e.g., about 5-500 Gauss, about 10-250 Guass, or about 50-200 Gauss), one or more of these properties are changed by about 5% or more (e.g., about 10% or more), such as about 15% or more (e.g., about 20% or more), or even about 25% or more (e.g., about 30% or more) as compared to the polishing pad in the absence of the applied magnetic field.

[0035] The polishing pad of the invention can also comprise other polishing pad elements such as stiffening layers, additional subpads, adhesive layers, backing materials, and other typical components.

[0036] The invention further provides a polishing system comprising (a) a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field, and (b) an adjustable-strength magnetic field positioned proximate to the polishing pad. The polishing pad of the polishing system is as described above with respect to the polishing pad of the invention.

[0037] The adjustable-strength magnetic field can be provided by any suitable apparatus, such as a magnet or an electromagnet. The term “adjustable-strength” as used herein encompasses variable-strength magnetic fields (e.g., variable on a continuum of strengths) as well as multiple-strength magnetic fields (e.g., having multiple fixed-strength settings). When the adjustable strength magnetic field is provided by a magnetic field having multiple fixed-strength settings, it is preferred that the magnetic field has more than two strength settings (e.g., more than an “on” and “off” setting) to allow greater flexibility in altering the properties of the polishing pad. The strength of the field can be adjusted, for example, by increasing or decreasing the amount of power supplied, or by shielding the polishing pad from the magnetic field to a greater or lesser degree. The adjustable-strength feature of the magnetic field allows a user of the polishing system to change the strength of the magnetic field and, thereby, control the properties of the polishing pad during use. As the magnetic field strength is increased, the force exerted by the magnetically sensitive particles on the deformable polishing pad body is increased, and the properties of the polishing pad comprising the deformable polishing pad body are altered to a greater degree. Similarly, as the magnetic field strength is reduced, the properties of the polishing pad are altered to a lesser degree.

[0038] The adjustable-strength magnetic field is positioned proximate to the polishing pad. For the purposes of this invention, the adjustable-strength magnetic field is considered to be “proximate” to the polishing pad if the adjustable strength magnetic field is close enough to the polishing pad to alter one or more properties of the polishing pad. The adjustable strength magnetic field can be oriented in any suitable position relative to the polishing pad. For the purposes of the present invention, the magnetic field is considered to have lines of force parallel to the direction of attraction and repulsion of the magnetic field. Typically, the magnetic field is positioned such that the lines of force are substantially perpendicular to the polishing surface of the polishing pad. Alternatively, the magnetic field can be positioned such that the lines of force are at an angle to the polishing surface of the polishing pad, or even substantially parallel to the polishing surface of the polishing pad. Also, the source of the magnetic field (e.g., the magnet or electromagnet) can be positioned relative to the polishing pad and the substrate being polished such that the substrate is between the source of the magnetic field and the polishing pad, or, preferably, such that the polishing pad is between the source of the magnetic field and the substrate.

[0039] The adjustable strength magnetic field should be capable of providing sufficient magnetic force to alter one or more properties of the polishing pad. The amount of force required for this purpose will depend upon the particular configuration of the polishing pad used in a given application. Generally, an adjustable strength magnetic field capable of generating about 1-1000 Gauss (e.g., about 5-500 Gauss, about 10-250 Gauss, or about 50-200 Gauss) or more will be sufficient.

[0040] The strength of the magnetic field can be manually controlled (e.g., operator-controlled). When manual controls are used, the applied magnetic field is typically adjusted by an operator to achieve or maintain desired polishing parameters (e.g., removal rate, friction, roughness, dishing, etc.), or at the beginning or end of a polishing stage or a predetermined time interval. For example, an operator monitoring the material removal rate during polishing can adjust the strength of the magnetic field to change or maintain a given material removal rate. Alternatively, or in addition to manual controls, the strength of the magnetic field can be automatically controlled, for example, through the use of a microprocessor. Automated controls can be used to automatically adjust the magnetic field strength according to a pre-programmed set of instructions, or in response to changes in polishing parameters. For example, the magnetic field can be automatically adjusted in response to changes in polishing conditions by incorporating into the polishing system a feedback mechanism, whereby monitors detect a change in one or more polishing conditions and deliver a signal to the automated controls to adjust the magnetic field appropriately.

[0041] The invention also provides a method of polishing a substrate comprising (a) providing a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field, (b) contacting the polishing pad with a substrate, (c) applying an adjustable-strength magnetic field to the polishing pad to alter one or more properties of the polishing pad, and (d) moving the polishing pad relative to the substrate, thereby polishing the substrate. The polishing pad and adjustable-strength magnetic field are as described herein with respect to the polishing pad and polishing system of the invention.

[0042] The method of the invention can further comprise adjusting the adjustable-strength magnetic field during polishing. The magnetic field can be adjusted manually, or via automated controls, as discussed above with respect to the polishing system of the invention. The magnetic field preferably is adjusted so as to achieve a desired polishing property, such as to reduce over-polishing or reduce dishing of the substrate (e.g., improve planarity and within-die uniformity).

[0043] The polishing pad and polishing system of the invention is particularly suited for use in conjunction with a chemical-mechanical polishing (CMP) apparatus. Typically, the apparatus comprises (a) a platen, which, when in use, is in motion and has a velocity that results from orbital, linear, or circular motion, (b) a polishing pad of the invention in contact with the platen and moving with the platen when in motion, and (c) a carrier that holds a workpiece to be polished by contacting and moving relative to the surface of the polishing pad. The polishing of the workpiece takes place by the workpiece being placed in contact with the polishing pad and then the polishing pad moving relative to the workpiece, typically with a polishing composition therebetween, so as to abrade at least a portion of the workpiece to polish the workpiece. The polishing composition typically comprises a liquid carrier (e.g., an aqueous carrier), a pH adjustor, and optionally an abrasive. Depending on the type of workpiece being polished, the polishing composition optionally may further comprise oxidizing agents, organic acids, complexing agents, pH buffers, surfactants, corrosion inhibitors, anti-foaming agents, and the like. The CMP apparatus can be any suitable CMP apparatus, many of which are known in the art. The polishing pad and polishing system of the invention also can be used with linear polishing tools.

[0044] The polishing pad, polishing system, and polishing method of the invention is suitable for use in a method of polishing many types of workpieces (e.g., substrates or wafers) and workpiece materials. For example, the polishing pads can be used to polish workpieces including memory storage devices, glass substrates, memory or rigid disks, metals (e.g., noble metals), magnetic heads, inter-layer dielectric (ILD) layers, polymeric films, low and high dielectric constant films, ferroelectrics, micro-electro-mechanical systems (MEMS), semiconductor wafers, field emission displays, and other microelectronic substrates, especially microelectronic substrates comprising insulating layers (e.g., silicon oxide, silicon nitride, or low dielectric materials) and/or metal-containing layers (e.g., copper, tantalum, tungsten, aluminum, nickel, titanium, platinum, ruthenium, rhodium, iridium, alloys thereof, and mixtures thereof). In addition, the workpiece can comprise, consist essentially of, or consist of any suitable metal composite. Suitable metal composites include, for example, metal nitrides (e.g., tantalum nitride, titanium nitride, and tungsten nitride), metal carbides (e.g., silicon carbide and tungsten carbide), nickel-phosphorus, alumino-borosilicate, borosilicate glass, phosphosilicate glass (PSG), borophosphosilicate glass (BPSG), silicon/germanium alloys, and silicon/germanium/carbon alloys. The workpiece can also comprise, consist essentially of, or consist of any suitable semiconductor base material. Suitable semiconductor base materials include single-crystal silicon, poly-crystalline silicon, amorphous silicon, silicon-on-insulator, and gallium arsenide.

EXAMPLE

[0045] The following example illustrates the preparation and use of a polishing pad, polishing system, and polishing method according to the invention.

[0046] A polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein is fabricated by blending polyurethane foam particles and magnetite (Fe_3O_4) at a temperature above the flow temperature of the polyurethane. The mixture is cast into a disc-shaped polishing pad.

[0047] The polishing pad is mounted on the platen of a CMP polishing machine as a subpad beneath a standard polyurethane top pad, and a patterned substrate is positioned on the polishing tool of the polishing machine in contact with the surface of the top pad. A variable-power electromagnet is positioned such that the polishing pad is between the electromagnet and the substrate, and the lines of force of the magnetic field are perpendicular to the surface of the polishing pad. The polishing process is started, and a polishing composition is supplied to the surface of the polishing pad and substrate. The electromagnet is in the “off” position. After several minutes, dishing in the surface of the substrate is detected, and the electromagnet is turned on at low power. The application of the magnetic field causes the subpad to compress against the platen, reducing the compressibility of the subpad. Polishing is continued for several more minutes, after which time the dishing in the substrate is reduced, but still evident. The strength of the electromagnet is increased, thereby causing the subpad to further compress against the platen, and polishing is continued with further reduction in the dishing of the substrate.

[0048] All references, including publications, patent applications, and patents, cited herein are hereby incorporated by reference to the same extent as if each reference were individually and specifically indicated to be incorporated by reference and were set forth in its entirety herein.

[0049] The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms "comprising,""having,""including," and "containing" are to be construed as open-ended terms (i.e., meaning "including, but not limited to,") unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., "such as") provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[0050] Preferred embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Variations of those preferred embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

1-30. (canceled)

31. A polishing system comprising

(a) a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field, and

(b) an adjustable-strength magnetic field positioned proximate to the polishing pad.

32. The polishing system of claim 31, wherein the strength of the magnetic field is manually controlled.

33. The polishing system of claim 31, wherein the strength of the magnetic field is automatically controlled.

34. The polishing system of claim 33, wherein the strength of the magnetic field automatically adjusts in response to changes in polishing conditions.

35. The polishing system of claim 33, wherein the strength of the magnetic field automatically adjusts according to a pre-set program.

36. The polishing system of claim 31, wherein the one or more properties of the polishing pad that are altered in the presence of an applied magnetic field are one or more properties selected from the group consisting of the storage modulus, compressibility, percent-rebound, and hardness of the polishing pad.

37. A method of polishing a substrate comprising

(a) providing a polishing pad comprising a deformable polishing pad body and magnetically sensitive particles dispersed therein, wherein one or more properties of the polishing pad are altered when in the presence of an applied magnetic field,

(b) contacting the polishing pad with a substrate,

(c) applying a magnetic field to the polishing pad to alter one or more properties of the polishing pad, and

(d) moving the polishing pad relative to the substrate, thereby polishing the substrate.

38. The method of claim 37, further comprising adjusting the strength of the magnetic field during polishing, thereby altering one or more properties of the polishing pad.

39. The method of claim 37, wherein the strength of the magnetic field is adjusted in response to a change in polishing conditions.

40. The method of claim 38, wherein the strength of the magnetic field is adjusted according to a pre-set program.

41. The method of claim 38, wherein adjusting the strength of the magnetic field reduces over-polishing dishing in the substrate.

42. The method of claim 37, wherein the one or more properties of the polishing pad that are altered in the presence of an applied magnetic field axe one or more properties selected from the group consisting of the storage modulus, compressibility, resilience, and hardness of the polishing pad.

43. The polishing system of claim 31, wherein the polishing pad has a storage modulus of about 100 to about 1000 MPa in the absence of an applied magnetic field.

44. The polishing system of claim 31, wherein the polishing pad has an average percent compressibility, under a load of about 32 kPa, of about 2% or more in the absence of an applied magnetic field.

45. The polishing system of claim 31, wherein the polishing pad has an average percent-rebound, after application of a load of about 32 kPa, of about 25% or more in the absence of an applied magnetic field.

46. The polishing system of claim 31, wherein the polishing pad has a Shore Durometer hardness of about 40 A to about 90 D in the absence of an applied magnetic field.

47. The polishing system of claim 31, wherein the deformable polishing pad body comprises a polymer.

48. The polishing system of claim 47, wherein the polymer is selected from the group consisting of elastomers, polyurethanes, polyolefins, polycarbonates, polyvinylalcohols, nylons, natural and synthetic rubbers, styrenic polymers, polyaromatics, fluoropolymers, polyimides, cross-linked polyurethanes, thermoset polyurethanes, cross-linked polyolefins, polyethers, polyesters, polyacrylates, elastomeric polyethylenes, copolymers and block copolymers thereof, and mixtures and blends thereof.

49. The polishing system of claim 48, wherein the deformable polishing pad body comprises a foam polymer.

50. The polishing system of claim 49, wherein the foam comprises predominantly open cells.

51. The polishing system of claim 49, wherein the foam comprises predominantly closed cells.

52. The polishing system of claim 49, wherein the foam comprises a mixture of open and closed cells.

53. The polishing system of claim 31, wherein the magnetically sensitive particles have an average particle diameter of about 5 μm or less.

54. The polishing system of claim 31, wherein the magnetically sensitive particles are inorganic particles.

55. The polishing system of claim 54, wherein the magnetically sensitive particles are selected from the group consisting of Fe_3O_4, Nd—Fe—B, Ba—Sr ferrite, Ni—Zn—Cu ferrite, $SmCo_5$, Sm_2Co_{17}, iron, steel, and mixtures thereof.

56. The polishing system of claim 54, wherein the magnetically sensitive particles are coated.

57. The polishing system of claim 31, wherein the magnetically sensitive particles are organic or metal-organic particles.

58. The polishing system of claim 57, wherein the magnetically sensitive particles are selected from the group consisting of V[tetracyanoethylene]$_{\sim 2}$, V[Cr(CN)]$_{\sim 0.9}$, Cr(tetracyanoethylene)$_2$, KV[Cr(CN)$_6$], and C-60 fullerene.

59. The polishing system of claim 31, wherein the magnetically sensitive particles are distributed uniformly throughout the deformable polishing pad body.

60. The polishing system of claim 31, wherein the magnetically sensitive particles are distributed throughout the deformable polishing pad body in a non-uniform manner.

61. The polishing system of claim 31, wherein the magnetically sensitive particles are distributed throughout the deformable polishing pad body according to a gradient.

62. The polishing system of claim 31, wherein the magnetically sensitive particles are distributed in selected areas of the pad.

63. The polishing system of claim 31 further comprising a polishing surface.

64. The polishing system of claim 63, wherein the polishing surface is provided by a surface of the deformable polishing pad body.

65. The polishing system of claim 63, wherein the polishing surface is provided by a separate layer.

66. The polishing system of claim 63, wherein the polishing surface comprises magnetically sensitive particles.

67. The polishing system of claim 66, wherein the magnetically sensitive particles are coated particles.

68. The polishing system of claim 66, wherein the magnetically sensitive particles are organic particles or metal-organic.

69. The polishing system of claim 63, wherein the polishing surface is free of magnetically sensitive particles.

70. The polishing system of claim 31, further comprising an endpoint detection port.

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