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(54) **METHOD OF REMOVAL PROFILE
MODULATION IN CMP PADS**

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(76) Inventors: **Rajeev Bajaj**, Fremont, CA (US);
Alan Nolet, Atherton, CA (US)

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Correspondence Address:
SONNENSCHN NATH & ROSENTHAL LLP
P.O. BOX 061080, WACKER DRIVE STATION,
SEARS TOWER
CHICAGO, IL 60606-1080 (US)

(57) **ABSTRACT**

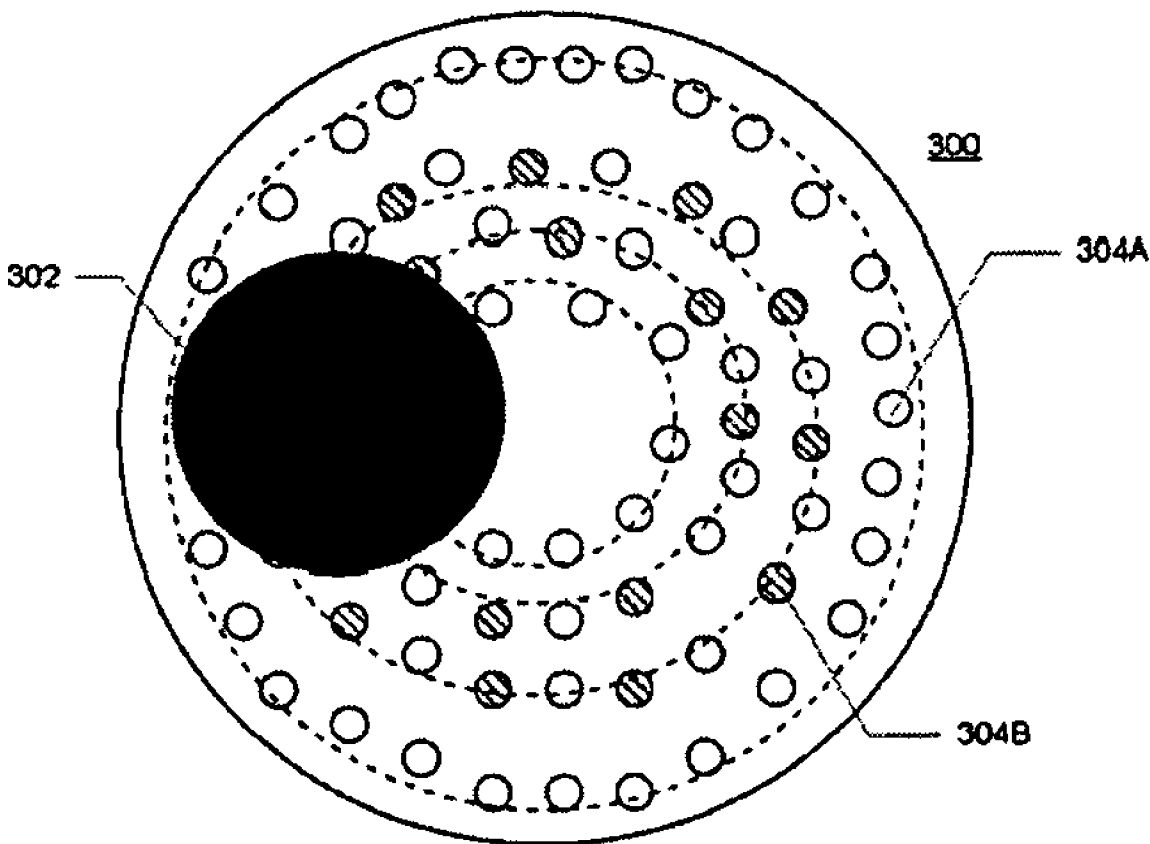
A polishing pad includes a plurality of polishing surfaces, a first group of the polishing surfaces made of a first material having a first coefficient of friction and a second group of the polishing surfaces made of a second material having a second coefficient of friction. The first and second groups of polishing surfaces may be arranged over the polishing pad so as to provide a non-planar material removal profile. The polishing surface layout may be designed by evaluating a material removal profile for an existing polishing pad of known characteristics, observing how variations in polishing surface densities and/or coefficients of friction affect that material removal profile, and then mapping the polishing surface coefficients of friction and density profiles to the subject polishing pad layout.

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Related U.S. Application Data

(63) Continuation-in-part of application No. 11/697,622,
filed on Apr. 6, 2007.



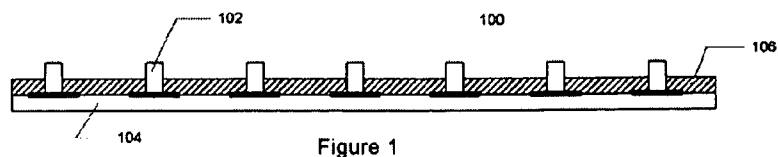


Figure 1

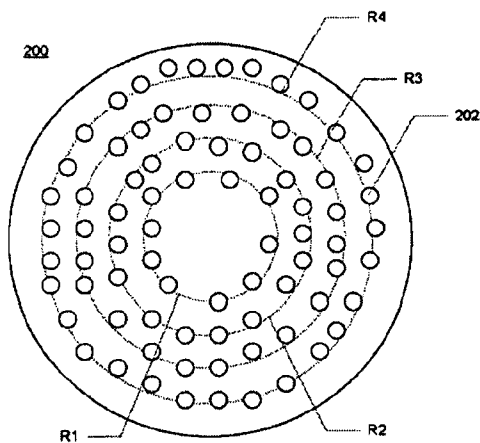


Figure 2A

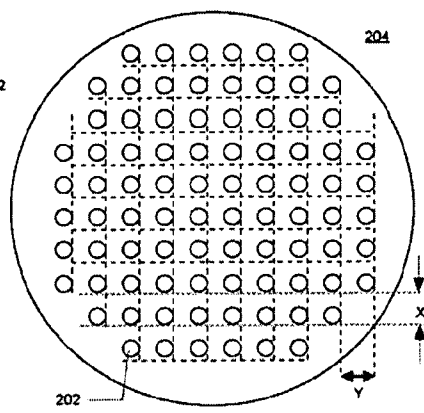


Figure 2B

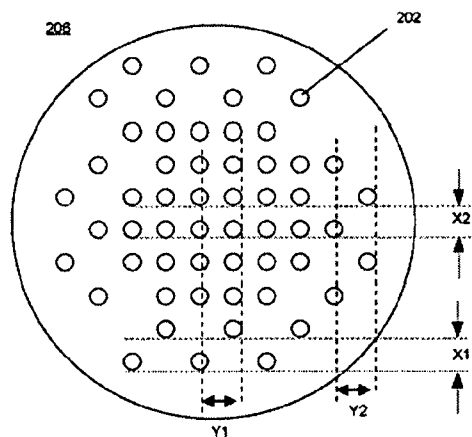


Figure 2C

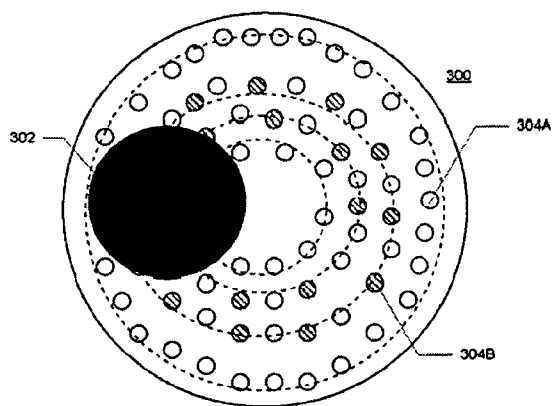


Figure 3

METHOD OF REMOVAL PROFILE MODULATION IN CMP PADS

RELATED APPLICATIONS

[0001] This is a Continuation-in-Part of U.S. patent application Ser. No. 11/697,622, filed 6 Apr. 2007, which application is assigned to the assignee of the present invention and incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to the field of chemical mechanical planarization (CMP) and relates specifically to a CMP polishing pad having a non-planar material removal profiles and methods for using such pads.

BACKGROUND

[0003] In modern integrated circuit (IC) fabrication, layers of material are applied to embedded structures previously formed on semiconductor wafers. Chemical mechanical planarization (CMP) is an abrasive process used to remove excess material from these layers and polish the resulting surface to achieve a desired structure and material profile. CMP may be performed on both oxides and metals and generally involves the use of chemical slurries applied in conjunction with a polishing pad that is put in motion relative to the wafer (e.g., rotational motion relative to the wafer). The resulting smooth flat surface is necessary to maintain proper photolithographic depth of focus for subsequent wafer processing steps and to ensure that metal interconnects are not deformed over underlying features on the wafer. Damascene processing requires metal, such as tungsten or copper, to be removed from a top surface of a dielectric to define interconnect structures, using CMP.

[0004] Polishing pads used in CMP processes are typically made of urethanes, either in cast form and filled with micro-porous elements, or from non-woven felt coated with polyurethanes. The polishing surface of a polishing pad is typically a single, continuous sheet of material, which may be grooved or perforated to facilitate slurry distribution across the surface. During polishing operations the polishing pad is rotated while contacting the wafer, which is also rotated, with the slurry layer disposed between the pad and the wafer, thus affecting polishing.

[0005] One consequence of the use of conventional polishing pads in polishing processes is that as pad moves relative to the wafer, sudden changes in pad compression will be experienced. These variations will give rise to "edge effects" on the wafer, causing material removal rates at the edge of the wafer to be different from those experienced at other points across the diameter of the wafer.

[0006] Further, conventional polishing pads have no inherent ability to modulate their material removal profile across the diameter of a wafer. Yet, in advanced wafer processing operations there are multiple films being deposited, each of which have specific deposition profiles. For example, electroplated copper films tend to be thickest at the edge of a wafer, while some dielectric films tend to have a smooth "M" or "W"-shaped profile across a diameter of a wafer. In cases of critical process modules, such as copper and STI polishing, the use of conventional polishing pads can lead to over-polishing of some areas in order to ensure that other areas of the wafer receive adequate polishing. In advanced technology nodes, the margin for such over-polishing (i.e., the ability to

tolerate such conditions and still have an acceptable wafer result from the process) is shrinking rapidly and in some cases allows for less than 5% polish time. This leads to loss of performance or, worse, loss of yield for some parts. There is therefore a need to provide means for tuning the removal profile of a polishing pad in polishing processes to minimize the need for over-polishing across the diameter of a wafer.

SUMMARY OF THE INVENTION

[0007] In one embodiment, a polishing pad includes a plurality of polishing surfaces, a first group of the polishing surfaces made of a first material having a first coefficient of friction and a second group of the polishing surfaces made of a second material having a second coefficient of friction. The first and second groups of polishing surfaces may be arranged over the polishing pad so as to provide a non-planar material removal profile. The first and second groups of polishing surfaces may be arranged to provide (1) an edge fast material removal profile; (2) an edge slow removal profile; (3) a center fast removal profile; or (4) a center slow removal profile.

[0008] The polishing surfaces of the polishing pad may, in some cases, be individual polishing elements, each polishing element supported by an underlying compressible foam layer and oriented with a long axis normal to a plane defined by the underlying compressible foam layer. The polishing elements may be spaced apart from one another so that displacement of one polishing element along its long axis in a direction normal to the plane defined by the underlying foam layer does not materially affect displacement of adjacent ones of the polishing elements. In some cases, the polishing elements of the first group may be made of polyurethane and the polishing elements of the second groups may be made of polyoxymethylene.

[0009] In varying embodiments of the invention, the first and second groups of polishing surfaces may be arranged in different densities over the polishing pad. In some cases, the different densities vary by radial distance of the polishing surfaces from a center of the polishing pad. In other cases, the different densities vary orthogonally across the polishing pad. In still other cases, the polishing surface density variations are implemented by varying groove pitch and/or groove size over the polishing pad. In still further cases, however, overall densities of polishing surfaces per unit area of the polishing pad is uniform for the polishing pad.

[0010] In some instances, the first and second groups of polishing surfaces may be laid out in uniform radial arrangement over the entire polishing pad. Each polishing surface of the first and second groups may have a common size and/or common shape or different sizes/shapes. Where the polishing surfaces are individual polishing elements, they may be laid out in an orthogonal arrangement where inter-polishing element spacing is defined by a pitch in each of two dimensions. This inter-polishing element pitch may vary in either or both of these dimensions. Further, where the polishing surfaces are individual polishing elements they may be laid out in a radial pattern such that polishing elements at different radial distances from a center of the polishing pad have different inter-polishing element spacing.

[0011] Further embodiments of the invention provide for polishing a workpiece using a polishing pad configured in any of the above-described fashions.

[0012] Moreover, designing a layout of polishing surfaces for a polishing pad to achieve a desired material removal profile for the polishing pad may be done by (a) determining

a first material removal profile of a first polishing pad having a known polishing surface layout, (b) applying polishing surface coefficient of friction variations and/or polishing surface density variations corresponding to regions of the first polishing pad where changes in the first material removal profile are desired, (c) determining what fraction of a total polishing time is spent by an area of a wafer of interest in the regions of the first pad, (d) determining, based on these fractional times, corresponding variations in the first material removal profile at pad-wafer locations of interest, and (e) determining the new pad layout to achieve the desired material removal profile by mapping new polishing surface coefficients of friction and density profiles to the subject polishing pad layout.

[0013] These and further embodiments of the invention are discussed in detail below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The present invention is illustrated by way of example, and not limitation, in the figures of the accompanying drawings, in which:

[0015] FIG. 1 illustrates an example of a polishing pad having individual polishing elements, densities of which across the pad may be varied according to the present invention;

[0016] FIG. 2A shows a polishing pad having polishing elements laid out in varying densities along circumferences of different radii in accordance with an embodiment of the present invention.

[0017] FIG. 2B shows a polishing pad in which polishing elements are laid out in an orthogonal arrangement and the inter-polishing element spacing is defined by a pitch in two dimensions.

[0018] FIG. 2C illustrates a polishing pad similar to that shown in FIG. 2B, with variations in polishing pad pitches in each dimension.

[0019] FIG. 3 shows a polishing pad with a wafer overlaid thereon (e.g., as may be the case during wafer polishing operations) and containing polishing elements laid out in a fixed radial density profile and in which polishing elements of two different types are present.

DETAILED DESCRIPTION

[0020] Described below is a polishing pad suitable for use in CMP and other applications, which pad is configured to provide a tunable, material removal profile across a workpiece being polished. Often, for example with CMP processes, the workpiece will be a semiconductor wafer (either a bare wafer or one that has already undergone one or more processing steps in a fabrication process), but this is not necessarily so. Other workpieces that are subject to polishing operations may also benefit from the use of the polishing pads configured in accordance with the present invention. Therefore, although the present polishing pad will be discussed in the context of semiconductor polishing operations (in particular CMP), it should be recognized that the present polishing pad may find use in many other applications.

[0021] In various embodiments, the present polishing pad consists of polishing elements which can be arranged over the surface of the pad in different configurations. For example the polishing elements may be arranged in a fixed area density configuration or a fixed radial density configuration. These different layouts offer specific advantages in their ability to

deliver uniform material removal profiles, depending on the motion of the pad relative to the wafer. A fixed area density profile may be more advantageous for linear or orbital relative motion, while a fixed radial density profile may be more suitable when relative rotary motion is employed. Of course, other polishing element layouts may also be used.

[0022] The above-cited U.S. patent application Ser. No. 11/697,622 described a polishing pad that includes a number of individual polishing elements. Such a pad **100** is illustrated in cross-section in FIG. 1. Each polishing element **102** is supported by an underlying compressible foam layer **104** and extends vertically through holes in a guide plate **106** affixed to that underlying foam layer. The polishing elements are maintained so that they are approximately normal with respect to a plane defined by the underlying foam layer and are spaced apart from one another so that displacement of one polishing element along its long axis in a direction normal to the plane defined by the underlying foam layer does not materially affect displacement of adjacent ones of the polishing elements.

[0023] The polishing pad described in the '622 application enabled very uniform pressure to be exerted onto a wafer surface during polishing operations. This translates to a very uniform material removal profile in which edge effects typically associated with conventional polishing pads are significantly reduced (or in some cases eliminated altogether). Nevertheless, in some instances it is desirable to tune the polishing profile of the polishing pad in order to effect different material removal profiles. Hence, in embodiments of the present invention, the individual polishing elements may be organized in many different arrangements (e.g., different density profiles that have more or fewer pads per unit area across the face of the pad) and/or may be made from different materials (e.g., having different coefficients of friction for the material being polished) in order to effect such varying material removal profiles.

[0024] In one embodiment, a polishing pad configured to effect non-planar material removal across a wafer during polishing is made up of a number of individual polishing elements, each supported by an underlying compressible foam layer and maintained in vertical orientation with respect to said foam underlayer by a guide plate having holes through which the individual polishing elements protrude. The nominal diameter of an individual polishing element may be approximately 0.25 inches and the nominal height of an individual polishing element may be approximately 0.160 inches. The compressible foam underlayer may be nominally 0.060 inches thick.

[0025] The polishing pad may include polishing elements made of two (or more) different materials, each having a different coefficient of friction for the film or material being polished. The polishing elements may be arranged such that the polishing elements with lower coefficient of friction, such as Delrin™ (polyoxymethylene), alternate in a desired fashion or density with polishing elements having higher coefficients of friction (e.g., polyurethane polishing elements). The ratio of one variety of polishing element to another may be varied to achieve different material removal rate performance.

[0026] The nominal coefficient of friction for polyurethane against an SiO₂ surface is 0.45, whereas the coefficient of friction for Delrin under similar conditions is 0.15. Therefore, the present polishing pad is expected to have a much lower material removal contribution from polishing elements made

of Delrin than for other polishing elements, thus leading to a lower overall material removal rate than for a pad having only non-Delrin polishing elements. During polishing, an area of a wafer in contact with a section of the pad that contains both Delrin and non-Delrin (e.g., polyurethane) polishing elements will have lower rate of material removal than an area of the wafer in contact with only non-Delrin (e.g., polyurethane) polishing elements.

[0027] In addition, embodiments of the present polishing pad may have polishing elements arranged to provide a fixed area density of polishing elements or a fixed radial density of polishing elements (either in total or per polishing element material). These different layouts offer specific advantages in their ability to deliver differing material removal rates profiles, depending on the relative motion of the polishing pad to the wafer. A fixed area density profile may be more advantageous for linear or orbital relative motion, while a fixed radial density profile may be more suitable when relative rotary motion is employed. FIG. 2A shows a polishing pad **200** having an arrangement of polishing elements **202** in which the polishing elements **202** are laid along circumferences of different radii (marked as R1, R2, R3 and R4). FIG. 2B shows a polishing pad **204** in which the polishing elements **202** are laid out in an orthogonal arrangement where the inter-polishing element spacing is defined by a pitch in both X and Y directions. As shown in FIG. 2C, either or both pitches (X, Y) may be varied across a diameter of a wafer **206** to provide two or more pitches (X1, X2; Y1, Y2) in each dimension.

[0028] FIG. 3 shows a polishing pad **300** with a wafer **302** overlaid on the pad (e.g., as may be the case during wafer polishing operations). The pad **300** contains polishing elements **304A**, **304B** laid out in a fixed radial density profile in which polishing elements of two different types are present. That is, polishing elements **304A** are made of a different material than polishing elements **304B**. For example, polishing elements **304A** may be made of polyurethane while polishing elements **304B** may be made of material having a different coefficient of friction with respect to a surface of wafer **302** (or a film on wafer **302**) presently being polished. Note that the polishing elements of different materials may be used with any of the configurations shown in FIGS. 2A-2C.

[0029] In an embodiment of the invention, a determination as to which polishing element material combination and/or layout to use in order to achieve a desired film removal profile may be accomplished. For example, the material removal rate for a given substrate or film will be proportional to the area of the polishing pad in contact with that substrate or film. This will, in turn, be affected by the density of polishing elements per unit area of the pad. The effective polishing element density of a pad may be varied by changing the pitch and/or size of polishing elements in any given area thereof. Therefore, assuming that as the wafer rotates relative to the pad, and the wafer traverses the entire radius of the pad during a polishing operation, then by varying the layout density of polishing elements (hence the effective contact area of the pad) and calculating the time spent by the wafer in areas of different polishing element densities across the entire wafer, a removal profile for the pad/substrate (or pad/film) combination can be predicted.

[0030] Conversely, by knowing the removal profile for a given polishing element material/density layout, a polishing pad can be constructed to achieve a desired layout/material removal profile. Of course, the same processes can be applied to polishing pads using polishing elements of different coef-

ficients of friction (or other polishing element characteristics that affect material removal rates) in lieu of or in addition to varying polishing element densities. Stated differently, the above-described processes can be used to develop custom tailored pads for given substrates or films and selected polishing element materials to provide desired material removal rates.

[0031] In various embodiments of the invention then, the polishing element density of a polishing pad may be varied over areas from 10 mm^2 to 1000 mm^2 , and preferably from 30 mm^2 to 250 mm^2 . Such polishing element densities may be varied radially across the pad surface or orthogonally across the pad surface. The polishing element density range across the pad may be between 20%-80% of the entire pad surface, and preferably between 35-60% of the pad surface. The polishing element density variation may be achieved by varying polishing element pitch and, optionally, the size of the discrete polishing element surfaces which contact the substrate or film to be polished. Alternatively, polishing element density variation may be achieved by varying groove pitch and/or groove size, as in the case of continuous polishing surfaces for continuous layer polishing pads.

[0032] In a further embodiment of the invention, desired material removal rates for a polishing pad may be obtained by varying polishing surface coefficients of friction over an area of the polishing pad. Such area may vary between 10 mm^2 - 1000 mm^2 , and preferably between 30 mm^2 - 250 mm^2 . Coefficients of friction of the polishing surfaces may be varied across the pad in the range of 0.1-0.8, and preferably 0.3-0.6. This variation in the coefficients of friction may be achieved by varying the material of which the subject polishing surface is made. In some cases, the polishing surface may be made up of multiple individual polishing element surfaces, while in other cases a continuous polishing surface may be used.

[0033] A polishing pad configured in accordance with the above practices may therefore contain a plurality of polishing surface materials, each having a different coefficient of friction, and arranged so as to achieve non-planar removal profile. For example, the materials may be arranged to achieve edge fast removal profile, an edge slow removal profile, a center fast removal profile, or a center slow removal profile. In one instance, a polishing pad contains a plurality of polishing surface materials each having different coefficient of friction and the materials of different coefficients of friction are arranged according to different layout densities over the surface of the pad to achieve the non planar removal profile.

[0034] For example, some of the plurality of polishing surface materials (which may be individual polishing element surfaces or areas of a continuous polishing surface) may be made from polyurethane and others of the plurality of polishing surfaces are made of Delrin. Each of the respective polishing surfaces may be arranged in a radial manner across the pad such that Delrin polishing surfaces make up 5-50% density in locations of the total polishing surface of the pad corresponding to areas requiring low material removal rates. The pad may be used in polishing operations such that it contacts a wafer or other substrate (or a film thereon), optionally in the presence of slurry, such that the wafer areas requiring low material removal rates are in contact with pad areas containing Delrin polishing surfaces in the desired density. In some instances, the overall density of polishing surfaces may be uniform per unit area of the polishing pad. Alternatively, or in addition, the polishing surfaces may be laid out in a uniform radial arrangement. Optionally, both the Delrin and

polyurethane polishing surfaces may have a common shape and size, but in other cases the respective polishing surfaces may have different sizes and shapes.

[0035] A polishing pad polishing surface layout designed to achieve a desired material removal profile may be achieved by (a) determining a removal profile of a known polishing pad polishing surface layout, (b) applying polishing surface coefficient of friction variations and/or density variations corresponding to regions of the pad where changes in material removal rates are desired, (c) determining what fraction of the total polishing time is spent by an area of the wafer of interest in the region of modified polishing surface coefficients of friction/densities of the pad, (d) determining, based on these fractional times, corresponding variations in material removal rates at a pad-wafer locations of interest, and (e) determining the new pad layout to achieve the desired material removal profile by mapping new polishing surface coefficients of friction and density profiles to the subject polishing pad layout.

[0036] Thus, a polishing pad suitable for use in CMP and other applications, which pad is configured to provide a tunable, material removal profile across a workpiece has been described. In the above description, a number of specifically illustrated embodiments were discussed in order to better explain the present invention, however, these examples should not be read to limit the scope of the invention. Instead, the invention should be measured only in terms of the following claims.

What is claimed is:

1. A polishing pad, comprising a plurality of polishing surfaces, a first group of the polishing surfaces made of a first material having a first coefficient of friction and a second group of the polishing surfaces made of a second material having a second coefficient of friction, the first and second groups of polishing surfaces arranged over the polishing pad so as to provide a non-planar material removal profile.

2. The polishing pad of claim 1, wherein the first and second groups of polishing surfaces are arranged to provide an edge fast material removal profile.

3. The polishing pad of claim 1, wherein the first and second groups of polishing surfaces are arranged to provide an edge slow removal profile.

4. The polishing pad of claim 1, wherein the first and second groups of polishing surfaces are arranged to provide a center fast removal profile.

5. The polishing pad of claim 1 wherein the first and second groups of polishing surfaces are arranged to provide a center slow removal profile.

6. The polishing pad of claim 1, wherein the polishing surfaces comprise individual polishing elements, each polishing element supported by an underlying compressible foam layer and oriented with a long axis normal to a plane defined by the underlying compressible foam layer.

7. The polishing pad of claim 6, wherein the polishing elements are spaced apart from one another so that displacement of one polishing element along its long axis in a direction normal to the plane defined by the underlying foam layer does not materially affect displacement of adjacent ones of the polishing elements.

8. The polishing pad of claim 1, wherein the polishing elements of the first group are made of polyurethane and the polishing elements of the second groups are made of polyoxymethylene.

9. The polishing pad of claim 1, wherein the first and second groups of polishing surfaces are arranged in different densities over the polishing pad.

10. The polishing pad of claim 9, wherein the different densities vary by radial distance of the polishing surfaces from a center of the polishing pad.

11. The polishing pad of claim 9, wherein the different densities vary orthogonally across the polishing pad.

12. The polishing pad of claim 9, wherein polishing surface density variations are implemented by varying groove pitch over the polishing pad.

13. The polishing pad of claim 9, wherein polishing surface density variations are implemented by varying groove size over the polishing pad.

14. The polishing pad of claim 1, wherein overall densities of polishing surfaces per unit area of the polishing pad is uniform for the polishing pad.

15. The polishing pad of claim 1, wherein the first and second groups of polishing surfaces are laid out in uniform radial arrangement over the entire polishing pad.

16. The polishing pad of claim 1, wherein each polishing surface of the first and second groups has a common size.

17. The polishing pad of claim 1, wherein each polishing surface of the first and second groups has a common shape.

18. The polishing pad of claim 1, wherein the polishing surfaces comprise individual polishing elements laid out in an orthogonal arrangement where inter-polishing element spacing is defined by a pitch in each of two dimensions.

19. The polishing pad of claim 18, wherein the inter-polishing element pitch in at least one of the two dimensions varies across the polishing pad.

20. The polishing pad of claim 18, wherein the inter-polishing element pitch in both of the two dimensions varies across the polishing pad.

21. The polishing pad of claim 1, wherein the polishing surfaces comprise individual polishing elements laid out in a radial pattern such that polishing elements at different radial distances from a center of the polishing pad have different inter-polishing element spacing.

22. A method, comprising polishing a workpiece using a polishing pad defined by any one of the preceding claims.

23. A method, comprising designing a layout of polishing surfaces for a polishing pad to achieve a desired material removal profile for the polishing pad by (a) determining a first material removal profile of a first polishing pad having a known polishing surface layout, (b) applying polishing surface coefficient of friction variations and/or polishing surface density variations corresponding to regions of the first polishing pad where changes in the first material removal profile are desired, (c) determining what fraction of a total polishing time is spent by an area of a wafer of interest in the regions of the first pad, (d) determining, based on these fractional times, corresponding variations in the first material removal profile at pad-wafer locations of interest, and (e) determining the new pad layout to achieve the desired material removal profile by mapping new polishing surface coefficients of friction and density profiles to the subject polishing pad layout.

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