# METHOD AND APPARATUS FOR IMPROVED CHEMICAL MECHANICAL PLANARIZATION

## RELATED APPLICATIONS

[0001] This application is a non-provisional of, related to, and claims the priority benefit of U.S. Provisional Application 60/616,944, filed October 6, 2004, and U.S. Provisional Application 60/639,257, filed December 27, 2004, each of which are 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 structural and material properties of a CMP polishing pad utilized in CMP processing.

## BACKGROUND OF THE INVENTION

[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 these layers and polish the surface of a wafer flat to achieve the desired structure. CMP may be performed on both oxides and metals and generally involves the use of chemical slurries applied via a polishing pad that is moved relative to the wafer (e.g., the pad may rotate circularly relative to the wafer). The resulting smooth, flat surface is necessary to maintain the photolithographic depth of focus for subsequent steps and to ensure that the metal interconnects are not deformed over contour steps. Damascene processing requires CMP to remove metals, such as tungsten or copper, from the top surface of a dielectric to define interconnect structures.

[0004] The planarization/polishing performance of a pad/slurry combination is impacted by the mechanical properties of the polishing pad and the chemical properties and distribution of the slurry. Often a polishing pad may be porous and/or include grooves to distribute slurry. However, this reduces the overall strength of the polishing pad, making it more flexible and thus reducing its planarization characteristic. For example, **Figure 1A** illustrates "dishing" as a result of applying a flexible polishing pad to wafer 100. The flexible polishing pad provides for a smooth surface but creates dishing 106 by over polishing softer elements, such as copper layer 104, on the surface of substrate 102. The consequence of dishing is an undesirable loss of metal thickness, leading to poor device performance.

**[0005]** Dishing can be reduced or eliminated through the use of a stiffer polishing pad, which can provide greater planarization. Pads may be made stiffer by reducing the number of pores and/or grooves in the pad, however, this can lead to different consequences, for example poor slurry distribution. The net effect may be to increase the number of surface defects 108 on the substrate 102 and/or copper layer 104 (e.g., by scratching and/or pitting the surface/layer), as shown for example in **Figure 1B** which illustrates surface defects 108 that may result from application of a relatively stiff polishing pad to wafer 100.

**[0006]** Whether flexible or inflexible, polishing pads are typically made of urethanes, either in cast form and filled with micro-porous elements or from non-woven felt coated with polyurethanes. During polishing, the pad surface undergoes deformation due to polishing forces. The pad surface therefore has to be "regenerated" through a conditioning process. The conditioning process involves pressing a fine, diamond covered disc against the pad surface while the pad is rotated much like during the polishing processes. The diamonds of the conditioning disc cut through and remove the top layer of the polishing pad, thereby exposing a fresh polishing pad surface underneath.

**[0007]** These concepts are illustrated graphically in **Figures 2A - 2C**. In particular, Figure 2A illustrates a side cutaway view of a conventional new polishing pad 110. Polishing pad 110 contains microelements 114, and grooves 116, much like those found in commercially available polishing pads such as the IC1000 of Rhom & Haas, Inc. Figure 2B shows the surface 112 of polishing pad 110 after polishing. The top surface of the pad shows degradation 118, especially around the microelements 114 where the edges are degraded due to plastic or viscous flow of the bulk urethane material. Figure 2C shows the surface 112 of the polishing pad after a conditioning process has been completed. Note the depth of grooves 116 is lower than was the case for the new pad illustrated in Figure 2A due to material removal during conditioning.

**[0008]** Over multiple cycles of polishing and conditioning, it is usually the case that the overall thickness of a pad wears up to a point such that the pad needs to be replaced. It is evident to those practicing in the art that pad wear rates differ from pad to pad and may also differ from one batch of pads to another batch. Currently no quantitative method exists to determine pad wear, hence end of pad life. Instead, the end of pad life is typically based on visual inspection of the pad surface to check for remaining groove depth. In the case of an un-grooved pad, end of pad life decisions are typically based on the number of wafers polished or the time elapsed since the pad was first put in service. Because such metrics are not particularly accurate it is desirable that a consistent, quantitative means to determine "end of pad life" be implemented. That is, a method

based on finite wear of the pad surface would be useful in establishing a consistent basis for pad changes.

## SUMMARY OF THE INVENTION

**[0009]** A polishing pad configured in accordance with an embodiment of the present invention includes a guide plate having affixed thereto a porous slurry distribution layer on one side and a compressible under-layer on the other side. A plurality of polishing elements interdigitated with one another through the slurry distribution layer and the guide plate, so as to be maintained in planar orientation with respect to one other and the guide plate, are affixed to the compressible under-layer with each polishing element protruding above the surface of the guide plate to which the slurry distribution layer is adjacent. Optionally, a membrane positioned between the guide plate and the slurry distribution layer may be included. Such a membrane may be conductive or non-conductive membrane and may be fastened to the guide plate by an adhesive. In some cases, the membrane may be an ion exchange membrane.

**[0010]** The guide plate of the polishing pad may be made of a non-conducting material and may include holes in which individual polishing elements are accommodated. Some of the polishing elements may have circular cross sections, while others may have triangular cross sections or any other shape. In any event, the polishing elements may be made from any one or combination of: a thermally conducting material, an electrically conducting material, or a non-conducting material. For example, the polishing elements may be made of a conductive polymer polyaniline, carbon, graphite, or metal-filled polymer. One or more of the polishing elements may be fashioned so as to make sliding contact with a wafer surface, while others may be fashioned so as to make rolling contact with a wafer surface (e.g., with a rolling tip made of a polymeric, metal oxide, or electrically conducting material).

**[0011]** The slurry distribution material may include a number of slurry flow resistant elements (e.g., pores) and be between 10 and 90 percent porosity. Preferably, though not necessarily, the slurry distribution material is fastened to the guide plate by an adhesive. In some cases the slurry distribution material may include multiple layers of different materials. For example, the slurry distribution material may include a surface layer having relatively large pores and a lower layer having relatively small pores. It is conceivable that the slurry distribution element and guide plate functions can be performed by a single material. Such a material may be a guide plate having a open pore foam surface or grooves or baffles to modulate the slurry flow across the surface.

[0012] The polishing pad may also include wear sensors configured to provide indications of pad wear and/or end-of-life.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0013] **Figure 1A** illustrates an example of dishing caused by the use of a relatively flexible conventional polishing pad during CMP operations.

[0014] **Figure 1B** illustrates examples of scratching or pitting of a wafer/layer resulting from the use of a relatively stiff polishing pad during CMP operations.

[0015] **Figures 2A - 2C** illustrates concepts of pad wear experienced by conventional polishing pads.

[0016] **Figure 3A** is a cut-away side view of a circular polishing pad configured in accordance with one embodiment of the present invention for use in CMP operations.

[0017] **Figure 3B** illustrates a polishing pad similar to that shown in Figure 2A, but which includes a compressible under layer in accordance with a further embodiment of the present invention.

[0018] **Figure 4** is a top view of a polishing pad having interdigitated polishing elements through which slurry may flow in accordance with still another embodiment of the present invention.

[0019] **Figure 5A** is a cut-away side profile view of an optical sensor 302 embedded in a pad 304

[0020] **Figures 5B – 5E** show various optical sensor designs which may be used in conjunction with polishing pads configured in accordance with embodiments of the present invention.

[0021] **Figure 6A** illustrates an electrochemical sensor positioned below a surface of a new pad in accordance with an embodiment of the present invention.

[0022] **Figure 6B** shows the electrochemical sensor of Figure 6A exposed as a result of pad wear.

[0023] **Figure 7A** shows an example of a conductive plate embedded below the surface of a polishing pad in accordance with still a further embodiment of the present invention.

[0024] **Figure 7B** shows an arrangement with an eddy current sensor held at the top surface of the pad shown in Figure 7A to assist in determining pad wear in accordance with an embodiment of the present invention.

## DETAILED DESCRIPTION

[0025] Described herein is an improved CMP polishing pad and process for polishing semiconductor wafers and structures layered thereon, including metal damascene structures on such wafers. The present invention recognizes the impact of the physical characteristics of a polishing pad in the quality of CMP processing. Specifically, it is known that a more flexible polishing pad produces dishing while a harder pad with reduced slurry distribution produces more surface defects. Although various polishing pad configurations (e.g., with specific examples of geometric ranges, ratios, and materials) and polishing processes are exemplified herein, it should be appreciated that the present invention can be equally applied to encompass other types of polishing pad fabrication materials and deposition removal techniques. Stated differently, the use of such other materials and techniques are deemed to be within the scope of the present invention as recited in the claims following this description.

[0026] In addition to various polishing pad configurations, the present invention includes polishing processes which involve pressing a wafer against the surface of an engineered, multi-stack, polymeric pad in combination with a polishing fluid that may contain sub-micron particles and moving the wafer relative to the polishing pad under pressure so that the moving, pressurized contact results in planar removal of the surface of said wafer. A polishing pad configured in accordance with an embodiment of the invention includes various elements: a polishing fluid distribution layer, polishing contacts or elements, a guide plate, and an optional elastic, resilient (i.e., compressible) under-layer. In some cases, the various pad elements are polymeric and the polishing elements may be made of an electrically conductive material such as a conductive polymer polyaniline commercially known as Pani™ (available under trade name ORMECOM™), carbon, graphite or metal filled polymer. In other embodiments, the polishing elements may be made of a thermally conductive material, such as carbon, graphite or metal filled polymer. The slurry distribution material may be an open cell foam and the compressible under-layer a closed cell foam. The slurry distribution function may also be accomplished by providing grooves on the guide plate or creating baffles such that slurry flow is modulated.

[0027] When the pad is in use (i.e., when it is moving relative to a wafer surface), the polishing elements may make sliding contact or rolling contact with the wafer's surface. In this latter case, one or more polishing elements may have a cylindrical body and a rolling tip. The rolling tip may be made of varying materials, such as polymeric, metal oxide or an electrically conducting material. A rolling tip polishing element may be incorporated into the pad material the same way as a sliding contact polishing element.

[0028] The polishing pad described herein may be used in a variety of processing steps associated with CMP processing. This includes utilization in a multi-step processes, wherein multiple polishing pads and slurries of varying characteristics are used in succession, to one step processes, where one polishing pad and one or more slurries are used throughout the entire polishing phase.

[0029] In some embodiments of the present invention, the polishing pad may be configured with the capability to quantitatively determine wear of the pad's polishing surface or simply "end of pad life". For example, an "end of pad life" sensor, or more generally a "detection sensor" may be embedded in the pad at a predetermined depth from the top surface (i.e., as measured from the tip of the polishing elements). As the pad wears up to the preset thickness at which the sensor is placed or activated, the sensor detects the wear and provides input to the polishing system.

[0030] The end of life sensor may consist of an optically transparent cylindrical plug having a top surface covered with reflective coating. The plug may be embedded in the pad such that the reflective end of the plug is positioned below the top surface of the pad by a predetermined height. A light source and detector are placed in the platen of the polishing apparatus through an optically transparent window. When the light bean is incident on the plug of a new pad, the reflective surface reflects back the light indicating the pad is still within its useful life. However, when the pad has worn to a predetermined level and the top of the plug is approximately level with the now exposed pad surface, the reflective surface will be abraded away and the light will be transmitted through the pad. The resulting change in the reflected light signal intensity thus provides feedback illustrative of the pad wear. This change can be used to determine "end of pad life" (e.g., end of life may be indicated by the reflected signal intensity being at or below a previously established threshold).

[0031] The detection hardware may lie below the pad (and platen) or above the pad and that the optical insert can be appropriately modified to detect and interpret the reflected light signal. One or multiple such plugs may be used to determine percentage of remaining pad life. For example,

different plugs may be embedded to different depths, corresponding to 25%, 50%, 75% and 100% (or other increments) of pad life. In this way pad wear information can be provided.

**[0032]** In another embodiment of the present invention a single conical plug may mounted flush with the pad surface such that the size of the plug opening exposed during pad usage provides information on the percentage of pad wear and, hence, pad life. In yet another embodiment the plug may have a multi-step surface, which is exposed to varying degrees as the pad wears. The height of the steps may be calibrated to provide information in terms of percentage of pad wear.

**[0033]** In still a further embodiment of the present invention, the pad life sensor plug may contain screens with varying degrees of transmission arranged in order of reflectivity. For example, the top layer may have 100% reflectivity (e.g., full reflectivity for that plug) and be flush (or nearly so) with the new pad surface. At 25% of plug depth, a screen with, say, 75% reflectivity may be embedded, and similarly at 50% of plug depth, a 50% reflectivity screen so embedded and at 75% of plug depth a 25% reflectivity screen so embedded. Of course these relative depths and reflectivity percentages may be varied to achieve similar functionality according to the designer's particular needs.

**[0034]** Initially with such a plug/screen arrangement, the incident beam will be completely reflected and pad life determined to be 100% (i.e., a new pad). As the pad wears, the top reflecting layer is removed and the 75% (and lower) reflectivity screens are engaged. As each such screen is exposed (and subsequently removed by further wear), the remaining pad life can be determined according to the intensity of the reflected signal. A single element can therefore be used to detect and monitor pad life.

**[0035]** In varying embodiments of the present invention, the sensor may be an electrochemical sensor containing two or more probes embedded in the pad at a predetermined depth or depths from the top surface of the pad when new. As the pad wears, exposing the probes, slurry provides electrical connectivity between the probes, and resulting electrical signal paths formed thereby can be used to transmit or transport signals to a detector so as to detect pad wear and, eventually, end of pad life.

**[0036]** In still other embodiments, the sensor may be a conductive plate embedded at a predetermined depth below the surface of a pad when new. An external capacitive or eddy current sensor may be used to detect distance from the conductive plate, hence pad thickness or pad wear. This and other embodiments of the present invention are discussed further below.

**[0037]** Referring now to **Figure 3A**, a cut-away side profile view of a circular polishing pad 200 used in CMP processing and configured according to one embodiment of the present invention is shown. In use, the polishing pad 200 rotates relative to the wafer surface being polished, the surface of the polishing pad making contact with the wafer (typically under pressure) at wafer contact surface 202. A slurry distribution material 204 provides flow control in the slurry pathways between polishing elements 206.

**[0038]** The foundation of polishing pad is the guide plate 208, which provides lateral support for the polishing elements 206 and may be made of a non-conducting material, such as a polymeric or polycarbonate material. In one embodiment of the present invention, the guide plate 208 includes holes fabricated into or drilled out of the guide plate 208 to accommodate each of the polishing elements 206. The polishing elements 206 may be fixed to a surface other than the guide plate 208 (through which the polishing elements pass); held in place by an adhesive, such as double sided tape or epoxy. For example, the polishing elements 206 may be affixed to a flexible under-layer (discussed below) or a housing (also discussed below), but are free to move in a vertical direction with respect to their long axis, through the holes in guide plate 208. The polishing elements may be constructed such that they have a base diameter larger than the diameter of the guide plate holes thru which they pass. For example, the body of the polishing elements may have a diameter "a" and the guide plate holes a diameter "b", such that "b" is slightly larger than "a", but nevertheless smaller than diameter "c", which is the diameter of the base of the polishing element. . In essence then polishing elements will resemble a cylinder on top of a flat plate. In varying embodiments, the depth and spacing of the holes throughout the guide plate 208 may be varied according to an optimized scheme tailored to specific CMP processes. The polishing elements are each maintained in planar orientation with respect to one other and the guide plate.

**[0039]** The polishing elements 206 may protrude above surface of the guide plate 208, as illustrated in **Figure 3A**. This provides a volume between the interdigitated polishing elements 206 and the guide plate 208 for slurry distribution. The polishing elements may be of varying geometric shapes (e.g., circular and/or triangular cross sections) and made from any one or combination of thermally or electrically conducting and non-conducting materials. For example, the polishing elements 206 may be made of an electrically or thermally conductive material, such as conductive polymer, polyaniline commercially known as Pani ™ (trade name ORMECOM™), carbon, graphite or metal filled polymer. The polishing elements 206 may be conventional polishing elements that make sliding contact with the wafer or some or each element may include a rolling contact. For example, some or each polishing element 206 may

have a cylindrical body and a rolling tip, similar to a ballpoint pen tip. The rolling tip may be a polymeric, metal oxide or electrically conducting material.

**[0040]** In various embodiments, the polishing elements 206 may also protrude above the slurry distribution material 204 by 2.5 millimeters or less. It will be appreciated, however, that this value may be greater than 2.5 millimeters depending on the material characteristics of the polishing elements 206 and the desired flow of slurry over the surface.

**[0041]** In one embodiment of the present invention, the volume between the interdigitated polishing elements 206 may be at least partially filled with the slurry distribution material 204. The slurry distribution material 204 may include flow resistant elements such as baffles or grooves (not shown), or pores, to regulate slurry flow rate during CMP processing. In varying embodiments, the porous slurry distribution material 204 has between 10 and 90 percent porosity and may be overlaid on guide plate 208. The slurry distribution material 204 may be fastened to the guide plate 208 by an adhesive, such as double sided tape. Additionally, the slurry distribution material 204 may be comprised of various layers of differing materials to achieve desired slurry flow rates at varying depths (from the polishing surface) of the slurry distribution material 204. For example, a surface layer at the polishing surface may have larger pores to increase the amount and rate of slurry flow on the surface while a lower layer has smaller pores to keep more slurry near the surface layer to help regulate slurry flow.

**[0042]** The polishing pad 200 may also include a membrane 210, located on the surface of the guide plate 208 and forming a barrier between the guide plate 208 and the slurry distribution material 204 and between each portion of the polishing elements 206 extending into the guide plate 208 and the interdigitated volume. In other cases, the membrane may be located below the guide plate 208. Membrane 210 may be a conductive or non-conductive membrane and fastened to the guide plate 208 by an adhesive, such as two-sided tape or epoxy. For example, the membrane 210 may be an ion exchange membrane that allows charge to pass but not liquid.

**[0043]** Polishing pad 200 may also include a housing 212, configured such that the guide plate 208, membrane 210, polishing elements 206, and slurry distribution material 204 are at least partially peripherally contained within the housing 212. The housing 212 may provide additional stability to the polishing pad 200 in addition to providing the interface to means for rotating or otherwise manipulating the pad 200 during polishing operations. The housing 212 may be made of any rigid material, such as a polymer, metal, etc., and fastened to the guide plate 208 by an adhesive, such as double sided tape or epoxy.

**[0044]** The thickness 214 (T) of the polishing pad 200 affects the rigidity and physical characteristics of the polish pad during use. In one embodiment, the thickness may be 25 millimeters, however, this value may vary from 3 to 10 millimeters according to the materials used in constructing the polishing pad 200 and the type of CMP process to be performed.

**[0045]** Turning now to **Figure 3B** a polishing pad 200A is shown. Pad 200A is similar in construction to pad 200 described with reference to Figure 2A, but includes a compressible under-layer 216. The compressible under-layer 216 provides, among others features, a positive pressure directed toward the polishing surface when compressed. Typically, the compression may be approximately 10% at 5 psi (pounds per square inch), however, it will be appreciated that the compression may be varied dependent upon the materials used in constructing the polishing pad 200 and the type of CMP process. The compressible under-layer 216 may be formed of BONDTEX™ foam made by RBX Industries, Inc. In varying embodiments, the compressible under layer 216 may be contained within the housing 212, external to housing 212, or used in place of housing 212.

**[0046]** **Figure 4** illustrates a top down view of a polishing pad 300, configured according to one embodiment of the present invention. Polishing elements 206 are interdigitated throughout polishing pad 300. The slurry distribution material 204 is permeated throughout the volume created by polishing elements 206 protruding from the guide plate (not shown) and enclosed by the housing 212. While the volume provides a slurry path 302, the slurry distribution material 204 provides a mechanism to control slurry flow throughout the volume as discussed above with reference to **Figure 3A.**

**[0047]** The distribution of the polishing elements 206 may vary according to specific CMP processes and slurry distribution characteristics. In varying embodiments, the polishing elements 206 may have a density of between 30 and 80 percent of the total polishing pad surface area, as determined by the diameter 304 (D) of each polishing elements 206 and the diameter of the polishing pad 300. In one embodiment, the diameter 304 is at least 50 micrometers. In other embodiments, the diameter may vary between 50 micrometers and 30 millimeters Typical diameters of the polishing elements are 3 – 10mm.

**[0048]** As indicated above, some polishing pads configured in accordance with embodiments of the present invention incorporate sensors to determine fractional or complete end of pad life (e.g., pad wear leading to end of life). Optical-, electrochemical- or current-based sensors can be used to determine such wear/end of life. The sensors are incorporated into the pad, at one or more

predetermined depths below the top surface thereof. The sensors, when exposed by pad wear, enable transmission of optical signals or, in case of electrochemical sensors, electrical conductivity to close circuits, thus enabling the transmission of such signals from the sensors to one or more detectors. In case of eddy current or capacitive sensors, a conductive plate may be embedded below the top surface of the pad and the detector is placed above or below the pad. The thickness of pad between the plate and the sensor thus affects the signal strength as perceived by the detector and is used to determine fractional or complete end of pad life.

**[0049]** **Figure 5A** is a cut-away side profile view of an optical sensor 302 embedded in a pad 304. The top surface of the optical sensor 306 is reflective to enable incident beam 308 to be reflected 310 back, while it is below the top surface. Such sensors are useful for some embodiments of the present invention in which the polishing pad is configured with the capability to quantitatively determine wear of the pad's polishing surface or simply "end of pad life". For example, optical sensor 302 may act as an "end of pad life" sensor, or more generally a "detection sensor" embedded in the pad 304 at a predetermined depth from the top surface (i.e., as measured from the tip of the polishing elements) thereof. As the pad wears up to the preset thickness at which the sensor is placed or activated, the sensor detects the wear and provides input to the polishing system.

**[0050]** The sensor 302 is an optically transparent cylindrical plug having a top surface covered with reflective coating. The plug may be embedded in the pad 304 such that the reflective end of the plug is positioned below the top surface of the pad by a predetermined height. A light source and detector are placed in the platen of the polishing apparatus through an optically transparent window. When the light beam is incident on the plug of a new pad, the reflective surface reflects back the light indicating the pad is still within its useful life. However, when the pad has worn to a predetermined level and the top of the plug is approximately level with the now exposed pad surface, the reflective surface will be abraded away and the light will be transmitted through the pad. The resulting change in the reflected light signal intensity thus provides feedback illustrative of the pad wear. This change can be used to determine "end of pad life" (e.g., end of life may be indicated by the reflected signal intensity being at or below a previously established threshold).

**[0051]** It should be apparent that the detection hardware may lie below the pad (and platen) or above the pad and that the optical insert can be appropriately modified to detect and interpret the reflected light signal. One or multiple such plugs may be used to determine percentage of remaining pad life. For example, different plugs may be embedded to different depths,

corresponding to 25%, 50%, 75% and 100% (or other increments) of pad life. In this way pad wear information can be provided.

**[0052]** In another embodiment of the present invention a single conical plug may mounted flush with the pad surface such that the size of the plug opening exposed during pad usage provides information on the percentage of pad wear and, hence, pad life. In yet another embodiment the plug may have a multi-step surface, which is exposed to varying degrees as the pad wears. The height of the steps may be calibrated to provide information in terms of percentage of pad wear.

**[0053]** In still a further embodiment of the present invention, the pad life sensor plug may contain screens with varying degrees of transmission arranged in order of reflectivity. For example, the top layer may have 100% reflectivity (e.g., full reflectivity for that plug) and be flush (or nearly so) with the new pad surface. At 25% of plug depth, a screen with, say, 75% reflectivity may be embedded, and similarly at 50% of plug depth, a 50% reflectivity screen so embedded and at 75% of plug depth a 25% reflectivity screen so embedded. Of course these relative depths and reflectivity percentages may be varied to achieve similar functionality according to the designer's particular needs.

**[0054]** **Figures 5B – 5E** show examples of the various optical sensor designs discussed above, which may be used in conjunction with a polishing pad 304 in accordance with embodiments of the present invention. Of course other configurations of optical sensors may also be used. In particular, Figure 5B shows a multi-step optical sensor 312 with reflective surfaces 306', Figure 5C shows a single sensor 314 with multiple reflective surfaces 306", Figure 5D shows another means for incorporating reflecting surfaces into a single sensor. In this case the reflecting surfaces 306''' comprise sides of a triangular cross-section sensor 316. Figure 5E shows a variable area optical sensor 318 whereby the cross-section area ratio of reflective surfaces 316, indicates the fractional pad life remaining. It should be apparent to those of ordinary skill in the art that sensors 312, 314, 316 and 318 can be incorporated in a polishing pad, flush with a top surface of the pad. Changes in reflected light signal intensity provide information on pad wear to determine end of pad life.

**[0055]** In further embodiments of the present invention, the end-of-life sensor may be an electrochemical sensor containing two or more probes embedded in the pad at a predetermined depth or depths from the top surface of the pad when new. An example of such a configuration is shown in **Figure 6A**, which illustrates an electrochemical sensor 402 positioned below a surface of a new pad 404. As the pad wears, exposing the probes, slurry provides electrical

connectivity between the probes, and resulting electrical signal paths formed thereby can be used to transmit or transport signals to a detector so as to detect pad wear and, eventually, end of pad life. **Figure 6B** shows the electrochemical sensor exposed due to pad wear and probes 406 are connected by the presence of slurry element 408. The continuity in the circuit indicates a certain pad wear has occurred.

**[0056]** In still other embodiments of the present invention, the end-of-life sensor may be a conductive plate embedded at a predetermined depth below the surface of a pad when new. An external capacitive or eddy current sensor may be used to detect distance from the conductive plate, hence pad thickness or pad wear. **Figure 7A** shows an example of this configuration with conductive plate 502 embedded below the pad surface 504. A capacitive sensor plate 506 is held at the top surface of the pad to determine separation, which is indicative of pad wear. **Figure 7B** shows this arrangement with eddy current sensor 508 held at the top surface of the pad to determine separation.

**[0057]** Thus, an improved CMP polishing pad and process for polishing semiconductor wafers and structures layered thereon, including metal damascene structures on such wafers, has been described. Although the present polishing pad and processes for using it have been discussed with reference to certain illustrated examples, it should be remembered that the scope of the present invention should not be limited by such examples. Instead, the true scope of the invention should be measured on in terms of the claims, which follow.

## CLAIMS

What is claimed is:

1. A polishing pad, comprising:

a guide plate having affixed thereto a porous slurry distribution layer on one side and a compressible under-layer on opposite side; and

a plurality of polishing elements interdigitated with one another through the slurry distribution layer and the guide plate so as to be maintained in planar orientation with respect to one other and the guide plate, each polishing element being affixed to the compressible under-layer and protruding above a surface of the guide plate to which the slurry distribution layer is adjacent.

2. The polishing pad of claim 1, further comprising a membrane positioned between the guide plate and the slurry distribution layer.

3. The polishing pad of claim 2, wherein the membrane comprises a conductive membrane.

4. The polishing pad of claim 2, wherein the membrane comprises a non-conductive membrane.

5. The polishing pad of claim 2, wherein the membrane is fastened to the guide plate by an adhesive.

6. The polishing pad of claim 2, wherein the membrane comprises an ion exchange membrane.

7. The polishing pad of claim 1, wherein the guide plate is made of a non-conducting material.

8. The polishing pad of claim 1, wherein at least some of the polishing elements have circular cross sections.

9. The polishing pad of claim 1, wherein at least some of the polishing elements have triangular cross sections.

10. The polishing pad of claim 1, wherein the polishing elements are made from any one or combination of: a thermally conducting material, an electrically conducting material, or a non-conducting material.

11. The polishing pad of claim 10, wherein the polishing elements are made of one of: a conductive polymer polyaniline, carbon, graphite, or metal-filled polymer.

12. The polishing pad of claim 1, wherein one or more of the polishing elements are fashioned so as to make sliding contact with a wafer surface.

13. The polishing pad of claim 1, wherein one or more of the polishing elements are fashioned so as to make rolling contact with a wafer surface.

14. The polishing pad of claim 13, wherein the one or more of the polishing elements fashioned so as to make rolling contact with a wafer surface has a cylindrical body and a rolling tip.

15. The polishing pad of claim 14, wherein the rolling tips of the one or more of the polishing elements are made of one of the following materials: a polymeric, metal oxide, or electrically conducting material.

16. The polishing pad of claim 1, wherein the slurry distribution material includes a number of slurry flow resistant elements.

17. The polishing pad of claim 16, wherein the slurry distribution material has between 10 and 90 percent porosity.

18. The polishing pad of claim 1, wherein the slurry distribution material is fastened to the guide plate by an adhesive.

19. The polishing pad of claim 1, wherein the slurry distribution material includes multiple layers of different materials.

20. The polishing pad of claim 19, wherein the slurry distribution material comprises a surface layer having relatively large pores and a lower layer having relatively small pores.

21. The polishing pad of claim 1, further comprising a housing configured to at least partially peripherally contain the guide plate, the polishing elements, and the slurry distribution material therein.

22. The polishing pad of claim 1, wherein the polishing pad has a thickness of between 3 and 10 millimeters.

23. The polishing pad of claim 1, wherein the compressible under-layer is formed of a foam or resilient polymer configured to provide a positive pressure directed toward a polishing surface of the polishing pad when compressed.

24. The polishing pad of claim 1, wherein the polishing elements are distributed across a face of the polishing pad such that collectively the polishing elements have a density of between 30 to 80 percent of a total polishing pad surface area.

25. The polishing pad of claim 1, further comprising a pad wear sensor embedded at a depth from a top surface of the pad as measured from a working end of one or more of the polishing elements.

26. The polishing pad of claim 25, wherein the pad wear sensor comprises an optically transparent plug having a top surface covered with reflective coating.

27. The polishing pad of claim 25, wherein the pad wear sensor comprises a number of optically transparent plugs embedded to different depths within the pad.

28. The polishing pad of claim 25, wherein the pad wear sensor comprises an optically transparent conical plug mounted flush with the top surface of the pad surface.

29. The polishing pad of claim 25, wherein the pad wear sensor comprises an optically transparent plug having a multi-step surface configured to be exposed to varying degrees as the pad wears.

30. The polishing pad of claim 25, wherein the pad wear sensor comprises an optically transparent plug containing screens with varying degrees of transmission arranged in order of reflectivity.

31. The polishing pad of claim 25, wherein the pad wear sensor comprises an electrochemical sensor containing two or more probes embedded in the pad.

32. The polishing pad of claim 25, wherein the pad wear sensor comprises a conductive plate embedded at a depth below the surface of the pad.