

HYBRID CMP CONDITIONING HEAD

CROSS-REFERENCE TO RELATED APPLICATION

[001] This application claims the benefit of priority to U.S. Provisional Patent Application 62/937,921 filed on November 20, 2019 and entitled “Hybrid CMP Conditioning Head”, which is incorporated by reference herein for all purposes.

TECHNICAL FIELD

[002] The present invention relates generally to a conditioning head comprising a substrate with protrusions extending from the substrate.

BACKGROUND

[003] The products of the present invention have utility in a wide variety of applications, including heads or disks for the conditioning of polishing pads, including pads used in Chemical-Mechanical-Planarization (CMP). CMP is an important process in the fabrication of integrated circuits, disk drive heads, nano-fabricated components, and the like. For example, in patterning semiconductor wafers, advanced small dimension patterning techniques require an absolutely flat surface. After the wafer has been sawed from a crystal ingot, and irregularities and saw damage has been removed by rough polishing, CMP is used as a final polishing step to remove high points on the wafer surface and provide an absolutely flat surface. During the CMP process, the wafer will be mounted in a rotating holder or chuck, and lowered onto a pad surface rotating in the same direction. When a slurry abrasive process is used, the pad is generally a cast and sliced polyurethane material, or a urethane-coated felt. A slurry of abrasive particles suspended in a mild etchant is placed on the polishing pad. The process removes material from high points, both by mechanical abrasion and by chemical conversion of material to, e.g., an oxide, which is then removed by mechanical abrasion. The result is an extremely flat surface.

[004] In addition, CMP can be used later in the processing of semiconductor wafers, when deposition of additional layers has resulted in an uneven surface. CMP is desirable in that it provides global planarization across the entire wafer, is applicable to all materials on the wafer surface, can be used with multi-material surfaces, and avoids use of hazardous gases. As an example, CMP can be used to remove metal overfill in damascene inlay processes.

[005] CMP represents a major portion of the production cost for semiconductor wafers. These CMP costs include those associated with polishing pads, polishing slurries, pad conditioning disks and a variety of CMP parts that become worn during the planarizing and polishing operations. The total cost for the polishing pad, the downtime to replace the pad and the cost of the test wafers to recalibrate the pad for a single wafer polishing run can be quite high. In many complex integrated circuit devices, up to thirty or more CMP runs are required for each finished wafer, which further increases the total manufacturing costs for such wafers.

[006] With polishing pads designed for use with abrasive slurries, the greatest amount of wear on the polishing pads is the result of polishing pad conditioning that is necessary to place the pad into a suitable condition for these wafer planarization and polishing operations. A typical polishing pad comprises closed-cell polyurethane foam approximately 1/16 inch thick.

[007] Pad conditioning determines the asperity structure (peaks and valleys) of the pad and acts to maintain the surface stability. During pad conditioning, the pads are subjected to mechanical abrasion to physically cut through the cellular layers of the surface of the pad. The exposed surface of the pad contains open cells, which trap abrasive slurry including the spent polishing slurry and material removed from the wafer. In each subsequent pad-conditioning step, the ideal conditioning head removes only the outer layer of cells containing the embedded materials without removing any of the layers below the outer layer.

[008] Conditioning also addresses the loss of polish rates caused by glazing of the pads surface. Glazing is known to be caused by plastic deformation which flattens the asperity peaks. Conditioning is used to break up the glazed area and restore the asperity structure to the pad.

SUMMARY OF THE INVENTION

[009] In various implementations, a conditioning head may include a substrate and a plurality of protrusions disposed on the surface. The plurality of protrusions may extend approximately 2 to approximately 75 microns from the substrate surface. The plurality of protrusions may be arranged in a plurality of sinusoidal wave patterns across at least a portion of the substrate surface.

[010] Implementations may include one or more of the following features. The substrate may be capable of being coated with a diamond layer. The plurality of sinusoidal wave patterns may include at least two sinusoidal wave patterns with a phase offset. The substrate may include a first side and an opposing second side. The plurality of protrusions may extend from the first side of the substrate. The substrate may include a macro pattern. The macro pattern may include one or more first portions and one or more second portions. The second portions of the macro pattern may be disposed closer to the second side of the conditioning head than the one or more first portions of the macro pattern. The macro pattern may include a radial pattern in which the one or more first portions of the macro pattern extend from a center of the substrate surface and the one or more second portions of the micropattern extend radial from the center of the substrate surface. The plurality of protrusions may be disposed on the first portion(s) of the macro pattern. The substrate surface may include a portion of the first layer or a portion of the second layer. The aspect ratio of height to width of each protrusion of the plurality of protrusions may be approximately 1: approximately 1. The plurality of protrusions may form an array comprising a plurality of repeating unit cells. A subset of the plurality of protrusions may be arranged in a plurality of sinusoidal wave patterns in each unit cell of the repeating unit cells. The density of protrusions may be approximately 1 protrusions/mm² to approximately 100 protrusions/mm². The wavelength of each wave pattern may be at least 6 protrusions, in some implementations. The protrusion(s) may have a width of approximately 10 microns to approximately 100 microns and/or protrusion(s) may have a length of approximately 10 microns to approximately 100 microns. The plurality of sinusoidal wave patterns may include at least two sinusoidal wave patterns with a phase offset. The sinusoidal wave pattern(s) in

the plurality of sinusoidal wave patterns may include different amplitude and/or different frequency than one or more other sinusoidal wave patterns in the plurality of sinusoidal wave patterns. The first subset of protrusions in the plurality of protrusions may not have the same cross-sectional shape as a second subset of protrusions in the plurality of protrusions. The sinusoidal wave pattern(s) may be defined by the formula:

$$Y = A * \sin(B(X - C)) + D;$$

wherein

A = amplitude of the wave;

B = the frequency of the wave;

C = the horizontal shift of the wave; and

D = the vertical shift of the wave.

[011] In some implementations, a substrate may include a carbide forming material such as Si, Ti, Mo, Nb, etc. In some implementations, a substrate may include a carbide ceramic such as SiC, TiC, MoC, etc. In some implementations, a substrate may include a composite that includes a carbide and a carbide forming material. In some implementations, a substrate may include a silicon wafer. In some implementations, a substrate may include a hybrid with a first layer and a second layer coupled to the first layer. The first layer may be a carbide ceramic and/or a composite that includes a carbide and a first carbide forming material.

[012] The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the implementations will be apparent from the description and drawings.

BRIEF DESCRIPTION OF THE FIGURES

[013] For a more complete understanding of this disclosure and its features, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

[014] Figure 1 illustrates a schematic diagram of an implementation of a conditioning head conditioning an example polishing pad.

[015] Figure 2 illustrates an implementation of a spiral arrangement defining example first portion(s) of an implementation of a macro design of a conditioning head.

[016] Figure 3 illustrates a magnified view of a portion of the example macro design on the conditioning head illustrated in Figure 4, in which an example sinusoidal protrusion pattern on first portion(s) is illustrated.

[017] Figure 4 illustrates a portion of an implementation of substrate with example protrusions.

[018] Figure 5 illustrates an implementation of an example protrusion on a substrate.

[019] Figure 6 illustrates an implementation of an example diamond coated protrusion and substrate.

[020] Figure 7 illustrates a 2D plot of an implementation of a unit cell illustrating example locations of protrusions along a virtual sinusoidal pathway.

[021] Figure 8 illustrates a 2D plot of an implementation of a plurality of the example unit cells, illustrated in Figure 2.

[022] Figure 9 illustrates graph with a comparison of coefficient of friction between a conventional pad and an implementation of an example conditioning head with a plurality of protrusions arranged in a plurality of sinusoidal wave patterns.

[023] Figure 10 illustrates graph with a comparison of mean pad temperature between a conventional pad and an implementation of an example conditioning head with a plurality of protrusions arranged in a plurality of sinusoidal wave patterns.

[024] Figure 11 illustrates graph with a comparison of copper removal rate between a conventional pad and an implementation of an example conditioning head with a plurality of protrusions arranged in a plurality of sinusoidal wave patterns.

[025] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[026] In various implementations, a conditioning head may be utilized in a CMP (Chemical-Mechanical Polishing) system. The conditioning head may be used to

condition the polishing pad that acts with a slurry to produce a desired surface on a substrate (e.g., for semi-conductor applications). Figure 1 illustrates an implementation of an example CMP apparatus. CMP apparatus 10 may include platen 12 with a polishing pad 14 securely fastened thereto. The polishing pad 14 may rotate, for example, in a clockwise direction. The semiconductor wafer holder 16 with a wafer 18 may be positioned to urge and to maintain the wafer 18 against the exposed surface of the pad 14. The holder 16 may rotate, for example, in a counter clockwise direction. The wafer 18 may be secured to the holder 16 by a vacuum or other commonly used techniques. The polishing slurry 20 may be dispensed within the center region of the polishing pad 14 through the nozzle of a conduit 22. The slurry 20 may include silicon dioxide dispersed within a suitable liquid, such as an acidic or alkaline etchant solution (e.g., potassium hydroxide diluted with water). The exact composition of the slurry may be selected to provide the desired planarization of the exposed surface of the wafer. Although the apparatus 10 shows a single wafer holder for simplicity, CMP equipment may include multiple holders to polish multiple wafers.

[027] The polishing pad conditioning head or disk 24 may include a substrate 26. The substrate may include a plurality of protrusions which are aligned along one or more sinusoidal virtual pathways (e.g., sinusoidal wave patterns).

[028] In some implementation, at least portions of the substrate 26 may include natural and/or synthetic diamond grit on a substrate surface 28 (e.g., the surface of the substrate that at least partially contacts the pad 14 during use). In some implementations, the diamond grit may be approximately evenly distributed over the surface of substrate 26. The diamond grit may include a continuous thin film 30 of CVD polycrystalline diamond (hereinafter referred to as “CVD diamond”) grown onto protrusion and/or substrate surface 28 of the substrate 26. Thus, in some implementations, the protrusion(s) may be encased in CVD diamond 30, which is bonded to the substrate surface 28 of substrate 26.

[029] The protrusions may be distributed across at least a portion of the substrate in a pattern (not shown). This pattern of protrusions may be configured such that the relative movement of the protrusions over the polishing pad 14 surface results in an approximately even distribution of protrusion impact tracks on the polishing pad surface, in some implementations.

[030] A conditioning head 24 may include a backing plate 25 and a substrate 26. The backing plate may be configured to couple with a predetermined CMP tool and/or system (e.g., it may include larger or smaller disks based on the CMP tool to which the conditioning head is designed to couple with). The backing plate may include stainless steel, a plastic (e.g., polycarbonate), and/or any other appropriate material for the slurry chemistry. For example, the slurry may include acidic or alkaline etchant solutions may be corrosive and thus a backing plate may be selected that resists corrosion from the slurry.

[031] In various implementations, the substrate may be coupled to the backing plate (e.g., pressure taped, bonded, epoxied, etc.). The substrate may include a carbide forming material (e.g., Si, Ti, Mo, Nb, etc.); a ceramic such as a carbide ceramic (e.g., SiC, TiC, MoC, etc.), composite that includes a carbide and a carbide forming material (e.g., Si:SiC; Ti:TiC; Ti:SiC, etc.); and/or any other appropriate material. For example, the substrate may include silicon, silicon carbide, silicon nitride (Si₃N₄), and/or combinations thereof. As another nonlimiting example, the substrate may include a ceramic carbide, such as titanium carbide, zirconium carbide, chromium carbide, tungsten carbide, molybdenum carbide, any other appropriate carbide, and/or combinations thereof. As another nonlimiting example, the substrate may include a silicon wafer and/or a reaction bonded silicon carbide. In some implementations, the substrate may include a composite such as the Reaction-Bonded Silicon Carbide (RBSiC) described in US Patent No. 7,367,875, which is incorporated herein by reference to the extent that it does not conflict with the teachings herein. The substrate may include a material that allows the growth of a of CVD polycrystalline diamond layer on the substrate surface.

[032] In some implementations, the substrate may include a hybrid substrate. For example, the substrate may include a first layer and a second layer. The first layer may include a carbide ceramic and/or composite (e.g., composite that includes a carbide and a carbide forming material). The second layer may include carbide forming material. For example, the first layer may include RBSiC. The second layer may include at least one of Si, Ti, and/or Mo. The second layer may be a coating on the first layer. The thickness of the second layer may or may not be the same thickness as the second layer. In some

implementations, the first layer may be similar in thickness to the height of one or more of the protrusions. For example, the protrusions may be etched into the second layer such that the first layer is exposed on the substrate surface (e.g., in areas without protrusions and/or as part of a macro design). As another example, the protrusions may be etched partially into the second layer such that the substrate surface without protrusions also includes the second layer at the substrate surface. As another nonlimiting example, the second layer may be etched completely away and/or partially etched to form the protrusions. The materials in the first layer may be more difficult to etch and/or resist etching which may increase the quality of the substrate and conditioning head (e.g., surfaces may be more uniform or conform to a specified patterning). In some implementations, the materials in the second layer may be selected based on ease of bonding to a selected first layer and/or ease of etching relative to the first layer.

[033] In some implementations, with a hybrid substrate, wherein greater than 50% of the protrusion may be material of the second layer. The protrusions may be 100% formed of the second layer material, in some hybrid substrates. In some implementations, the substrate may include areas that are protrusions and base areas (e.g., valleys between protrusions, planar areas, etc.). The base areas of a hybrid substrate may include a substrate surface that exposes the first layer and/or the second layer.

[034] In various implementations, substrate may have any appropriate shape and/or size. The substrate may be approximately disk shaped and/or annular ring shaped. The substrate may have a length of approximately two inches (approximately 50 mm) to approximately four inches (approximately 100 mm). The substrate may have a width of approximately two inches (approximately 50 mm) to approximately four inches (approximately 100 mm). The thickness of substrate may be approximately 0.5 mm to approximately 6.5 mm. In some implementations, the thickness of the substrate may be approximately 1 mm to approximately 3 mm. In some implementations, substrates with a width greater than 100 mm may include thickness of approximately 1 mm to approximately 6.5 mm. For example, substrates with a width greater than approximately 100mm may include thickness of approximately 2 mm to approximately 4 mm.

[035] In various implementations, the substrate may be approximately planar and/or nonplanar. For example, an approximately planar substrate may be utilized to create a

more uniform contact area with a polishing pad. In some implementations, portions of the substrate surface may be planar.

[036] In various implementations, the substrate may include a macro design on a first side of the substrate and/or conditioning head (e.g., in which the conditioning head comprises a first side and a second opposing side and at least a portion of the first side contacts the polishing pad during use). The macro design may include a pattern over at least a portion of the substrate.

[037] The macro design may include first portion(s) and/or second portion(s). The pattern can include any appropriate number of first and/or second portions. For example, the macro pattern may include 3 first portions and a set of second portions. The second portion(s) may be closer to the second side of the conditioning head than the first portion(s). For example, the second portion(s) may include channels, depressed regions, etc. A macro pattern may utilize second portions to allow slurry and/or other debris to accumulate and/or move external to the conditioning head. The second portions may or may not all have the same depth. The first portions may or may not all have the same height. Since the first portion(s) of the macro design may be disposed closer to the first side of the conditioning head than the second portion(s), the first portion(s) may act as abrasive region(s) (e.g., at least a portion may contact the polishing pad) and the second portion(s) may act as nonabrasive region(s) (e.g., the second portions may not contact the polishing pad or may have less contact than the first portion(s) with the polishing pad during normal use).

[038] Figure 2 illustrates an implementation of a conditioning pad 24 with a macro pattern on the substrate. Figure 3 illustrates a magnified portion of the example conditioning pad illustrated in Figure 2. As illustrated, the macro pattern includes 8 first portions 200 separated by 8 radial second portions 210 and a central second portion 220. The conditioning pad 24 may have a diameter of approximately 100 mm. The macro pattern includes first portions 200 and second portions 210, 220. As illustrated in Figures 2-3, the first portions 200 radially extend from a center of the substrate. At least one second portion 210 radially extends from a center of the substrate. Although a radial pattern is illustrated, macro patterns may include any appropriate pattern such as

trapezoidal regions, trapezoidal first portions proximate the perimeter of the substrate, etc.

[039] As illustrated in Figures 2-3, one of the second portions 220 may be disposed proximate a center of the substrate. The first portions 200 of the conditioning pad may be abrasive regions (e.g., at least a portion contacts the polishing pad during use). First portions 200 may be separated by second portions 210 (e.g., non-abrasive regions) that include channels. The channels may enable particulates (e.g., slurry and pad debris) to be removed from the conditioning head surface. Particulates accumulating in the central second portion 220 may be pushed external to the perimeter of the conditioning head through the channels 210 as the conditioning head rotates, in some implementations. The channels may provide a non-abrasive region between adjacent abrasion regions of 2.55mm. The central second non-abrasive region 220 may have a diameter of about 32 mm.

[040] In some implementations, the macro pattern of the substrate may include vane(s) or other raised regions (e.g., in a regular pattern such as spiral, concentric, etc and/or irregular pattern). US Patent Publication No. 2009/0224370 and U.S. Patent Publication No. 2009/0224370 describes some variations in configuration and methods of producing the abrasive region that may be utilized and is incorporated by reference to the extent that their teachings do not conflict with the teachings herein. In some implementations, a top of a spiral vane may be raised approximately 0.5mm to approximately 2mm from the natural plane (e.g., base) of the substrate.

[041] In various implementations, the substrate may include a plurality of protrusions. Figure 4 illustrates a portion of an implementation of substrate 26 with example protrusions 29. Figure 5 illustrates a portion of an implementation of a protrusion 29 on an example substrate 26. The protrusions may be distributed on the entire substrate or a portion thereof. For example, the protrusion may be disposed on at least a part of the first portion(s) of a macro pattern on the substrate. As another example, the protrusions may be disposed across the entire substrate. As another nonlimiting example, protrusions may be disposed on first portion(s), second portion(s), and/or raised feature(s) (e.g., vanes).

[042] In some implementations, protrusion(s) may be etched into the substrate (e.g., CNC milled, laser machined, Plunged EDM, etc.), deposited using for example

lithography (e.g., photolithography), and/or combinations thereof. For example, photolithography and etching process may be utilized. In some implementations, the protrusions may be added to the substrate (e.g., 3D printed, deposited, etc.). Protrusions may be etched into a substrate surface or deposited on a substrate surface. For example, portions of the substrate may be removed to create protrusions extending from a base of the substrate surface. As another example, protrusions may be added to the substrate surface by depositing material similar or dissimilar to at least a portion of the substrate. As another nonlimiting example, the substrate may be a hybrid substrate in which at least a portion of the second layer is removed such that protrusions are created in the second layer. The first layer may or may not be exposed on the substrate surface.

[043] The protrusions may have any appropriate size and/or shape. For example, protrusions may be cylindrical and/or pyramidal. The protrusions may have any appropriate cross-sectional shape such as triangular, square (e.g., as illustrated in Figure 5), hexagonal, convex polygons, circular, and/or any other regular or irregular polygon. Protrusions on a substrate may have similar or dissimilar shapes. For example, a first set of protrusions may have a first cross-sectional shape and other protrusions may have similar or dissimilar cross-sectional shapes.

[044] The height of the protrusion (e.g., the distance at which it extends from the substrate surface) may be approximately 2 microns to approximately 100 microns. A protrusion may have a height of approximately 2 microns to approximately 75 microns. A protrusion may have a width of approximately 5 microns to approximately 75 microns. The width of the protrusion (e.g., in which a circumscribed circle of the cross-sectional shape of the protrusion may be used as the width, as illustrated in Figure 5) may be approximately 2 microns to approximately 100 microns. The length of the protrusion may be approximately 2 microns to approximately 100 microns. A protrusion may have a width of approximately 2 microns to approximately 75 microns and/or a length of approximately 2 microns to approximately 75 microns. A protrusion may have a width of approximately 5 microns to approximately 75 microns and/or a length of approximately 5 microns to approximately 75 microns. A protrusion may have a width of approximately 10 microns to approximately 100 microns and/or a length of approximately 10 microns to approximately 100 microns. The protrusion may or may not have the same width and

length in the cross-section. The cross-section of the protrusion may or may not change along the height of the cross-section. In some implementations, a width to height ratio may be approximately 1: approximately 1 (e.g., in which a circumscribed circle of the cross-sectional shape of the protrusion may be used as the width, as illustrated in Figure 5).

[045] In some implementations, the substrate may have a density of approximately 5 to approximately 100 protrusions/mm². In some implementations, the substrate may have a density of approximately 10 to approximately 50 protrusions/mm². A substrate may have a density of protrusions of approximately 1 protrusions/mm² to approximately 100 protrusions/mm².

[046] In various implementations the protrusion may be arranged across at least a portion of the surface of the substrate in a pattern, such as a grid shaped pattern (e.g., rectangular grid pattern) and/or other pattern such as an array (e.g., of unit cells). The protrusions may be arranged across at least a portion of the surface of the substrate in a pattern, such as a plurality of sinusoidal waves. For example, a plurality of protrusions may be disposed in an array of two or more sinusoidal waves. The pattern of sinusoidal waves may be repeating or nonrepeating. For example, a substrate may include a unit cell that is repeated (e.g., in an array) across at least parts of the substrate. As illustrated in Figure 4, the red square illustrates a unit cell that may be repeated over at least a portion of the substrate in an array. For example, the substrate may include a micropattern, as illustrated in Figure 2, and the protrusions may be disposed on the first portions 200 and may not be disposed on second portions 210, 220. As illustrated, the array may not be rectangular and/or the array may not be confined to rectangular patches of the substrate. Instead, the protrusions may be with a shape specified in a macro pattern, for example, or a shape of a substrate. Within the unit cell the protrusions may be positioned in a pattern. As illustrated in Figure 4, the protrusions may be positioned in a plurality of sinusoidal wave patterns within the unit cell. This pattern may be repeated in adjacent unit cells over at least a portion of the substrate (e.g., protrusions may form an array that includes a plurality of repeating unit cells, and a subset of these protrusions may be arranged a plurality of sinusoidal wave patterns in each unit cell). As illustrated in Figure 3, the pattern of protrusions (e.g., in an array, in a unit cell of an array, etc.)

may be disposed on first portion(s) of a macro pattern in a substrate. As illustrated, the protrusions may be positioned in a plurality of sinusoidal wave patterns on first portions 200 and not be positioned on one or more second portions 210, 220. These protrusions may be a portion of the abrasive region of the substrate and contact the polishing pad.

[047] In various implementations, the sinusoidal wave pattern in which protrusions are positioned on a substrate may be any appropriate sinusoidal wave pattern. The sinusoidal wave patterns on the substrate may or may not be similar. The sinusoidal wave pattern may include at least one first sinusoidal wave pattern of protrusions and at least one second sinusoidal wave pattern of protrusions. The first sinusoidal wave pattern and the second sinusoidal wave pattern may or may not be offset. For example, the offset may be between approximately 30 degrees and approximately 270 degrees. As another example, at least a portion of the sinusoidal wave patterns may include a Fourier series. As another example, smaller amplitude and/or frequency sinusoidal wave patterns may be disposed at least partially within another sinusoidal wave pattern (e.g., the amplitude of one sinusoidal wave pattern may be less than the amplitude of another sinusoidal wave pattern; the frequency of one sinusoidal wave pattern may be less than the frequency of another sinusoidal wave pattern, etc.). In some implementations, at least one of the sinusoidal wave patterns in the plurality of sinusoidal wave patterns includes at least one of different amplitude or different frequency than one or more other sinusoidal wave patterns in the plurality of sinusoidal wave patterns.

[048] In some implementations, a sinusoidal wave pattern may include at least 6 protrusions. A sinusoidal wave pattern may include 8 or more protrusions. In some implementations, the protrusions may be arranged such that they lie within a predetermined area proximate the amplitude of a sinusoidal wave pattern in which they are disposed (e.g., 20% of the amplitude of a virtual pathway of the one or more sinusoidal wave patterns).

[049] Figure 7 illustrates an implementation of a graphic plot of protrusions on an example, substrate of a conditioning head. As illustrated, 1 mm² a two dimension graphic plot 110 illustrates the location of protrusions 120 along a virtual sinusoidal pathway 130. The plot 110 describes an implementation of a unit cell (e.g., in an array, repeated in a array, etc.). The unit cell 110 represents a repeatable sinusoidal pattern,

which includes two sine waves 130, 160 and two cosine waves 140, 150. The unit cell has an array of 18 protrusions, with each corner protrusion shared with 4 adjacent unit cells, resulting in a protrusion density of 18 protrusions/mm².

[050] In some implementations, at least a portion of the protrusions of a substrate may be positioned according to sine wave pattern 130, 140, 150, and/160.

Sine wave 130 is defined by the formula: $Y = A_1 \sin(B_1(X + \pi)) + D_1$

Sine wave 140 is defined by the formula: $Y = A_2 \cos(B_2(X + \pi)) + D_2$

Sine wave 150 is defined by the formula: $Y = A_3 \cos(B_3X) + D_3$

Sine wave 160 is defined by the formula: $Y = A_4 \sin(B_4X) + D_4$

where,

$$A_1 = A_4$$

$$A_2 = A_3$$

$$B_1 = B_4$$

$$B_2 = B_3$$

$$D_1 = D_4, D_2 = D_3$$

[051] In some implementations, $A_1 = A_2 = A_3 = A_4$.

[052] In some implementations,

$$A_1 = A_2 \sim 1/5Uc; (uc = \text{unit cell})$$

$$B_1 = B_2 = 1;$$

$$D_1 = (N-1)*Uc;$$

$$D_2 = (N-1/2)*Uc;$$

Where,

Uc = Unit cell; and

N = row number of array

[053] Multiple unit cells may be conveniently used to generate a pattern across a regions such as first portions of a macro design (e.g., abrasive area). For example, as illustrated in Figure 8, an array of 6 x 4 unit cells is illustrated in which protrusions are positioned in a plurality of sinusoidal wave patterns.

[054] In various implementations, the unit size of an array of protrusions may be any appropriate size. In some implementations, unit size cells may have side dimensions of approximately 100 μm to approximately 100,000 μm . The unit cell(s) illustrated in Figures 7 and 8 have dimensions of approximately 1000 μm by 1000 μm .

[055] Although a specific set of sinusoidal wave patterns have been described, sine waves patterns 130-160 and/or other sine wave patterns in which protrusions on a substrate are disposed may have different values (e.g., for amplitude, frequency, and/or offset) than illustrated. For example, the array of protrusions in sinusoidal wave patterns may include sinusoidal wave patterns with at least two sinusoidal wave patterns with larger amplitudes than at least two other sinusoidal wave patterns with smaller amplitudes (e.g., relative to each other), in which the smaller amplitude sinusoidal wave patterns nest within the larger amplitude sinusoidal wave patterns. The sinusoidal wave patterns may or may not be synchronous. As another nonlimiting example, the sinusoidal wave patterns may intersect each other (e.g., when they are offset).

[056] As illustrated in Figure 7 and 8, the sine wave pattern (e.g., half wavelengths) 130, 160 of the unit cell is formed from 6 protrusions, including two protrusions which are shared with neighboring unit cells. The cosine wave pattern (e.g., half wavelength) 140, 150 includes 5 protrusions, including at shared protrusion at coordinate 500, 500. This nesting configuration of sinusoidal wave patterns may allow a higher density of protrusions per unit area on the substrate. As illustrated, in one implementation, the number of protrusions in a unit cell is 18 (e.g., with four corner protrusions being shared with neighboring unit cells, such that the four corner protrusions contribute to a single protrusion to the unit cell). As indicated in Table 1, there may be a variation in the calculated protrusion density of a sinusoidal wave pattern design and the actual generated. Variations in the density of positioning of the protrusions may be due to variations in the manufacturing process, in some implementations.

[057] The sinusoidal wave pattern of protrusions may be used as a template to be overlaid onto the macro design of the conditioning head (e.g., as illustrated in Figures 2-3). In some implementations, the sinusoidal wave patterns may form abrasive regions on the first portions or other portions of the conditioning head which are separated by second

portions or non-abrasive regions. The sinusoidal wave patterns may be overlaid onto the entire substrate in some implementations.

[058] To produce the conditioning head, a diamond grit such as a layer of polycrystalline CVD diamonds may be disposed on at least a portion of the substrate. A CVD diamond layering / growth process such as the process described in US Patent Publication No. 2009/0224370 and/or US Patent No. 6054183, both of which are incorporated by reference to the extent that their teachings do not conflict with the teachings herein, may be utilized. In some implementations, the entire substrate surface (e.g., the surface proximate the first side of the conditioning head) may include a layer of diamond (e.g., polycrystalline CVD diamonds). For example, polycrystalline CVD diamond layer may cover the substrate including vanes, first portions, second portions, protrusions, etc. In some implementations the CVD diamond layer may be approximately 5 to approximately 30 microns. The CVD diamond layer may be approximately 8 microns to approximately 25 microns. The individual diamonds in the CVD diamond layer may not be exactly uniform in shape and/or size. The use of the protrusions with the CVD diamond layer though may allow an approximately uniform contact surface with the conditioning pad, in some implementations.

[059] Figure 6 illustrates the example protrusion illustrated in Figure 5 with a diamond layer. As illustrated, the substrate is covered with a layer of diamond (e.g., CVD diamond). The protrusion(s) and the underlying substrate is coated. For example, in hybrid substrates, the diamond layer may coat different layers of substrate (e.g., the material forming the protrusion and the other portions of the substrate surface). As illustrated, the dimensioning and features of the protrusion are intact even after the coating. The diamond surface acts as an abrasive hard coating. Thus, the top of the protrusion (e.g., the diamonds on the top surface of free end of a protrusion) provide an active area which cuts the polishing pad, as desired. The diamond layer may inhibit corrosion from the slurry and/or debris. Thus, by coating the substrate surface, the areas without protrusions (e.g., lower lying areas of the first portions, second portions, etc.) may also be inhibited from corrosion and/or wear during use.

[060] The described conditioning heads may have more uniform and/or effective active areas due to the protrusions in a sinusoidal wave pattern. For example, the conditioning

heads may have reproduceable effects on conditioning pads, which is not existent in current industry conditioning heads. As another example, the conditioning heads may have less wear and/or be more effective when compared to previous versions of conditioning heads available commercially. Generally, commonly used conditioning heads have only an approximately 1% active area (e.g., 100 diamonds out of 10000 diamonds are cutting the polishing pad), but the described conditioning heads are an order of magnitude greater in terms of active area. The greater active area of the described substrate and described conditioning head results in a longer life cycle for the conditioning head (e.g., due to less wear). Additionally, the described conditioning head with the plurality of protrusions in sinusoidal wave patterns may be more effective than commercially available conditioning heads. For example, they may produce cutting in the polishing pad in a more reproduceable way which leads to more reproducible results in the CMP processing of wafers (e.g., wafers processed at different times may have similar processing despite different conditioner heads). Reproducibility may also increase user satisfaction with the conditioner head and CMP system. In some implementations, the conditioning heads may be more effective because a set of protrusions in sinusoidal wave patterns, as described, may cut different paths than another set of protrusions. In some implementations, most of the protrusions cut different paths in the polishing path than each other (e.g., greater than 75% of the protrusions). This is in contrast to other commercially available conditioning heads that result in active areas overlapping paths in the polishing pad and/or tracing each others' paths. Since less overlap in paths of active areas (e.g., individual diamonds in active areas) results in better cutting and better conditioning of the polishing pad (e.g., because more grooves from the paths of the active area means more conditioning of the polishing pad), the described conditioning heads with protrusions in sinusoidal patterns may be more effective than commercially available conditioning heads. The described sizing of the protrusions may produce a better conditioning head by reducing wear on the polishing pad (e.g., since the small protrusions cut less deeply into the pad initially which produces longer pad life), in some implementations.

[061] Conventional conditioner heads possess a correlation between pad cut rate and texture, with a higher texture on the polishing pad correlating with a higher pad cut rate.

In various implementations, the described conditioner heads with a plurality of protrusions in sinusoidal wave patterns have been able to decouple this correlation through achieving a similar polishing pad texture, but at a significantly lower pad cut rate, thereby producing a high performance polishing pad with a longer effective service life. The described conditioning head may have a lower pad cut rate but slightly greater texture, which may create a higher copper removal rate. In some implementations, this greater texture contributed to the ability of the described conditioning head to kept the pore structure more open on the conditioning pad than conventional conditioning heads (e.g., a big problem with the pads, the conditioning pad pores fill with slurry and/or debris, here the pads stay open and cleaner than when using conventional conditioning heads). Commonly, when a conventional conditioning head has a higher pad cut rate it also produces a greater texture of the pad; however, here the described conditioning head has a lower cut rate than conventional conditioning heads but greater texturing of the pad.

[062] EXAMPLES

[063] EXAMPLE 1

[064] A conditioning head was produced with a macro design outlining the abrasive and non-abrasive regions illustrated in Figure 2-3. The abrasive region included protrusions (CVD coated SiC) having a sinusoidal pattern based on a unit cell as illustrated in Figures 7-8. The unit cells and parts thereof form the basis spiral abrasive region illustrates in Figures 3 and 4.

[065] The comparative conditioning head had a conventional square array pattern.

[066] The conditioning heads were used to condition 8" diameter microporous polyurethane polishing pad sold under the tradename IC1010 available from DOW®.

[067] The polishing pad were conditioned using a slurry including deionized water at a flow rate of 10 ml/min using 4" (100mm) diameter conditioner heads as described in Table 1. A Bruker C4 machine was used at a platen speed of 160 rpm and a conditioner head speed of 160 rpm with a downforce of 8 lbs. The conditioner head sweep setting was 1 mm.

[068] The polishing pads were conditioned for 30 minutes with the polishing pad thickness measured with a Qnix® probe before and after the test to determine pad removal rate.

[069] Example 1, the conditioning head with a plurality of protrusions in a sinusoidal wave pattern, has a lower cut rate than the comparative example, but provides similar pad texture. Thus, the protrusions in a sinusoidal wave pattern produce a better conditioning head than in when protrusions are oriented in a square grid.

Table 1

Parameter	Example 1	Comparative example 1
Array type	Sinusoidal	Square
Unit cell size (μ)	1000	225
Density Calc ($\#/mm^2$)	18	20
Density actual ($\#/mm^2$)	20.7	19.2
Feature shape	Square	Square
Feature size* (μ)	44.4	44
Feature height (μ)	32.0	37
Pad cut rate (μ/hr)	16.4 $\pm$ 9.1	29.0 $\pm$ 8.1
Pad texture, Sa (μ)	4.18 $\pm$ 0.55	4.27 $\pm$ 0.64

*largest cross sectional dimension

[070] EXAMPLE 2

[071] Example 2 conditioning head was created with a diamond layer on a flat substrate. The diamonds on the flat substrate were different in size, as commonly found in conventional conditioning heads. Example 3 was a conditioning head that included a substrate with a plurality of protrusions in sinusoidal wave patterns. Specifically, the sinusoidal wave pattern array was created using sinusoidal wave patterns according to the following formulas:

$$Y = A_1 \sin(B_1(X + \pi)) + D_1$$

$$Y = A_2 \cos(B_2(X + \pi)) + D_2$$

$$Y = A_1 \cos(B_2X) + D_2$$

$$Y = A_1 \sin(B_1X) + D_1$$

Where, $A_1 = A_2 \sim 1/5U_c$;

$$B_1 = B_2 = 1;$$

$$D_1 = (N-1) \cdot U_c;$$

$$D_2 = (N-1/2) \cdot U_c;$$

U_c = Unit cell; and

N = row number of array

[072] The conditioning heads were used to condition a polishing pad using the same CMP system for wafers. Figure 9 illustrates graph of comparative coefficient of frictions, Figure 10 illustrates graph of comparative mean pad temperatures, and Figure 11

illustrates graph with comparative copper removal rates between Example 2 and Example 3 conditioning heads. As illustrated, the coefficient of friction results in Figure 9 indicate that the pad was smoother so more pad was in contact with the wafer with Example 3 when compared to Example 2. This is further illustrated by the data of Figure 10, in which the pad temperature is higher for Example 3 when compared with Example 2. This indicates more of the pad is in contact with the wafer. As illustrated in Figure 11, the conditioning head of Example 3 has a higher material removal rate of copper than Example 2. In fact, Example 3, which includes a substrate with a plurality of protrusions arranged in an array of sinusoidal wave patterns has an approximately 14.8% higher removal rate on average. A higher copper removal rate increases user satisfaction (e.g., less time on tool, more wafers processed, etc.).

[073] With conventional conditioning heads, such as Example 2 and others, to get a high removal rate, you would need a course pattern but that in turn creates a lot of defects in the wafer. However, with substrates with the protrusions in the plurality of sinusoidal patterns, such as Example 3, you are able to make the conditioner less aggressive (e.g., it is smoother) without sacrificing removal rate, as illustrated in Figure 11. Thus, the conditioning head with substrates with the protrusions in the plurality of sinusoidal patterns provides a removal rate of a more aggressive/course pattern but with less defects, which increases user satisfaction.

[074] END OF EXAMPLES

[075] Although the array has been described as sinusoidal, other patterns may be utilized, rectangular, grid array, and/or other types of array. In some implementations, the protrusions may be regularly spaced intervals and/or irregularly spaced intervals.

[076] In some implementations, a protrusion may be in the shape of a sinusoidal wave (e.g., extending across a unit cell and/or the substrate or portions thereof). The sinusoidal wave protrusion(s) may interlock, connect, contact, and/or merge such that the array of sinusoidal waves are formed. The diamond layer may be provided on the sinusoidal wave protrusions and other regions of the substrate. In some implementations, a protrusion may include a set of sinusoidal waves (e.g., two or more sinusoidal waves shapes set together and/or interlocked).

[077] In some implementations, the described conditioning head may achieve a rapid and complete removal of the top most layer of cells of the polishing pad with the least possible removal of underlying cell layers of the polishing pad that do not contain embedded materials to maximize the useful life of the pad. In some implementations, the described conditioning head may rejuvenate the asperity structure of the pad to maintain the polishing rate and performance of the pad. In some implementations, the described conditioning head may remove the spent slurry and debris from the conditioning pad's pores without cutting out the pores, resulting in less aggressive conditioning and a longer pad life. The conditioning pad may inhibit over-texturing of the pad (e.g., which results in a shortening of the pad life) while maintaining enough texturing to inhibit insufficient material removal rate during the CMP step and/or inhibit lack of wafer uniformity.

[078] In some implementations, the use of a plurality of protrusions in a plurality of sinusoidal wave patterns may produce a combination of low cut rates of the pads being conditions, while providing sufficient rejuvenation of the asperity structure of the pad to maintain the polishing rate and performance of the pad.

[079] In some implementations, a conditioning head may include a substrate with a substrate surface; and a plurality of protrusions extending approximately 5 to approximately 250 microns from the substrate surface. The plurality of protrusions may form one or more sinusoidal wave patterns on the substrate surface. The use of protrusions in a sinusoidal wave pattern may produce a combination of low cut rates of the pads being conditions, while providing sufficient rejuvenation of the asperity structure of the pad to maintain the polishing rate and performance of the pad (e.g., by using protrusion pattern which is based upon the relative rotational movement of the conditioning head and the pad to avoid the tendency of the conditioning pad to unevenly remove layers of the pad during conditioning).

[080] The sinusoidal wavelength (λ) may include at least 6 protrusions, at least 8 protrusion, at least 10 protrusions, at least 12 protrusion, at least 14 protrusions, at least 16 protrusion, at least 18 protrusions, and/or at least 20 protrusions per wavelength (i.e., 2π , 360 degree angular rotation). The maximum protrusions per wave period may be determined by practical considerations relating to the size of the conditioning head; required density of protrusions; and the rotational movement between the conditioning

head and the pad. In some implementations, the wave pattern (e.g., on a unit cell, on a conditioning head) may include less than 30 protrusions. In some implementations, the wave pattern (e.g., on a unit cell, on a conditioning head) may include less than 20 protrusions.

[081] In some implementations, the plurality of protrusions are within 5 mm, within 1 mm, within 500 μm , within 100 μm , within 50 μm , within 20 μm , or within 10 μm distance of a virtual pathway of the one of more sinusoidal wave patterns. In some implementations, 95% of the protrusions are less than approximately 5 mm or less than approximately 1 mm or less than approximately 500 μm or less than approximately 100 μm or less than approximately 50 μm or less than approximately 20 μm or less than approximately 10 μm distance from a virtual pathway of the one of more sinusoidal wave patterns. In some implementations, the variation of the protrusions from the virtual pathway is less than approximately 20%, less than approximately 10%, less than approximately 5%, less than approximately 3%, less than approximately 2%, or less than approximately 1% of the amplitude of the sinusoidal wave pattern. In some implementations, 90% or 95% of protrusions fall within these limits.

[082] In some implementations, some of the protrusions may not be on the sinusoidal wave pattern. In some implementations, the protrusions may lie generally on a sinusoidal wave pattern. A virtual sinusoidal pathway may be the virtual line formed by the sinusoidal equation, from which protrusions are located (on or near to) to produce the sinusoidal wave pattern.

[083] As previously described, the sinusoidal wave pattern of the (X,Y) 2D plot may be represented by the formula:

[084]
$$Y = A * \sin(B(X - C)) + D$$

[085] Where:

[086] A = amplitude of the wave;

[087] B = the frequency of the wave;

[088] C = the horizontal shift of the wave; and

[089] D = the vertical shift of the wave.

[090] A unit cell may have a plurality of sinusoidal wave patterns which have the same or different amplitude, frequency, horizontal and/or vertical shifts.

[091] In some implementations, the wave may extend in a horizontal direction and some sinusoidal waves are horizontally offset from adjacent vertically adjacent waves.

[092] The period or wavelength ($1/B$ or λ) of the wave is the distance, in the direction of the wave progression, of a single oscillation (e.g. peak to peak).

[093] A unit cell may have a frequency of a half wavelength, such that the unit cell can be disposed against each other while maintaining the continuum of the sinusoidal wave pattern.

[094] The horizontal shift of the wave may be conveniently expressed in terms of the angular position in the wave cycle, expressed in degrees (>0 degrees to <360 degrees) or rad (>0 to $<2\pi$). Alternatively, the horizontal shift may be expressed as a proportion of the wavelength (λ).

[095] In some implementations, the relationship between adjacent or intersecting wave patterns may be governed by a requirement that a protrusion disposed on the wave pattern is set at a minimum distance to an adjacent protrusion on the same or adjacent wave pattern.

[096] In some implementations, the design of the conditioning head takes into account the relative rotational speeds of the conditioning head and/or the pathway that the conditioning head progresses over the polishing pad. An arrangement of protrusions defining a sinusoid wave pattern may be selected such that it produces an approximately uniform protrusion indentation pattern on the polishing pad. In some implementations, a rotational speed of the polishing pad and the conditioning head; and relative pathway thereof may provide an approximately uniform protrusion indentation pattern on the polishing pad.

[097] The protrusions in a wave pattern may or may not be spaced at equidistance along the wave pattern. The distance between protrusions on a first wave pattern may or may not be different to the distance between protrusions on a second wave pattern.

[098] In some implementations, the plurality of protrusions form at least two sinusoidal wave patterns, wherein the wave patterns have a phase offset of approximately 30 degrees to approximately 270 degrees. In some implementations, the phase offset is about 180 degrees (half a wavelength), which enables sinusoidal waves of the same wave length to nest together, which enables the density of protrusions to be increased.

[0099] In some implementations, the wave patterns may or may not include waves with different amplitudes. In some implementations, the wave patterns may or may not include waves with different frequencies. The overall sinusoidal wave pattern may be selected for a particular CMP application using a number of factors, such as the characteristics of the pad being conditioned; the relatively rotational movement between the conditioning head and pad; and/or the degree of texturing required.

[0100] In some implementations, the plurality of protrusions form an array comprising a plurality of repeating unit cells. Each of the unit cells may be in the shape of an irregular or regular polygon, such as a square or rectangle. The unit cells may be a full or part segment of a sinusoidal wave (e.g. a half wave segments). Neighboring unit cells may include one or more common protrusions at the unit cell interfaces. In some implementations, a protrusion defines a corner of a cell forming part of an adjacent unit cell. The unit cells may form a building block which enables the array (and sinusoidal pattern comprised therein) to extend across the surface of the conditioning head.

[0101] In some implementations, use of a unit cell arrangement on a conditioning head may allow the size of the unit cells to be proportionally adjusted to change the density of protrusions, enabling the same sinusoidal pattern to be conveniently scaled depending upon the specific needs of the application.

[0102] Each unit cell may include at least 5, at least 8, at least 12, or at least 20 protrusions. The size of the unit cell may depend on the specific application, but the average length of a side of the unit cells may be approximately 100 μm to approximately 10,000 μm . The surface area of the unit cell may be 0.01 mm^2 to 100 mm^2 .

[0103] The relative positioning of the sinusoidal pattern design may provide that neighboring protrusions have a minimum separation distance. The minimum separate distance between protrusions (edge to edge) may be at least 50 μm , at least 100 μm , at least 150 μm , at least 200 μm , or at least 250 μm , in some implementations. A minimum separate distance may reduce the likelihood that localized protrusion density produces uneven conditioning of the resultant polishing pad, in some implementations.

[0104] In some implementations, one or more sinusoidal patterns may be determined based on relative rotational movement of the conditioning head and a polishing pad, target pad cut rate; the polishing pad material; and/or the slurry characteristics.

[0105] The protrusions may include any suitable material, including refractory particles, including diamond grit, cubic boron carbide, boron suboxide, boron carbide, silicon carbide, tungsten carbide, titanium carbide and chromium boride; composite materials comprising said refractory particles disperse in a matrix of filler or bond material including ceramic or polymeric bond matrixes. The protrusions may be coated with a refractory coating, such as a CVD diamond layer.

[0106] Each protrusion may have a height above the mean height of the substrate surface (e.g., in the range of 5 μm to 250 μm , in the range of 10 μm to 150 μm , in the range of 15 μm to 100 μm , in the range of 20 μm to 60 μm , etc.). In some implementations of the CMP system that specify low polishing pad wear rates, each protrusion may have a height above the mean height of the substrate of less than 55 μm , less than 50 μm , less than 45 μm , or less than 40 μm .

[0107] The abrasive region may include a plurality of spiral vanes. In one some implementations, the top of the vanes may be raised above the substrate surface with the protrusion extending from the raised vane surface.

[0108] Protrusion(s) may have any appropriate shape, such as rounded, convex, and/or has a flat top surface. In some implementations, the protrusions are geometric in shape (e.g. polygon, square, circle, triangle, hexagon etc.). In some implementations, the protrusions are non-geometric in shape (e.g. refractory particles, such as diamond grit). In some implementations, where protrusions are formed from refractory particles, conditioner heads may be monitored to screen out over-sized protrusions that may detrimentally impact upon the balance between pad wear rate, wafer material removal from the polishing pad, rejuvenation of asperity structure of the polishing pad, and slurry retention of the polishing pad.

[0109] In some implementations, the second portions of the substrate may carry away debris and slurry particles from the conditioning head surface. The substrate may include channels which radiate from a central portion of the conditioning head to an outer portion of the conditioning head. The channels may be in the form of a single spiral or a plurality of spirals. The channels may be defined between abrasive regions (e.g., protrusions, first portions, etc.). The width of the channel may approximately 100 μm to approximately 20

mm in width. The width of the channel may be approximately 200 μm to approximately 5 mm.

[0110] In some implementations, the macro pattern and/or vanes may form a spiral pattern. The spiral pattern can be discrete, continuous, separate and/or joined. Separate spirals may emanate from different central points (i.e., each spiral has its own central point), may emanate from a common central point (i.e., each spiral shares a central point), and/or combinations thereof. Spiral patterns may include: an Archimedean spiral; a Euler spiral, Cornu spiral, or clothoid; a Fermat's spiral; a hyperbolic spiral; a lituus; a logarithmic spiral; a Fibonacci spiral; a golden spiral; and/or combinations thereof.

[0111] In some implementations, the substrate may also include second zones at or near the center of the conditioning head. By leaving a central non-abrasive zone (e.g., second zone) around the axis of rotation of the conditioning head, an otherwise high concentration of wear near the axis of rotation may be avoided. This non-abrasive region may include at least 2%, at least 5%, at least 10%, or at least 20% of the radial length from the central axis to the peripheral edge of the conditioning head.

[0112] As used herein, the meaning of the term “conditioning” may include the removal of the outer layers of the polishing pad and the embedded wafer material embedded therein and/or the rejuvenation of the polishing pad's asperity structure. As used herein, the term “conditioning head” and the term “conditioner head” are terms which may be used interchangeably.

[0113] As used herein, the term “wear rate” (unless context dictates otherwise) may include the rate of removal of the outer layers of the polishing pad, which is a measure of the durability of the polishing pad.

[0114] Great Britain Application No. 2000018.8 filed on January 2, 2020 is also incorporated by reference herein to the extent that it does not conflict with the teachings herein.

[0115] Described features(es) may be implemented in various systems, such as the described conditioning head system(s). In addition, various features may be added, deleted, and/or modified. Described process(es) may be implemented by various systems, such as the described conditioning head system(s). In some implementations, described operations(s) may be utilized in combination with other described processes.

[0116] It is to be understood the implementations are not limited to particular systems or processes described which may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular implementations only, and is not intended to be limiting. As used in this specification, the singular forms “a”, “an” and “the” include plural referents unless the content clearly indicates otherwise. Thus, for example, reference to “a carbide forming material” includes a combination of two or more carbide forming material and reference to “a substrate” includes different types and/or combinations of substrates. As another example, “a protrusion” includes different types and/or combinations of protrusions.

[0117] Although the present disclosure has been described in detail, it should be understood that various changes, substitutions and alterations may be made herein without departing from the spirit and scope of the disclosure as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular implementations of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding implementations described herein may be utilized according to the present disclosure. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.