plane may be between the diaphragm and the first reference plane and the center portion may have one or more passages extending therethrough.

[0004] In some implementations of the end effector pad, the center portion, the ring, and the diaphragm may form a contiguous structure made of a material having a modulus of elasticity of at least 0.8 GPa.

[0005] In some implementations of the end effector pad, the diaphragm may include at least three rib regions in which the thickness of the diaphragm is thicker than in regions of the diaphragm in between the rib regions, each rib region extending from the center portion to the ring.

[0006] In some implementations of the end effector pad, regions of the diaphragm between the rib regions may have a thickness between 0.003 inches and 0.005 inches.

[0007] In some implementations of the end effector pad, regions of the diaphragm between the rib regions may have a thickness between 0.005 inches and 0.007 inches.

[0008] In some implementations of the end effector pad, regions of the diaphragm between the rib regions may have a thickness between 0.007 inches and 0.009 inches.

[0009] In some implementations of the end effector pad, each rib region may have a surface of that rib region that is closest to the first reference plane that defines a third reference plane that is perpendicular to the longitudinal axis. The second reference plane may be between the third reference plane and the first reference plane.

[0010] In some implementations of the end effector pad, at least a portion of each rib region may have a width in a direction transverse to a radial axis perpendicular to the longitudinal axis that is between 0.02 inches and 0.04 inches.

[0011] In some implementations of the end effector pad, the diaphragm may have four rib regions.

[0012] In some implementations of the end effector pad, the intersection of the ring and the first reference plane may form a contact region with a radial width that is < 5% than a diameter of the ring.

[0013] In some implementations of the end effector pad, the one or more hard-stop surfaces may have a radial width that is less than 5% of the maximum dimension of the center portion in a direction perpendicular to the longitudinal axis.

[0014] In some implementations of the end effector pad, the one or more hard-stop structures may be a ring-like structure having a diameter the same as the diameter of the center portion.

[0015] In some implementations of the end effector pad, the one or more hard-stop structures may be a single structure that provides a single hard-stop surface.

[0016] In some implementations of the end effector pad, the one or more hard-stop structures may be a plurality of arcuate wall segments arranged in a circular array around a center axis of the center portion.

[0017] In some implementations of the end effector pad, the diaphragm may have at least three rib regions in which the thickness of the diaphragm is thicker than in regions of the diaphragm in between the rib regions. Each rib region may extend from the center portion to the ring and each arcuate wall segment may be positioned at an interior end of a corresponding one of the rib regions.

[0018] In some implementations of the end effector pad, at least a portion of the passage may have a hexagonal cross-sectional shape.

[0019] In some implementations of the end effector pad, each corner of the hexagonal cross-sectional shape may have an arcuate notch.

[0020] In some implementations of the end effector pad, at least a portion of an exterior surface of the center portion may be threaded.

[0021] In some implementations of the end effector pad, the end effector pad may be made of plastic.

[0022] In some implementations of the end effector pad, the plastic may be a conductive electrostatic discharge-rated plastic.

[0023] In some implementations of the end effector pad, the plastic may be a polybenzimidazole (PBI).

the substrates processed may develop a bow with a planarity of 1 mm or more, e.g., if the bowed substrate is placed concave-side down on a flat surface, the highest point of the wafer from the flat surface may be 1mm higher or more than the nominal thickness of the substrate. Further, the direction of the bow can vary, e.g., some substrates have a bow that is concave-up and other substrates concave-down, so direction of slope can reverse depending on the orientation (or wafers may be flipped upside down in between some processing operations, resulting in the bow direction reversing). The sloping underside of bowed substrates can result in i) effector pads, which are typically arranged so as to evenly contact a planar surface, not contacting the underside with enough surface area to produce desired friction forces that act to hold the wafer in place during movement of the end effector and ii) end effector pads with vacuum-assist not being able to form a seal to allow an applied vacuum to develop vacuum clamping forces.

[0042] Some existing elastomeric end effector pads could conform to the slight amount of slope in the underside of a bowed wafer, but end effector pads made of softer, more compliant elastomeric material suitable for use in suction cups or similar devices would have material incompatibilities with the substrates, generally have poor resistance to high temperatures (for example, the end effector pads described herein are suitable for use at temperatures of 250°C or higher, whereas the select few elastomeric materials that are capable of surviving such temperatures may become tacky or sticky under such conditions and make it difficult to remove the wafer from the pad), and could potentially introduce an element of compliance that would result in less precise substrate positioning due to their lower elastic modulus (for example, having greater variability in vertical positioning of the wafer supported thereby), which could prove problematic given the tolerances and clearance zones that need to be available in wafer handling systems. Embodiments of the present disclosure describe a superior solution to elastomeric end effector pads. According to some embodiments, an end effector pad made of a single piece of material, e.g., as a single contiguous structure, with a relatively high tensile modulus, e.g., ≥ 0.8 GPa, and a relatively high flexural modulus, e.g., ≥ 0.9 GPa, is disclosed. The end effector pad is generally rigid except for the ability to flex slightly so as to conform to the slope of the underside of a bowed substrate and thereby have full contact with the underside of the bowed substrate while providing a rigid structure that predictably locates the wafer in space relative to the end

substrate is pulled down against the pad 202 and that limits the vertical travel of the substrate. The hard-stop surfaces 218 of the one or more hard-stop structures 226 define a hard-stop reference plane 219 as shown in FIG. 4-2. The hard-stop reference plane 219, which may also be referred to herein as a second reference plane, is substantially perpendicular to the center axis 222 and is at a defined distance from the face reference plane 217 of the center portion 208 along the center axis 222. By having a defined distance between the hard-stop reference plane 219 and the face reference plane 217 of the center portion 208, a substrate placed on the end effector pad 202 will always be at a known distance away from a top surface of an end effector. In some embodiments, the hard-stop reference plane 219 may be coplanar with the face reference plane 217. In some alternate embodiments, however, the hard-stop reference plane 219 may be closer to a ring reference plane 236 (as shown in FIG. 4-2) that is defined by a surface of the ring that contacts the substrate when the pad is used to support the substrate; the ring reference plane may also be referred to herein as a first reference plane. The application of vacuum to the region between the pad and a substrate placed thereupon may act to pull down the substrate to the hard-stop structure 226 and thus to a repeatable height above the end effector. With a wafer handling robot transferring substrates to locations with small height clearance, e.g., less than 10 mm, the ability to consistently secure substrates at a predetermined height above the end effector allows more of such a height clearance range to be used to accommodate potential variance in other aspects of the wafer handling system, such as wafer bow, end effector placement accuracy, assembly tolerances, etc. In particular, since most substrate handling systems are designed with clearance envelopes and tolerances that assume a planar substrate, the presence of a bowed substrate in such systems may pose particular challenges since a bowed substrate may, in some cases, be twice as “thick” than a planar substrate due to the bow. For example, the outer edge of such a substrate may be displaced upward or downward by some amount due to the bow, while the center of the substrate may be displaced in the opposite direction by some amount. The difference between the maximum or minimum elevation at the center of the bowed wafer and the edges of the bowed substrate may represent a “thickness” of the substrate that is significantly thicker than the planar thickness of the substrate (for example, a typical semiconductor wafer may be approximately 0.750 mm thick,

and such a substrate that is bowed may be bowed by an amount that is greater than the planar thickness of the substrate.) This additional thickness may reduce the available clearances that have been designed into the substrate handling system, thereby reducing the operating margins that are available to the system. By using a hard-stop structure, the end effector pads in some embodiments of the present disclosure may reduce or minimize the amount of vertical placement uncertainty that may exist for substrates supported thereby, thus potentially offsetting at least some of the operating margins that are lost due to bowing of the substrate.

[0048] As shown in FIGS. 2 and 4-1 and 4-2, in some embodiments, the center portion 208 may have a single hard-stop structure 226. For example, the hard-stop structure may simply be a ring-shaped hard-stop structure 226 around the center axis 222. In another example, the single hard-stop structure 226 may be the top area of the center portion 208 and may have hard-stop surface 218 above the face 216 of the center portion 208 (e.g., the center portion 208 may extend past the diaphragm 212).

[0049] In other implementations, as shown in FIG. 3, a plurality of hard-stop structures 326 may be provided that are in the form of arcuate wall segments that are arranged in a circular array so as to encircle the passage 314. In such an implementation, channels 346 may be provided in between each such hard-stop structure 326 to allow for fluid flow between the hard-stop structures 326 so that a vacuum can be reliably drawn across the entire surface area of the end effector pad. The substrate may, when vacuum clamped to the pad, come into contact with arc-shaped hard-stop surfaces 318 due to flexure of the diaphragm 312 and downward displacement of the ring 310. In some implementations, the corners of the cross-sectional shape of the passage 314 may have circular or arcuate notches 345 that may be provided to reduce stress concentrations at such locations, reduce the risk of damage to the pad during installation, and ease manufacturability; such features may be used in any of the implementations discussed herein.

[0050] In some embodiments, there may be two or more hard-stop structures 226. In the embodiment shown in FIG. 3 there are four hard-stop structures 326 with four channels 346. In some implementations, each hard-stop surface 318 of each of the hard-stop structures 326 may be thin relative to the diameter of the ring 310 to minimize the contact between the pad and a

substrate. For example, in some implementations, the radial width of a hard-stop surface 318 may be less than 5% of the maximum diameter of the center portion. Such radial widths may be used in the hard-stop structures shown in other implementations discussed above as well.

[0051] Returning to FIGS. 4-1 and 4-2, the elevation (with respect to the orientations of FIGS. 4-1 and 4-2) of hard-stop surfaces 218 (co-planar with line 219 in FIG. 4-2) is between the elevations of a ring contact surface 234 (co-planar with line 236 in FIG. 4-2) of the ring 210 and the top surface of the diaphragm 212 (co-planar with line 217 in FIG. 4-2). This allows the ring 210 to make initial contact with the substrate and allows the pad 202 to pull vacuum between the substrate and the pad. In some embodiments, the hard-stop surface 218 is above the highest surface of the diaphragm 212. This prevents any contact between the diaphragm 212 and the substrate, thereby reducing particle generation due to contact between the substrate and the diaphragm.

[0052] The flexibility of the diaphragm 212 allows the ring 210 to pivot slightly about an axis that is perpendicular to the center axis 222 and relative to the center portion 208. In some embodiments, the diaphragm 212 may have rib regions 230 and webs 232 in between the rib regions 230. The rib regions 230 are stiffer than the webs 232 and, generally speaking, serve as radial stiffeners that prevent the ring from collapsing radially inward when subjected to vacuum during the vacuum clamping of the substrate. The webs 232 are more compliant than the rib regions 230 and enable the diaphragm 212 to be sufficiently flexible so that the diaphragm 212 can flex so as to allow the ring to tilt slightly so as to conform to the underside of a bowed substrate.

[0053] The diaphragm 212 may have three or more rib regions 230 according to some embodiments. Shown in the top view in FIG. 2, the pad 202 has four rib regions 230. Generally, the rib regions 230 have a smaller surface area perpendicular to the center axis 222 than the webs 232. For example, the rib regions 230 may have a width between 0.02 inches and 0.04 inches. The web 232, depending on the material, may have a thickness of between 0.003 inches and 0.005 inches. In some embodiments, the web 232 may have a thickness between 0.005 and 0.007 inches. In still some other embodiments, the web may have a thickness between 0.007 inches and 0.009 inches. The rib regions 230, in contrast, may have a thickness between 0.008 inches and 0.015 inches. It will be understood that the term “between,” as used herein to refer

CLAIMS

1. An end effector pad for supporting a substrate, the end effector pad comprising:

a center portion extending along a longitudinal axis;

a ring extending around, and radially offset from, the center portion;

a diaphragm connecting the ring with the center portion; and

one or more hard-stop structures, wherein:

the diaphragm includes at least three rib regions,

each rib region extends from the center portion to the ring,

a thickness of the diaphragm is thicker in the rib regions than in between the rib regions,

a surface of the ring that is furthest from the center portion and offset from the diaphragm along the longitudinal axis defines a first reference plane that is perpendicular to the longitudinal axis,

one or more hard-stop surfaces of the one or more hard-stop structures that are furthest from the center portion define a second reference plane that is also perpendicular to the longitudinal axis,

the second reference plane is between the diaphragm and the first reference plane, and

the center portion has one or more passages extending therethrough.

2. The end effector pad of claim 1, wherein the center portion, the ring, and the diaphragm form a contiguous structure made of a material having a modulus of elasticity of at least 0.8 GPa.

3. The end effector pad of claim 1, wherein regions of the diaphragm between the rib regions have a thickness between 0.003 inches and 0.005 inches.

4. The end effector pad of claim 1, wherein regions of the diaphragm between the rib regions have a thickness between 0.005 inches and 0.007 inches.

5. The end effector pad of claim 1, wherein regions of the diaphragm between the rib regions have a thickness between 0.007 inches and 0.009 inches.

6. The end effector pad of claim 1, wherein, for each rib region:

a surface of that rib region that is closest to the first reference plane defines a third reference plane that is perpendicular to the longitudinal axis, and

the second reference plane is between the third reference plane and the first reference plane.

7. The end effector pad of claim 1, wherein at least a portion of each rib region has a width in a direction transverse to a radial axis perpendicular to the longitudinal axis that is between 0.02 inches and 0.04 inches.

8. The end effector pad of claim 1, wherein the diaphragm has four rib regions.

9. The end effector pad of claim 1, wherein an intersection of the ring and the first reference plane forms a contact region with a radial width that is < 5% than a diameter of the ring.

10. The end effector pad of claim 1, wherein the one or more hard-stop surfaces have a radial width that is less than 5% of the maximum dimension of the center portion in a direction perpendicular to the longitudinal axis.

11. The end effector pad of claim 1, wherein the one or more hard-stop structures is a ring-like structure having a diameter the same as the diameter of the center portion.

12. The end effector pad of claim 1, wherein the one or more hard-stop structures is a single structure that provides a single hard-stop surface.

13. The end effector pad of claim 1, wherein the one or more hard-stop structures comprises a plurality of arcuate wall segments arranged in a circular array around a center axis of the center portion.

14. The end effector pad of claim 13, wherein:

the diaphragm includes at least three rib regions in which the thickness of the diaphragm is thicker than in regions of the diaphragm in between the rib regions, each rib region extending from the center portion to the ring, and

each arcuate wall segment is positioned at an interior end of a corresponding one of the rib regions.

15. The end effector pad of claim 1, wherein at least a portion of the passage has a hexagonal cross-sectional shape.

16. The end effector pad of claim 15, wherein each corner of the hexagonal cross-sectional shape has an arcuate notch.

17. The end effector pad of claim 1, wherein at least a portion of an exterior surface of the center portion is threaded.

18. The end effector pad of claim 1, wherein the end effector pad is made of plastic.

19. The end effector pad of claim 18, wherein the plastic is a conductive electrostatic discharge-rated plastic.

20. The end effector pad of claim 19, wherein the plastic is a carbon-filled polyetheretherketone (PEEK).

21. The end effector pad of claim 19, wherein the plastic is a polybenzimidazole (PBI).

22. The end effector pad of claim 1, wherein the ring has a diameter between 0.20 inches and 1.50 inches.

23. The end effector pad of claim 1, wherein the ring has a diameter between 0.40 inches and 0.80 inches.

24. A kit for use on a wafer handling robot, the kit comprising at least three of the end effector pads of any one of claims 1 through 14 or 17 through 23.

25. The kit of claim 24, wherein at least a portion of the passage has a hexagonal cross-sectional shape.

26. The kit of claim 25, further comprising a hex wrench configured to fit in the portion of the passage with the hexagonal cross-sectional shape.