

POLISHING APPARATUS AND POLISHING METHOD

BACKGROUND OF THE INVENTION

Field of the Invention:

5 The present invention relates to a polishing apparatus for polishing a wafer, and more particularly to a technique for detecting a change in wafer condition during polishing of the wafer.

Description of the Related Art:

Chemical mechanical polishing (which will be hereinafter called CMP) is a
10 technique of polishing a wafer by placing the wafer in sliding contact with a polishing surface of a polishing pad while supplying slurry, containing abrasive grains such as silica (SiO_2), onto the polishing surface. The polishing pad is supported by a polishing table and rotates together with the polishing table. The slurry is supplied onto the polishing surface of the rotating polishing pad, and the wafer is pressed against the polishing surface by a
15 polishing head. The surface of the wafer is polished by the chemical action of the slurry and the mechanical action of the abrasive grains contained in the slurry.

In CMP, it is important to accurately detect a change in wafer condition in order to detect a polishing end point of a wafer and to adjust polishing conditions for a wafer. A wafer to be polished typically has a multi-layer structure that includes multiple films.
20 During polishing of the wafer, an upper film, forming an exposed surface of the wafer, is brought into sliding contact with the polishing pad in the presence of the slurry. When the upper film is removed by the polishing operation, a lower film is exposed. This exposed lower film is then brought into sliding contact with the polishing pad in the presence of the slurry.

25 Usually, a frictional force acting between the lower film and the polishing pad is different from a frictional force acting between the upper film and the polishing pad. Therefore, when the upper film is removed and the lower film is exposed, a motor current

necessary to rotate the polishing table changes. Therefore, a point of change in surface condition of the wafer, i.e., a point at which the upper film is removed, can be determined from the change in the motor current.

Citation List

5 Patent Literature

Patent document 1: Japanese laid-open patent publication No. H11-860

However, the above-described detection method based on the change in the motor current cannot accurately detect a point of change in the surface condition of the wafer when the motor current does not change much. For example, when compositions of the upper
10 film and the lower film, constituting the multilayer structure of the wafer, are similar, the motor current may not change significantly when the upper film is removed and the lower film is exposed. In such a case, it is difficult to accurately detect the point of change in the surface condition of the wafer.

15 SUMMARY OF THE INVENTION

Therefore, the present invention provides a polishing apparatus and a polishing method capable of accurately detecting a change in wafer condition.

In an embodiment, there is provide a polishing apparatus comprising: a polishing table for supporting a polishing pad having a polishing surface; a rotatable head body having
20 a pressing surface arranged to press a wafer against the polishing surface; a retainer ring surrounding the pressing surface, the retainer ring being rotatable together with the head body and arranged to press the polishing surface; a non-rotating member that does not rotate together with the retainer ring; a vibration transmission member in contact with both the retainer ring and the non-rotating member; and a sensor secured to the non-rotating member.

25 In an embodiment, the polishing apparatus further comprises a condition detector configured to detect a change in condition of the wafer based on output signal of the sensor.

In an embodiment, the condition detector is configured to detect a point of change

in surface condition of the wafer based on the output signal of the sensor.

In an embodiment, the condition detector is configured to detect the point of change in the surface condition which is a point in time at which an amplitude of the output signal of the sensor exceeds or falls below a threshold value.

5 In an embodiment, the condition detector is configured to detect a point of change in contact state between the wafer and the retainer ring based on the output signal of the sensor.

In an embodiment, the condition detector is configured to detect the point of change in the contact state between the wafer and the retainer ring which is a point in time at which
10 the output signal of the sensor falls below a threshold value.

In an embodiment, the polishing apparatus further comprises a local-load exerting device coupled to the non-rotating member, the local-load exerting device being configured to press the non-rotating member toward the retainer ring.

In an embodiment, the vibration transmission member includes a rotary ring having
15 a plurality of rollers arranged along a circumferential direction of the retainer ring, the rotary ring being rotatable together with the retainer ring.

In an embodiment, the sensor is located above a downstream portion of the retainer ring with respect to a moving direction of the polishing surface.

In an embodiment, the sensor is located above an upstream portion of the retainer
20 ring with respect to a moving direction of the polishing surface.

In an embodiment, the sensor comprises a plurality of sensors secured to the non-rotating member.

In an embodiment, there is provide a polishing method comprising: rotating a polishing table supporting a polishing pad; pressing a wafer against a polishing surface of the
25 polishing pad by a pressing surface of a head body, while rotating the head body; pressing a retainer ring against the polishing surface, while rotating the retainer ring together with the head body and the wafer, the retainer ring being arranged around the wafer; and measuring,

by a sensor, a vibration transmitted from the retainer ring to a non-rotating member via a vibration transmission member, the sensor being secured to the non-rotating member.

In an embodiment, the polishing method further comprises detecting a change in condition of the wafer based on output signal of the sensor.

5 In an embodiment, detecting the change in condition of the wafer based on the output signal of the sensor comprising detecting a point of change in surface condition of the wafer based on the output signal of the sensor.

In an embodiment, detecting the point of change in the surface condition based on the output signal of the sensor comprising detecting a point of change in the surface
10 condition which is a point in time at which an amplitude of the output signal of the sensor exceeds or falls below a threshold value.

In an embodiment, detecting the change in condition of the wafer based on the output signal of the sensor comprising detecting a point of change in contact state between the wafer and the retainer ring based on the output signal of the sensor.

15 In an embodiment, detecting the point of change in contact state between the wafer and the retainer ring based on the output signal of the sensor comprising detecting a point of change in the contact state between the wafer and the retainer ring which is a point in time at which the output signal of the sensor falls below a threshold value.

During polishing of a wafer, the wafer is rotated and pressed against the retainer
20 ring by the frictional force acting between the wafer and the polishing pad. Due to the contact with the wafer, an impact is continuously applied from the wafer to the retainer ring. Since not only the wafer but also the polishing pad is rotating, the retainer ring vibrates due to the impact applied to the retainer ring.

When an upper film, forming the surface of the wafer, is removed by polishing of
25 the wafer, a lower film is exposed. Usually, a frictional force acting between the lower film and the polishing pad is different from a frictional force acting between the upper film and the polishing pad. This difference in frictional force causes a difference in the impact

applied to the retainer ring from the wafer, and consequently causes a change in the manner of vibration of the retainer ring. The sensor detects the vibration of the retainer ring transmitted to the non-rotating member via the vibration transmission member. A change in the output signal of the sensor, i.e., a change in the vibration of the retainer ring, indicates
5 a change in the polished surface condition of the wafer. Therefore, the condition detector can detect a point of change in the polished surface condition of the wafer based on the output signal of the sensor.

During polishing of the wafer, the wafer rotates relative to the retainer ring, and a notch formed in a peripheral portion of the wafer eventually faces the inner surface of the
10 retainer ring. Since the notch is a cut, the impact exerted by the wafer on the retainer ring is reduced when the notch faces the inner surface of the retainer ring. As a result, the manner of vibration of the retainer ring changes. The condition detector can detect, based on the output signal of the sensor, a point of change in the contact state between the wafer and the retainer ring, i.e., a point in time when the notch of the wafer faces the inner surface of the
15 retainer ring.

In particular, since the sensor is fixed to the non-rotating member, the sensor can detect the vibration of the retainer ring at a fixed position. As a result, the condition detector can accurately detect a change in wafer condition based on the output signal of the sensor.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view showing an embodiment of a polishing apparatus;

FIG. 2 is a perspective view of local-load exerting devices;

FIG. 3 is a top view schematically showing a positional relationship between a
25 wafer and pressing members during polishing of the wafer;

FIG. 4 is a cross-sectional view of a polishing head;

FIG. 5 is a perspective view of rollers and an annular rail;

FIG. 6 is a top view schematically showing an arrangement of a sensor;

FIG. 7 is a graph showing an example of output signal of the sensor along time axis;

FIG. 8 is a top view showing an embodiment in which a plurality of sensors are arranged above a downstream portion of the retainer ring;

FIG. 9 is a top view showing another embodiment in which a plurality of sensors are arranged above a downstream portion of the retainer ring;

FIG. 10 is a cross-sectional view showing an embodiment in which a sensor is arranged above an upstream portion of the retainer ring;

FIG. 11 is a cross-sectional view showing an embodiment in which sensors are arranged above the upstream portion and the downstream portion of the retainer ring;

FIG. 12 is a graph showing the output signal of the sensor which changes as the wafer rotates relative to the retainer ring;

FIG. 13 is a schematic diagram when polishing a wafer having a large film thickness in an edge region located opposite to the notch;

FIG. 14 is a cross-sectional view showing another embodiment of the polishing apparatus;

FIG. 15 is a cross-sectional view showing an embodiment in which a sensor is arranged above the upstream portion of the retainer ring; and

FIG. 16 is a cross-sectional view showing an embodiment in which sensors are arranged above the upstream portion and the downstream portion of the retainer ring.

DESCRIPTION OF EMBODIMENTS

Embodiments will be described below with reference to the drawings. FIG. 1 is a schematic view showing an embodiment of a polishing apparatus. As shown in FIG. 1, a polishing apparatus 1 includes a polishing head 10 for holding and rotating a wafer which is an example of a substrate, a polishing table 3 for supporting a polishing pad 2 thereon, and a

slurry-supply nozzle 5 for supplying slurry onto the polishing pad 2. The polishing pad 2 has an upper surface which provides a polishing surface 2a for polishing the wafer. The polishing pad 2 is configured to be rotatable together with the polishing table 3.

5 The polishing head 10 is coupled to a lower end of a polishing head shaft 12, which is rotatably held by a head arm 16. In this head arm 16, there are disposed a rotating device (not shown) for rotating the polishing head shaft 12 and an elevating device (not shown) for elevating and lowering the polishing head shaft 12. The polishing head 10 is rotated by the rotating device through the polishing head shaft 12, and is elevated and lowered by the elevating device through the polishing head shaft 12. The head arm 16 is secured to a pivot
10 shaft 15, so that the head arm 16 can move the polishing head 10 outwardly of the polishing table 3 as the pivot shaft 15 rotates.

The polishing head 10 is configured to be able to hold the wafer on its lower surface by vacuum suction. The polishing head 10 and the polishing table 3 (and the polishing pad 2) rotate in the same direction as indicated by arrows. In this state, the
15 polishing head 10 presses the wafer against the polishing surface 2a of the polishing pad 2. The slurry is supplied from the slurry-supply nozzle 5 onto the polishing surface 2a of the polishing pad 2, so that the wafer is placed in sliding contact with the polishing surface 2a in the presence of the slurry. The surface of the wafer is polished by chemical action of the slurry and mechanical action of abrasive grains contained in the slurry.

20 The polishing head 10 includes a head body 11 for pressing the wafer against the polishing pad 2, and a retainer ring 20 arranged so as to surround the wafer. The head body 11 and the retainer ring 20 are configured to be rotatable together with the polishing head shaft 12. The retainer ring 20 is configured to be movable in vertical directions independently of the head body 11. The retainer ring 20 projects radially outwardly from
25 the head body 11. During polishing of the wafer, the retainer ring 20 contacts the polishing surface 2a of the polishing pad 2, and presses the polishing pad 2 outside the wafer while the retainer ring 20 is rotating.

The polishing head 10 further includes a rotary ring 51 having a plurality of rollers (which will be discussed later), and a stationary ring 91 as a non-rotating member. The rotary ring 51 is arranged to be rotatable together with the retainer ring 20. The stationary ring 91 is located on the rotary ring 51. The rotary ring 51 rotates together with the retainer ring 20, while the stationary ring 91 does not rotate with the retainer ring 20 and remains stationary.

The polishing apparatus 1 further includes a first local-load exerting device 30A for applying a local load to a part of the retainer ring 20, and a second local-load exerting device 30B for applying a local load to a part of the retainer ring 20. The local-load exerting devices 30A, 30B are located above the retainer ring 20. The local-load exerting devices 30A, 30B are fixed to the head arm 16. While the retainer ring 20 rotates about its central axis during polishing of the wafer, the local-load exerting devices 30A, 30B do not rotate together with the retainer ring 20 and remain stationary. The stationary ring 91 is coupled to the local-load exerting devices 30A, 30B. The first local-load exerting device 30A is arranged at an upstream side of the retainer ring 20 with respect to the moving direction of the polishing surface 2a of the polishing pad 2 (i.e., arranged at one side of the retainer ring 20 into which the polishing surface 2a moves). The second local-load exerting device 30B is arranged at a downstream side of the retainer ring 20 with respect to the moving direction of the polishing surface 2a of the polishing pad 2 (i.e., arranged at the opposite side of the retainer ring 20 from which the polishing surface 2a moves out).

FIG. 2 is a perspective view of the local-load exerting devices 30A, 30B. As shown in FIG. 2, the local-load exerting devices 30A, 30B include pressing members 31A, 31B each for applying a downward local load to the stationary ring 91, bridges 33A, 33B, air cylinders 35A, 35B each for generating a downward force, pressure regulators R1, R2 for regulating pressures of compressed gases in the air cylinders 35A, 35B, linear guides 38A, 38B, guide rods 39A, 39B, and unit bases 40A, 40B.

Specifically, the first local-load exerting device 30A includes the first pressing

member 31A, the first bridge 33A, the first air cylinder 35A, the first pressure regulator R1, the first linear guide 38A, the first guide rod 39A, and the first unit base 40A. The second local-load exerting device 30B includes the second pressing member 31B, the second bridge 33B, the second air cylinder 35B, the second pressure regulator R2, the second linear guide 38B, the second guide rod 39B, and the second unit base 40B.

A piston rod 36a of the first air cylinder 35A is coupled to the first pressing member 31A through the first bridge 33A, and an end portion of the first pressing member 31A is coupled to the stationary ring 91. Therefore, the force generated by the first air cylinder 35A is transmitted to the first pressing member 31A, and the first pressing member 31A applies the local load to a part of the stationary ring 91. Similarly, a piston rod 36b of the second air cylinder 35B is coupled to the second pressing member 31B through the second bridge 33B, and an end portion of the second pressing member 31B is coupled to the stationary ring 91. Therefore, the force generated by the second air cylinder 35B is transmitted to the second pressing member 31B, and the second pressing member 31B applies the local load to a part of the stationary ring 91.

In this embodiment, a combination of the first air cylinder 35A and the first pressure regulator R1 constitutes a first actuator 37A for regulating the local load applied from the first pressing member 31A to the stationary ring 91, and a combination of the second air cylinder 35B and the second pressure regulator R2 constitutes a second actuator 37B for regulating the local load applied from the second pressing member 31B to the stationary ring 91. In one embodiment, the first actuator 37A and the second actuator 37B may be each composed of a combination of a servomotor, a ball screw mechanism, and a motor driver.

The first pressing member 31A includes two push rods 32a, and the second pressing member 31B includes two push rods 32b. The push rods 32a and the push rods 32b are coupled to the stationary ring 91. The first pressing member 31A is coupled to the stationary ring 91 at the upstream side of the retainer ring 20 with respect to the moving

direction of the polishing surface 2a of the polishing pad 2. The second pressing member 31B is coupled to the stationary ring 91 at the downstream side of the retainer ring 20 with respect to the moving direction of the polishing surface 2a of the polishing pad 2. In other words, the first pressing member 31A is arranged to apply the local load to the upstream portion of the stationary ring 91 with respect to the moving direction of the polishing surface 2a of the polishing pad 2, and the second pressing member 31B is arranged to apply the local load to the downstream portion of the stationary ring 91 with respect to the moving direction of the polishing surface 2a of the polishing pad 2.

The local-load exerting devices 30A, 30B are fixed to the head arm 16 through the unit bases 40A, 40B, respectively. Therefore, during polishing of the wafer, the polishing head 10 and the wafer are rotating, while the local-load exerting devices 30A, 30B remain stationary. Similarly, during polishing of the wafer, the rotary ring 51 is rotating together with the polishing head 10, while the stationary ring 91 remains stationary.

The local-load exerting devices 30A, 30B have the same construction. The following descriptions relate to the first local-load exerting device 30A, but are applied to the second local-load exerting device 30B as well. The first air cylinder 35A and the first linear guide 38A are mounted to the first unit base 40A. The piston rod 36a of the first air cylinder 35A and the first guide rod 39A are coupled to the first bridge 33A. The first guide rod 39A is vertically movably supported by the first linear guide 38A with low friction. The first linear guide 38A allows the first bridge 33A to move smoothly in the vertical directions without being inclined.

The air cylinders 35A, 35B are coupled to a compressed-gas supply source (not shown) through gas delivery lines F1, F2. The pressure regulators R1, R2 are attached to the gas delivery lines F1, F2, respectively. Compressed gases from the compressed-gas supply source are supplied through the pressure regulators R1, R2 into the air cylinders 35A, 35B, respectively and independently.

The pressure regulators R1, R2 are configured to regulate the pressures of the

compressed gases in the air cylinders 35A, 35B, respectively. The pressure regulators R1, R2 can change independently the pressures of the compressed gases in the air cylinders 35A, 35B, so that the air cylinders 35A, 35B can generate the forces independently of each other.

5 The polishing apparatus 1 further includes a controller 42. The pressure regulators R1, R2 are electrically connected to the controller 42. During polishing of the wafer W, the controller 42 instructs one of the pressure regulators R1, R2 to regulate the pressure of the compressed gas in the air cylinder 35A or the air cylinder 35B.

10 The forces generated by the air cylinders 35A, 35B are transmitted to the bridges 33A, 33B, respectively. The bridges 33A, 33B are coupled to the stationary ring 91 through the pressing members 31A, 31B. The pressing members 31A, 31B transmit the forces of the air cylinders 35A, 35B, applied to the bridges 33A, 33B, to the stationary ring 91. Specifically, the first pressing member 31A presses a part of the stationary ring 91 with a local load corresponding to the force generated by the first air cylinder 35A, and the second pressing member 31B presses a part of the stationary ring 91 with a local load corresponding
15 to the force generated by the second air cylinder 35B.

Each of the local-load exerting devices 30A, 30B is configured to push the stationary ring 91 (which is a non-rotating member) and the rotatory ring 51 (which is a rotating member) toward the retaining ring 20 to exert the downward local load on a part of the retainer ring 20 through the stationary ring 91 and the rotary ring 51. Specifically, the
20 downward local load is transmitted through the stationary ring 91 and the rotary ring 51 to the retainer ring 20.

The polishing apparatus 1 polishes the wafer while rotating the rotary ring 51 together with the retainer ring 20 and applying the local load to the stationary ring 91 from the first pressing member 31A or the second pressing member 31B. During polishing of
25 the wafer, the rotating retainer ring 20 contacts the polishing surface 2a of the polishing pad 2, while pressing the polishing pad 2 outside the wafer.

When the downward local load is applied to a part of the retainer ring 20, a part of

the polishing surface 2a rises upward. The upwardly-raised polishing surface 2a applies in turn an upward local load to the wafer W. In the following descriptions, this upward local load is referred to as a local repulsive force. A magnitude of the local repulsive force depends on a magnitude of the force with which the retainer ring 20 presses the polishing
5 pad 2. A polishing rate changes in accordance with the magnitude of the local repulsive force. Specifically, the greater the local repulsive force, the higher the polishing rate.

The wafer is polished, while the local load is applied from either the first pressing member 31A or the second pressing member 31B to the stationary ring 91 to thereby generate the local repulsive force corresponding to the local load, so that a polishing rate of a
10 portion of the wafer receiving the local repulsive force can be changed.

FIG. 3 is a top view schematically showing a positional relationship between the wafer W and the pressing members 31A, 31B during polishing of the wafer W. An arrow in FIG. 3 indicates the moving direction of the polishing surface 2a. Where a linear line passing through a center P of the retainer ring 20 and a center O of the polishing table 3 is referred to a reference linear line LO, the first pressing member 31A and the second pressing
15 member 31B are located at both sides of the reference linear line LO. More specifically, the first pressing member 31A is located upstream of the reference linear line LO in the moving direction of the polishing surface 2a, and the second pressing member 31B is located downstream of the reference linear line LO in the moving direction of the polishing surface
20 2a. In this embodiment, the first pressing member 31A and the second pressing member 31B are located on a linear line LP perpendicular to the reference linear line LO and passing through the center P of the retainer ring 20.

The polishing surface 2a can be divided into an upstream side and a downstream side, which are located upstream and downstream of the reference linear line LO with respect to the moving direction. In other words, the upstream side and the downstream side
25 of the reference linear line LO are an upstream side and a downstream side of the retainer ring 20 and the stationary ring 91 with respect to the moving direction of the polishing

surface 2a.

In FIG. 3, one of two intersections of the linear line LP and a peripheral edge of the retainer ring 20, located at the upstream side, is defined as an angle of 0 degrees, and the other intersection located at the downstream side is defined as an angle of 180 degrees.

5 One of two intersections of the reference linear line LO and the peripheral edge of the retainer ring 20, located at a center side of the polishing surface, is defined as an angle of 270 degrees, and the other intersection located at a peripheral side of the polishing surface is defined as an angle of 90 degrees. In one embodiment, the first pressing member 31A may be located within a range of $0^\circ \pm 30^\circ$, and the second pressing member 31B may be located
10 within a range of $180^\circ \pm 30^\circ$. Furthermore, in one embodiment, the first pressing member 31A may be located within a range of $0^\circ \pm 60^\circ$, and the second pressing member 31B may be located within a range of $180^\circ \pm 60^\circ$.

Next, the details of the polishing head 10 will be described. FIG. 4 is a cross-sectional view of the polishing head 10. The polishing head 10 includes the head body 11
15 and the retainer ring 20. The head body 11 includes a carrier 43 coupled to the polishing head shaft 12 (see FIG. 1), an elastic membrane (or a membrane) 45 attached to a lower surface of the carrier 43, and a spherical bearing 47 supporting the retainer ring 20 while allowing the retainer ring 20 to tilt and move in the vertical directions relative to the carrier 43. The retainer ring 20 is secured to a drive ring 21, which is coupled to a coupling
20 member 75. The retainer ring 20 is coupled to and supported by the spherical bearing 47 through the drive ring 21 and the coupling member 75. This coupling member 75 is disposed in the carrier 43 and is vertically movable in the carrier 43.

The elastic membrane 45 has a lower surface that provides a pressing surface 45a. This pressing surface 45a is brought into contact with an upper surface (a surface at an
25 opposite side from a surface to be polished) of the wafer W. A plurality of pressure chambers 46A, 46B, 46C, and 46D are provided between the carrier 43 and the elastic membrane 45. These pressure chambers 46A, 46B, 46C, and 46D are coupled to a

pressurized-fluid supply source (not shown) through pressurized-fluid lines L1, L2, L3, and L4, respectively. Pressure regulators G1, G2, G3, and G4 are attached to the pressurized-fluid lines L1, L2, L3, and L4, respectively.

When pressurized fluid (for example, pressurized gas, such as pressurized air) is
5 supplied into the pressure chambers 46A to 46D, the pressing surface 45a of the elastic
membrane 45, receiving the fluid pressures in the pressure chambers 46A to 46D, presses the
wafer W against the polishing surface 2a of the polishing pad 2. The pressures of the
pressurized fluid in the pressure chambers 46A to 46D can be adjusted separately by the
pressure regulators G1 to G4. Therefore, the polishing head 10 can push a plurality of
10 regions of the wafer W corresponding to the pressure chambers 46A to 46D with different
forces. When negative pressures are formed in the pressure chambers 46A to 46D, the
pressing surface 45a of the elastic membrane 45 is dented upward, and the wafer W is held
by the suction cup effect. In one embodiment, a single pressure chamber may be provided
between the carrier 43 and the elastic membrane 45.

15 The retainer ring 20 is arranged so as to surround the wafer W and the pressing
surface 45a of the elastic membrane 45. An upper portion of the retainer ring 20 is secured
to the drive ring 21. More specifically, the retainer ring 20 is coupled to the drive ring 21
by a plurality of bolts (now shown).

The coupling member 75 includes a shaft portion 76 located in the center of the
20 head body 11, and a plurality of spokes 78 extending radially from the shaft portion 76.
The shaft portion 76 extends in the vertical direction through the spherical bearing 47 that is
located in the center of the head body 11. The shaft portion 76 is supported by the
spherical bearing 47 such that the shaft portion 76 can be movable in the vertical directions.
The drive ring 21 is coupled to the spokes 78. With these configurations, the coupling
25 member 75, the drive ring 21, and the retainer ring 20 can move relative to the head body 11
in the vertical directions.

The spherical bearing 47 includes an inner race 48, and an outer race 49 that

slidably supports an outer circumferential surface of the inner race 48. The inner race 48 is coupled to the drive ring 21 through the coupling member 75. The outer race 49 is fixed to the carrier 43. The shaft portion 76 of the coupling member 75 is supported by the inner race 48 such that the shaft portion 76 can move in the vertical directions. The drive ring 21 and the retainer ring 20 are tiltably supported by the spherical bearing 47 through the coupling member 75.

The spherical bearing 47 is configured to allow the drive ring 21 and the retainer ring 20 to move in the vertical directions and tilt, while restricting a lateral movement (horizontal movement) of the drive ring 21 and the retainer ring 20. During polishing of the wafer W, the retainer ring 20 receives from the wafer W a lateral force (an outward force in the radial direction of the wafer W) that is generated due to the friction between the wafer W and the polishing pad 2. This lateral force is received by the spherical bearing 47. In this manner, the spherical bearing 47 serves as a bearing device configured to receive the lateral force (the outward force in the radial direction of the wafer W) that is applied from the wafer W to the retainer ring 20 due to the friction between the wafer W and the polishing pad 2 during polishing of the wafer W, while restricting the lateral movement of the retainer ring 20 (i.e., fixing the horizontal position of the retainer ring 20).

Plural pairs of drive collars 80 are fixed to the carrier 43. Each pair of drive collars 80 are arranged on both sides of each spoke 78. The rotation of the carrier 43 is transmitted through the drive collars 80 to the spokes 78 and the drive ring 21, so that the retainer ring 20, fixed to the drive ring 21, can rotate together with the head body 11. The drive collars 80 are just in contact with the spokes 78 and do not prevent the vertical movement and the tilt of the coupling member 75, the drive ring 21, and the retainer ring 20.

The upper portion of the retainer ring 20 is coupled to an annular retainer-ring pressing mechanism 60 via the drive ring 21. This retainer-ring pressing mechanism 60 is configured to exert a uniform downward load on an entire upper surface of the retainer ring 20 (more specifically, an upper surface of the drive ring 21) to thereby press a lower surface

of the retainer ring 20 against the polishing surface 2a of the polishing pad 2.

The retainer-ring pressing mechanism 60 includes an annular piston 61 secured to the upper portion of the drive ring 21, and an annular rolling diaphragm 62 connected to an upper surface of the piston 61. The rolling diaphragm 62 forms a pressure chamber 63
5 therein. This pressure chamber 63 is coupled to the pressurized-fluid supply source (not shown) through a pressurized-fluid line L5. A pressure regulator G5 is attached to the pressurized-fluid line L5.

When a pressurized fluid (e.g., pressurized air) is supplied into the pressure chamber 63, the rolling diaphragm 62 pushes down the piston 61, which in turn pushes down
10 the entirety of the drive ring 21 and the entirety of the retainer ring 20. In this manner, the retainer-ring pressing mechanism 60 presses the entire lower surface of the retainer ring 20 against the polishing surface 2a of the polishing pad 2. The pressure of the pressurized fluid in the pressure chamber 63 can be regulated by the pressure regulator G5. Therefore, the force with which the retainer ring 20 presses the polishing surface 2a of the polishing pad
15 2 can be adjusted by the pressure regulator G5.

The rotary ring 51 includes a plurality of rollers 52, roller shafts 54 that support the rollers 52 respectively, and a roller housing 55 holding the roller shafts 54. Although only two rollers 52 are illustrated in FIG. 4, a plurality of rollers 52, which are more than two, are evenly arranged along the circumferential direction of the retainer ring 20 in the present
20 embodiment. The roller shafts 54 are also provided so as to correspond to the rollers 52. The roller housing 55 has an annular shape and is fixed to the upper surface of the drive ring 21. Each roller 52 is rotatable around each roller shaft 54.

The stationary ring 91 includes an annular rail 92 which is in contact with tops of the rollers 52, and an annular rail base 94 to which the annular rail 92 is fixed. The rollers
25 52 rotate while being in rolling contact with the annular rail 92. The push rods 32a, 32b are coupled to the top portion of the rail base 94.

The rotary ring 51 is fixed to the drive ring 21. Therefore, the rotary ring 51

having the plurality of rollers 52 rotates together with the drive ring 21 and the retainer ring 20, while the stationary ring 91 does not rotate. The rollers 52 revolve (or move) around the axis of the retainer ring 20, while the rollers 52 are making rolling contact with the stationary ring 91. The stationary ring 91 is located above the drive ring 21 and the retainer ring 20, and is not in contact with the drive ring 21 and the retainer ring 20. In the present embodiment, the vibration transmission member that is in contact with both the stationary ring 91 (which is a non-rotating member) and the retainer ring 20 (which is a rotating element) is constituted by the rotary ring 51 and the drive ring 21. The rotary ring 51 and the drive ring 21 that constitute the vibration transmission member can rotate together with the retainer ring 20. The rotary ring 51 and the drive ring 21 are arranged between the retainer ring 20 and the stationary ring 91.

FIG. 5 is a perspective view of the rollers 52 and the annular rail 92. In this embodiment, the rotary ring 51 has twenty-four rollers 52. During polishing of a wafer, these rollers 52 revolve together with the retainer ring 20, while the annular rail 92 remains stationary. Accordingly, the rollers 52 make rolling contact with the annular rail 92. The load of each of the first local-load exerting device 30A and the load of the second local-load exerting device 30B is transmitted from the annular rail 92 to the rollers 52. Each roller 52 receives the load only when the roller 52 passes a point of application of the load.

As shown in FIG. 4, the polishing apparatus further includes a sensor 100 fixed to the stationary ring 91 which is a non-rotating member, and a condition detector 105 for detecting a change in condition of the wafer W based on output signal of the sensor 100. The sensor 100 is located above the downstream portion of the polishing head 10, more specifically, above the downstream portion of the retainer ring 20. The sensor 100 is provided to sense an impact applied from the wafer W to the retainer ring 20 during polishing of the wafer W.

During polishing of the wafer W, the wafer W is pressed against the polishing surface 2a of the polishing pad 2, while the wafer W and the polishing pad 2 are rotated

individually. A frictional force acts between the wafer W and the polishing pad 2. This frictional force presses the wafer W against the downstream portion of the retainer ring 20. As a result, the impact is continuously applied from the wafer W to the retainer ring 20. Since not only the wafer W but also the polishing pad 2 is rotating, the retainer ring 20
5 vibrates due to the continuous impact applied to the retainer ring 20.

The vibration of the retainer ring 20 is transmitted to the rotary ring 51 through the drive ring 21 that is in contact with the retainer ring 20, and is further transmitted to the stationary ring 91 that is in contact with the rotary ring 51. The sensor 100 is fixed to the stationary ring 91. Therefore, the vibration of the retainer ring 20 is sensed by the sensor
10 100. In this embodiment, the sensor 100 is fixed to (e.g., embedded in) the annular rail 92 of the stationary ring 91. In one embodiment, the sensor 100 may be fixed to (e.g., embedded in) the rail base 94 of the stationary ring 91.

The sensor 100 is located above the retainer ring 20, more specifically above the roller 52. The vibration of the retainer ring 20 is transmitted to the stationary ring 91 via
15 the drive ring 21 and the rotary ring 51 which function as the vibration transmission member, so that the vibration of the retainer ring 20 is detected by the sensor 100 fixed to the stationary ring 91.

Examples of the sensor 100 include an acceleration sensor, a pressure sensor, an acoustic wave sensor, a force sensor (such as a load cell), a strain sensor, each of which can
20 detect vibration of several Hz to several tens of kHz, or an AE sensor (acoustic emission sensor) that can detect a vibration of several hundreds of kHz to several tens of MHz. However, the type of sensor 100 is not particularly limited as long as it can sense an impact applied to the retainer ring 20.

The sensor 100 is electrically connected to the condition detector 105, and the
25 output signal of the sensor 100 is transmitted to the condition detector 105. The condition detector 105 includes memory 105a storing program therein, and an arithmetic device 105b that performs an arithmetic operation according to an instruction included in the program.

The arithmetic device 105b includes a CPU (central processing unit) or a GPU (graphic processing unit) that performs an arithmetic operation according to an instruction included in the program. The memory 105a includes a main memory (for example, a random access memory) to which the arithmetic device 105b can access, and an auxiliary memory (for
5 example, a hard disk drive or a solid state drive) that stores data and programs therein. The condition detector 105 may be composed of at least one computer.

FIG. 6 is a top view schematically showing an arrangement of the sensor 100. Symbols shown in FIG. 6 are the same as the symbols shown in FIG. 3. As shown in FIG. 6, during polishing of the wafer W, the wafer W is pressed against the downstream portion
10 of the retainer ring 20. The sensor 100 is arranged above the downstream portion of the retainer ring 20, i.e., directly above the vibration source. Therefore, the sensor 100 can accurately sense the vibration of the retainer ring 20 that is generated due to the contact between the wafer W and the retainer ring 20.

FIG. 7 is a graph showing an example of the output signal of the sensor 100 along
15 time axis. During polishing of the wafer W, the retainer ring 20 vibrates with certain amplitudes due to the contact between the rotating wafer W and the rotating retainer ring 20 (upper-film polishing period T1). When the upper film, forming the exposed surface of the wafer W, is removed as the polishing of the wafer W progresses, the lower film, which exists underneath the upper film, begins to be exposed. Typically, a frictional force acting
20 between the lower film and the polishing pad 2 is different from a frictional force acting between the upper film and the polishing pad 2. This difference in frictional force causes a difference in the impact applied from the wafer W to the retainer ring 20, and consequently changes the manner of vibration of the retainer ring 20.

In the example shown in FIG. 7, when the upper film is gradually removed and the
25 lower film is appearing, the amplitude of the output signal of the sensor 100 indicating the vibration of the retainer ring 20 gradually increases (transition period T2). When the entire upper film is removed from the wafer W, the frictional force acting between the lower film

and the polishing pad 2 becomes dominant. As a result, the amplitude of the output signal of the sensor 100, which indicates the vibration of the retainer ring 20, further increases (lower-film polishing period T3).

5 In this manner, the vibration of the retainer ring 20 changes as the polishing of the wafer W progresses. The sensor 100 detects the vibration of the retainer ring 20 transmitted to the stationary ring 91 via the drive ring 21 and the rotary ring 51. The change in the output signal of the sensor 100, i.e., the change in the vibration of the retainer ring 20, indicates the change in the polished surface condition of the wafer W. Therefore, the condition detector 105 can detect a point of change in the polished surface condition of
10 the wafer W based on the output signal of the sensor 100.

In particular, since the sensor 100 is fixed to the stationary ring 91 which is a non-rotating member, the sensor 100 can sense the vibration of the retainer ring 20 at a fixed position. As a result, the condition detector 105 can accurately detect a point of change in the polished surface condition of the wafer W based on the output signal of the sensor 100.

15 In the present embodiment, the condition detector 105 calculates the amplitude of the output signal of the sensor 100, and detects a point of change in the surface condition of the wafer W at which the amplitude exceeds a threshold value. Depending on materials of the upper film and the lower film, the vibration of the retainer ring 20 may decrease when the upper film is removed and the lower film is exposed. Therefore, in this case, the
20 condition detector 105 detects a point of change in the surface condition of the wafer W at which the amplitude of the output signal of the sensor 100 falls below a threshold value.

The point of change in the surface condition of the wafer W can be used as an index of a polishing end point of the wafer W or a point of change in polishing condition for the wafer W. Therefore, in one embodiment, the condition detector 105 is configured to
25 determine a polishing end point of the wafer W based on the output signal of the sensor 100. More specifically, the condition detector 105 is configured to calculate the amplitude of the output signal of the sensor 100 and determine a polishing end point of the wafer W at which

the amplitude exceeds or falls below a threshold value.

Further, in one embodiment, the condition detector 105 is configured to determine a point of change in polishing condition for the wafer W based on the output signal of the sensor 100. More specifically, the condition detector 105 is configured to calculate the amplitude of the output signal of the sensor 100 and determine a point of change in the polishing condition for the wafer W at which the amplitude exceeds or falls below a threshold value. Examples of the point of change in the polishing condition for the wafer W include, for example, a point of change in the force with which the polishing head 10 presses the wafer W against the polishing pad 2, and a point of change in the local load applied to the retainer ring 20 from either the first pressing member 31A or the second pressing member 31B.

During polishing of the wafer W, the wafer W contacts the downstream portion of the retainer ring 20. This contact position between the wafer W and the retainer ring 20 may vary within a certain range. Therefore, in one embodiment, as shown in FIG. 8, a plurality of sensors 100 may be arranged above the downstream portion of the retainer ring 20. These sensors 100 are arranged along the circumferential direction of the retainer ring 20. Also in this embodiment, the plurality of sensors 100 are fixed to the stationary ring 91. The plurality of sensors 100 may be arranged at the same intervals as the arrangement intervals of the rollers 52. Although three sensors 100 are arranged in FIG. 8, two sensors 100 or four or more sensors 100 may be arranged.

The contact point between the wafer and the retainer ring 20 may vary depending on the structure of the wafer itself or process conditions such as polishing condition. For example, as shown in FIG. 9, the contact point between the wafer W and the retainer ring 20 may be shifted from the downstream position of the retainer ring 20. Therefore, the number and location of sensors 100 are determined based on the process conditions.

According to the embodiments shown in FIGS. 8 and 9, the condition detector 105 detects the point of change in the surface condition of the wafer W based on the output

signal of at least one of the plurality of sensors 100. In one example, the condition detector 105 monitors respective output signals of the plurality of sensors 100 during polishing of the wafer W, and detects a point of change in the surface condition of the wafer W which is a point in time at which the amplitude of the output signal of any one of the plurality of sensors 100 exceeds or falls below a threshold value. In another example, the condition detector 105 monitors respective output signals of the plurality of sensors 100 during polishing of the wafer W, calculates an average or a sum of amplitudes of the output signals of the plurality of sensors 100, and detects a point of change in the surface condition of the wafer W which is a point in time at which the calculated average or sum exceeds or falls below a threshold value.

During polishing of the wafer W, either the first local-load exerting device 30A or the second local-load exerting device 30B applies a downward local load to the upstream portion or the downstream portion of the retainer ring 20. In other words, depending on the process of the wafer W, a downward local load may be applied to the upstream portion of the retainer ring 20 from the first local-load exerting device 30A, or a downward local load may be applied to the downstream portion of the retainer ring 20 from the second local-load exerting device 30B. In any case, during polishing of the wafer W, the wafer W is pressed against the downstream portion of the retainer ring 20 by the frictional force acting between the wafer W and the polishing pad 2.

When the downward local load is applied from the first local-load exerting device 30A to the upstream portion of the retainer ring 20, the stationary ring 91, which is a non-rotating member, is pressed against the vibration transmission member (i.e., the drive ring 21 and the rotary ring 51) at a position above the upstream portion of the retainer ring 20, while the stationary ring 91 is just in contact with the vibration transmission members 21, 51 at a position above the downstream portion of the retainer ring 20. Therefore, the vibration of the retainer ring 20 is more likely to be transmitted to the stationary ring 91 from the upstream portion of the retainer ring 20 through the vibration transmission member (i.e., the

drive ring 21 and the rotary ring 51) than from the downstream portion of the retainer ring 20.

Therefore, in one embodiment, as shown in FIG. 10, the sensor 100 may be disposed above the upstream portion of the retainer ring 20. Further, in one embodiment, in consideration of the process diversity of the wafer W, as shown in FIG. 11, two sensors
5 100 may be arranged above both the upstream portion and the downstream portion of the retainer ring 20. The condition detector 105 can detect a point of change in the surface condition of the wafer W based on the output signal of one or both of the two sensors 100.

In each of the embodiments described above, the condition detector 105 is configured to detect a point of change in the surface condition of the wafer W based on the
10 output signal of the sensor 100. In one embodiment, the condition detector 105 may detect not only a point of change in the surface condition of the wafer W, but also a point of change in the contact state between the wafer W and the retainer ring 20 during polishing of the wafer W.

As shown in FIG. 12, during polishing of the wafer W, the wafer W rotates
15 gradually relative to the retainer ring 20. Typically, the wafer W has a notch (or a cut) V in its peripheral portion. The wafer W rotates relative to the retainer ring 20, and the notch V eventually faces the inner surface of the retainer ring 20. Since the notch V is a cut, the impact applied from the wafer W to the retainer ring 20 is reduced when the notch V faces the inner surface of the retainer ring 20. As a result, the manner of vibration of the retainer
20 ring 20 changes.

The condition detector 105 detects a point of change in the contact state between the wafer W and the retainer ring 20, i.e., a point in time at which the notch V of the wafer W faces the inner surface of the retainer ring 20, based on the output signal of the sensor 100. More specifically, the condition detector 105 is configured to detect a point of change in the
25 contact state between the wafer W and the retainer ring 20 (i.e., a point in time at which the notch V of the wafer W faces the inner surface of the retainer ring 20) which is a point in time at which the output signal of the sensor 100 falls below a threshold value.

Furthermore, the condition detector 105 is configured to change the polishing condition for the wafer W when detecting the point of change in the contact state between the wafer W and the retainer ring 20.

5 The pressure regulators G1, G2, G3, G4, G5 shown in FIG. 4 are electrically connected to the condition detector 105, so that the operations of the pressure regulators G1 to G5 are controlled by the condition detector 105. In one embodiment, when the condition detector 105 detects the point of change in the contact state between the wafer W and the retainer ring 20, the condition detector 105 sends a command signal to the pressure regulator G5 to allow the pressure regulator G5 to change the pressure of the pressurized fluid in the
10 pressure chamber 63 (i.e., change the pressing force of the retainer ring 20 applied to the polishing surface 2a of the polishing pad 2). For example, when a film thickness in a certain region of the wafer W is larger than that in another region, the pressing force of the retainer ring 20 is increased or decreased to increase a polishing rate only in the region where the film thickness is large.

15 FIG. 13 is a schematic diagram when polishing a wafer W having a large film thickness in an edge region E1 located opposite to the notch V. In this example, when the pressing force of the retainer ring 20 against the polishing pad 2 increases, the polishing rate in the edge region E1 located in the upstream side of the wafer W increases. In such a case, when the notch V is located at the downstream side of the retainer ring 20 (i.e., when the
20 condition detector 105 detects a point in time at which the notch V faces the inner surface of the retainer ring 20), the condition detector 105 sends a command signal to the pressure regulator G5 to allow the pressure regulator G5 to increase the pressure of the pressurized fluid in the pressure chamber 63 (i.e., increase the pressing force of the retainer ring 20 against the polishing surface 2a of the polishing pad 2). With such an operation, the
25 polishing rate in the edge region E1 is locally increased, and the film thickness in the edge region E1 can be reduced. As a result, the entire surface of the wafer W can be flattened.

FIG. 14 is a cross-sectional view showing another embodiment of the polishing

apparatus. Configurations of this embodiment, which will not be particularly described, are the same as those of the embodiments described with reference to FIGS. 1 to 13, and thus duplicate descriptions thereof will be omitted. The polishing apparatus of this embodiment includes two rollers 52a and 52b supported by the push rods 32a and 32b, respectively.

5 These two rollers 52a and 52b are arranged above the upstream portion and the downstream portion of the retainer ring 20, respectively. Two roller housings 55a and 55b are fixed to the push rods 32a and 32b, respectively, and two roller shafts 54a and 54b are supported by the roller housings 55a and 55b, respectively. The rollers 52a and 52b are supported by the roller shafts 54a and 54b, respectively, and are rotatable about the roller shafts 54a and 54b.

10 The two rollers 52a and 52b can rotate about the roller shafts 54a and 54b, but the rollers 52a and 52b and the roller housings 55a and 55b do not rotate together with the retainer ring 20. The drive ring 21 rotates together with the retainer ring 20, and the rollers 52a and 52b make rolling contact with the upper surface of the drive ring 21. The roller housings 55a and 55b are located above the drive ring 21 and the retainer ring 20, and are
15 not in contact with the drive ring 21 and the retainer ring 20. In this embodiment, an element corresponding to the stationary ring 91 described above is not provided.

The sensor 100 is fixed to the roller housing 55b at the downstream side. More specifically, the sensor 100 is embedded in the roller housing 55b at the downstream side. The vibration of the retainer ring 20 is transmitted to the roller housing 55b via the drive ring
20 21, the roller 52b, and the roller shaft 54b. Therefore, the sensor 100 can sense the vibration of the retainer ring 20. In this embodiment, the non-rotating member is the roller housing 55b. The vibration transmission member that contacts both the non-rotating member and the retainer ring 20 is constituted by the roller shaft 54b, the roller 52b, and the drive ring 21.

25 In one embodiment, as shown in FIG. 15, the sensor 100 may be fixed to (e.g., embedded in) the roller housing 55a at the upstream side. In the embodiment shown in FIG. 15, the non-rotating member is the roller housing 55a. The vibration transmission member

that contacts both the non-rotating member and the retainer ring 20 is constituted by the roller shaft 54a, the roller 52a, and the drive ring 21.

Further, in one embodiment, as shown in FIG. 16, two sensors 100 may be fixed to (e.g., embedded in) the upstream roller housing 55a and the downstream roller housing 55b, respectively. In the embodiment shown in FIG. 16, the non-rotating members are roller housings 55a and 55b. The vibration transmission members that contact both the non-rotating members and the retainer ring 20 are constituted by the roller shafts 54a and 54b, the rollers 52a and 52b, and the drive ring 21.

The previous description of embodiments is provided to enable a person skilled in the art to make and use the present invention. Moreover, various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles and specific examples defined herein may be applied to other embodiments. Therefore, the present invention is not intended to be limited to the embodiments described herein but is to be accorded the widest scope as defined by limitation of the claims.

What is claimed is:

A polishing apparatus comprising:

a polishing table for supporting a polishing pad having a polishing surface;

5 a rotatable head body having a pressing surface arranged to press a wafer against the polishing surface;

a retainer ring surrounding the pressing surface, the retainer ring being rotatable together with the head body and arranged to press the polishing surface;

a non-rotating member that does not rotate together with the retainer ring;

10 a vibration transmission member in contact with both the retainer ring and the non-rotating member; and

a sensor secured to the non-rotating member.

2. The polishing apparatus according to claim 1, further comprising a condition
15 detector configured to detect a change in condition of the wafer based on output signal of the sensor.

3. The polishing apparatus according to claim 2, wherein the condition detector is configured to detect a point of change in surface condition of the wafer based on the output
20 signal of the sensor.

4. The polishing apparatus according to claim 3, wherein the condition detector is configured to detect the point of change in the surface condition which is a point in time at which an amplitude of the output signal of the sensor exceeds or falls below a threshold
25 value.

5. The polishing apparatus according to claim 2, wherein the condition detector is

configured to detect a point of change in contact state between the wafer and the retainer ring based on the output signal of the sensor.

5 6. The polishing apparatus according to claim 5, wherein the condition detector is configured to detect the point of change in the contact state between the wafer and the retainer ring which is a point in time at which the output signal of the sensor falls below a threshold value.

10 7. The polishing apparatus according to any one of claims 1 to 6, further comprising a local-load exerting device coupled to the non-rotating member, the local-load exerting device being configured to press the non-rotating member toward the retainer ring.

15 8. The polishing apparatus according to any one of claims 1 to 7, wherein the vibration transmission member includes a rotary ring having a plurality of rollers arranged along a circumferential direction of the retainer ring, the rotary ring being rotatable together with the retainer ring.

20 9. The polishing apparatus according to any one of claims 1 to 8, wherein the sensor is located above a downstream portion of the retainer ring with respect to a moving direction of the polishing surface.

25 10. The polishing apparatus according to any one of claims 1 to 8, wherein the sensor is located above an upstream portion of the retainer ring with respect to a moving direction of the polishing surface.

11. The polishing apparatus according to any one of claims 1 to 10, wherein the sensor comprises a plurality of sensors secured to the non-rotating member.

12. A polishing method comprising:
rotating a polishing table supporting a polishing pad;
pressing a wafer against a polishing surface of the polishing pad by a pressing
5 surface of a head body, while rotating the head body;
pressing a retainer ring against the polishing surface, while rotating the retainer ring
together with the head body and the wafer, the retainer ring being arranged around the wafer;
and
measuring, by a sensor, a vibration transmitted from the retainer ring to a non-
10 rotating member via a vibration transmission member, the sensor being secured to the non-
rotating member.
13. The polishing method according to claim 12, further comprising detecting a
change in condition of the wafer based on output signal of the sensor.
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14. The polishing method according to claim 13, wherein detecting the change in
condition of the wafer based on the output signal of the sensor comprising detecting a point
of change in surface condition of the wafer based on the output signal of the sensor.
- 20
15. The polishing method according to claim 14, wherein detecting the point of
change in the surface condition based on the output signal of the sensor comprising detecting
a point of change in the surface condition which is a point in time at which an amplitude of
the output signal of the sensor exceeds or falls below a threshold value.
- 25
16. The polishing method according to claim 13, wherein detecting the change in
condition of the wafer based on the output signal of the sensor comprising detecting a point
of change in contact state between the wafer and the retainer ring based on the output signal

of the sensor.

17. The polishing method according to claim 16, wherein detecting the point of change in contact state between the wafer and the retainer ring based on the output signal of the sensor comprising detecting a point of change in the contact state between the wafer and the retainer ring which is a point in time at which the output signal of the sensor falls below a threshold value.