

METHOD OF CREATING RESPONSIVE PROFILE OF POLISHING RATE OF WORKPIECE, POLISHING METHOD, AND POLISHING APPARATUS

BACKGROUND OF THE INVENTION

5 Field of the Invention:

[0001] The present invention relates to a technique of polishing a workpiece, such as a wafer, a substrate, or a panel, for use in manufacturing of semiconductor devices, and more particularly, to a technique of calculating a responsiveness of a polishing rate to change in pressure for pressing the workpiece against a polishing pad.

10 Description of the Related Art:

[0002] Chemical mechanical polishing (hereinafter referred to as CMP) is a process of polishing a workpiece (e.g., a wafer, a substrate, a panel, etc.) by placing the workpiece in sliding contact with a polishing pad while supplying a polishing liquid containing abrasive grains, such as silica (SiO_2), onto the polishing pad. A polishing apparatus for performing
15 the CMP includes a polishing table that supports the polishing pad having a polishing surface, and a polishing head for pressing the workpiece against the polishing pad.

[0003] The polishing head is configured to press the workpiece against the polishing pad with an elastic membrane forming a pressure chamber. A compressed gas is supplied into the pressure chamber, and the pressure of the gas is applied to the workpiece through the
20 elastic membrane. Therefore, a force with which the workpiece is pressed against the polishing pad can be regulated by the pressure in the pressure chamber.

[0004] The polishing apparatus polishes the workpiece as follows. While the polishing table and the polishing pad are rotated together, a polishing liquid (typically slurry) is supplied onto the polishing surface of the polishing pad. The polishing head presses a
25 surface of the workpiece against the polishing surface of the polishing pad while rotating the workpiece. The workpiece is brought into sliding contact with the polishing pad in the presence of the polishing liquid. The surface of the workpiece is polished by a chemical action of the polishing liquid and mechanical actions of the polishing pad and abrasive

grains contained in the polishing liquid.

[0005] A film thickness of the workpiece gradually decreases with polishing time. A rate at which the film thickness of the workpiece reduces is often represented by a polishing rate. The polishing rate is an amount of surface material of the workpiece that has been reduced
5 by polishing per unit time, and the amount of reduction is represented by a thickness. The polishing rate is also referred to as a removal rate.

[0006] In order to optimize the CMP process, it is important to determine a responsiveness of the polishing rate of the workpiece to a pressure change in the pressure chamber of the polishing head. The responsiveness of the polishing rate means a change in the polishing
10 rate in response to a change in unit pressure in the pressure chamber. Determining the responsiveness of the polishing rate enables polishing of the workpiece at a required polishing rate to achieve a target profile.

Citation List

Patent Literature

15 [0007] Patent document 1: Japanese laid-open patent publication No. 2006-43873

[0008] It is known that the polishing rate basically obeys Preston's law as follows.

$$\text{polishing rate} \propto \text{pressing pressure} \times \text{relative speed}$$

However, the pressing pressure applied to the workpiece from the elastic membrane of the polishing head is not constant within a pressing surface of the elastic
20 membrane, and the pressing pressure varies due to various factors, such as temperature, a polishing pad, and a polishing liquid.

SUMMARY OF THE INVENTION

[0009] Accordingly, the present invention provides a method and a polishing apparatus
25 capable of accurately obtaining polishing-rate responsiveness to a change in pressure for pressing a workpiece, such as a wafer, against a polishing pad. The present invention further provides a polishing method and a polishing apparatus for polishing a workpiece using a polishing-rate responsiveness profile.

[0010] In an embodiment, there is provided a method of creating a polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in a first pressure chamber and a second pressure chamber when a workpiece used for manufacturing a semiconductor device is pressed against a polishing pad with an elastic
5 membrane forming the first pressure chamber and the second pressure chamber, the method comprising: creating an estimated polishing-rate responsiveness profile using simulation, the estimated polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the first pressure chamber; creating an actual polishing-rate responsiveness profile using polishing results of a workpiece, the actual polishing-rate
10 responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the second pressure chamber; and creating a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile.

[0011] In an embodiment, creating the estimated polishing-rate responsiveness profile
15 comprises: performing simulation to calculate a pressing-pressure responsiveness profile indicating a distribution of pressing pressure changed in response to a change in unit pressure in the first pressure chamber, the pressing pressure being applied from a first workpiece to the polishing pad in the simulation; polishing the first workpiece by pressing the first workpiece against the polishing pad while maintaining a predetermined pressure in
20 the first pressure chamber; creating a polishing-rate profile indicating a distribution of polishing rate of the polished first workpiece; and creating the estimated polishing-rate responsiveness profile based on the pressing-pressure responsiveness profile, the predetermined pressure, and the polishing-rate profile.

In an embodiment, creating the estimated polishing-rate responsiveness profile
25 comprises: multiplying the pressing-pressure responsiveness profile by the predetermined pressure and a polishing-rate coefficient to create a virtual polishing-rate profile; determining the polishing-rate coefficient that minimizes a difference between the polishing-rate profile and the virtual polishing-rate profile; and multiplying the pressing-pressure

responsiveness profile by the determined polishing-rate coefficient to create the estimated polishing-rate responsiveness profile.

[0012] In an embodiment, calculating the pressing-pressure responsiveness profile comprises: performing simulation to calculate a distribution of first pressing pressure when a
5 gas having a first pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a second pressure is supplied into the first pressure chamber; and calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the first pressure
10 and the second pressure at each of radial positions on the first workpiece.

In an embodiment, creating the actual polishing-rate responsiveness profile comprises: polishing a second workpiece by pressing the second workpiece against the polishing pad while changing the pressure in the second pressure chamber; calculating polishing rates of the second workpiece corresponding to different pressures in the second
15 pressure chamber; and calculating polishing-rate responsiveness to pressure change in the second pressure chamber.

[0013] In an embodiment, creating the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile comprises: polishing a first workpiece by pressing the first workpiece against the polishing pad while a predetermined first pressure is
20 maintained in the first pressure chamber and a predetermined second pressure is maintained in the second pressure chamber; creating an actual polishing-rate profile indicating a distribution of polishing rates of the polished first workpiece; creating a first polishing-rate profile based on the first pressure, a first polishing-rate coefficient, and a pressing-pressure responsiveness profile calculated by simulation; creating a second polishing-rate profile
25 based on the second pressure, a second polishing-rate coefficient, and a provisional polishing-rate responsiveness profile created from polishing results of a second workpiece; creating a third polishing-rate profile by combining the first polishing-rate profile and the second polishing-rate profile; determining the first polishing-rate coefficient and the second

polishing-rate that minimize a difference between the actual polishing-rate profile and the third polishing-rate profile; creating the estimated polishing-rate responsiveness profile by multiplying the determined first polishing-rate coefficient by the pressing-pressure responsiveness profile; and creating the actual polishing-rate responsiveness profile by
5 multiplying the determined second polishing-rate coefficient by the provisional polishing-rate responsiveness profile.

In an embodiment, calculating the pressing-pressure responsiveness profile comprises: performing simulation to calculate a distribution of first pressing pressure when a gas having a third pressure is supplied into the first pressure chamber and a distribution of
10 second pressing pressure when a gas having a fourth pressure is supplied into the first pressure chamber; and calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the third pressure and the fourth pressure at each of radial positions on the first workpiece.

[0014] In an embodiment, calculating the pressing-pressure responsiveness profile comprises: performing simulation to calculate a distribution of first pressing pressure when a gas having a third pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a fourth pressure is supplied into the first pressure chamber; and calculating a pressing pressure changed in response to a change in
20 unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the third pressure and the fourth pressure at each of radial positions on the first workpiece.

[0015] According to the present invention, an accurate polishing-rate responsiveness profile can be obtained based on the estimated polishing-rate responsiveness profile
25 generated by the simulation and the actual polishing-rate responsiveness profile obtained by actual polishing.

BRIEF DESCRIPTION OF THE DRAWINGS

polishing surface 2a, and an arithmetic system 10 configured to create a polishing-rate responsiveness profile, which will be described later.

[0018] The polishing head 7 is configured to be able to hold the wafer W on its lower surface. The wafer W has a film to be polished. In the following embodiments, a wafer is
5 used as an example of the workpiece, but the workpiece is not limited to the wafer, and may be a circular substrate, a rectangular substrate, a panel, etc., as long as they are for use in manufacturing of semiconductor devices.

[0019] The arithmetic system 10 is composed of at least one computer. The arithmetic system 10 includes a memory 10a storing programs for creating the polishing-rate
10 responsiveness profile, which will be described later, and a processor 10b configured to perform arithmetic operations according to instructions contained in the programs. The memory 10a includes a main memory, such as a random-access memory (RAM), and an auxiliary memory, such as a hard disk drive (HDD) or a solid state drive (SSD). Examples
15 of the processor 10b include a CPU (central processing unit) and a GPU (graphic processing unit). However, the specific configuration of the arithmetic system 10 is not limited to these examples. The arithmetic system 10 may be disposed in a polishing module, in a polishing apparatus, in a substrate processing system including a plurality of polishing modules, in a management system of a factory where the polishing apparatus is installed, outside the factory where the polishing apparatus is installed, etc.

[0020] The polishing apparatus further includes a support shaft 14, a polishing-head oscillation arm 16 coupled to an upper end of the support shaft 14, and a polishing-head shaft 18 rotatably supported by a free end of the polishing-head oscillation arm 16. The
polishing head 7 is fixed to a lower end of the polishing-head shaft 18. A polishing-head rotating mechanism (not shown) having an electric motor and other elements is disposed in
25 the polishing-head oscillation arm 16. This polishing-head rotating mechanism is coupled to the polishing-head shaft 18, and is configured to rotate the polishing-head shaft 18 and the polishing head 7 in a direction indicated by an arrow.

[0021] The polishing-head shaft 18 is coupled to a not-shown polishing-head elevating

mechanism (including a ball screw mechanism or the like). The polishing-head elevating mechanism is configured to vertically move the polishing-head shaft 18 relative to the polishing-head oscillation arm 16. The vertical movement of the polishing-head shaft 18 allows the polishing head 7 to move vertically relative to the polishing-head oscillation arm 5 16 and the polishing table 5 as indicated by an arrow.

[0022] The polishing apparatus further includes a table rotating motor 21 configured to rotate the polishing pad 2 and the polishing table 5 about their own axes. The table rotating motor 21 is disposed below the polishing table 5, and the polishing table 5 is coupled to the table rotating motor 21 via a table shaft 5a. The polishing table 5 and the polishing pad 2 10 are rotated by the table rotating motor 21 about the table shaft 5a in a direction indicated by an arrow. The polishing pad 2 is attached to an upper surface of the polishing table 5. An exposed surface of the polishing pad 2 constitutes the polishing surface 2a for polishing the wafer W.

[0023] Polishing of the wafer W is performed as follows. The wafer W, with its surface 15 to be polished facing downward, is held by the polishing head 7. While the polishing head 7 and the polishing table 5 are rotating independently, the polishing liquid (e.g., slurry containing abrasive grains) is supplied onto the polishing surface 2a of the polishing pad 2 from the polishing-liquid supply nozzle 8 provided above the polishing table 5. The polishing pad 2 rotates about its central axis together with the polishing table 5. The 20 polishing head 7 is moved to a predetermined height by the polishing-head elevating mechanism (not shown). Further, while the polishing head 7 is maintained at the above predetermined height, the polishing head 7 presses the wafer W against the polishing surface 2a of the polishing pad 2. The wafer W rotates together with the polishing head 7. The wafer W is brought into sliding contact with the polishing surface 2a in the presence of the 25 polishing liquid on the polishing surface 2a of the polishing pad 2. The surface of the wafer W is polished by a combination of a chemical action of the polishing liquid and mechanical actions of the polishing pad 2 and the abrasive grains contained in the polishing liquid.

[0024] The polishing apparatus includes a film-thickness sensor 42 configured to measure a film thickness of the wafer W on the polishing surface 2a. The film-thickness sensor 42 is configured to generate a polishing index value that directly or indirectly indicates the film thickness of the wafer W. Since this polishing index value varies according to the film thickness of the wafer W, the polishing index value indicates the film thickness of the wafer W. The polishing index value may be a value representing the film thickness of the wafer W itself, or may be a physical quantity or a signal value before being converted into the film thickness.

[0025] Examples of the film-thickness sensor 42 include an optical film-thickness sensor and an eddy-current sensor. The optical film-thickness sensor is configured to irradiate the surface of the wafer W with light, and determine the film thickness of the wafer W from spectrum of reflected light from the wafer W. The eddy-current sensor is configured to induce an eddy current in a conductive film formed on the wafer W, and output a signal value that varies according to an impedance of an electrical circuit including the conductive film and a coil of the eddy-current sensor. The optical film-thickness sensor and the eddy-current sensor to be used may be known devices.

[0026] The film-thickness sensor 42 is disposed in the polishing table 5, and rotates together with the polishing table 5. More specifically, the film-thickness sensor 42 is configured to measure the film thickness at a plurality of measurement points on the wafer W while moving across the wafer W on the polishing surface 2a each time the polishing table 5 makes one rotation. In this embodiment, the film-thickness sensor 42 is arranged so as to measure the film thickness at a plurality of measurement points including the center of the wafer W. Therefore, the plurality of measurement points are aligned in a radial direction of the wafer W.

[0027] The film-thickness sensor 42 is coupled to the arithmetic system 10. The measurement values of the film thickness produced by the film-thickness sensor 42 are monitored by the arithmetic system 10. More specifically, the measurement values of the film thickness at the plurality of measurement points of the wafer W are output from the

film-thickness sensor 42, are transmitted to the arithmetic system 10, and are stored in the memory 10a. The arithmetic system 10 creates a film-thickness profile of the wafer W based on the measurement values of the film thickness. The film-thickness profile represents a distribution of film thicknesses along the radial direction of the wafer W.

5 [0028] Next, the polishing head 7 will be described. FIG. 2 is a cross-sectional view showing an embodiment of the polishing head 7. The polishing head 7 includes a head body 31 fixed to the end of the polishing-head shaft 18, an elastic membrane 34 attached to a lower portion of the head body 31, and a retainer ring 32 arranged below the head body 31. The retainer ring 32 is arranged around the elastic membrane 34. The retainer ring 32 is an
10 annular structure configured to retain the wafer W so as to prevent the wafer W from being ejected from the polishing head 7 during polishing of the wafer W.

[0029] Four pressure chambers C1, C2, C3, and C4 are provided between the elastic membrane 34 and the head body 31. The pressure chambers C1, C2, C3 and C4 are formed by the elastic membrane 34 and the head body 31. The central pressure chamber
15 C1 has a circular shape, and the other pressure chambers C2, C3, and C4 have an annular shape. These pressure chambers C1, C2, C3, and C4 are in a concentric arrangement.

[0030] Gas delivery lines F1, F2, F3, and F4 are coupled to the pressure chambers C1, C2, C3, and C4, respectively. Ends of the gas delivery lines F1, F2, F3, and F4 are coupled to a compressed-gas supply source (not shown), which is provided as one of utilities in a factory
20 in which the polishing apparatus is installed. A compressed gas, such as a compressed air, is supplied into the pressure chambers C1, C2, C3, and C4 through the gas delivery lines F1, F2, F3, and F4, respectively. The compressed gas in the pressure chambers C1, C2, C3, and C4 presses the wafer W against the polishing surface 2a of the polishing pad 2 through the elastic membrane 34.

25 [0031] The gas delivery line F3, which communicates with the pressure chamber C3, is coupled to a vacuum line (not shown), so that a vacuum can be formed in the pressure chamber C3. The elastic membrane 34 has an opening in a portion that forms the pressure chamber C3, so that the wafer W can be held by the polishing head 7 via vacuum suction by

producing a vacuum in the pressure chamber C3. Further, the wafer W can be released from the polishing head 7 by supplying the compressed gas into the pressure chamber C3.

[0032] An annular elastic membrane 36 is provided between the head body 31 and the retainer ring 32. A pressure chamber C5 is formed in the elastic membrane 36. The pressure chamber C5 communicates with the above-described compressed-gas supply source through a gas delivery line F5. The compressed gas is supplied into the pressure chamber C5 through the gas delivery line F5, so that the compressed gas in the pressure chamber C5 presses the retainer ring 32 against the polishing pad 2.

[0033] The gas delivery lines F1, F2, F3, F4, and F5 extend via a rotary joint 40 attached to the polishing-head shaft 18. The gas delivery lines F1, F2, F3, F4, and F5, communicating with the pressure chambers C1, C2, C3, C4, and C5, respectively, are provided with pressure regulators R1, R2, R3, R4, and R5, respectively. The compressed gas from the compressed-gas supply source is supplied through the pressure regulators R1 to R5 into the pressure chambers C1 to C5, respectively and independently. The pressure regulators R1 to R5 are configured to regulate the pressures of the compressed gases in the pressure chambers C1 to C5.

[0034] The pressure regulators R1 to R5 can independently change the pressures in the pressure chambers C1 to C5 to thereby independently adjust pressing pressures on corresponding four areas of the wafer W, i.e., a central portion, an inner intermediate portion, an outer intermediate portion, and an edge portion, and a pressing pressure of the retainer ring 32 against the polishing pad 2. The gas delivery lines F1, F2, F3, F4, and F5 are coupled to vent valves (not shown), respectively, so that the pressure chambers C1 to C5 can be vented to the atmosphere. In this embodiment, the elastic membrane 34 forms the four pressure chambers C1 to C4, while in one embodiment, the elastic membrane 34 may form less than four pressure chambers or more than four pressure chambers.

[0035] The pressure regulators R1 to R5 are coupled to the arithmetic system 10. The arithmetic system 10 receives the measurement value of the film thickness of the wafer W from the film-thickness sensor 42 (see FIG. 1), determines target pressure values of the

pressure chambers C1 to C5 based on the measurement value of the film thickness for achieving a target film-thickness profile, and transmits the target pressure values to the pressure regulators R1 to R5, respectively. The pressure regulators R1 to R5 operate so as to maintain the pressures in the pressure chambers C1 to C5 at the corresponding target pressure values.

[0036] The polishing head 7 can apply independent pressures to the plurality of areas of the wafer W, respectively. For example, the polishing head 7 can press the different areas of the surface of the wafer W at different pressures against the polishing surface 2a of the polishing pad 2. Therefore, the polishing head 7 can control the film-thickness profile of the wafer W so as to achieve the target film-thickness profile.

[0037] In order to optimize the polishing process, it is important to determine a responsiveness of a polishing rate of the wafer W to the pressures in the pressure chambers C1 to C4. The polishing rate is an amount of surface material of the wafer W that been reduced by polishing per unit time, and the amount of reduction is represented by a thickness. The polishing rate is also referred to as a removal rate. The responsiveness of the polishing rate represents a change in the polishing rate in response to a change in unit pressure in the pressure chamber.

[0038] In the embodiments described below, the arithmetic system 10 creates polishing-rate responsiveness profiles indicating distributions of the responsiveness of the polishing rate to pressure changes in the pressure chambers C1 to C4 when the elastic membrane 34 of the polishing head 7 presses the wafer W against the polishing pad 2. More specifically, the arithmetic system 10 performs simulation to create estimated polishing-rate responsiveness profiles that represent distributions of polishing-rate responsiveness to pressure changes in the pressure chambers C1 to C3, creates actual polishing-rate responsiveness profile that represents a distribution of polishing-rate responsiveness to pressure change in the pressure chamber C4 using polishing results of a wafer as a workpiece, and creates a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profiles and the actual polishing-rate responsiveness

profile.

[0039] Specifically, the polishing-rate responsiveness profiles for the pressure chambers C1 to C3 are created based on the simulation, and the polishing-rate responsiveness profile for the pressure chamber C4 is created based on the actual polishing results. The hybrid
5 polishing-rate responsiveness profile which is the combination of these polishing-rate responsiveness profiles is created. The pressure chamber C4 is the outermost pressure chamber for pressing the edge portion of the wafer against the polishing pad 2. A relationship between the pressure in the outermost pressure chamber C4 and the polishing rate may be different from relationships between the pressures in the other pressure
10 chambers C1 to C3 and polishing rates. Furthermore, it is difficult to simulate the polishing-rate responsiveness profile for the outermost pressure chamber C4, and the simulation accuracy may be low. This is because the edge portion of the wafer pressed by the pressure chamber C4 comes into contact with the retainer ring during polishing of the wafer, and the rotating polishing pad 2 moves under the wafer from the edge portion of the
15 wafer. Therefore, in this embodiment, the actual polishing-rate responsiveness profile is created for the outermost pressure chamber C4 based on the actual polishing results.

[0040] However, the pressure chamber for which the actual polishing-rate responsiveness profile is created based on the actual polishing results is not limited to the pressure chamber C4, and may be any one of the pressure chambers C1 to C4. In one embodiment, estimated
20 polishing-rate responsiveness profiles may be created by simulation for the pressure chambers C2 to C4, and actual polishing-rate responsiveness profile may be created for the central pressure chamber C1 based on actual polishing results. In another embodiment, estimated polishing-rate responsiveness profiles may be created by simulation for the pressure chambers C1 and C2, and actual polishing-rate responsiveness profiles may be
25 created for the pressure chambers C3 and C4 based on actual polishing results. Even if there are three or less pressure chambers or five or more pressure chambers, the pressure chamber for which the actual polishing-rate responsiveness profile is created is not limited to the outermost pressure chamber, and may be any one of the multiple pressure chambers.

[0041] An installation location of the arithmetic system 10 for creating the hybrid polishing-rate responsiveness profile is not particularly limited. For example, the arithmetic system 10 may be remote from the polishing module including the polishing table 5 and polishing head 7 for performing the polishing operation. The arithmetic system 10 may be coupled to the polishing module by a communication system, such as the Internet or a local area network. For example, the arithmetic system 10 may be comprised of a workstation coupled to the communication system, or may be comprised of a combination of edge server and cloud server.

[0042] FIG. 3 is a flowchart illustrating an embodiment of creating the hybrid polishing-rate responsiveness profile.

In step 101, the arithmetic system 10 performs simulation to calculate pressing-pressure responsiveness profiles indicating distributions of the pressing pressures, which are applied from a wafer W1 to the polishing pad 2, changed in response to changes in unit pressure in the pressure chambers C1 to C4. The simulation is performed using mathematical models of the elastic membrane 34 of the polishing head 7, the polishing pad 2, and wafer. Thus, a shape and an elasticity of the elastic membrane 34, an elasticity of the polishing pad 2, and a rigidity of the wafer W1 are reflected in the simulation result. The simulation is not limited as long as it can calculate intended pressing-pressure responsiveness profiles, while in this embodiment, a simulation is based on the finite element method. The simulation in this embodiment is performed under a condition that the wafer W1 and the polishing pad 2 are not rotated, while the simulation may be performed under a condition that the wafer W1 and the polishing pad 2 are rotated as in the actual polishing.

[0043] In step 102, the polishing apparatus shown in FIG. 1 actually polishes the wafer W1 by pressing the wafer W1 against the polishing pad 2 with the polishing head 7 while the pressures in the pressure chambers C1 to C4 of the polishing head 7 are maintained at predetermined pressures. The polishing of the wafer W1 is performed, as described above, by pressing the surface (surface to be polished) of the wafer W1 against the polishing

surface 2a by the polishing head 7 in the presence of the polishing liquid on the polishing surface of the polishing pad 2, while the polishing table 5 and the polishing pad 2 are rotated and the wafer W1 is rotated by the polishing head 7.

[0044] During polishing of the wafer W1, the film-thickness sensor 42 measures the film thickness at multiple measurement points on the wafer W1 while the film-thickness sensor 42 moves across the wafer W1. In this embodiment, the multiple measurement points are aligned along the radial direction of the wafer W1. The measurement values of the film thickness are transmitted from the film-thickness sensor 42 to the arithmetic system 10. The polishing of the wafer W1 is terminated when the film thickness of the wafer W1 reaches a target value. The film-thickness sensor 42 continuously measures the film thickness of the wafer W1 from the start to the end of polishing of the wafer W1, and transmits the measurement values of the film thickness to the arithmetic system 10. The step 102 may be performed before the step 101.

[0045] In step 103, the arithmetic system 10 creates a polishing-rate profile indicating a distribution of the polishing rate of the polished wafer W1. This polishing-rate profile represents a polishing rate at each radial position on the wafer W1.

[0046] In step 104, the arithmetic system 10 creates estimated polishing-rate responsiveness profiles based on the pressing-pressure responsiveness profiles calculated in the step 101, the predetermined pressures in the pressure chambers C1 to C4 set in the step 102, and the polishing-rate profile calculated in the step 103. The estimated polishing-rate responsiveness profiles represent distributions of estimated polishing-rate responsiveness to pressure changes in the pressure chambers C1 to C4 at multiple radial positions (i.e., at the multiple measurement points for the film-thickness) on the wafer W1.

[0047] In step 105, the polishing apparatus shown in FIG. 1 actually polishes a wafer W2 by pressing the wafer W2 against the polishing pad 2 with the polishing head 7, while the pressures in the pressure chambers C1 to C3 of the polishing head 7 are kept constant and while the pressure in the pressure chamber C4 is changed. The polishing of the wafer W2 is performed, as described above, by pressing the surface (surface to be polished) of the

wafer W2 against the polishing surface 2a by the polishing head 7 in the presence of the polishing liquid on the polishing surface of the polishing pad 2, while the polishing table 5 and the polishing pad 2 are rotated and the wafer W2 is rotated by the polishing head 7.

[0048] During polishing of the wafer W2, the film-thickness sensor 42 measures film thickness at multiple measurement points on the wafer W2 while the film-thickness sensor 42 moves across the wafer W2. In this embodiment, the multiple measurement points are aligned along the radial direction of the wafer W2. The measurement values of the film thickness are transmitted from the film-thickness sensor 42 to the arithmetic system 10. The polishing of the wafer W2 is terminated when the film thickness of the wafer W2 reaches a target value. The film-thickness sensor 42 continuously measures the film thickness of the wafer W2 from the start to the end of polishing of the wafer W2, and transmits the measurement values of the film thickness to the arithmetic system 10.

[0049] In step 106, the arithmetic system 10 calculates polishing rates of the wafer W2 corresponding to different pressures in the pressure chamber C4 from the measurement values of the film thickness, and calculates polishing-rate responsiveness to the pressure change in the pressure chamber C4.

In step 107, the arithmetic system 10 creates the actual polishing-rate responsiveness profile from the polishing-rate responsiveness for the pressure chamber C4 calculated in the step 106.

In one embodiment, the steps 105 to 107 may be performed before the steps 101 to 104.

[0050] In step 108, the arithmetic system 10 create the hybrid polish-rate responsiveness profile by combining the estimated polishing-rate responsiveness profiles for the pressure chambers C1 to C3 determined in the above step 104 and the actual polishing-rate responsiveness profile for the pressure chamber C4 determined in the above step 107. In this embodiment, the arithmetic system 10 create the hybrid polish-rate responsiveness profile by replacing the estimated polishing-rate responsiveness profile for the pressure chamber C4 determined in the step 104 with the actual polishing-rate responsiveness profile

for the pressure chamber C4 determined in the step 107. The arithmetic system 10 can correctly determine pressures in the pressure chambers C1 to C4 for achieving a target film thickness profile based on the hybrid polishing-rate responsiveness profile.

[0051] Each of the steps will be described in detail below.

5 FIG. 4 is a diagram illustrating an embodiment of calculating the pressing-pressure responsiveness profiles in the step 101 shown in FIG. 3. Vertical axis in FIG. 4 represents pressure applied from the wafer W1 to the polishing surface 2a of the polishing pad 2 (hereinafter, referred to as pressing pressure), and horizontal axis represents radial position on the wafer W1. The horizontal axis in FIG. 4 shows a case where the radius of the wafer
10 W1 is 150 mm, but the radius of the wafer W1 is not limited to the example of FIG. 4.

[0052] First, a distribution (indicated by a reference symbol CP1+) of the pressing pressure when a gas having a pressure P1 is supplied into the pressure chamber C1 shown in FIG. 2 is calculated by the simulation. Next, a distribution (indicated by a reference symbol CP1-) of the pressing pressure when a gas having a pressure P2 is supplied into the
15 same pressure chamber C1 is calculated by the simulation. Both the pressure P1 and the pressure P2 are preset pressures, and the pressure P1 is higher than the pressure P2.

[0053] Similarly, a distribution (indicated by a reference symbol CP2+) of the pressing pressure when a gas having the pressure P1 is supplied into the pressure chamber C2, a distribution (indicated by a reference symbol CP2-) of the pressing pressure when a gas
20 having the pressure P2 is supplied into the pressure chamber C2, a distribution (indicated by a reference symbol CP3+) of the pressing pressure when a gas having the pressure P1 is supplied into the pressure chamber C3, a distribution (indicated by a reference symbol CP3-) of the pressing pressure when a gas having the pressure P2 is supplied into the pressure chamber C3, a distribution (indicated by a reference symbol CP4+) of the pressing
25 pressure when a gas having the pressure P1 is supplied to the pressure chamber C4, and a distribution (indicated by a reference symbol CP4-) of the pressing pressure when a gas having the pressure P2 is supplied into the pressure chamber C4 are calculated by the simulation.

[0054] Next, the arithmetic system 10 calculates a pressing pressure changed in response to a change in unit pressure of the gas in the pressure chamber C1 by dividing a difference between the pressing pressure CP1+ and the pressing pressure CP1- by a difference between the pressure P1 and the pressure P2 at each radial position on the wafer W1.

5 Similarly, the arithmetic system 10 calculates a pressing pressure changed in response to a change in unit pressure of the gas in the pressure chamber C2 by dividing a difference between the pressing pressure CP2+ and the pressing pressure CP2- by the difference between the pressure P1 and the pressure P2 at each radial position on the wafer W1, calculates a pressing pressure changed in response to a change in unit pressure of the gas in

10 the pressure chamber C3 by dividing a difference between the pressing pressure CP3+ and the pressing pressure CP3- by the difference between the pressure P1 and the pressure P2 at each radial position on the wafer W1, and calculates a pressing pressure changed in response to a change in unit pressure of the gas in the pressure chamber C4 by dividing a difference between the pressing pressure CP4+ and the pressing pressure CP4- by the difference

15 between the pressure P1 and the pressure P2 at each radial position on the wafer W1.

[0055] FIG. 5 is a graph showing an example of the pressing-pressure responsiveness profiles. Vertical axis in FIG. 5 represents pressing pressure changed in response to the change in the unit pressure in the pressure chamber, and horizontal axis represents radial position on the wafer W1. A reference symbol PP1 in FIG. 5 represents a distribution of

20 the pressing pressure changed in response to the change in the unit pressure of the gas in the pressure chamber C1, a reference symbol PP2 represents a distribution of the pressing pressure changed in response to the change in the unit pressure of the gas in the pressure chamber C2, a reference PP3 represents a distribution of the pressing pressure changed in response to the change in the unit pressure of the gas in the pressure chamber C3, and a

25 reference symbol PP4 represents a distribution of the pressing pressure in response to the change in the unit pressure of the gas in the pressure chamber C4. In this manner, the arithmetic system 10 creates the pressing-pressure responsiveness profiles.

[0056] As described with reference to FIG. 4, the pressing-pressure responsiveness

profiles are created by performing the simulation under the condition that the pressures in the pressure chambers C1 to C4 are set to the pressure P1 and the pressure P2 which are preset values. The pressing-pressure responsiveness profiles may change depending on the set values of the pressures in the pressure chambers C1 to C4. Moreover, the pressures in the pressure chambers C1 to C4 in the actual polishing of a wafer may change depending on the wafer structure, the film thickness, etc.

[0057] Thus, in one embodiment, the arithmetic system 10 performs the simulation multiple times while setting the pressures in the pressure chambers C1 to C4 to different values to further calculate (create) the pressing-pressure responsiveness profiles. For example, the arithmetic system 10 creates multiple pressing-pressure responsiveness profiles by performing the simulation to calculate first pressing-pressure responsiveness profiles indicating distributions of the pressing pressure changed in response to a change from pressure P1 to pressure P2 in the pressure chambers C1 to C4, and calculate second pressing-pressure responsiveness profiles indicating distributions of the pressing pressure changed in response to a change from pressure P3 to pressure P4 in the pressure chambers C1 to C4. The pressure P3 and the pressure P4 are different from the pressure P1 and the pressure P2.

[0058] The arithmetic system 10 may further create a new pressing-pressure responsiveness profile by interpolation or extrapolation using the pressing-pressure responsiveness profiles that have been calculated by the simulation. In one embodiment, the arithmetic system 10 may further create a pressing-pressure responsiveness profile by inputting the pressing-pressure responsiveness profiles created by the simulation into a model constructed by machine learning, and outputting a new pressing-pressure responsiveness profile from the model. The plurality of pressing-pressure responsiveness profiles created in this manner are stored in the memory 10a of the arithmetic system 10. The arithmetic system 10 creates the estimated polishing-rate responsiveness profile in the step 104 by using one of the pressing-pressure responsiveness profiles.

[0059] The above-described embodiments relate to the pressure for pressing the wafer W1

against the polishing pad 2 by the elastic membrane 34 of the polishing head 7. In one embodiment, the pressing-pressure responsiveness profile may include the pressure for pressing the retainer ring 32 of the polishing head 7 against the polishing pad 2. More specifically, the simulation may be performed using mathematical models of the elastic
5 membrane 34 of the polishing head 7, the polishing pad 2, the retainer ring 32, and the wafer W1.

[0060] Next, the step 102 will be described in detail. In this step 102, the wafer W1 is actually polished. The polishing apparatus shown in FIG. 1 presses the wafer W1 against the polishing pad 2 by the polishing head 7 to polish the wafer W1 while the pressures in the
10 pressure chambers C1 to C4 of the polishing head 7 are maintained at predetermined pressures. The pressures in the pressure chambers C1, C2, C3, and C4 of the polishing head 7 are set to predetermined pressures SP1, SP2, SP3, and SP4, respectively. In one example, the predetermined pressures SP1, SP2, SP3, and SP4 are lower than or equal to the pressure P1 used in the above-described step 101 and are higher than or equal to the pressure
15 P2. The predetermined pressures SP1, SP2, SP3, and SP4 may be different from each other, or some or all of them may be the same. The polishing of the wafer W1 is performed at least until the film thickness of the wafer W1 reaches a target value. The film-thickness sensor 42 continuously measures the film thickness of the wafer W1 from the start to the end of polishing of the wafer W1, and transmits the measurement values of the
20 film thickness to the arithmetic system 10.

[0061] Next, the step 103 will be described in detail. In this step 103, the arithmetic system 10 calculates polishing rates at the multiple measurement points on the wafer W1 by dividing a difference between an initial film thickness and a final film thickness at each of the multiple measurement points on the wafer W1 by a polishing time for the wafer W1.
25 These multiple measurement points on the wafer W1 correspond to the pressure chambers C1, C2, C3, and C4. The initial film thickness is a film thickness before the polishing of the wafer W1, and the final film thickness is a film thickness at the end of the polishing of the wafer W1. The arithmetic system 10 creates the polishing-rate profile by allotting the

calculated polishing rates to the multiple measurement points corresponding to the pressure chambers C1, C2, C3, and C4.

[0062] In the actual polishing of the wafer, set pressures in the pressure chambers C1 to C4 may change depending on the wafer structure, the film thickness, or the like. Thus, in one embodiment, a plurality of polishing-rate profiles may be created by polishing a plurality of wafers with different pressures set in the pressure chambers C1 to C4. More specifically, the plurality of wafers are pressed one by one against the polishing pad 2 with different pressures set in the pressure chambers C1 to C4 for each of the plurality of wafers, so that these plurality of wafers are polished. The arithmetic system 10 produces the plurality of polishing-rate profiles indicating distributions of the polishing rate of the plurality of polished wafers. The plurality of polishing-rate profiles created in this manner are stored in the memory 10a of the arithmetic system 10. The arithmetic system 10 creates the estimated polishing-rate responsiveness profile in the next step 104 by using one of the plurality of polishing-rate profiles.

[0063] Next, the step 104 will be described in detail. In this step 104, the arithmetic system 10 calculates by using the following formulae stored in the memory 10a,

$$\sum_{r=0}^{ra} \left| Rate(r) - \sum_{n=1}^{nt} [AP(n) * F(n) * P(n, r)] \right| \quad (1)$$

$$Resp(n, r) = F(n) * P(n, r) \quad (2)$$

where r is a radial position on the wafer W1, ra is the radius of the wafer W1, Rate (r) is a polishing rate (actually-measured value) at the radial position r, n is the number of the pressure chamber, nt is the number of pressure chambers (nt = 4 in the embodiment), AP(n) is a pressure of the gas in a n-th pressure chamber when the wafer W1 is actually polished, F(n) is a polishing-rate coefficient for the n-th pressure chamber, P(n, r) is a responsiveness of the pressing pressure at the radial position r for the n-th pressure chamber, and Resp(n, r) is a polishing-rate responsiveness at the radial position r for the n-th pressure chamber.

[0064] The arithmetic system 10 calculates a virtual polishing-rate profile by multiplying the pressing-pressure responsiveness profile by a candidate for the polishing-rate coefficient

F(n) and a predetermined pressure AP(n) and determines the polishing-rate coefficient F(n) that minimizes a difference (absolute value) between the actual polishing-rate profile and the virtual polishing-rate profile which is represented by the formula (1). A known algorithm, such as an optimization method, can be applied to determine the polishing-rate coefficient
5 F(n) that minimizes the above formula (1).

[0065] The polishing-rate coefficient F(n) is a polishing-rate coefficient for the n-th pressure chamber, while the same polishing-rate coefficient F(n) may be used for the pressure chambers C1 to C4. Alternatively, a plurality of polishing-rate coefficients F(n) corresponding to the plurality of pressure chambers C1 to C4, respectively, may be used.

10 Compared with the former, the latter can more minimize the difference between the actual polishing-rate profile and the virtual polishing-rate profile represented by the above formula (1).

[0066] The arithmetic system 10 further multiplies the pressing-pressure responsiveness profile by the determined polishing-rate coefficient F(n) to thereby calculate (create) the
15 estimated polishing-rate responsiveness profile represented by the formula (2).

[0067] Next, the above step 105 will be explained in detail. In this step 105, the wafer W2 is actually polished. The polishing apparatus shown in FIG. 1 polishes the wafer W2 by pressing the wafer W2 against the polishing pad 2 with the polishing head 7 while changing the pressure in the pressure chamber C4 and while maintaining the pressures in the
20 pressure chambers C1 to C3 of the polishing head 7 constant. For example, while the pressure in the pressure chamber C4 of the polishing head 7 is maintained at a predetermined pressure TP1, the polishing head 7 presses the wafer W2 against the polishing pad 2 to polish the wafer W2 for a predetermined first polishing time. Then, while the pressure in the pressure chamber C4 of the polishing head 7 is maintained at a
25 predetermined pressure TP2, the polishing head 7 presses the wafer W2 against the polishing pad 2 to polish the wafer W2 for a predetermined second polishing time. The pressure TP2 is different from the pressure TP1. The pressures within the pressure chambers C1 to C3 are constant. The film thickness sensor 42 continues to measure the

film thickness at multiple measurement points on the wafer W2 corresponding to the pressure chamber C4 during at least the first polishing time and the second polishing time and transmits measurement values of the film thickness to the arithmetic system 10.

[0068] Next, the step 106 will be explained in detail. In this step 106, the arithmetic system 10 calculates first polishing rates at the multiple measurement points of the wafer W2 when polished at the pressure TP1, and second polishing rates at the multiple measurement points of the wafer W2 when polished at the pressure TP2. The first polishing rates and the second polishing rates are calculated from the measurement values of the film thickness, the first polishing time, and the second polishing time. Furthermore, the arithmetic system 10 divides differences between the first polishing rates and the second polishing rates at the multiple measurement points corresponding to the pressure chamber C4 by a difference between the pressure TP1 and the pressure TP2, thereby determining (or calculating) the polishing-rate responsiveness to the pressure change in the pressure chamber C4. The arithmetic system 10 creates the actual polishing-rate responsiveness profile by allotting the calculated polishing-rate responsiveness to the multiple measurement points corresponding to the pressure chamber C4.

[0069] FIG. 6 is a graph showing an example of the estimated polishing-rate responsiveness profiles calculated by the simulation for all pressure chambers C1 to C4, and FIG. 7 is a graph showing an example of the actual polishing-rate responsiveness profiles for all pressure chambers C1 to C4 calculated based on actual polishing. Vertical axis in FIGS. 6 and 7 represents the polishing rate that changes in response to the change in unit pressure within each pressure chamber, and horizontal axis represents the radial position of the wafer.

[0070] Symbol ER1 in FIG. 6 represents an estimated polishing-rate responsiveness profile regarding the pressure chamber C1, symbol ER2 represents an estimated polishing-rate responsiveness profile regarding the pressure chamber C2, symbol ER3 represents an estimated polishing-rate responsiveness profile regarding the pressure chamber C3, and symbol ER4 represents an estimated polishing-rate responsiveness profile regarding the pressure chamber C4. Symbol RR1 in FIG. 7 represents an actual polishing-rate

responsiveness profile regarding the pressure chamber C1, symbol RR2 represents an actual polishing-rate responsiveness profile regarding the pressure chamber C2, symbol RR3 represents an actual polishing-rate responsiveness profile regarding pressure chamber C3, and symbol RR4 represents an actual polishing-rate responsiveness profile regarding the pressure chamber C4.

[0071] As can be seen from the comparison between FIG. 6 and FIG. 7, the estimated polishing-rate responsiveness profiles ER1, ER2, ER3 are similar to the actual polishing-rate responsiveness profiles RR1, RR2, RR3, but the estimated polishing-rate responsiveness profiles ER4 is significantly different from the actual polishing-rate responsiveness profile RR4. As a result, if the estimated polishing-rate responsiveness profiles are created by the simulation for all of the pressure chambers C1 to CP4, an intended film thickness profile may not be achieved.

[0072] According to the embodiment described above, as shown in FIG. 8, the estimated polishing-rate responsiveness profiles ER1, ER2, ER3 created by the simulation and the actual polishing-rate responsiveness profile RR4 obtained by the actual polishing are combined to provide the accurate hybrid polishing-rate responsiveness profile.

[0073] Furthermore, use of the simulation can reduce the number of wafers (workpieces) and working time for obtaining the polishing-rate responsiveness can be reduced. Specifically, the number of wafers actually polished in the step 102 can be reduced. The number of wafers actually polished in the step 102 may be one or more, and the number of wafers required to obtain the polishing-rate profile in the step 102 can be less than the number of pressure chambers C1 to C3 of the polishing head 7.

[0074] The hybrid polishing-rate responsiveness profile obtained as described above can be used to optimize polishing conditions for other wafer to be polished next. In one embodiment, the arithmetic system 10 creates a current film-thickness profile of the other wafer from measurement values of the film thickness obtained from the film-thickness sensor 42 (see FIG. 1) during polishing of the other wafer, and determines pressures in the pressure chambers C1 to C4 for minimizing a difference between the current film-thickness

profile and a target film-thickness profile based on the hybrid polishing-rate responsiveness profile. In another embodiment, the arithmetic system 10 creates a film-thickness profile before polishing of a wafer and a film-thickness profile after polishing of the wafer which has been used to create the polishing-rate profile, and determines pressures in the pressure chambers C1 to C4 based on the film-thickness profile before the polishing, the film-thickness profile after the polishing, a target film-thickness profile, and the hybrid polishing-rate responsiveness profile.

[0075] Next, another embodiment for creating a hybrid polishing-rate responsiveness profile will be described. Details of this embodiment, which will not be particularly described, are the same as those of the above-mentioned embodiments, and therefore, redundant descriptions thereof will be omitted.

[0076] As well as the embodiments described above, the arithmetic system 10 performs simulation to create estimated polishing-rate responsiveness profiles that represent distributions of polishing-rate responsiveness to pressure changes in the pressure chambers C1 to C3, creates actual polishing-rate responsiveness profile that represents a distribution of polishing-rate responsiveness to pressure change in the pressure chamber C4 using polishing results of a wafer as a workpiece, and creates a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profiles and the actual polishing-rate responsiveness profile.

[0077] FIG. 9 is a flowchart for explaining an embodiment of creating the hybrid polishing-rate responsiveness profile.

In step 201, the polishing apparatus shown in FIG. 1 polishes a wafer W3 by pressing the wafer W3 against the polishing pad 2 with the polishing head 7 while the pressures in the pressure chambers C1, C2, C3, and C4 of the polishing head 7 are maintained at predetermined pressures UP1, UP 2, UP3, and UP4. The predetermined pressures UP1, UP 2, UP3, and UP4 may be different from each other, or some or all of them may be the same. The polishing of the wafer W3 is performed, as described above, by pressing the surface (surface to be polished) of the wafer W3 against the polishing

surface 2a by the polishing head 7 in the presence of the polishing liquid on the polishing surface of the polishing pad 2, while the polishing table 5 and the polishing pad 2 are rotated and the wafer W3 is rotated by the polishing head 7.

[0078] During polishing of the wafer W3, the film-thickness sensor 42 measures film thickness at multiple measurement points on the wafer W3 while the film-thickness sensor 42 moves across the wafer W3. In this embodiment, the multiple measurement points are aligned along the radial direction of the wafer W3. The measurement values of the film thickness are transmitted from the film-thickness sensor 42 to the arithmetic system 10. The polishing of the wafer W3 is terminated when the film thickness of the wafer W3 reaches a target value. The film-thickness sensor 42 continuously measures the film thickness of the wafer W3 from the start to the end of polishing of the wafer W3, and transmits the measurement values of the film thickness to the arithmetic system 10.

[0079] In step 202, the arithmetic system 10 creates an actual polishing-rate profile indicating a distribution of polishing rates of the polished wafer W3. This polishing-rate profile represents polishing rates at respective radial positions on the wafer W3. This step 202 is performed in the same manner as the step 103 described above, and its repetitive explanations will be omitted.

[0080] In step 203, the arithmetic system 10 performs simulation to calculate pressing-pressure responsiveness profiles indicating distributions of the pressing pressures, which are applied from the wafer W3 to the polishing pad 2, changed in response to changes in unit pressure in the pressure chambers C1 to C3. This simulation is performed in the same manner as the simulation in the step 101 in the above-described embodiment, and its repetitive explanations will be omitted. In one embodiment, the step 203 may be performed before the step 201.

[0081] In step 204, the arithmetic system 10 creates a first polishing-rate profile based on the pressures UP1, UP2, UP3 in the pressure chambers C1 to C3 set in the step 201, the pressing-pressure responsiveness profiles calculated in the step 203, and first polishing-rate coefficient. The first polishing-rate profile represents a distribution of polishing rates of the

wafer W3 for the pressure chambers C1 to C3. The first polishing-rate profile is expressed by

$$\text{first polishing rate profile} = \sum_{n=1}^{nt} [AP(n) * F(n) * P_{sim}(n, r)] \quad (3)$$

where, r is radial position on the wafer W3, n is the number of the pressure chamber, nt is the number of pressure chambers (nt=3 in this embodiment), AP(n) is a pressure of the gas in a n-th pressure chamber when the wafer W3 is actually polished (i.e., the pressures UP1, UP2, UP3), F(n) is the first polishing-rate coefficient for the n-th pressure chamber, and P_{sim}(n, r) is pressing-pressure responsiveness at the radial position r for the n-th pressure chamber.

[0082] In step 205, the polishing apparatus shown in FIG. 1 actually polishes a wafer W4 by pressing the wafer W4 against the polishing pad 2 with the polishing head 7, while the pressures in the pressure chambers C1 to C3 of the polishing head 7 are kept constant and while the pressure in the pressure chamber C4 is changed. The polishing of the wafer W4 is performed, as described above, by pressing the surface (surface to be polished) of the wafer W4 against the polishing surface 2a by the polishing head 7 in the presence of the polishing liquid on the polishing surface of the polishing pad 2, while the polishing table 5 and the polishing pad 2 are rotated and the wafer W4 is rotated by the polishing head 7. This step 205 is performed in the same manner as the step 105 described above, and its repetitive explanations will be omitted.

[0083] During polishing of the wafer W4, the film-thickness sensor 42 measures film thickness at multiple measurement points on the wafer W4 while the film-thickness sensor 42 moves across the wafer W4. In this embodiment, the multiple measurement points are aligned along the radial direction of the wafer W4. The measurement values of the film thickness are transmitted from the film-thickness sensor 42 to the arithmetic system 10. The polishing of the wafer W4 is terminated when the film thickness of the wafer W4 reaches a target value. The film-thickness sensor 42 continuously measures the film

thickness of the wafer W4 from the start to the end of polishing of the wafer W4, and transmits the measurement values of the film thickness to the arithmetic system 10.

[0084] In step 206, the arithmetic system 10 calculates polishing rates of the wafer W4 corresponding to different pressures in the pressure chamber C4 from the measurement values of the film thickness, and calculates polishing-rate responsiveness to the pressure change in the pressure chamber C4.

In step 207, the arithmetic system 10 creates a provisional polishing-rate responsiveness profile from the polishing-rate responsiveness for the pressure chamber C4 determined in the step 206. The steps 206 and 207 are performed in the same manner as the steps 106 and 107 described above, and their repetitive explanations will be omitted.

[0085] In step 208, the arithmetic system 10 creates a second polishing-rate profile based on the pressure UP4 in the pressure chamber C4 set in the step 201, the provisional polishing-rate responsiveness profile for the pressure chamber C4 created in the step 207, and second polishing-rate coefficient. The second polishing-rate profile represents a distribution of polishing rates of the wafer W4 for the pressure chamber C4. The second polishing-rate profile is expressed by

$$\text{second polishing rate profile} = AP(m) * F(m) * R_{real}(m, r) \quad (4)$$

where, r is radial position on the wafer W4, m is the number of the pressure chamber (m=4 in this embodiment), AP(m) is a pressure of the gas in m-th pressure chamber when the wafer W4 is actually polished (i.e., the pressure UP4), F(m) is the second polishing-rate coefficient for the m-th pressure chamber, and Rreal(m, r) is provisional polishing-rate responsiveness profile at the radial position r for the m-th pressure chamber.

In one embodiment, the steps 205 to 208 may be performed before the steps 201 to 204.

[0086] In step 209, the arithmetic system 10 combines the first polishing-rate profile and the second polishing-rate profile to create a third polishing-rate profile. The third polishing-rate profile is expressed as follows.

$$\sum_{n=1}^{nt} [AP(n) * F(n) * P_{sim}(n, r)] + AP(m) * F(m) * R_{real}(m, r) \quad (5)$$

[0087] In step 210, the arithmetic system 10 determines the first polishing-rate coefficient $F(n)$ and the second polishing-rate coefficient $F(m)$ that minimize a difference (absolute value) between the actual polishing-rate profile created in the step 202 and the third polishing-rate profile created in the step 209. The difference between the actual polishing-rate profile and the third polishing-rate profile is expressed by

$$\sum_{r=0}^{ra} \left| Rate(r) - \left[\sum_{n=1}^{nt} [AP(n) * F(n) * P_{sim}(n, r)] + AP(m) * F(m) * R_{real}(m, r) \right] \right| \quad \cdot \cdot \cdot (6)$$

where, r represents a radial position on the wafer, ra represents the radius of the wafer, and $Rate(r)$ represents the polishing rate (actually measured value) at the radial position r calculated in the step 202.

A known algorithm, such as an optimization method, can be applied to the algorithm for determining the first polishing-rate coefficient $F(n)$ and the second polishing-rate coefficient $F(m)$ that minimize the above equation (6).

[0088] In step 211, the arithmetic system 10 multiplies the determined first polishing-rate coefficient $F(n)$ by the pressing-pressure responsiveness profile $P_{sim}(n, r)$ to create an estimated polishing-rate responsiveness profile. The arithmetic system 10 multiplies the determined second polishing-rate coefficient $F(m)$ by the provisional polishing-rate responsiveness profile $R_{real}(m, r)$ to create an actual polishing-rate responsiveness profile.

In step 212, the arithmetic system 10 creates a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile created in the step 210.

[0089] The above steps 211 and 212 are expressed by

$$Resp(l, r) = F(n) * P_{sim}(n, r) + F(m) * R_{real}(m, r) \quad (7)$$

where, $Resp(l, r)$ represents the polishing-rate responsiveness at the radial position r regarding the l -th pressure chamber. The arithmetic system 10 has the above equations (1)

to (7) stored in its memory 10a.

[0090] According to the embodiment described above, the accurate hybrid polishing-rate responsiveness profile can be obtained from the combination of the estimated polishing-rate responsiveness profile generated by the simulation and the actual polishing-rate responsiveness profile obtained by actual polishing. Furthermore, use of the simulation can reduce the number of wafers (workpieces) and work time required to obtain the polishing-rate responsiveness.

[0091] The hybrid polishing-rate responsiveness profile obtained as described above can be used to optimize polishing conditions for other wafer to be polished next. In one embodiment, the arithmetic system 10 creates a current film-thickness profile of the other wafer from measurement values of the film thickness obtained from the film-thickness sensor 42 (see FIG. 1) during polishing of the other wafer, and determines pressures in the pressure chambers C1 to C4 for minimizing a difference between the current film-thickness profile and a target film-thickness profile based on the hybrid polishing-rate responsiveness profile. In another embodiment, the arithmetic system 10 creates a film-thickness profile before polishing of a wafer and a film-thickness profile after polishing of the wafer which has been used to create the polishing-rate profile, and determines pressures in the pressure chambers C1 to C4 based on the film-thickness profile before the polishing, the film-thickness profile after the polishing, a target film-thickness profile, and the hybrid polishing-rate responsiveness profile.

[0092] In the embodiment described with reference to the flowchart of FIG. 3, the step of determining the polishing-rate coefficient for bringing the simulation results for the pressure chambers C1 to C3 closer to the actual polishing results is performed independently of the step of calculating the actual polishing-rate responsiveness profile for the pressure chamber C4. In contrast, in the embodiment described with reference to the flowcharts of FIGS. 9 and 10, the step of determining the first polishing-rate coefficient and the second polishing-rate coefficient for the pressure chambers C1 to C4 is performed according to substantially the same operations as the step of calculating the estimated polishing-rate responsiveness

profile for the pressure chambers C1 to C3 and the step of calculating the actual polishing-rate responsiveness profile for the pressure chamber C4. Actual polishing results have shown the fact that the embodiment described with reference to the flowcharts of FIGS. 9 and 10 can create a more accurate polishing-rate responsiveness profile than that in the

5 embodiment described with reference to the flowchart of FIG. 3.

[0093] In the embodiments described so far, the hybrid polishing-rate responsiveness profile for four pressure chambers C1 to C4 are obtained. In one embodiment, a hybrid polishing-rate responsiveness profile may be determined for three or less, or five or more pressure chambers as well.

10 [0094] The arithmetic system 10 operates according to instructions included in the programs electrically stored in the memory 10a, and executes the operations of each of the embodiments described above. Specifically, the arithmetic system 10 uses the simulation to create an estimated polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in a first pressure chamber (for example,

15 the pressure chamber CP1), creates an actual polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in a second pressure chamber (for example, the pressure chamber CP4) using polishing results of a workpiece, and creates a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile.

20 [0095] The programs for causing the arithmetic system 10 to execute the operations of each of the embodiments described above are stored in a computer-readable storage medium which is a non-transitory tangible medium, and are provided to the arithmetic system 10 via the storage medium. Alternatively, the programs may be input to the arithmetic system 10 via a communication network, such as the Internet or a local area network.

25 [0096] 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:

1. A method of creating a polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in a first pressure chamber and a second pressure chamber when a workpiece used for manufacturing a semiconductor device is pressed against a polishing pad with an elastic membrane forming the first pressure chamber and the second pressure chamber, the method comprising:

creating an estimated polishing-rate responsiveness profile using simulation, the estimated polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the first pressure chamber;

creating an actual polishing-rate responsiveness profile using polishing results of a workpiece, the actual polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the second pressure chamber; and

creating a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile.

2. The method according to claim 1, wherein creating the estimated polishing-rate responsiveness profile comprises:

performing simulation to calculate a pressing-pressure responsiveness profile indicating a distribution of pressing pressure changed in response to a change in unit pressure in the first pressure chamber, the pressing pressure being applied from a first workpiece to the polishing pad in the simulation;

polishing the first workpiece by pressing the first workpiece against the polishing pad while maintaining a predetermined pressure in the first pressure chamber;

creating a polishing-rate profile indicating a distribution of polishing rate of the polished first workpiece; and

creating the estimated polishing-rate responsiveness profile based on the pressing-pressure responsiveness profile, the predetermined pressure, and the polishing-rate profile.

3. The method according to claim 2, wherein creating the estimated polishing-rate responsiveness profile comprises:

5 multiplying the pressing-pressure responsiveness profile by the predetermined pressure and a polishing-rate coefficient to create a virtual polishing-rate profile;

determining the polishing-rate coefficient that minimizes a difference between the polishing-rate profile and the virtual polishing-rate profile; and

10 multiplying the pressing-pressure responsiveness profile by the determined polishing-rate coefficient to create the estimated polishing-rate responsiveness profile.

4. The method according to claim 2, wherein calculating the pressing-pressure responsiveness profile comprises:

15 performing simulation to calculate a distribution of first pressing pressure when a gas having a first pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a second pressure is supplied into the first pressure chamber; and

20 calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the first pressure and the second pressure at each of radial positions on the first workpiece.

5. The method according to claim 2, wherein creating the actual polishing-rate responsiveness profile comprises:

25 polishing a second workpiece by pressing the second workpiece against the polishing pad while changing the pressure in the second pressure chamber;

calculating polishing rates of the second workpiece corresponding to different pressures in the second pressure chamber; and

calculating polishing-rate responsiveness to pressure change in the second pressure

chamber.

6. The method according to claim 1, wherein creating the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile comprises:

5 polishing a first workpiece by pressing the first workpiece against the polishing pad while a predetermined first pressure is maintained in the first pressure chamber and a predetermined second pressure is maintained in the second pressure chamber;

 creating an actual polishing-rate profile indicating a distribution of polishing rates of the polished first workpiece;

10 creating a first polishing-rate profile based on the first pressure, a first polishing-rate coefficient, and a pressing-pressure responsiveness profile calculated by simulation;

 creating a second polishing-rate profile based on the second pressure, a second polishing-rate coefficient, and a provisional polishing-rate responsiveness profile created from polishing results of a second workpiece;

15 creating a third polishing-rate profile by combining the first polishing-rate profile and the second polishing-rate profile;

 determining the first polishing-rate coefficient and the second polishing-rate that minimize a difference between the actual polishing-rate profile and the third polishing-rate profile;

20 creating the estimated polishing-rate responsiveness profile by multiplying the determined first polishing-rate coefficient by the pressing-pressure responsiveness profile; and

 creating the actual polishing-rate responsiveness profile by multiplying the determined second polishing-rate coefficient by the provisional polishing-rate
25 responsiveness profile.

7. The method according to claim 6, wherein calculating the pressing-pressure responsiveness profile comprises:

performing simulation to calculate a distribution of first pressing pressure when a gas having a third pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a fourth pressure is supplied into the first pressure chamber; and

5 calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the third pressure and the fourth pressure at each of radial positions on the first workpiece.

10 8. A polishing method comprising:

 optimizing a polishing condition for a workpiece using the hybrid polishing-rate responsiveness profile created by the method according to any one of claims 1 to 7; and

 polishing the workpiece by pressing the workpiece against the polishing pad with the elastic membrane under the optimized polishing condition.

15

 9. A polishing apparatus for polishing a workpiece, comprising:

 a polishing table configured to support a polishing pad having a polishing surface;

 a polishing head configured to press the workpiece against the polishing surface;

and

20 an arithmetic system including a memory storing a program therein and a processor configured to execute arithmetic operations according to instructions included in the program,

 wherein the polishing head has an elastic membrane forming a first pressure chamber and a second pressure chamber,

25 the arithmetic system is configured to create a polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the first pressure chamber and the second pressure chamber when the workpiece is pressed against the polishing pad with the elastic membrane,

the arithmetic system is configured to:

create an estimated polishing-rate responsiveness profile using simulation, the estimated polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the first pressure chamber;

5 create an actual polishing-rate responsiveness profile using polishing results of a workpiece, the actual polishing-rate responsiveness profile indicating a distribution of polishing-rate responsiveness to pressure change in the second pressure chamber; and

create a hybrid polishing-rate responsiveness profile by combining the estimated polishing-rate responsiveness profile and the actual polishing-rate responsiveness profile.

10

10. The polishing apparatus according to claim 9, wherein the arithmetic system is configured to:

perform simulation to calculate a pressing-pressure responsiveness profile indicating a distribution of pressing pressure changed in response to a change in unit
15 pressure in the first pressure chamber, the pressing pressure being applied from a first workpiece to the polishing pad in the simulation;

polish the first workpiece by pressing the first workpiece against the polishing pad while maintaining a predetermined pressure in the first pressure chamber;

20 create a polishing-rate profile indicating a distribution of polishing rate of the polished first workpiece; and

create the estimated polishing-rate responsiveness profile based on the pressing-pressure responsiveness profile, the predetermined pressure, and the polishing-rate profile.

25 11. The polishing apparatus according to claim 10, wherein the arithmetic system is configured to:

multiply the pressing-pressure responsiveness profile by the predetermined pressure and a polishing-rate coefficient to create a virtual polishing-rate profile;

determine the polishing-rate coefficient that minimizes a difference between the

polishing-rate profile and the virtual polishing-rate profile; and

multiply the pressing-pressure responsiveness profile by the determined polishing-rate coefficient to create the estimated polishing-rate responsiveness profile.

5 12. The polishing apparatus according to claim 10, wherein the arithmetic system is configured to calculate the pressing-pressure responsiveness profile by:

performing simulation to calculate a distribution of first pressing pressure when a gas having a first pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a second pressure is supplied into the first
10 pressure chamber; and

calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the first pressure and the second pressure at each of radial positions on the first workpiece.

15

13. The polishing apparatus according to claim 10, wherein the arithmetic system is configured to create the actual polishing-rate responsiveness profile by:

polishing a second workpiece by pressing the second workpiece against the polishing pad while changing the pressure in the second pressure chamber;

20 calculating polishing rates of the second workpiece corresponding to different pressures in the second pressure chamber; and

calculating polishing-rate responsiveness to pressure change in the second pressure chamber.

25 14. The polishing apparatus according to claim 9, wherein the arithmetic system is configured to:

create an actual polishing-rate profile indicating a distribution of polishing rates of a first workpiece that has been polished by being pressed by the polishing head against the

- polishing pad while a predetermined first pressure is maintained in the first pressure chamber and a predetermined second pressure is maintained in the second pressure chamber;
- create a first polishing-rate profile based on the first pressure, a first polishing-rate coefficient, and a pressing-pressure responsiveness profile calculated by simulation;
- 5 create a second polishing-rate profile based on the second pressure, a second polishing-rate coefficient, and a provisional polishing-rate responsiveness profile created from polishing results of a second workpiece;
- create a third polishing-rate profile by combining the first polishing-rate profile and the second polishing-rate profile;
- 10 determine the first polishing-rate coefficient and the second polishing-rate that minimize a difference between the actual polishing-rate profile and the third polishing-rate profile;
- create the estimated polishing-rate responsiveness profile by multiplying the determined first polishing-rate coefficient by the pressing-pressure responsiveness profile;
- 15 and
- create the actual polishing-rate responsiveness profile by multiplying the determined second polishing-rate coefficient by the provisional polishing-rate responsiveness profile.
- 20 15. The polishing apparatus according to claim 14, wherein the arithmetic system is configured to calculate the pressing-pressure responsiveness profile by:
- performing simulation to calculate a distribution of first pressing pressure when a gas having a third pressure is supplied into the first pressure chamber and a distribution of second pressing pressure when a gas having a fourth pressure is supplied into the first
- 25 pressure chamber; and
- calculating a pressing pressure changed in response to a change in unit pressure of gas in the first pressure chamber by dividing a difference between the first pressing pressure and the second pressing pressure by a difference between the third pressure and the fourth

pressure at each of radial positions on the first workpiece.

16. The polishing apparatus according to claim 9, wherein the arithmetic system is configured to optimize a polishing condition using the hybrid polishing-rate responsiveness
5 profile, and

the polishing head is configured to polish a workpiece by pressing the workpiece against the polishing pad with the elastic membrane under the optimized polishing condition.