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SUBSTRATE PROCESSING APPARATUS AND SUBSTRATE PROCESSING METHOD

Abstract

A substrate processing apparatus includes: a processing container having an internal processing space which is depressurized to a pressure lower than atmospheric pressure, and an opening through which a substrate is loaded into and unloaded from the processing space; a substrate holding/rotating mechanism configured to horizontally hold the substrate and including a substrate holder for holding the substrate inside the processing space and a driving force source configured to generate a driving force for rotationally driving the substrate holder; a housing having an internal space hermetically isolated from the processing space; a horizontal movement mechanism configured to move the housing in a horizontal direction so as to move the substrate holder in the horizontal direction; and a gas nozzle configured to inject a gas so as to irradiate a gas cluster onto an upper surface of the substrate held by the substrate holder.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is based upon and claims the benefit of priority from Japanese Patent Application No. 2024-024823, filed on Feb. 21, 2024, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present disclosure relates to a substrate processing apparatus and a substrate processing method.

BACKGROUND

[0003] In manufacturing semiconductor devices, the adhesion of particles to a substrate is a factor that deteriorates product yield. For this reason, before and after substrate processing such as film formation, cleaning of the substrate is performed to remove such particles. Methods of cleaning the substrate include wet cleaning and dry cleaning. Gas cluster cleaning is one type of dry cleaning. The gas cluster cleaning is a method in which a gas cluster is irradiated onto a surface of the substrate placed inside a vacuum processing chamber, and the physical energy of the gas cluster peels off the particles adhered to the surface of the substrate.

[0004] An apparatus for performing the gas cluster cleaning is disclosed in, for example, Patent Document 1. The apparatus disclosed in Patent Document 1 adjusts an irradiation position of the gas cluster by moving a stage which holds a substrate using an XY table equipped with an X-axis rail and a Y-axis rail. The stage and the XY table are exposed to an internal atmosphere of a vacuum processing chamber.

PRIOR ART DOCUMENT

Patent Document

[0005] Patent Document 1: Japanese Laid-Open Patent Publication No. 2015-026745

SUMMARY

[0006] According to one embodiment of the present disclosure, a substrate processing apparatus includes: a processing container having a processing space provided in an interior of the processing container, which is depressurized to a pressure lower than atmospheric pressure, and an opening through which a substrate is loaded into and unloaded from the processing space; a substrate holding/rotating mechanism configured to hold the substrate in a horizontal posture and rotate the substrate around a vertical axis, and including a substrate holder configured to hold the substrate inside the processing space and a driving force source configured to generate a driving force for rotationally driving the substrate holder; a housing having an internal space hermetically isolated from the processing space, wherein the driving force source of the substrate holding/rotating mechanism is accommodated in the internal space; a horizontal movement mechanism configured to move the housing in a horizontal direction so as to move the substrate holder in the horizontal direction; and a gas nozzle configured to inject a gas so as to irradiate a gas cluster onto an upper surface of the substrate held by the substrate holder.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0007] The accompanying drawings, which are incorporated in and constitute a portion of the specification, illustrate embodiments of the present disclosure, and together with the general description given above and the detailed description of the embodiments given below, serve to explain the principles of the present disclosure.

[0008] FIG. **1** is a schematic transverse cross-sectional view of a substrate processing system according to an embodiment of a substrate processing apparatus.

[0009] FIG. **2**A is a schematic longitudinal cross-sectional view illustrating an embodiment of a gas cluster cleaning unit incorporated in the substrate processing system, which schematically illustrates a state when a gas cluster cleaning is performed on a substrate.

[0010] FIG. **2**B is a view schematically illustrating a state in which the substrate is loaded into or unloaded from a processing container in the gas cluster cleaning unit illustrated in FIG. **2**A.

[0011] FIG. **3**A is a plan view illustrating a configuration example of the gas cluster cleaning unit in which a ceiling wall is removed from the processing container, which illustrates a state in which a housing and a rotational stage are at a substrate transfer position.

[0012] FIG. **3**B is a view illustrating a state in which the housing and the rotational stage are at a substrate processing position in the gas cluster cleaning unit illustrated in FIG. **3**A.

[0013] FIG. **4** is a view illustrating a gas nozzle and a gas supply mechanism.

[0014] FIGS. **5**A to **5**F are operational views illustrating a transition of a positional relationship between the processing chamber, the substrate, and the gas nozzle as viewed directly from above when the substrate is loaded or unloaded and the substrate is processed.

[0015] FIG. **6** is a longitudinal cross-sectional view illustrating another embodiment of the gas cluster cleaning unit.

DETAILED DESCRIPTION

[0016] Hereinafter, a configuration of a substrate processing system **100** according to an embodiment of a substrate processing apparatus will be described with reference to the accompanying drawings. In this specification and drawings, for the clarification of a positional relationship, an XYZ orthogonal coordinate system in which an X-axis direction, a Y-axis direction, and a Z-axis direction are orthogonal to one another is defined, and descriptions will be given with reference to this coordinate system as necessary. A positive Z-axis direction is defined as a vertical upward direction. In the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the present disclosure. However, it will be apparent to one of ordinary skill in the art that the present disclosure may be practiced without these specific details. In other instances, well-known methods, procedures, systems, and constituent elements have not been described in detail so as not to unnecessarily obscure aspects of the various embodiments.

[0017] As illustrated in FIG. **1**, the substrate processing system **100** includes three loading/unloading ports **104** arranged in the X-axis direction. A front opening unified pod (FOUP) **102**, which is a sealed substrate transfer container accommodating, for example, 25 substrates W (for example, semiconductor wafers), is placed on each of the three loading/unloading ports **104**. An atmospheric transfer chamber **106** kept at atmospheric pressure is provided on an inner side of the loading/unloading ports **104**. A gate door **108**, which is opened and closed together with a lid of the FOUP **102**, is provided on a front wall of the atmospheric transfer chamber **106**.

[0018] Two load lock chambers **110** and **112** are connected to a rear wall of the atmospheric transfer chamber **106**. An internal atmosphere of each of the load lock chambers **110** and **112** may be switched between a normal pressure (atmospheric pressure) atmosphere and a medium vacuum atmosphere of about 1 Pa by a vacuum pump and a leak valve (all not illustrated). In FIG. **1**, a member designated by reference symbol G denotes a gate valve.

[0019] The atmospheric transfer chamber **106** is provided with a first substrate transfer mechanism

114 for transferring the substrate W. An alignment chamber **116** is connected to a left wall of the atmospheric transfer chamber **106**. The alignment chamber **116** is provided with an aligner (not illustrated) for aligning a notch of the substrate W. The first substrate transfer mechanism **114** delivers the substrate W to the FOUP **102**, the load lock chambers **110** and **112**, and the alignment chamber **116**.

[0020] A vacuum transfer chamber **118** is connected to rear sides of the load lock chambers **110** and **112**. The vacuum transfer chamber **118** is suctioned by a vacuum pump (not illustrated) and maintained at a medium vacuum of, for example, about 1 Pa.

[0021] A plurality of processing units **120** is connected to the vacuum transfer chamber **118**. At least one of the plurality of processing units **120** is a gas cluster cleaning unit **10** described later. At least one of the other processing units **120** may be, for example, a vacuum bake unit for removing organic compounds from the substrate W before a gas cluster cleaning is performed. At least one of the other processing units **120** may be a film formation unit which performs a vacuum film formation process based on chemical vapor deposition (CVD) or sputtering with respect to the substrate W that has been subjected to the gas cluster cleaning.

[0022] The vacuum transfer chamber **118** is provided with a second substrate transfer mechanism **122** for transferring the substrate W. For example, the second substrate transfer mechanism **122** includes a substrate holder **124** of a fork shape, which functions as an end effector. The second substrate transfer mechanism **122** delivers the substrate W to the load lock chambers **110** and **112**, and the processing units **120**.

[0023] The substrate processing system **100** is provided with a control device **130**. The control device **130** includes, for example, a computer equipped with an operation controller **132** and a storage **134**.

[0024] The storage **134** stores a processing recipe that defines various processing sequences executed by the substrate processing system **100** and a control program for controlling various processes. The control device **130** controls operations of the substrate processing system **100** by reading and executing the processing recipe and the program stored in the storage **134**.

[0025] The program may be recorded in a non-transitory computer-readable storage medium and installed from a storage medium in the storage **134** of the control device **130**. Examples of the computer-readable storage medium may include a magnetic disk such as a hard disk drive (HDD) or a floppy disk (FD), an optical disc such as a compact disc (CD), a magneto-optical (MO) disk, a semiconductor memory such as a solid-state drive (SSD) or a memory card, and the like.

[0026] In the above-described substrate processing system **100**, the first substrate transfer mechanism **114** takes the substrate W out of the FOUP **102** placed on the loading/unloading port **104** to load the same into the load lock chamber **110** (or **112**). When the interior of the load lock chamber is depressurized to the medium vacuum, the second substrate transfer mechanism **122** takes the substrate W out of the load lock chamber **110** (or **112**) to load the substrate W into a predetermined processing unit among the plurality of processing units **120**. An interior of the respective processing unit **120** is depressurized to a high vacuum, and predetermined vacuum processing is performed in the interior of the processing unit **120**. The substrate W that has been subjected to the predetermined vacuum processing in one or plural processing units **120** is loaded into the load lock chamber **110** (or **112**) by the second substrate transfer mechanism **122**. When the interior of the load lock chamber **110** (or **112**) is increased to atmospheric pressure, the first substrate transfer mechanism **114** takes the processed substrate W out of the load lock chamber **110** (or **112**) and stores the same in the original FOUP **102** placed on the loading/unloading port **104**. In a series of operations described above, the gate valve G is appropriately opened and closed.

[0027] An overall configuration and operation of the substrate processing system **100** described above are well known in a multi-chamber-type vacuum processing system, and thus detailed descriptions thereof will be omitted. In addition, the overall configuration of the substrate processing system **100** described above is merely one example of a configuration of a substrate processing system which may incorporate the gas cluster cleaning unit **10** described below. Various modifications may be added to such a configuration example.

[0028] Next, one example of the configuration of the gas cluster cleaning unit **10** will be described with reference to FIGS. **2**A and **2**B, and FIGS. **3**A and **3**B. FIGS. **2**A and **2**B are longitudinal cross-sectional views schematically illustrating the configuration of the gas cluster cleaning unit **10**. Herein, a horizontal positional relationship between constituent elements may be different from that of the actual gas cluster cleaning unit **10** in order to represent a plurality of constituent elements in the same cross section. The horizontal positional relationship between the constituent elements will be described with reference to FIGS. **3**A and **3**B.

[0029] The gas cluster cleaning unit **10** includes a processing container **11** configured as a vacuum processing chamber. A processing space (processing chamber) **12** is defined inside the processing container **11**. An exhaust port **13** is provided in a bottom wall of the processing container **11**. The processing space **12** may be depressurized to a high vacuum of about 1×10.sup.−5 Pa via the exhaust port **13** by a vacuum pump, for example, a turbo-molecular pump **14** (TMP).

[0030] An opening **15** is provided in one sidewall of the processing container **11**. The opening **15** may be hermetically sealed by an air-tight door such as a gate valve **16** (corresponding to the gate valve G in FIG. **1**). The substrate holder **124** of the second substrate transfer mechanism **122** (see FIG. **1**) may load or unload the substrate W into or from the processing space **12** via the opening **15** with the gate valve **16** open while holding the substrate W.

[0031] A swivel housing **20** is provided inside the processing space **12**. The housing **20** has an internal space **21** that is hermetically isolated from an atmosphere of the processing space **12**. A hollow swivel shaft **22** extends vertically downward from a bottom surface of the housing **20**. The swivel shaft **22** penetrates a bottom wall of the processing container **11** and extends outward of the processing container **11**.

[0032] As illustrated in FIG. **2**A, a swivel-shaft drive mechanism **23** for rotating the swivel shaft **22** around a vertical axis is provided outside the processing container **11**. The swivel-shaft drive mechanism **23** may be constituted with, for example, an electric rotary motor **24** and a power transmission mechanism such as a transmission gear, a timing belt or the like. The electric rotary motor **24** may directly rotate the swivel shaft **22**.

[0033] The electric rotary motor **24** may be any motor as long as it may accurately determine swivel angle positions of the swivel shaft **22** and the housing **20** coupled to the swivel shaft **22**. For example, a stepping motor or a servo motor with a rotary encoder may be used as the electric rotary motor **24**.

[0034] A rotational stage **30** is provided inside the processing space (processing chamber) **12**. The substrate W to be processed is held by the rotational stage **30** in a horizontal posture in a state in which a surface (front surface) to be processed of the substrate W faces upward. As illustrated in FIG. **3**A, the rotational stage **30** includes a disc-like plate **31** having approximately the same shape as the substrate W, and a plurality of (for example, six) substrate holding hooks **32** provided on a peripheral portion of the plate **31**.

[0035] As illustrated in FIG. **2**A, a rotary shaft **33** extends vertically downward from a bottom surface of the center of the plate **31**. The rotary shaft **33** penetrates a ceiling wall of the housing **20** and extends into the internal space **21** of the housing **20**. A rotation driver **34** configured to rotate the rotational stage **30** around a vertical axis is provided in the internal space **21** of the housing **20** and is fixed to a wall of the housing **20**. The rotation driver **34** is constituted with, for example, an electric rotary motor **35**, which is a driving force generation source. An extension portion of a rotational shaft of the electric rotary motor **35** may serve as the rotary shaft **33** of the rotational stage **30**. Further, the rotational shaft of the electric rotary motor **35** and the rotary shaft **33** of the rotational stage **30** may be arranged coaxially and coupled to each other. Further, the electric rotary motor **35** may be configured to rotate the rotary shaft **33** via a power transmission mechanism (a gear box, a belt, and the like) arranged in the internal space **21** of the housing **20**. The rotational

stage **30**, the rotary shaft **33**, and the rotation driver **34** (the electric rotary motor **35**) constitute a substrate holding/rotating mechanism.
[0036] By driving the electric rotary motor **35**, the rotational stage **30** and the substrate W held thereon may be rotated around the vertical axis. The electric rotary motor **35** may have a function of positioning a rotational angle position of the rotational stage **30** and a function of adjusting a rotational speed of the rotational stage **30**. For example, a stepper motor or a servo motor with a rotary encoder may be used as the electric rotary motor **35**.
[0037] A gas nozzle **50** is provided on a ceiling wall of the processing container **11**. The gas nozzle **50** injects gas (a CO.sub.2 gas, a He gas, or the like) downward to irradiate a gas cluster (indicated by reference symbol GC in FIG. **2**A) onto an upper surface of the substrate W held by the rotational stage **30**.
[0038] In the embodiment illustrated herein, the gas nozzle **50** is firmly fixed to the ceiling wall of the processing container **11** such that the gas nozzle **50** is immovable. When the gas nozzle **50** vibrates, variation in a gas flow (i.e., movement of the cluster) occurs, which may result in variation in a processing result. By making the gas nozzle **50** immovable, the gas nozzle **50** does not vibrate as the gas nozzle moves. This provides an effect of stabilizing the processing result.
[0039] FIGS. **3**A and **3**B are plan views illustrating the processing container **11** in which the ceiling wall is removed, and major constituent elements provided in the interior of the processing container **11**.
[0040] From a comparison of FIG. **3**A and FIG. **3**B, swiveling motions of the housing **20** and the rotational stage **30** coupled thereto by the swivel-shaft drive mechanism **23** may be understood. A swiveling axial line of the swiveling motion is indicated by reference symbol SC. By the swiveling motion, the rotational stage **30** may swivel around a vertical axis between a substrate delivery position (substrate transfer region) (a position illustrated in FIG. **3**A, which is relatively close to the opening **15** of the processing container **11**) and a processing position (substrate processing region) (a position illustrated in FIG. **3**B, which is relatively far from the opening **15**). In FIGS. **3**A and **3**B, a rotation axial line of the rotational motion of the rotational stage **30** is indicated by reference symbol RC.
[0041] In FIGS. **3**A and **3**B, a position directly below the gas nozzle **50** is indicated by a double circle with reference numeral **50**. In FIG. **3**B, since a position indicated by reference symbol RC and a position indicated by reference numeral **50** coincide with each other, it may be difficult to distinguish these positions.
[0042] When the gas cluster is irradiated from the gas nozzle **50** in the state of FIG. **3**B, the gas cluster collides with the center of the substrate W (which coincides with the center of the rotational stage **30**). In this state, any radial position on the surface of the substrate W may be positioned directly below the gas nozzle **50** by swiveling the rotational stage **30** about the swiveling axial line SC via the housing **20**. In a configuration example illustrated in FIG. **3**B, any radial position on the surface of the substrate W may be positioned directly below the gas nozzle **50** by swiveling the housing **20** and the rotational stage **30** approximately 45 degrees counterclockwise from the position illustrated in FIG. **3**B.
[0043] By combining the swiveling motion about the swiveling axial line SC and the rotational motion about the rotational axis RC of the rotational stage **30**, any position on the surface of the substrate W held by the rotational stage **30** may be positioned directly below the gas nozzle **50**. In other words, the gas cluster may be irradiated onto the entire surface of the substrate W.
[0044] When processing the substrate W, a distance between the gas nozzle **50** and the surface of the substrate W may be reduced to increase an efficiency of the gas cluster cleaning. On the other hand, when the substrate W is loaded or unloaded into or from the processing container **11**, a space is required to lift the substrate W by lift pins **70** described below. For this reason, the ceiling wall of the processing container **11** may be provided such that a vertical distance between the ceiling wall of the processing container **11** and the rotational stage **30** when the rotational stage **30** is at the

substrate delivery position is greater than a vertical distance between the ceiling wall of the processing container **11** and the rotational stage **30** when the rotational stage **30** is at the processing position.

[0045] For example, in a case in which a mechanism configured to raise and lower the gas nozzle **50**, or a mechanism configured to raise and lower the housing **20** or the rotational stage **30** is provided, swiveling angle ranges of the housing **20** and the rotational stage **30** may be set by shifting the rotational stage **30** by a distance approximately corresponding to a radius of the substrate W from the substrate delivery position. This makes it possible to further reduce a volume of the processing space **12**. However, such a volume reduction is in a trade-off relationship with an increase in apparatus cost.

[0046] Further, two or more gas nozzles **50** may be provided on the ceiling wall of the processing container **11**. In this case, in the plan view illustrated in FIG. **3**B, the two gas nozzles may be arranged on a circumference with the swiveling axial line SC as the center and a line segment SCRC as a radius. In such a configuration, by appropriately combining the swiveling motion of the rotational stage **30** about the swiveling axial line SC and the rotational motion of the rotational stage **30** about the rotational axis RC, any position on the surface of the substrate W held by the rotational stage **30** may be positioned directly below each gas nozzle.

[0047] The same gas cluster may be irradiated from the two gas nozzles **50**. In this case, one gas nozzle **50** may be used to irradiate the gas cluster onto a central region of the substrate W, and the other gas nozzle **50** may be used to irradiate the gas cluster onto a peripheral region of the substrate W. This makes it possible to reduce a time required to process one sheet of substrate W by almost half.

[0048] Different gas clusters may be irradiated from two or more gas nozzles **50**. In this case, the gas cluster cleaning under different conditions may be performed by one gas cluster cleaning unit **10**.

[0049] As illustrated in FIG. **2**A, a disc-like heater **60** is provided below the plate **31** of the rotational stage **30**. When electric current is supplied to the heater **60**, the heater **60** generates heat, and the plate **31** is heated by thermal radiation from the heater **60**. The substrate W held by the rotational stage **30** may be heated by the heated plate **31**. The heater **60** is configured to be capable of substantially evenly heating the entire substrate W. For example, the heater **60** may be a resistance heater equipped with a heating element which extends in a meandering manner so as to cover the entire area of the plate **31**.

[0050] The heater **60** is supported by a plurality of pillars **61** which stand on the ceiling wall of the housing **20**. A power feeding line **62** for supplying power to the heater **60** may be provided inside each pillar **61**. In one configuration example illustrated in FIG. **2**A, the power feeding line **62** is drawn to the internal space **21** of the housing **20** via an interior of each pillar **61**. The power feeding line **62** may be further drawn from the internal space **21** outward of the processing container **11** via an internal space of the hollow swivel shaft **22**, and may be connected to a power supply device (PS) **63**.

[0051] Although not illustrated, a detection signal line may be provided in parallel with the power feeding line **62**. A detection signal obtained by a temperature sensor such as a thermocouple embedded in the heater **60** is sent to the power supply device **63** via control/detection signal lines. Then, a temperature controller incorporated in the power supply device **63** controls the power to be sent to the heater **60** via the power feeding line **62**.

[0052] A plurality of lift pins **70** (three lift pins in this example) for raising and lowering the substrate W relative to the rotational stage **30** is provided below the plate **31** of the rotational stage **30** and below the heater **60**. Lower ends of the lift pins **70** are fixed to a ring-like pin support **71**. A lift rod (lifting body) **72** extends vertically downward from a lower surface of an extension portion that extends radially from a ring-like portion of the pin support **71**. The lift rod **72** penetrates the ceiling wall of the housing **20** and extends to the internal space **21** of the housing **20**. A lifting drive mechanism **73** for raising and lowering the lift rod **72** is provided in the internal space **21**. The lifting drive mechanism **73** is constituted with an appropriate linear actuator, for example, a ball screw. The lifting drive mechanism **73** may be constituted with an air cylinder. When the ball screw is used as the lifting drive mechanism **73**, it is desirable to construct the lifting drive mechanism **73** may be constructed such that the lift rod **72** does not rotate while facilitating sealing of the lift rod **72** (which will be described later).

[0053] As illustrated in FIG. **2**B, by raising the lift pin **70** using the lifting drive mechanism **73**, the lift pin **70** may be positioned at a raised position at which an upper end of the lift pin **70** protrudes upward from an upper surface of the plate **31** of the rotational stage **30**. As illustrated in FIG. **2**A, by lowering the lift pin **70** using the lifting drive mechanism **73**, the lift pin **70** may be positioned at a position at which the lift pin **70** does not interfere with the rotation of the rotational stage **30**, preferably, at a lowered position at which the upper end of the lift pin **70** is positioned below a lower surface of the heater **60**.

[0054] Through-holes through which the lift pins **70** pass respectively when they are raised and lowered are provided in the plate **31** and the heater **60** (although they not illustrated in FIGS. **2**A and **2**B). In FIGS. **3**A and **3**B, the through-holes for the lift pins **70** provided in the plate **31** are indicated by reference numeral **37**. Even in the heater **60**, the same through-holes as the through-holes **37** are provided at positions directly below the through-holes **37**.

[0055] When the substrate W is loaded into the processing container **11**, the rotational stage **30** is positioned at the substrate delivery position (a position illustrated in FIG. **3**A), and the lift pins **70** are positioned at the raised position (the position illustrated in FIG. **2**A). In this state, the substrate holder **124** of the second substrate transfer mechanism **122** holding the substrate W enters the processing space **12** via the opening **15** with the gate valve **16** open, and the substrate W held by the substrate holder **124** is positioned directly above the rotational stage **30**. Subsequently, the lift pins **70** are further raised such that the substrate holder **124** lifts the substrate W. Thereafter, the substrate holder **124** is withdrawn from the processing space **12**. Subsequently, the substrate W is delivered onto the rotational stage **30** while the lift pins **70** are lowered to a lowered position. Alternatively, the substrate holder **124** of the substrate transfer mechanism **122** holding the substrate W directly above the rotational stage **30** may be lowered to place the substrate W on the lift pins **70** at the raised position, thereby delivering the substrate W from the substrate holder **124** to the lift pins **70**. That is, the delivery of the substrate W between the substrate holder **124** and the lift pins **70** may be performed by raising and lowering the lift pins **70** or by raising and lowering the substrate holder **124**. When the substrate W is unloaded from the processing container **11**, a reverse operation to the above-described operation is performed.

[0056] The internal space **21** of the housing **20** is in communication with an internal atmosphere (atmospheric atmosphere) of a clean room in which the substrate processing system **1** is installed, via the hollow swivel shaft **22**. Therefore, the internal space **21** of the housing **20** is always maintained at an atmospheric atmosphere (normal pressure). On the other hand, during the operation of the substrate processing system **1**, the interior of the processing container **11**, i.e., the processing space **12**, is maintained at a depressurized atmosphere. For example, the processing space **12** is set to a medium vacuum (i.e., the same vacuum level as that of the interior of the vacuum transfer chamber **118** (FIG. **1**)) when the substrate W is loaded into or unloaded from the processing space **12**, and is set to a high vacuum when the substrate is processed inside the processing space **12**. In any case, there is a large pressure difference between the processing space **12** of the processing container **11** and the internal space **21** of the housing **20** (or an external space of the processing container **11**).

[0057] For this reason, it is necessary to apply vacuum seal to movable members (specifically, the rotary shaft **33** of the rotational stage **30**, and the lift rod **72** configured to raise and lower the lift pins **70**) which extend through the wall of the housing **20**, and a movable member (specifically, the swivel shaft **22** of the housing **20**) which extends through the wall of the processing container **11**.

The vacuum seal may be appropriately selected from vacuum seals known in the technical field of the present disclosure.

[0058] In FIG. **2**A, the vacuum seal is indicated by reference number **80**. For example, in the housing **20**, a portion through which the swivel shaft **22** passes and a portion through which the rotary shaft **33** passes may be sealed by the vacuum seal **80** made of a magnetic fluid seal. The lift rod **72** performs only a slide motion. Thus, the lift rod **72** may be sealed by the vacuum seal **80** made of an O-ring (preferably, a plurality of O-rings arranged in series in an axial direction of the lift rod **72**). Further, a sealed portion of the lift rod **72**, which is sealed by the O-ring, is a smooth cylindrical portion.

[0059] The internal space **21** of the housing **20** is kept at the atmospheric atmosphere. Thus, a driving force source (the electric rotary motor **35**) of the rotation driver **34** and a driving force source (for example, the electric rotary motor for the ball screw) of the lifting drive mechanism **73** may be cooled using air as a cooling medium. Therefore, the driving force sources may be cooled more efficiently than when the driving force sources are arranged in a vacuum. In addition, inexpensive driving force sources (compared to those designed for use in the vacuum atmosphere) designed for use in the atmospheric atmosphere may be used. In addition, by arranging the driving force sources in a space isolated from the processing space **12**, it is possible to prevent the processing space **12** from being contaminated by dust (particle-causing substances) generated by the driving force sources.

[0060] In order to promote the air cooling of the driving force sources, a configuration may be adopted in which cooling air is suctioned to and exhausted from the internal space **21** of the housing **20** via the hollow swivel shaft **22**. Specifically, for example, the internal space **21** of the housing **20** is suctioned and exhausted via the internal space of the hollow rotating shaft **26** using an exhaust mechanism **28** such as an exhaust fan or an ejector. A tube **25**, which is open at one end to the atmospheric atmosphere and at the other end to the internal space **21** of the housing **20** (preferably an inner side of the housing **20**), may be installed inside the hollow swivel shaft **22**.

[0061] The power feeding line and the control/detection signal lines (which are indicated by reference number **36** in FIG. **2**A) connected to the electric rotary motor **35** may pass through the internal space of the hollow swivel shaft **22**. Further, a power feeding line and control/detection signal lines (which are indicated by reference number **74** in FIG. **2**A) connected to the linear actuator of the lifting drive mechanism **73** may pass through internal space of the hollow swivel shaft **22**. The control/detection signal lines **36** and **74** are connected to the power supply device **63**. The rotational angle position of the rotational table **30** and a height position of the lift rod **72** are controlled via a controller incorporated in the power supply device **63**.

[0062] The gas nozzle **50** and the gas supply mechanism **52** configured to supply the gas to the gas nozzle **50** may adopt known ones. Examples of these constituent elements will be described below with reference to FIG. **4**.

[0063] The gas nozzle **50** includes a substantially cylindrical pressure chamber **501**. An orifice **502** having an opening diameter of, for example, about 0.1 mm is provided at a lower end portion of the pressure chamber **501**. A gas diffusion portion **503**, a diameter of which increases downward, is connected to the orifice **502**.

[0064] The gas supply mechanism **52** includes a CO.sub.2 gas (carbon dioxide gas) supplier **53** and a He gas (helium gas) supplier **54**. The CO.sub.2 gas supplier **53** includes a CO.sub.2 gas supply path **532** connected to a CO.sub.2 gas source **531**, and an opening/closing valve **533** and a flow rate control valve **534** which are provided in the CO.sub.2 supply path **532**. The He gas supplier includes a He gas supply path **542** connected to a He gas source **541**, and an opening/closing valve **543** and a flow rate control valve **544** which are provided in the He gas supply path **542**.

[0065] The CO.sub.2 gas supply path **532** and the He gas supply path **542** are joined to constitute a gas supply path **55**. A downstream end of the gas supply path **55** is connected to an upper end portion of the pressure chamber **501** of the gas nozzle **50**. A pressure control valve **56** is provided in

the gas supply path **55**. A pressure sensor **57** is provided in the gas supply path **55** to detect an internal pressure of the gas supply path **55**. The pressure sensor **57** may detect an internal pressure of the pressure chamber **501** of the gas nozzle **50**. A controller **58** for the gas supply mechanism **52** adjusts an opening degree of the pressure control valve **56** so that the pressure detected by the pressure sensor **57** reaches a predetermined value. Thus, the internal pressure of the pressure chamber **501** of the gas nozzle **50** is controlled to a desired value. In addition, the controller **58** controls a mixing ratio of the CO.sub.2 gas and the He gas by adjusting the opening degrees of the flow rate control valves **534** and **544**.
[0066] The orifice **502** is provided in the gas nozzle **50**. Thus, when the gas is injected from the gas nozzle **50** into the depressurized processing space **12**, a significant pressure drop occurs at the orifice **502**. As a result, the gas passing through the orifice **502** undergoes adiabatic expansion. Thus, a gas cluster **505**, which is an aggregate of atoms or molecules **504** of a cleaning gas (the CO.sub.2 gas in this example), is generated. The He gas is a gas for accelerating a gas flow, i.e., the gas cluster. The He gas hardly forms the cluster. Thus, the He gas may be mixed with the CO.sub.2 gas to increase a speed of the cluster generated from the CO.sub.2 gas. When the gas clusters **505** collide with the surface of the substrate W, contaminants such as particles adhering to the surface of the substrate W may be blown by a kinetic energy of the gas cluster **505**.
[0067] The gas nozzle **50** is provided to irradiate the gas clusters **504** are irradiated substantially perpendicularly to the surface of the substrate W. Herein, the expression “substantially perpendicularly” means that, as illustrated in FIGS. **5**A to **5**F, an angle α between a track directional vector of a main flow of the gas cluster when the gas cluster is incident on the surface of the substrate W and the surface of the substrate W held by the rotational stage **30** is in a range of 90 degrees±15 degrees.
[0068] In order to irradiate the gas clusters substantially perpendicularly to the surface of the substrate W, the gas nozzle **50** may be provided so that the angle α between a central axis line of an outlet of the gas nozzle **50** and the surface of the substrate W is in the range of 90 degrees±15 degrees. In a modification, the gas cluster discharged from the gas nozzle **50** may be ionized midway and an electric field may be applied to the ionized gas cluster to change the track of the gas cluster. Even in this case, the angle α between the track directional vector of the main flow of the gas cluster when the gas cluster is incident on the surface of the substrate W and the surface of the substrate W held by the rotational stage **30** may be in the range of 90 degrees±15 degrees.
[0069] In the present specification, an operation of the gas nozzle **50** will be described based on a premise that the gas nozzle **50** discharges the gas vertically downward and the gas cluster is substantially perpendicularly incident on the surface of the substrate W in a horizontal posture.
[0070] As illustrated in FIG. **3**A, the exhaust port **13** of the processing container **11** may be located directly below the gas nozzle **50**. With this configuration, when dummy dispense of gas is performed from the gas nozzle **50**, the gas is quickly discharged from the processing space **12**. Even when two or more gas nozzles **50** are provided, it is desirable that the opening of the exhaust port **13** is located directly below each gas nozzle **50**.
[0071] The gas cluster irradiated from the gas nozzle **50** returns to gas molecules after colliding with the substrate W. Gas molecules remaining in the vicinity of the surface of the substrate W reduce the kinetic energy of the gas cluster by colliding with the gas cluster. When the exhaust port **13** is located below the substrate W, the gas molecules derived from the gas cluster may be quickly removed from the vicinity of the surface of the substrate W. When the exhaust port **13** of the processing container **11** is provided directly below the gas nozzle **50**, it is located below the substrate W held by the rotational stage **30** at the processing position.
[0072] An example of a processing procedure performed by the gas cluster cleaning unit **10** will be described below with reference to FIGS. **3**A and **3**B, and FIGS. **5**A to **5**F. The following procedure is executed by the control device **130** (see FIG. **1**) controlling the operations of the constituent elements of the gas cluster cleaning unit **10**. FIGS. **5**A to **5**F schematically illustrate a transition of

a positional relationship between the processing space **12**, the substrate W, and the gas nozzle **50** as viewed from directly above.

[0073] First, the substrate W is loaded into the processing container **11** and is held by the rotational stage **30** at the substrate delivery position (FIG. **3**A and FIG. **5**A).

[0074] Subsequently, the housing **20** and the rotational stage **30** are swiveled to locate the center of the substrate W at a position (the substrate processing position) directly below the outlet of the gas nozzle **50** (FIG. **3**B, and FIGS. **5**A and **5**B).

[0075] Subsequently, the substrate W begins to rotate, and the gas nozzle **50** begins the irradiation of the gas cluster. While continuing the rotation of the substrate W and the irradiation of the gas cluster from the gas nozzle **50**, the housing **20** and the rotational stage **30** are swiveled counterclockwise until a peripheral portion of the substrate W is located directly below the outlet of the gas nozzle **50**. An irradiation position of the gas cluster on the surface of the substrate W is moved from the center of the substrate W to the peripheral portion of the substrate W over, for example, 30 seconds (FIGS. **5**C and **5**D).

[0076] Subsequently, while continuing the rotation of the substrate W and the irradiation of the gas cluster from the gas nozzle **50**, the housing **20** and the rotational stage **30** are rotated in an opposite direction, and the irradiation position of the gas cluster on the surface of the substrate W is moved from the peripheral portion of the substrate W to the center of the substrate W over, for example, 30 seconds (FIGS. **5**D and **5**E). As a result, the gas cluster is irradiated over the entire surface of the substrate W so that the gas cluster cleaning ends.

[0077] Thereafter, the housing **20** and the rotational stage **30** are swiveled to the substrate delivery position where the substrate W is unloaded from the processing container **11** (FIG. **5**F).

[0078] According to the above embodiment, all of the driving force sources of the mechanisms for moving (rotating, swiveling, raising and lowering, and the like) the substrate W are disposed at a position that is not exposed to the internal atmosphere of the processing space **12** (inward of the housing **20** or outward of the processing container **11**). This eliminates a need to use expensive driving force sources intended for use in the vacuum atmosphere. That is, inexpensive driving force sources may be used. In addition, since all of the driving force sources of the mechanisms for moving the substrate W are disposed in the atmospheric atmosphere, it is possible to cool (release heat from) the driving force sources using air as a heat transfer medium. In other words, such a cooling may be performed at a lower cost than when heat conduction in the vacuum atmosphere is performed. In addition, dust (particle-causing substances) from the driving force sources is not introduced into the processing space **12**. This makes it possible to prevent the contamination of the substrate W.

[0079] In the above embodiment, by combining the rotational motion of the rotational stage **30** and the swiveling motion of the housing **20** (which causes the housing **20** to move in the horizontal direction), the irradiation of the gas clusters to any position on the surface of the substrate W is possible. However, the present disclosure is not limited thereto. The housing **20** may translate in the horizontal direction.

[0080] Specifically, for example, as illustrated in FIG. **6**, a linear motion mechanism **90** may be provided on one sidewall of the housing **20**. As an example, the linear motion mechanism **90** may include a linear actuator such as a ball screw (not illustrated), which is driven by an electric motor (driving force source) (not illustrated), and a driving rod **92** which moves forward and backward in the horizontal direction by the linear actuator. The driving rod **92** extends horizontally via the sidewall of the processing container **11**. A tip of the driving rod **92** is fixed to the housing **20**.

[0081] A hollow driven rod **94** is provided on the other sidewall of the housing **20**. The driven rod **94** extends horizontally via the sidewall of the processing container **11**. A tip of the driven rod **94** is fixed to the housing **20**. The driven rod **94** is supported by a linear bearing **96**.

[0082] A portion of the sidewall of the housing **20** through which the driving rod **92** and the driven rod **94** pass is sealed by a vacuum seal **80** (which is constituted with, for example, a plurality of O

rings arranged in series in an axial direction of the driving rod **92** and the driven rod **94**).
[0083] By moving the driving rod **92** forward and backward in the horizontal direction, the housing **20** and various devices attached thereto (the rotational stage **30**, the lift pins **70** and the drive mechanisms thereof, the heater **60**, and the like) may be moved together in the horizontal direction. By combining the horizontal translational motion of the housing **20** and the rotational motion of the rotational stage **30**, any position on the surface of the substrate W may be located directly below the gas nozzle **50** and the gas cluster may be irradiated to the respective position.
[0084] The power feeding lines and the control/detection signal lines may pass through an internal space of the hollow driven rod **94** like the internal space of the hollow swivel shaft **22**. Further, the internal space of the hollow driven rod **94** may be used to suction and exhaust the internal space **21** of the housing **20**.
[0085] Even in Modification illustrated in FIG. **6**, substantially the same effects as the embodiment illustrated in FIG. **2**A may be obtained.
[0086] According to the present disclosure in some embodiments, it is possible to suppress a substrate from being contaminated by particles generated from a drive mechanism for moving the substrate.
[0087] It should be noted that the embodiments and the modification disclosed herein are exemplary in all aspects and are not restrictive. The above-described embodiments may be omitted, replaced, or modified in various forms without departing from the scope and spirit of the appended claims.
[0088] The substrate to be processed is not limited to a semiconductor wafer and may be various substrates used in the field of semiconductor device manufacturing, such as glass substrates and ceramic substrates.

Claims

1. A substrate processing apparatus, comprising: a processing container having a processing space provided in an interior of the processing container, which is depressurized to a pressure lower than atmospheric pressure, and an opening through which a substrate is loaded into and unloaded from the processing space; a substrate holding/rotating mechanism configured to hold the substrate in a horizontal posture and rotate the substrate around a vertical axis, and including a substrate holder configured to hold the substrate inside the processing space and a driving force source configured to generate a driving force for rotationally driving the substrate holder; a housing having an internal space hermetically isolated from the processing space, wherein the driving force source of the substrate holding/rotating mechanism is accommodated in the internal space; a horizontal movement mechanism configured to move the housing in a horizontal direction so as to move the substrate holder in the horizontal direction; and a gas nozzle configured to inject a gas so as to irradiate a gas cluster onto an upper surface of the substrate held by the substrate holder.
2. The substrate processing apparatus of claim 1, wherein the horizontal movement mechanism includes a swivel mechanism configured to swivel the housing around a swiveling axial line extending in a vertical direction to swivel the substrate holder.
3. The substrate processing apparatus of claim 1, wherein the horizontal movement mechanism includes a linear movement mechanism configured to linearly move the housing so as to linearly move the substrate holder.
4. The substrate processing apparatus of claim 1, wherein the internal space of the housing is in communication with an external space of the processing container.
5. The substrate processing apparatus of claim 1, further comprising: an exhaust mechanism configured to exhaust an atmosphere of the internal space of the housing.
6. The substrate processing apparatus of claim 2, wherein the swivel mechanism has a hollow swivel shaft extending downward from the housing to an outer side of the processing container, and

wherein the internal space of the housing is in communication with an outer space of the processing container through an internal space of the hollow swivel shaft.
7. The substrate processing apparatus of claim 6, further comprising: an exhaust mechanism configured to exhaust an atmosphere of the internal space of the housing via the internal space of the hollow swivel shaft.
8. The substrate processing apparatus of claim 6, wherein a power feeding line configured to supply power to the driving force source of the substrate holding/rotating mechanism extends from an outside of the processing container to the internal space of the housing via the internal space of the hollow swivel shaft.
9. The substrate processing apparatus of claim 1, further comprising: a plurality of lift pins configured to support the substrate by upper ends of the plurality of lift pins; and a lifting drive mechanism configured to raise and lower the substrate relative to the substrate holder by raising and lowering the plurality of lift pins relative to the substrate holder, wherein at least the driving force source of the lifting drive mechanism is accommodated in the housing.
10. The substrate processing apparatus of claim 1, wherein the gas nozzle is fixed to the processing container such that the gas nozzle is immovable.
11. The substrate processing apparatus of claim 10, wherein an exhaust port configured to vacuum-suction the processing space is provided to be open immediately below the gas nozzle.
12. The substrate processing apparatus of claim 1, further comprising: a control device configured to control at least operations of the driving force source of the substrate holding/rotating mechanism, the horizontal movement mechanism, and a gas supply mechanism configured to supply the gas to the gas nozzle, wherein the control device controls the operations of the driving force source of the substrate holding/rotating mechanism and the horizontal movement mechanism, when the gas cluster is irradiated onto the substrate from the gas nozzle, to sequentially irradiate the gas cluster onto an irradiation target region of the upper surface of the substrate.
13. The substrate processing apparatus of claim 9, further comprising: a control device configured to control at least operations of the driving force source of the substrate holding/rotating mechanism, the horizontal movement mechanism, and a gas supply mechanism configured to supply the gas to the gas nozzle, wherein a substrate delivery region relatively close to the opening and a substrate processing region relatively far from the opening are set in the processing space, and wherein the control device executes: controlling the operation of the horizontal movement mechanism and an operation of the lifting drive mechanism to deliver the substrate to a rotational stage from an external substrate transfer mechanism using the plurality of lift pins by positioning the substrate holder in the substrate delivery region; controlling the operation of the horizontal movement mechanism to position the substrate holder in the substrate processing region; controlling the operations of the driving force source of the substrate holding/rotating mechanism and the horizontal movement mechanism, while controlling the irradiating of the gas cluster onto the substrate from the gas nozzle, to sequentially irradiate the gas cluster onto an irradiation target region of the upper surface of the substrate; and controlling the operations of the horizontal movement mechanism and the lifting drive mechanism to return the substrate holder to the substrate delivery region and deliver the substrate from the substrate holder to the external substrate transfer mechanism using the plurality of lift pins.
14. A substrate processing method executed using a substrate processing apparatus, wherein the substrate processing apparatus includes: a processing container having a processing space provided in an interior of the processing container, which is depressurized to a pressure lower than atmospheric pressure, and an opening through which a substrate is loaded into and unloaded from the processing space; a substrate holding/rotating mechanism configured to hold the substrate in a horizontal posture and rotate the substrate around a vertical axis, and including a substrate holder configured to hold the substrate inside the processing space and a driving force source configured to generate a driving force for rotationally driving the substrate holder; a housing having an internal

space hermetically isolated from the processing space, wherein the driving force source of the substrate holding/rotating mechanism is accommodated in the internal space; a horizontal movement mechanism configured to move the housing in a horizontal direction so as to move the substrate holder in the horizontal direction; and a gas nozzle configured to inject a gas so as to irradiate a gas cluster onto an upper surface of the substrate held by the substrate holder, wherein the substrate processing method comprises: irradiating the gas cluster onto the substrate held by the substrate holder from the gas nozzle; and controlling operations of the driving force source of the substrate holding/rotating mechanism and the horizontal movement mechanism, when the gas cluster is irradiated onto the substrate, to sequentially irradiate the gas cluster onto an irradiation target region of the upper surface of the substrate.