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Plasma processing apparatus and plasma processing method

Abstract

A plasma processing apparatus disclosed includes a chamber, a substrate support, a radio-frequency power supply, and a bias power supply. The substrate support includes an electrode and is provided in the chamber. The radio-frequency power supply supplies radio-frequency power for generating plasma from a gas in the chamber. The bias power supply is electrically coupled to the electrode of the substrate support. The radio-frequency power supply is configured to supply the radio-frequency power in an ignition period in which the plasma is ignited in the chamber. The bias power supply is configured to sequentially apply a plurality of bias pulses, each of which has a negative voltage, to the electrode of the substrate support, and stepwisely or gradually increase absolute values of voltage levels of the plurality of bias pulses in the ignition period.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a bypass continuation application of international application No. PCT/JP2022/002243 having an international filing date of Jan. 21, 2022 and designating the United States, the international application being based upon and claiming the benefit of priority from Japanese Patent Application No. 2021-016592, filed on Feb. 4, 2021, the entire contents of each are incorporated herein by reference.

TECHNICAL FIELD
(1) Exemplary embodiments of the present disclosure relate to a plasma processing apparatus and a plasma processing method.
BACKGROUND
(2) A plasma processing apparatus is used in substrate processing. One type of plasma processing apparatus includes a chamber, a substrate support, a radio-frequency power supply, and a bias power supply. The substrate support includes an electrode and is provided in the chamber. The radio-frequency power supply supplies radio-frequency power for generating plasma from a gas in the chamber. The bias power supply provides bias energy to the electrode of the substrate support to draw ions into a substrate. Patent Document 1 below describes use of a negative direct-current voltage pulse as the bias energy.
PRIOR ART DOCUMENTS
Patent Documents
(3) Patent Document 1: JP-A-2019-036658
SUMMARY
Technical Problem
(4) The present disclosure provides a technique for reducing power of reflected waves of radio-frequency power in an ignition period of plasma.
Solution to Problem
(5) In an exemplary embodiment, a plasma processing apparatus is provided. The plasma processing apparatus includes a chamber, a substrate support, a radio-frequency power supply, and a bias power supply. The substrate support includes an electrode and is provided in the chamber. The radio-frequency power supply supplies radio-frequency power for generating plasma from a gas in the chamber. The bias power supply is electrically coupled to the electrode of the substrate support. The radio-frequency power supply is configured to supply the radio-frequency power in an ignition period in which the plasma is ignited in the chamber. The bias power supply is configured to sequentially apply a plurality of bias pulses, each of which has a negative voltage, to the electrode of the substrate support in the ignition period, and stepwisely or gradually increase absolute values of voltage levels of the plurality of bias pulses.
Advantageous Effects of the Invention
(6) According to the exemplary embodiment, power of reflected waves of radio-frequency power in an ignition period of plasma can be reduced.

Description

BRIEF DESCRIPTION OF DRAWINGS
(1) FIG. **1** is a diagram schematically showing a plasma processing apparatus according to an

exemplary embodiment.
(2) FIG. **2** is a diagram showing a configuration in the chamber of the plasma processing apparatus according to the exemplary embodiment.
(3) FIG. **3** is a timing chart of an example of processing in the plasma processing apparatus shown in FIG. **1**.
(4) FIG. **4** is a timing chart of an example of processing in the plasma processing apparatus shown in FIG. **1**.
(5) FIG. **5** is a timing chart of an example of a bias pulse for a substrate and a bias pulse for an edge ring.
(6) FIG. **6** is a flowchart of a plasma processing method according to an exemplary embodiment.
(7) FIGS. **7**A and **7**B are graphs showing absolute values of voltage levels of bias pulses and reflected waves of radio-frequency power in a first experiment, respectively.
(8) FIGS. **8**A and **8**B are graphs showing absolute values of voltage levels of bias pulses and reflected waves of radio-frequency power in a second experiment, respectively.
(9) FIGS. **9**A and **9**B are graphs showing absolute values of voltage levels of bias pulses and reflected waves of radio-frequency power in a third experiment, respectively.
(10) FIGS. **10**A and **10**B are graphs showing absolute values of voltage levels of bias pulses and reflected waves of radio-frequency power in a fourth experiment, respectively.

DETAILED DESCRIPTION

(11) Hereinafter, various exemplary embodiments will be described.
(12) In an exemplary embodiment, a plasma processing apparatus is provided. The plasma processing apparatus includes a chamber, a substrate support, a radio-frequency power supply, and a bias power supply. The substrate support includes an electrode and is provided in the chamber. The radio-frequency power supply supplies radio-frequency power for generating plasma from a gas in the chamber. The bias power supply is electrically coupled to the electrode of the substrate support. The radio-frequency power supply is configured to supply the radio-frequency power in an ignition period in which the plasma is ignited in the chamber. The bias power supply is configured to sequentially apply a plurality of bias pulses, each of which has a negative voltage, to the electrode of the substrate support in the ignition period, and stepwisely or gradually increase absolute values of voltage levels of the plurality of bias pulses.
(13) When the absolute values of the voltage levels of the bias pulses are rapidly increased, power of reflected waves of the radio-frequency power is increased. In the above embodiment, the levels of the plurality of bias pulses are stepwisely or gradually increased in the ignition period of the plasma. Therefore, according to the above embodiment, the power of the reflected waves of the radio-frequency power is reduced. In addition, since the power of the reflected waves is reduced, the plasma can be stably generated in a short time, and a time length until start of substrate processing by the plasma can be shortened.
(14) In one exemplary embodiment, the bias power supply may set the absolute value of the voltage level of each of the plurality of bias pulses to a value larger than an absolute value of a voltage level of any bias pulse that is previously applied to the electrode of the substrate support. That is, the absolute values of the voltage levels of the plurality of bias pulses sequentially applied to the electrode of the substrate support in the ignition period of the plasma may be ramped up.
(15) In one exemplary embodiment, each of the plurality of bias pulses may be a direct-current voltage pulse.
(16) In one exemplary embodiment, the radio-frequency power supply supplies the radio-frequency power also in a process period in which a substrate is processed in the chamber using the plasma after the ignition period. The bias power supply sequentially applies a plurality of bias pulses, each of which has a negative voltage, to the electrode also in the process period.
(17) In one exemplary embodiment, the plasma processing apparatus may further include a pressure controller configured to adjust a pressure in the chamber. The pressure controller may set a

pressure in the chamber in the process period to a pressure different from a pressure in the chamber in the ignition period. The pressure controller may set the pressure in the chamber in the process period to a pressure lower than the pressure in the chamber in the ignition period.
(18) In one exemplary embodiment, the radio-frequency power supply may set a frequency of the radio-frequency power in the process period to a frequency different from a frequency of the radio-frequency power in the ignition period. The radio-frequency power supply may set the frequency of the radio-frequency power in the process period to a frequency lower than the frequency of the radio-frequency power in the ignition period.
(19) In one exemplary embodiment, the radio-frequency power supply may set a power level of the radio-frequency power in the process period to a power level different from a power level of the radio-frequency power in the ignition period. The radio-frequency power supply may set the power level of the radio-frequency power in the process period to a power level higher than the power level of the radio-frequency power in the ignition period.
(20) In one exemplary embodiment, the plasma processing apparatus may further include a gas supply configured to supply gases to the chamber. The plasma processing apparatus generates the plasma in the chamber from the gases supplied from the gas supply. The gas supply may set a flow rate of at least one gas supplied to the chamber in the process period to a flow rate different from a flow rate of the at least one gas supplied to the chamber in the ignition period.
(21) In one exemplary embodiment, each of the ignition period and the process period may include a plurality of periodic pulse periods. The bias power supply may apply the plurality of bias pulses to the electrode in an ON period of each of the plurality of pulse periods. In this case, the bias power supply applies the plurality of bias pulses to the electrode in a bias cycle shorter than a pulse cycle that is a time interval of the ON period in the ON period of each of the plurality of pulse periods. The bias power supply may stop the application of the plurality of bias pulses to the electrode in an OFF period of each of the plurality of pulse periods.
(22) In one exemplary embodiment, the bias power supply may adjust a duty ratio that is a ratio of a time length of each ON period to a time length of the pulse cycle. The bias power supply may set a duty ratio in the process period to a ratio different from a duty ratio in the ignition period. The bias power supply may set the duty ratio in the process period to a ratio smaller than the duty ratio in the ignition period.
(23) In one exemplary embodiment, the substrate support may support an edge ring placed thereon. The plasma processing apparatus may apply the plurality of bias pulses, each of which has a negative voltage, to the edge ring.
(24) In another exemplary embodiment, a plasma processing method is provided. The plasma processing method includes a step of igniting plasma in a chamber of a plasma processing apparatus in an ignition period. The plasma processing apparatus includes a substrate support that includes an electrode and is provided in the chamber. The plasma processing method further includes a step of successively applying a plurality of bias pulses to the electrode in the ignition period. The plurality of bias pulses have negative voltages, and absolute values of voltage levels of the plurality of bias pulses are stepwisely or gradually increased in the ignition period.
(25) Hereinafter, various exemplary embodiments will be described in detail with reference to the drawings. Further, like reference numerals will be given to like or corresponding parts throughout the drawings.
(26) FIG. **1** is a diagram schematically showing a plasma processing apparatus according to an exemplary embodiment. A plasma processing apparatus **1** shown in FIG. **1** includes a chamber **10**. FIG. **2** is a diagram showing a configuration in the chamber of the plasma processing apparatus according to the exemplary embodiment. As shown in FIG. **2**, the plasma processing apparatus **1** may be a capacitively-coupled plasma processing apparatus.
(27) The chamber **10** provides an interior space **10***s* therein. A central axis of the interior space **10***s* is an axis AX extending in a vertical direction. In an embodiment, the chamber **10** includes a

chamber body **12**. The chamber body **12** has a substantially cylindrical shape. The interior space **10***s* is provided in the chamber body **12**. The chamber body **12** is made of, e.g., aluminum. The chamber body **12** is electrically grounded. An inner wall surface of the chamber body **12**, that is, a wall surface defining the interior space **10***s* may be covered with a plasma-resistant film. This film may be a film formed by anodization or a ceramic film such as a film formed of yttrium oxide.

(28) A passage **12***p* is provided on a side wall of the chamber body **12**. A substrate W passes through the passage **12***p* when being transferred between the interior space **10***s* and an outside of the chamber **10**. A gate valve **12***g* is provided along the side wall of the chamber body **12** to open and close the passage **12***p*.

(29) The plasma processing apparatus **1** is further provided with a substrate support **16**. The substrate support **16** supports the substrate W placed thereon in the chamber **10**. The substrate W has a substantially disk shape. The substrate support **16** is supported by a support **17**. The support **17** extends upward from a bottom of the chamber body **12**. The support **17** has a substantially cylindrical shape. The support **17** is formed of an insulating material such as quartz.

(30) In the embodiment, the substrate support **16** includes a lower electrode **18** and an electrostatic chuck **20**. The lower electrode **18** and the electrostatic chuck **20** are provided in the chamber **10**. The lower electrode **18** is formed of a conductive material such as aluminum and has a substantially disk shape.

(31) A flow path **18***f* is provided in an inside of the lower electrode **18**. The flow path **18***f* is a flow path for a heat exchange medium. The heat exchange medium is, for example, a liquid coolant. The flow path **18***f* receives a heat exchange medium supplied from a heat exchange medium supply device (for example, a chiller unit) through a pipe **23***a*. The supply device is provided outside the chamber **10**. The heat exchange medium supplied to the flow path **18***f* flows through the flow path **18***f* and returns to the supply device through a pipe **23***b*.

(32) The electrostatic chuck **20** is provided on the lower electrode **18**. As shown in FIG. **1**, the electrostatic chuck **20** includes a dielectric portion **20***d* and an electrode **21***a*. The electrostatic chuck **20** may further include an electrode **22***a* and an electrode **22***b*. The substrate W is placed on the electrostatic chuck **20** and held by the electrostatic chuck **20** when being processed in the interior space **10***s*. In addition, the substrate support **16** supports an edge ring ER placed thereon. The edge ring ER is a plate having a substantially annular shape. The edge ring ER may have electrical conductivity. The edge ring ER is formed of, for example, silicon or silicon carbide. As shown in FIG. **2**, the edge ring ER is placed on the substrate support **16** such that a central axis thereof coincides with the axis AX. The substrate W accommodated in the chamber **10** is disposed on the electrostatic chuck **20** and in a region surrounded by the edge ring ER.

(33) The plasma processing apparatus **1** may further include a gas line **25**. The gas line **25** supplies a heat transfer gas, for example, a He gas, from a gas supply mechanism to a gap between an upper surface of the electrostatic chuck **20** (first region to be described later) and a rear surface (lower surface) of the substrate W.

(34) The plasma processing apparatus **1** may further include an outer peripheral portion **28** and an outer peripheral portion **29**. The outer peripheral portion **28** extends upward from the bottom of the chamber body **12**. The outer peripheral portion **28** is substantially cylindrical and extends along the outer periphery of the support **17**. The outer peripheral portion **28** is substantially cylindrical and formed from a conductive material. The outer peripheral portion **28** is electrically grounded. A surface of the outer peripheral portion **28** may be covered with a plasma-resistant film. This film may be a film formed by anodization or a ceramic film such as a film formed of yttrium oxide.

(35) The outer peripheral portion **29** is located on the outer peripheral portion **28**. The outer peripheral portion **29** is formed from an insulating material. The outer peripheral portion **29** is substantially cylindrical and is formed from, for example, ceramic such as quartz. The outer peripheral portion **29** has a substantially cylindrical shape. The outer peripheral portion **29** extends along the outer peripheries of the lower electrode **18** and the electrostatic chuck **20**.

(36) The plasma processing apparatus **1** is further provided with an upper electrode **30**. The upper electrode **30** is provided above the substrate support **16**. The upper electrode **30** closes an upper opening of the chamber body **12** together with a member **32**. The member **32** has an insulating property. The upper electrode **30** is supported on an upper portion of the chamber body **12** through the member **32**.
(37) The upper electrode **30** may include a ceiling plate **34** and a support **36**. A lower surface of the ceiling plate **34** defines the interior space **10***s*. A plurality of gas holes **34***a* are provided on the ceiling plate **34**. Each of the plurality of gas holes **34***a* penetrates the ceiling plate **34** in a plate thickness direction (vertical direction). The ceiling plate **34** is formed of, for example, silicon. Alternatively, the ceiling plate **34** may have a structure in which a plasma-resistant film is provided on a surface of a member made of aluminum. This film may be a film formed by anodization or a ceramic film such as a film formed of yttrium oxide.
(38) The support **36** detachably supports the ceiling plate **34**. The support **36** is formed from a conductive material such as aluminum. A gas diffusion chamber **36***a* is provided in an inside of the support **36**. A plurality of gas holes **36***b* are further provided on the support **36**. The plurality of gas holes **36***b* extend downward from the gas diffusion chamber **36***a*. The plurality of gas holes **36***b* communicate with the plurality of gas holes **34***a*, respectively. A gas introduction port **36***c* is further provided on the support **36**. The gas introduction port **36***c* is connected to the gas diffusion chamber **36***a*. A gas supply pipe **38** is connected to the gas introduction port **36***c*.
(39) A gas source group **40** is connected to the gas supply pipe **38** through a valve group **41**, a flow rate controller group **42**, and a valve group **43**. The gas source group **40**, the valve group **41**, the flow rate controller group **42**, and the valve group **43** configure a gas supply. The gas source group **40** includes a plurality of gas sources. Each of the valve group **41** and the valve group **43** includes a plurality of valves (for example, on-off valves). The flow rate controller group **42** includes a plurality of flow rate controllers. Each of the plurality of flow rate controllers of the flow rate controller group **42** is a mass flow controller or a pressure control type flow rate controller. Each of the plurality of gas sources of the gas source group **40** is connected to the gas supply pipe **38** through a corresponding valve of the valve group **41**, a corresponding flow rate controller of the flow rate controller group **42**, and a corresponding valve of the valve group **43**. The plasma processing apparatus **1** can supply a gas from one or more gas sources selected from the plurality of gas sources of the gas source group **40** to the interior space **10***s* at an individually adjusted flow rate.
(40) A baffle plate **48** is located between the outer peripheral portion **28** and the side wall of the chamber body **12**. The baffle plate **48** may include, for example, an aluminum member covered with ceramic such as yttrium oxide. The baffle plate **48** has many through-holes. An exhaust pipe **52** is connected to the bottom of the chamber body **12** below the baffle plate **48**. An exhaust device **50** is connected to the exhaust pipe **52**. The exhaust device **50** includes a pressure controller such as an automatic pressure control valve, and a vacuum pump such as a turbo molecular pump, and can reduce a pressure in the interior space **10***s*.
(41) FIGS. **3** to **5** will be referred to together with FIGS. **1** and **2** below. FIGS. **3** and **4** are timing charts of examples of processing in the plasma processing apparatus shown in FIG. **1**. FIG. **5** is a timing chart of an example of a bias pulse for a substrate and a bias pulse for an edge ring.
(42) As shown in FIG. **1**, the plasma processing apparatus **1** further includes a radio-frequency power supply **57**. The radio-frequency power supply **57** is coupled to the lower electrode **18** through a matcher **58**. The radio-frequency power supply **57** is a power supply that generates radio-frequency power RF for plasma generation. The radio-frequency power RF has a frequency in a range of 27 MHz to 100 MHz, for example, a frequency of 40 MHz or 60 MHz. The matcher **58** includes a matching circuit for matching impedance of the radio-frequency power supply **57** on a load side (lower electrode **18** side) with output impedance of the radio-frequency power supply **57**. The radio-frequency power supply **57** may not be electrically coupled to the lower electrode **18**,

and may be coupled to the upper electrode **30** through the matcher **58**.

(43) In the plasma processing apparatus **1**, a radio-frequency electric field is generated in the chamber **10** by the radio-frequency power RF from the radio-frequency power supply **57**. A gas in the chamber **10** is excited by the generated radio-frequency electric field. As a result, plasma is ignited and generated in the chamber **10**. As shown in FIG. **3**, the radio-frequency power supply **57** supplies the radio-frequency power RF in both an ignition period Pi and a process period Pp. The ignition period Pi is a period in which the plasma is ignited in the chamber **10**. The process period Pp is a period after the ignition period Pi. The substrate W is processed with chemical species such as ions and/or radicals from the plasma generated in the chamber **10** in the process period Pp.

(44) As shown in FIG. **1**, in the embodiment, the substrate support **16** may include a first region **21** and a second region **22**. The first region **21** is a central region of the substrate support **16**. The first region **21** includes a central region of the electrostatic chuck **20** and a central region of the lower electrode **18**. The second region **22** extends radially outside the first region **21** in a circumferential direction. The second region **22** includes a peripheral region of the electrostatic chuck **20** and a peripheral region of the lower electrode **18**. In the plasma processing apparatus **1**, the first region **21** and the second region **22** are constituted by a single electrostatic chuck, and are integrated with each other. In FIG. **1**, a boundary between the first region **21** and the second region **22** is indicated by a broken line. In another embodiment, the first region **21** and the second region **22** may be constituted by separate electrostatic chucks.

(45) The first region **21** supports the substrate W placed thereon (that is, placed on an upper surface thereof). The first region **21** is a region having a disk shape. A central axis of the first region **21** substantially coincides with the axis AX. The first region **21** shares the dielectric portion **20***d* with the second region **22**. The dielectric portion **20***d* is formed of a dielectric such as aluminum nitride or aluminum oxide. The dielectric portion **20***d* has a substantially disk shape. In the embodiment, a thickness of the dielectric portion **20***d* in the second region **22** is smaller than a thickness of the dielectric portion **20***d* in the first region **21**. A position of an upper surface of the dielectric portion **20***d* in the second region **22** in the vertical direction may be lower than a position of the upper surface of the dielectric portion **20***d* in the first region **21** in the vertical direction.

(46) The first region **21** has the electrode **21***a* (chuck electrode). The electrode **21***a* is a film-like electrode, and is provided in the dielectric portion **20***d* within the first region **21**. The electrode **21***a* is coupled to a direct-current power supply **55** through a switch **56**. When a direct-current voltage from the direct-current power supply **55** is applied to the electrode **21***a*, an electrostatic attraction force is generated between the first region **21** and the substrate W. Due to the generated electrostatic attraction force, the substrate W is attracted to the first region **21** and held by the first region **21**.

(47) The first region **21** further has a first electrode **21***c*. The first electrode **21***c* is a film-like electrode, and is provided in the dielectric portion **20***d* within the first region **21**. The electrode **21***a* may extend nearer the upper surface of the first region **21** than the first electrode **21***c* in the vertical direction.

(48) The plasma processing apparatus **1** further includes a first bias power supply **61**. The first bias power supply **61** is electrically coupled to the first electrode **21***c*. The first bias power supply **61** may be coupled to the first electrode **21***c* through a filter **62**. The filter **62** is an electric filter that blocks or attenuates the radio-frequency power RF from the radio-frequency power supply **57**.

(49) As shown in FIGS. **1** and **5**, the first bias power supply **61** sequentially applies a plurality of bias pulses BW to the first electrode **21***c*. Each of the plurality of bias pulses BW is a voltage pulse. In the embodiment, each of the plurality of bias pulses BW is a negative voltage pulse. In an example, the negative voltage pulse is a negative direct-current voltage pulse. An output voltage of the first bias power supply **61** may be 0 V when the bias pulses BW are not output. Alternatively, the output voltage of the first bias power supply **61** has a voltage level of an absolute value smaller than absolute values |V.sub.BW| of voltage levels V.sub.BW of the bias pulses BW when the bias

pulses BW are not output.
(50) The first bias power supply **61** may periodically apply the bias pulses BW to the first electrode **21***c* at a time interval T.sub.B specified by a bias frequency f.sub.B. The time interval T.sub.B is a bias cycle, and is a reciprocal of the bias frequency f.sub.B. The bias frequency f.sub.B is, for example, a frequency within a range of 200 kHz to 13.56 MHz. A percentage of a period (time length T.sub.A) in which the bias pulses BW are applied to the first electrode **21***c* at the time interval T.sub.B (that is, duty ratio D.sub.B=T.sub.A/T.sub.B×100(%)) is larger than 0 and smaller than 100.
(51) In the embodiment, each of the above ignition period Pi and the process period Pp may include a plurality of periodic pulse periods P.sub.L. As shown in FIG. **4**, each of the plurality of pulse periods P.sub.L includes an ON period P.sub.ON and an OFF period P.sub.OFF. That is, the ON period P.sub.ON appears at the same time interval T.sub.P as a time length of the plurality of pulse periods P.sub.L. The first bias power supply **61** may apply the plurality of bias pulses BW to the first electrode **21***c* in the ON period P.sub.ON of each of the plurality of periodic pulse periods P.sub.L. The first bias power supply **61** may stop the application of the bias pulses BW to the first electrode **21***c* in the OFF period P.sub.OFF of each of the plurality of pulse periods P.sub.L. A percentage of the ON period P.sub.ON (time length T.sub.ON) at the time interval T.sub.P (that is, duty ratio D.sub.P=T.sub.ON/T.sub.P×100(%)) is larger than 0 and smaller than 100. The bias cycle described above, that is, the time interval T.sub.B is shorter than the pulse cycle, that is, the time interval T.sub.P of the ON period P.sub.ON. Therefore, as shown in FIG. **5**, in each ON period P.sub.ON, some bias pulses BW are sequentially applied to the first electrode **21***c* at the time interval T.sub.B.
(52) As shown in FIG. **1**, the second region **22** extends to surround the first region **21**. The second region **22** is a substantially annular region. A central axis of the second region **22** substantially coincides with the axis AX. The second region **22** supports the edge ring ER placed thereon (that is, placed on an upper surface thereof). The second region **22** shares the dielectric portion **20***d* with the first region **21**.
(53) In the embodiment, the second region **22** may hold the edge ring ER by an electrostatic attraction force. In the embodiment, the second region **22** may have one or more electrodes (chuck electrodes). In the embodiment shown in FIG. **1**, the second region **22** has a pair of electrodes, that is, the electrodes **22***a* and **22***b*. The electrodes **22***a* and **22***b* are provided in the dielectric portion **20***d* within the second region **22**. The electrodes **22***a* and **22***b* constitute a bipolar electrode. Each of the electrodes **22***a* and **22***b* is a film-like electrode. The electrodes **22***a* and **22***b* may extend at substantially the same height position in the vertical direction.
(54) The electrode **22***a* is coupled to a direct-current power supply **71** through a switch **72** and a filter **73**. The filter **73** is an electric filter that blocks or attenuates the radio-frequency power RF, the bias pulses BW, and bias pulses BE to be described later. The electrode **22***b* is coupled to a direct-current power supply **74** through a switch **75** and a filter **76**. The filter **76** is an electric filter that blocks or reduces the radio-frequency power RF, the bias pulses BW, and the bias pulses BE.
(55) The direct-current power supplies **71** and **74** respectively apply direct-current voltages to the electrodes **22***a* and **22***b* to generate an electrostatic attraction force for attracting the edge ring ER to the second region **22**. A set potential of each of the electrodes **22***a* and **22***b* may be any of a positive potential, a negative potential, and 0 V. For example, the potential of the electrode **22***a* may be set to a positive potential, and the potential of the electrode **22***b* may be set to a negative potential. In addition, a potential difference between the electrodes **22***a* and **22***b* may be formed by using a single direct-current power supply, instead of two direct-current power supplies.
(56) When the direct-current voltages are applied to the electrodes **22***a* and **22***b*, the electrostatic attraction force is generated between the second region **22** and the edge ring ER. The edge ring ER is attracted to the second region **22** by the generated electrostatic attraction force and is held by the second region **22**.

(57) The second region **22** may further have a gas line **22***g*. The gas line **22***g* is a gas line provided to supply a heat transfer gas G.sub.HT, for example, a He gas, to a gap between the second region **22** and the edge ring ER. The gas line **22***g* is connected to a gas supply mechanism **86**, which is a source of the heat transfer gas G.sub.HT.
(58) The second region **22** may further have a second electrode **22***c*. The second electrode **22***c* is a film-like electrode. The second electrode **22***c* is provided in the dielectric portion **20***d* within the second region **22**. The second electrode **22***c* is separated from the first electrode **21***c*. The electrodes **22***a* and **22***b* may extend nearer the upper surface of the second region **22** than the second electrode **22***c* in the vertical direction. The second electrode **22***c* may be disposed outside the second region **22**. For example, the second electrode **22***c* may be provided below the edge ring ER and in the outer peripheral portion **29**.
(59) The plasma processing apparatus **1** may further include a second bias power supply **81**. The second bias power supply **81** is electrically coupled to the second electrode **22***c*. The second bias power supply **81** may be coupled to the second electrode **22***c* through a filter **82**. The filter **82** is an electric filter that blocks or attenuates the radio-frequency power RF.
(60) As shown in FIGS. **1** and **5**, the second bias power supply **81** successively applies a plurality of bias pulses BE to the second electrode **22***c*. The plurality of bias pulses BE are applied to the edge ring ER through the second electrode **22***c*. Each of the plurality of bias pulses BE is a voltage pulse. In the embodiment, each of the plurality of bias pulses BE is a negative voltage pulse. In an example, the negative voltage pulse is a negative direct-current voltage pulse. An output voltage of the second bias power supply **81** may be 0 V when the bias pulses BE are not output. Alternatively, the output voltage of the second bias power supply **81** has a voltage level of an absolute value smaller than absolute values |V.sub.BE| of voltage levels V.sub.BE of the bias pulses BE when the bias pulses BE are not output. The bias pulses BE may be synchronized with the bias pulses BW. The bias pulses BE may not be synchronized with the bias pulses BW.
(61) The second bias power supply **81** may periodically apply the bias pulses BE to the second electrode **22***c* at a time interval T.sub.BE. The time interval T.sub.BE is a bias cycle, and is a reciprocal of a bias frequency f.sub.BE. The bias frequency f.sub.BE is, for example, a frequency within a range of 200 kHz to 13.56 MHz. The time interval T.sub.BE may be the same as the time interval T.sub.B as shown in FIG. **5** or different from the time interval T.sub.B.
(62) A percentage of a period (time length T.sub.AE) in which one bias pulse BE is applied to the second electrode **22***c* at the time interval T.sub.BE (that is, duty ratio D.sub.BE=T.sub.AE/T.sub.BE×100(%)) is larger than 0 and smaller than 100. The time length T.sub.AE may be the same as the time length T.sub.A as shown in FIG. **5** or different from the time length T.sub.A. In addition, the duty ratio D.sub.BE may be the same as or different from the duty ratio D.sub.B.
(63) In the embodiment, each of the above ignition period Pi and the process period Pp may include a plurality of periodic pulse periods P.sub.L_E. As shown in FIG. **4**, each of the plurality of pulse periods P.sub.L_E includes an ON period P.sub.ON_E and an OFF period P.sub.OFF_E. That is, the ON period P.sub.ON_E appears at the same time interval T.sub.P_E as a time length of the plurality of pulse periods P.sub.L_E. The second bias power supply **81** may apply the plurality of bias pulses BE to the second electrode **22***c* in the ON period P.sub.ON_E of each of the plurality of periodic pulse periods P.sub.L_E. The second bias power supply **81** may stop the application of the bias pulses BE to the second electrode **22***c* in the OFF period P.sub.OFF_E of each of the plurality of pulse periods P.sub.L_E. A percentage of the ON period P.sub.ON_E (time length T.sub.ON_E) at the time interval T.sub.P_E (that is, duty ratio D.sub.P_E=T.sub.ON_E/T.sub.P_E×100(%)) is larger than 0 and smaller than 100. The bias cycle described above, that is, the time interval T.sub.BE is shorter than the pulse cycle, that is, the time interval T.sub.P_E of the ON period P.sub.ON_E. Therefore, as shown in FIG. **5**, in each ON period P.sub.ON_E, some bias pulses BE are sequentially applied to the second electrode **22***c* at the time interval T.sub.BE. The ON period

P.sub.ON_E may be synchronized with the ON period P.sub.ON. The ON period P.sub.ON_E may not be synchronized with the ON period P.sub.ON.

(64) In the embodiment, as shown in FIG. **4**, the radio-frequency power supply **57** may supply the radio-frequency power RF in an ON period P.sub.ON_R of each of a plurality of periodic pulse periods P.sub.L_R of each of the ignition period Pi and the process period Pp. That is, the radio-frequency power supply **57** may supply the radio-frequency power RF in the ON period P.sub.ON_R that appears at a time interval T.sub.P_R. The radio-frequency power supply **57** may stop the supply of the radio-frequency power RF in an OFF period P.sub.OFF_R of each of the plurality of pulse periods P.sub.L_R. A percentage of the ON period P.sub.ON_R (time length T.sub.ON_R) at the time interval T.sub.P_R (that is, duty ratio D.sub.P_R=T.sub.ON_R/T.sub.P_R×100(%)) is larger than 0 and smaller than 100. The ON period P.sub.ON_R may be synchronized with the ON period P.sub.ON and the ON period P.sub.ON_E. The ON period P.sub.ON_R may not be synchronized with at least one of the ON period P.sub.ON and the ON period P.sub.ON_E.

(65) In the embodiment, the plasma processing apparatus **1** may further include a power supply **88**. The power supply **88** applies a voltage DCS to the upper electrode **30**. The power supply **88** may apply the voltage DCS to the upper electrode **30** in each of the ignition period Pi and the process period Pp. The voltage DCS may be a negative voltage. The voltage DCS may be a negative direct-current voltage.

(66) In the embodiment, as shown in FIG. **4**, the power supply **88** may apply the voltage DCS to the upper electrode **30** in an ON period P.sub.ON_D of each of a plurality of periodic pulse periods P.sub.L_D of each of the ignition period Pi and the process period Pp. That is, the power supply **88** may apply the voltage DCS to the upper electrode **30** in the ON period P.sub.ON_D that appears at a time interval T.sub.P_D. The power supply **88** may stop the application of the voltage DCS in an OFF period P.sub.OFF_D of each of the plurality of pulse periods P.sub.L_D. A percentage of the ON period P.sub.ON_D (time length T.sub.ON_D) at the time interval T.sub.P_D (that is, duty ratio D.sub.P_D=T.sub.ON_D/T.sub.P_D×100(%)) is larger than 0 and smaller than 100. The ON period P.sub.ON_D may be synchronized with the ON period P.sub.ON, the ON period P.sub.ON_R, and the ON period P.sub.ON_E. The ON period P.sub.ON_D may not be synchronized with at least one of the ON period P.sub.ON, the ON period P.sub.ON_R, and the ON period P.sub.ON_E.

(67) In the embodiment, the plasma processing apparatus **1** may further include a controller MC as shown in FIG. **2**. The controller MC is a computer that includes a processor, a storage unit, an input unit, a display unit, and the like, and controls each unit of the plasma processing apparatus **1**. Specifically, the controller MC executes a control program stored in the storage unit, and controls each unit of the plasma processing apparatus **1** based on recipe data stored in the storage unit. A process designated by the recipe data is performed in the plasma processing apparatus **1** under control by the controller MC.

(68) Hereinafter, a plasma processing method according to an exemplary embodiment will be described with reference to FIGS. **1** to **5**, and **6**. In addition, a detailed example of operation of each unit of the plasma processing apparatus **1** will be described. FIG. **6** is a flowchart of a plasma processing method according to an exemplary embodiment.

(69) In the plasma processing method shown in FIG. **6** (hereinafter referred to as a “method MT”), the edge ring ER is held by the second region **22**, and the substrate W is held by the first region **21** of the substrate support **16**. Then, the gas supply supplies processing gases to the chamber **10**. In the example shown in FIG. **3**, the gas supply supplies the processing gases to the chamber **10** from a time point t**0**. The supply of the processing gases to the chamber is continued in the ignition period Pi and the process period Pp. In addition, the exhaust device **50** (pressure controller thereof) adjusts a pressure in the chamber **10** to a designated pressure. Further, the gas supply mechanism **86** starts supply of the heat transfer gas G.sub.HT at a time point between the time point t**0** and a start time point t**1** of the ignition period Pi. The heat transfer gas G.sub.HT is supplied to the gap

between the second region **22** and the edge ring ER. The supply of the heat transfer gases G.sub.HT is continued in the ignition period Pi and the process period Pp.
(70) Then, step STa is performed in the ignition period Pi. That is, in the ignition period Pi, the plasma is ignited in the chamber **10**. The radio-frequency power supply **57** supplies the radio-frequency power RF in the ignition period Pi. In the example shown in FIG. **3**, the supply of the radio-frequency power RF is started at the time point t**1**.
(71) Step STb is performed in the ignition period Pi. In step STb, the first bias power supply **61** sequentially applies the plurality of bias pulses BW to the first electrode **21***c*. In the example shown in FIG. **3**, the application of the plurality of bias pulses BW to the first electrode **21***c* is started at a time point t**3** after the time point t**1**, and is continued in the ignition period Pi. In addition, in step STb, the first bias power supply **61** stepwisely or gradually increases the absolute values |V.sub.BW| of the voltage levels V.sub.BW of the plurality of bias pulses BW.
(72) In the embodiment, in the ignition period Pi, the first bias power supply **61** sets the absolute value of the voltage level of each of the plurality of bias pulses BW to a value larger than an absolute value of a voltage level of any bias pulse BW that is previously applied to the first electrode **21***c*. That is, as shown in FIG. **5**, the absolute values |V.sub.BW| of the voltage levels V.sub.BW of the plurality of bias pulses BW sequentially applied to the first electrodes **21***c* in the ignition period Pi may be ramped up.
(73) When the absolute values of the voltage levels of the bias pulses BW are rapidly increased, power of reflected waves of the radio-frequency power RF is increased. In the plasma processing apparatus **1**, the levels of the plurality of bias pulses BW are stepwisely or gradually increased in the ignition period Pi. Therefore, according to the plasma processing apparatus **1**, the power of the reflected waves of the radio-frequency power RF is reduced. In addition, since the power of the reflected waves is reduced, the plasma can be stably generated in a short time, and a time length until start of a period for the substrate processing by the plasma can be shortened.
(74) In the embodiment, the second bias power supply **81** sequentially applies the plurality of bias pulses BE to the second electrode **22***c* in the ignition period Pi. The plurality of bias pulses BE are applied to the edge ring ER through the second electrode **22***c*. In the example shown in FIG. **3**, the application of the plurality of bias pulses BE to the second electrode **22***c* is started at the time point t**3** and is continued in the ignition period Pi. In addition, the second bias power supply **81** stepwisely or gradually increases the absolute values |V.sub.BE| of the voltage levels V.sub.BE of the plurality of bias pulses BE. Also, in this case, the power of the reflected waves of the radio-frequency power RF is reduced.
(75) In the embodiment, in the ignition period Pi, the second bias power supply **81** sets the absolute value of the voltage level of each of the plurality of bias pulses BE to a value larger than an absolute value of a voltage level of any bias pulse BE that is previously applied to the second electrode **22***c*. That is, as shown in FIG. **5**, the absolute values |V.sub.BE| of the voltage levels V.sub.BE of the plurality of bias pulses BE sequentially applied to the second electrodes **22***c* in the ignition period Pi may be ramped up.
(76) In the embodiment, the power supply **88** applies the voltage DCS to the upper electrode **30** in the ignition period Pi. In the example shown in FIG. **3**, the application of the voltage DCS to the upper electrode **30** is started at the time point t**2** between the time point t**1** and the time point t**3**, and is continued in the ignition period Pi (see a voltage level V.sub.DCS of the voltage DCS in FIG. **3**).
(77) In the method MT, then, step STc is performed. Step STc is performed in the process period Pp after the ignition period Pi. In the example shown in FIG. **3**, the process period Pp is started at a time point t**4**. In the process period Pp, the substrate W is processed in the chamber by plasma continuously generated from the ignition period Pi.
(78) In the embodiment, the gas supply may set a flow rate of at least one gas among the processing gases supplied to the chamber **10** in the process period Pp to a flow rate different from a flow rate

of the at least one gas supplied to the chamber **10** in the ignition period Pi. The flow rate of the at least one gas may be changed at a time point t**5** after the time point t**4**. A time length between the time point t**4** and the time point t**5** is, for example, 0.6 seconds.
(79) The processing gases include, for example, a deposition gas and an oxygen-containing gas. The deposition gas is, for example, a carbon-containing gas such as a fluorocarbon gas. The oxygen-containing gas is, for example, an O.sub.2 gas. The gas supply may set a flow rate of the deposition gas supplied to the chamber **10** in the process period Pp to a flow rate smaller than a flow rate of the deposition gas supplied to the chamber **10** in the ignition period Pi. The gas supply may set a flow rate of the oxygen-containing gas supplied to the chamber **10** in the process period Pp to a flow rate larger than a flow rate of the oxygen-containing gas supplied to the chamber **10** in the ignition period Pi.
(80) In the embodiment, the pressure controller of the exhaust device **50** may set a pressure in the chamber **10** in the process period Pp to a pressure different from a pressure in the chamber in the ignition period Pi. The pressure controller may set the pressure in the chamber **10** in the process period Pp to a pressure lower than the pressure in the chamber **10** in the ignition period Pi, as shown by a solid line in FIG. **3**. When the pressure in the chamber **10** in the process period Pp is equal to or larger than a threshold value, the pressure controller may set the pressure in the chamber **10** in the ignition period Pi (pressure indicated by a broken line in FIG. **3**) to the same pressure as the pressure in the chamber **10** in the process period Pp. When the pressure in the chamber **10** in the process period Pp is smaller than the threshold value, the pressure controller may set the pressure in the chamber **10** in the ignition period Pi to the same value as the threshold value. The threshold value of the pressure in the chamber **10** is, for example, 2.666 Pa (20 mTorr).
(81) The radio-frequency power supply **57** supplies the radio-frequency power RF also in the process period Pp in order to continuously generate the plasma from the processing gases from the ignition period Pi.
(82) In the embodiment, the radio-frequency power supply **57** may set a frequency of the radio-frequency power RF in the process period Pp to a frequency different from a frequency of the radio-frequency power RF in the ignition period Pi. As shown in FIG. **3**, the radio-frequency power supply **57** may set the frequency of the radio-frequency power RF in the process period Pp to a frequency lower than the frequency of the radio-frequency power RF in the ignition period Pi.
(83) In the embodiment, the radio-frequency power supply **57** may set a power level of the radio-frequency power RF in the process period Pp to a power level different from a power level of the radio-frequency power RF in the ignition period Pi. The radio-frequency power supply **57** may set the power level of the radio-frequency power RF in the process period Pp to a power level higher than the power level of the radio-frequency power RF in the ignition period Pi, as indicated by a solid line in FIG. **3**. When the power level of the radio-frequency power RF in the process period Pp is equal to or lower than a threshold value, the radio-frequency power supply **57** may set the power level of the radio-frequency power RF in the ignition period Pi to the same level as the power level of the radio-frequency power RF in the process period Pp. See the power level of the radio-frequency power RF indicated by a broken line in FIG. **3**. When the power level of the radio-frequency power RF in the process period Pp is higher than the threshold value, the radio-frequency power supply **57** may set the power level of the radio-frequency power RF in the ignition period Pi to the same value as the threshold value. The threshold value of power level of the radio-frequency power RF is, for example, 2500 W.
(84) In the embodiment, the radio-frequency power supply **57** may set the duty ratio D.sub.P_R in the process period Pp to a ratio different from the duty ratio D.sub.P_R in the ignition period Pi. The radio-frequency power supply **57** may set the duty ratio D.sub.P_R in the process period Pp to a ratio smaller than the duty ratio D.sub.P_R in the ignition period Pi. When the duty ratio D.sub.P_R in the process period Pp is equal to or larger than a threshold value, the radio-frequency power supply **57** may set the duty ratio D.sub.P_R in the ignition period Pi to the same ratio as the

duty ratio D.sub.P_R in the process period Pp. When the duty ratio D.sub.P_R in the process period Pp is smaller than the threshold value, the radio-frequency power supply **57** may set the duty ratio D.sub.P_R in the ignition period Pi to the same value as the threshold value. The threshold value of the duty ratio D.sub.P_R is, for example, 30%.
(85) The first bias power supply **61** successively applies the plurality of bias pulses BW to the first electrode **21***c* also in the process period Pp. The plurality of bias pulses BW may be sequentially applied to the first electrode **21***c* in the process period Pp in the same manner as in the ignition period Pi. The voltage levels of the plurality of bias pulses BW may be the same in the process period Pp.
(86) In the embodiment, the first bias power supply **61** may set the duty ratio D.sub.P in the process period Pp to a ratio different from the duty ratio D.sub.P in the ignition period Pi. The first bias power supply **61** may set the duty ratio D.sub.P in the process period Pp to a ratio smaller than the duty ratio D.sub.P in the ignition period Pi, as indicated by a solid line in FIG. **3**. When the duty ratio D.sub.P in the process period Pp is equal to or larger than a threshold value, the first bias power supply **61** may set the duty ratio D.sub.P in the ignition period Pi to the same ratio as the duty ratio D.sub.P in the process period Pp, as indicated by a broken line in FIG. **3**. When the duty ratio D.sub.P in the process period Pp is smaller than the threshold value, the first bias power supply **61** may set the duty ratio D.sub.P in the ignition period Pi to the same value as the threshold value. The threshold value of the duty ratio D.sub.P is, for example, 30%.
(87) The second bias power supply **81** successively applies the plurality of bias pulses BE to the second electrode **22***c* also in the process period Pp. The plurality of bias pulses BE may be sequentially applied to the second electrode **22***c* in the process period Pp in the same manner as in the ignition period Pi. The voltage levels of the plurality of bias pulses BE may be the same in the process period Pp.
(88) In the embodiment, the second bias power supply **81** may set the duty ratio D.sub.P_E in the process period Pp to a ratio different from the duty ratio D.sub.P_E in the ignition period Pi. The second bias power supply **81** may set the duty ratio D.sub.P_E in the process period Pp to a ratio smaller than the duty ratio D.sub.P_E in the ignition period Pi. When the duty ratio D.sub.P_E in the process period Pp is equal to or larger than a threshold value, the second bias power supply **81** may set the duty ratio D.sub.P_E in the ignition period Pi to the same ratio as the duty ratio D.sub.P_E in the process period Pp. When the duty ratio D.sub.P_E in the process period Pp is smaller than the threshold value, the second bias power supply **81** may set the duty ratio D.sub.P_E in the ignition period Pi to the same value as the threshold value. The threshold value of the duty ratio D.sub.P_E is, for example, 30%.
(89) The power supply **88** applies the voltage DCS to the upper electrode **30** also in the process period Pp. A voltage level of the voltage DCS in the process period Pp may be the same as a voltage level of the voltage DCS in the ignition period Pi.
(90) In the embodiment, the power supply **88** may set the duty ratio D.sub.P_D in the process period Pp to a ratio different from the duty ratio D.sub.P_D in the ignition period Pi. The power supply **88** may set the duty ratio D.sub.P_D in the process period Pp to a ratio smaller than the duty ratio D.sub.P_D in the ignition period Pi. When the duty ratio D.sub.P_D in the process period Pp is equal to or larger than a threshold value, the power supply **88** may set the duty ratio D.sub.P_D in the ignition period Pi to the same ratio as the duty ratio D.sub.P_D in the process period Pp. When the duty ratio D.sub.P_D in the process period Pp is smaller than the threshold value, the power supply **88** may set the duty ratio D.sub.P_D in the ignition period Pi to the same value as the threshold value. The threshold value of the duty ratio D.sub.P_D is, for example, 30%.
(91) The gas supply mechanism **86** supplies the heat transfer gas G.sub.HT to the gap between the second region **22** and the edge ring ER also in the process period Pp. The gas supply mechanism **86** may set a pressure of the heat transfer gas G.sub.HT in the process period Pp to a pressure different from a pressure of the heat transfer gas G.sub.HT in the ignition period Pi. The gas supply

mechanism **86** may set the pressure of the heat transfer gas G.sub.HT in the process period Pp to a pressure higher than the pressure of the heat transfer gas G.sub.HT in the ignition period Pi.
(92) While various exemplary embodiments have been described above, various additions, omissions, substitutions and changes may be made without being limited to the exemplary embodiments described above. Indeed, the embodiments described herein may be embodied in a variety of other forms.
(93) For example, in another embodiment, the bias pulses BW from the first bias power supply **61** may be applied to the lower electrode **18**. In this case, the plasma processing apparatus **1** may not include the first electrode **21***c*. The bias pulses BW from the first bias power supply **61** may be applied to the electrode **21***a*. Also, in this case, the plasma processing apparatus **1** may not include the first electrode **21***c*.
(94) In another embodiment, the bias pulses BE from the second bias power supply **81** may be applied to the electrodes **22***a* and **22***b*. In this case, the plasma processing apparatus **1** may not include the second electrode **22***c*.
(95) In another embodiment, the plasma processing apparatus may be a capacitively-coupled plasma processing apparatus different from the plasma processing apparatus **1**. In another embodiment, the plasma processing apparatus may be another type of plasma processing apparatus. The another type of plasma processing apparatus may be an inductively-coupled plasma processing apparatus, an electron cyclotron resonance (ECR) plasma processing apparatus, or a plasma processing apparatus that generates plasma by using surface waves such as microwaves.
(96) In another embodiment, the voltage levels of the plurality of bias pulses BW may be stepwisely or gradually changed from positive voltage levels to negative voltage levels. Also, in this case, after positive voltage pulses are switched to negative voltage pulses, the absolute values |V.sub.BW| of the voltage levels V.sub.BW of the plurality of bias pulses BW are stepwisely or gradually increased as described above. Similarly, the voltage levels of the plurality of bias pulses BE may be stepwisely or gradually changed from positive voltage levels to negative voltage levels. Also, in this case, after positive voltage pulses are switched to negative voltage pulses, the absolute values |V.sub.BE| of the voltage levels V.sub.BE of the plurality of bias pulses BE are stepwisely or gradually increased as described above.
(97) Hereinafter, first to fourth experiments will be described. In the first to fourth experiments, the power of the reflected waves of the radio-frequency power RF in the ignition period Pi was measured by using the plasma processing apparatus **1**. In the first to third experiments, the absolute values of the voltage levels of the plurality of bias pulses BW were ramped up from 0 V to 9500 V between the time point t**3** and the time point t**4** in the ignition period Pi. The time lengths between the time point t**3** and the time point t**4** in the first to third experiments were 1 second, 2 seconds, and 3 seconds, respectively. In addition, in the fourth experiment, the absolute values of the voltage levels of the plurality of bias pulses BW were stepwisely increased to 2500 V, 6000 V, and 9500 V between the time point t**3** and the time point t**4** in the ignition period Pi.
(98) FIGS. **7**A and **7**B are graphs showing the absolute values |V.sub.BW| of the voltage levels of the bias pulses BW and power Pr of the reflected waves of the radio-frequency power RF in the first experiment, respectively. FIGS. **8**A and **8**B are graphs showing the absolute values |V.sub.BW| of the voltage levels of the bias pulses BW and power Pr of the reflected waves of the radio-frequency power RF in the second experiment, respectively. FIGS. **9**A and **9**B are graphs showing the absolute values |V.sub.BW| of the voltage levels of the bias pulses BW and power Pr of the reflected waves of the radio-frequency power RF in the third experiment, respectively. FIGS. **10**A and **10**B are graphs showing the absolute values |V.sub.BW| of the voltage levels of the bias pulses BW and power Pr of the reflected waves of the radio-frequency power RF in the fourth experiment, respectively. As shown in these drawings, it has been confirmed that the power Pr of the reflected waves of the radio-frequency power RF could be reduced by stepwisely or gradually increasing the absolute values |V.sub.BW| of the power levels of the plurality of bias pulses BW. In particular, in

the third experiment and the fourth experiment, by ramping the absolute values |V.sub.BW| from 0 V to 9500 V in a period of 2 seconds or more, the power Pr of the reflected waves of the radio-frequency power RF immediately after the start of the application of the bias pulses BW could be significantly reduced.

(99) From the foregoing, it will be appreciated that various embodiments of the present disclosure have been described herein for purposes of illustration, and that various modifications may be made without departing from the scope and spirit of the present disclosure. Accordingly, the various embodiments disclosed herein are not intended to be limiting, with the true scope and spirit being indicated by the following claims.

Claims

1. A plasma processing apparatus comprising: a chamber; a substrate support including an electrode and provided in the chamber; a radio-frequency power supply configured to supply radio-frequency power for generating plasma from a gas in the chamber; a bias power supply electrically coupled to the electrode; and a controller configured to: control the radio-frequency power supply to supply the radio-frequency power in an ignition period in which the plasma is ignited in the chamber, and control the bias power supply to sequentially apply exclusively negative voltage bias pulses to the electrode in the ignition period, and stepwisely or gradually increase absolute values of voltage levels of the negative voltage bias pulses.
2. The plasma processing apparatus according to claim 1, wherein each of the negative voltage bias pulses is a direct-current voltage pulse.
3. The plasma processing apparatus according to claim 1, wherein the controller is configured to: control the radio-frequency power supply to supply the radio-frequency power also in a process period in which a substrate is processed in the chamber using the plasma after the ignition period, and control the bias power supply to sequentially apply the negative voltage bias pulses to the electrode also in the process period.
4. The plasma processing apparatus according to claim 3, further comprising: a pressure controller configured to adjust a pressure in the chamber, wherein the pressure controller is configured to set a pressure in the chamber in the process period to a pressure different from a pressure in the chamber in the ignition period.
5. The plasma processing apparatus according to claim 4, wherein the pressure controller is configured to set the pressure in the chamber in the process period to a pressure lower than the pressure in the chamber in the ignition period.
6. The plasma processing apparatus according to claim 3, wherein the controller is configured to control the radio-frequency power supply to set a frequency of the radio-frequency power in the process period to a frequency different from a frequency of the radio-frequency power in the ignition period.
7. The plasma processing apparatus according to claim 6, wherein the controller is configured to control the radio-frequency power supply to set the frequency of the radio-frequency power in the process period to a frequency lower than the frequency of the radio-frequency power in the ignition period.
8. The plasma processing apparatus according to claim 3, wherein the controller is configured to control the radio-frequency power supply to set a power level of the radio-frequency power in the process period to a power level different from a power level of the radio-frequency power in the ignition period.
9. The plasma processing apparatus according to claim 8, wherein the controller is configured to the radio-frequency power supply to set the power level of the radio-frequency power in the process period to a power level higher than the power level of the radio-frequency power in the ignition period.

10. The plasma processing apparatus according to claim 3, further comprising: a gas supply configured to supply gases from which the plasma is generated in the chamber to the chamber, wherein the controller is configured to control the gas supply to set a flow rate of at least one gas supplied to the chamber in the process period to a flow rate different from a flow rate of the at least one gas supplied to the chamber in the ignition period.
11. The plasma processing apparatus according to claim 3, wherein each of the ignition period and the process period includes a plurality of periodic pulse periods, and the controller is configured to control the bias power supply to apply the negative voltage bias pulses to the electrode in a bias cycle shorter than a pulse cycle that is a time interval of an ON period in the ON period of each of the plurality of pulse periods, and stop the application of the negative voltage bias pulses to the electrode in an OFF period of each of the plurality of pulse periods.
12. The plasma processing apparatus according to claim 11, wherein the controller is configured to control the bias power supply to adjust a duty ratio that is a ratio of a time length of each ON period to a time length of the pulse cycle, and set a duty ratio in the process period to a ratio different from a duty ratio in the ignition period.
13. The plasma processing apparatus according to claim 12, wherein the controller is configured to control the bias power supply to set the duty ratio in the process period to a ratio smaller than the duty ratio in the ignition period.
14. The plasma processing apparatus according to claim 1, wherein the substrate support is configured to support an edge ring placed thereon, and the plasma processing apparatus further comprises another bias power supply configured to apply the negative voltage bias pulses to the edge ring.
15. The plasma processing apparatus according to claim 1, wherein the controller is configured to control the bias power supply such that each of the negative voltage bias pulses itself is a constant voltage.
16. The plasma processing apparatus according to claim 1, wherein the ignition period immediately precedes a process period in which a substrate is processed in the chamber using the plasma ignited during the ignition period.
17. The plasma processing apparatus according to claim 16, wherein the controller is configured to control the bias power supply to sequentially apply exclusively negative voltage bias pulses to the electrode during the process period.
18. The plasma processing apparatus according to claim 17, wherein absolute values of voltage levels of the negative voltage bias pulses applied during the process period are constant with respect to one another.