DESCRIPTION

Title of Invention: PLASMA TREATMENT DEVICE, POWER SUPPLY SYSTEM, AND PLASMA TREATMENT METHOD

Technical Field

[0001] Example embodiments of the present disclosure relate to a plasma processing apparatus, a power supply system, and a plasma processing method.

Background Art

[0002] A plasma processing apparatus is used in plasma processing of a substrate. The plasma processing apparatus described in Patent Literature 1 includes a chamber and a substrate support electrode. The substrate support electrode is disposed in the chamber. The substrate support electrode holds a substrate placed on a main surface thereof. The plasma processing apparatus described in Patent Literature 1 further includes a radio frequency generator and a DC negative pulse generator. The radio frequency generator applies a radio frequency voltage to the substrate support electrode. In addition, the radio frequency voltage is alternately switched on and off. A DC negative pulse voltage is applied from the DC negative pulse generator to the substrate support electrode in accordance with the timing of ON and OFF of the radio frequency voltage.

Citation List

Patent Literature

[0003] [Patent Literature 1] Japanese Unexamined Patent Publication No. 2009-187975

Summary of Invention

Technical Problem

[0004] The present disclosure provides a technology for suppressing a decrease in etch rate.

Solution to Problem

[0005] In one example embodiment, a plasma processing apparatus is disclosed. The plasma processing apparatus includes a chamber, a substrate support in the chamber, a radio frequency power supply, a bias supply, and a controller. The radio frequency power supply is configured to supply source radio frequency power to generate a plasma from a gas in the chamber. The bias supply is configured to supply an electrical bias to the substrate support to attract ions from the plasma to a substrate on the substrate support. The controller is configured to control the radio frequency power supply and the bias supply to, in a plasma processing period, supply the source radio frequency power and the electrical bias continuously and simultaneously, and set a power level of the source radio frequency power to 3 kW or less, a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias to less than 400 kHz, and a voltage amplitude of the electrical bias to 3 kV or more.

Advantageous Effects of Invention

[0006] According to one example embodiment, a technology for suppressing a decrease in etch rate is provided.

Brief Description of Drawings

[0007] [FIG. 1] FIG. 1 illustrates an example configuration of a plasma processing system.

[FIG. 2] FIG. 2 illustrates an example configuration of a capacitively coupled plasma processing apparatus.

[FIG. 3] FIG. 3 is a diagram illustrating a plasma processing apparatus according to one example embodiment.

[FIG. 4] FIG. 4 is a diagram illustrating an example of a waveform of an electrical bias.

[FIG. 5] FIG. 5(a) is a timing chart of an example of source radio frequency power, and FIG. 5(b) is a timing chart of an example of an electrical bias.

[FIG. 6] FIG. 6 is a diagram illustrating an example of a plasma and a sheath in a chamber.

[FIG. 7] FIG. 7 is a diagram illustrating a plasma processing method according to one example embodiment.

[FIG. 8] FIG. 8 is a diagram illustrating results of a first experiment.

[FIG. 9] FIG. 9 is a diagram illustrating results of a second experiment.

[FIG. 10] FIG. 10 is a diagram illustrating a plasma processing apparatus according to another example embodiment.

[FIG. 11] FIG. 11 is a block diagram of processing circuitry for performing computer-based operations described herein.

Description of Embodiments

[0008] Hereinafter, various example embodiments will be described in detail with reference to the drawings. In the drawings, the same or equivalent portions are denoted by the same reference signs.

[0009] FIG. 1 illustrates an example configuration of a plasma

processing system. In an embodiment, the plasma processing system includes a plasma processing apparatus 1 and a controller 2. The plasma processing system is an example substrate processing system, and the plasma processing apparatus 1 is an example substrate processing apparatus. The plasma processing apparatus 1 includes a plasma processing chamber 10, a substrate support 11, and a plasma generator 12. The plasma processing chamber 10 has a plasma processing space. The plasma processing chamber 10 further has at least one gas inlet for supplying at least one process gas into the plasma processing space and at least one gas outlet for exhausting gases from the plasma processing space. The gas inlet is connected to a gas supply 20 described below and the gas outlet is connected to a gas exhaust system 40 described below. The substrate support 11 is disposed in the plasma processing space and has a substrate supporting surface for supporting a substrate.

[0010] The plasma generator 12 is configured to generate a plasma from the at least one process gas supplied into the plasma processing space. The plasma formed in the plasma processing space may be, for example, a capacitively coupled plasma (CCP), an inductively coupled plasma (ICP), an electron-cyclotron-resonance (ECR) plasma, a helicon wave plasma (HWP), or a surface wave plasma (SWP). Various types of plasma generators may also be used, such as an alternating current (AC) plasma generator and a direct current (DC) plasma generator. In an embodiment, an AC signal (AC power) used in the AC plasma generator has a frequency in a range of 100 kHz to 10 GHz. Hence, examples of the AC signal include a radio frequency (RF) signal and a microwave signal. In an embodiment, the RF signal has a frequency in a range of

100 kHz to 150 MHz.

[0011] The controller 2 processes computer executable instructions causing the plasma processing apparatus 1 to perform various steps described in this disclosure. The controller 2 may be configured to control individual components of the plasma processing apparatus 1 such that these components execute the various steps. In an embodiment, the controller 2 may be partially or entirely incorporated into the plasma processing apparatus 1. The controller 2 may include a processor 2a1, a storage 2a2, and a communication interface 2a3. The controller 2 is implemented in, for example, a computer 2a. The processor 2a1 may be configured to read a program from the storage 2a2, and then perform various control operations by executing the read program. This program may be preliminarily stored in the storage 2a2 or retrieved via any medium, when needed. The retrieved program is stored in the storage 2a2, and then the processor 2a1 reads and executes the program from the storage 2a2. The medium may be any of various storage media which can be accessed by the computer 2a or may be a communication line connected to the communication interface 2a3. The processor 2a1 may be a central processing unit (CPU). The storage 2a2 may include a random access memory (RAM), a read only memory (ROM), a hard disk drive (HDD), a solid state drive (SSD), or any combination thereof. The communication interface 2a3 may communicate with the plasma processing apparatus 1 via a communication line, such as a local area network (LAN).

[0012] An example configuration of a capacitively coupled plasma processing apparatus, which is an example of the plasma processing

apparatus 1, will now be described. FIG. 2 illustrates the example configuration of the capacitively coupled plasma processing apparatus.

[0013] The capacitively coupled plasma processing apparatus 1 includes a plasma processing chamber 10, a gas supply 20, an electric power source 30, and a gas exhaust system 40. The plasma processing apparatus 1 further includes a substrate support 11 and a gas introduction unit. The gas introduction unit is configured to introduce at least one process gas into the plasma processing chamber 10. The gas introduction unit includes a showerhead 13. The substrate support 11 is disposed in the plasma processing chamber 10. The showerhead 13 is disposed above the substrate support 11. In an embodiment, the showerhead 13 functions as at least part of the ceiling of the plasma processing chamber 10. The plasma processing chamber 10 has a plasma processing space 10s that is defined by the showerhead 13, a sidewall 10a of the plasma processing chamber 10, and the substrate support 11. The plasma processing chamber 10 is grounded. The showerhead 13 and the substrate support 11 are electrically insulated from the housing of the plasma processing chamber 10.

[0014] The substrate support 11 includes a body 111 and a ring assembly 112. The body 111 has a central region 111a for supporting a substrate W and an annular region 111b for supporting the ring assembly 112. An example of the substrate W is a wafer. The annular region 111b of the body 111 surrounds the central region 111a of the body 111 in plan view. The substrate W is disposed on the central region 111a of the body 111, and the ring assembly 112 is disposed on the annular region 111b of the body 111 so as to surround the substrate W on the central region 111a of

the body 111. Thus, the central region 111a is also called a substrate supporting surface for supporting the substrate W, while the annular region 111b is also called a ring supporting surface for supporting the ring assembly 112.

[0015] In an embodiment, the body 111 includes a base 1110 and an electrostatic chuck 1111. The base 1110 includes a conductive member. The conductive member of the base 1110 can function as a lower electrode. The electrostatic chuck 1111 is disposed on the base 1110. The electrostatic chuck 1111 includes a ceramic member 1111a and an electrostatic electrode 1111b disposed in the ceramic member 1111a. The ceramic member 1111a has the central region 111a. In an embodiment, the ceramic member 1111a also has the annular region 111b. Any other member, such as an annular electrostatic chuck or an annular insulating member, surrounding the electrostatic chuck 1111 may have the annular region 111b. In this case, the ring assembly 112 may be disposed on either the annular electrostatic chuck or the annular insulating member, or on both the electrostatic chuck 1111 and the annular insulating member. At least one RF/DC electrode coupled to an RF source 31 and/or a DC source 32 described below may be disposed in the ceramic member 1111a. In this case, the at least one RF/DC electrode functions as the lower electrode. If a bias RF signal and/or a DC signal described below are supplied to the at least one RF/DC electrode, the RF/DC electrode is also called a bias electrode. It is noted that the conductive member of the base 1110 and the at least one RF/DC electrode may function as a plurality of lower electrodes. The electrostatic electrode 1111b may also function as a lower electrode.

The substrate support 11 accordingly includes at least one lower electrode.

[0016] The ring assembly 112 includes one or more annular members. In an embodiment, the annular members include one or more edge rings and at least one cover ring. The one or more edge rings are made of a conductive or insulating material, whereas the cover ring is made of an insulating material.

[0017] The substrate support 11 may also include a temperature adjusting module that is configured to adjust at least one of the electrostatic chuck 1111, the ring assembly 112, and the substrate to a target temperature. The temperature adjusting module may include a heater, a heat transfer medium, a flow passage 1110a, or any combination thereof. A heat transfer fluid, such as brine or gas, flows into the flow passage 1110a. In an embodiment, the flow passage 1110a is formed in the base 1110, and one or more heaters are disposed in the ceramic member 1111a of the electrostatic chuck 1111. The substrate support 11 may further include a heat transfer gas supply configured to supply a heat transfer gas to a gap between the rear surface of the substrate W and the central region 111a.

[0018] The showerhead 13 is configured to introduce at least one process gas from the gas supply 20 into the plasma processing space 10s. The showerhead 13 has at least one gas inlet 13a, at least one gas diffusing space 13b, and a plurality of gas feeding ports 13c. The process gas supplied to the gas inlet 13a passes through the gas diffusing space 13b and is then introduced into the plasma processing space 10s from the gas feeding ports 13c. The showerhead 13 further includes at

least one upper electrode. The gas introduction unit may include one or more side gas injectors provided at one or more openings formed in the sidewall 10a, in addition to the showerhead 13.

[0019] The gas supply 20 may include at least one gas source 21 and at least one flow controller 22. In an embodiment, the gas supply 20 is configured to supply at least one process gas from the corresponding gas source 21 through the corresponding flow controller 22 to the showerhead 13. Each flow controller 22 may include, for example, a mass flow controller or a pressure-controlled flow controller. The gas supply 20 may include at least one flow modulation device that can modulate or pulse the flow of the at least one process gas.

[0020] The electric power source 30 includes an RF source 31 coupled to the plasma processing chamber 10 through at least one impedance matching circuit. The RF source 31 is configured to supply at least one RF signal (RF power) to at least one lower electrode and/or at least one upper electrode. A plasma is thereby formed from at least one process gas supplied into the plasma processing space 10s. Thus, the RF source 31 can function as at least part of the plasma generator 12. The bias RF signal supplied to the at least one lower electrode causes a bias potential to occur in the substrate W, which potential then attracts ionic components in the plasma to the substrate W.

[0021] In an embodiment, the RF source 31 includes a first RF generator 31a and a second RF generator 31b. The first RF generator 31a is coupled to the at least one lower electrode and/or the at least one upper electrode through the at least one impedance matching circuit and is configured to generate a source RF signal (source RF power) for

generating a plasma. In an embodiment, the source RF signal has a frequency in a range of 10 MHz to 150 MHz. In an embodiment, the first RF generator 31a may be configured to generate a plurality of source RF signals having different frequencies. The generated source RF signal(s) is supplied to the at least one lower electrode and/or the at least one upper electrode.

[0022] The second RF generator 31b is coupled to the at least one lower electrode through the at least one impedance matching circuit and is configured to generate a bias RF signal (bias RF power). The bias RF signal and the source RF signal may have the same frequency or different frequencies. In an embodiment, the bias RF signal has a frequency which is lower than that of the source RF signal. In an embodiment, the bias RF signal has a frequency in a range of 100 kHz to 60 MHz. In an embodiment, the second RF generator 31b may be configured to generate a plurality of bias RF signals having different frequencies. The generated bias RF signal(s) is supplied to the at least one lower electrode. In various embodiments, at least one of the source RF signal and the bias RF signal may be pulsed.

[0023] The electric power source 30 may also include a DC source 32 coupled to the plasma processing chamber 10. The DC source 32 includes a first DC generator 32a and a second DC generator 32b. In an embodiment, the first DC generator 32a is connected to the at least one lower electrode and is configured to generate a first DC signal. The generated first DC signal is applied to the at least one lower electrode. In an embodiment, the second DC generator 32b is connected to the at least one upper electrode and is configured to generate a second DC signal.

The generated second DC signal is applied to the at least one upper electrode.

[0024] In various embodiments, the first and second DC signals may be pulsed. In this case, a sequence of voltage pulses is applied to the at least one lower electrode and/or the at least one upper electrode. The voltage pulses may have a rectangular, trapezoidal, or triangular pulse waveform, or a pulse waveform of a combination thereof. In an embodiment, a waveform generator for generating a sequence of voltage pulses from the DC signal is connected between the first DC generator 32a and the at least one lower electrode. The first DC generator 32a and the waveform generator thereby function as a voltage pulse generator. In the case that the second DC generator 32b and the waveform generator function as a voltage pulse generator, the voltage pulse generator is connected to the at least one upper electrode. The voltage pulses may have positive polarity or negative polarity. A sequence of voltage pulses may also include one or more positive voltage pulses and one or more negative voltage pulses in a cycle. The first and second DC generators 32a, 32b may be disposed in addition to the RF source 31, or the first DC generator 32a may be disposed in place of the second RF generator 31b.

[0025] The gas exhaust system 40 may be connected to, for example, a gas outlet 10e provided in the bottom of the plasma processing chamber 10. The gas exhaust system 40 may include a pressure regulation valve and a vacuum pump. The pressure regulation valve enables the pressure in the plasma processing space 10s to be adjusted. The vacuum pump may include a turbo-molecular pump, a dry pump, or a combination thereof.

[0026] Hereinafter, reference is made to FIG. 3. FIG. 3 is a diagram illustrating a plasma processing apparatus according to one example embodiment. As illustrated in FIG. 3, the plasma processing apparatus 1 includes a radio frequency power supply 41 and a bias supply 42. The radio frequency power supply 41 and the bias supply 42 constitute a power supply system 30S. The power supply system 30S may further include the controller 2. Alternatively, the power supply system 30S may include, in place of the controller 2, a controller other than the controller 2 that can perform the same control of the radio frequency power supply 41 and the bias supply 42 as that performed by the controller 2 as described below. Alternatively, the power supply system 30S may not include a controller, and the radio frequency power supply 41 and the bias supply 42 may be configured to perform their respective operations described below.

[0027] The radio frequency power supply 41 is the first RF generator 31a. The radio frequency power supply 41 is configured to generate a source RF signal, that is, source radio frequency power HF. The source radio frequency power HF has a source frequency. That is, the source radio frequency power HF has a sinusoidal waveform whose frequency is the source frequency. The source frequency may be a frequency in a range of 10 MHz to 150 MHz.

[0028] The radio frequency power supply 41 is electrically connected to a radio frequency electrode via a matcher 43, and is configured to supply the source radio frequency power HF to the radio frequency electrode. The radio frequency electrode may be disposed in the substrate support 11. The radio frequency electrode may be the conductive member of the

base 1110 or at least one electrode disposed in the ceramic member 1111a. Alternatively, the radio frequency electrode may be an upper electrode. When the source radio frequency power HF is supplied to the radio frequency electrode, a plasma is generated from the gas in the chamber 10.

[0029] The matcher 43 has a variable impedance. The variable impedance of the matcher 43 is set so as to reduce reflection of the source radio frequency power HF from a load. The matcher 43 may be controlled by, for example, the controller 2.

[0030] The bias supply 42 includes the second RF generator 31b or the first DC generator 32a. The bias supply 42 is electrically coupled to the substrate support 11. The bias supply 42 is electrically connected to a bias electrode in the substrate support 11 and is configured to supply an electrical bias EB to the bias electrode. The bias electrode may be the conductive member of the base 1110 or at least one electrode disposed in the ceramic member 1111a. The bias electrode may be common with the radio frequency electrode. When the electrical bias EB is supplied to the bias electrode, ions from the plasma are attracted to the substrate W.

[0031] Hereinafter, reference is made to FIG. 4 together with FIG. 3. FIG. 4 is a diagram illustrating an example of a waveform of an electrical bias. The bias supply 42 is configured to periodically apply an electrical bias EB having a waveform cycle C_W to the bias electrode. That is, the electrical bias EB is applied to the bias electrode in each of a plurality of waveform cycles C_W which are repetitions of the waveform cycle C_W. The waveform cycle C_W is defined by a bias frequency. The bias frequency is, for example, a frequency of 50 kHz or more and 27

MHz or less. The electrical bias EB has the bias frequency. The time length of the waveform cycle C_W is the reciprocal of the bias frequency. The bias frequency may be 13.56 MHz or less, or 400 kHz or less.

[0032] The electrical bias EB may be a bias RF signal, that is, a bias radio frequency power LF having the bias frequency. That is, the electrical bias EB may have a sinusoidal waveform whose frequency is the bias frequency. In this case, the bias supply 42 is electrically connected to the bias electrode via a matcher 44. The variable impedance of the matcher 44 is set so as to reduce reflection of the bias radio frequency power LF from a load.

[0033] Alternatively, the electrical bias EB may include a pulsed first DC signal, that is, a voltage pulse VP. The voltage pulse VP is applied to the bias electrode within the waveform cycle C_W. The voltage pulse VP is periodically applied to the bias electrode at a time interval equal to the time length of the waveform cycle C_W. The waveform of the voltage pulse VP may be a rectangular wave, a triangular wave, or any waveform. The polarity of the voltage of the voltage pulse VP is set so as to create a potential difference between the substrate W and the plasma to attract ions from the plasma to the substrate W. The voltage pulse VP is applied to the bias electrode such that the waveform cycle C_W includes a period during which the potential of the substrate W is a negative potential. The voltage pulse VP applied to the bias electrode may have a negative potential, a positive potential, or a potential that varies between a positive potential and a negative potential. The voltage pulse VP may be a negative voltage pulse or a negative DC voltage pulse. When the electrical bias EB is the voltage pulse VP, the plasma

processing apparatus 1 need not include the matcher 44.

[0034] Hereinafter, reference is made to FIG. 5(a) and FIG. 5(b) together with FIG. 3. FIG. 5(a) is a timing chart of an example of source radio frequency power, and FIG. 5(b) is a timing chart of an example of an electrical bias. In FIG. 5(a), ON of the source radio frequency power HF indicates that the source radio frequency power HF is being supplied, and OFF of the source radio frequency power HF indicates that the source radio frequency power HF is stopped. In FIG. 5(b), ON of the electrical bias EB indicates that the electrical bias EB is being supplied, and OFF of the electrical bias EB indicates that the electrical bias EB is stopped.

[0035] As illustrated in FIG. 5(a), the controller 2 controls the radio frequency power supply 41 and the bias supply 42 to supply the source radio frequency power HF and the electrical bias EB continuously and simultaneously in the plasma processing period P_S. In the example illustrated in FIG. 5(a), the source radio frequency power HF and the electrical bias EB may be supplied continuously for 1 minute or more, 5 minutes or more, or 10 minutes or more. In the plasma processing period P_S, the substrate W on the substrate support 11 may be processed using the plasma generated in the chamber 10.

[0036] The controller 2 controls the radio frequency power supply 41 and the bias supply 42 so as to set the power level of the source radio frequency power HF to 3 kW or less, the bias frequency to less than 400 kHz, and the voltage amplitude of the electrical bias EB to 3 kV or more in the plasma processing period P_S. The voltage amplitude of the electrical bias EB may be the voltage amplitude of the electrical bias EB

at the output of the bias supply 42, at the bias electrode, or at the substrate W. When the electrical bias EB includes the voltage pulse VP, the voltage amplitude of the electrical bias EB is the amplitude of the voltage pulse VP. When the electrical bias EB includes the voltage pulse VP, the voltage amplitude of the electrical bias EB may be the absolute value of the voltage level of the voltage pulse VP with respect to a reference potential. The reference potential of the voltage pulse VP is the voltage level of the electrical bias EB during the period in the waveform cycle C_W when the voltage pulse VP is not generated, and is, for example, 0 V. When the electrical bias EB is the bias radio frequency power LF, the voltage amplitude of the electrical bias EB is the peak-to-peak voltage (V_{PP}) of the bias radio frequency power LF.

[0037] In the plasma processing apparatus 1, the source radio frequency power HF having a relatively low power level is used in the plasma processing period P_S. Therefore, according to the plasma processing apparatus 1, it is possible to reduce the size and power consumption of the radio frequency power supply 41.

[0038] Also, in the plasma processing apparatus 1, an electrical bias EB having a bias frequency of less than 400 kHz is used. According to the electrical bias EB having a bias frequency of less than 400 kHz, reflection of the source radio frequency power HF from the load of the radio frequency power supply 41 is suppressed, and coupling of the source radio frequency power HF to the plasma is promoted.

[0039] Hereinafter, reference is made to FIG. 6. FIG. 6 is a diagram illustrating an example of a plasma and a sheath in a chamber. In FIG. 6, the plasma PL when the electrical bias EB has a negative-side peak

voltage is shown by a solid line, and the plasma PL when the electrical bias EB has a positive-side peak voltage is shown by a dashed line. In the case where the electrical bias EB includes the voltage pulse VP, the negative-side peak voltage is the voltage of the voltage pulse VP during the period in the waveform cycle C_W when the voltage pulse VP is being output. In the case where the electrical bias EB includes the voltage pulse VP, the positive-side peak voltage is the voltage of the electrical bias EB during the period in the waveform cycle C_W when the voltage pulse VP is stopped. In the case where the electrical bias EB is the bias radio frequency power LF, the negative-side peak voltage is the negative-side peak voltage of the bias radio frequency power LF within the waveform cycle C_W. Also, In the case where the electrical bias EB is the bias radio frequency power LF, the positive-side peak voltage is the positive-side peak voltage of the bias radio frequency power LF within the waveform cycle C_W.

[0040] As illustrated in FIG. 6, when the electrical bias EB has a relatively positive-side peak voltage, the thickness of the sheath SB (plasma sheath) between the plasma PL and the substrate W is small, and the sheath voltage is also small. On the other hand, when the electrical bias EB has the negative-side peak voltage, the thickness of the sheath SA (plasma sheath) between the plasma PL and the substrate W is large, and the sheath voltage is also large. When the voltage of the electrical bias EB switches from the positive-side peak voltage to the negative-side peak voltage, that is, when the sheath voltage (potential difference) between the plasma PL and the substrate W switches from a minimum to a maximum, many of the ions in the plasma PL that existed

in a region VR of the sheath SA excluding the region of the sheath SB are accelerated by the relatively large sheath voltage and attracted to the substrate W. In the plasma processing apparatus 1, as described above, since the voltage amplitude of the electrical bias EB is set to 3 kV or more in the plasma processing period P_S, the thickness of the region VR in the plasma processing period P_S can be made large. Therefore, according to the plasma processing apparatus 1, even when the density of the plasma PL is low, a large amount of ions having high energy can be attracted to the substrate W. Hence, according to the plasma processing apparatus 1, it is possible to suppress a decrease in etch rate. Also, in the plasma processing apparatus 1, source radio frequency power with a low power level may be used, and even when source radio frequency power with a low power level is used, it is possible to suppress a decrease in etch rate.

[0041] In one embodiment, the controller 2 may change one or more control parameters of the plasma processing apparatus 1 over time during the plasma processing period P_S. The one or more control parameters include at least one control parameter selected from the group consisting of the voltage amplitude of the electrical bias EB, the bias frequency, the duty ratio (ON duty) of the voltage pulse VP in the waveform cycle C_W, the pressure in the chamber 10, the power level of the source radio frequency power HF, the frequency of the source radio frequency power HF, and the temperature of the substrate support 11.

[0042] In one embodiment, the controller 2 may control the bias supply 42 so as to increase the voltage amplitude of the electrical bias EB over time during the plasma processing period P_S. In this case, it is possible

to increase ion energy over time during the plasma processing period P_S. As a result, it is possible to supply ions to the bottom of a high-aspect-ratio recess in the substrate W.

[0043] In one embodiment, the controller 2 may control the bias supply 42 so as to change the bias frequency over time during the plasma processing period P_S. When the bias frequency is decreased over time during the plasma processing period P_S, the time during which electrons are supplied to the bottom of the recess in the substrate W increases over time during the plasma processing period P_S. As a result, charging of the substrate W is alleviated or eliminated, and supply of ions to the bottom of the high-aspect-ratio recess in the substrate W is promoted. When the bias frequency is increased over time during the plasma processing period P_S, supply of ions having low energy to the bottom of the recess in the substrate W due to charging of the substrate W is suppressed. Also, since the number of ion incidences increases, the etch rate increases.

[0044] In one embodiment, the controller 2 may control the bias supply 42 so as to decrease the duty ratio of the voltage pulse VP in the waveform cycle C_W over time during the plasma processing period P_S. In this case, the time during which electrons are supplied to the bottom of the recess in the substrate W increases over time during the plasma processing period P_S. As a result, charging of the substrate W is alleviated or eliminated, and supply of ions to the bottom of the high-aspect-ratio recess in the substrate W is promoted.

[0045] In one embodiment, the controller 2 may control the gas exhaust system 40 so as to decrease the pressure in the chamber 10 over time during the plasma processing period P_S. In this case, the mean free path

of active species such as ions and/or radicals becomes larger over time during the plasma processing period P_S, and supply of active species to the bottom of the high-aspect-ratio recess in the substrate W is promoted.

[0046] In one embodiment, the controller 2 may control the radio frequency power supply 41 so as to change the power level of the source radio frequency power HF over time during the plasma processing period P_S. The power level of the source radio frequency power HF may be increased or decreased depending on the balance between ions and radicals at the bottom of the recess in the substrate W.

[0047] In one embodiment, the controller 2 may control the radio frequency power supply 41 so as to change the frequency of the source radio frequency power HF over time during the plasma processing period P_S. The frequency of the source radio frequency power HF may be changed so as to suppress reflection of the source radio frequency power HF from the load of the radio frequency power supply 41.

[0048] In one embodiment, the controller 2 may control a temperature adjustment mechanism so as to decrease the temperature of the substrate support 11 over time during the plasma processing period P_S. The temperature adjustment mechanism may be the temperature adjusting module described above. The temperature adjustment mechanism controls, for example, the temperature of a heat transfer fluid supplied to the flow passage 1110a. In this case, the adsorption coefficient of radicals on the surface defining the bottom of the recess in the substrate W increases over time during the plasma processing period P_S.

[0049] In the above-described embodiments, the controller 2 changes

one or more control parameters of the plasma processing apparatus 1 over time during the plasma processing period P_S. Instead of this, the controller 2 may change one or more control parameters of the plasma processing apparatus 1 in accordance with an increase in depth of a recess formed in the substrate W by etching or an increase in the aspect ratio of the recess. Alternatively, the controller 2 may change one or more control parameters of the plasma processing apparatus 1 in accordance with the amount of etching by-products measured by a sensor. The sensor may be, for example, an optical analyzer or a quadrupole mass spectrometer that analyzes light emission or light absorption of by-products. Alternatively, the controller 2 may change one or more control parameters of the plasma processing apparatus 1 in accordance with a result of calculation from one or more of the elapsed time during the plasma processing period P_S, the depth of the recess, the aspect ratio of the recess, and the amount of etching by-products measured by the sensor.

[0050] Hereinafter, a plasma processing method according to one example embodiment will be described with reference to FIG. 7. FIG. 7 is a diagram illustrating a plasma processing method according to one example embodiment. In the plasma processing method illustrated in FIG. 7 (hereinafter referred to as "method MT"), each unit of the plasma processing apparatus 1 can be controlled by the controller 2. The method MT includes operation STa and operation STb. The method MT may further include operation STp.

[0051] In operation STp, a substrate W is prepared in the chamber 10. The substrate W is placed on the substrate support 11. Operation STa

and operation STb can be performed with the substrate W placed on the substrate support 11.

[0052] In operation STa, the source radio frequency power HF is supplied from the radio frequency power supply 41 to the radio frequency electrode to generate a plasma from a gas in the chamber 10 in the plasma processing period P_S. Operation STb is performed simultaneously with operation STa. In operation STb, the electrical bias EB is supplied to the substrate support 11 simultaneously and continuously with the supply of the source radio frequency power HF in the plasma processing period P_S, in order to attract ions from the plasma to the substrate W.

[0053] In the plasma processing period P_S, the power level of the source radio frequency power HF is set to 3 kW or less, the bias frequency of the electrical bias EB is set to less than 400 kHz, and the voltage amplitude of the electrical bias EB is set to 3 kV or more. In the plasma processing period P_S, as described above, one or more control parameters may be changed.

[0054] In the method MT, a silicon-containing film of the substrate W may be etched. The silicon-containing film may be a single-layer film including at least one selected from the group consisting of a silicon oxide film, a silicon nitride film, and a polycrystalline silicon film, or a multilayer film including two or more films selected from the group. In this case, the gas used to generate the plasma in operation STa may include hydrogen fluoride gas. The gas may also further include a phosphorus-containing gas. The gas may also further include an oxygen-containing gas and/or a noble gas.

[0055] Hereinafter, experiments conducted for the evaluation of the plasma processing apparatus 1 will be described.

[0056] (First Experiment)

[0057] In the first experiment, the thickness ΔT of the region VR was measured by observing the light emission of the plasma in the chamber 10 with a camera while changing the power level of the source radio frequency power HF. In the first experiment, a voltage pulse VP was used as the electrical bias EB. The bias frequency of the electrical bias EB, the amplitude of the voltage pulse VP, and the duty ratio of the voltage pulse VP were 400 kHz, -5 kV, and 20%, respectively. FIG. 8 is a diagram illustrating results of the first experiment. In FIG. 8, the horizontal axis indicates the power level of the source radio frequency power HF, and the vertical axis indicates the thickness ΔT. As illustrated in FIG. 8, according to the first experiment, it was confirmed that the thickness ΔT becomes large when the power level of the source radio frequency power HF is 3 kW or less.

[0058] (Second Experiment)

[0059] In the second experiment, the thickness ΔT of the region VR was measured by observing the light emission of the plasma in the chamber 10 with a camera while changing the amplitude of the voltage pulse VP of the electrical bias EB. In the second experiment, the bias frequency of the electrical bias EB, the duty ratio of the voltage pulse VP, and the power level of the source radio frequency power HF were 400 kHz, 20%, and 1 kW, respectively. FIG. 9 is a diagram illustrating results of the second experiment. In FIG. 9, the horizontal axis indicates the amplitude of the voltage pulse VP, and the vertical axis indicates the

thickness ΔT. As illustrated in FIG. 9, according to the second experiment, it was confirmed that the thickness ΔT becomes large when the amplitude of the voltage pulse VP is greater than 2 kV. It was also confirmed that the thickness ΔT becomes significantly large when the amplitude of the voltage pulse VP is greater than 3 kV.

[0060] (Third Experiment)

[0061] In the third experiment, three types of voltage pulses VP having the same ON time length were used as the electrical bias EB, and the reflectance of the source radio frequency power HF during the plasma processing period P_S was measured. The reflectance is the ratio of the power level of the reflected wave of the source radio frequency power HF to the power level of the traveling wave of the source radio frequency power HF. The bias frequency and the duty ratio of the first voltage pulse among the three types of voltage pulses VP were 400 kHz and 20%, respectively. The bias frequency and the duty ratio of the second voltage pulse among the three types of voltage pulses VP were 200 kHz and 10%, respectively. The bias frequency and the duty ratio of the third voltage pulse among the three types of voltage pulses VP were 100 kHz and 5%, respectively. In the third experiment, the power level of the source radio frequency power HF was 0.6 kW. As a result of the third experiment, the reflectances when the first to third voltage pulses were used were 34.4%, 23.4%, and 15.6%, respectively. According to the third experiment, it was confirmed that by using the electrical bias EB with a bias frequency of less than 400 kHz, it is possible to greatly reduce the reflectance.

[0062] Hereinafter, reference is made to FIG. 10. FIG. 10 is a diagram

illustrating a plasma processing apparatus 1A according to another example embodiment. Hereinafter, the plasma processing apparatus 1A will be described in terms of differences from the plasma processing apparatus 1.

[0063] As illustrated in FIG. 10, in the plasma processing apparatus 1A, the radio frequency power supply 41 is electrically connected to the base 1110 of the substrate support 11 via the matcher 43.

[0064] The substrate support 11 includes a first region R1 and a second region R2. In FIG. 10, the boundary between the first region R1 and the second region R2 is indicated by a dashed line. The first region R1 is a region intersecting an axis AX and has a substantially disk shape. The axis AX is a central axis of the substrate support 11 and may coincide with a central axis of the chamber 10. The first region R1 includes, as its upper surface, the above-described substrate supporting surface 111a. The second region R2 extends so as to surround the first region R1. The substrate W is placed on the substrate supporting surface 111a and is supported on the first region R1. The second region R2 is an annular region around the axis AX. The second region R2 includes, as its upper surface, the above-described ring supporting surface 111b. The edge ring ER included in the ring assembly 112 is placed on the ring supporting surface 111b and is supported on the second region R2. The substrate W is disposed in a region surrounded by the edge ring ER.

[0065] The substrate support 11 includes, as bias electrodes, a first electrode BE1 and a second electrode BE2. The first electrode BE1 extends below the substrate supporting surface 111a and is disposed in the first region R1. The first electrode BE1 may be a film formed of a

conductive material. The first electrode BE1 may have a substantially circular planar shape. The first electrode BE1 may be disposed such that a center thereof is located on the axis AX.

[0066] The second electrode BE2 extends below the ring supporting surface 111b and extends in the second region R2. The second electrode BE2 may be a film formed of a conductive material. The second electrode BE2 may have a substantially annular planar shape. The second electrode BE2 may be disposed such that a center thereof is located on the axis AX.

[0067] As illustrated in FIG. 10, the electrostatic chuck 1111 may include a dielectric portion 1111d. The dielectric portion 1111d may be the above-described ceramic member 1111a. A central portion of the dielectric portion 1111d may constitute the first region R1 and may have the substrate supporting surface 111a as an upper surface thereof. A peripheral portion of the dielectric portion 1111d may constitute the second region R2 and may have the ring supporting surface 111b as an upper surface thereof.

[0068] The electrostatic chuck 1111 may include a chuck electrode CE1 as part of the electrostatic electrode 1111b. The chuck electrode CE1 is disposed in the dielectric portion 1111d and in the first region R1. The chuck electrode CE1 may be a film formed of a conductive material. The chuck electrode CE1 may have a substantially circular planar shape. The chuck electrode CE1 may be disposed such that a center thereof is located on the axis AX. The chuck electrode CE1 may extend between the substrate supporting surface 111a and the first electrode BE1.

[0069] The electrostatic chuck 1111 may also include chuck electrodes

CE2 and CE3 as another part of the electrostatic electrode 1111b. Each of the chuck electrodes CE2 and CE3 is disposed in the dielectric portion 1111d and in the second region R2. Each of the chuck electrodes CE2 and CE3 may be a film formed of a conductive material. Each of the chuck electrodes CE2 and CE3 may extend circumferentially around the axis AX and may have a substantially annular planar shape. The chuck electrode CE2 is disposed radially inward of the chuck electrode CE3. That is, a radial distance between the chuck electrode CE2 and the axis AX is smaller than a radial distance between the chuck electrode CE3 and the axis AX. Each of the chuck electrodes CE2 and CE3 may extend between the ring supporting surface 111b and the second electrode BE2.

[0070] The plasma processing apparatus 1A may further include a DC power supply 51p. The DC power supply 51p is electrically connected to the chuck electrode CE1 via a switch 51s. A filter 51f may further be connected between the DC power supply 51p and the chuck electrode CE1. The filter 51f is a low-pass filter configured to block or attenuate an RF signal such as the source radio frequency power HF. When a voltage from the DC power supply 51p is applied to the chuck electrode CE1, an electrostatic attraction force is generated between the electrostatic chuck 1111 and the substrate W. The substrate W is attracted to the first region R1 by the generated electrostatic attraction force and is held by the first region R1.

[0071] The plasma processing apparatus 1A may further include DC power supplies 52p and 53p. The DC power supply 52p is electrically connected to the chuck electrode CE2 via a switch 52s. A filter 52f may further be connected between the DC power supply 52p and the chuck

electrode CE2. The filter 52f is a low-pass filter configured to block or attenuate an RF signal such as the source radio frequency power HF. The DC power supply 53p is electrically connected to the chuck electrode CE3 via a switch 53s. A filter 53f may further be connected between the DC power supply 53p and the chuck electrode CE3. The filter 53f is a low-pass filter configured to block or attenuate an RF signal such as the source radio frequency power HF. When voltages from the DC power supplies 52p and 53p are applied to the chuck electrodes CE2 and CE3, respectively, an electrostatic attraction force is generated between the electrostatic chuck 1111 and the edge ring ER. The edge ring ER is attracted to the second region R2 by the generated electrostatic attraction force and is held by the second region R2. Voltages may be applied to the chuck electrode CE2 and the chuck electrode CE3 such that a potential difference is generated between them. That is, the second region R2 may constitute a bipolar electrostatic chuck.

[0072] In the plasma processing apparatus 1A, the bias supply 42 is configured to supply the electrical bias EB to both the first electrode BE1 and the second electrode BE2. The bias supply 42 may be a single power supply configured to distribute the electrical bias EB to both the first electrode BE1 and the second electrode BE2. The bias supply 42 may include a first power supply 421 electrically connected to the first electrode BE1 and a second power supply 422 electrically connected to the second electrode BE2. The first power supply 421 supplies the electrical bias EB to the first electrode BE1, and the second power supply 422 supplies the electrical bias EB to the second electrode BE2.

[0073] In the plasma processing apparatus 1A, the controller 2 may control the bias supply 42 so as to increase the level of the electrical bias EB supplied to the second electrode BE2 relative to the level of the electrical bias EB supplied to the first electrode BE1 as the amount of wear of the edge ring ER increases. When the electrical bias EB includes the voltage pulse VP, the level of the electrical bias EB is the amplitude of the voltage pulse VP. When the electrical bias EB is the bias radio frequency power LF, the level of the electrical bias EB is the power level of the bias radio frequency power LF. According to the plasma processing apparatus 1A, by adjusting the level of the electrical bias EB supplied to the second electrode BE2 relative to the level of the electrical bias EB supplied to the first electrode BE1, it is possible to reduce the difference between the upper end position of the sheath on the substrate W and the upper end position of the sheath on the edge ring ER. As a result, it is possible to correct the traveling direction of ions with respect to the edge of the substrate W to a vertical direction.

[0074] The thickness of the sheath is inversely proportional to the square root of the density of the plasma. Since the source radio frequency power HF is continuously supplied during the plasma processing period P_S, the variation in the density of the plasma is small. Therefore, by continuously supplying the electrical biases EB of which levels are individually adjusted to the first electrode BE1 and the second electrode BE2, it is possible to reduce the difference between the upper end position of the sheath on the substrate W and the upper end position of the sheath on the edge ring ER.

[0075] Hereinafter, an example of a processing circuitry that can be used

as one or more processing circuits in the plasma processing apparatuses 1 and 1A, such as the controller 2 and/or the controller of the power supply system 30S, will be described. FIG. 11 is a block diagram of processing circuitry for performing computer-based operations described herein. FIG. 11 illustrates processing circuitry 130 that may be used to control any computer-based control processes, descriptions or blocks in flowcharts can be understood as representing modules, segments or portions of code which include one or more executable instructions for implementing specific logical functions or steps in the process, and alternate implementations are included within the scope of the exemplary embodiments of the present advancements in which functions can be executed out of order from that shown or discussed, including substantially concurrently or in reverse order, depending upon the functionality involved, as would be understood by those skilled in the art. The various elements, features, and processes described herein may be used independently of one another or may be combined in various ways. All possible combinations and sub-combinations are intended to fall within the scope of this disclosure.

[0076] In FIG. 11, the processing circuitry 130 includes a CPU 1200 which performs one or more of the control processes described above/below. The process data and instructions may be stored in memory 1202. These process data and instructions may also be stored on a storage medium disk 1204 such as a hard drive (HDD) or portable storage medium or may be stored remotely. Further, the claimed advancements are not limited by the form of the computer-readable media on which the instructions of the inventive process are stored. For

example, the instructions may be stored on CDs, DVDs, in FLASH memory, RAM, ROM, PROM, EPROM, EEPROM, hard disk or any other information processing device with which the processing circuitry 130 communicates, such as a server or computer.

[0077] Further, the claimed advancements may be provided as a utility application, background daemon, or component of an operating system, or combination thereof, executing in conjunction with CPU 1200 and an operating system such as Microsoft Windows, UNIX, Solaris, LINUX, Apple MAC-OS and other systems known to those skilled in the art.

[0078] The hardware elements in order to achieve the processing circuitry 130 may be realized by various circuitry elements. Further, each of the functions of the above described embodiments may be implemented by circuitry, which includes one or more processing circuits. A processing circuit includes a particularly programmed processor, for example, processor (CPU) 1200, as shown in FIG. 11. A processing circuit also includes devices such as an application specific integrated circuit (ASIC) and conventional circuit components arranged to perform the recited functions.

[0079] In FIG. 11, the processing circuitry 130 includes a CPU 1200 which performs the processes described above. The processing circuitry 130 may be a general-purpose computer or a particular, special-purpose machine. In one embodiment, the processing circuitry 130 becomes a particular, special-purpose machine when the processor 1200 is programmed to control the plasma generator 12 and the gas supply 20, or alternatively or additionally, to control the radio frequency power supply 41 and the bias supply 42.

[0080] Alternatively, or additionally, the CPU 1200 may be implemented on an FPGA, ASIC, PLD or using discrete logic circuits, as one of ordinary skill in the art would recognize. Further, CPU 1200 may be implemented as multiple processors cooperatively working in parallel to perform the instructions of the inventive processes described above.

[0081] The processing circuitry 130 in FIG. 11 also includes a network controller 1206, such as an Intel Ethernet PRO network interface card from Intel Corporation of America, for interfacing with network 1228. As can be appreciated, the network 1228 can be a public network, such as the Internet, or a private network such as a LAN or WAN network, or any combination thereof and can also include PSTN or ISDN sub-networks. The network 1228 can also be wired, such as an Ethernet network, or can be wireless such as a cellular network including EDGE, 3G and 4G wireless cellular systems. The wireless network can also be Wi-Fi, Bluetooth (registered trademark), or any other wireless form of communication that is known.

[0082] The processing circuitry 130 further includes a display controller 1208, such as a graphics card or graphics adaptor for interfacing with display 1210, such as a monitor. A general purpose I/O interface 1212 interfaces with a keyboard and/or mouse 1214 as well as a touch screen panel 1216 on or separate from display 1210. The general purpose I/O interface also connects to a variety of peripherals 1218 including printers and scanners.

[0083] The storage controller 1224 connects the storage medium disk 1204 with communication bus 1226, which may be an ISA, EISA, VESA, PCI, or similar, for interconnecting all of the components of the

processing circuitry 130. A description of the general features and functionality of the display 1210, keyboard and/or mouse 1214, as well as the display controller 1208, storage controller 1224, network controller 1206, sound controller 1220, and general purpose I/O interface 1212 is omitted herein for brevity as these features are known.

[0084] The exemplary circuit elements described in the context of the present disclosure may be replaced with other elements and structured differently than the examples provided herein. Moreover, circuitry configured to perform features described herein may be implemented in multiple circuit units (e.g., chips), or the features may be combined in circuitry on a single chipset.

[0085] The functions and features described herein may also be executed by various distributed components of a system. For example, one or more processors may execute these system functions, wherein the processors are distributed across multiple components communicating in a network. The distributed components may include one or more client and server machines, which may share processing, in addition to various human interface and communication devices (e.g., display monitors, smart phones, tablets, personal digital assistants (PDAs)). The network may be a private network, such as a LAN or WAN, or may be a public network, such as the Internet. Input to the system may be received via direct user input and received remotely either in real-time or as a batch process. Additionally, some implementations may be performed on modules or hardware not identical to those described. Accordingly, other implementations are within the scope that may be claimed.

[0086] Although various example embodiments have been described above, various additions, omissions, substitutions, and changes may be made without being limited to the example embodiments described above. It is also possible to combine elements in different embodiments to form other embodiments.

[0087] Here, various example embodiments included in the present disclosure are described in [E1] to [E17] below.

[0088] [E1]

A plasma processing apparatus including:

a chamber;

a substrate support in the chamber;

a radio frequency power supply configured to supply source radio frequency power to generate a plasma from a gas in the chamber;

a bias supply configured to supply an electrical bias to the substrate support to attract ions from the plasma to a substrate on the substrate support; and

a controller configured to control the radio frequency power supply and the bias supply,

wherein the controller is configured to control the radio frequency power supply and the bias supply to, in a plasma processing period, supply the source radio frequency power and the electrical bias continuously and simultaneously, and set a power level of the source radio frequency power to 3 kW or less, a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias to less than 400 kHz, and a voltage amplitude of the electrical bias to 3 kV or more.

[0089] [E2]

The plasma processing apparatus according to E1, wherein the controller is configured to control the bias supply so as to increase the voltage amplitude over time during the plasma processing period.

[0090] [E3]

The plasma processing apparatus according to E1 or E2, wherein the controller is configured to control the bias supply to change the bias frequency over time during the plasma processing period.

[0091] [E4]

The plasma processing apparatus according to any one of E1 to E3, wherein the electrical bias is a voltage pulse periodically supplied at a time interval of the waveform cycle, and the voltage amplitude is an amplitude of the voltage pulse.

[0092] [E5]

The plasma processing apparatus according to E4, wherein the controller is configured to control the bias supply to decrease a duty ratio of the voltage pulse in the waveform cycle over time during the plasma processing period.

[0093] [E6]

The plasma processing apparatus according to any one of E1 to E3, wherein the electrical bias is a bias radio frequency power having the bias frequency, and the voltage amplitude is a peak-to-peak voltage of the bias radio frequency power.

[0094] [E7]

The plasma processing apparatus according to any one of E1 to E6, further including an exhaust system configured to exhaust a gas in

the chamber,

wherein the controller is configured to control the exhaust system to decrease a pressure in the chamber over time during the plasma processing period.

[0095] [E8]

The plasma processing apparatus according to any one of E1 to E7, wherein the controller is configured to control the radio frequency power supply to change the power level of the source radio frequency power over time during the plasma processing period.

[0096] [E9]

The plasma processing apparatus according to any one of E1 to E8, further including a temperature adjustment mechanism configured to adjust a temperature of the substrate support,

wherein the controller is configured to control the temperature adjustment mechanism to decrease the temperature of the substrate support over time during the plasma processing period.

[0097] [E10]

A power supply system including:

a radio frequency power supply configured to supply source radio frequency power to generate a plasma from a gas in a chamber of a plasma processing apparatus; and

a bias supply configured to supply an electrical bias to a substrate support to attract ions from the plasma to a substrate on the substrate support in the chamber,

wherein the radio frequency power supply and the bias supply are configured to respectively supply the source radio frequency power

and the electrical bias continuously and simultaneously in a plasma processing period, the radio frequency power supply is configured to set a power level of the source radio frequency power to 3 kW or less in the plasma processing period, and the bias supply is configured to set a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias to less than 400 kHz and a voltage amplitude of the electrical bias to 3 kV or more in the plasma processing period.

[0098] [E11]

The power supply system according to E10, wherein the bias supply is configured to increase the voltage amplitude over time during the plasma processing period.

[0099] [E12]

The power supply system according to E10 or E11, wherein the bias supply is configured to change the bias frequency over time during the plasma processing period.

[0100] [E13]

The power supply system according to any one of E10 to E12, wherein the electrical bias is a voltage pulse periodically supplied at time intervals of the waveform cycle, and the voltage amplitude is an amplitude of the voltage pulse.

[0101] [E14]

The power supply system according to E13, wherein the bias supply is configured to decrease a duty ratio of the voltage pulse in the waveform cycle over time during the plasma processing period.

[0102] [E15]

The power supply system according to any one of E10 to E12,

wherein the electrical bias is a bias radio frequency power having the bias frequency, and the voltage amplitude is the peak-to-peak voltage of the bias radio frequency power.

[0103] [E16]

The power supply system according to any one of E10 to E15, wherein the radio frequency power supply is configured to change the power level of the source radio frequency power over time during the plasma processing period.

[0104] [E17]

A plasma processing method including:

(a) continuously supplying source radio frequency power to generate a plasma from a gas in a chamber of a plasma processing apparatus in a plasma processing period; and

(b) supplying an electrical bias to a substrate support simultaneously and continuously with supply of the source radio frequency power in the (a), in the plasma processing period, to attract ions from the plasma to a substrate on the substrate support in the chamber,

wherein, in the plasma processing period, the power level of the source radio frequency power is set to 3 kW or less, a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias is set to less than 400 kHz, and a voltage amplitude of the electrical bias is set to 3 kV or more.

[0105] From the above description, it will be understood 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, and the true scope and spirit are indicated by the appended claims.

Reference Signs List

[0106] 1: plasma processing apparatus, 2: controller, 10: chamber, 11: substrate support, 41: radio frequency power supply, 42: bias supply.

CLAIMS

WHAT IS CLAIMED IS:

[Claim 1]

A plasma processing apparatus comprising:

a chamber;

a substrate support in the chamber;

a radio frequency power supply configured to supply source radio frequency power to generate a plasma from a gas in the chamber;

a bias supply configured to supply an electrical bias to the substrate support to attract ions from the plasma to a substrate on the substrate support; and

a controller configured to control the radio frequency power supply and the bias supply,

wherein the controller is configured to control the radio frequency power supply and the bias supply to, in a plasma processing period, supply the source radio frequency power and the electrical bias continuously and simultaneously, and set a power level of the source radio frequency power to 3 kW or less, a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias to less than 400 kHz, and a voltage amplitude of the electrical bias to 3 kV or more.

[Claim 2]

The plasma processing apparatus according to claim 1, wherein the controller is configured to control the bias supply to increase the

voltage amplitude over time during the plasma processing period.

[Claim 3]

The plasma processing apparatus according to claim 1, wherein the controller is configured to control the bias supply to change the bias frequency over time during the plasma processing period.

[Claim 4]

The plasma processing apparatus according to any one of claims 1 to 3, wherein the electrical bias is a voltage pulse periodically supplied at a time interval of the waveform cycle, and the voltage amplitude is the amplitude of the voltage pulse.

[Claim 5]

The plasma processing apparatus according to claim 4, wherein the controller is configured to control the bias supply to decrease a duty ratio of the voltage pulse in the waveform cycle over time during the plasma processing period.

[Claim 6]

The plasma processing apparatus according to any one of claims 1 to 3, wherein the electrical bias is a bias radio frequency power having the bias frequency, and the voltage amplitude is a peak-to-peak voltage of the bias radio frequency power.

[Claim 7]

The plasma processing apparatus according to any one of claims 1 to 3, further comprising an exhaust system configured to exhaust a gas in the chamber,

wherein the controller is configured to control the exhaust system to decrease a pressure in the chamber over time during the plasma processing period.

[Claim 8]

The plasma processing apparatus according to any one of claims 1 to 3, wherein the controller is configured to control the radio frequency power supply to change the power level of the source radio frequency power over time during the plasma processing period.

[Claim 9]

The plasma processing apparatus according to any one of claims 1 to 3, further comprising a temperature adjustment mechanism configured to adjust a temperature of the substrate support,

wherein the controller is configured to control the temperature adjustment mechanism to decrease the temperature of the substrate support over time during the plasma processing period.

[Claim 10]

A power supply system comprising:

a radio frequency power supply configured to supply source radio frequency power to generate a plasma from a gas in a chamber of a plasma processing apparatus; and

a bias supply configured to supply an electrical bias to a substrate support to attract ions from the plasma to a substrate on the substrate support in the chamber,

wherein the radio frequency power supply and the bias supply are configured to respectively supply the source radio frequency power and the electrical bias continuously and simultaneously in a plasma processing period, the radio frequency power supply is configured to set a power level of the source radio frequency power to 3 kW or less in the plasma processing period, and the bias supply is configured to set a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias to less than 400 kHz and a voltage amplitude of the electrical bias to 3 kV or more in the plasma processing period.

[Claim 11]

The power supply system according to claim 10, wherein the bias supply is configured to increase the voltage amplitude over time during the plasma processing period.

[Claim 12]

The power supply system according to claim 10, wherein the bias supply is configured to change the bias frequency over time during the plasma processing period.

[Claim 13]

The power supply system according to any one of claims 10 to 12, wherein the electrical bias is a voltage pulse periodically supplied at

a time interval of the waveform cycle, and the voltage amplitude is an amplitude of the voltage pulse.

[Claim 14]

The power supply system according to claim 13, wherein the bias supply is configured to decrease a duty ratio of the voltage pulse in the waveform cycle over time during the plasma processing period.

[Claim 15]

The power supply system according to any one of claims 10 to 12, wherein the electrical bias is a bias radio frequency power having the bias frequency, and the voltage amplitude is a peak-to-peak voltage of the bias radio frequency power.

[Claim 16]

The power supply system according to any one of claims 10 to 12, wherein the radio frequency power supply is configured to change the power level of the source radio frequency power over time during the plasma processing period.

[Claim 17]

A plasma processing method comprising:

(a) continuously supplying source radio frequency power to generate a plasma from a gas in a chamber of a plasma processing apparatus in a plasma processing period; and

(b) supplying an electrical bias to a substrate support

simultaneously and continuously with supply of the source radio frequency power in the (a), in the plasma processing period, to attract ions from the plasma to a substrate on the substrate support in the chamber,

wherein, in the plasma processing period, a power level of the source radio frequency power is set to 3 kW or less, a bias frequency which is a reciprocal of a time length of a waveform cycle of the electrical bias is set to less than 400 kHz, and a voltage amplitude of the electrical bias is set to 3 kV or more.