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Inventor(s)	Li; Lifu et al.

Upper electrode assembly

Abstract

An upper electrode assembly used in a plasma processing apparatus is provided. The upper electrode assembly comprises: an electrode plate; a metal plate; and a heat transfer sheet disposed between the electrode plate and the metal plate and having a vertically oriented portion. The vertically oriented portion has a plurality of vertically oriented graphene structures oriented along a vertical direction.

Inventors: **Li; Lifu (Miyagi, JP), Kobune; Takaki (Miyagi, JP), Tsujimoto; Hiroshi (Miyagi, JP)**

Applicant: **Tokyo Electron Limited** (Tokyo, JP)

Family ID: **1000008750736**

Assignee: **TOKYO ELECTRON LIMITED (Tokyo, JP)**

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Primary Examiner: MacArthur; Sylvia

Attorney, Agent or Firm: XSENSUS LLP

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

(1) This application claims priority to Japanese Patent Application No. 2021-062928, filed on Apr. 1, 2021, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

(2) The present disclosure relates to an upper electrode assembly.

BACKGROUND

(3) Japanese Patent Application Publication No. 2014-120440 discloses an electrode unit disposed in a substrate processing apparatus including a processing chamber for processing a substrate using plasma. The electrode unit described in Japanese Patent Application Publication No. 2014-120440 has an electrode layer, a heating layer, and a cooling layer arranged in that order from the

processing chamber side. The heating layer completely covers the electrode layer. The cooling layer completely covers the electrode layer with the heating layer interposed therebetween. A heat transfer sheet is disposed between the heating layer and the cooling layer.

SUMMARY
(4) The technique of the present disclosure provides an upper electrode assembly capable of appropriately improving a heat transfer efficiency in a thickness direction.
(5) To this end, an upper electrode assembly used in a plasma processing apparatus provided, the assembly comprising: an electrode plate; a metal plate; and a heat transfer sheet disposed between the electrode plate and the metal plate and having a vertically oriented portion, wherein the vertically oriented portion has a plurality of vertically oriented graphene structures oriented along a vertical direction.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The objects and features of the present disclosure will become apparent from the following description of embodiments, given in conjunction with the accompanying drawings, in which:
(2) FIG. **1** is a vertical cross-sectional view showing a configuration of a plasma processing system according to an embodiment;
(3) FIG. **2** is a vertical cross-sectional view showing a configuration of an upper electrode assembly according to an embodiment;
(4) FIG. **3** is a cross-sectional view showing a configuration of a heat transfer sheet according to an embodiment;
(5) FIG. **4** is a perspective view showing the configuration of the heat transfer sheet according to the embodiment;
(6) FIG. **5** explains a heat transfer performance of the heat transfer sheet;
(7) FIG. **6** explains another configuration example of the heat transfer sheet;
(8) FIG. **7** explains the heat transfer performance of the heat transfer sheet;
(9) FIG. **8** explains in-plane temperature non-uniformity on an electrode plate;
(10) FIG. **9**A explains another configuration example of the heat transfer sheet;
(11) FIG. **9**B explains yet another configuration example of the heat transfer sheet;
(12) FIG. **10**A explains yet another configuration example of the heat transfer sheet;
(13) FIG. **10**B explains yet another configuration example of the heat transfer sheet;
(14) FIG. **11** explains yet another configuration example of the heat transfer sheet; and
(15) FIG. **12** is a vertical cross-sectional view showing a configuration of an upper electrode assembly according to a second embodiment.
DETAILED DESCRIPTION
(16) In a semiconductor device manufacturing process, plasma is produced by exciting a processing gas supplied to a chamber, and various plasma processings, such as etching, film formation, diffusion, and the like, are performed on a semiconductor substrate (hereinafter, simply referred to as “substrate”) supported by a substrate support. Such plasma processings are performed by, e.g., a capacitively coupled plasma (CCP) processing apparatus including an upper electrode assembly constituting a part of a ceiling portion of the chamber.
(17) Here, in a recent semiconductor device manufacturing process, along with a demand for miniaturization of a pattern formed on a substrate surface, it is required to perform high-speed switching (e.g., ON/OFF switching) of a radio frequency (RF) power supply with a high output in a plasma processing apparatus. However, in the case of performing the high-speed switching of the RF power supply with a high output, a heat input from plasma to the upper electrode assembly disposed adjacent to a plasma processing space varies, so that a temperature of the upper electrode

assembly may vary.
(18) When the temperature of the upper electrode assembly varies, the distribution of plasma processing results on a substrate may not be uniform. Therefore, in order to control the plasma processing results to be uniform throughout the substrate, it is necessary to control the temperature of the upper electrode assembly in response to the variation of the heat input from the plasma.
(19) The above-described Japanese Patent Application Publication No. 2014-120440 discloses that the temperature of the electrode layer of the electrode unit is controlled by the heating layer or the cooling layer disposed in the electrode unit. Further, in accordance with Japanese Patent Application Publication No. 2014-120440, a heat transfer layer (e.g., a heat transfer sheet) is disposed between the heating layer and the cooling layer, so that the cooling layer effectively cools the electrode layer.
(20) In the electrode unit disclosed in Japanese Patent Application Publication No. 2014-120440, the heat transfer in a plane direction (horizontal direction) is mainly promoted depending on the heat transfer layer disposed between the heating layer and the cooling layer, and, thus, the temperature of the entire electrode layer is appropriately controlled. However, when the high-speed switching of the RF power supply is performed with a high output as described above, it is important to process an instantaneous heat input from the plasma as quickly as possible. In other words, it is important to minimize a thermal resistance of the electrode unit in a vertical direction (thickness direction). From this perspective, the conventional electrode unit needs to be improved, and it is required to develop an electrode unit having an improved heat transfer performance especially in the vertical direction.
(21) In view of the above, the technique of the present disclosure provides an upper electrode assembly capable of appropriately improving the heat transfer efficiency in the thickness direction. Hereinafter, a plasma processing system including the upper electrode assembly according to the present embodiment will be described with reference to the accompanying drawings. Like reference numerals will be used for like parts having substantially the same functions throughout this specification and the drawings, and redundant description thereof will be omitted.
(22) <Plasma Processing Apparatus>
(23) First, the plasma processing system according to the present embodiment will be described. FIG. **1** is a vertical cross-sectional view showing a schematic configuration of the plasma processing system according to the present embodiment.
(24) The plasma processing system includes a capacitively coupled plasma processing apparatus **1** and a controller **2**. The plasma processing apparatus **1** includes a plasma processing chamber **10**, a gas supply **20**, a power supply **30**, and an exhaust system **40**. Further, the plasma processing apparatus **1** includes a substrate support **11** and a gas introduction unit. The substrate support **11** is disposed in the plasma processing chamber **10**. The gas introduction unit is configured to introduce at least one processing gas into the plasma processing chamber **10**. The gas introduction unit includes an upper electrode assembly **13**. The upper electrode assembly **13** is disposed above the substrate support **11**. In one embodiment, the upper electrode assembly **13** constitutes at least a part of a ceiling of the plasma processing chamber **10**. The plasma processing chamber **10** has a plasma processing space **10***s* defined by the upper electrode assembly **13**, sidewalls **10***a* of the plasma processing chamber **10**, and the substrate support **11**. The plasma processing chamber **10** has at least one gas inlet for supplying at least one processing gas to the plasma processing space **10***s* and at least one gas outlet for exhausting gases from the plasma processing space **10***s*. The sidewalls **10***a* are grounded. The upper electrode assembly **13** and the substrate support **11** are electrically insulated from the plasma processing chamber **10**.
(25) The substrate support **11** includes a main body **111** and a ring assembly **112**. An upper surface of the main body **111** has a central region **111***a* (substrate supporting surface) for supporting the substrate (wafer) W and an annular region **111***b* (ring supporting surface) for supporting the ring assembly **112**. The annular region **111***b* surrounds the central region **111***a* in plan view. The ring

assembly **112** includes one or more annular members, and at least one of them is an edge ring.
(26) In one embodiment, the main body **111** includes a base **113** and an electrostatic chuck **114**. The base **113** includes a conductive member. The conductive member of the base **113** functions as a lower electrode. The electrostatic chuck **114** is disposed on an upper surface of the base **113**. The upper surface of the electrostatic chuck **114** has the above-described central region **111***a* and annular region **111***b*.
(27) Although not shown, the substrate support **11** may include a temperature control module configured to control at least one of the ring assembly **112**, the electrostatic chuck **114**, and the substrate W to a target temperature. The temperature control module may be a heater, a heat transfer medium, a flow passage, or a combination thereof. A heat transfer fluid, such as brine and gas, flows into the flow passage. The substrate support **11** may include a heat transfer gas supply configured to supply a heat transfer gas (backside gas) to a gap between the backside of the substrate W and an upper surface of the electrostatic chuck **114**.
(28) As shown in FIG. **2**, in one embodiment, the upper electrode assembly **13** includes an electrode plate **120** and a metal plate **130**. The electrode plate **120** and the metal plate **130** are laminated in a vertical direction with a heat transfer sheet **140** interposed therebetween. In other words, in the upper electrode assembly **13**, the electrode plate **120**, the heat transfer sheet **140**, and the metal plate **130** are laminated in that order from the plasma processing space **10***s* side.
(29) The electrode plate **120** includes a conductive member, such as aluminum or the like. The conductive member of the electrode plate **120** functions as an upper electrode. A plurality of gas inlet ports **13***a* are formed through the electrode plate **120** in the thickness direction (vertical direction). The gas inlet ports **13***a* are connected to the gas supply **20** through a gas diffusion space **13***b* and a gas supply port **13***c* formed in the metal plate **130** to be described later, and are configured to introduce at least one processing gas from the gas supply **20** into the plasma processing space **10***s*.
(30) The metal plate **130** is laminated on the electrode plate **120**, and functions as a support for the electrode plate **120**. At least one gas diffusion space **13***b* and at least one gas supply port **13***c* are formed in the metal plate **130**. The gas diffusion space **13***b* and the gas supply port **13***c* are connected to the gas supply **20**, and are configured to introduce at least one processing gas from the gas supply **20** into the plasma processing space **10***s* through the gas inlet ports **13***a* formed in the electrode plate **120**, as described above.
(31) Further, the metal plate **130** has therein at least one coolant flow passage **131** and at least one heating module **132** configured to control the electrode plate **120** whose temperature varies due to the heat input from the plasma to a target temperature. A heat transfer fluid, such as brine or gas, flows through the coolant flow passage **131**. The heating module **132** may be a heater, a heat transfer medium, a flow passage, or a combination thereof. Further, in one embodiment, the coolant flow passage **131** and the heating module **132** are arranged in the metal plate **130** without overlapping in the vertical direction (in plan view), and are configured such that they do not interfere with each other when heat is transferred between the electrode plate **120** and the metal plate **130**.
(32) As shown in FIGS. **3** and **4**, in one embodiment, the heat transfer sheet **140** has a vertically oriented portion R**1**. The vertically oriented portion R**1** forms a partial region or the entire region of the heat transfer sheet **140**. In one embodiment, the vertically oriented portion R**1** is formed in a partial region or the entire region of the heat transfer sheet **140** in the horizontal direction. In one embodiment, the vertically oriented portion R**1** is formed in a partial region or the entire region of the heat transfer sheet **140** in the vertical direction. Here, the partial region may be one region, or may be a plurality of regions. The vertically oriented portion R**1** is formed by laminating a plurality of graphite sheets **141** having heat transfer anisotropy in the plane direction (horizontal direction). Further, as shown in FIG. **5**, each of the graphite sheets **141** has a plurality of graphene structures **141***a* oriented along the plane direction (i.e., the vertical direction) of the graphite sheet **141**. In

other words, in one embodiment, the heat transfer sheet **140** has the plurality of graphene structures (a plurality of vertically oriented graphene structures) **141***a* oriented along the vertical direction (Z-direction) that is the lamination direction of the electrode plate **120** and the metal plate **130**.
(33) Here, the thermal conductivity in the orientation directions (X-direction and Z-direction) of the graphene structures **141***a* is higher than the thermal conductivity in the lamination direction (Y-direction) of the graphene structures **141***a*. In other words, in one embodiment, the heat transfer sheet **140** is disposed such that the thermal conductivity in the vertical direction (Z-direction in FIG. **4**) and the one plane direction (X direction in FIG. **4**), which are the orientation directions of the graphene structures **141***a*, becomes higher than the thermal conductivity in the lamination direction of the graphene structures **141***a*, i.e., in the other plane direction (Y-direction in FIG. **4**) orthogonal to the one plane direction.
(34) In the upper electrode assembly **13**, the temperature control in response to the variation of the temperature of the electrode plate **120** can be appropriately performed simply by inserting a heat transfer sheet formed by laminating graphite sheets having high thermal conductivity between the electrode plate **120** and the metal plate **130**. However, in the present embodiment, as shown in FIGS. **3** and **4**, the heat transfer sheet **140** is formed by laminating the plurality of graphite sheets **141** in the plane direction (horizontal direction) such that the plurality of graphene structures **141***a* are oriented along the vertical direction. Accordingly, the heat transfer efficiency in the vertical direction can be improved compared to a heat transfer sheet **140′** (see FIG. **7** to be described later) formed by horizontally laminating the plurality of graphite sheets **141**. In other words, the temperature of the electrode plate **120** can be controlled more appropriately.
(35) In the following description, as shown in FIG. **4**, a portion of the heat transfer sheet **140** where the plurality of graphene structures **141***a* are oriented along the vertical direction may be referred to as “vertically oriented portion R**1**”. In other words, in the vertically oriented portion R**1** of the heat transfer sheet **140**, the thermal conductivity in the vertical direction is higher than the thermal conductivity in the plane direction.
(36) In one example, in the graphite sheet **141**, the thermal conductivity in the orientation direction of the graphene structures **141***a* is 2000 W/m.Math.K, and the thermal conductivity in the lamination direction of the graphene structures **141***a* is 10 W/m.Math.K.
(37) The gas introduction unit may include, in addition to the upper electrode assembly **13**, one or more side gas injectors (SGI) attached to one or more openings formed in the sidewall **10***a*.
(38) Referring back to FIG. **1**, the gas supply **20** may include at least one gas source **21** and at least one flow rate controller **22**. In one embodiment, the gas supply **20** is configured to supply at least one processing gas from the corresponding gas source **21** through the corresponding flow rate controller **22** into the upper electrode assembly **13**. Each flow rate controller **22** may be, for example, a mass flow controller or pressure-controlled flow rate controller. The gas supply **20** may include one or more flow modulation devices for modulating the flow rate of at least one processing gas or causing it to be pulsed.
(39) The power supply **30** includes an RF power supply **31** connected to the plasma processing chamber **10** through at least one impedance matching circuit. The RF power supply **31** is configured to supply at least one RF signal (RF power), such as a source RF signal and a bias RF signal, to the conductive member (lower electrode) of the substrate support **11** and/or the conductive member (upper electrode) of the upper electrode assembly **13**. Accordingly, plasma is produced from at least one processing gas supplied into the plasma processing space **10***s*. Hence, the RF power supply **31** may function as at least part of a plasma generator configured to generate plasma from one or more treated gases in the plasma processing chamber **10**. Further, by supplying the bias RF signal to the lower electrode, a bias potential is generated at the substrate W, and ions in the produced plasma can be attracted to the substrate W.
(40) In one embodiment, the RF power supply **31** includes a first RF generator **31***a* and a second RF generator **31***b*. The first RF generator **31***a* is connected to the lower electrode and/or the upper

electrode through at least one impedance matching circuit and is configured to generate a source RF signal (source RF power) for plasma generation. In one embodiment, the source RF signal has a frequency within a range of 13 MHz to 160 MHz. In one embodiment, the first RF generator **31***a* may be configured to generate multiple source RF signals having different frequencies. The generated one or multiple source RF signals are supplied to the lower electrode and/or the upper electrode. The second RF generator **31***b* is connected to the lower electrode through at least one impedance matching circuit and is configured to generate a bias RF signal (bias RF power). In one embodiment, the bias RF signal has a frequency lower than that of the source RF signal. In one embodiment, the bias RF signal has a frequency within a range of 400 kHz to 13.56 MHz. In one embodiment, the second RF generator **31***b* may be configured to generate multiple bias RF signals having different frequencies. The generated one or multiple bias RF signals are supplied to the lower electrode. In various embodiments, at least one of the source RF signal and the bias RF signal may be pulsed.
(41) The power supply **30** may also include a DC power supply **32** connected to the plasma processing chamber **10**. The DC source **32** includes a first DC generator **32***a* and a second DC generator **32***b*. In one embodiment, the first DC generator **32***a* is connected to the lower electrode and is configured to generate a first DC signal. The generated first bias DC signal is applied to the lower electrode. In one embodiment, the first DC signal may be applied to another electrode, such as an attracting electrode in the electrostatic chuck **114**. In one embodiment, the second DC generator **32***b* is connected to the upper electrode and is configured to generate a second DC signal. The generated second DC signal is applied to the upper electrode. In various embodiments, at least one of the first and second DC signals may be pulsed. The first and second DC generator **32***a* and **32***b* may be provided in addition to the RF power source **31**, or the first DC generator **32***a* may be provided instead of the second RF generator **31***b*.
(42) The exhaust system **40** may be connected to a gas outlet **10***e* disposed at a bottom portion of the plasma processing chamber **10**, for example. The exhaust system **40** may include a pressure control valve and a vacuum pump. The pressure control valve adjusts the pressure in the plasma processing space **10***s*. The vacuum pump may be a turbo molecular pump, a dry pump, or a combination thereof.
(43) The controller **2** processes computer-executable instructions that cause the plasma processing apparatus **1** to perform the various steps described in the present disclosure. The controller **2** may be configured to control individual components of the plasma processing apparatus **1** to perform various steps described herein. In one embodiment, the controller **2** may be partially or entirely included in the plasma processing apparatus **1**. The controller **2** may include, e.g., a computer **2***a*. The computer **2***a* may include, e.g., a central processing unit (CPU) **2***a***1**, a storage device **2***a***2**, and a communication interface **2***a***3**. The central processing unit **2***a***1** may be configured to perform various operations based on a program stored in the storage device **2***a***2**. The storage device **2***a***2** may include a random access memory (RAM), a read only memory (ROM), a hard disk drive (HDD), a solid state drive (SSD), or a combination thereof. The communication interface **2***a***3** may communicate with the plasma processing apparatus **1** via a communication line such as a local area network (LAN).
(44) While various embodiments have been described above, the present disclosure is not limited to the above-described embodiments, and various additions, omissions, substitutions and changes may be made. Further, other embodiments can be implemented by combining elements in different embodiments.
(45) For example, in the above embodiment, in the heat transfer sheet **140** of the upper electrode assembly **13**, the vertically oriented portion R**1** is formed by laminating the plurality of vertically oriented graphite sheets **141** in the plane (horizontal) direction, so that the plurality of vertically oriented graphene structures **141***a* are oriented along the vertical direction. However, the configuration of the heat transfer sheet **140** is not limited thereto, and the vertically oriented portion

R**1** may be formed by a vertically oriented carbon nanotube (CNT) sheet **142** having a plurality of carbon nanotubes **142***a* extending along the thickness direction (vertical direction) as shown in FIG. **6**. As shown in FIG. **6**, the vertically oriented carbon nanotube **142***a* has a plurality of vertically oriented graphene structures **141***a* oriented along the extension direction of the vertically oriented carbon nanotube **142***a*. In other words, each of the vertically oriented carbon nanotubes **142***a* has the plurality of vertically oriented graphene structures **141***a*. In other words, in one embodiment, in the vertically oriented portion R**1** of the heat transfer sheet **140**, the thermal conductivity in the vertical direction, which is the extension direction of the vertically oriented carbon nanotube **142***a* (the orientation direction of the vertically oriented graphene structures **141***a*), is higher than the thermal conductivity in the plane (horizontal) direction.

(46) <Substrate Processing Method Performed by Plasma Processing Apparatus>

(47) Next, an example of a method for processing the substrate W in the plasma processing apparatus **1** configured as described above will be described. In the plasma processing apparatus **1**, various plasma processings, such as etching, film formation, diffusion, and the like, are performed on the substrate W.

(48) First, the substrate W is loaded into the plasma processing chamber **10** and placed on the electrostatic chuck **114** of the substrate support **11**. Next, a voltage is applied to the attracting electrode of the electrostatic chuck **114**, so that the substrate W is attracted and held on the electrostatic chuck **114** by an electrostatic force.

(49) When the substrate W is attracted and held on the electrostatic chuck **114**, the plasma processing chamber **10** is depressurized to a predetermined vacuum level. Next, the processing gas is supplied from the gas supply **20** to the plasma processing space **10***s* via the upper electrode assembly **13**. Further, the source RF power for plasma generation is supplied from the first RF generator **31***a* to the lower electrode. Accordingly, the processing gas is excited, and plasma is generated. In this case, the bias RF power may be supplied from the second RF generator **31***b*. Then, in the plasma processing space **10***s*, the substrate W is subjected to plasma processing by the action of the generated plasma.

(50) Here, during the plasma processing of the substrate W, the temperature of the electrode plate **120** of the upper electrode assembly **13** disposed adjacent to the plasma processing space **10***s* varies due to the heat input from the plasma. When the temperature of the electrode plate **120** varies, the plasma processing result may be non-uniform in the plane of the substrate W.

(51) Therefore, in the present embodiment, the temperature of the electrode plate **120** is controlled by the coolant flow passage **131** and the heating module **132** in response to the variation of the temperature of the electrode plate **120**. Specifically, for example, when the temperature of the electrode plate **120** increases due to the heat input from the plasma, the temperature of the metal plate **130** is lowered by circulating a heat transfer fluid in the coolant flow passage **131**. Accordingly, the heat transfer from the electrode plate **120** to the metal plate **130** is promoted, thereby lowering the temperature of the electrode plate **120**.

(52) Here, in the upper electrode assembly **13** according to the present embodiment, the heat transfer sheet **140** having the vertically oriented portion R**1** is inserted between the electrode plate **120** and the metal plate **130**. As described above, the plurality of vertically oriented graphene structures **141***a* are oriented along the vertical direction in the vertically oriented portion R**1**, so that the thermal conductivity in the vertical direction is higher than the thermal conductivity in the plane (horizontal) direction. Accordingly, in the present embodiment, the heat transfer in the vertical direction, which is the lamination direction of the electrode plate **120** and the metal plate **130**, is promoted. In other words, the temperature of the electrode plate **120** can be effectively controlled. Further, when the heat transfer sheet **140** is inserted between the electrode plate **120** and the metal plate **130**, a load may be applied to the heat transfer sheet **140** in order to obtain a desired contact pressure. As the contact pressure increases, the thermal contact resistance decreases, which makes it possible to obtain a higher heat transfer performance.

(53) When the plasma processing is completed, the supply of the source RF power from the first RF generator **31***a* and the supply of the processing gas from the gas supply **20** are stopped. In the case of supplying the bias RF power during the plasma processing, the supply of the bias RF power is also stopped.
(54) Next, the attraction and holding of the substrate W on the electrostatic chuck **114** is stopped, and the substrate W that has been subjected to the plasma processing and the electrostatic chuck **114** are neutralized. Then, the substrate W is separated from the electrostatic chuck **114** and taken out from the plasma processing apparatus **1**. In this manner, a series of plasma processing is completed.
(55) <Operation and Effect of the Upper Electrode Assembly of the Present Disclosure>
(56) As described above, in accordance with the upper electrode assembly of the present embodiment, the heat transfer sheet **140** having the vertically oriented portion R**1** is inserted between the electrode plate **120** disposed adjacent to the plasma processing space **10***s* and the metal plate **130** laminated on the electrode plate **120** and having therein the coolant flow passage **131** and the heating module **132** for temperature control. Accordingly, in the vertically oriented portion R**1**, the heat transfer in the vertical direction, which is the orientation direction of the vertically oriented graphene structures **141***a*, is promoted. In other words, the heat transfer performance between the electrode plate **120** whose temperature varies due to the heat input from the plasma and the coolant flow passage **131** and the heating module **132** can be improved, and the temperature of the electrode plate **120** can be appropriately controlled.
(57) Specifically, the present inventors have studied and found that the electrode plate **120** can be cooled more effectively compared to when the heat transfer sheet **140′** formed by laminating the plurality of graphite sheets **141** in the vertical direction is inserted between the electrode plate **120** and the metal plate **130**, as shown in FIG. **7**. They also have found that the effect of cooling the electrode plate **120** is further improved especially when the RF power is applied with a high output during plasma processing.
(58) In other words, by inserting the heat transfer sheet **140** having the vertically oriented portion R**1** between the electrode plate **120** and the metal plate **130**, the efficiency of cooling the electrode plate **120** is increased. As a result, in the plasma processing apparatus, the electrode plate **120** can be appropriately cooled even when the high-speed switching of the RF power source is performed with a high output.
(59) Further, in accordance with the present embodiment, as shown in FIG. **2**, the coolant flow passage **131** and the heating module **132** are arranged in the metal plate **130** without overlapping in the vertical direction. Accordingly, for example, when the heat transfer fluid circulates in the coolant flow passage **131** to cool the electrode plate **120**, the interference of the heating module **132** with the heat transfer between the electrode plate **120** and the coolant flow passage **131** is suppressed. In other words, the electrode plate **120** can be cooled more appropriately.
(60) In the above embodiment, the heat transfer sheet **140** inserted between the electrode plate **120** and the metal plate **130** of the upper electrode assembly **13** is formed by laminating the plurality of vertically oriented graphite sheets **141** in the plane (horizontal) direction, for example. Accordingly, in the heat transfer sheet **140**, the thermal conductivity in the vertical direction (Z-direction in FIG. **4**) and one plane direction (X-direction in FIG. **4**) is higher than the thermal conductivity in the other plane direction (Y-direction in FIG. **4**).
(61) Here, it is known that in general plasma processing performed by the plasma processing apparatus **1**, the heat input from the plasma is higher on the center side (radially inner side) of the electrode plate **120** than on the edge side (radially outer side) thereof. Therefore, the temperature variation of the electrode plate **120** due to the heat input from the plasma tends to be greater on the center side than on the edge side. In other words, the temperature on the center side tends to be higher than the temperature on the edge side. Hence, when the heat transfer sheet **140** is inserted between the electrode plate **120** and the metal plate **130**, the amount of heat transfer from the center

side to the edge side of the heat transfer sheet **140** becomes non-uniform in one plane direction (X-direction) and the other plane direction (Y-direction) as shown in FIG. **8**. As a result, it may be difficult to control the cooling of the electrode plate **120** to be uniform especially in a circumferential direction.

(62) Therefore, in the upper electrode assembly **13**, as shown in FIG. **9**A, a heat transfer sheet **150** having the vertically oriented portion R**1** formed by concentrically arranging the plurality of vertically oriented graphite sheets **141** may be inserted between the electrode plate **120** and the metal plate **130**. Further, the vertically oriented carbon nanotube sheet **142** having at least one vertically oriented carbon nanotube **142***a* may be disposed at the center of the plurality of vertically oriented graphite sheets **141** concentrically arranged.

(63) In accordance with the heat transfer sheet **150** shown in FIG. **9**A, the thermal conductivity in the vertical direction (Z-direction) and the circumferential direction (θ-direction) of the heat transfer sheet **150** is higher than the thermal conductivity in the radial direction (X-direction and Y-direction) of the heat transfer sheet **150**. Accordingly, the amount of heat transfer in the circumferential direction of the heat transfer sheet **150** becomes greater than the amount of heat transfer in the radial direction thereof. As a result, the temperature of the electrode plate **120** can be controlled to be uniform especially in the circumferential direction.

(64) Further, in the upper electrode assembly **13**, as shown in FIG. **9**B, a heat transfer sheet **160** having the vertically oriented portion R**1** formed by arranging the plurality of vertically oriented graphite sheets **141** along the radial direction, i.e., in a radial shape, may be inserted between the electrode plate **120** and the metal plate **130**.

(65) In accordance with the heat transfer sheet **160** shown in FIG. **9**B, the thermal conductivity in the vertical direction (Z-direction) and the radial direction (X-direction and Y-direction) of the heat transfer sheet **160** is higher than the thermal conductivity in the circumferential direction (θ-direction) of the heat transfer sheet **160**. Further, in accordance with the heat transfer sheet **160**, it is possible to control the amount of heat transfer from the center side to the edge side of the heat transfer sheet **160** to be uniform in one plane direction (X-direction) and the other plane direction (Y-direction). As a result, the temperature of the electrode plate **120** can be controlled to be uniform in the circumferential direction, and the heat input from the plasma to the center side of the heat transfer sheet **160** can be processed toward the edge side thereof. In other words, the temperature on the center side and the edge side can be controlled to be uniform. That is, the temperature of the electrode plate **120** can be controlled to be uniform in the plane.

(66) In the above embodiment, the case where the heat transfer sheet **140** having only the vertically oriented portion R**1** is inserted between the electrode plate **120** and the metal plate **130** has been described as an example. However, the configuration of the heat transfer sheet is not limited thereto. Specifically, the heat transfer sheet having, in addition to the vertically oriented portion R**1**, the portion in which the plurality of graphene structures **141***a* are oriented along the plane (horizontal) direction may be inserted between the electrode plate **120** and the metal plate **130**, depending on the heat removal design of the electrode plate **120** to be cooled. The portion in which the plurality of graphene structures **141***a* are oriented along the plane (horizontal) direction may be referred to as “horizontally oriented portion R**2**” (see FIGS. **10**A and **10**B). Further, the graphene structures **141***a* oriented along the plane (horizontal) direction constitute “horizontally oriented graphene structures” of the present disclosure. In other words, in the horizontally oriented portion R**2**, the thermal conductivity in the plane (horizontal) direction is higher than the thermal conductivity in the vertical direction.

(67) FIG. **10** explains a schematic configuration of a heat transfer sheet **170** according to an embodiment that has the vertically oriented portion R**1** and the horizontally oriented portion R**2**.

(68) As shown in FIG. **10**A, in one embodiment, the heat transfer sheet **170** has the vertically oriented portion R**1**, which is disposed on the center side of the heat transfer sheet **170** and formed in a substantially circular shape in plan view, and the horizontally oriented portion R**2**, which is

disposed on the edge side of the heat transfer sheet **170** and formed in a substantially annular shape in plan view. In other words, the vertically oriented portion R**1** and the horizontally oriented portion R**2** of the heat transfer sheet **170** are arranged side by side (side by side in the planar (horizontal) direction) between the electrode plate **120** and the metal plate **130** at the same height in the vertical direction.

(69) In accordance with the heat transfer sheet **170** shown in FIG. **10**A, in the vertically oriented portion R**1** on the center side, the thermal conductivity in the vertical direction (Z-direction) and one plane direction (X-direction) is higher than the thermal conductivity in the other plane direction (Y-direction). On the other hand, in the horizontally oriented portion R**2** on the edge side, the thermal conductivity in the plane directions (X-direction and Y-direction) is higher than the thermal conductivity in the vertical direction (Z-direction).

(70) As described above, in the general plasma processing performed by the plasma processing apparatus **1**, the temperature tends to be higher on the center side of the electrode plate **120** than on the edge side thereof. Therefore, in the heat transfer sheet **170**, as shown in FIG. **10**A, the vertically oriented portion R**1** having a high thermal conductivity in the vertical direction is disposed on the center side where the temperature of the electrode plate **120** is relatively high, and the horizontally oriented portion R**2** having a high thermal conductivity in the plane (horizontal) direction is disposed on the edge side where the temperature is relatively low. Accordingly, on the center side of the electrode plate **120**, the heat transfer in the vertical direction is promoted to lower the temperature, and on the edge side of the electrode plate **120**, the heat transfer in the plane (horizontal) direction is promoted to improve the temperature uniformity.

(71) As described above, in the upper electrode assembly **13**, the temperature of the electrode plate **120** can be appropriately controlled by appropriately arranging the vertically oriented portion R**1** and the horizontally oriented portion R**2** depending on the in-plane distribution of the temperature variation of the electrode plate **120** due to the heat input from the plasma. Specifically, the vertically oriented portion R**1** is correspondingly disposed to the portion where the temperature of the electrode plate **120** is relatively high to thereby promote the cooling, and the horizontally oriented portion R**2** is correspondingly disposed to the portion where the temperature of the electrode plate **120** is relatively low to thereby improve the in-plane temperature uniformity. In that case, the amount of heat transfer in the vertical direction from the electrode plate **120**, i.e., the temperature of the electrode plate **120**, can be controlled by changing the area of the vertically oriented portion R**1** depending on the temperature variation of the electrode plate **120**, for example.

(72) In the example shown in FIG. **10**A, the vertically oriented portion R**1** is formed by horizontally laminating the plurality of vertically oriented graphite sheets **141**. However, the vertically oriented portion R**1** may be formed by laminating the plurality of vertically oriented graphite sheets **141** concentrically or radially as shown in FIGS. **9**A and **9**B. Further, as shown in FIG. **10**B, for example, the vertically oriented portion R**1** may be formed by the vertically oriented carbon nanotube sheet **142** having the plurality of vertically oriented carbon nanotubes **142***a* extending in the vertical direction.

(73) Further, in the examples shown in FIGS. **10**A and **10**B, the horizontally oriented portion R**2** is formed by horizontally laminating the plurality of horizontally oriented graphite sheets **141**. However, the horizontally oriented portion R**2** may be formed (not shown) by the horizontally oriented carbon nanotube sheet **142** having the plurality of horizontally oriented carbon nanotubes **142***a* extending in the plane (horizontal) direction.

(74) In order to improve the in-plane temperature uniformity of the electrode plate **120**, the vertically oriented portion R**1** and the horizontally oriented portion R**2** may be laminated when viewed from a side, as in the heat transfer sheet **180** shown in FIG. **11**. In other words, the heat transfer sheet **180** may further include, in addition to the vertically oriented portion R**1**, the horizontally oriented portion R**2** disposed between the electrode plate **120** and the vertically oriented portion R**1**, between the metal plate **130** and the vertically oriented portion R**1**, or between

the vertically oriented portions R**1**.

(75) In accordance with the heat transfer sheet **180** shown in FIG. **11**, in the vertically oriented portions R**1** that are laminated in the vertical direction, the cooling of the electrode plate **120** is promoted by promoting the heat transfer in the vertical direction is promoted. On the other hand, in the horizontally oriented portions R**2** that are laminated in the vertical direction, the in-plane temperature uniformity of the electrode plate **120** is improved by promoting the heat transfer in the plane (horizontal) direction. In other words, by combining the vertically oriented portions R**1** and the horizontally oriented portions R**2** in multiple layers, the thermal conductivity in each of the vertical direction and the plane (horizontal) direction can be increased. In other words, the cooling of the electrode plate **120** can be effectively and uniformly performed.

(76) In order to effectively, i.e., quickly, cool the electrode plate **120**, it is preferable to minimize the thickness of the horizontally oriented portions R**2** that are laminated compared to the thickness of the vertically oriented portions R**1**.

(77) <Upper Electrode Assembly According to a Second Embodiment>

(78) In the above embodiment, the case where the upper electrode assembly **13** includes the electrode plates **120**, the heat transfer sheet, and the metal plate **130** that are laminated horizontally has been described as an example. However, the configuration of the upper electrode assembly disposed in the plasma processing apparatus **1** is not limited thereto.

(79) FIG. **12** is a vertical cross-sectional view showing a schematic configuration of the upper electrode assembly **200** according to a second embodiment.

(80) As shown in FIG. **12**, in one embodiment, the upper electrode assembly **200** includes the electrode plate **120**, the metal plate **210**, and an additional metal plate **220**. The electrode plate **120** and the metal plate **210** are laminated in the vertical direction with the heat transfer sheet **140** interposed therebetween. Further, the metal plate **210** and the additional metal plates **220** are laminated in the vertical direction with the heat transfer sheet **140** interposed therebetween. In other words, the upper electrode assembly **200** is formed by laminating the electrode plate **120**, the heat transfer sheet **140**, the metal plate **210**, the heat transfer sheet **140**, and the additional metal plates **220** in that order from the plasma processing space **10***s* side.

(81) The heat transfer sheet inserted between the electrode plate **120** and the metal plate **210** is not limited to the heat transfer sheet **140** shown in FIGS. **3** and **4**, and at least one of the heat transfer sheets **150**, **160**, **170** or **180** shown in FIGS. **8** to **11** may be used appropriately. Further, the heat transfer sheet inserted between the metal plate **210** and the additional metal plate **220** is not limited to the heat transfer sheet **140**, and at least one of the heat transfer sheets **150**, **160**, **170** or **180** may be used appropriately.

(82) Further, the heat transfer sheet inserted between the electrode plate **120** and the metal plate **210** and the heat transfer sheet inserted between the metal plate **210** and the additional metal plate **220** may have the same structure, or may have different structures.

(83) In the present embodiment, the heat transfer sheet inserted between the metal plate **210** and the additional metal plate **220** constitutes “an additional heat transfer sheet” of the present disclosure. Further, the vertically oriented portion R**1** and the horizontally oriented portion R**2** of the additional heat transfer sheet constitute “an additional vertically oriented portion” and “an additional horizontally oriented portion” of the present disclosure. Similarly, the graphene structures **141***a* of the additional vertically oriented portion and the additional horizontally oriented portion constitute “additional vertically oriented graphene structures” and “additional horizontally oriented graphene structures” of the present disclosure. Similarly, when the additional heat transfer sheet has the graphite sheets **141** or the carbon nanotubes **142**, the graphite sheets **141** or the carbon nanotubes **142** constitute “additional graphite sheets” and “additional carbon nanotubes” of the present disclosure.

(84) The electrode plate **120** has the same configuration as that of the electrode plate **120** of the upper electrode assembly **13** according to the first embodiment. In other words, the electrode plate

120 includes the conductive member functioning as the upper electrode, and the plurality of gas inlet ports **13***a* are formed through the electrode plate **120** in the thickness direction.
(85) The metal plate **210** is laminated on the electrode plate **120**, and functions as a support for the electrode plate **120**. At least one gas diffusion space **13***b* is formed in the metal plate **210**.
(86) Further, the metal plate **210** has therein at least one heating module **211** configured to control the electrode plate **120** whose temperature varies due to the heat input from the plasma to a target temperature. The heating module **211** may be a heater, a heat transfer medium, a flow passage, or any combination thereof.
(87) The additional metal plate **220** is laminated on the metal plate **210**, and function as a support for the electrode plate **120** while being integrated with the metal plate **210**. At least one gas supply port **13***c* is formed at the additional metal plate **220**.
(88) Further, the additional metal plate **220** has therein at least one coolant flow passage **221** configured to control the electrode plate **120** whose temperature varies due to the heat input from the plasma to a target temperature. A heat transfer fluid such as brine or gas flows in the coolant flow passage **221**.
(89) Further, in one embodiment, the coolant flow passage **221** formed in the additional metal plate **220** and the heating module **211** disposed in the metal plate **210** are arranged without overlapping in the vertical direction (in plan view).
(90) The heat transfer sheet inserted between the electrode plate **120** and the metal plate **210**, or the heat transfer sheet inserted between the metal plate **210** and the additional metal plate **220** may have any configuration depending on the heat removal design corresponding to the temperature control of the electrode plate **120**, as described above. In other words, the heat transfer sheet inserted between the electrode plate **120** and the metal plate **210** and between the metal plate **210** and the additional metal plate **220** may have only the vertically oriented portion R**1** or may further have the horizontally oriented portion R**2**. Further, the arrangement of the vertically oriented portion R**1** and the horizontally oriented portion R**2** may be randomly selected.
(91) The upper electrode assembly **200** according to the second embodiment is configured as described above. Even when the upper electrode assembly is formed by laminating the plurality of metal plates, the temperature of the electrode plate **120** can be appropriately controlled by arranging the heat transfer sheets of the present disclosure on the interfaces of the metal plates.
(92) The embodiments of the present disclosure are illustrative in all respects and are not restrictive. The above-described embodiments may be omitted, replaced, or changed in various forms without departing from the scope of the appended claims and the gist thereof.
(93) For example, in the above embodiments, the case where the heat transfer sheet having the plurality of graphene structures oriented in the lamination direction is inserted between the electrode plate and the metal plate constituting the upper electrode assembly has been described as an example. However, the member using the heat transfer sheet is not limited to the upper electrode assembly, and the heat transfer sheet may be used for any member that requires effective heat treatment. Specifically, for example, in the substrate support **11**, the heat transfer sheet may be inserted between the base **113** and the electrostatic chuck **114**.
(94) While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosures. Indeed, the embodiments described herein may be embodied in a variety of other forms. Furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the disclosures. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the disclosures.

Claims

1. An upper electrode assembly used in a plasma processing apparatus, the upper electrode assembly comprising: an electrode plate; a metal plate; and a heat transfer sheet disposed between the electrode plate and the metal plate, the heat transfer sheet having a vertically oriented portion, wherein the vertically oriented portion includes a plurality of nanotubes extending along a vertical direction, each nanotube, of the plurality of nanotubes, has a plurality of graphene sheets, and each graphene sheet is normal to a horizontal direction.
2. The upper electrode assembly of claim 1, wherein the plurality of vertically oriented nanotubes are carbon nanotubes.
3. The upper electrode assembly of claim 1, wherein the plurality of graphene sheets are laminated along the horizontal direction.
4. The upper electrode assembly of claim 1, wherein the heat transfer sheet further includes a horizontally oriented portion, the horizontally oriented portion includes a plurality of horizontally oriented graphene structures oriented along the horizontal direction, and the vertically oriented portion and the horizontally oriented portion are laminated along the vertical direction.
5. The upper electrode assembly of claim 4, wherein the horizontally oriented portion has a plurality of horizontally oriented carbon nanotubes oriented along the horizontal direction.
6. The upper electrode assembly of claim 4, wherein the each of the plurality of graphene structures is a graphene sheet, and the plurality of horizontally oriented graphene structures is laminated in the vertical direction.
7. The upper electrode assembly of claim 1, wherein the heat transfer sheet further includes a horizontally oriented portion, the horizontally oriented portion includes a plurality of horizontally oriented graphene structures oriented along the horizontal direction, and the vertically oriented portion and the horizontally oriented portion are arranged along the horizontal direction.
8. The upper electrode assembly of claim 1, wherein the metal plate has at least one coolant flow passage, at least one gas diffusion space, and at least one heating module.
9. The upper electrode assembly of claim 8, wherein said at least one heating module is disposed so as not to overlap said at least one coolant flow passage.
10. The upper electrode assembly of claim 1, further comprising: an additional metal plate; and an additional heat transfer sheet disposed between the metal plate and the additional metal plate and having an additional vertically oriented portion, wherein the additional vertically oriented portion includes a plurality of additional nanotubes extending along the vertical direction.
11. The upper electrode assembly of claim 10, wherein the metal plate has therein at least one gas diffusion space, the additional metal plate has therein at least one coolant flow passage, and at least one of the metal plate or the additional metal plate has therein at least one heating module.
12. The upper electrode assembly of claim 11, wherein said at least one heating module is disposed so as not to vertically overlap said at least one coolant flow passage.
13. The upper electrode assembly of claim 10, wherein the additional heat transfer sheet has an additional horizontally oriented portion having a plurality of additional horizontally oriented graphene structures oriented along the horizontal direction, and the additional vertically oriented portion and the additional horizontally oriented portion are laminated in the vertical direction.
14. The upper electrode assembly of claim 13, wherein the additional horizontally oriented portion has a plurality of additional horizontally oriented carbon nanotubes oriented along the horizontal direction, and each of the plurality of additional horizontally oriented carbon nanotubes has the plurality of additional horizontally oriented graphene structures.
15. The upper electrode assembly of claim 13, wherein the additional horizontally oriented portion has a plurality of additional horizontally oriented graphite sheets that are laminated in the vertical direction, and each of the plurality of additional horizontally oriented graphite sheets has the plurality of additional horizontally oriented graphene structures.
16. The upper electrode assembly of claim 10, wherein the additional heat transfer sheet has an

additional horizontally oriented portion having a plurality of additional horizontally oriented graphene structures oriented along the horizontal direction, and the additional vertically oriented portion and the additional horizontally oriented portion are arranged along the horizontal direction.