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## Inductive coil structure and inductively coupled plasma generation system


### Abstract

An inductively-coupled plasma (ICP) generation system may include a dielectric tube, a first inductive coil structure to enclose the dielectric tube, an RF power supply, a first main capacitor between a positive output terminal of the RF power supply and one end of the first inductive coil structure, and a second main capacitor between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure. The first inductive coil structure may include inductive coils connected in series to each other and placed at different layers, the inductive coils having at least one turn at each layer, and auxiliary capacitors, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils.



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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS (1) This application is a continuation of U.S. patent application Ser. No. 18/050,655, filed Oct. 28, 2022, which is a continuation of U.S. patent application Ser. No. 17/122,930, filed Dec. 15, 2020, now U.S. Pat. No. 11,521,829, issued Dec. 6, 2022, which is a continuation of U.S. patent application Ser. No. 16/703,618, filed Dec. 4, 2019, now U.S. Pat. No. 10,896,806, issued Jan. 19, 2021, which is a continuation of U.S. patent application Ser. No. 15/836,388, filed on Dec. 8, 2017, now U.S. Pat. No. 10,541,114, issued Jan. 21, 2020, which is a continuation of and claims priority to PCT/KR2017/012040 filed on Oct. 30, 2017, which claims priority to Korea Patent Application No. 10-2016-0146058 filed on Nov. 3, 2016, the entireties of which are both hereby incorporated by reference.

BACKGROUND
(1) The present disclosure relates to an inductively-coupled plasma (ICP) generation system, and in particular, to an ICP generation system including a capacitor interposed between a plurality of antennas and having a voltage division structure.
(2) Plasma is used for a process of etching a substrate (e.g., a semiconductor wafer) or of depositing a layer the substrate. Furthermore, the plasma is used for synthesis of new materials, surface treatment, and environment purification. In addition, an atmospheric pressure plasma is used for plasma scrubber, cleaning, sterilization, and skin care.
(3) To generate a conventional inductively-coupled plasma (ICP), a dielectric discharge tube wound by an inductive coil is used. However, the conventional inductive coil structure suffers from low discharge stability and a low plasma density.
(4) The present invention provides a novel inductive coil structure, which is configured to stably generate inductively-coupled plasma at an atmospheric pressure or a high pressure of several Torr or higher.
SUMMARY
(5) Some embodiments of the inventive concept provide an inductive coil structure, which is used to produce inductively-coupled plasma with improved discharge stability and efficiency while suppressing capacitive-coupling components.
(6) Some embodiments of the inventive concept provide an inductive coil structure, which is configured to prevent a voltage increase caused by an increase in the winding number of an inductive coil, and a plasma generation system including the same.
(7) Some embodiments of the inventive concept provide an inductive coil structure, which is

configured to maximally increase the number of windings per unit length and to suppress capacitive coupling.

(8) According to some embodiments of the inventive concept, an inductively-coupled plasma (ICP) generation system may include a dielectric tube extending in a length direction, a first inductive coil structure provided to enclose the dielectric tube and to produce ICP in the dielectric tube, an RF power supply configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency, a first main capacitor provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure, and a second main capacitor provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure. The first inductive coil structure may include inductive coils connected in series to each other and placed at different layers, the inductive coils having at least one turn at each layer, and auxiliary capacitors, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils.

(9) In some embodiments, each of the inductive coils may have the same inductance of first inductance L**1**, each of the auxiliary capacitors may have the same capacitance of first capacitance C**1**, and a driving frequency of the RF power may be controlled to coincide with a resonance frequency, which is determined by the first inductance L**1** and the first capacitance C**1** connected in series to each other.

(10) In some embodiments, each of the first main capacitor and the second main capacitor may have the same capacitance of second capacitance C**2**, and the second capacitance C**2** may be two times the first capacitance C**1**.

(11) In some embodiments, each of the inductive coils may be a 2- to 4-turn antenna.

(12) In some embodiments, the ICP generation system may further include a second inductive coil structure provided to enclose the dielectric tube, to produce ICP in the dielectric tube, and to have the same structure as the first inductive coil structure, the second inductive coil structure being spaced apart from the first inductive coil structure. One end of the second inductive coil structure may be connected to one end of the first inductive coil structure, an opposite end of the second inductive coil structure may be connected to an opposite end of the first inductive coil structure, and the first inductive coil structure and the second inductive coil structure may be connected in parallel to each other between the first main capacitor and the second main capacitor.

(13) In some embodiments, each of the inductive coils constituting the first inductive coil structure and the second inductive coil structure may have the same inductance of first inductance L**1**, each of the auxiliary capacitors constituting the first inductive coil structure and the second inductive coil structure may have the same capacitance of first capacitance C**1**, and a driving frequency of the RF power may be controlled to coincide with a resonance frequency, which is determined by the first inductance L**1** and the first capacitance C**1** connected in series to each other.

(14) In some embodiments, each of the first main capacitor and the second main capacitor may have the same capacitance of second capacitance C**2**, and the second capacitance C**2** may be four times the first capacitance CL.

(15) In some embodiments, the one end of the first inductive coil structure and the one end of the second inductive coil structure may be placed to be adjacent to each other, and the one end of the first inductive coil structure and the one end of the second inductive coil structure may be connected to each other and may be connected to the first main capacitor.

(16) In some embodiments, each of the inductive coils may include a first circular arc portion, which has a portion opened in a first direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius, a second circular arc portion, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion, a first connecting portion, which is provided on

the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction, a “U”-shaped first circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion with one end of the second circular arc portion, and a second connecting portion, which is provided on the arrangement plane to be connected to an opposite end of the second circular arc portion and to extend in the first direction.

(17) In some embodiments, each of the inductive coils may include a first circular arc portion, which has a portion opened in a first direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius, a second circular arc portion, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion, a third circular arc portion, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion, a first connecting portion, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction, a “U”-shaped first circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion with one end of the second circular arc portion, a “U”-shaped second circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion, and a second connecting portion, which is provided on the arrangement plane to be connected to an opposite end of the third circular arc portion and to extend in the first direction.

(18) In some embodiments, each of the inductive coils may include a first circular arc portion, which has a portion opened in a first direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius, a second circular arc portion, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion, a third circular arc portion, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion, a fourth circular arc portion, which is provided on the arrangement plane to have a fourth central angle less than the third central angle, to have a fourth radius larger than the third radius, and to have the same center axis as the center axis of the first circular arc portion, a first connecting portion, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction, a “U”-shaped first circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion with one end of the second circular arc portion, a “U”-shaped second circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion, a “U”-shaped third circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the third circular arc portion to one end of the fourth circular arc portion, and a second connecting portion, which is provided on the arrangement plane to be connected to an opposite end of the fourth circular arc portion and to extend in the first direction.

(19) In some embodiments, the first inductive coil structure and the second inductive coil structure may be provided to have a vertical mirror symmetry with reference to a point of the dielectric discharge tube, and current may be vertically divided at a center and then may be collected at both ends.

(20) In some embodiments, power input terminals of the inductive coils may be arranged to maintain a uniform angle in an azimuth direction.

(21) In some embodiments, at least a portion of the inductive coils may be fixed by a ceramic mold.

(22) In some embodiments, the ICP generation system may further include a washer-shaped insulating spacer, which is provided between the inductive coils to electrically disconnect the inductive coils from each other.
(23) In some embodiments, the inductive coils may include first to fourth inductive coils sequentially stacked, and the auxiliary capacitor may include first to third auxiliary capacitors. When compared with the first inductive coil, the second inductive coil may be rotated counterclockwise by 90° and may be placed below and aligned with the first inductive coil. When compared with the second inductive coil, the third inductive coil may be rotated counterclockwise by 90° and may be placed below and aligned with the second inductive coil. When compared with the third inductive coil, the fourth inductive coil may be rotated counterclockwise by 90° and may be placed below and aligned with the third inductive coil. One end of the first inductive coil may be connected to a positive output terminal of the RF power supply through the first main capacitor, an opposite end of the first inductive coil may be connected to one end of the second inductive coil through the first auxiliary capacitor, an opposite end of the second inductive coil may be connected to one end of the third inductive coil through the second auxiliary capacitor, an opposite end of the third inductive coil may be connected to one end of the fourth inductive coil through the third auxiliary capacitor, and an opposite end of the fourth inductive coil may be connected to a negative output terminal of the RF power supply through the second main capacitor.
(24) According to some embodiments of the inventive concept, a substrate processing system may include a process chamber configured to process a semiconductor substrate, and an ICP generation system configured to provide active species, which are provided by plasma, into the process chamber. The ICP generation system may include a dielectric tube extending in a length direction, a first inductive coil structure provided to enclose the dielectric tube and to produce ICP in the dielectric tube, an RF power supply configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency, a first main capacitor provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure, and a second main capacitor provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure. The first inductive coil structure may include inductive coils connected in series to each other and placed at different layers, the inductive coils having at least one turn at each layer, and auxiliary capacitors, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils.
(25) According to some embodiments of the inventive concept, an inductive coil structure may be provided to enclose a dielectric tube and to produce ICP in the dielectric tube. The inductive coil structure may include inductive coils connected in series to each other and placed at different layers, the inductive coils having at least one turn at each layer and having the same structure, and auxiliary capacitors, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils.
(26) In some embodiments, each of the inductive coils may include a first circular arc portion, which has a portion opened in a first direction in a rectangular coordinate system and may be provided on an arrangement plane to have a first central angle and a constant first radius, a second circular arc portion, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion, a third circular arc portion, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion, a first connecting portion, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction, a “U”-shaped first circular arc connecting portion, which is provided on the

arrangement plane to connect an opposite end of the first circular arc portion with one end of the second circular arc portion, a “U”-shaped second circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion, a second connecting portion, which is provided on the arrangement plane to be connected to an opposite end of the third circular arc portion and to extend in the first direction.

(27) In some embodiments, each of the inductive coils may include a first circular arc portion, which has a portion opened in a first direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius, a second circular arc portion, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion, a third circular arc portion, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion, a fourth circular arc portion, which is provided on the arrangement plane to have a fourth central angle less than the third central angle, to have a fourth radius larger than the third radius, and to have the same center axis as the center axis of the first circular arc portion, a first connecting portion, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction, a “U’-shaped first circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion with one end of the second circular arc portion, a “U”-shaped second circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion, a “U”-shaped third circular arc connecting portion, which is provided on the arrangement plane to connect an opposite end of the third circular arc portion to one end of the fourth circular arc portion, and a second connecting portion, which is provided on the arrangement plane to be connected to an opposite end of the fourth circular arc portion and to extend in the first direction.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) Example embodiments will be more clearly understood from the following brief description taken in conjunction with the accompanying, example drawings. The accompanying drawings represent non-limiting, example embodiments as described herein.

(2) FIG. **1** is a conceptual diagram illustrating a semiconductor substrate processing system according to example embodiments of the inventive concept.

(3) FIG. **2**A is a conceptual diagram illustrating an ICP generation system according to example embodiments of the inventive concept.

(4) FIG. **2**B is a circuit diagram illustrating the ICP generation system of FIG. **2**A.

(5) FIG. **2**C is a diagram illustrating voltage division in the ICP generation system of FIG. **2**A.

(6) FIG. **2**D is a plan view illustrating the ICP generation system of FIG. **2**A.

(7) FIG. **2**E is a plan view illustrating an inductive coil of the ICP generation system of FIG. **2**A.

(8) FIG. **3**A is a conceptual diagram illustrating an ICP generation system according to other example embodiments of the inventive concept.

(9) FIG. **3**B is a circuit diagram illustrating the ICP generation system of FIG. **3**A.

(10) FIG. **3**C is a diagram illustrating a voltage division in an inductive coil structure of the ICP generation system of FIG. **3**A.

(11) FIG. **4**A is a conceptual diagram illustrating an ICP generation system according to still other example embodiments of the inventive concept.

(12) FIG. **4**B is a circuit diagram illustrating the ICP generation system of FIG. **4**A.
(13) FIG. **4**C is a diagram illustrating voltage division in an inductive coil structure of the ICP generation system of FIG. **4**A.
(14) FIG. **4**D is a plan view illustrating an inductive coil of the ICP generation system of FIG. **4**A.
(15) FIG. **5**A is a conceptual diagram illustrating an ICP generation system according to even other example embodiments of the inventive concept.
(16) FIG. **5**B is a plan view illustrating an inductive coil of the ICP generation system of FIG. **5**A.
(17) It should be noted that these figures are intended to illustrate the general characteristics of methods, structure and/or materials utilized in certain example embodiments and to supplement the written description provided below. These drawings are not, however, to scale and may not precisely reflect the precise structural or performance characteristics of any given embodiment, and should not be interpreted as defining or limiting the range of values or properties encompassed by example embodiments. For example, the relative thicknesses and positioning of molecules, layers, regions and/or structural elements may be reduced or exaggerated for clarity. The use of similar or identical reference numbers in the various drawings is intended to indicate the presence of a similar or identical element or feature.

DETAILED DESCRIPTION

(18) In an antenna provided to surround a dielectric discharge tube, high voltage electric potential (3 kV or higher) is applied in the dielectric discharge tube under the condition of low pressure (lower than several tens of Torr without fluid effects). In this case, plasma is generated in the dielectric discharge tube. A surface of the dielectric discharge tube is heated by collision of ions. Accordingly, the dielectric discharge tube is heated to a temperature of 1000° C. or higher. This may lead to a change in surface characteristics of the dielectric discharge tube or perforation of the dielectric discharge tube.
(19) The high electric potential applied to the antenna is affected by inductance, frequency, and current of the antenna. In the high power condition, a high electric potential is necessarily applied to the antenna. Thus, it is necessary to lower the high electric potential in the antenna.
(20) According to some embodiments of the inventive concept, in the case where the high power of several kW or higher is applied, a method of lowering the applied high voltage and of minimizing a heating issue by ion collision is proposed.
(21) The inductively-coupled plasma (ICP) system may be used for a semiconductor processing apparatus, an inductively coupled spectral analysis apparatus, an ion beam generating apparatus, an apparatus for cleaning a deposition chamber, an apparatus for cleaning an exhaust hole of a deposition chamber, a plasma scrubber for removing waste gas from a semiconductor processing apparatus, or a cleaning apparatus for cleaning a process chamber of a chemical vapor deposition system.
(22) In some embodiments, an ICP generation system may be used as a remote plasma source providing active species into a semiconductor processing chamber.
(23) An inductive coil generating the ICP and plasma may be modeled as a transformer circuit. Accordingly, the ICP is called “transformer coupled plasma”. The inductive coil serves as a primary coil of the transformer circuit, and the plasma serves as a secondary coil of the transformer circuit. A magnetic flux confinement material such as a magnetic material may be used to increase a magnetic coupling between the inductive coil and the plasma. However, it is difficult to apply the magnetic flux confinement material to a cylindrical dielectric discharge container. Another method for enhancing the magnetic coupling between the inductive coil and the plasma is to increase inductance or winding number of inductive coil. However, the increase in inductance of the inductive coil increases impedance and makes it difficult to transmit the power efficiently. In addition, the increase in inductance of the inductive coil may increase voltage to be applied to the inductive coil, thereby causing parasitic arc discharge. Also, high voltage applied to the inductive coil may lead to capacitively-coupled discharge and the damage of the dielectric discharge

container by ion collision and heat.

(24) According to some embodiments of the inventive concept, a capacitor may be provided between series-connected inductive coils, and this makes it possible to reduce the voltage applied to the inductive coil and allows the overall voltage to be distributed between the inductive coil and the capacitor. In detail, the inductive coil may be divided into a plurality of inductive coils, auxiliary capacitors may be provided between the divided inductive coils, and main capacitors may be provided at both ends of the inductive coil. In this case, the electrostatic field may be reduced by the screening effect, and according to the voltage distribution model, the voltage applied to the inductive coil may be reduced. The divided inductive coils and the auxiliary capacitors therebetween may constitute a series resonant circuit, and the resonance circuit may be configured to have the same resonance frequency as the driving frequency of the AC power supply. Accordingly, even when a low voltage is applied to the inductive coil, the impedance matching operation can be performed stably.

(25) Inductively coupled plasma is generated using a driving frequency of several MHz, typically at a pressure of hundreds of mTorr. However, since the inductive electric field is weak, it is difficult to use the ICP for the discharge at atmospheric pressure or at high pressure of several Torr or higher. Accordingly, it is necessary to sufficiently increase the strength of the induced electric field and to provide an additional component for an initial discharge.

(26) In the case where an ICP discharge is performed by applying RF power to the inductive coil surrounding the dielectric tube, the dielectric tube may be heated and damaged by the ICP. That is, the ICP has a structural limitation at high power of several tens of kWatt or higher.

(27) In some embodiments, in order to improve the efficiency or stability of conventional ICPs, 1) an antenna (or a coil structure) is provided in a stacked form, thereby increasing an intensity of an inductive electric field, 2) an inductive coil is divided into a plurality of inductive coils and a capacitor for reducing impedance is disposed between the inductive coils, 3) main capacitors are connected to both ends of the inductive coil to satisfy the overall resonance condition, and 4) a frequency-varying AC power part is provided to improve plasma stability of the inductive coil. Thus, it is possible to perform a process at a flow rate of several tens to several hundreds of liters per minute and at a high pressure of several Torr or higher, which cannot be realized by the conventional ICP generation system. In addition, there is no need for an additional electrode for the initial discharge, and the initially discharge may be performed even when the driving frequency of the AC power part does not satisfy the resonance condition. In the case where the resonance condition is not satisfied, high voltage is applied to the inductive coil to perform the initial discharge, and then, a main discharge is performed by changing the driving frequency of the AC power part to the resonance condition.

(28) The terms “inductive coil” and “antenna” are used interchangeably in the following. For an ICP antenna, an intensity of inductive electric field transmitted to the plasma is proportional to a current and frequency of the inductive coil and proportional to square of a winding number. Therefore, by increasing the winding number of the inductive coil or antenna, it may be possible to apply a strong electric field to the plasma. However, if the winding number of a solenoid coil increases, energy is dispersed in a length direction of the dielectric discharge tube, due to spatial constraint. In addition, the high inductance (impedance) of the inductive coil makes it difficult to transfer power from the RF power generator to the inductive coil or the antenna.

(29) It is necessary to increase the density of the electric field near the plasma, and thus, it is necessary to maximize the number of windings per unit length in the length direction of the dielectric discharge tube. In the case where a high voltage is applied to the inductive coil, the inductive coil generates a capacitively coupled plasma reducing stability of the discharge. The capacitively coupled plasma is advantageous for the initial discharge, but since it causes ion acceleration, a dielectric tube or a dielectric window, through which an inductive electric field is transmitted, may be damaged.

(30) In some embodiments, to solve the damage problem of the dielectric discharge tube due to the high voltage applied to the antenna, capacitors may be interposed between antennas placed in each layer. Thus, even if more power is applied to the antenna, the dielectric discharge tube may not be damaged. The capacitor may be used between the unit antennas to lower a voltage applied to the antenna. In addition, it may be possible to suppress a parasitic discharge, owing to a high voltage between the antenna and a power input terminal and between the antenna and a power output terminal.
(31) If the high voltage is applied to the antenna, it may lead to acceleration and collision of ions, and the surface may be heated to high temperature and may be damaged. Owing to these problems, it is difficult to apply the high power condition to the ICP, and alternatively, methods of reducing inductance or spacing the antenna away from the tube are used.
(32) In some embodiments, in the case where capacitors are placed in series between the unit antennas constituting the antenna, the highest electric potential may be reduced in inverse proportion to the division number of the unit antennas, and the damage of the dielectric discharge tube may be reduced even at high power.
(33) According to a comparative example, antennas with the same inductance were tested. The capacitor was not applied to one of the antennas, but in the other of the antennas, the capacitor was placed in series between the unit antennas constituting the antenna. For the conventional antenna, the dielectric discharge tube was damaged at the power of 2 kW. However, for the case according to the inventive concept, the dielectric discharge tube was not damaged even at the power of 8 kW and provided improved discharge characteristics. In detail, for the conventional antenna, N2 gas could not be injected at the power of 4 kW or lower, but for the improved antenna, it was possible to inject from the power of 1.5 kW.
(34) Example embodiments of the inventive concept will now be described more fully with reference to the accompanying drawings, in which example embodiments are shown. Example embodiments of the inventive concept may, however, be embodied in many different forms and should not be construed as being limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the concept of example embodiments to those of ordinary skill in the art. In the drawings, the thicknesses of layers and regions are exaggerated for clarity. Like reference numerals in the drawings denote like elements, and thus their description will be omitted.
(35) FIG. **1** is a conceptual diagram illustrating a semiconductor substrate processing system according to example embodiments of the inventive concept.
(36) Referring to FIG. **1**, a semiconductor substrate processing system **2** may include a process chamber **92**, which is used to process a substrate **94**, and an ICP generation system **100**, which is configured to provide active species produced by an inductively-coupled plasma into the process chamber.
(37) The process chamber **92** may be configured to deposit a thin film (e.g., a tungsten layer) on the substrate **94**. The process chamber **92** may be configured to receive a first process gas (e.g., WF6) and the active species (e.g., hydrogen active species) from the ICP generation system **100**. The active species may be produced from hydrogen (H2) plasma. The process chamber **92** may include a gas distributing part **91**. The gas distributing part **91** may be configured to receive the first process gas from a process gas supplying part **96** and the active species from the ICP generation system **100**. To uniformly deposit a thin film on the substrate, the gas distributing part **91** may spatially distribute the gas supplied thereto.
(38) The ICP generation system **100** may be a remote plasma source. The ICP generation system **100** may be configured to produce hydrogen plasma with high efficiency, under a high pressure of several Torr. The ICP generation system **100** may include an inductive discharge module **191** and an RF power supply **140**, which is configured to supply an electric power to the inductive discharge module **101**. The ICP generation system **100** may be configured to receive a second process gas, to

produce active species from the second process gas using ICP, and to provide the active species to the process chamber **92**.
(39) A substrate holder **93** may be provided in the process chamber **92** to face and be parallel to the gas distributing part **91**, and the substrate **94** may be provided on the substrate holder **93** and in the process chamber **92**. The substrate holder **93** may be heated, for a chemical vapor deposition process. The substrate **94** may be a semiconductor substrate. In detail, the substrate may be a silicon wafer. A vacuum pump **95** may be provided to exhaust gas from the process chamber **92**.
(40) In certain embodiments, the active species may be directly supplied to the process chamber **92**, not through the gas distributing part **91**.
(41) In certain embodiments, the semiconductor substrate processing system **2** is not limited to be used for the chemical vapor deposition process, and the semiconductor substrate processing system **2** may be used to perform various processes.
(42) In certain embodiments, the ICP generation system **100** is not limited to be used for the chemical vapor deposition process and may be used for a process of cleaning the process chamber **92**. For example, the semiconductor substrate processing system **2** may include an additional remote plasma source, which is configured to discharge NF3 and to perform a cleaning process on the process chamber **92**. In this case, since fluorine leads to a change in process environment of the process chamber **92**, the ICP generation system **100** may provide the hydrogen active species to the process chamber **92**. Accordingly, fluorine adsorbed on an inner surface of the process chamber **92** may be reacted with the hydrogen active species and may be removed.
(43) FIG. **2**A is a conceptual diagram illustrating an ICP generation system according to example embodiments of the inventive concept.
(44) FIG. **2**B is a circuit diagram illustrating the ICP generation system of FIG. **2**A.
(45) FIG. **2**C is a diagram illustrating voltage division in the ICP generation system of FIG. **2**A.
(46) FIG. **2**D is a plan view illustrating the ICP generation system of FIG. **2**A.
(47) FIG. **2**E is a plan view illustrating an inductive coil of the ICP generation system of FIG. **2**A.
(48) Referring to FIGS. **2**A through **2**E, the ICP generation system **100** may include a dielectric tube **130** extending in a length direction, a first inductive coil structure **110**, which is provided to enclose the dielectric tube **130** and to produce ICP in the dielectric tube **130**; an RF power supply **140**, which is configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency; a first main capacitor **121** provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure; and a second main capacitor **122** provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure.
(49) The first inductive coil structure **110** may include inductive coils **112**, **114**, **116**, and **118**, which are connected in series to each other and are placed at different layers, and auxiliary capacitors **113**, **115**, and **117**, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils. The inductive coils **112**, **114**, **116**, and **118** may be provided to have at least one turn at each layer.
(50) The driving frequency of the RF power supply **140** may range from several hundreds of kHz to several MHz. An output power of the RF power supply **140** may range from several tens of watts to several tens of kW. The RF power supply **140** may supply an electric power to a time-varying load (ICP) through the first inductive coil structure. The inductive coil of the first inductive coil structure **110** may be electromagnetically coupled with the ICP. Accordingly, an apparatus for impedance matching between the RF power supply **140** and the first inductive coil structure **110** may be required. The RF power supply **140** may be configured to output a first output power and a second output power whose phases are opposite to each other. At a certain time, the first output power and the second output power may have opposite phases with respect to the ground.
(51) A conventional impedance matching network may include two variable reactance devices

(e.g., vacuum variable capacitors) or transformers for the impedance matching. In this case, the first inductive coil structure **110** may have a difficulty in stably meeting resonance condition with the driving frequency. Thus, a RF power with a variable driving frequency may be used to allow a pair of the inductive coil and the auxiliary capacitor, which are adjacent to each other in the first inductive coil structure, to meet a series resonance condition.

(52) The dielectric tube **130** may have a cylindrical shape and may extend in a length direction. The dielectric tube **130** may be formed of a material (e.g., glass, quartz, ceramic, alumina, or sapphire) having a good heat-resistance property. An inner diameter of the dielectric tube **130** may be several tens of millimeters. A length of the dielectric tube **130** may be several tens of centimeters.

(53) A cylindrical ICP generation system may include a cylindrical dielectric discharge tube and an antenna provided to surround the discharge tube. In the cylindrical ICP, an inductive electric field may not be vertically incident into the dielectric discharge tube, and thus, it may be possible to reduce damage caused by ion impact. The cylindrical ICP may produce an inductive electric field in a direction of a center axis of the cylindrical dielectric discharge tube. However, if the antenna is applied with a high voltage, the antenna may produce capacitively-coupled plasma to heat the dielectric tube. Accordingly, a novel inductive coil structure is required to prevent high voltage from being applied to the antenna.

(54) In the first inductive coil structure **110**, the inductive electric field may depend on the driving frequency and a current (or the number of turns per unit length). Also, the highest voltage to be applied to the first inductive coil structure **110** may be determined depending on the total impedance and current of the first inductive coil structure **110**. Impedance of the first inductive coil structure **110** may depend on the inductance and the driving frequency of the first inductive coil structure **110**. Accordingly, if the inductance of the first inductive coil structure is increased to reduce the highest voltage to be applied to the first inductive coil structure, the inductive electric field may have an increased strength, but a capacitive coupling effect may be increased by the highest voltage. Thus, to reduce the impedance of the first inductive coil structure, the first inductive coil structure **10** may include a plurality of inductive coils **112**, **114**, **116**, and **118** and a plurality of auxiliary capacitors **113**, **115**, and **117**, each of which is interposed between adjacent ones of the inductive coils. Furthermore, the inductive coil and the auxiliary capacitor adjacent thereto may be connected in series to each other to form a series resonance circuit. The inductive coils and the auxiliary capacitors may be electrically and alternately arranged and may be connected in series to each other. Accordingly, the first inductive coil structure may provide an overall low impedance. The number of the auxiliary capacitors may be less by one than the number of the inductive coils.

(55) In addition, the first inductive coil structure **110** may constitute a perfect resonance circuit overall. For this, the first main capacitor **121** may be connected to one end of the first inductive coil structure **110**, and the second main capacitor **122** may be connected to an opposite end of the first inductive coil structure **110**. To realize the perfect resonance circuit, capacitance C**2** of the first main capacitor **121** may be two times capacitance C**1** of the auxiliary capacitor (i.e., C**2**=2C**1**).

(56) If such a resonance circuit is configured, the highest voltage to be applied to the first inductive coil structure **110** may be inversely proportional to the number of the inductive coils.

(57) The first inductive coil structure **110** may include inductive coils **112**, **114**, **116**, and **118**, which are connected in series to each other and are placed at different layers, and auxiliary capacitors **113** and **115**, which are respectively provided between adjacent ones of the inductive coils to distribute a voltage applied to the inductive coils. The inductive coils **112**, **114**, **116**, and **118** may be provided to have at least one turn at each layer.

(58) The inductive coils may include first to fourth inductive coils **112**, **114**, **116**, and **118**. The auxiliary capacitor may include first to third auxiliary capacitors **113**, **115**, and **117**. All of the first to fourth inductive coils **112**, **114**, **116**, and **118** may have the same inductance of L**1**. All of the first to third auxiliary capacitors **113**, **115**, and **117** may have the same capacitance of C**1**. Each of the

first to third auxiliary capacitors **113**, **115**, and **117** may have 2C**1** and thus it may be depicted as a pair of serially-connected imaginary capacitors. Accordingly, the first main capacitor **121**, the first inductive coil **112**, and the imaginary capacitor may constitute a resonance circuit, thereby reducing the voltage overall.

(59) When compared with the case in which the auxiliary capacitors **113**, **115**, and **117** are not provided, if the auxiliary capacitors are provided, the voltage may be decreased in inverse proportion to the number of the inductive coil. Nevertheless, the overall number of turns per unit length in the dielectric tube may be maintained. To meet such a resonance condition, the driving frequency may be controlled to coincide with the resonance frequency.

(60) In addition, to increase the number of turns per unit length in the dielectric tube and thereby to increase the strength of the inductive electric field, each of the inductive coils **112**, **114**, **116**, and **118** may be a 3-turn coil or a 4-turn coil. The inductive coils **112**, **114**, **116**, and **118** may be vertically stacked with a sufficiently small distance, and a space for electric connection may be required. To satisfy this requirement, each inductive coil may not have a portion jumping an arrangement plane, and input and output terminals of each inductive coil should not be placed at a mutually-stacked position. For this, the inductive coil having the following structure is proposed.

(61) The inductive coils **112**, **114**, **116**, and **118** may include first to fourth inductive coils **112**, **114**, **116**, and **118**, which are sequentially stacked. The auxiliary capacitors **113**, **115**, and **117** may include first to third auxiliary capacitors **113**, **115**, and **117**.

(62) The auxiliary capacitor between each pair of the inductive coils may be configured to reverse the electric potential. In other words, on the same arrangement plane, a turn (or a first circular arc portion) close to the dielectric tube and the farthest turn (or a fourth circular arc portion) may be induced to have electric potentials opposite to each other. In the dielectric tube, the electric potential of the inductive coil may be canceled, and thus, an electrostatic electric field toward the dielectric tube by a capacitive-coupling may not occur. This reduction of the electrostatic electric field may reduce a capacitive coupling effect.

(63) In a conventional structure, inductance may cause a large potential difference at both ends of an antenna, and the large potential difference may result in ion acceleration, energy loss, and heating and damage of the dielectric tube. By contrast, in the case where the auxiliary capacitor is provided between the inductive coils, a potential difference may be reduced and the electric potential may have opposite signs at internal and outer regions of each inductive coil. The electric potentials having opposite signs may act as a dipole field in the dielectric tube, thereby reducing an electrostatic electric field. Each of the inductive coils **112**, **114**, **116**, and **118** may include a plurality of winding wires, which are wound outward on the same plane.

(64) The first inductive coil **112** may be provided to surround the dielectric tube. When compared with the first inductive coil **112**, the second inductive coil **114** may be rotated counterclockwise by 90° and may be placed below and aligned with the first inductive coil **112**. When compared with the second inductive coil **114**, the third inductive coil **116** may be rotated counterclockwise by 90° and may be placed below and aligned with the second inductive coil **114**. When compared with the third inductive coil **116**, the fourth inductive coil **118** may be rotated counterclockwise by 90° and may be placed below and aligned with the third inductive coil **116**. One end of the first inductive coil **112** may be connected to the positive output terminal of the RF power supply **140** through the first main capacitor **121**. An opposite end of the first inductive coil **112** may be connected to one end of the second inductive coil **114** through the first auxiliary capacitor **113**. An opposite end of the second inductive coil **114** may be connected to one end of the third inductive coil **116** through the second auxiliary capacitor **115**. An opposite end of the third inductive coil **116** may be connected to one end of the fourth inductive coil **118** through the third auxiliary capacitor **117**. An opposite end of the fourth inductive coil **118** may be connected to the negative output terminal of the RF power supply **140** through the second main capacitor **122**. To maintain the azimuthal symmetry, each of the first to fourth inductive coils may be rotated by 90°, when it is stacked on

another.
(65) A voltage (e.g., 2V) of the innermost winding wire of each of inductive coils may have a phase opposite to a voltage (e.g., −2V) of the outermost winding wire. In addition, the innermost winding wires of all inductive coils may have the same voltage. Accordingly, parasitic capacitance between adjacent ones of the inductive coils may be reduced and a discharge property may be improved. In addition, since plasma in the dielectric tube is affected by the same voltage of the inner winding wires, a local ion sputtering may be reduced.
(66) The inductive coil may be divided into a plurality of inductive coils, and auxiliary capacitors may be interposed between the divided inductive coils to reduce the highest voltage. However, to provide a sufficiently high inductive electric field, it is necessary to increase the number of turns per unit length. To increase the number of turns per unit length, the number of turns in each of the inductive coils **112**, **114**, **116**, and **118** may be increased. However, it is necessary to dispose each inductive coil on the same arrangement plane. If each inductive coil has a wiring portion that is not positioned on the arrangement plane, it may cause a difficult in densely stacking other inductive coils disposed on an adjacent layer. Each inductive coil may have 3 or 4 turns on the same arrangement plane.
(67) In certain embodiments, the winding number of each inductive coil may be configured to have five or more turns.
(68) Each of the inductive coils **112**, **114**, **116**, and **118** may include a first circular arc portion **22***a*, which has a portion opened in a first or x-axis direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius; a second circular arc portion **22***b*, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion; a third circular arc portion **22***c*, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion; a fourth circular arc portion **22***d*, which is provided on the arrangement plane to have a fourth central angle less than the third central angle, to have a fourth radius larger than the third radius, and to have the same center axis as the center axis of the first circular arc portion; a first connecting portion **23***a*, which is provided on the arrangement plane to be connected to one end of the first circular arc portion **22***a* and to extend in the first or x-axis direction; a “U”-shaped first circular arc connecting portion **24***a*, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion **22***a* with one end of the second circular arc portion **22***b*; a “U”-shaped second circular arc connecting portion **24***b*, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion; a “U”-shaped third circular arc connecting portion **24***c*, which is provided on the arrangement plane to connect an opposite end of the third circular arc portion to one end of the fourth circular arc portion; and a second connecting portion **23***b*, which is provided on the arrangement plane to be connected to an opposite end of the fourth circular arc portion **22***d* and to extend in the first direction. The fourth central angle may be equal to or greater than 270°. The first circular arc connecting portion **24***a*, the second circular arc connecting portion **24***b*, and the third circular arc connecting portion **24***c* may be provided in such a way that they are not overlapped with each other. The first circular arc connecting portion **24***a* may be provided in a region defined by the second circular arc connecting portion **24***b*.
(69) In each of the inductive coils **112**, **114**, **116**, and **118**, a space between winding wires (e.g., the first to fourth circular arc portions) may be uniform. For example, the space may range from 1 mm to 3 mm. To allow the inductive coil to have sufficient azimuthal symmetry, the first to fourth central angles may be equal to or greater than 270°. To suppress occurrence of arc discharge at atmospheric pressure by a voltage difference, the first to fourth circular arc portions may be spaced apart from each other by a sufficiently large distance of several mm or larger.

(70) Inductive coils provided at adjacent layers may be electrically disconnected from each other by an insulating spacer **150**. The insulating spacer **150** may be provided in the form of a washer (e.g., a thin circular plate with central penetration hole) and may be inserted to enclose an outer side surface of the dielectric tube **130**. The insulating spacer **150** may be glass, plastic, or Teflon. A thickness of the insulating spacer **150** may be of the order of several mm. An inner radius of the insulating spacer **150** may be substantially equal to the outer radius of the dielectric tube **130**, and an outer radius of the insulating spacer **150** may be substantially equal to an outermost radius of the inductive coil. A distance between inner and outer radii of the insulating spacer **150** may range from several to several tens of cm.
(71) In some embodiments, at least a portion of the inductive coils **112**, **114**, **116**, and **118** may be molded by a ceramic paste. A ceramic mold **152** encapsulating at least a portion of the inductive coil may be in thermal contact with the dielectric tube **130**. Accordingly, in the case where there is refrigerant flowing in the inductive coils **112**, **114**, **116**, and **118**, the inductive coil may refrigerate the ceramic mold **152**, and the ceramic mold **152** may refrigerate indirectly the dielectric tube **130**.
(72) Each of the inductive coils **112**, **114**, **116**, and **118** may be provided to be outward wound around the dielectric tube four times at each layer. A pair of inductive coils placed at adjacent layers may be connected in series to each other by an auxiliary capacitor therebetween. The auxiliary capacitor may be provided to have capacitance canceling the inductance of the inductive coil. Four inductive coils may constitute one group. The four inductive coils may be arranged in such a way that each of them is rotated counterclockwise by 90° with respect to a previous one.
(73) Both ends of the dielectric tube may be sealed by a flange. An upper flange **132** may fasten one end of the dielectric tube and may include a nozzle **131** supplying a mixture gas of hydrogen and nitrogen. The inductive coils **112**, **114**, **116**, and **118** enclosing a center portion the dielectric tube may generate ICP in the dielectric tube. A lower flange **134** may fasten an opposite end of the dielectric tube, and gas, which can be additionally decomposed by the ICP, may be provided to the opposite end of the dielectric tube.
(74) FIG. **3**A is a conceptual diagram illustrating an ICP generation system according to other example embodiments of the inventive concept.
(75) FIG. **3**B is a circuit diagram illustrating the ICP generation system of FIG. **3**A.
(76) FIG. **3**C is a diagram illustrating a voltage division in an inductive coil structure of the ICP generation system of FIG. **3**A.
(77) Referring to FIGS. **3**A through **3**C, an ICP generation system **200** may include a dielectric tube **130** extending in a length direction; a first inductive coil structure **110**, which is provided to enclose the dielectric tube **130** and to produce ICP in the dielectric tube **130**; an RF power supply **140**, which is configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency; a first main capacitor **121** provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure; and a second main capacitor **122** provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure.
(78) A second inductive coil structure **210** may be provided to surround the dielectric tube **130** and may be spaced apart from the first inductive coil structure **110** in the length direction. The second inductive coil structure **210** may have the same structure as the first inductive coil structure **110** and may be used to generate ICP in the dielectric tube **130**.
(79) One end of the second inductive coil structure **210** may be connected to the one end of the first inductive coil structure **110**, and an opposite end of the second inductive coil structure **210** may be connected to the opposite end of the first inductive coil structure **110**. The first inductive coil structure **110** and the second inductive coil structure **210** may be connected in parallel to each other, between the first main capacitor **121** and the second main capacitor **122**.
(80) Each of the inductive coils **112**, **114**, **116**, and **118** constituting the first inductive coil structure

**110** and the second inductive coil structure **210** may have the same inductance (e.g., of first inductance L**1**). Each of the auxiliary capacitors **113**, **115**, and **117** constituting the first inductive coil structure **110** and the second inductive coil structure **210** may have the same capacitance of first capacitance CL. A driving frequency of the RF power supply **140** may be controlled to coincide with a resonance frequency, which is determined by the first inductance L**1** and the first capacitance C**1** connected in series to each other.
(81) The first main capacitor and the second main capacitor may have the same capacitance (e.g., of second capacitance C**2**), and the second capacitance C**2** may be four times the first capacitance C**1**.
(82) The one end of the first inductive coil structure **110** may be disposed adjacent to the one end of the second inductive coil structure **210**. The one end of the first inductive coil structure and the one end of the second inductive coil structure may be connected to each other and may be connected to the first main capacitor **121**. The opposite end of the first inductive coil structure **110** and the opposite end of the second inductive coil structure **210** may be connected to each other and may be connected to the second main capacitor.
(83) The first inductive coil structure **110** and the second inductive coil structure **210** may be provided to have a vertical mirror symmetry with reference to a point of the dielectric discharge tube **130**. Current may be vertically divided at a center and then may be collected at both ends.
(84) In addition, the first inductive coil structure **110** and the second inductive coil structure **210** may constitute a perfect resonance circuit overall. For this, the first main capacitor **121** may be connected to the one end of the first inductive coil structure **110** and the one end of the second inductive coil structure **210**. The second main capacitor **122** may be connected to the opposite end of the first inductive coil structure **110** and the opposite end of the second inductive coil structure **210**. To realize the perfect resonance circuit, capacitance C**2** of the first main capacitor **121** may be four times capacitance C**1** of the auxiliary capacitor (i.e., C**2**=4C**1**). The first main capacitor may be depicted as a parallel-connected capacitor and may have 2C**1**.
(85) The inductive coils may include first to fourth inductive coils **112**, **114**, **116**, and **118**. The auxiliary capacitor may include first to third auxiliary capacitors **113**, **115**, and **117**. All of the first to fourth inductive coils **112**, **114**, **116**, and **118** may have the same inductance of L**1**. All of the first to third auxiliary capacitors **113**, **115**, and **117** may have the same capacitance of C**1**. Each of the first to third auxiliary capacitors **113**, **115**, and **117** may be depicted as a pair of serially-connected imaginary capacitors and may have 2C**1**. Accordingly, a portion (2C**1**) of the first main capacitor **121**, the first inductive coil **112**, and the imaginary capacitor (2C**1**) may constitute a resonance circuit, thereby reducing the voltage overall.
(86) The first inductive coil structure **110** and the second inductive coil structure **210** may be connected in parallel to each other, and thus, the ICP generation system **200** may include eight inductive coils. The inductive coils of the first inductive coil structure ma y be sequentially arranged in such a way that each of them is rotated counterclockwise by 90° with respect to a previous one. The inductive coils of the second inductive coil structure may be sequentially arranged in such a way that each of them is rotated clockwise by 90° with respect to a previous one.
(87) The auxiliary capacitor may be provided to cancel an imaginary part of impedance between the inductive coils. Both ends of two groups (i.e., the first and second inductive coil structures), each of which includes four serially-connected inductive coils, may be connected in parallel to each other and then may be electrically connected to an outer terminal.
(88) The auxiliary capacitor between each pair of the inductive coils may be configured to reverse the electric potential. In other words, on the same arrangement plane, the innermost turn (or a first circular arc portion) close to the dielectric tube and the outermost turn (or a fourth circular arc portion) may be induced to have electric potentials opposite to each other. In the dielectric tube, the electric potential of the inductive coil may be canceled, and thus, an electrostatic electric field

toward the dielectric tube by a capacitive-coupling may not occur. This reduction of the electrostatic electric field may reduce a capacitive coupling effect.

(89) In a conventional structure, inductance may cause a large potential difference at both ends of an antenna, and the large potential difference may result in ion acceleration, energy loss, and heating and damage of the dielectric tube. By contrast, in the case where the auxiliary capacitor is provided between the inductive coils, a potential difference may be reduced and the electric potential may have opposite signs at internal and outer regions of each inductive coil. The electric potentials having opposite signs may act as a dipole field in the dielectric tube, thereby reducing an electrostatic electric field.

(90) FIG. **4**A is a conceptual diagram illustrating an ICP generation system according to still other example embodiments of the inventive concept.

(91) FIG. **4**B is a circuit diagram illustrating the ICP generation system of FIG. **4**A.

(92) FIG. **4**C is a diagram illustrating voltage division in an inductive coil structure of the ICP generation system of FIG. **4**A.

(93) FIG. **4**D is a plan view illustrating an inductive coil of the ICP generation system of FIG. **4**A.

(94) Referring to FIGS. **4**A through **4**D, an ICP generation system **300** may include a dielectric tube **130** extending in a length direction; a first inductive coil structure **310**, which is provided to enclose the dielectric tube **130** and to produce ICP in the dielectric tube **130**; an RF power supply **140**, which is configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency; a first main capacitor **121** provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure; and a second main capacitor **122** provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure.

(95) The first main capacitor **121** and the second main capacitor **122** may have the same capacitance (e.g., of second capacitance C**2**), and the second capacitance C**2** may be two times the first capacitance C**1** of the auxiliary capacitor.

(96) Inductive coils may include first to fourth inductive coils **312**, **314**, **316**, and **318**. The auxiliary capacitor may include first to third auxiliary capacitors **113**, **115**, and **117**. All of the first to fourth inductive coils **312**, **314**, **316**, and **318** may have the same inductance of L**1**. All of the first to third auxiliary capacitors **113**, **115**, and **117** may have the same capacitance of C**1**. Each of the first to third auxiliary capacitors **113**, **115**, and **117** may be depicted as a pair of serially-connected imaginary capacitors and may have 2C**1**. Accordingly, a portion (2C**1**) of the first main capacitor **121**, the first inductive coil **312**, and the imaginary capacitor (2C**1**) may constitute a resonance circuit, thereby reducing the voltage overall.

(97) Each of the inductive coils **312**, **314**, **316**, and **318** may include a first circular arc portion **32***a*, which has a portion opened in a first or x-axis direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius; a second circular arc portion **32***b*, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion; a third circular arc portion **32***c*, which is provided on the arrangement plane to have a third central angle less than the second central angle, to have a third radius larger than the second radius, and to have the same center axis as the center axis of the first circular arc portion; a first connecting portion **33***a*, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction; a "U"-shaped first circular arc connecting portion **34***a*, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion to one end of the second circular arc portion; a "U"-shaped second circular arc connecting portion **34***b*, which is provided on the arrangement plane to connect an opposite end of the second circular arc portion to one end of the third circular arc portion; and a second connecting portion **33***b*, which is provided on

the arrangement plane to be connected to an opposite end of the third circular arc portion and to extend in the first direction. The third central angle may be equal to or greater than 270.
(98) FIG. **5**A is a conceptual diagram illustrating an ICP generation system according to even other example embodiments of the inventive concept.
(99) FIG. **5**B is a plan view illustrating an inductive coil of the ICP generation system of FIG. **5**A.
(100) Referring to FIGS. **5**A and **5**B, an ICP generation system **400** may include a dielectric tube **130** extending in a length direction; a first inductive coil structure **410**, which is provided to enclose the dielectric tube **130** and to produce ICP in the dielectric tube **130**; an RF power supply **140**, which is configured to provide positive and negative powers having opposite phases, to respectively supply positive and negative powers of RF power to both ends of the first inductive coil structure, and to change a driving frequency; a first main capacitor **121** provided between a positive output terminal of the RF power supply and one end of the first inductive coil structure; and a second main capacitor **122** provided between a negative output terminal of the RF power supply and an opposite end of the first inductive coil structure.
(101) The first main capacitor **121** and the second main capacitor **122** may have the same capacitance (e.g., of second capacitance C**2**), and the second capacitance C**2** may be two times the first capacitance C**1** of the auxiliary capacitor.
(102) Inductive coils may include first to fourth inductive coils **412**, **414**, **416**, and **418**. The auxiliary capacitor may include first to third auxiliary capacitors **113**, **115**, and **117**. All of the first to fourth inductive coils **412**, **414**, **416**, and **418** may have the same inductance of L**1**. All of the first to third auxiliary capacitors **113**, **115**, and **117** may have the same capacitance of C**1**. Each of the first to third auxiliary capacitors **113**, **115**, and **117** may be depicted as a pair of serially-connected imaginary capacitors and may have 2C**1**. Accordingly, a portion (2C**1**) of the first main capacitor **121**, the first inductive coil **412**, and the imaginary capacitor (2C**1**) may constitute a resonance circuit, thereby reducing the voltage overall.
(103) Each of the inductive coils **412**, **414**, **416**, and **418** may include a first circular arc portion **42***a*, which has a portion opened in a first direction in a rectangular coordinate system and is provided on an arrangement plane to have a first central angle and a constant first radius; a second circular arc portion **42***b*, which is provided on the arrangement plane to have a second central angle less than the first central angle, to have a second radius larger than the first radius, and to have the same center axis as a center axis of the first circular arc portion; a first connecting portion **43***a*, which is provided on the arrangement plane to be connected to one end of the first circular arc portion and to extend in the first direction; a “U”-shaped first circular arc connecting portion **44***a*, which is provided on the arrangement plane to connect an opposite end of the first circular arc portion to one end of the second circular arc portion; and a second connecting portion **43***b*, which is provided on the arrangement plane to be connected to an opposite end of the second circular arc portion and to extend in the first direction. The second central angle may be equal to or greater than 270.
(104) According to some embodiments of the inventive concept, a plasma generation system may include an inductive coil structure, which is configured to suppress a capacitive coupling effect and to stably and efficiently generate ICP.
(105) According to some embodiments of the inventive concept, an auxiliary capacitor is provided to serially connect inductive coils, which constitute an inductive coil structure of a plasma generation system, to each other, and this makes it possible to distribute a voltage and to reduce the overall highest voltage.
(106) According to some embodiments of the inventive concept, a plasma generation system is configured to have the same electric potential at positions, where each of inductive coils constituting an inductive coil structure is in contact with a dielectric tube, and thus, it may be possible to suppress occurrence of a parasitic capacitor, to improve discharge stability, and to suppress a local ion sputtering.

(107) While example embodiments of the inventive concepts have been particularly shown and described, it will be understood by one of ordinary skill in the art that variations in form and detail may be made therein without departing from the spirit and scope of the attached claims.

## Claims

1. A plasma generating apparatus comprising: a dielectric tube providing a space for inductively coupled plasma (ICP); and a first antenna structure having (i) a first end and (ii) a second end opposite to the first end; a second antenna structure having (i) a third end and (ii) a fourth end opposite to the third end, wherein the first antenna structure and the second antenna structure surround an outer side wall of the dielectric tube; and a Radio Frequency (RF) generator providing an AC power to the first antenna structure and the second antenna structure, wherein the RF generator is interposed between the first end and the second end and the first antenna structure is electrically connected to the RF generator in series, wherein the RF generator is interposed between the third end and the fourth end and the second antenna structure is electrically connected to the RF generator in series, wherein the first antenna structure is electrically connected to the second antenna structure in parallel, wherein the first antenna structure and the second antenna structure co-operate with each other to induce the ICP by receiving the AC power from the RF generator, wherein the first antenna structure comprises a first layer antenna, a second layer antenna and a first inter-layer capacitor, wherein the first layer antenna has a first arc having a first radius and a second arc having a second radius greater than the first radius, and is disposed in a plane among a plurality of planes, wherein the second layer antenna has a third arc having the first radius and a forth arc having the second radius, and is disposed in a plane, different the plane in which the first layer antenna disposed, among the plurality of planes, and wherein the first inter-layer capacitor is electrically interposed between the second arc and the third arc, wherein the second antenna structure comprises a third layer antenna, a fourth layer antenna and a second inter-layer capacitor, wherein the third layer antenna has a fifth arc having the first radius and a sixth arc having the second radius, and is disposed in a plane among a plurality of planes, wherein the fourth layer antenna has a seventh arc having the first radius and an eighth arc having the second radius, and is disposed in a plane, different the plane in which the third layer antenna disposed, among the plurality of planes, and wherein the second inter-layer capacitor is electrically interposed between the sixth arc and the seventh arc, wherein the plurality of planes are perpendicular to a center axis of the dielectric tube.
2. The plasma generating apparatus of claim 1, wherein a first terminal capacitor is electrically interposed between the first end and the RF generator, and wherein the first terminal capacitor is electrically interposed between the third end and the RF generator.
3. The plasma generating apparatus of claim 2, wherein capacitance of the first terminal capacitor is greater than at least one of capacitance of the first inter-layer capacitor and capacitance of the second inter-layer capacitor.
4. The plasma generating apparatus of claim 2, wherein the RF generator has a first and a second terminals to provide the AC power to the first antenna structure and the second antenna structure, wherein the first terminal is electrically connected to the first terminal capacitor, and wherein the first antenna structure and the second antenna structure are electrically connected in parallel and are interposed between the first terminal capacitor and the second terminal.
5. The plasma generating apparatus of claim 1, wherein a second terminal capacitor is electrically interposed between the second end and the RF generator, and wherein the second terminal capacitor is electrically interposed between the fourth end and the RF generator.
6. The plasma generating apparatus of claim 5, wherein capacitance of the second terminal capacitor is greater than at least one of capacitance of the first inter-layer capacitor and capacitance of the second inter-layer capacitor.

7. The plasma generating apparatus of claim 5, wherein the RF generator has a first and a second terminals to provide the AC power to the first antenna structure and the second antenna structure, wherein the second terminal is electrically connected to the second terminal capacitor, and wherein the first antenna structure and the second antenna structure are electrically connected in parallel and are interposed between the second terminal capacitor and the first terminal.

8. The plasma generating apparatus of claim 1, wherein capacitance of the first inter-layer capacitor is identical to capacitance of the second inter-layer capacitor.