

ELECTRODE, PLASMA ASSISTED CHEMICAL VAPOR DEPOSITION APPARATUS, AND METHODS OF FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10201810370U filed November 21, 2018, the contents of it being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] Various aspects of this disclosure relate to an electrode for plasma assisted chemical vapor deposition. Various aspects of this disclosure relate to a plasma assisted deposition apparatus. Various aspects of this disclosure relate to a method of forming an electrode for plasma assisted chemical vapor deposition. Various aspects of this disclosure relate to a method of forming a plasma assisted deposition apparatus.

BACKGROUND

[0003] Chemical vapor deposition (CVD) is a well-established and proven method in depositing dielectric, metal, and semiconductor thin films on a substrate in the fabrication of semiconductor devices, for example logic and memory devices. Basically, there are two types of CVDs: thermal CVD and plasma enhanced CVD (PE-CVD). In thermal CVD, the required chemical reactions are activated by thermal energy so that the substrate has to be heated to a higher temperature to provide sufficient heat energy to trigger and complete the chemical reaction. In general, temperature requirements for most of the commonly usable films lie in the range of 300°C-500°C.

[0004] Higher temperature requirements limit the applicability of thermal CVD in the fabrication for most semiconductor films, for example silicon dioxide (SiO₂), silicon nitride (SiN), hafnium oxide (HfO₂) etc. Conversely, PE-CVD facilitates low-temperature deposition since

plasma helps precursor gases to dissociate at low temperatures and to form reactive ions and/or free-radicals. From the physics point of view, low-temperature thin film deposition helps to reduce film's internal stress and external stress with respect to adjacent films. In addition, low-temperature deposition helps reduce the intermixing or inter-reaction between depositing film and the under-layer film. This results in better interface properties, which in turn contribute to improve the device thermal stability and operational reliability.

[0005] The other important point in thin film deposition is to maintain uniform film properties such as chemical homogeneity, optical refractive index, film stress, adhesion, and thickness over the entire wafer surface. In general, these optical and mechanical properties are correlated to film thickness, a quickly measurable parameter. As such, CVD reactors are designed to generate uniform radial film thickness.

[0006] Film thickness uniformity in thermal CVD in general depends on the temperature uniformity of wafer. By designing the heater configuration and selecting suitable wafer stage materials, for example higher thermal conducting materials, the temperature uniformity of wafer can be significantly improved. Therefore, thermal CVD tends to yield more uniform film thicknesses. Conversely, thickness uniformity of films deposited by PE-CVD basically depends on plasma density uniformity over the wafer surface. Controlling plasma density uniformity and gas flow dynamics above the wafer surface are rather difficult. As such, PE-CVD with the use of capacitively coupled plasma (CCP) may yield films with a higher thickness non-uniformity. The film thickness profiles of films formed in most of conventional PE-CVD systems may have a higher thickness at the wafer center.

SUMMARY

[0007] Various embodiments may relate to an electrode for plasma assisted chemical vapor deposition. The electrode may include an electrically conductive first part configured to be electrically connected to a radio frequency (rf) power generator. The electrode may also include an electrically conductive second part connected to the electrically conductive first part, the electrically second part configured to generate plasma upon application of an electric current, e.g. a radio frequency (rf) electric current to the electrically conductive first part. The electrode may

additionally include a dielectric slab in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part. The electrically conductive second part may define a plurality of holes.

[0008] Various embodiments may relate to a plasma assisted chemical vapor deposition apparatus. The plasma assisted chemical vapor deposition apparatus may include a chamber including an electrode as described herein. The plasma assisted chemical vapor deposition apparatus may also include a stage for holding a substrate. The plasma assisted chemical vapor deposition apparatus may further include one or more gas inlets. The plasma assisted chemical vapor deposition apparatus may additionally include a vacuum system connected to the chamber.

[0009] Various embodiments may relate to a method of forming an electrode for plasma assisted chemical vapor deposition. The method may also include providing an electrically conductive first part configured to be electrically connected to a radio frequency power generator. The method may also include connecting an electrically conductive second part to the electrically conductive first part, the electrically second part configured to generate plasma upon application of an electric current, e.g. a radio frequency electric current to the electrically conductive first part. The method may further include arranging a dielectric slab so that the dielectric slab is in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part. The electrically conductive second part may define a plurality of holes.

[0010] Various embodiments may relate to a method of forming a plasma-assisted chemical vapor deposition apparatus. The method may include forming a chamber including an electrode as described herein. The chamber may also include a stage for holding a substrate. The chamber may further include one or more gas inlets. The method may also include connecting a vacuum system to the chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

FIG. 1 is a schematic showing (a) the cross-sectional side view of a plasma enhanced chemical vapor deposition (PE-CVD) system with conventional capacitively coupled plasma (CCP) configuration; and (b) a plot of film thickness / plasma density as a function of the position across a wafer showing the radial profile of the capacitively coupled plasma density, and the radial profile of the film thickness.

FIG. 2 is a schematic showing (a) the cross-sectional side view of another plasma enhanced chemical vapor deposition (PE-CVD) system with conventional capacitively coupled plasma (CCP) configuration; and (b) a plot of film thickness / plasma density as a function of the position across a wafer showing the radial profile of the capacitively coupled plasma density, the radial profile of the plasma density generated by the loop antennas, and the radial profile of the film thickness.

FIG. 3A is a general illustration of an electrode for plasma assisted chemical vapor deposition according to various embodiments.

FIG. 3B is a general illustration of a plasma assisted chemical vapor deposition apparatus according to various embodiments.

FIG. 4A is a general illustration of a method of forming an electrode for plasma assisted chemical vapor deposition according to various embodiments.

FIG. 4B is a general illustration of a method of forming a plasma-assisted chemical vapor deposition apparatus according to various embodiments.

FIG. 5A is a schematic showing the cross-sectional side view of a plasma assisted chemical vapor deposition apparatus according to various embodiments.

FIG. 5B is a schematic showing the perspective view of the radio frequency (rf) electrode included in the plasma assisted chemical vapor deposition apparatus according to various embodiments.

FIG. 5C shows (a) a bottom view of the mesh of the electrode shown in FIG. 5B according to various embodiments; and (b) a cross-sectional side view of a portion of the electrode according to various embodiments.

FIG. 6 shows (a) a bottom view of another mesh according to various embodiments; (b) a cross-sectional side view of a portion of the electrode including the mesh according to various embodiments; and (c) a plot of plasma density as a function of the position showing the radial profile of plasma just below the electrode, and the radial profile of plasma just above the surface of the wafer.

FIG. 7 is a schematic showing a cross-sectional side view of another electrode according to various embodiments.

DETAILED DESCRIPTION

[0012] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, and logical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0013] Embodiments described in the context of one of the methods or electrodes/apparatuses is analogously valid for the other methods or electrodes/apparatuses. Similarly, embodiments described in the context of a method are analogously valid for an electrode or an apparatus, and vice versa.

[0014] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0015] The word "over" used with regards to a deposited material formed "over" a side or surface, may be used herein to mean that the deposited material may be formed "directly on", e.g. in direct contact with, the implied side or surface. The word "over" used with regards to a deposited material formed "over" a side or surface, may also be used herein to mean that the

deposited material may be formed "indirectly on" the implied side or surface with one or more additional layers being arranged between the implied side or surface and the deposited material. In other words, a first layer "over" a second layer may refer to the first layer directly on the second layer, or that the first layer and the second layer are separated by one or more intervening layers.

[0016] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements.

[0017] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a reasonable variance.

[0018] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0019] FIG. 1 is a schematic showing (a) the cross-sectional side view of a plasma enhanced chemical vapor deposition (PE-CVD) system with conventional capacitively coupled plasma (CCP) configuration 1; and (b) a plot of film thickness / plasma density as a function of the position across a wafer showing the radial profile 2 of the capacitively coupled plasma density, and the radial profile 3 of the film thickness. The plasma system 1 may include a wafer stage 4, top radio frequency (rf) electrode 5, gas inlet 6, gas outlet 7, and gate valve 8. The rf electrode 5 may be connected a rf power source via a matching circuit 11. The major drawback of the CCP configuration is that the plasma density drops close to chamber walls 9, as ions and electrons lose their ionic status upon collision with the chamber walls 9. That causes highly non-uniform plasma density 2 over the surface of the wafer 10. As a result, the radial profile 3 of film thickness on the wafer surface may also be non-uniform.

[0020] Some researchers have included one or more loop antennas to generate an inductively coupled plasma (ICP) close the walls of the chamber. FIG. 2 is a schematic showing (a) the cross-sectional side view of another plasma enhanced chemical vapor deposition (PE-CVD) system with conventional capacitively coupled plasma (CCP) configuration 16; and (b) a plot of film thickness / plasma density as a function of the position across a wafer showing the radial profile 2 of the capacitively coupled plasma density, the radial profile 14 of the plasma density generated by the loop antennas 13, and the radial profile 3 of the film thickness. Similar to plasma system 1, the plasma system 16 may include a wafer stage 4, top radio frequency (rf) electrode 5, gas inlet 6, gas outlet 7, and gate valve 8. The rf electrode 5 may be connected a rf power source via a matching

circuit 11. In addition, the plasma system 16 may have one or more loop antennas 13 and an additional gas inlet 15 to the plasma generating chamber. The loop antenna 13 generates a plasma just below the antenna and spread out towards center and sidewalls. Thus, the plasma density profile generated by loop antenna 13 appears as the curve 14 shown in FIG. 2(b). The combination of plasma densities generated by CCP and ICP may yield a fairly uniform plasma density 3 over the wafer surface.

[0021] One issue with the plasma system configuration 16 is that it needs two rf power sources, matching circuits and other peripheral devices, leading to higher hardware cost. Further, it takes more time to make a stable plasma if there are two sources of plasmas within the same chamber.

[0022] Multiple ring-electrodes have also been proposed as a means of improving film thickness uniformity. Each ring-electrode is categorized as a region, and each region has its own film deposition parameters such as rf power, reactive gas flux, time, etc. It has also been proposed to optimize the film thickness by combining depositions at different regions, by using a feedback controlling mechanism. The possible disadvantage of this methodology is the lower deposition rate or the lower throughput, since deposition is carried out with the use of one region at a time.

[0023] In addition, an RF antenna configuration to generate inductively coupled plasma to control the radial plasma density over the wafer surface has also been presented. In that configuration, there are two rf antennas, a first rf antenna to generate a plasma that yields a higher plasma density at the center of cavity, and a second loop-rf antenna that yields a higher plasma density close to the chamber wall. By controlling the rf current applied to these two antennas, the radial density of plasma across the wafer can be controlled. The issues facing this configuration include higher hardware costs, and more time required to generate a stable plasma.

[0024] There are also other plasma system configurations including different types and shapes of rf electrodes for CVD deposition.

[0025] Various embodiments may address or mitigate various problems facing conventional apparatuses or systems. Various embodiments may seek to address or solve the non-uniformity of plasma over the surface of a wafer or substrate by removing selected sections of a capacitively coupled rf electrode, which functions as a source of plasma. In other words, various embodiments may seek to provide a more uniform plasma for CVD. Various embodiments may seek to address

or solve the non-uniformity of plasma at relatively low hardware costs, and/or with a relatively short time to achieve a stable plasma.

[0026] FIG. 3A is a general illustration of an electrode for plasma assisted chemical vapor deposition according to various embodiments. The electrode may include an electrically conductive first part configured to be electrically connected to a radio frequency (rf) power generator. The electrode may also include an electrically conductive second part connected to the electrically conductive first part, the electrically second part configured to generate plasma upon application of an electric current, e.g. a radio frequency (rf) electric current to the electrically conductive first part. The electrode may additionally include a dielectric slab in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part. The electrically conductive second part may define a plurality of holes.

[0027] In other words, the electrode may include an electrically conductive first part and an electrically conductive second part in contact with the electrically conductive first part. The electrically conductive second part may be used to generate plasma based on an electric current to the electrically conductive first part. The electrically conductive second part may include a plurality of holes. The electrode may also include a dielectric slab configured to dissipate heat from the electrically conductive second part.

[0028] For avoidance of doubt, FIG. 3A seeks to illustrate some features of an electrode according to various embodiments, and is not intended to limit the arrangement, sizes, shapes, orientation etc. of the various features.

[0029] The electrically conductive first part may be referred to as an upper part of the electrode, and the electrically conductive second part may be referred to as a lower part of the electrode. The terms “upper” and “lower” may not be intended to limit the relative positions or arrangements of the two parts, although during operation, the electrode according to various embodiments may be so arranged such that the first part is above the second part, which faces the stage.

[0030] As highlighted above, the electrically second part may be configured to generate plasma. The holes may help in the generation of a radially more uniform plasma, leading to more uniform deposition on the substrate or wafer. The holes may reduce the surface area of the rf electrode and may define the locations for plasma generation.

[0031] In various embodiments, the electrically conductive second part may include a mesh defining the plurality of holes.

[0032] In various embodiments, the dielectric slab may include a plurality of grooves for accommodating the mesh. The mesh may be embedded in the dielectric slab to form a flat surface with the mesh exposed on one surface of the dielectric slab. An exposed surface of the mesh may be flush with an exposed surface of the dielectric slab. The plurality of holes defined by the mesh may include or be filled with dielectric material of the dielectric slab.

[0033] In various other embodiments, the mesh may be in contact with a planar surface of the dielectric slab. In other words, an entire surface of the dielectric slab may be flat, and the mesh may be in contact with the flat surface of the dielectric slab. In various embodiments, a length of each opening may be at least an order of magnitude or 10 times a depth of the respective opening. A width of each opening may also be at least an order of magnitude or 10 times the depth of the respective opening. The length and the width of an opening may be dimensions parallel to the surface of the dielectric slab, while the depth of the opening may be perpendicular to the dielectric slab.

[0034] In various embodiments, the mesh may include a first plurality of metal stripes along a first direction and a second plurality of metal stripes along a second direction. The second direction may be perpendicular to the first direction.

[0035] In various embodiments, the electrode may include at least one connector (e.g. screw) to connect the electrically conductive first part and the electrically conductive second part. The electrically conductive first part and the electrically conductive second part may be in contact with each other, e.g. at an outer periphery of the electrode.

[0036] In various other embodiments, the electrically conductive first part may be joined or welded to the electrically conductive second part.

[0037] In various embodiments, the electrically conductive first part may cooperate with the electrically conductive second part to define a cavity. The dielectric slab may be arranged within the cavity. The dielectric slab may be between the electrically conductive first part and the electrically conductive second part.

[0038] In various embodiments, the plurality of holes may be of the same size. A size of an inner hole near a center of the electrically conductive second part (or mesh) may be equal to a size of an outer hole further from the center of the electrically conductive second part (or mesh).

[0039] In various other embodiments, the sizes of the holes may decrease from a center of the electrically conductive second part (or mesh) to the circumference or perimeter of the electrically conductive second part (or mesh). A size of an inner hole near a center of the electrically conductive second part may be greater than a size of an outer hole further from the center of the electrically conductive second part.

[0040] In various embodiments, the electrode may further include a plate covering at least a portion of the electrically conductive second part. The plate may include a dielectric material or a semiconductor material.

[0041] In various embodiments, the electrode may be configured to generate plasma via capacitive coupling.

[0042] FIG. 3B is a general illustration of a plasma assisted chemical vapor deposition apparatus according to various embodiments. The plasma assisted chemical deposition vapor apparatus may include a chamber including an electrode as described herein. The plasma assisted chemical vapor deposition apparatus may also include a stage for holding a substrate, e.g. a wafer. The plasma assisted chemical vapor deposition apparatus may further include one or more gas inlets. The plasma assisted chemical vapor deposition apparatus may additionally include a vacuum system connected to the chamber.

[0043] In other words, the apparatus may include an electrode as described herein together with a stage, and one or more gas inlets for introducing the gases for chemical deposition vapor. A vacuum system may be coupled to the chamber including the electrode, the stage and the one or more gas inlets.

[0044] For avoidance of doubt, FIG. 3B seeks to illustrate some features of a plasma assisted chemical deposition apparatus according to various embodiments, and is not intended to limit the arrangement, sizes, shapes, orientation etc. of the various features.

[0045] In various embodiments, the plasma assisted chemical vapor apparatus may also include an inert gas source connected to a first gas inlet of the one or more gas inlets. The plasma assisted

chemical vapor apparatus may further include a reactive gas source connected to a second gas inlet of the one or more gas inlets.

[0046] In various embodiments, the plasma assisted chemical vapor apparatus may also include a radio frequency matching circuit in electrical connection with the electrode. The plasma assisted chemical vapor apparatus may also include a radio frequency power generator in electrical connection with the matching circuit.

[0047] In various embodiments, the stage may include an electrostatic chuck. The electrostatic chuck for holding or securing a substrate or wafer. A surface of the rf electrode, e.g. a surface of the second part may substantially be parallel to the substrate or wafer.

[0048] In various embodiments, the stage may include an embedded heater. The embedded heater may be used to heat the stage.

[0049] In various embodiments, a diameter of the electrically conductive second part may be greater than a diameter of the stage.

[0050] FIG. 4A is a general illustration of a method of forming an electrode for plasma assisted chemical vapor deposition according to various embodiments. The method may also include, in S1, providing or forming an electrically conductive first part configured to be electrically connected to a radio frequency power generator. The method may also include, in S2, connecting an electrically conductive second part to the electrically conductive first part, the electrically second part configured to generate plasma upon application of an electric current, e.g. a radio frequency electric current, to the electrically conductive first part. The method may further include, in S3, arranging a dielectric slab so that the dielectric slab is in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part. The electrically conductive second part may define a plurality of holes.

[0051] For avoidance of doubt, FIG. 4A is not intended to limit the sequence of the steps. For instance, S3 may occur before, at the same time, or after S2.

[0052] In various embodiments, the electrically conductive second part may include a mesh defining the plurality of holes.

[0053] In various embodiments, the method may also include using or providing at least one connector to connect or secure the electrically conductive first part and the electrically conductive

second part. In various other embodiments, the method may include joining or welding the electrically conductive first part and the electrically conductive second part.

[0054] In various embodiments, the method may include forming or attaching a plate covering at least a portion of the electrically conductive second part. The plate may include a dielectric material or a semiconductor material.

[0055] FIG. 4B is a general illustration of a method of forming a plasma-assisted chemical vapor deposition apparatus according to various embodiments. The method may include, in T1, forming or defining a chamber. The chamber may include an electrode as described herein. The chamber may also include a stage for holding a substrate. The chamber may further include one or more gas inlets. The method may also include, in T2, connecting a vacuum system to the chamber.

[0056] In various embodiments, the method may also include connecting an inert gas source to a first gas inlet of the one or more gas inlets. The method may further include connecting a reactive gas source to a second gas inlet of the one or more gas inlets.

[0057] In various embodiments, the method may further include electrically connecting a radio frequency matching circuit with the electrode. The method may also include electrically connecting a radio frequency power generator with the matching circuit.

[0058] **Working Example One**

[0059] FIG. 5A is a schematic showing the cross-sectional side view of a plasma assisted chemical vapor deposition apparatus 101 according to various embodiments. FIG. 5B is a schematic showing the perspective view of the radio frequency (rf) electrode included in the plasma assisted chemical vapor deposition apparatus according to various embodiments. The plasma assisted chemical vapor deposition apparatus 101 may include, in addition to the electrode, a wafer stage 102, gas inlet channels 104, 105, and gas outlet channel 106. The plasma assisted chemical vapor deposition apparatus 101 may have a ceiling 111. The electrode may include a first or upper part 109, a second or lower part 103, and a dielectric slab 114. The upper part 109 may be made of metal such as aluminum. The lower part 103 may be made of a thin metal sheet including for instance aluminum. The gas inlet 104 may be in fluidic communication with cavity 110, which in turn is in fluidic communication with channels 124 extending through the dielectric slab 114.

[0060] FIG. 5C shows (a) a bottom view of the mesh of the electrode shown in FIG. 5B according to various embodiments; and (b) a cross-sectional side view of a portion of the electrode according to various embodiments. As shown in FIGS. 5A-C, the lower part 103 may be a mesh including a first plurality of metal stripes 103a, 103b etc. along a first direction and a second plurality of metal stripes along a second direction perpendicular to the first direction. The stripes may extend across a ring which forms the circumference of the mesh 103. The strips may define a plurality of holes 107. The lower part 103 may have a diameter slightly larger than the wafer or substrate 112.

[0061] In various embodiments, the thickness of the lower part 103 may be of a value in the range from about 0.1 mm to about 5 mm. The lower part may be fabricated directly on the surface of the dielectric slab 114 by thin film deposition techniques. This may provide a better surface contact between the mesh 103 and the dielectric slab 114, which is useful for efficient heat transfer from the mesh 103 to the dielectric slab 114.

[0062] The dielectric slab 114 may be made of any suitable dielectric material, for instance glass, quartz, ceramic, thermoplastic, aluminum nitride (AlN). The dielectric slab 114 may be required to have a higher thermal budget as it gets heated by the mesh 103 during the plasma CVD deposition. As such, a material with a higher thermal conductivity such as aluminum nitride (AlN) may be selected. This may facilitate better heat transfer from the mesh 103 via the dielectric slab 114 to the upper part 109. In various embodiments, the thickness of the dielectric slab 114 may be of any value in the range from about 1 mm to about 10 mm. In various embodiments, a thinner slab 114 may be used to facilitate better heat transfer from the lower part 103 to the upper part 109.

[0063] The lower part 103 may be electrically connected to the upper part 109. The lower part 103 and the upper part 109 may be secured in contact with each other via several screws positioned at the outer edges of the lower part 103 and the upper part 109. However, various other embodiments may involve any other suitable means to fix the lower part 103 to the upper part 109, for example via electrical welding. The lower part 103 and the upper part 109 may be required to be in tight secured, joined or welded such that they come into contact with the dielectric slab 114 for efficient heat transfer from the lower part 103 to the dielectric slab 114 and from the dielectric slab 114 to the upper part of rf electrode 109. In various embodiments, grooves may be made on

the dielectric slab 114 as shown in FIG. 5A such that the depth of the grooves is equal to the thickness of mesh 103. The mesh 103 may be partially embedded in the dielectric slab 114 such that an exposed surface of the mesh 103 may be flush with an exposed surface of the dielectric slab 114.

[0064] In various other embodiments, an entire surface of the dielectric slab 114 may be substantially planar or flat. The mesh 103 may be in contact with the dielectric slab 114. In various embodiments, the dimensions of the holes 107 may be of any suitable value from about 5mm x about 5 mm to about 30 mm x about 30 mm. In various embodiments, the holes 114 may be uniformly distributed over the lower part 103. The length or x dimension 115 and the width or y dimension 116 of the holes 107 may be much larger than the thickness the depth w 117. In various embodiments, the length and the width of the hole may each be at least an order of magnitude (i.e. 10 times) greater than the depth of the hole. Therefore, the lower part 103 and the slab 114 may form a small cavity or no cavity.

[0065] If dimensions 115, 116 and 117 are comparable, cavities may be formed by the lower part 103 and the slab 114, and plasma generated may get confined within the cavities, which provides an increased surface area for plasma generation. However, various embodiments seek not to increase the effective surface area of the rf electrode but to reduce the surface area for improving radial plasma density profile over the wafer surface.

[0066] The wafer stage 102 may include a heated stage 123 and an electrostatic chuck 122. During operation, the wafer 112 may be electrostatically chucked on to the heated wafer stage 123 so that wafer 112 does not get displaced during gas pressure changes inside the reactor.

[0067] At the time of film deposition, the pressure inside the reactor 101 may be maintained in the range of about 1 Pa to about 100 Pa. Suitable reactive gases may be introduced inside the reactor 101 via inlet channels 104, 109. The inlet channels 104, 109 may lead to gas inlets 113. Then the rf electrode may be connected to a rf power generator 108 via a matching circuit 121. A rf current may be provided to the rf electrode via the matching circuit 121. The frequency of the rf current may for instance, be of 13.56 MHz, or any other suitable frequency. The rf current may generate the plasma by the capacitively coupled mechanism and may support a stable constant plasma. The rf current coupling may occur only through the stripes 103a, 103b etc. of the lower part 103. As such, the surface area of the lower part 103 that allows rf current coupling to the

plasma may be significantly reduced. However, the stripes of the rf electrode may spread over an area larger than the substrate or wafer. This mechanism may therefore help to generate a relatively lower density plasma which spread over an area larger than the substrate or wafer. The plasma generated below the stripes 103a, 103b, etc of the lower part 103 may diffuse to area where there is no plasma generation, e.g. areas below holes 107. The mechanism may help not to concentrate or condense plasma about the center of the substrate or wafer, thereby generating a fairly radially uniform plasma.

[0068] Various embodiments may facilitate generating radially uniform plasma above the surface of the substrate or wafer. That in turn may yield more uniform physical and chemical reactions on the surface of the wafer or substrate which is of importance in the deposition of CVD films to fabricate semiconductor devices with a higher yield.

[0069] **Working Example Two**

[0070] FIG. 6 shows (a) a bottom view of another mesh 103' according to various embodiments; (b) a cross-sectional side view of a portion of the electrode including the mesh 103' according to various embodiments; and (c) a plot of plasma density 120 as a function of the position showing the radial profile 118 of plasma just below the electrode, and the radial profile 119 of plasma just above the surface of the wafer. The remaining features of the plasma assisted chemical vapor deposition apparatus used with the mesh 103' may be similar to the apparatus 101 shown in FIG. 5A.

[0071] For mesh 103', the size of the holes may increase or get larger from the outer edge to the center of the mesh 103'. As explained above, if the plasma is generated by a planar rf electrode without any holes, the plasma density tends to increase near the center of rf electrode and decreases towards the chamber walls. Therefore, in order to get a radially more uniform plasma, the plasma generation area close to the center may have to be reduced by making holes 107 near the center bigger compared to the holes that are close to the edges of rf electrode. The x dimension and y dimension of holes 107 may be of any suitable values but may be in the range of about 5 mm x 5 mm to 30 mm x 30 mm. Accordingly, the active surface area of rf electrode may get smaller towards the center which in turn facilitates lower plasma density 120 towards the center. FIG. 6(c) shows the profile 118 of plasma density just below the rf electrode and the radial profile 119 of plasma density just above the wafer surface. The non-uniform plasma generated just below the rf

electrode may diffuse inwards as it drifts towards the wafer 112 and may have improved radial uniformity above the surface of the wafer.

[0072] **Working Example Three**

[0073] FIG. 7 is a schematic showing a cross-sectional side view of another electrode according to various embodiments. The electrode may include upper part 109, lower part 103, and the dielectric slab 114, similar to the electrode shown in FIGS. 5A-C. The electrode may further include a plate 125 at the bottom of the rf electrode. The plate 125 may cover the lower part of rf electrode 103. Therefore, with this configuration, the active rf electrode, i.e. the lower part 103, may not be seen from the bottom side of rf electrode.

[0074] The bottom-most plate 125 may include a dielectric material or a semiconductor material. For instance, the plate 125 may include glass, quartz, or silicon. The material for the plate may be selected based on the type of film to be deposited. The thickness of the bottom plate 125 may be of any suitable value, e.g. of any value in the range from about 1 mm to about 5 mm. RF current coupling to the plasma may occur through this bottom plate 125. Therefore, it may be desirable to have a plate with smaller thickness. The gas inlet 104 may be in fluidic communication with cavity 110, which in turn is in fluidic communication with channels 124 extending through the dielectric slab 114 and the plate 125.

[0075] The plasma generation mechanism with this configuration may be similar to that of working examples one and two. However, since there is no direct metal in contact with the plasma compared to the working example one and two, metal contamination to deposited films may be eliminated or reduced.

[0076] While the invention has been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

Claims

1. An electrode for plasma assisted chemical vapor deposition, the electrode comprising:
 - an electrically conductive first part configured to be electrically connected to a radio frequency power generator;
 - an electrically conductive second part connected to the electrically conductive first part, the electrically second part configured to generate plasma upon application of a radio frequency electric current to the electrically conductive first part; and
 - a dielectric slab in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part;wherein the electrically conductive second part defines a plurality of holes.
2. The electrode according to claim 1, wherein the electrically conductive second part comprises a mesh defining the plurality of holes.
3. The electrode according to claim 2, wherein the dielectric slab comprises a plurality of grooves for accommodating the mesh.
4. The electrode according to claim 2, wherein the mesh is in contact with a planar surface of the dielectric slab.
5. The electrode according to any one of claims 2 to 4, wherein the mesh comprises a first plurality of metal stripes along a first direction and a second plurality of metal stripes along a second direction.
6. The electrode according to any one of claims 1 to 5, further comprising at least one connector to connect the electrically conductive first part and the electrically conductive second part.
7. The electrode according to any one of claims 1 to 6,

wherein the electrically conductive first part cooperates with the electrically conductive second part to define a cavity; and wherein the dielectric slab is arranged within the cavity.

8. The electrode according to any one of claims 1 to 7,
wherein a size of an inner hole near a center of the electrically conductive second part is equal to a size of an outer hole further from the center of the electrically conductive second part.
9. The electrode according to any one of claims 1 to 7,
wherein a size of an inner hole near a center of the electrically conductive second part is greater than a size of an outer hole further from the center of the electrically conductive second part.
10. The electrode according to any one of claims 1 to 9, further comprising:
a plate covering at least a portion of the electrically conductive second part;
wherein the plate comprises a dielectric material or a semiconductor material.
11. A plasma assisted chemical vapor deposition apparatus comprising:
a chamber comprising:
an electrode according to any one of claims 1 to 10;
a stage for holding a substrate; and
one or more gas inlets; and
a vacuum system connected to the chamber.
12. The plasma assisted chemical vapor apparatus according to claim 11, further comprising:
an inert gas source connected to a first gas inlet of the one or more gas inlets; and
a reactive gas source connected to a second gas inlet of the one or more gas inlets.
13. The plasma assisted chemical vapor deposition apparatus according to claim 11 or claim 12, further comprising:

a radio frequency matching circuit in electrical connection with the electrode; and
a radio frequency power generator in electrical connection with the matching circuit.

14. The plasma assisted chemical vapor deposition apparatus according to any one of claims 11 to 13, wherein the stage comprises an electrostatic chuck.

15. The plasma assisted chemical vapor deposition apparatus according to any one of claims 11 to 14, wherein the stage comprises an embedded heater.

16. The plasma assisted chemical vapor deposition apparatus according to any one of claims 11 to 15, wherein a diameter of the electrically conductive second part is greater than a diameter of the stage.

17. A method of forming an electrode for plasma assisted chemical vapor deposition, the method comprising:

providing an electrically conductive first part configured to be electrically connected to a radio frequency power generator;
connecting an electrically conductive second part to the electrically conductive first part, the electrically second part configured to generate plasma upon application of a radio frequency electric current to the electrically conductive first part; and
arranging a dielectric slab so that the dielectric slab is in contact with the electrically conductive first part and the electrically conductive second part, the dielectric slab configured to carry heat from the electrically conductive second part to the electrically conductive first part;
wherein the electrically conductive second part defines a plurality of holes.

18. The method according to claim 17,

wherein the electrically conductive second part comprises a mesh defining the plurality of holes.

19. A method of forming a plasma-assisted chemical vapor deposition apparatus, the method comprising:

forming a chamber comprising:

an electrode according to any one of claims 1 to 10;

a stage for holding a substrate; and

one or more gas inlets; and

connecting a vacuum system to the chamber.