

plasma in the plasma discharge tube be spatially uniform, so that the resulting plasma is relatively free of hot spots.

SUMMARY

[0005] According to an embodiment, a plasma applicator is provided. The plasma applicator includes a plasma discharge tube in which plasma can be generated, the plasma discharge tube having a process gas inlet for allowing a plasma process gas to enter the plasma discharge tube, the plasma discharge tube having a longitudinal axis. A microwave cavity at least partially surrounds a portion of the plasma discharge tube. The plasma applicator includes a coupling iris at which microwave energy can be coupled to the microwave cavity such that the microwave energy can generate a plasma in the portion of the plasma discharge tube. The microwave cavity has three orthogonal dimensions including a length, a width and a height, at least two of the orthogonal dimensions being selected such that the microwave energy in the microwave cavity propagates in a transverse electric (TE) mode.

[0006] In some embodiments, primary electric fields generated from the microwave energy combine with an evanescent electric field generated from the coupling iris, such that a combined electric field in the microwave cavity is substantially uniform along the longitudinal axis of the plasma discharge tube.

[0007] In some embodiments, the microwave energy has a power of approximately 1kW.

[0008] In some embodiments, a length of the plasma discharge tube is approximately 11 inches.

[0009] In some embodiments, an outer diameter of the plasma discharge tube is approximately one inch.

[0010] In some embodiments, a width of the microwave cavity is approximately three inches.

[0011] In some embodiments, a length of the microwave cavity is approximately 4.5 inches.

[0012] In some embodiments, a source of the microwave energy comprises a solid state generator.

[0013] In some embodiments, a source of the microwave energy comprises a magnetron.

[0014] In some embodiments, the plasma discharge tube is made of a material including at least one of quartz, sapphire, ceramic, aluminum nitride and boron nitride.

[0015] In some embodiments, the process gas comprises at least one of oxygen, nitrogen,

hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 .

[0016] In some embodiments, the plasma applicator further comprises a plurality of radial microwave chokes disposed over an exterior of the plasma discharge tube and disposed at ends of the microwave cavity for substantially containing the microwave energy in the microwave cavity, positions of the microwave chokes being such that microwave energy propagating in the TE mode and the transverse electric magnetic (TEM) mode is attenuated. In some embodiments, the plurality of radial microwave chokes comprise a first inner choke and a first outer choke located at a first end of the microwave cavity and a second inner choke and a second outer choke located at a second end of the microwave cavity, a first space between the first inner choke and the first outer choke and a second space between the second inner choke and the second outer choke being selected to provide attenuation of the microwave energy propagating in the TE mode and the TEM mode. The first and second spaces can be substantially equal, and, in a particular exemplary embodiment, at least one of the spaces is approximately 0.38 inch.

[0017] In a first aspect aspect, the present disclosure provides a plasma applicator comprising a plasma discharge tube in which plasma can be generated, the plasma discharge tube having a process gas inlet for allowing a plasma process gas to enter the plasma discharge tube, the plasma discharge tube having a longitudinal axis; a microwave cavity at least partially surrounds a portion of the plasma discharge tube; and a coupling iris at which microwave energy can be coupled to the microwave cavity such that the microwave energy can generate a plasma in the portion of the plasma discharge tube, wherein primary electric fields generated from the microwave energy combine with an evanescent electric field generated from the coupling iris, such that a combined electric field in the microwave cavity is substantially uniform along the longitudinal axis of the plasma discharge tube.

[0018] In some embodiments, the microwave cavity has three orthogonal dimensions including a length, a width and a height, at least two of the orthogonal dimensions being selected such that the microwave energy in the microwave cavity propagates in a transverse electric (TE) mode.

[0019] In some embodiments, the plasma applicator further comprises a plurality of radial microwave chokes disposed over an exterior of the plasma discharge tube and disposed at ends of the microwave cavity for substantially containing the microwave energy in the microwave cavity, positions of the microwave chokes being such that microwave energy propagating in the

TE mode and the transverse electric magnetic (TEM) mode is attenuated. In some embodiments, the plurality of radial microwave chokes comprise a first inner choke and a first outer choke located at a first end of the microwave cavity and a second inner choke and a second outer choke located at a second end of the microwave cavity, a first space between the first inner choke and the first outer choke and a second space between the second inner choke and the second outer choke being selected to provide attenuation of the microwave energy propagating in the TE mode and the TEM mode. The first and second spaces can be substantially equal, and, in a particular exemplary embodiment, at least one of the spaces is approximately 0.38 inch.

[0020] In some embodiments, the microwave energy has a power of approximately 1kW.

[0021] In some embodiments, a length of the plasma discharge tube is approximately 11 inches.

[0022] In some embodiments, an outer diameter of the plasma discharge tube is approximately one inch.

[0023] In some embodiments, a width of the microwave cavity is approximately three inches.

[0024] In some embodiments, a length of the microwave cavity is approximately 4.5 inches.

[0025] In some embodiments, a source of the microwave energy comprises a solid state generator.

[0026] In some embodiments, a source of the microwave energy comprises a magnetron.

[0027] In some embodiments, the plasma discharge tube is made of a material including at least one of quartz, sapphire, ceramic, aluminum nitride and boron nitride.

[0028] In some embodiments, the process gas comprises at least one of oxygen, nitrogen, hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 .

[0029] In a second aspect, the present disclosure provides a plasma applicator comprising a plasma discharge tube in which plasma can be generated, the plasma discharge tube having a process gas inlet for allowing a plasma process gas to enter the plasma discharge tube, the plasma discharge tube having a longitudinal axis; a microwave cavity at least partially surrounds a portion of the plasma discharge tube; and a coupling iris at which microwave energy can be coupled to the microwave cavity such that the microwave energy can generate a plasma in the portion of the plasma discharge tube, wherein a plurality of radial microwave chokes is disposed over an exterior of the plasma discharge tube and disposed at ends of the microwave cavity for substantially containing the microwave energy in the microwave

hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 .

BRIEF DESCRIPTION OF THE DRAWINGS

[0042] The present disclosure is further described in the detailed description which follows, in reference to the noted plurality of drawings by way of non-limiting examples of embodiments of the present disclosure, in which like reference numerals represent similar parts throughout the several views of the drawings.

[0043] FIG. 1 includes a schematic cross-sectional diagram of a compact, low-power plasma applicator, according to exemplary embodiments.

[0044] FIGs. 2A and 2B include schematic block diagrams of two plasma generation systems, which include the plasma applicator of FIG. 1, according to exemplary embodiments.

[0045] FIGs. 3A and 3B are schematic diagrams illustrating propagation and field patterns for a rectangular TE_{10} mode waveguide.

[0046] FIG. 4A is a schematic diagram of a plasma applicator in which chokes are not optimally positioned with respect to each other.

[0047] FIG. 4B includes graphs illustrating the resulting electric field attenuation in a microwave cavity of a plasma applicator for multiple plasma density conditions, resulting from the choke positions illustrated in FIG. 4A.

[0048] FIG. 5A is a schematic diagram of a plasma applicator in which chokes are optimally positioned with respect to each other, according to exemplary embodiments.

[0049] FIG. 5B includes graphs illustrating the resulting electric field attenuation in a microwave cavity of a plasma applicator for multiple plasma density conditions, resulting from the choke positions illustrated in FIG. 5A.

[0050] FIG. 6A includes a schematic perspective view of a portion of cooling jacket, illustrating IR transparent windows, according to exemplary embodiments.

[0051] FIG. 6B includes a schematic perspective view of one of IR-transparent windows illustrated in FIG. 6A, according to exemplary embodiments.

[0052] FIG. 7 is a schematic functional diagram of operation of a cooling system for a plasma generating system, according to exemplary embodiments.

[0053] FIG. 8 is a schematic cross-sectional diagram of a plasma applicator with the optimized cooling described herein, according to exemplary embodiments.

[0054] FIG. 9 is a schematic diagram illustrating the relationship between plasma discharge tube wall thickness and temperature.

[0055] FIG. 10 is a schematic cross-sectional diagram of another plasma applicator, according to exemplary embodiments, illustrating design and test parameters used in optimizing cooling of the plasma applicator 200, according to exemplary embodiments.

[0056] FIG. 11 is a detailed schematic cross-sectional diagram of the plasma applicator illustrated in FIG. 10, according to exemplary embodiments.

[0057] FIG. 12 includes a schematic pictorial perspective view of a substantially cylindrical plasma applicator, according to exemplary embodiments.

[0058] FIG. 13 includes a schematic pictorial perspective view of a substantially rectangular plasma applicator, according to exemplary embodiments.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0059] FIG. 1 includes a schematic cross-sectional diagram of a compact, low-power plasma applicator 100, according to exemplary embodiments. Referring to FIG. 1, plasma applicator 100 includes a plasma discharge tube 102 having a longitudinal axis 136, in which one or more process gases are excited by microwave energy coupled into a microwave cavity 106 at least partially surrounding plasma discharge tube 102. In some exemplary embodiments, the process gas comprises at least one of oxygen, nitrogen, hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 , or one or more other process gases. The microwave energy is directed into the microwave cavity 106 via a coupling iris 124 from a microwave waveguide (not shown) coupled to the outer housing 122 of plasma applicator 100 at coupling iris 124. In exemplary embodiments, plasma applicator 100 includes air-filled radial waveguide chokes 108, 110, 112, 114, which are sized and located as shown in pairs at opposite ends of and surrounding plasma discharge tube 102 to provide containment of the microwave energy within microwave cavity 106. That is, the sizes and relative positions with respect to microwave cavity 106 and each other are such that the microwave energy is substantially prevented from propagating out of microwave cavity 106. Process gas used in generating the plasma enters plasma discharge tube 102 at a process gas inlet 116. The resulting plasma products exit plasma discharge tube 102 for use in the desired application processing through an outlet 120.

[0060] Plasma applicator 100 also includes a cooling jacket 104 at least partially surrounding plasma discharge tube 102. Cooling jacket 104 contains a cooling fluid circulating around the exterior of plasma discharge tube 102 to control temperature, i.e., provide cooling, of plasma discharge tube 102. According to exemplary embodiments, plasma applicator 100 operates at relatively low power, e.g., approximately 1 kW, such that the cooling fluid circulating in cooling jacket 104 can be a gas, such as air. That is, in some exemplary embodiments, because of the low-power operation of plasma applicator 100, liquid, i.e., water, cooling is not required. Cooling jacket 104 includes an air cooling inlet 118, through which the cooling air enters cooling jacket 104. The air circulates through cooling jacket 104 and exits cooling jacket 104 at air cooling outlet 130. Cooling jacket 104 can be sealed to the exterior of plasma discharge tube 102 by O-ring seals 132.

[0061] As noted above, plasma applicator 100 is a compact, low-power generator, having a height H and a width W. In some exemplary embodiments, the height H can be approximately 11 inches, and the width W can be approximately 3.5 inches. As noted above, plasma applicator 100 can operate at relatively low microwave power, which in some particular exemplary embodiments is approximately 1kW, and can be up to 1.5kW.

[0062] FIGs. 2A and 2B include schematic block diagrams of two plasma generation systems 150A and 150B, which include plasma applicator 100 of FIG. 1, according to exemplary embodiments. FIG. 2A illustrates two different alternative coupling structures which can be used to integrate a solid state microwave generator 141 via a coaxial cable 143. One structure includes a coax feed 142 which directly couples to applicator 100 via a coax connector, at which coaxial cable 143 can be connected. Another structure includes a waveguide feed 138 for coupling microwave excitation energy to microwave cavity 106 via coupling iris 124. A coax-to-waveguide transition 140 couples the microwave energy from solid state microwave generator 141 via a coaxial cable 143 to waveguide feed 138. The waveguide feed provides the additional advantage of a fixed tuning stub 142 or binary tuning, which is used to provide one tuning position for ignition of the plasma and one fixed position for operation. This structure provides additional tuning enhancement to the automatic frequency tuning by the solid state generator 141. It is noted that FIG. 2A illustrates the solid state microwave generator 141 connected via coaxial cable 143 to coax-to-waveguide transition 140. In the case in which the coax feed 142 is used, coax cable 143 is directly connected to a coax connector on which directly couples to

air to cool plasma discharge tube 102.

[0089] According to exemplary embodiments, gap g between plasma discharge tube 102 and cooling jacket 104 is a dimension that is optimized. For a given air system, g determines the heat transfer coefficient (h) and air flow rate (f). As g increases, f also increases, but h decreases. The size of gap g is selected to optimize air flow rate and heat transfer coefficient. In some exemplary embodiment, plasma discharge tube has an outer diameter (OD) of 1.00 inch (25.4mm). Various standard-size cooling jackets 104, having different inside diameters (ID), such as 26mm, 27mm, 28mm, 29mm and 30mm would operate with a 1.00-inch OD plasma discharge tube 102. Among these possible cooling jackets 104, it has been determined by simulation and empirical data that the cooling jacket having an ID of 27mm provides the lowest temperature at the plasma discharge tube 102. This results in the size of the gap g being approximately 0.8mm.

[0090] FIG. 8 is a schematic cross-sectional diagram of plasma applicator 100 with the optimized cooling described herein, according to exemplary embodiments. Referring to FIG. 8, once the value of g is determined, the cooling can be further enhanced by increasing the flow conductance outside the tube cooling section C2. The flow conductance in each of three different sections of applicator 100, indicated as C1, C2 and C3, is generally different. The total conductance of applicator 100 can be written as

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} ; \quad (3)$$

where C is the total conductance, C_1 is the conductance of the upstream section of applicator 100, C_2 is the conductance of the tube cooling section, and C_3 is the conductance of the downstream section of applicator 100. In exemplary embodiments, C_1 and C_3 are further maximized to obtain the highest total conductance and flow rate, and therefore to maximize the cooling performance in applicator 100. This includes the use of a maximum number of largest injection holes, shortest cooling air passage and largest cross-sectional area, when possible.

discharge tube 102 and cooling jacket 104. A radial outlet flange 208B is disposed at the outlet inlet end of plasma applicator 200 around the exterior of plasma discharge tube 102 and cooling jacket 104.

[0099] In addition to the air cooling of plasma applicator 200 provided via cooling jacket 104, plasma applicator 200 also provides cooling of flanges 202A, 202B, 208A and 208B by a liquid such as water. To that end, plasma applicator 200 includes radial water fittings 206A and 206B through which water can pass into and out of circulating water passages 204A and 204B.

[00100] FIGs. 12 and 13 include schematic pictorial perspective views of alternative embodiments of plasma applicators, according to exemplary embodiments. Specifically, FIG. 12 includes a schematic pictorial perspective view of a substantially cylindrical plasma applicator 300, according to exemplary embodiments, and FIG. 13 includes a schematic pictorial perspective view of a substantially rectangular plasma applicator 400, according to exemplary embodiments. The entire detailed description herein applies to the embodiments of plasma applicators 300 and 400 in FIGs. 12 and 13, respectively, unless the context dictates otherwise.

[00101] Referring to FIGs. 12 and 13, plasma applicators 300 and 400 include igniter lamp assemblies 311, 411 for initiating ignition of plasma. Plasma applicators 300, 400 include process gas inlets 316, 416, as well as air cooling inlets 318, 418 and air cooling outlets 330, 430, for providing air cooling according to the exemplary embodiments described above in detail. Plasma applicators 300, 400 also include water cooling ports 3063, 406 for providing water cooling of flanges according to the exemplary embodiments described above in detail. Plasma applicators 300, 400 also include coupling irises 324, 424 at which a waveguide can be mounted to couple microwave energy into microwave cavities 306, 406 for generation of plasma. Plasma applicators 300, 400 also include microwave chokes or traps 308, 310, 312, 314 and 408, 410, 412, 414, as described above in detail, according to exemplary embodiments.

[00102] While the present inventive concept has been particularly shown and described with reference to exemplary embodiments thereof, it will be understood by those of ordinary skill in the art that various changes in form and details may be made therein without departing from the spirit and scope of the present inventive concept as defined by the following claims.

CLAIMS

1. A plasma applicator, comprising:
 - a plasma discharge tube in which plasma can be generated, the plasma discharge tube having a process gas inlet for allowing a plasma process gas to enter the plasma discharge tube, the plasma discharge tube having a longitudinal axis;
 - a microwave cavity at least partially surrounding a portion of the plasma discharge tube;
 - and
 - a coupling iris at which microwave energy can be coupled to the microwave cavity such that the microwave energy can generate a plasma in the portion of the plasma discharge tube;wherein

primary electric fields generated from the microwave energy combine with an evanescent electric field generated from the coupling iris, such that a combined electric field in the microwave cavity is substantially uniform along the longitudinal axis of the plasma discharge tube.

2. The plasma applicator of claim 1, wherein the microwave cavity has three orthogonal dimensions including a length, a width and a height, at least two of the orthogonal dimensions being selected such that the microwave energy in the microwave cavity propagates in a transverse electric (TE) mode.
3. The plasma applicator of claim 1, further comprising a plurality of radial microwave chokes disposed over an exterior of the plasma discharge tube and disposed at ends of the microwave cavity for substantially containing the microwave energy in the microwave cavity, positions of the microwave chokes being such that microwave energy propagating in the TE mode and the transverse electric magnetic (TEM) mode is attenuated.
4. The plasma applicator of claim 3, wherein the plurality of radial microwave chokes comprise a first inner choke and a first outer choke located at a first end of the microwave cavity and a second inner choke and a second outer choke located at a second end of the microwave cavity, a first space between the first inner choke and the first outer choke and a second space between the second inner choke and the second outer choke being selected to provide attenuation of the microwave energy propagating in the TE mode and the TEM mode.
5. The plasma applicator of claim 4, wherein at least one of the first and second spaces is approximately 0.38 inch.
6. The plasma applicator of claim 4, wherein the first and second spaces are substantially equal.
7. The plasma applicator of claim 1, wherein the microwave energy has a power of approximately 1kW.

8. The plasma applicator of claim 1, wherein a source of the microwave energy comprises a solid state generator.
9. The plasma applicator of claim 1, wherein a source of the microwave energy comprises a magnetron.
10. The plasma applicator of claim 1, wherein the plasma discharge tube is made of a material including at least one of quartz, sapphire, ceramic, aluminum nitride and boron nitride.
11. The plasma applicator of claim 1, wherein the process gas comprises at least one of oxygen, nitrogen, hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 .
12. A plasma applicator, comprising:
 - a plasma discharge tube in which plasma can be generated, the plasma discharge tube having a process gas inlet for allowing a plasma process gas to enter the plasma discharge tube, the plasma discharge tube having a longitudinal axis;
 - a microwave cavity at least partially surrounding a portion of the plasma discharge tube;
 - a coupling iris at which microwave energy can be coupled to the microwave cavity such that the microwave energy can generate a plasma in the portion of the plasma discharge tube; and
 - a plurality of radial microwave chokes disposed over an exterior of the plasma discharge tube and disposed at ends of the microwave cavity for substantially containing the microwave energy in the microwave cavity, positions of the microwave chokes being such that microwave energy propagating in a transverse electric (TE) mode and a transverse electric magnetic (TEM) mode is attenuated.
13. The plasma applicator of claim 12, wherein the plurality of radial microwave chokes comprise a first inner choke and a first outer choke located at a first end of the microwave cavity and a second inner choke and a second outer choke located at a second end of the microwave cavity, a first space between the first inner choke and the first outer choke and a second space between the second inner choke and the second outer choke being selected to provide attenuation

of the microwave energy propagating in the TE mode and the TEM mode.

14. The plasma applicator of claim 13, wherein at least one of the first and second spaces is approximately 0.38 inch.

15. The plasma applicator of claim 13, wherein the first and second spaces are substantially equal.

16. The plasma applicator of claim 12, wherein the microwave cavity has three orthogonal dimensions including a length, a width and a height, at least two of the orthogonal dimensions being selected such that the microwave energy in the microwave cavity propagates in a transverse electric (TE) mode.

17. The plasma applicator of claim 12, wherein primary electric fields generated from the microwave energy combine with an evanescent electric field generated from the coupling iris, such that a combined electric field in the microwave cavity is substantially uniform along the longitudinal axis of the plasma discharge tube.

18. The plasma applicator of claim 12, wherein the microwave energy has a power of approximately 1kW.

19. The plasma applicator of claim 12, wherein a source of the microwave energy comprises a solid state generator.

20. The plasma applicator of claim 12, wherein a source of the microwave energy comprises a magnetron.

21. The plasma applicator of claim 12, wherein the plasma discharge tube is made of a material including at least one of quartz, sapphire, ceramic, aluminum nitride and boron nitride.

22. The plasma applicator of claim 12, wherein the process gas comprises at least one of

oxygen, nitrogen, hydrogen, fluorinated gas, forming gas, NF_3 , NH_3 , C_2F_4 , and C_2F_6 .