Claims

1. A microwave plasma reactor for manufacturing synthetic diamond material via chemical vapour deposition, the microwave plasma reactor comprising:

a plasma chamber;

a substrate holder disposed in the plasma chamber and comprising a supporting surface for supporting a substrate on which the synthetic diamond material is to be deposited in use;

a microwave coupling configuration for feeding microwaves from a microwave generator into the plasma chamber; and

a gas flow system for feeding process gases into the plasma chamber and removing them therefrom;

wherein the microwave plasma reactor further comprises an electrically conductive plasma stabilizing annulus disposed around the substrate holder within the plasma chamber.

2. A microwave plasma reactor according to claim 1, wherein the substrate holder is disposed on an end of the plasma chamber and the electrically conductive plasma stabilizing annulus is disposed on said end of the plasma chamber or on a side wall of the plasma chamber around the substrate holder.

3. A microwave plasma reactor according to claim 1 or 2, wherein the electrically conductive plasma stabilizing annulus forms a complete continuous ring around the substrate holder.

4. A microwave plasma reactor according to any one of claims 1 or 2, wherein the electrically conductive plasma stabilizing annulus comprises a plurality of arcuate segments and gaps therebetween, the plurality of arcuate segments forming a broken, discontinuous ring around the substrate holder.

5. A microwave plasma reactor according to claim 4, wherein the plurality of arcuate segments extended around at least 30%, 40%, 50%, 60%, 70%, 80%, or 90% of a circumference of the electrically conductive plasma stabilizing annulus.

6. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is symmetrical around a central axis of the plasma chamber.

7. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has a radial width relative to a diameter of the plasma chamber in the range 1% to 30%, 3% to 20%, 5% to 15%, or 8% to 12%.

8. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has a radial width in a range: 10 mm to 165 mm, 20 mm to 100 mm, or 40mm to 80 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 5 mm to 100 mm, 10 mm to 50 mm, or 20mm to 40 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 2 mm to 30 mm, 4 mm to 20 mm, or 6mm to 15 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

9. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the plasma chamber no less than 50%, 60%, 70%, 75%, or 80%.

10. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the plasma chamber no more than 95%, 90%, 85%, or 80%.

11. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter no less than: 300 mm, 400 mm, 450 mm, or 500 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 150 mm, 200 mm, 240 mm, or 280 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 50 mm, 70 mm, 85 mm, or 95 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

12. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter no more than: 950 mm, 850 mm, 800 mm, 720 mm, or 680 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 450 mm, 400 mm, 350 mm, or 330 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 170 mm, 150 mm, 130 mm, or 120 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

13. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter wherein a ratio of the inner diameter / plasma chamber height is in the range 0.9 to 2, 0.95 to 1.8, 1.0 to 1.5, or 1.1 to 1.3.

14. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth relative to a height of the plasma chamber in the range 1% to 30%, 2% to 20%, or 5% to 15%.

15. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth relative to a vertical distance between two electric field antinodes of the plasma chamber in the range 1% to 30%, 2% to 20%, or 5% to 15%.

16. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth in a range: 10 mm to 200 mm, 10 mm to 150 mm, 20 mm to 100 mm, 40mm to 80 mm, or 40 mm to 60 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 5 mm to 100 mm, 5 mm to 75 mm, 10 mm to 50 mm, 20mm to 40 mm, or 20 mm to 30 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 2 mm to 35 mm, 2 mm to 30 mm, 4 mm to 20 mm, 7 mm to 15 mm, or 7 mm to 10 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

17. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is positioned to have a lower surface at a height equal to or less than 50%, 40%, 30%, 20% or 10% of a height of

the plasma chamber from an end of the plasma chamber on which the substrate holder is disposed.

18. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is positioned at a height within ±100 mm, 70 mm, 50 mm, 30 mm, 20 mm, or 10 mm of a height of the supporting surface of the substrate holder.

19. A microwave plasma reactor according to any preceding claim, wherein the plasma chamber is substantially cylindrical with at least 80% of a side wall of the plasma chamber having a circumference within 10% or 40 mm of a mean circle.

20. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus defines a substantially circular shape having a circumference within 10% or 40 mm of a mean circle.

21. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed of a material having a melting point of at least 100°C, an electrical conductivity of at least 1×10^6 Sm^{-1}, and/or a thermal conductivity of at least 10 $WK^{-1}m^{-1}$.

22. A microwave plasma reactor according to claim 21, wherein said material is metallic.

23. A microwave plasma reactor according to claim 21 or 22, wherein said material comprises at least 80%, 90%, 95%, or 98% of one or more of stainless steel, copper, aluminium, molybdenum, and tantalum.

24. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed of the same material as a wall of the plasma chamber on which it is disposed.

25. A microwave plasma reactor according to any preceding claim, wherein more than one electrically conductive plasma stabilizing annulus is provided within the plasma chamber.

26. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is in the form of a projecting ring which protrudes into the plasma chamber from a wall of the plasma chamber.

27. A microwave plasma reactor according to any one of claims 1 to 25, wherein the electrically conductive plasma stabilizing annulus is in the form of a ring-shaped recess formed in a wall of the plasma chamber.

28. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed so as to comprise a smooth cross-sectional shape without any sharp edges.

29. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus comprises at least a portion having a curved cross-sectional shape with a radius of curvature in a range 1 mm to 40 mm, 2 mm to 30 mm, 3 mm to 20 mm, or 5 mm to 15 mm.

30. A microwave plasma reactor according to claim 29, where said portion has a constant radius of curvature or a varying radius of curvature.

31. A microwave plasma reactor according to claim 30, where said portion has a varying radius of curvature including a lower portion which has a larger radius of curvature than an upper portion.

32. A microwave plasma reactor according to claim 31, wherein said lower portion has a radius of curvature in a range 10 mm to 40 mm, 10 mm to 30 mm, or 12 mm to 20 mm and said upper portion has a radius of curvature in a range 1 mm to 10 mm, 2 mm to 8 mm, or 3 mm to 7 mm.

33. A microwave plasma reactor according to any preceding claim, wherein the microwave coupling configuration is arranged to inductively couple microwaves into the plasma chamber at an opposite end of the plasma chamber to that where the substrate holder and electrically conductive plasma stabilizing annulus are disposed.

34. A microwave plasma reactor according to any preceding claim, wherein the gas flow system is configured to feed process gases into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and electrically conductive plasma stabilizing annulus are disposed.

35. A microwave plasma reactor according to claim 34, wherein the gas flow system is configured to inject process gases towards the growth surface of the substrate.

36. A method of manufacturing synthetic diamond material using a chemical vapour deposition process, the method comprising:

providing a microwave plasma reactor according to any preceding claim;

disposing a substrate over the supporting surface of the substrate holder, the substrate have a growth surface;

feeding microwaves from a microwave generator into the plasma chamber;

feeding process gases into the plasma chamber; and

forming synthetic diamond material on said growth surface of the substrate.

37. A method according to claim 36, wherein the electrically conductive plasma stabilizing annulus is positioned at a height, relative to a base of the plasma chamber, within ±100 mm, 70 mm, 50 mm, 30 mm, 20 mm, or 10 mm of a height of the growth surface of the substrate.

38. A method according to claim 36 or 37, wherein the electrically conductive plasma stabilizing annulus is positioned at a height which is aligned with a plasma formed within the plasma chamber in use.

39. A method according to claim any one of claims 36 to 38, wherein the electrically conductive plasma stabilizing annulus has a radial width relative to a

diameter of the substrate in the range 10% to 50%, 15% to 40%, 20% to 35%, or 25% to 30%.

40. A method according to claim any one of claims 36 to 39, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of visible plasma within the plasma chamber in the range 110% to 250%, 120% to 200%, 120% to 160%, or 130% to 150%.

41. A method according to claim any one of claims 36 to 40, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the substrate in the range 150% to 400%, 150% to 350%, or 200% to 320%.

42. A method according to any one of claims 36 to 41, wherein the electrically conductive plasma stabilizing annulus has an axial depth in the range 1% to 100%, 10 % to 75%, 20% to 50%, or 30% to 50% of an axial depth of visible plasma in the plasma chamber in use.

43. A method according to any one of claims 36 to 42, wherein an operating pressure within the plasma chamber is equal to or greater than: 200, 220, 240, 260, 280, 300, or 320 Torr at a microwave frequency in a range 2300 to 2600 MHz; 120, 140 160, 180, 200, or 220 Torr at a microwave frequency in a range 800 to 1000 MHz; or 60, 70, 80, 100, or 120 Torr at a microwave frequency in a range 400 to 500 MHz.

44. A method according to any one of claims 36 to 43, wherein a power densities delivered to the substrate may be equal to or greater than 0.05, 0.1, 0.5, 1, 1.5, 2.0, 2.5, 2.75, 3.0, 3.2, or 3.5 W/mm^2 of the growth surface.

45. A method according to any one of claims 36 to 44, wherein the microwaves are coupled into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and the electrically conductive plasma stabilizing annulus are disposed.

46. A method according to any one of claims 36 to 45, wherein the process gases are fed into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and the electrically conductive plasma stabilizing annulus are disposed, the process gases being injected towards the growth surface of the substrate.

47. A method according to any one of claims 36 to 46, wherein the microwave plasma reactor is inverted whereby a base of the plasma chamber supporting the substrate forms an upper wall of the plasma chamber relative to earth.

Claims

1. A microwave plasma reactor for manufacturing synthetic diamond material via chemical vapour deposition, the microwave plasma reactor comprising:

a plasma chamber;

a substrate holder disposed in the plasma chamber and comprising a supporting surface for supporting a substrate on which the synthetic diamond material is to be deposited in use;

a microwave coupling configuration for feeding microwaves from a microwave generator into the plasma chamber; and

a gas flow system for feeding process gases into the plasma chamber and removing them therefrom;

wherein the microwave plasma reactor further comprises an electrically conductive plasma stabilizing annulus disposed around the substrate holder within the plasma chamber when viewed down a central axis of the plasma chamber, and

wherein the electrically conductive plasma stabilizing annulus is in the form of a projecting ring which protrudes into the plasma chamber from a side wall of the plasma chamber.

2. A microwave plasma reactor according to claim 1 wherein the electrically conductive plasma stabilizing annulus forms a complete continuous ring around the substrate holder.

3. A microwave plasma reactor according to claim 1, wherein the electrically conductive plasma stabilizing annulus comprises a plurality of arcuate segments and gaps therebetween, the plurality of arcuate segments forming a broken, discontinuous ring around the substrate holder.

4. A microwave plasma reactor according to claim 3, wherein the plurality of arcuate segments extended around at least 30%, 40%, 50%, 60%, 70%, 80%, or 90% of a circumference of the electrically conductive plasma stabilizing annulus.

5. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is symmetrical around a central axis of the plasma chamber.

6. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has a radial width relative to a diameter of the plasma chamber in the range 1% to 30%, 3% to 20%, 5% to 15%, or 8% to 12%.

7. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has a radial width in a range: 10 mm to 165 mm, 20 mm to 100 mm, or 40mm to 80 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 5 mm to 100 mm, 10 mm to 50 mm, or 20mm to 40 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 2 mm to 30 mm, 4 mm to 20 mm, or 6mm to 15 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

8. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the plasma chamber no less than 50%, 60%, 70%, 75%, or 80%.

9. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the plasma chamber no more than 95%, 90%, 85%, or 80%.

10. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter no less than: 300 mm, 400 mm, 450 mm, or 500 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 150 mm, 200 mm, 240 mm, or 280 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 50 mm, 70 mm, 85 mm, or 95 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

11. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter no more than:

950 mm, 850 mm, 800 mm, 720 mm, or 680 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 450 mm, 400 mm, 350 mm, or 330 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 170 mm, 150 mm, 130 mm, or 120 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

12. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an inner diameter wherein a ratio of the inner diameter / plasma chamber height is in the range 0.9 to 2, 0.95 to 1.8, 1.0 to 1.5, or 1.1 to 1.3.

13. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth relative to a height of the plasma chamber in the range 1% to 30%, 2% to 20%, or 5% to 15%.

14. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth relative to a vertical distance between two electric field antinodes of the plasma chamber in the range 1% to 30%, 2% to 20%, or 5% to 15%.

15. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus has an axial depth in a range: 10 mm to 200 mm, 10 mm to 150 mm, 20 mm to 100 mm, 40mm to 80 mm, or 40 mm to 60 mm for a microwave frequency f in the range 400 MHz to 500 MHz; 5 mm to 100 mm, 5 mm to 75 mm, 10 mm to 50 mm, 20mm to 40 mm, or 20 mm to 30 mm for a microwave frequency f in the range 800 MHz to 1000 MHz; or 2 mm to 35 mm, 2 mm to 30 mm, 4 mm to 20 mm, 7 mm to 15 mm, or 7 mm to 10 mm for a microwave frequency f in the range 2300 MHz to 2600 MHz.

16. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is positioned to have a lower surface at a height equal to or less than 50%, 40%, 30%, 20% or 10% of a height of the plasma chamber from an end of the plasma chamber on which the substrate holder is disposed.

17. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is positioned at a height within ±100 mm, 70 mm, 50 mm, 30 mm, 20 mm, or 10 mm of a height of the supporting surface of the substrate holder.

18. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed of a material having a melting point of at least 100°C, an electrical conductivity of at least 1×10^6 Sm^{-1}, and/or a thermal conductivity of at least 10 $WK^{-1}m^{-1}$.

19. A microwave plasma reactor according to claim 18, wherein said material is metallic.

20. A microwave plasma reactor according to claim 18 or 19, wherein said material comprises at least 80%, 90%, 95%, or 98% of one or more of stainless steel, copper, aluminium, molybdenum, and tantalum.

21. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed of the same material as a wall of the plasma chamber on which it is disposed.

22. A microwave plasma reactor according to any preceding claim, wherein more than one electrically conductive plasma stabilizing annulus is provided within the plasma chamber.

23. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus is formed so as to comprise a smooth cross-sectional shape without any sharp edges.

24. A microwave plasma reactor according to any preceding claim, wherein the electrically conductive plasma stabilizing annulus comprises at least a portion having a curved cross-sectional shape with a radius of curvature in a range 1 mm to 40 mm, 2 mm to 30 mm, 3 mm to 20 mm, or 5 mm to 15 mm.

25. A microwave plasma reactor according to claim 24, where said portion has a constant radius of curvature or a varying radius of curvature.

26. A microwave plasma reactor according to claim 25, where said portion has a varying radius of curvature including a lower portion which has a larger radius of curvature than an upper portion.

27. A microwave plasma reactor according to claim 26, wherein said lower portion has a radius of curvature in a range 10 mm to 40 mm, 10 mm to 30 mm, or 12 mm to 20 mm and said upper portion has a radius of curvature in a range 1 mm to 10 mm, 2 mm to 8 mm, or 3 mm to 7 mm.

28. A microwave plasma reactor according to any preceding claim, wherein the microwave coupling configuration is arranged to inductively couple microwaves into the plasma chamber at an opposite end of the plasma chamber to that where the substrate holder and electrically conductive plasma stabilizing annulus are disposed.

29. A microwave plasma reactor according to any preceding claim, wherein the gas flow system is configured to feed process gases into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and electrically conductive plasma stabilizing annulus are disposed.

30. A microwave plasma reactor according to claim 29, wherein the gas flow system is configured to inject process gases towards the growth surface of the substrate.

31. A method of manufacturing synthetic diamond material using a chemical vapour deposition process, the method comprising:

providing a microwave plasma reactor according to any preceding claim;

disposing a substrate over the supporting surface of the substrate holder, the substrate have a growth surface;

feeding microwaves from a microwave generator into the plasma chamber;

feeding process gases into the plasma chamber; and

forming synthetic diamond material on said growth surface of the substrate.

32. A method according to claim 31, wherein the electrically conductive plasma stabilizing annulus is positioned at a height, relative to a base of the plasma chamber, within ±100 mm, 70 mm, 50 mm, 30 mm, 20 mm, or 10 mm of a height of the growth surface of the substrate.

33. A method according to claim 31 or 32, wherein the electrically conductive plasma stabilizing annulus is positioned at a height which is aligned with a plasma formed within the plasma chamber in use.

34. A method according to any one of claims 31 to 33, wherein the electrically conductive plasma stabilizing annulus has a radial width relative to a diameter of the substrate in the range 10% to 50%, 15% to 40%, 20% to 35%, or 25% to 30%.

35. A method according to any one of claims 31 to 34, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of visible plasma within the plasma chamber in the range 110% to 250%, 120% to 200%, 120% to 160%, or 130% to 150%.

36. A method according to any one of claims 31 to 35, wherein the electrically conductive plasma stabilizing annulus has an inner diameter relative to a diameter of the substrate in the range 150% to 400%, 150% to 350%, or 200% to 320%.

37. A method according to any one of claims 31 to 36, wherein the electrically conductive plasma stabilizing annulus has an axial depth in the range 1% to 100%, 10 % to 75%, 20% to 50%, or 30% to 50% of an axial depth of visible plasma in the plasma chamber in use.

38. A method according to any one of claims 31 to 37, wherein an operating pressure within the plasma chamber is equal to or greater than: 200, 220, 240, 260, 280, 300, or 320 Torr (i.e. 26.6, 29.3, 31.9, 34.6, 37.2, 39.9, or 42.6 kPa) at a microwave frequency in a range 2300 to 2600 MHz; 120, 140 160, 180, 200, or 220 Torr (i.e. 15.9, 18.6, 21.3, 23.9, 26.6, or 29.3 kPa) at a microwave frequency in a

range 800 to 1000 MHz; or 60, 70, 80, 100, or 120 Torr (i.e. 7.9, 9.3, 10.6, 13.3, or 15.9 kPa) at a microwave frequency in a range 400 to 500 MHz.

39. A method according to any one of claims 31 to 38, wherein a power densities delivered to the substrate may be equal to or greater than 0.05, 0.1, 0.5, 1, 1.5, 2.0, 2.5, 2.75, 3.0, 3.2, or 3.5 W/mm^2 of the growth surface.

40. A method according to any one of claims 31 to 39, wherein the microwaves are coupled into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and the electrically conductive plasma stabilizing annulus are disposed.

41. A method according to any one of claims 31 to 40, wherein the process gases are fed into the plasma chamber at an opposite end of the plasma chamber to that where the substrate and the electrically conductive plasma stabilizing annulus are disposed, the process gases being injected towards the growth surface of the substrate.

42. A method according to any one of claims 31 to 41, wherein the microwave plasma reactor is inverted whereby a base of the plasma chamber supporting the substrate forms an upper wall of the plasma chamber relative to earth.