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 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 gas flow system comprises a gas inlet nozzle array comprising a plurality of gas inlet nozzles disposed opposite the substrate holder for directing process gases towards the substrate holder, the gas inlet nozzle array comprising:

at least six gas inlet nozzles disposed in a substantially parallel or divergent orientation relative to a central axis of the plasma chamber;

a gas inlet nozzle number density equal to or greater than 0.1 nozzles/cm^2, wherein the gas inlet nozzle number density is measured by projecting the nozzles onto a plane whose normal lies parallel to the central axis of the plasma chamber and measuring the gas inlet number density on said plane; and

a nozzle area ratio of equal to or greater than 10, wherein the nozzle area ratio is measured by projecting the nozzles onto a plane whose normal lies parallel to the central axis of the plasma chamber, measuring the total area of the gas inlet nozzle area on said plane, dividing by the total number of nozzles to give an area associated with each nozzle, and dividing the area associated with each nozzle by an actual area of each nozzle.

2. A microwave plasma reactor according to claim 1, wherein the gas inlet nozzle number density is equal to or greater than 0.2, 0.5, 1, 2, 5, or 10 nozzles/cm^2.

3. A microwave plasma reactor according to claim 1 or 2, wherein the gas inlet nozzle number density is equal to or less than 100, 50, or 10 nozzles/cm^2.

4. A microwave plasma reactor according to any preceding claim, wherein the nozzle area ratio is equal to or greater than 30, 100, 300, 1000, or 3000.

5. A microwave plasma reactor according to any preceding claim, wherein the nozzle area ratio is equal to or less than 100000, 30000, or 10000.

6. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises equal to or greater than 7, 9, 10, 15, 20, 30, 40, 60, 90, 120, 150, 200, 300, 500, 700, 1000, 1200, 1500 gas inlet nozzles.

7. A microwave plasma reactor according to any preceding claim, wherein each gas inlet nozzle has an outlet diameter in the range 0.1 mm to 5 mm, 0.2 mm to 3.0 mm, 2.0 mm to 3 mm, 0.2 mm to 2 mm, 0.25 mm to 2 mm, or 0.25 mm to 1.5 mm.

8. A microwave plasma reactor according to any preceding claim, wherein a ratio of total nozzle area / area of the gas inlet nozzle array is equal to or less than 0.5, 0.35, 0.3, 0.2, 0.1, 0.05, 0.02, 0.01, or 0.007.

9. A microwave plasma reactor according to any preceding claim, wherein a total area of nozzles in the gas inlet nozzle array, given in mm^2, is in a range 1 to 5000, 5 to 3000, 10 to 3000, 20 to 2750, 30 to 2750, or 50 to 2700.

10. A microwave plasma reactor according to any preceding claim, wherein a total area of the gas inlet nozzle array over which the gas inlet nozzles are spaced, given in mm^2, is in a range 100 to 15000, 200 to 15000, 400 to 10000, 800 to 10000, or 1000 to 8000.

11. A microwave plasma reactor according to any preceding claim, wherein at least 50%, 60%, 70%, 80%, or 90% of the gas inlet nozzles have the same diameter.

12. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzles are uniformly spaced.

13. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises a hexagonal close-packed array of gas inlet nozzles.

14. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises one or more central gas inlet nozzles disposed in a parallel orientation relative to the central axis of the plasma chamber.

15. A microwave plasma reactor according to claim 14, wherein the gas inlet nozzle array comprises a plurality of outer gas inlet nozzles disposed in a divergent orientation relative to the central axis of the plasma chamber.

16. A microwave plasma reactor according to claim 14, wherein substantially all the gas inlet nozzles are disposed in a parallel orientation relative to the central axis of the plasma chamber.

17. A microwave plasma reactor according to any preceding claim, wherein a minimum distance D_c between the gas inlet nozzle array and the substrate holder is less than or equal to $6R_s$, $4R_s$, or $2R_s$, where R_s is a radius of the substrate holder.

18. A microwave plasma reactor according to any preceding claim, wherein a maximum radius of the gas inlet nozzle array R_m meets the criteria: $R_m \times F_m$ is greater than or equal to R_s, where R_s is a radius of the substrate holder and Fm is equal to or greater than 0.5, 0.6, 0.7, 0.8, 0.9, or 1 and equal to or less than 1.5, 1.3, 1.2, or 1.1.

19. A microwave plasma reactor according to any preceding claim, wherein each gas inlet nozzle has an inlet portion having a first diameter and an outlet portion having a second diameter, the first diameter being larger than the second diameter.

20. A microwave plasma reactor according to any preceding claim, wherein the microwave coupling configuration for feeding microwaves from the microwave generator into the plasma chamber is disposed at an end of the plasma chamber upstream of the substrate holder.

21. A microwave plasma reactor according to claim 20, wherein the gas inlet array is disposed in a central region of said end and the microwave coupling configuration comprises a microwave window disposed in a ring around the gas inlet array.

22. A microwave plasma reactor according to any one of claims 21, wherein the plurality of gas inlet nozzles are disposed down-stream from the microwave window whereby the plurality of gas inlet nozzles are located closer to the substrate holder than the microwave window.

23. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises a housing defining a cavity for receiving process gases from one or more gas inlet pipes, the housing further defining the plurality of inlet nozzles for injecting process gases from the cavity into the plasma chamber and towards the substrate holder.

24. A microwave plasma reactor according to claim 23, wherein the housing is located within the plasma chamber.

25. A microwave plasma reactor according to claim 23 or 24, wherein the cavity is configured to mix at least some of the process gases prior to injection of the process gases through gas inlet nozzle array.

26. A microwave plasma reactor according to any preceding claim, wherein the gas inlet array is configured to transport different gas compositions though different nozzles.

27. A method of manufacturing synthetic diamond material using the microwave plasma reactor according to any preceding claim, the method comprising:

injecting process gases into the plasma chamber through the plurality of gas inlet nozzles;

feeding microwaves from a microwave generator into the plasma chamber through the microwave coupling configuration to form a plasma above a substrate disposed over the substrate holder; and

growing synthetic diamond material on a growth surface of the substrate.

28. A method according to claim 27, wherein a total gas flow fed through the gas inlet nozzle array is equal to or greater than 500, 750, 1000, 2000, 5000, 10000, 15000, 20000, 25000, 30000, 35000, or 40000 standard cm^3 per minute.

29. A method according to claim 27 or 28, wherein a total gas flow fed through the gas inlet nozzle array is equal to or greater than 3, 10, 20, 50, 100, 200, 500, or 1000 standard cm^3 per minute per cm^2 of the growth surface area and equal to or less than 50000, 20000, 10000, or 5000 standard cm^3 per minute per cm^2 of the growth surface area.

30. A method according to any one of claims 27 to 29, wherein a minimum distance D_c between the gas inlet nozzle array and the substrate is less than or equal to $6R_s$, $4R_s$, or $2R_s$, where R_s is a radius of the substrate.

31. A method according to any one of claims 27 to 30, wherein a maximum radius of the gas inlet nozzle array R_m meets the criteria: $R_m \times F_m$ is greater than or equal to R_s, where R_s is a radius of the substrate and Fm is equal to or greater than 0.5, 0.6, 0.7, 0.8, 0.9, or 1 and equal to or less than 1.5, 1.3, 1.2, or 1.1.

32. A method according to any one of claims 27 to 31, wherein the process gases are injected into the plasma chamber through the plurality of gas inlet nozzles with a Reynolds number equal to or less than 100, 80, 50, 30, 20, 10, 5, 3, 2, or 1.

33. A method according to any one of claims 27 to 32, wherein an operating pressure within the plasma chamber is equal to or greater than: 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, or 400 Torr at a microwave frequency in a range 2300 to 2600 MHz; 120, 140 160, 180, 200, 220, 240, or 260 Torr at a microwave frequency in a range 800 to 1000 MHz; or 60, 70, 80, 100, 120, 140, or 150 Torr at a microwave frequency in a range 400 to 500 MHz.

34. A method according to any one of claims 27 to 33, wherein at least 45%, 50%, 55%, 60%, 65%, or 70% of power fed into the plasma chamber is transmitted through a base of the plasma chamber.

35. A method according to any one of claims 27 to 34, wherein a power density 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.

36. A method according to any one of claims 27 to 35, wherein gas streams from the plurality of gas inlet nozzles flow downwards with gravity.

37. A method according to any one of claims 27 to 36, wherein the microwave plasma reactor is inverted whereby gas streams from the plurality of gas inlet nozzles flow upwards against gravity.

38. A method according to any one of claims 27 to 37, wherein the process gases comprise one or more dopants.

39. A method according to claims 38, wherein the one or more dopants comprise boron.

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 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 gas flow system comprises a gas inlet nozzle array comprising a plurality of gas inlet nozzles disposed opposite the substrate holder for directing process gases towards the substrate holder, the gas inlet nozzle array comprising:

at least six gas inlet nozzles disposed in a substantially parallel or divergent orientation relative to a central axis of the plasma chamber;

a gas inlet nozzle number density equal to or greater than 5 nozzles/cm^2, wherein the gas inlet nozzle number density is measured by projecting the nozzles onto a plane whose normal lies parallel to the central axis of the plasma chamber and measuring the gas inlet number density on said plane; and

a nozzle area ratio of equal to or greater than 10, wherein the nozzle area ratio is measured by projecting the nozzles onto a plane whose normal lies parallel to the central axis of the plasma chamber, measuring the total area of the gas inlet nozzle area on said plane, dividing by the total number of nozzles to give an area associated with each nozzle, and dividing the area associated with each nozzle by an actual area of each nozzle,

wherein the gas inlet nozzle number density and the nozzle area ratio are calculated over at least 50% of all the gas inlet nozzles in the gas inlet nozzle array.

2. A microwave plasma reactor according to claim 1, wherein the gas inlet nozzle number density is equal to or greater than 10 nozzles/cm^2.

3. A microwave plasma reactor according to claim 1 or 2, wherein the gas inlet nozzle number density is equal to or less than 100, 50, or 10 nozzles/cm^2.

4. A microwave plasma reactor according to any preceding claim, wherein the nozzle area ratio is equal to or greater than 30, 100, 300, 1000, or 3000.

5. A microwave plasma reactor according to any preceding claim, wherein the nozzle area ratio is equal to or less than 100000, 30000, or 10000.

6. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises equal to or greater than 7, 9, 10, 15, 20, 30, 40, 60, 90, 120, 150, 200, 300, 500, 700, 1000, 1200, 1500 gas inlet nozzles.

7. A microwave plasma reactor according to any preceding claim, wherein each gas inlet nozzle has an outlet diameter in the range 0.1 mm to 5 mm, 0.2 mm to 3.0 mm, 2.0 mm to 3 mm, 0.2 mm to 2 mm, 0.25 mm to 2 mm, or 0.25 mm to 1.5 mm.

8. A microwave plasma reactor according to any preceding claim, wherein a ratio of total nozzle area / area of the gas inlet nozzle array is equal to or less than 0.5, 0.35, 0.3, 0.2, 0.1, 0.05, 0.02, 0.01, or 0.007.

9. A microwave plasma reactor according to any preceding claim, wherein a total area of nozzles in the gas inlet nozzle array, given in mm^2, is in a range 1 to 5000, 5 to 3000, 10 to 3000, 20 to 2750, 30 to 2750, or 50 to 2700.

10. A microwave plasma reactor according to any preceding claim, wherein a total area of the gas inlet nozzle array over which the gas inlet nozzles are spaced, given in mm^2, is in a range 100 to 15000, 200 to 15000, 400 to 10000, 800 to 10000, or 1000 to 8000.

11. A microwave plasma reactor according to any preceding claim, wherein at least 50%, 60%, 70%, 80%, or 90% of the gas inlet nozzles have the same diameter.

12. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzles are uniformly spaced.

13. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises a hexagonal close-packed array of gas inlet nozzles.

14. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises one or more central gas inlet nozzles disposed in a parallel orientation relative to the central axis of the plasma chamber.

15. A microwave plasma reactor according to claim 14, wherein the gas inlet nozzle array comprises a plurality of outer gas inlet nozzles disposed in a divergent orientation relative to the central axis of the plasma chamber.

16. A microwave plasma reactor according to claim 14, wherein substantially all the gas inlet nozzles are disposed in a parallel orientation relative to the central axis of the plasma chamber.

17. A microwave plasma reactor according to any preceding claim, wherein a minimum distance D_c between the gas inlet nozzle array and the substrate holder is less than or equal to $6R_s$, $4R_s$, or $2R_s$, where R_s is a radius of the substrate holder.

18. A microwave plasma reactor according to any preceding claim, wherein a maximum radius of the gas inlet nozzle array R_m meets the criteria: $R_m \times F_m$ is greater than or equal to R_s, where R_s is a radius of the substrate holder and Fm is equal to or greater than 0.5, 0.6, 0.7, 0.8, 0.9, or 1 and equal to or less than 1.5, 1.3, 1.2, or 1.1.

19. A microwave plasma reactor according to any preceding claim, wherein each gas inlet nozzle has an inlet portion having a first diameter and an outlet portion having a second diameter, the first diameter being larger than the second diameter.

20. A microwave plasma reactor according to any preceding claim, wherein the microwave coupling configuration for feeding microwaves from the microwave

generator into the plasma chamber is disposed at an end of the plasma chamber upstream of the substrate holder.

21. A microwave plasma reactor according to claim 20, wherein the gas inlet array is disposed in a central region of said end and the microwave coupling configuration comprises a microwave window disposed in a ring around the gas inlet array.

22. A microwave plasma reactor according to any one of claims 21, wherein the plurality of gas inlet nozzles are disposed down-stream from the microwave window whereby the plurality of gas inlet nozzles are located closer to the substrate holder than the microwave window.

23. A microwave plasma reactor according to any preceding claim, wherein the gas inlet nozzle array comprises a housing defining a cavity for receiving process gases from one or more gas inlet pipes, the housing further defining the plurality of inlet nozzles for injecting process gases from the cavity into the plasma chamber and towards the substrate holder.

24. A microwave plasma reactor according to claim 23, wherein the housing is located within the plasma chamber.

25. A microwave plasma reactor according to claim 23 or 24, wherein the cavity is configured to mix at least some of the process gases prior to injection of the process gases through gas inlet nozzle array.

26. A microwave plasma reactor according to any preceding claim, wherein the gas inlet array is configured to transport different gas compositions though different nozzles.

27. A method of manufacturing synthetic diamond material using the microwave plasma reactor according to any preceding claim, the method comprising:

injecting process gases into the plasma chamber through the plurality of gas inlet nozzles;

feeding microwaves from a microwave generator into the plasma chamber through the microwave coupling configuration to form a plasma above a substrate disposed over the substrate holder; and

growing synthetic diamond material on a growth surface of the substrate.

28. A method according to claim 27, wherein a total gas flow fed through the gas inlet nozzle array is equal to or greater than 500, 750, 1000, 2000, 5000, 10000, 15000, 20000, 25000, 30000, 35000, or 40000 standard cm^3 per minute.

29. A method according to claim 27 or 28, wherein a total gas flow fed through the gas inlet nozzle array is equal to or greater than 3, 10, 20, 50, 100, 200, 500, or 1000 standard cm^3 per minute per cm^2 of the growth surface area and equal to or less than 50000, 20000, 10000, or 5000 standard cm^3 per minute per cm^2 of the growth surface area.

30. A method according to any one of claims 27 to 29, wherein a minimum distance D_c between the gas inlet nozzle array and the substrate is less than or equal to $6R_s$, $4R_s$, or $2R_s$, where R_s is a radius of the substrate.

31. A method according to any one of claims 27 to 30, wherein a maximum radius of the gas inlet nozzle array R_m meets the criteria: $R_m \times F_m$ is greater than or equal to R_s, where R_s is a radius of the substrate and Fm is equal to or greater than 0.5, 0.6, 0.7, 0.8, 0.9, or 1 and equal to or less than 1.5, 1.3, 1.2, or 1.1.

32. A method according to any one of claims 27 to 31, wherein the process gases are injected into the plasma chamber through the plurality of gas inlet nozzles with a Reynolds number equal to or less than 100, 80, 50, 30, 20, 10, 5, 3, 2, or 1.

33. A method according to any one of claims 27 to 32, wherein an operating pressure within the plasma chamber is equal to or greater than: 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, or 400 Torr (i.e., 26.7, 29.3, 32.0, 34.7, 37.3, 40.0, 42.7, 45.3, 48.0, 50.7, or 53.3 kPa) at a microwave frequency in a range 2300 to 2600 MHz; 120, 140 160, 180, 200, 220, 240, or 260 Torr (i.e., 16.0, 18.7, 21.3, 24.0, 26.7, 29.3, 32.0, or 34.7 kPa) at a microwave frequency in a range 800 to 1000 MHz; or 60, 70,

80, 100, 120, 140, or 150 Torr (i.e., 8.00, 9.33, 10.7, 13.3, 16.0, 18.7, or 20.0 kPa) at a microwave frequency in a range 400 to 500 MHz.

34. A method according to any one of claims 27 to 33, wherein at least 45%, 50%, 55%, 60%, 65%, or 70% of power fed into the plasma chamber is transmitted through a base of the plasma chamber.

35. A method according to any one of claims 27 to 34, wherein a power density 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.

36. A method according to any one of claims 27 to 35, wherein gas streams from the plurality of gas inlet nozzles flow downwards with gravity.

37. A method according to any one of claims 27 to 36, wherein the microwave plasma reactor is inverted whereby gas streams from the plurality of gas inlet nozzles flow upwards against gravity.

38. A method according to any one of claims 27 to 37, wherein the process gases comprise one or more dopants.

39. A method according to claims 38, wherein the one or more dopants comprise boron.