

CLAIMS:

1. Apparatus for electron irradiation scrubbing, said apparatus comprising:
5 an anode;
a cathode;
a nanostructure located between said anode and said cathode, said nanostructure being configured to field-emit electrons in response to the presence of an electric field between the anode and cathode when a potential
10 difference is established therebetween; and
a housing coupled to said nanostructure and configured for locating the nanostructure so that it extends into a container containing gas to be scrubbed such that an interior of said container can be exposed to said electrons.
- 15 2. The apparatus of claim 1, wherein the nanostructure has an aspect ratio of at least 1000, optionally at least 5000, optionally at least 10,000.
3. The apparatus of either of claims 1 or 2, wherein the nanostructure is a carbon, silicon or titanium oxide nanotube, nanowire or nanohorn.
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4. The apparatus of claim 3, wherein the nanostructure is a carbon nanotube (CNT).
5. The apparatus of claim 4, wherein said nanostructure is a multi-walled
25 CNT (MWNT) or metallic single walled CNT (metallic SWNT).
6. The apparatus of any of claims 1 to 5, wherein the nanostructure is electrically connected to the cathode.
- 30 7. The apparatus of claim 4, or of either of claims 5 or 6 as dependent thereon, further comprising an additional electron source configured to impinge free electrons onto the CNT to induce stimulated electron field-emission therefrom.

8. The apparatus of claim 7, wherein said additional electron source is another nanostructure.

9. The apparatus of any preceding claim, further comprising an electrical
5 power supply connection operatively coupled to the nanostructure and configured to provide a voltage pulse to the nanostructure.

10. The apparatus of any preceding claim, comprising an array of nanostructures located between the anode and the cathode and electrically
10 connected to the cathode, of which said nanostructure is one, said array being configured to field-emit electrons in response to the presence of an electric field between the anode and cathode when a potential difference is established therebetween.

15 11. The apparatus of claim 10 as dependent directly or indirectly on claim 4, wherein the array consists of:

multi walled CNTs (MWNTs); and/or

single walled CNTs (SWNTs), optionally wherein the array comprises more metallic SWNTs than semiconducting SWNTs.

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12. The apparatus of either of claims 10 or 11, wherein adjacent nanostructures of the array are separated by a distance less than or equal to 400 nm.

25 13. The apparatus of any of claims 10 to 12, further comprising a substrate on which the array is formed.

14. The apparatus of claim 13, wherein said substrate is comprised in or electrically connected to the cathode.

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15. The apparatus of either of claims 13 or 14, wherein said substrate comprises one or both of silicon and a metal;

said silicon optionally being highly doped conductive silicon, optionally coated with aluminium at least on a side on which said array is formed;

said metal optionally comprising titanium, and/or a titanium alloy, and/or aluminium, and/or an aluminium alloy, and/or copper, and/or a copper alloy, and optionally being polished.

5 16. The apparatus of any preceding claim, further comprising a heating element arranged to heat the nanostructure.

17. The apparatus of claim 16 as dependent directly or indirectly on claim 13, wherein said heating element is arranged in thermal contact with a side of said
10 substrate reverse to that on which the array is present such that the heating element can conduct heat through the substrate to the array.

18. The apparatus of claim 13 or any of claims 14 to 17 as dependent thereon, further comprising a current controlled power supply configured to heat
15 said substrate by Ohmic heating.

19. The apparatus of claim 18 as dependent directly or indirectly on claim 14, as dependent indirectly on claim 9, wherein said current controlled power supply is grounded by the cathode;

20 the apparatus further comprising a voltage controlled power supply configured to provide said voltage pulse to said connection, wherein said voltage controlled power supply is:

electrically connected between the connection and the anode; and
grounded by the cathode.

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20. The apparatus of any preceding claim, wherein the nanostructure is at least partially coated in a material having a work function of less than 4 eV, said material optionally comprising caesium or hafnium.

30 21. The apparatus of claim 20, as dependent directly or indirectly on claim 16 or claim 18, wherein the coating material has a melting point of at least 400°C.

22. The apparatus of any preceding claim, wherein the nanostructure is at least partially coated in a catalytic coating.

23. The apparatus of claim 22, wherein said catalytic coating comprises one or more of vanadium oxide, zinc oxide and tungsten trioxide.
- 5 24. The apparatus of either of claims 22 or 23, wherein said catalytic coating is applied over a stabilising coating such as titanium dioxide.
25. The apparatus of any of claims 20 to 24 as dependent directly or indirectly on claim 10, wherein the array comprises a combination of at least two
10 of: one or more uncoated nanostructures, one or more nanostructures at least partially coated in a material having a work function of less than 4 eV, and one or more nanostructures at least partially coated in a catalytic coating.
26. The apparatus of any preceding claim, wherein the nanostructure is
15 hollow, its interior being at least partially filled with a stiffening material, the stiffening material optionally comprising a transition metal such as titanium, iron or copper.
27. The apparatus of claim 26 as dependent directly or indirectly on claim 13,
20 wherein the stiffening material comprises a material the substrate comprises, and optionally carbon.
28. The apparatus of claim 27, wherein the substrate comprises titanium and the stiffening material comprises titanium carbide.
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29. The apparatus of any preceding claim, wherein the nanostructure is doped with an electron transport enhancing material or electrical conductivity enhancing material.
- 30 30. A system for electron irradiation scrubbing of flue gases, said system comprising multiple apparatuses according to any preceding claim, configured to be arranged concentrically, stacked or arrayed in a chimney cavity.

31. A system for electron irradiation scrubbing of flue gases, said system comprising:

at least four nanostructure arrays, of which the array of claim 10, or of any of claims 11 to 29 as dependent thereon, is one, each array formed on an

5 electrically conductive substrate;

an electrical power supply;

electrical connections connecting said substrates, said power supply and ground in such a way that each substrate is at a different electrical potential; and

10 one or more housings coupled to the substrates and configured for locating said arrays such that their nanostructures extend into the container containing gas to be scrubbed such that an interior of said container can be exposed to electrons field-emitted by the arrays;

wherein the substrates are arranged such that, for all the substrates except that at the highest electrical potential, a straight line path exists from a
15 surface of each array defined by free ends of nanostructures forming that array to a corresponding surface of the array formed on the substrate at the next highest potential.

32 The system of claim 31, wherein the substrates are arranged in a double
20 zigzag pattern.

33. An electron irradiation scrubbing method to be performed with the apparatus of any of claims 1 to 29 or the system of any of claims 30 to 32, the method comprising:

25 establishing a potential difference between the anode and the cathode such that the nanostructure, which is electrically connected to said cathode, is exposed to an electric field, resulting in field-emission of electrons by said nanostructure; and

exposing the gas to be scrubbed to said electrons.

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34. The method of claim 33 as dependent directly or indirectly on claim 4, further comprising exposing the CNT to a free electron to induce stimulated electron field-emission from the CNT.

35. The method of claim 34, wherein said free electron was emitted from an additional electron source by field-emission or stimulated field-emission, said additional electron source being another nanostructure.

5 36. The method of any of claims 33 to 35, further comprising providing a voltage pulse to the nanostructure, said pulse optionally having a magnitude lower than a breakdown voltage of said gas.

37. The method of any of claims 33 to 36, wherein said nanostructure is
10 arranged to generate said electron beam in an environment at an absolute pressure of no less than 80 kPa.

38. The method of claim 36 or claim 37 as dependent thereon, wherein said voltage pulse has:

15 an absolute amplitude of from 100 V to 5 kV; and/or
 a duration of from 1 μ s to 1 ms.

39. The method of claim 36 or either of claims 37 or 38 as dependent thereon, wherein said voltage pulse is repeated periodically, optionally with a
20 frequency of from 100 Hz to 500 kHz, optionally with a duty cycle of less than 50%.

40. The method of any of claims 33 to 39, further comprising heating the nanostructure during said field-emission.

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41. The method of claim 40, wherein the nanostructure is heated to between 200 and 1000°C, optionally to between 300 and 900°C, optionally to between 400 to 800°C, optionally to between 400 and 600°C.

30 42. The method of any of claims 33 to 41, further comprising:
 prior to exposing said gas to said electrons, mixing the gas with ammonia to form a gas mixture; and
 subsequent to exposing said gas mixture to the electrons, collecting a powder produced thereby.

43. The method of any of claims 33 to 42, wherein said gas comprises emissions from a ship.

5 44. A ship comprising the apparatus of any of claims 1 to 29, or the system of any of claims 30 to 32, wherein the container is configured to contain emissions from said ship.

45. Apparatus substantially as herein described, with reference to the
10 accompanying figures.

46. A system substantially as herein described, with reference to the accompanying figures.

15 47. A method substantially as herein described with reference to the accompanying figures.

48. A ship substantially as herein described with reference to the accompanying figures.