**Pub. No.:** WO/2007/010191 **International Application No.:** PCT/GB2006/002516
**Publication Date:** 25.01.2007 **International Filing Date:** 06.07.2006

**IPC:** ***D01F 9/127*** (2006.01), ***D01F 11/12*** (2006.01), ***D01F 9/133*** (2006.01)

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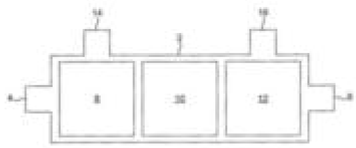
**Priority Data:** 0515170.9 22.07.2005 GB

**Title:** METHOD AND APPARATUS FOR THE PRODUCTION OF NANOSTRUCTURES

**Abstract:** A method for the production of nanostructures comprising the steps of passing gases containing the constituents of the nanostructures to one or more hollow cathode reactors to form the nanostructures, collecting the nanostructures and then removing by-products from the exhaust gases by passing them through one or more hollow cathode reactors together with an oxidising gas.



**Designated States:** AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
African Regional Intellectual Property Org. (ARIPO) (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW)
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African Intellectual Property Organization (OAPI) (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Publication Language:** English (EN)

**Filing Language:** English (EN)

WO 2007010191 20070125

METHOD AND APPARATUS FOR THE PRODUCTION OF NANOSTRUCTURES

This invention relates to the production of nanostructures, and which in its preferred embodiment finds use in the formation of carbon nanotubes in a continuous batch process.

The term nanotechnology is commonly used to refer to objects between 1.0 and 100.0 nm in size. Since the theory of nanotechnology was suggested, over 40 years ago, it has become one of the fastest moving scientific fields.

The batch production of nanostructures is essential to their integration into everyday items. Recently a number of methods and apparatus for the batch production of nanostructures have been reported. Most of these methods use a plasma or very hot furnace to produce atomic carbon vapour, which is then condensed onto a suitable substrate. This forms an array of carbon nanostructures, including nanotubes. If atomic metal is provided in the production single walled nanotubes are predominantly formed and without the metal atoms multilayer carbon nanotubes are usually formed.

Along with nanotubes a wide range of particle sizes are also produced. Some of these particles will invariably be atomic carbon and clusters thereof, which is the focus of some debate due to their unknown effects on the environment or human health and therefore there are concerns about their release into the atmosphere. It is currently believed that such particles could be readily absorbed through the skin or inhaled, could be cancer forming and/or could interfere with major organs such as the heart and lungs.

In a first aspect, the present invention provides a method of producing nanostructures, the method comprising the steps of conveying gases containing constituents of the nanostructures to a housing to form a gas stream within the housing; conveying an oxygen-containing gas into the housing; within the housing, performing the steps of: forming nanostructures from the constituents contained within the gas stream, separating the thus- formed nanostructures from the gas stream for subsequent collection thereof, and removing a by-product of the nanostructure formation from the gas stream by reacting the by-product with the oxygen-containing gas; and exhausting the gas stream from the housing.

The method thus provides a new enabling technology for the bulk production of nanostructures such as carbon nanotubes in a simple and environmentally safe manner, which can utilise low cost power supplies and vacuum components. The aspects of the production process can be provided in a single and compact housing, thereby limiting the user's exposure to potentially dangerous by-product, for example carbon nanoparticles.

The nanostructures are preferably formed in, and the by-product is preferably removed from the gas stream in, respective hollow cathode reactors.

Therefore, in a second aspect the present invention provides a method of producing nanostructures, the method comprising the steps of passing gases containing constituents of the nanostructures to a first hollow cathode reactor to form the nanostructures; separating the nanostructures from a gas exhaust from the first hollow cathode reactor for collection thereof; and subsequently removing a by-product of the nanostructure formation from the exhaust gas by passing the exhaust gas through a second hollow cathode reactor together with an oxygen-containing gas.

Hollow cathode reactions may be energised with low cost power supplies. They are typically small in size and safe to operate at low frequencies. The gas temperature obtained in a hollow cathode reactor is adequate for the gas reactions that take place in production of nanostmctures and the removal of carbon nanoparticles from the exhaust gas.

The variety of choice.of both hollow cathode material and process gases in this method give the-advantage of allowing the user of the device to produce an array of different types and quality of carbon nanostructures.

The first hollow cathode reactor preferably comprises a parallel array of bores in a solid electrically conducting body, preferably formed from one of aluminium, copper, stainless steel, tungsten and graphite, in which a plasma is formed of the gases passed thereto.

A metal-containing gas may be passed through the first hollow cathode reactor to form a metallic nanostructure, where the metal contained in the gas is advantageously Fe, Ni, Mo, Co, Pt and Pd. The metallic nanostructure provides a surface frorrv which a carbon nanostructure can grow. The metal- containing gas may be passed through the first hollow cathode reactor with an electronically excitable gas, for example argon, helium and nitrogen, which can initiate and enhance the formation of the metallic nanostructures.

Alternatively or additionally a carbon-containing gas, comprising, for example, at least one of acetylene, methane, ethane, carbon monoxide, carbon dioxide, methanol, ethanol, tetrafluoromethane and hexafluoroethane, may be passed through the first hollow cathode reactor to form a carbon nanostructure. It is advantageous for the carbon-containing gas to be passed through the first hollow cathode reactor with an electronically excitable gas, for example at least one of argon, helium and nitrogen.

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The nanostructures are preferably formed using a plurality of said first hollow cathode reactors. " --

The nanostructures may be separated from the gas using a single or array of electrostatic precipitators either at the same or at different voltages, which advantageously enables the collection of all or a variety of nanostructure sizes. Preferably, the voltage across the array of electrostatic precipitators increases in the direction of the gas flow through the array.

The nanostructures may also be separated from the gas by collection on a substrate. The substrate may be cooled to a temperature below room temperature, for example, using liquid nitrogen, or heated to above room temperature in the presence of an oxygen-containing gas for example at least one of oxygen, air, ethanol, methanol, hydrogen peroxide and ozone. This advantageously removes unwanted reaction by-products which are also separated from the gas from the formation of the nanostructures.

The use of a substrate advantageously enables removal of the nanostructures collected thereby by isolation of the substrate using, for example, a load lock.

The second hollow cathode reactor is preferably a parallel array of bores in a solid electrically conducting body, preferably formed of the same materials as the first hollow cathode reactor, in which a plasma is formed of the gases passed thereto. An oxygen-containing gas, for example, oxygen, air, ethanol, methanol, hydrogen peroxide and ozone, hollow is preferably supplied to the second hollow cathode reactor, preferably with an electronically excitable gas such as one of argon, nitrogen and helium.

In a third aspect the present invention provides apparatus for producing nanostructures, the apparatus comprising a housing comprising means for receiving gases containing constituents of the nanostructures to form a gas stream within the housing, and means for receiving an oxygen-containing gas,

the housing containing means for forming nanostructures from the constituents contained within the gas stream, means for separating the thus- formed nanostructures from the gas stream for subsequent collection thereof, and means for removing a by-product of the nanostructure formation from the gas stream by reacting the by-product with the oxygen-containing gas, the housing further comprising means for exhausting the gas stream therefrom.

In a fourth aspect the present invention provides apparatus for producing nanostructures, the apparatus comprising a first hollow cathode reactor, means for supplying gases containing constituents of the nanostructures to the first hollow cathode reactor to form the nanostructures, means for separating the nanostructures from a gas exhaust from the first hollow cathode reactor for collection thereof, a second hollow cathode reactor for subsequently receiving the exhaust gas, and means for supplying an oxygen- containing gas to the second hollow cathode reactor for removal of byproducts of the formation of nanostructure formation from the exhaust gas.

Features described above in relation to method aspects of the invention are equally applicable to apparatus aspects and visa versa.

Preferred features of the present invention will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 illustrates a general schematic of an apparatus for the production of nanostructures;

Figure 2 illustrates a first embodiment of a device for forming nanostructures;

Figure 3 illustrates a second embodiment of a device for forming nanostructures;

Figure 4 illustrates a third embodiment of a device for forming nanostructures;

Figure 5 illustrates a first embodiment of a device for collecting the nanostructures;

Figure 6 illustrates a second embodiment of a device for collecting the nanostructures;

Figure 7 illustrates a first embodiment of a device for removing from a gas a by-product from the nanostructure formation; and

Figure 8 illustrates a second embodiment of a device for removing from a gas a by-product from the nanostructure formation.

Figure 1 illustrates schematically an apparatus for the production of nanostructures. The apparatus comprises a housing or body 2, in which there is located a first device 8 for the formation of nanostructures, a second device 10 for the collection of the nanostructures formed by the first device 8, and a third device 12 for the removal from a gas stream of the reaction by-products from the formation of the nanostructures before the gas stream is exhausted from the body 2. The body 2 includes inlets 4, 14 for receiving gases for use in the production of nanostructures, and an inlet 16 for receiving gases for use in the removal of the by-products from the gas stream. Inlets 4 and 14 may also be used for the receipt of gases for use in the removal of the by-products from the gas stream. The body 2 also includes an exhaust 6 for exhausting the exhaust gases therefrom towards a mechanical vacuum pump.

Various embodiments of the first device 8a, 8b and 8c for the formation of nanostructures are illustrated in more detail in Figures 2, 3, 4 respectively.

In the first embodiment illustrated in Figure 2, the body 2 comprises a substantially cylindrical body having a first formation device gas inlet 4 arranged substantially co-axially therewith for receiving gases that form a gas

stream within the body 2. The first device 8a comprises an electrically non- "conductive inner shell 20 located within the body 2rThe inner shell 20 supports a substantially cylindrical electrically conductive block 22. The block 22 has formed therein a plurality of bores of axial orientation. The inner shell 20 also supports a substantially ring shaped anode 24. A multiplicity of perforated anode points 26 extends from the anode 24 in the direction of the outer periphery of the near flat face of the block 22. Such anode points can assist in maintaining a plasma - and hollow cathode effect - in each of the bores of block 22.

A power source 28 is provided to charge block 22 to a cathode (negative) potential and the anode 24 to an anode (positive) potential. A gas outlet from first device 8a is identified at 40 in Figure 2, from which a gas stream exhaust from the first device 8a is conveyed to the second device 10.

In use of the first device 8a illustrated in Figure 2 a vapour of a metal- containing compound, for example at least one of a metalocene, a metal sponge, organometallic compound and metal halide, is conveyed continuously or periodically via first formation device gas inlet 4 and the anode 24 to the block 22, wherein the metal containing compound is dissociated in a plasma to the atomic form of the metal. The metal containing vapour can be conveyed to the first formation device gas inlet 4 together with or separate from an electronically excitable gas, for example at least one of nitrogen, argon and helium.

Simultaneously with, or separately from, the metal containing vapour and electronically excitable gases, a carbon containing gas, for example at least one of acetylene, methane, ethane, carbon monoxide, carbon dioxide, methanol, ethanol, tetrafluoromethane and hexafluoroethane, is conveyed continuously or periodically via the first production device gas inlet 4 and the anode 24 to the block 22, wherein the gas is dissociated to atomic carbon and clusters thereof in a plasma. The atomic metal and atomic carbon combine to

promote the formation of single walled nanotubes together with an array of other carbon nanostructures in the gas stream downstream from the block 22, within the bores of the block 22 and on the surfaces of the second device for the collection of nanostructures 12.

An oxygen-containing gas, for example at least one of oxygen, air, ethanol, methanol, hydrogen peroxide, water and ozone, may optionally be conveyed via the first device inlet 4 and anode 24 to block 22 wherein the gas is dissociated to oxygen radicals. The oxygen radicals formed therein can react with carbon nanoparticles formed in the first device 8a, and any carbon nanoparticles formed in the second device 10, to remove the carbon nanoparticles from the apparatus 2.

The second embodiment of the first device 8b is illustrated in Figure 3. In this second embodiment, the body 2 comprises a substantially cylindrical body having a first production device gas inlet 4 arranged substantially co-axially therewith, and a second production device gas inlet 14 for conveying gas substantially radially into the body. Inner shell 20 supports two, spaced, substantially cylindrical electrically conductive blocks 22 and 34. As in the block 22 of the first embodiment, the blocks 22, 34 have formed therein a plurality of bores of axial orientation. An annular insulating element 32 is located between the blocks 22, 34 to provide further insulation between the blocks 22, 34. As illustrated in Figure 3, the blocks 22, 34 are located on either side of the second formation device gas inlet 14.

As in the first embodiment, the inner shell 20 supports a substantially ring shaped anode 24. A multiplicity of perforated anode points 26 extends from the anode 24 in the direction of the outer periphery of the near flat face of the block 22. Such anode points can assist in maintaining a plasma - and hollow cathode effect - in each of the bores of blocks 22, 34. A gas outlet from first device 8b is identified at 40 in Figure 3, from which a gas stream exhaust from the first device 8b is conveyed to the second device 10.

A power source 28 is provided to charge block 22 to a cathode (negative) potential and the anode 24 to an anode (positive) potential. A similar power source 29 is provided to charge block 34 to a cathode (negative) potential and the anode 24 to an anode (positive) potential.

In use of thexlevice 8b illustrated in Figure 3, as in the first embodiment a vapour of a metal-containing compound is conveyed continuously or periodically via first production device gas inlet 4 and the anode 24 to the blocks 22 and 34, wherein the metal-containing compound is dissociated in a plasma to the atomic form of the metal. The vapour can be conveyed to the first production device gas inlet 4 together with, or separate from, an electronically excitable gas.

Simultaneously with, or separately from the metal containing vapour and electronically excitable gases, a carbon-containing gas is conveyed continuously or periodically via the second production device gas inlet 14 to the block 34, wherein the gas is dissociated to atomic carbon and clusters thereof in a plasma. The atomic metal and atomic carbon can then combine to promote the formation of single walled nanotubes together with an array of other carbon nanostructures in the gas stream downstream from the metal block, and within the bores of the blocks 22, 34.

An oxygen-containing gas may optionally be conveyed via the first production device inlet 4 and anode 24 to blocks 22, 34, and via second production device gas inlet 14 to block 34, wherein the gas is dissociated to oxygen radicals: The oxygen radicals formed therein can react with carbon nanoparticles formed in the first device 8b, and any carbon nanoparticles formed in the second device 10, to remove the carbon nanoparticles from the apparatus 2.

The third embodiment of the first device 8c is illustrated in Figure 4. In this third embodiment, the body 2 of the device 8c comprises two substantially orthogonal, connected cylindrical arms 3,5. The first production device gas inlet 4 is arranged substantially co-axially with the first arm 3. The first arm 3 comprises an electrically non-conductive inner shell 20, which supports a substantially cylindrical electrically conductive block 22. The block 22 has formed therein a plurality of bores of axial orientation. The inner shell 20 also supports a substantially ring shaped anode 24- A multiplicity of perforated anode points 26 extends from the anode 24 in the direction of the outer periphery of the near flat face of the block 22.

The second arm 5 comprises a second production device gas inlet 14 arranged substantially co-axially therewith. The second arm 5 also comprises part of the electrically non-condúctive inner shell 20, which supports a substantially cylindrical electrically conductive block 35. The block 35 has formed therein a plurality of bores of axial orientation. The inner shell 20 also supports a substantially ring shaped anode 25 within the second arm 5. A multiplicity of perforated anode points 27 extends from the anode 25 in the direction of the outer periphery of the near flat face of the-block 35: A gas outlet from first device 8c is identified at 40 in Figure 4.

A power source 28 is provided to charge block 22 to a cathode (negative) potential and the anode 24 to an anode (positive) potential. A similar power source 29 is provided to charge block 35 to a cathode (negative) potential and the anode 25 to an anode (positive) potential.

In use a vapour of a metal-containing compound is conveyed continuously or periodically via first production device gas inlet 4 and the anode 24 to the ■ block 22, wherein the metal-containing compound is dissociated in a plasma to the atomic form of the metal. The metal-containing vapour may be conveyed to the first production device gas inlet 4 together with or separate from an electronically excitable gas. Simultaneously with, or separately from, the metal-containing vapour and electronically excitable gases, a carbon containing gas is conveyed continuously or periodically, via the second production device gas inlet 14 and the anode 25 to the block 35, wherein the gas is dissociated to atomic carbon and clusters thereof in a plasma. The atomic metal and atomic carbon then combine to promote the formation of single walled nanotubes, together with an array of other carbon nanostructures, in the gas stream downstream from the metal block, within the bores of the blocks 22, 35 and on the surfaces of the second device 10 for the collection of the thus-formed nanostructures.

As discussed above in relation to the first and second embodiments of the firsf device 8a, 8b, an oxygen-containing gas may also be conveyed via the first production device inlet 4 and anode 24 to blocks 22, 34, and via the second production device gas inlet 14 and anode 25 to block 35, wherein the gas is dissociated to oxygen radicals for reaction with the carbon nanoparticles.

In each of the embodiments described above, the gas stream output from the first device 8 is conveyed within the body 2 to the second device 10 for the collection of nanostructures contained therein. Two embodiments of the second device 10a, 10b will now be described in more detail with reference to Figures 5 and 6 respectively.

In the first embodiment illustrated in Figure 5, the device 10a comprises a first nanostructure collection device gas inlet 60 for receiving from the first device 8 the gas stream containing the nanostructures and by-products from the formation of the nanostructures, such as smaller nanoparticles. The second device 10a comprises an electrically non-conductive inner shell 50 located within the body 2. The inner shell 50 supports a first electrostatic precipitator device 52. As is know, an electrostatic precipitator device 52 comprising a plurality of parallel spaced, high voltage charged, substantially rectangular collector plates 54 and grounded plates 56 supported in alternating sequence on suitable transverse support rods, insulators and spacers so as to form the collection section of the electrostatic precipitator device 52, with each plate in the sequence having an opposite polarity to the immediately adjacent plate(s). As is also known, ionising wires 58 and extended ground plates 56a are positioned in proximity to first collection device gas inlet 60 in such a manner to create a corona current extending towards the extended ground plates 56a, thereby forming an ionisation section of high concentration ion curtains. A gas outlet from the inner shell 50 is identified at 65 in Figure 5.

In use, as the gas stream enters the device 10a through the first nanostructure collection device gas inlet 60, the nanostructures entrained therein are charged as they pass into the concentrated ion curtain, and are separated from the gas stream by attraction onto the surface of the collector plates 54, which provide substrates which can be removed from the apparatus 2 for collection of the nanostructures located thereon. The smaller nanoparticles contained in the gas stream are not collected on the collector plates 54, and therefore pass through the device 10a.

In the second embodiment illustrated in Figure 6, the second device 10b comprises -<a first nanostructure collection device gas inlet 60 for receiving from the first device 8 the gas stream containing the nanostructures and nanoparticle by-products. As in the first embodiment, the second device 10b comprises an electrically non-conductive inner shell 50 located within the body 2. In this second embodiment, the inner shell 50 supports an array of substantially identical electrostatic precipitator devices 52', each being similar to the device 52 of the first embodiment. In the second embodiment, the collector plates 54 in each of the electrostatic precipitator devices 52' are preferably set at an increased voltage to the previous electrostatic precipitator in the direction of the gas flow. By creating an increasing voltage in the direction of gas flow through the device 10b, the separation of different sized nanostructures on respective collector plates 54 is enabled, with the smaller nanostructures being attracted to the downstream collector plates 54. In the illustrated embodiment, three electrostatic precipitator devices 52' are shown, but it is possible to use more or less than three. A gas outlet from the inner shell 50 is identified at 65 in Figure 6.

In either of the above embodiments of the second device 10, the collector plates 54 may be cooled, for example using liquid nitrogen conveyed about the device 10, to promote the separation of the nanostructures from the gas stream. Depending on the composition of .the nanostructures, alternatively the separation of the nanostructures from the gas stream may be promoted by heating the collector plates 54, for example, using a heater extending about the device 10. A load lock device (not shown) may also be provided for isolating the collector plates 54 and the nanostructures collected thereon from the gas stream. This allows the user to remove the collected nanostructures without the need to break the vacuum seals and reduces the risk of exposure to potentially harmful nanoparticles.

In each of the embodiments described above, the gas stream output from the second device 10 is conveyed within the body 2 to the third device 12 for the removal from the gas stream of any nanoparticles by-products contained therein. Two embodiments of the third device 12a, 12b will now be described [1^] in more detail with reference to Figures 7 and 8 respectively.

In the first embodiment illustrated in Figure 7, the third device 12a comprises a first removal device gas inlet 90 for receiving the gas stream from the second device 10, and a second removal device gas inlet 16 through which an oxygen-containing gas enters substantially radially into the body 2.

Examples of a suitable oxygen-containing gas include one or more of oxygen, air, ethanol, methanol, hydrogen peroxide, water and ozone.

Similar to the embodiments of the first device 8 described above, in this embodiment the third device 12a comprises an electrically non-conductive inner shell 70 located within the body 2. The inner shell 70 supports a substantially cylindrical electrically conductive block 76. The block 76 has

formed therein a plurality of bores of axial orientation. The inner shell 70 also supports a substantially Ting shaped anode 80. A multiplicity of perforated anode points 82 extends from the anode 80 in the direction of the outer periphery of the near flat face of the block 76. Such anode points can assist in maintaining a plasma - and hollow cathode effect - in each of the bores of block 76. A power source 78 is provided to charge block 76 to a cathode (negative) potential and the anode 80 to an anode (positive) potential.

In use, the gas stream containing the by-products is conveyed through the inlet 90 to the metal block 76 of the third device 12a. The oxygen-containing gas entering the device 12a through the inlet 16 mixes with the gas stream containing the by-products from the nanostructure formation. The mixed gas stream is dissociated in a plasma formed in block 76, whereupon the byproducts react with oxygen radicals to form an array of oxidised forms of carbon, for example carbon dioxide and carbon monoxide, which are exhaust out from the body 2 with the gas stream to a mechanical vacuum pump via gas outlet 6.

The second embodiment 12b illustrated in Figure 8 is similar to the first embodiment. In this second embodiment, the inner shell 70 supports two, spaced, substantially cylindrical electrically conductive blocks 74 and 76. As in the first embodiment, the metal blocks 74, 76 have formed therein a plurality of bores of axial orientation. An annular insulating element 72 is located between the metal blocks 74, 76 to provide further insulation between the metal blocks 74, 76. As illustrated in Figure 8, the metal blocks 74, 76 are located on either side of the second removal device gas inlet 16. A power source 78 is provided to charge the block 74 to a cathode (negative) potential and the anode 80 to an anode (positive) potential. A similar power source 78a is provided to charge the block 76 to a cathode (negative) potential and the anode 80 to an anode (positive) potential.

The embodiments of the first, second and third devices 8, 10, 12 described above may be used in any combination in the apparatus 2. For example, in one preferred embodiment of the apparatus 2, the first device 8 is as illustrated in figure 3, the second device 10 is as illustrated in figure 6, and the third device 12 is as illustrated in figure 8.

In any combination of the first, second and third devices-8, 10, 12 described above, the electrically non-conducting inner shells 20, 50 and 70 may be either separate shell or a continuous shell throughout the apparatus 2.

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CLAIMS

1. A method of producing nanostructures, the method comprising the steps of conveying gases containing constituents of the nanostructures to a housing to form a gas stream within the housing; conveying an oxygen-containing gas into the housing; within the housing, performing the steps of: forming nanostructures from the constituents contained within the gas stream, separating the thus-formed nanostructures from the gas stream for subsequent collection thereof, and removing a by- product of the nanostructure formation from the gas stream by reacting the by-product with the oxygen-containing gas; and exhausting the gas stream from the housing.

2. A method according to Claim 1 , wherein the nanostructures are formed in a first hollow cathode reactor.

3. A method according to Claim 2, wherein the by-product is removed from the gas stream using a second hollow cathode reactor.

4. A method of producing nanostructures, the method comprising the steps of passing gases containing constituents of the nanostructures to a first hollow cathode reactor to form the nanostructures; separating the nanostructures from a gas exhaust from the first hollow cathode reactor for collection thereof; and subsequently removing a by-product of the nanostructure formation from the exhaust gas by passing the exhaust gas through a second hollow cathode reactor together with an oxygen-containing gas.

5. A method according to any of Claims 2 to 4, wherein the first hollow cathode reactor comprises a parallel array of bores in a solid electrically conducting body in which a plasma is formed of the gases passed thereto.

6. A method according to Claim 5, wherein the body is formed from one of aluminium.Wpper, stainless steel, tungsten and graphite.

7. A method according to any of Claims 2 to 6, wherein a metal- containing gas is passed through the first hollow cathode reactor to form a metallic nanostructure.

8. A method according to Claim 7, wherein the metal comprises at least one of Fe, $Ni_1$ Mo, Co, Pt and Pd.

9. A method according to Claims 7 or Claim 8, wherein the metal containing gas is passed through the first hollow cathode reactor with an electronically excitable gas.

10. A method according to Claim 9, wherein the electronically excitable gas comprises at least one of argon, helium and nitrogen.

11. A method according to any of Claims 2 to 10, wherein a carbon- containing gas is passed through the first hollow cathode reactor to form a carbon nanostructure.

12. A method according to Claim 11 , wherein the carbon-containing gas comprises at least one of acetylene, methane, ethane, carbon monoxide, carbon dioxide, methanol, ethanol, tetrafluoromethane and hexafluoroethane.

13. A method according to Claim 11 or Claim 12, wherein the carbon- containing gas is passed through the first hollow cathode reactor with an electronically excitable gas.

14. A method according to Claim 13, wherein the electronically excitable gas comprises at least one of argon, helium and nitrogen.

15. A method according to any of Claims 2 to 14, wherein the nanostructures are formed using a plurality of said first hollow cathode reactors.

16. A method according to any preceding claim, wherein the nanostructures are separated from the gas using an electrostatic precipitator.

17. A method according to Claim 16, wherein the nanostructures are separated from the gas using an array of electrostatic precipitators.

18. A method according to Claim 17, wherein the electrostatic precipitators are at the same voltage.

19. A method according to Claim 17, wherein the electrostatic precipitators are at different voltages.

20. A method according to Claim 19, wherein the voltage across the array of electrostatic precipitators increases[1] in the direction of the gas flow through the array.

21. A method according to any preceding claim, wherein the nanostructures are separated from the gas by collection on a substrate.

22. A method according to Claim 21 , wherein the substrate is cooled to a temperature below room temperature.

23. A method according to Claim 22, wherein the substrate is cooled using liquid nitrogen.

24. A method according to Claim 21 , wherein the substrate is heated to a temperature above room temperature.

25. A method according to Claim 24, wherein the substrate is heated in the presence of an oxygen-containing gas.

26. A method according to Claim 24 or Claim 25, wherein the substrate is heated in the presence of at least one of oxygen, air, ethanol, methanol, hydrogen peroxide and ozone.

27. A method according to any of Claims 21 to 26, wherein the substrate is isolated from the gas for removal of the nanostructures collected thereby.

28. A method according to Claim 27, wherein the substrate is isolated using a load lock.

29. A method according to any of Claims 3 to 28, wherein the second hollow cathode reactor is a parallel array of bores in a solid electrically conducting body in which a plasma is formed of the gases passed

! ' thereto.

30. A method according to Claim 29, wherein the solid electrically conducting body is formed from one of aluminium, copper, graphite, stainless steel and tungsten.

31. A method according to any preceding claim, wherein the oxygen- containing gas comprises at least one of oxygen, air, ethanol, methanol, hydrogen peroxide and ozone.

32. A method according to any preceding claim, wherein the oxygen- containing gas is supplied with an electronically excitable gas.

33. A method according to Claim 32, wherein the electronically excitable gas comprises one of argon, nitrogen and helium.

34. Apparatus for producing nanostructures, the apparatus comprising a housing comprising means for receiving gases containing constituents of the nanostructures to form a gas stream within the housing, and means for receiving an oxygen-containing gas, the housing containing means for forming nanostructures from the constituents contained within the gas stream, means for separating the thus-formed nanostructures from the gas stream for subsequent collection thereof, and means for removing a by-product of the nanostructureTormation from the gas stream by reacting the by-product with the oxygen- containing gas, the housing further comprising means for exhausting the gas stream therefrom.

35. Apparatus according to Claim 34, wherein the nanostructure forming means comprises a hollow cathode reactor.

36. Apparatus according to Claim 34 or Claim 35, wherein the by-product removal means comprises a hollow cathode reactor.

37. Apparatus for producing nanostructures, the apparatus comprising a first hollow cathode reactor, means for supplying gases containing constituents of the nanostructures to the first hollow cathode reactor to form the nanostructures, means for separating the nanostructures from a gas exhaust from the first hollow cathode reactor for collection thereof, a second hollow cathode reactor for subsequently receiving the exhaust gas, and means for supplying an oxygen-containing gas to the second hollow cathode reactor for removal of by-products of the formation of nanostructure formation from the exhaust gas.