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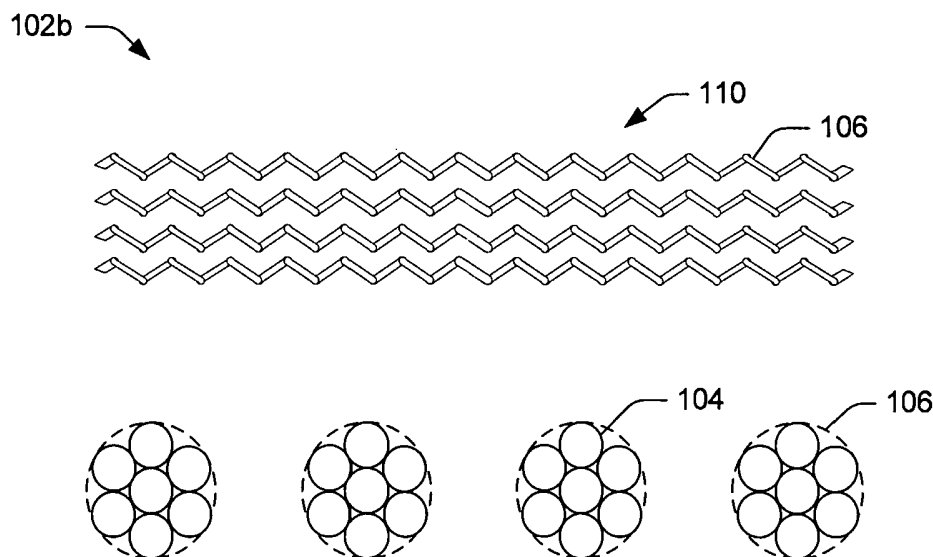
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[Continued on next page]

(54) Title: CONTINUOUS CARBON-NANOTUBE FILAMENTS FOR RADIATION-EMITTING DEVICES AND RELATED METHODS



(57) Abstract: This disclosure relates to continuous carbon-nanotube filaments (202) of radiation-emitting devices and methods for fabricating them.



— GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG) as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations 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, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VC, VN, YU, ZA, ZM, ZW, ARIPO patent (BW, GH, GM, KE,

LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG) as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

## **CONTINUOUS CARBON-NANOTUBE FILAMENTS FOR RADIATION- EMITTING DEVICES AND RELATED METHODS**

### **TECHNICAL FIELD**

**[0001]** This invention relates to filaments for radiation-emitting devices.

### **BACKGROUND**

**[0002]** Incandescent light sources are brighter and more efficient the closer their temperature is to 6500K (about 6200 degrees Celsius). At this temperature, the human eye can see in the form of visible light about forty percent of the energy expended by the source. This is the maximum amount of energy visible from an incandescent light source.

**[0003]** Solid, man-made incandescent light sources can not operate at this brightness and efficiency, however. This is because solid materials cannot be heated to 6500K (the surface of the sun is 6500K, but it is made up of plasma, not solid materials).

**[0004]** Various notable scientists and engineers have struggled to determine what solid material makes the best light source. In 1800, Humphry Davy invented the first electric light but it had a very short lifespan. Much later, physicist Sir Joseph Swan (c. 1860) developed a longer-lasting electric light with a carbon paper filament. Unfortunately, Sir Swan's design also had a short lifespan. Thomas Edison later developed (c. 1879) a filament made of carbon black (elemental, simple carbon) coated over a piece of string. His early design

lasted 40 hours in an oxygen-free bulb. Lewis Latimer, a member of Edison's research team, later patented a method for manufacturing carbon filaments in 1881. Carbon-coated filaments, however, were ultimately found to be inadequate because of their low reliability and low operating temperature.

**[0005]** William Coolidge (c. 1910) later used tungsten filaments. Tungsten filaments were found to have a longer lifespan than Edison's carbon-coated filaments. Tungsten has the second-highest melting point of any material, about 3700K, allowing it to be heated to a high temperature. Tungsten, however, is not capable of being heated to near 3700K without rapidly failing. It, like most materials, vaporizes at a faster rate the closer its temperature is to its melting point. Because of this, there is a trade off between a material's efficiency, which is enabled by high-temperature operation, and its lifespan. Many currently used tungsten-filament devices operate at a temperature of about 2800K to give them an acceptable lifespan and efficiency. At this temperature they are about ten percent efficient—about ten percent of the energy expended is visible to the human eye.

**[0006]** The lifespan of a filament can also depend on the filament's structure. If a filament has a polycrystalline structure, for instance, there may be localized heating at the crystal boundaries. Localized heating increases the temperature around the crystal boundaries, causing these areas to fail more quickly, such as by melting or vaporizing faster due to their higher temperature. Tungsten filaments often have a polycrystalline structure, which can limit their lifespan.

**[0007]** There is, therefore, a need for radiation and/or incandescent light-emitting devices having a higher efficiency and/or longer lifespan.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates two discontinuous carbon-nanotube filaments.

Fig. 2 includes top-plan and clipped-plane views of two continuous carbon-nanotube filaments.

Fig. 3 includes a light-emitting device with a continuous carbon-nanotube filament.

The same numbers are used throughout the disclosure and figures to reference like components and features.

## DETAILED DESCRIPTION

### *Overview*

**[0008]** This document discloses radiation- and light-emitting devices having a continuous carbon-nanotube filament. Some of these filaments have a high mechanical strength, allowing devices incorporating them to have long life, high efficiency, and be heated to a high operating temperature. Alternately or additionally, the filaments have few areas of localized heating, also enabling long life and high efficiency.

### *Carbon Nanotubes*

**[0009]** Generally, carbon nanotubes are strong and have a high boiling point and few impurities. This high boiling point has been simulated to be up to or more than about 4000 K by David Tomanek. (See Tomanek et al. at <http://www.pa.msu.edu/cmp/csc/simtubemlt.html>.) This high boiling point enables carbon nanotubes to efficiently transform energy into visible light, as well as ultra-violet radiation. Carbon nanotubes' few impurities and high strength can enable them to survive high temperatures for a relatively long time.

**[0010]** A discontinuous structure of carbon nanotubes, however, does not take full advantage of some of these attributes. A discontinuous structure of carbon nanotubes is generally weaker than a continuous structure. As such, a filament having a discontinuous structure can have a lower energy efficiency and lifespan than a filament having a continuous one.

**[0011]** Similarly, while carbon nanotubes generally have few impurities and thus few regions of localized heating, a discontinuous structure of carbon nanotubes can inherently have many regions of localized heating even if the carbon nanotubes in the discontinuous structure have few impurities.

**[0012]** Referring to Figure 1, two discontinuous carbon-nanotube filaments 102a and 102b are shown. Filament 102a has a yarn structure, with each carbon nanotube 104 touching end-to-end with other carbon nanotubes 104.

Filament 102b has a substantially randomly oriented fabric structure, with each nanotube 104 touching the other nanotubes at generally random points along each nanotube's elongate axis. Both of the discontinuous filaments have areas of localized heating at regions of discontinuity 106. At these regions, a current (marked "Current") traveling through the discontinuous filament encounters a higher resistance. This resistance causes the discontinuous region to be heated to a higher temperature. The higher temperature in these discontinuous regions causes faster vaporization or melting, thereby reducing the filament's life and/or efficiency.

#### *Forming Continuous Carbon-Nanotube Filaments*

**[0013]** Referring to Figure 2, a continuous carbon-nanotube filament 202 (202a and 202b) is formed from carbon nanotubes 204. The carbon nanotubes are oriented continuous from one end of the filament to the other. By so doing, the filament has a high mechanical strength. In the illustrated embodiment, the filament has a tensile strength of about 150 GPa, which is about 375 times stronger than steel. The illustrated filament also has a Young's modulus of about 1100-1200 GPa, compared with steel's 208 GPa per cross-sectional area. This high mechanical strength can enable higher operating temperatures and thus a higher-efficiency and longer-lasting light-emitting device. This continuity of the carbon nanotubes also enables extremely few regions of localized heating, thereby also permitting a more efficient and/or longer-lasting device.

**[0014]** In one illustrated embodiment, filament 202a comprises a twisted rope structure. This structure, shown in top-plan and expanded clipped-plane cross-sectional views, has micro coils 206 of the nanotubes 204 wrapped together. These micro coils 206 are wrapped into larger, macro coils 208.

**[0015]** In another illustrated embodiment shown in Figure 2, filament 202b comprises a substantially planar structure. This planar structure, shown in top-plan and expanded clipped-plane cross-sectional views, has micro coils 206 of the nanotubes 204 wrapped together. These micro coils are arranged into a planar array 210. The planar array illustrated has four micro coils, but in other embodiments can have many hundreds or thousands of micro coils. This planar

array enables improved two-dimensional focus when a light-emitting device having this array is used in a projection system. In this embodiment, the micro coils 206 have a thickness of about thirty nanometers, which permits the planar array to have an overall thickness as little as about thirty nanometers if the micro coils are substantially uncoiled or straight. If not, the planar array can have a larger overall thickness based on how much the micro coils are coiled, such as about sixty nanometers for tightly coiled micro coils.

**[0016]** In the illustrated embodiments, the filament is made predominantly of conductive carbon nanotubes. Carbon nanotubes are formed and then separated in accordance with their conductivity. Specifically, carbon nanotubes can be resistive, semiconductive, and highly conductive. Highly conductive carbon nanotubes include those that exhibit metallic properties. In this embodiment, the filament is made up predominantly of highly conductive, semiconductive, or a mix of both of these types of carbon nanotubes.

**[0017]** The carbon nanotubes used in the filament can be of various sizes, such as having a diameter of about one to eleven nanometers and a length of about one millimeter to one centimeter. In one embodiment, the nanotubes are packed with fullerenes creating a pea pod structure. The nanotubes have carbon spheres (fullerenes) packed inside their walls. To do so, the nanotubes have a diameter slightly larger than the diameter of the fullerenes. In one embodiment, the carbon nanotubes have a diameter of about one nanometer and are packed with fullerenes having a diameter of about 0.8 nanometers.

#### *Forming The Device*

**[0018]** Referring to Figure 3, the continuous carbon-nanotube filament 202 is oriented in electrical communication with electrical contacts 302 and 304, such as by clamping ends of the filament at the contacts.

**[0019]** The filament and the contacts are disposed in an encapsulant capable of maintaining a controlled atmosphere. In the illustrated embodiment, the filament and contacts are encapsulated within a bulb 306 having an argon atmosphere at a pressure of about 0.8 atmospheres (i.e., about 12 pounds per square inch). Other controlled atmospheres may also be used, such as a vacuum or a xenon

atmosphere. The resulting light-emitting device 308 is capable of emitting light through the filament by passing a current through the contacts and the filament.

**[0020]** The continuity of the carbon nanotubes 204 in the filament 202 (shown in Figure 2 as 202a and 202b) enables fewer regions of localized heating 106 (shown in Figure 1). Thus, not only is the filament made of a material capable of high temperature and high mechanical strength, it is structured to take advantage of the material's capabilities. The filament 202 is structured through its continuity to have high mechanical strength and few regions of localized heating. These few regions of localized heating and high strength enable the device 308 to be operated at higher temperatures or with a higher lifespan.

**[0021]** By way of example, the device 308 is capable of an energy efficiency of about twelve or more percent with a lifespan of about 1000-2400 hours (depending on a halogen composition in the bulb). This is enabled by the filament 202 being heated to a temperature of about 3100K. This is about a twenty percent improvement in energy efficiency and brightness over many tungsten-filament incandescent lights. Efficiencies above twelve percent are also possible. In another embodiment, for instance, the device 308 is capable of an efficiency of about fifteen percent with a lifespan of about 1000-2400 hours by the filament being heated to about 3500 K. The device may also be capable of an efficiency of about twenty percent with a lifespan of about 1000-2400 hours, if the filament is heated to about 4000 K.

**[0022]** Also by way of example, the device 308 is capable of an energy efficiency of about ten percent with a lifespan of about 2400 hours. In another embodiment, the device 308 is capable of this efficiency with a lifespan of about 10000 hours. These long lifespans are enabled by the filament being heated to a temperature of about 2800K but with a slow rate of failure. These lifespans are about a twenty to 500 percent improvement over the current lifespan of many tungsten-filament incandescent lights.

**[0023]** The device 308 is also capable of gradual, rather than catastrophic failure. The carbon nanotubes 204 of Figure 2 act in the device as many parallel conductors. Thus, as one fails, the resistance of the filament 202 increases marginally, thereby marginally dropping the current. Because of this,

the brightness of the device drops a very small amount with each nanotube's failure. In some incandescent light devices, a failure at one point in a filament causes a catastrophic failure, such that the entire filament fails. This can cause a light-emitting device to instantly fail. The illustrated device 308, however, gradually dims, thereby allowing a user to change the device at his or her convenience whenever the device is dimmer than needed.

**[0024]** Although the invention is described in language specific to structural features and methodological steps, it is to be understood that the invention defined in the appended claims is not necessarily limited to the specific features or steps described. Rather, the specific features and steps disclosed represent exemplary forms of implementing the claimed invention.

What is Claimed is:

## CLAIMS

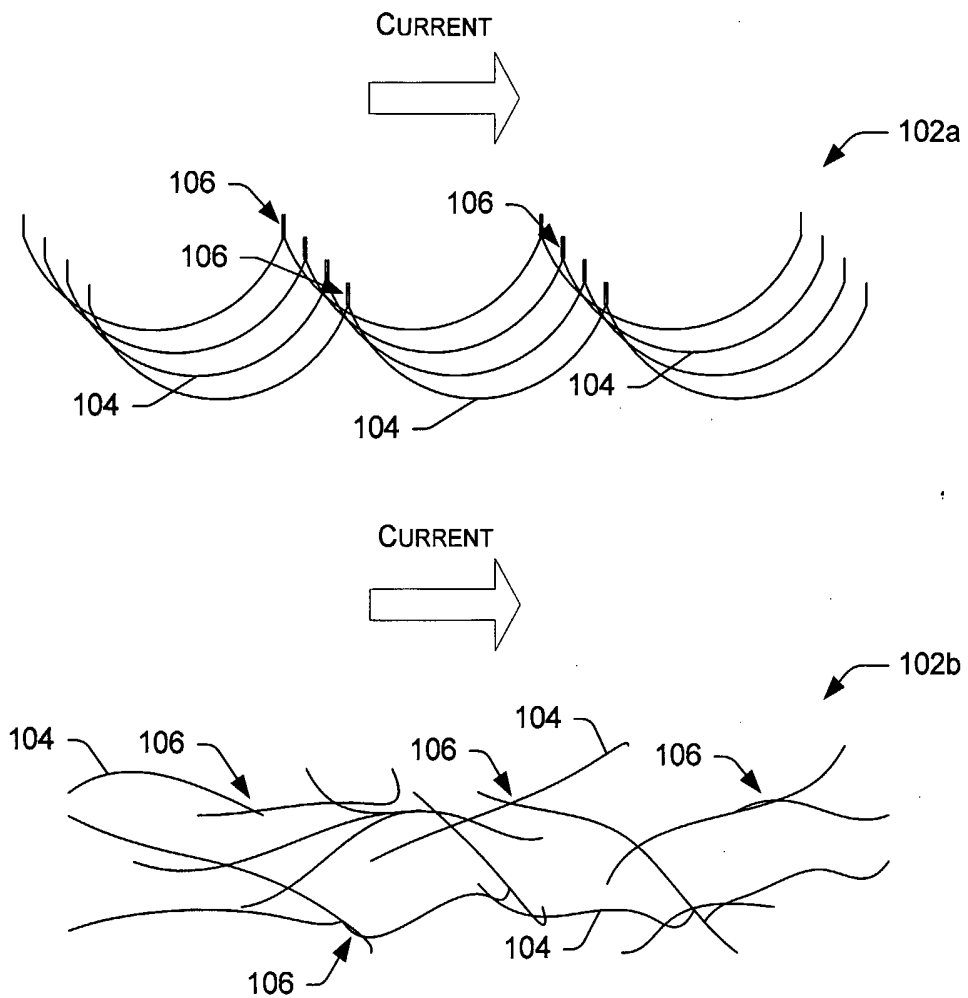
1. A device comprising:
  - a continuous carbon-nanotube filament 202;
  - electrical contacts 302 and 304 in electrical communication with the filament 202; and
  - an encapsulant 306 encapsulating the filament 202 and electrical contacts 302 and 304, the encapsulant 306 providing a controlled atmosphere, wherein the filament 202 is configured to emit radiation when an electric current is passed between the electrical contacts 302 and 304 and through the filament 202.
2. The device of claim 1, wherein the filament 202 has a tensile strength of at least 150 GPa.
3. The device of claim 1, wherein the filament 202 is capable of emitting light at an efficiency of about twelve or more percent for 2000 hours.
4. The device of claim 1, wherein the filament 202 is capable of emitting light at an efficiency of about ten or more percent for about 2400 hours.
5. The device of claim 1, wherein the filament 202 is capable of emitting light at an efficiency of about ten or more percent for about 10000 hours.
6. A method comprising:
  - providing a structure 202 having carbon nanotubes 204, a majority of the carbon nanotubes 204 being continuous between opposing ends of an axis of the structure 202;
  - orienting the ends of the structure 202 in electrical communication with electrical contacts 302 and 304; and

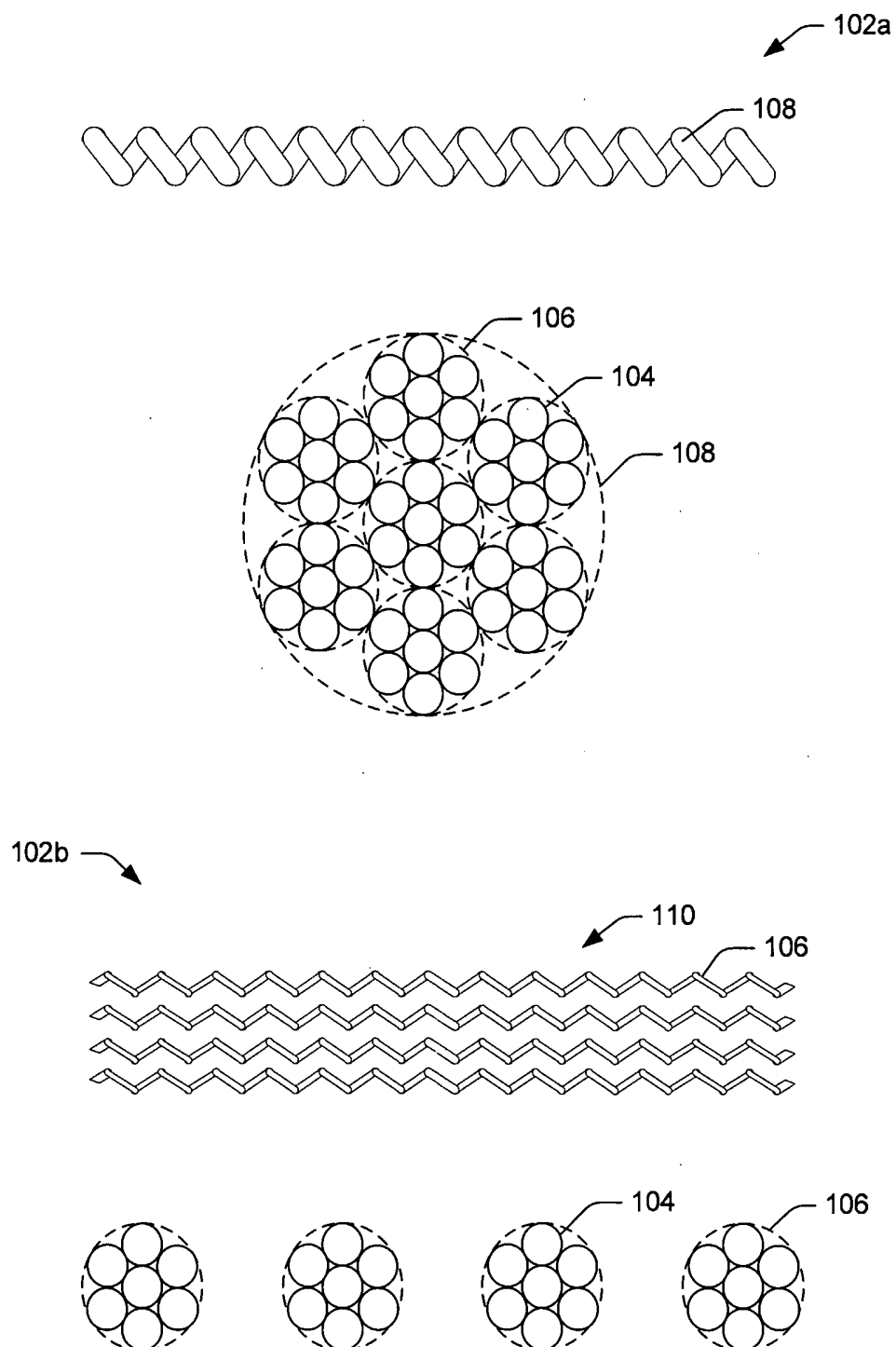
encapsulating the structure 202 and the electrical contacts 302 and 304 within an inert atmosphere.

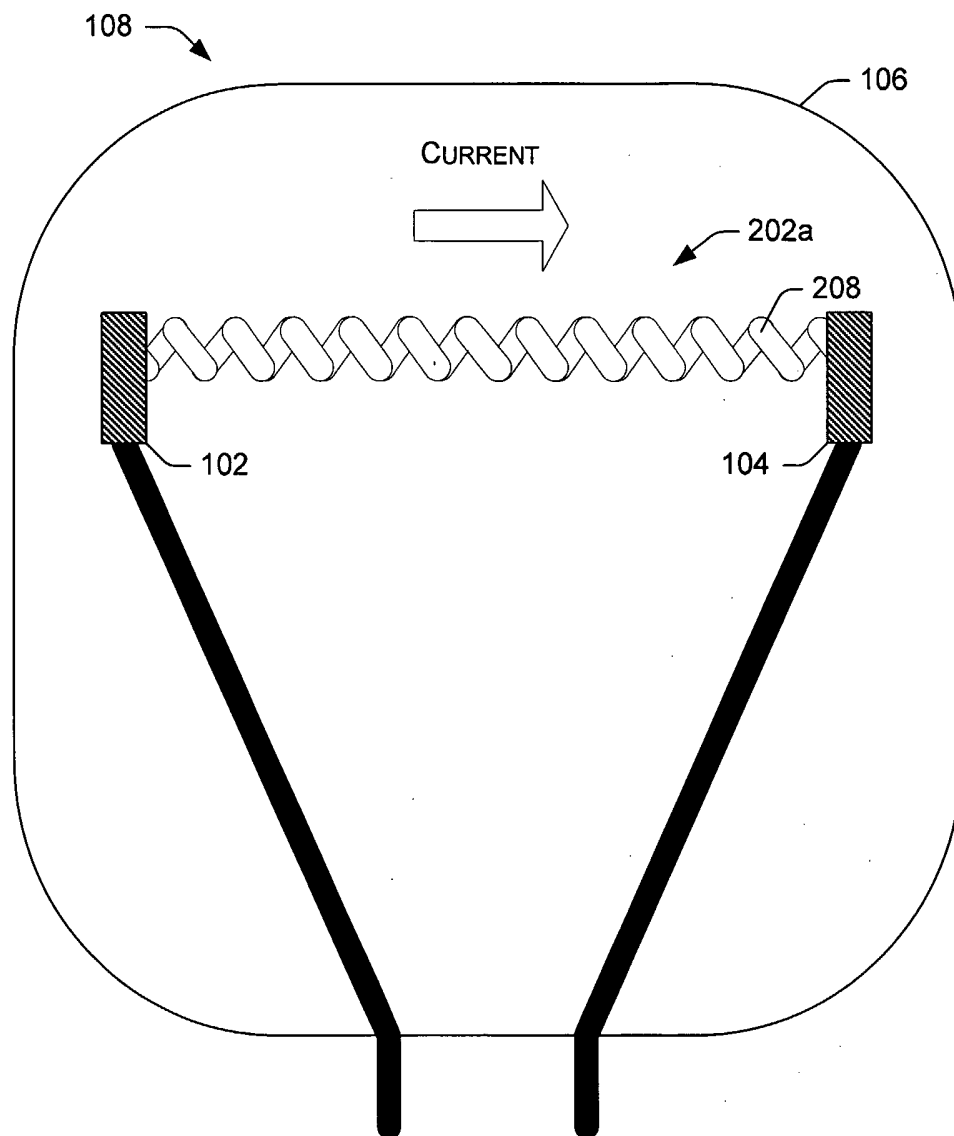
7. The method of claim 6, wherein the act of providing the structure 202 comprises providing the structure 202 having predominantly carbon nanotubes 204.

8. The method of claim 6, wherein the structure 202 is elongate along the axis.

9. The method of claim 6, wherein the act of providing the structure 202 comprises providing the structure 202 having substantially all of the carbon nanotubes 204 being continuous between the opposing ends.

*Fig. 1*

*Fig. 2*

*Fig. 3*

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US2005/023929

## A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 H01K1/06 H01K3/02 C01B31/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01J H01K C01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, COMPENDEX, WPI Data, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                    | Relevant to claim No. |
|------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X          | <p>WEI J ET AL: "CARBON NANOTUBE FILAMENTS IN HOUSEHOLD LIGHT BULBS" APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 84, no. 24, 14 June 2004 (2004-06-14), pages 4869-4871, XP001222425 ISSN: 0003-6951 the whole document</p> <p style="text-align: center;">-----<br/>-/--</p> | 1,3-9                 |



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

\* Special categories of cited documents:

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Date of the actual completion of the international search

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Name and mailing address of the ISA

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# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US2005/023929

| C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT |                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                       |
|------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| Category °                                           | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                                                                                                                                                                                                                                    | Relevant to claim No. |
| X                                                    | <p>LI PENG ET AL: "Polarized incandescent light emission from carbon nanotubes"<br/>APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 82, no. 11,<br/>17 March 2003 (2003-03-17), pages 1763-1765, XP012033543<br/>ISSN: 0003-6951<br/>abstract; page 1763, left-hand column - page 1764, left-hand column; page 1765; figures 2(a), 2(b)</p> <p style="text-align: center;">-----</p>                                              | 1,2,6-9               |
| A                                                    | <p>ZHU H W ET AL: "Direct synthesis of long single-walled carbon nanotube strands"<br/>SCIENCE, vol. 296, no. 5569,<br/>3 May 2002 (2002-05-03), pages 884-886, XP002273566<br/>AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE, US<br/>ISSN: 0036-8075<br/>abstract; page 884, left-hand column; page 885, left-hand column - page 886, left-hand column; figures 1, 4</p> <p style="text-align: center;">-----</p>                                              | 1,2,6-9               |
| A                                                    | <p>YA-LI LI ET AL.: "Direct Spinning of Carbon Nanotube Fibers from Chemical Vapor Deposition Synthesis"<br/>SCIENCE, vol. 304, no. 5668,<br/>9 April 2004 (2004-04-09), pages 276-278, XP002348114<br/>AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE, US<br/>page 276, middle column; page 277, right-hand column - page 278, left-hand column; figures 1, 3</p> <p style="text-align: center;">-----</p>                                                      | 1,2,6-9               |
| A                                                    | <p>DEMZYK B G ET AL: "Direct mechanical measurement of the tensile strength and elastic modulus of multiwalled carbon nanotubes"<br/>MATERIALS SCIENCE AND ENGINEERING A (STRUCTURAL MATERIALS: PROPERTIES, MICROSTRUCTURE AND PROCESSING), vol. 334, no. 1-2,<br/>September 2002 (2002-09), pages 173-178, XP002348115<br/>Elsevier, Switzerland<br/>abstract; page 174, left-hand column; page 176, right-hand column;</p> <p style="text-align: center;">-----</p> | 2                     |
| A                                                    | <p>US 2004/051432 A1 (JIANG KAILI ET AL)<br/>18 March 2004 (2004-03-18)<br/>paragraphs '0018! - '0025!; figure 2</p> <p style="text-align: center;">-----</p> <p style="text-align: center;">-/--</p>                                                                                                                                                                                                                                                                 | 1-9                   |

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/US2005/023929

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages                                                                                                                                                                          | Relevant to claim No. |
|------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| P,X        | <p>PATENT ABSTRACTS OF JAPAN<br/>vol. 2003, no. 12,<br/>5 December 2003 (2003-12-05)<br/>-&amp; JP 2005 100757 A (ANDO YOSHINORI),<br/>14 April 2005 (2005-04-14)<br/>abstract; paragraphs '0027! - '0031!,<br/>'0035! - '0038!; figures 1, 4<br/>-----</p> | 1,3-9                 |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US2005/023929

| Patent document<br>cited in search report | Publication<br>date | Patent family<br>member(s)      | Publication<br>date      |
|-------------------------------------------|---------------------|---------------------------------|--------------------------|
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| JP 2005100757 A                           | 14-04-2005          | NONE                            |                          |