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(71) Applicant *(for all designated States except US)*: **NANOCOMP TECHNOLOGIES, INC.** [US/US]; 162 Pembroke Road, Concord, NH 03301 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **LASHMORE, David, S.** [US/US]; 60 Farr Road, Lebanon, NH 03766 (US). **BRADEN, Robert** [US/US]; 442 North Pembroke Rod., Pembroke, NH 03275 (US). **HART, Anastasios, John** [US/US]; 98 Prospect St., #3, Somerville, MA 02143 (US). **WELCH, John** [US/US]; 418 Nadine Road, Pembroke, NH 03275 (US).

(74) Agent: **PHAM, Chinh, H.**; Greenberg Traurig, LLP, One International Place, Boston, MA 02110 (US).

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(54) Title: CHEMICALLY-ASSISTED ALIGNMENT OF NANOTUBES WITHIN EXTENSIBLE STRUCTURES

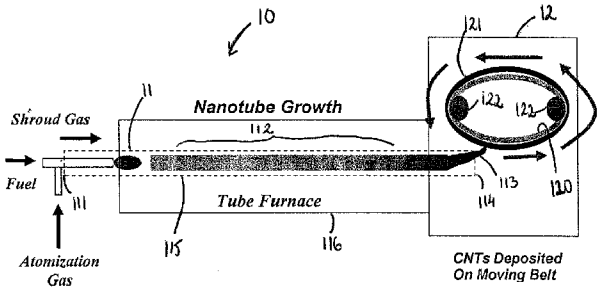


Fig. 1A

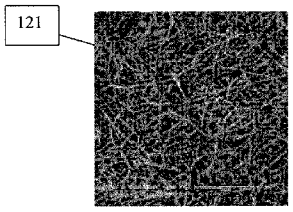


Fig. 1B

(57) Abstract: A method and system for aligning nanotubes within an extensible structure such as a yarn or non-woven sheet. The method includes providing an extensible structure having non-aligned nanotubes, adding a chemical mixture to the extensible structure so as to wet the extensible structure, and stretching the extensible structure so as to substantially align the nanotubes within the extensible structure. The system can include opposing rollers around which an extensible structure may be wrapped, mechanisms to rotate the rollers independently or away from one another as they rotate to stretch the extensible structure, and a reservoir from which a chemical mixture may be dispensed to wet the extensible structure to help in the stretching process.

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CHEMICALLY-ASSISTED ALIGNMENT OF NANOTUBES WITHIN EXTENSIBLE STRUCTURES

TECHNICAL FIELD

[0001] The present invention relates to methods for alignment of nanotubes, and more particularly, to methods of substantially aligning nanotubes within extensible structures, such as yarns or non-woven sheets made from nanotubes.

BACKGROUND ART

[0002] Nanotubes may be fabricated using a variety of approaches. For example, nanotubes can be produced by conducting chemical vapor deposition (CVD) in such a manner that the nanotubes can be caused to deposit either on a moving belt or cylinder, where the nanotubes consolidate so as to form a non-woven sheet. Alternatively, the nanotubes can be taken up by a spinning device and spun into a yarn. Nanotubes collected as yarns, non-woven sheets, or similar extensible structures can also be fabricated by other means. For instance, the nanotubes can be dispersed in a water surfactant solution, then caused to precipitate onto a filter drum or membrane, where they can be subsequently be dried and removed as a sort of paper. Similarly, nanotubes collected as yarns can also be produced from solutions, and is well know in the art. In general, the nanotubes produced within these extensible structures can be either single-walled (SWNT) or multi-walled (MWNT), and may be made from, for example, carbon, boron, or a combination thereof.

[0003] Due to the random nature of the growth and fabrication process, as well as the collection process, the texture, along with the position of the nanotubes relative to adjacent nanotubes within the extensible structure may also be random. In other words, the nanotubes within these extensible structures may not be well aligned, particularly for the non-woven sheets.

[0004] Since there are certain physical and mechanical properties that are dependent on alignment, the random nature of the nanotubes within these extensible structures can affect the properties of these extensible structures. The properties that may be affected include tensile strength and modulus, electrical

conductivity, thermal conductivity, Seebeck coefficient, Peltier coefficient, and density. Other properties which may be affected, include the complex index of refraction, the frequency dependency of resistivity, and chemical reactivity.

[0005] To address the nanotube alignment issue prior to the formation of the extensible structure can be cumbersome, expensive, and cost prohibitive in connection with the fabrication process.

[0006] Accordingly, it would be desirable to provide a process which can enhance nanotube alignment within an extensible structure, while being economical, subsequent to the formation of the extensible structure.

SUMMARY OF THE INVENTION

[0007] The present invention provides, in one embodiment, a method for substantially aligning nanotubes within an extensible structure. The method includes adding a chemical to the extensible structure having non-aligned nanotubes, so as to wet the extensible structure. Next, the extensible structure may be stretched to substantially align the nanotubes within the extensible structure relative to one another. The stretched extensible structure may also exhibit enhanced contacts between adjacent nanotubes, which can result in increased electrical and thermal conductivity, as well as tensile strength. In an embodiment, the amount of stretch can be from about 5 percent to several times the original length of the extensible structure. Thereafter, the stretched structure may be washed and/or exposed to heat in order to remove any residue. In one embodiment, the step of washing may be accomplished using a thermal treatment, a chemical treatment, a electrochemical treatment, or a combination thereof.

[0008] The present invention also provides, in an embodiment, a system for substantially aligning nanotubes within an extensible structure. The system includes a pinch roller stretching apparatus having, among other things, gears which can create a difference in roller velocities, so as to stretch the nanotubes into alignment within the extensible structure. In one embodiment, stepper motors may be used in place of gears to generate a difference in roller

velocities. The system may include a mechanism for wetting the extensible structure to help in the stretching process.

[0009] The present invention further provides a system for substantially aligning nanotubes within an extensible non-woven sheet. The system, in one embodiment, includes opposing rollers, around which the non-woven sheet may be wrapped. The opposing rollers may be designed to rotate, while one or both translate (i.e., move away from the other). The system may include a mechanism such as a reservoir for wetting the extensible non-woven sheet to help in the stretching process.

BRIEF DESCRIPTION OF DRAWINGS

[00010] Fig. 1A illustrates a system for generating nanotubes and collecting the nanotubes as a non-woven sheet.

[00011] Fig 1B illustrates a portion of an a non-woven sheet prior to being stretched with the nanotubes intermingled and substantially in non-alignment relative to one another.

[00012] Fig. 2 illustrates a pinch roller stretching system for use in connection with one embodiment of the present invention.

[00013] Fig. 3 illustrates another stretching system for use in stretching extensible non-woven sheets.

[00014] Fig. 4 is a scanning electron micrograph illustrating the relative position of the nanotubes in an extensible structure before and after stretching.

[00015] Fig. 5 illustrates a system for generating nanotubes and collecting the nanotubes as a yarn.

DESCRIPTION OF SPECIFIC EMBODIMENTS

[00016] Nanotubes for use in connection with the present invention may be fabricated using a variety of approaches. Presently, there exist multiple processes and variations thereof for growing nanotubes. These include: (1) Chemical Vapor Deposition (CVD), a common process that can occur at near

ambient or at high pressures, and at temperatures above about 400° C, (2) Arc Discharge, a high temperature process that can give rise to tubes having a high degree of perfection, and (3) Laser ablation. It should be noted that although reference is made below to nanotube synthesized from carbon, other compound(s) may be used in connection with the synthesis of nanotubes for use with the present invention. Other methods, such as plasma CVD or the like are also possible. In addition, it is understood that boron nanotubes may also be grown in a similar environment, but with different chemical precursors.

[00017] The present invention, in one embodiment, employs a CVD process or similar gas phase pyrolysis procedures known in the industry to generate the appropriate nanostructures, including nanotubes. In particular, since growth temperatures for CVD can be comparatively low ranging, for instance, from about 400° C to about 1300° C, carbon nanotubes, both single wall (SWNT) or multiwall (MWNT), may be grown, in an embodiment, from nanostructural catalyst particles introduced into reagent carbon-containing gases (i.e., gaseous carbon source), either by addition of existing particles or by in situ synthesis of the particles from a metal-organic precursor, or even non-metallic catalysts. Although both SWNT and MWNT may be grown, in certain instances, SWNT may be preferred due to their relatively higher growth rate and tendency to form ropes, which may offer advantages in handling, safety, and strength.

[00018] Moreover, the strength of the individual SWNT and MWNT generated for use in connection with the present invention may be about 30 GPa or more. Strength, as should be noted, is sensitive to defects. However, the elastic modulus of the SWNT and MWNT fabricated for use with the present invention is typically not sensitive to defects and can vary from about 1 to about 1.2 TPa. Moreover, the strain to failure, which generally can be a structure sensitive parameter, may range from a few percent to a maximum of about 12% in the present invention.

[00019] Furthermore, the nanotubes of the present invention can be provided with relatively small diameter, so that relatively high capacitance can be generated. In an embodiment of the present invention, the nanotubes of the

present invention can be provided with a diameter in a range of from less than 1 nm to about 10 nm. It should be appreciated that the smaller the diameter of the nanotubes, the higher the surface area per gram of nanotubes can be provided, and thus the higher the capacitance that can be generated. For example, assuming a 50 micron Farads per cm capacitance for graphene and a density of about 1.5 g/cc for the SWNT, capacitance can be calculated using the following formula:

[00020] Capacitance (Farads/gram) = 1333/d (nm)

[00021] Therefore, assuming a uniform textile of 1 nm diameter tubes with no shielding, then a specific capacitance of 1333 Farads per gram should be feasible, neglecting the loss in surface area when ropes are formed and neglecting the loss of active area for the nanotubes that may be shielded by neighboring nanotubes.

[00022] With reference now to Fig. 1A, there is illustrated a system 10, similar to that disclosed in U.S. Patent Application Serial No. 11/488,387 (incorporated herein by reference), for use in the fabrication of nanotubes. System 10, in an embodiment, may be coupled to a synthesis chamber 11. The synthesis chamber 11, in general, includes an entrance end 111, into which reaction gases may be supplied, a hot zone 112, where synthesis of extended length nanotubes 113 may occur, and an exit end 114 from which the products of the reaction, namely the nanotubes and exhaust gases, may exit and be collected. The nanotubes generated, in an embodiment, may be individual nanotubes, bundles of nanotubes and/or intertwined nanotubes (e.g., ropes of nanotubes). In addition, synthesis chamber 11 may include, in an embodiment, a quartz tube 115 extending through a furnace 116.

[00023] System 10, in one embodiment of the present invention, may also includes a housing 12 designed to be substantially airtight, so as to minimize the release of potentially hazardous airborne particulates from within the synthesis chamber 11 into the environment. The housing 12 may also act to prevent oxygen from entering into the system 10 and reaching the synthesis chamber 11.

In particular, the presence of oxygen within the synthesis chamber 11 can affect the integrity and compromise the production of the nanotubes 113.

[00024] System 10 may also include a moving belt 120, positioned within housing 12, designed for collecting synthesized nanotubes 113 made from a CVD process within synthesis chamber 11 of system 10. In particular, belt 120 may be used to permit nanotubes collected thereon to subsequently form a substantially continuous extensible structure 121, for instance, a non-woven sheet, as illustrated in Fig. 1B, or a yarn of twisted and intertwined nanotubes. Such a non-woven sheet may be generated from compacted, substantially non-aligned, and intermingled nanotubes 113, bundles of nanotubes, or intertwined nanotubes (e.g., ropes of nanotubes), with sufficient structural integrity to be handled as a sheet.

[00025] To collect the fabricated nanotubes 113, belt 120 may be positioned adjacent the exit end 114 of the synthesis chamber 11 to permit the nanotubes to be deposited on to belt 120. In one embodiment, belt 120 may be positioned substantially parallel to the flow of gas from the exit end 114, as illustrated in Fig. 1A. Alternatively, belt 120 may be positioned substantially perpendicular to the flow of gas from the exit end 114 and may be porous in nature to allow the flow of gas carrying the nanomaterials to pass therethrough. Belt 120 may be designed as a continuous loop, similar to a conventional conveyor belt. To that end, belt 120, in an embodiment, may be looped about opposing rotating elements 122 (e.g., rollers) and may be driven by a mechanical device, such as an electric motor. In one embodiment, the motor may be controlled through the use of a control system, such as a computer or microprocessor, so that tension and velocity can be optimized.

[00026] Although not shown, it should be appreciated that the nanotubes generated by system 10 may also be collected as a yarn, as provided below in Example II. Such an approach is disclosed in U.S. Patent Application Serial No. 11/488,387, which is hereby incorporated herein by reference.

Stretching procedure and apparatus

[00027] Once the nanotubes 113 have been collected and the extensible structure 121 formed on belt 120, the extensible structure 121 may be removed from belt 120 for stretching.

[00028] Stretching, in accordance with one embodiment of the present invention, allows the intermingled and substantially non-aligned nanotubes, bundles of nanotubes, and/or ropes of nanotubes within the extensible structure to be pulled into substantial alignment. In addition, stretching may pull adjacent nanotubes into contact with one another, and can enhance points of contact between adjacent nanotubes, bundles of nanotubes, and/or ropes of nanotubes. The enhanced contact between adjacent nanotubes, in one embodiment, can lead to increased conductivity (e.g., electrical and thermal), as well as tensile strength of the extensible structure 121, in comparison to that of an extensible structure with substantially non-aligned nanotubes.

[00029] It should be appreciated that the extensible structure 121 may be stretched to permit nanotube alignment using any type of apparatus that produces a local stretching. The stretching, for example, may be done over a large amount of extensible structure material. However, the risk of the material elongating at a weak area or defect, in such an approach, can be higher than if the stretching apparatus were designed to stretch the material incrementally over a relatively smaller length (i.e. local stretching). In accordance with an embodiment of the present invention, systems 20 or 30, as illustrated in Fig. 2 and Fig. 3 respectively, may be used in connection with the stretching procedure incrementally over a relatively smaller distance.

[00030] In one embodiment, prior to stretching, the extensible structure 121 may be exposed to certain chemicals (e.g. mixture or solution) or to permit wetting of the structure, so that sufficient stretching can subsequently be carried out. To wet the extensible structure 121, the structure can, in an embodiment, be immersed in a liquid solution prior to mounting the structure on stretching system 20 or stretching system 30. Alternatively, the extensible structure 121 may be first mounted in the stretching system, then subsequently sprayed with

the appropriate chemical mixture or solution until the structure can be sufficiently wetted. In accordance with one embodiment, it can be advantageous for the extensible structure 121 to remain substantially wet over a period of time, for example, from about a few minutes to more than a day, depending on the thickness of the extensible structure or the nature of the chemicals being used.

[00031] Once sufficiently wetted, the extensible structure 121 may be subject to elongation (i.e., stretching) in order to cause the intermingled and substantially non-aligned nanotubes 113 to substantially align along the direction of the stretching.

[00032] Looking now at Fig. 2, system 20 is provided for stretching extensible structure 121. System 20, in an embodiment, may include a first set of pinch rollers 21A, B and a second set of pinch rollers 22A, B positioned within framework 23. The design of pinch rollers 21A, B and pinch roller 22A, B, as illustrated, permits extensible structure 121 to be fed and pinch between each of pinch rollers 21A, B and pinch rollers 22 A, B. In addition, first set of pinch rollers 21A, B and second set of pinch rollers 22A, B may be designed be rotate at different velocities to permit stretching of the extensible structure 121. As an example, the differences in velocities between the two sets of pinch rollers may range from about 1 percent to about 30 percent, and in one embodiment, about 5 percent. In an embodiment, the differences in the rotating velocities of pinch rollers 21 may be controlled by the used of gears 24. Alternatively, stepper motors may be used to control the rotating velocities of the pinch rollers 21. Of course, any control mechanism known in the art may be used, so long as the rotating velocities may be sufficiently controlled.

[00033] With reference now to Fig. 3, system 30 is provided for stretching extensible structure 121. System 30, in an embodiment, may include opposing rollers 31, each capable of rotating about its axis. By providing opposing rollers 31, the extensible structure 121 can be positioned as a loop about the opposing rollers 31. Opposing rollers 31, in one embodiment, may be PTFE rollers, and may be mounted on a translating mechanism 32 to permit the rollers to move

away from one another. The ability to rotate, while having one or both rollers 31 simultaneously translate (i.e., move away from the other) can permit the extensible structure 121 to be stretched, once the extensible structure 121 has been positioned about the opposing rollers 31. In one embodiment, the approximate distance at the start of the stretching between opposing rollers 31 may be at a predetermined distance, for instance, about 15 inches or any desired distance appropriate for the extensible structure 121 being stretched. The stretching time, on the other hand, may be conducted over about two hours or until about 30% elongation or more can be achieved. System 30 may also include a spray system (not shown) having a reservoir with the chemical mixture or solution for wetting the extensible structure 121. Such a spray system may also be provided for system 20, if so desired.

[00034] In general, the rate of elongation, when using either system 20 or system 30, can be from about 0.001 percent per minute to about 5 percent per minute. Sufficiently good results can be obtained with the rate of elongation being about 0.3 percent per minute.

[00035] In an embodiment whereupon a yarn may be stretched, such a yarn may be stretched to a point where its diameter (i.e., tex) can be reduced, so as to enable post spinning to increase tensile strength.

[00036] For extensible structures 121 that are either an non-woven sheet or a yarn, the amount of stretching can be from about 5 percent to several times the original length of the sheet or yarn.

[00037] It should be appreciated that although stretching can be done mechanically by the system 20 (Fig. 2) and/or system 30 (Fig. 3), stretching of the extensible structure 121 to permit substantial alignment of the nanotubes can also be accomplished by hand, by pressurized gas blowing on the extensible structure 121, by vacuum, or a combination thereof.

[00038] Upon sufficient stretching, substantial alignment of the nanotubes within extensible structure 121 can be achieved, as illustrated in Fig. 4. This alignment, in an embodiment, may be proportional to the degree of stretching, as evidenced and described below by the change in the resistivity with the degree of stretch,

and with the increase in the mechanical properties with the degree of stretch. In addition, stretching may also enhance other properties of the extensible structure 121. Specifically, contacts between adjacent nanotubes, bundles of nanotubes, and/or ropes of nanotubes, can be enhanced, which can result in increased conductivity (e.g., electrical and thermal) as well as tensile strength of the extensible structure 121.

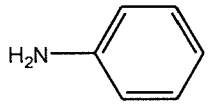
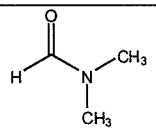
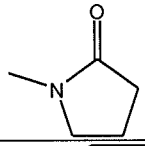
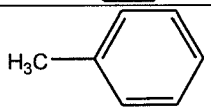
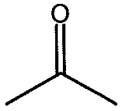
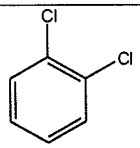
Chemical Treatment

[00039] In accordance with one embodiment of the present invention, wetting of the extensible structure 121 may be carried out at a temperature range of from about 20° C to about 50° C. In a particular embodiment, the wetting of the structure 121 may be performed at a temperature of about 23° C.

[00040] The chemical mixture or solution used for wetting the extensible structure 121 in connection with the stretching procedure of the present invention can include, in an embodiment, a mixture of solvents and surfactants listed in Tables 1 and 2 below, in any various combination.

[00041] Solvents that can be used in connection with the present invention may be common chemistries for dispersion of carbon nanotubes (CNT')s. Moreover, tested solvents were chosen for their ability to wet CNT's, and as a carrier for surfactants (Table 1).

Table 1. *Solvents used to dissolve surfactant and wet the surface of CNT's.*

Chemical	Formula	Structure
Aniline (Phenyl amine, Amino benzene)	C_6H_7N	
DMF (Dimethyl formamide)	C_3H_7NO	
NMP (N-methylpyrrolidone)	C_5H_9NO	
Toluene (methylbenzene)	C_7H_8	
Acetone (Dimethyl ketone)	CH_3COCH_3	
Dichlorobenzene	$C_6H_4Cl_2$	

[00042] It should be noted that Aniline, DMF and NMP have reactive amide/amine functional groups that can form hydrogen or ionic bonds with open binding sites on the carbon nanotube surface. Depending on downstream processing goals, this bonding can be useful.

[00043] Surfactants that can be used in connection with the present invention, on the other hand, may include surfactants that can interact with the surface of carbon nanotubes by way of, for example, van der Waals forces. In particular, polar solvents used herewith can cause van der Waals interactions between the hydrophobic 'tails' of the surfactant molecules and the surface of the carbon nanotubes, so as to allow the charged 'head' of the surfactant molecule to orientate away from the surface of the carbon nanotubes, thus better solubilizing or wetting the carbon nanotubes in the solvent. Moreover, once the surfactant is

on the surface of carbon nanotubes, it can prevent re-flocculation of the carbon nanotubes via, for example, steric and electrostatic effects.

[00044] It should be appreciated that since nanotubes are generally inert and hydrophobic, a substantially pristine surface may be ideal for interactions with the hydrophobic 'tail' of the surfactant. Furthermore, although binding sites on the surface of the carbon nanotubes can be utilized to functionalize the nanotubes, as discussed above, such binding sites may be blocked by the presence of the surfactant. This is not because the surfactant is taking the available bond, but because the size of the surfactant can act to block the solvent from binding sterically to the carbon nanotubes.

[00045] In one embodiment of the present invention, the concentration of the surfactant, such as ZetaSperse, that may be used ranges from about 0.1 percent to about 5 percent by volume, and may preferably be about 1 percent by volume.

[00046] In another embodiment of the invention, large chain polymers can also be used as dispersants for carbon nanotubes. These polymers differ from surfactants in the way they keep the carbon nanotubes separated. In particular, the size of these polymers can enable these large polymer chains to sterically separate the nanotubes.

[00047] Surfactants and polymers suitable for this application are provided below in Table 2.

Table 2. *Surfactants and polymers used as lubricants for chemically assisted mechanical elongation of CNT textile*

Anionic Surfactants	- Sodium dodecyl sulfate (SDS) - Sodium dodecylbenzenesulfonate (SDBS, NaDDBS) - Sodium dodecylsulfonate (SDSA) - Sodium sodium *n*-lauroylsarcosinate (Sarkosyl) - Sodium alkyl allyl sulfosuccinate (TREM) - Polystyrene sulfonate (PSS) - Sodium cholate
Cationic Surfactants	- Dodecyltrimethylammonium bromide (DTAB) - Cetyltrimethylammonium bromide (CTAB)
Anionic/Cationic Surfactants	- ZetaSperse 2300
Nonionic Surfactants	- Brij Series - Tween Series - Triton X Series - Poly(vinylpyrrolidone) (PVP) - PEO-PBO-PEO triblock polymer (EBE) - PEO-PPO-PEO triblock polymers (Pluronic® Series

[00048] The chemical mixture for use in connection with the wetting procedure of the present invention, thus, can include (i) a solvent, including, Aniline (Phenyl amine, Amino benzene), DMF (Dimethyl formamide), NMP (N-methylpyrrolidone), Toluene (methylbenzene), Acetone (Dimethyl ketone), or Dichlorobenzene, (ii) a surfactant, including an anionic surfactant, a cationic surfactant, an anionic/cationic surfactant, or a non-ionic surfactant, as provided above, in any combination, and may also include (iii) a dispersant, including any of the large chain polymers provided above.

Removing the Chemical

[00049] Following the elongation or stretching procedure, the extensible structure 121 may be washed in an appropriate solvent, such as acetone. Thereafter, the stretched structure may be air dried, then baked in a oven in air at temperatures that may be below about 400° C. The washing and drying procedure can be effective in removing chemicals used in the stretching process. The washing and drying procedure, when acetone is used, in one embodiment, can also

further enhance contacts between adjacent nanotubes, so as to further increase conductivity (e.g., electrical and thermal) of the extensible structure 121.

[00050] Although acetone is disclosed, it should be appreciated that the step of washing may be accomplished using one of a thermal treatment, a chemical treatment, a electrochemical treatment, or a combination thereof.

Example I

[00051] A single wall carbon nanotube non-woven sheet was produced by CVD deposition on a moving belt. This non-woven sheet (i.e., extensible structure) had dimensions of about 8 inches by about 36 inches, with an area density of about 1 mg/cm^2. The approximate volumetric density of this non-woven sheet was about 0.2 g/cm^3. This non-woven sheet was mounted in system 30 of Figure 3, and sprayed with a solution of DMF and ZetaSperse. The solution of DMF and ZetaSperse was allowed to soak in for a period of about 10 minutes. The non-woven sheet was then stretched on system 30 at an elongation rate of about 1 inch/hr at a rotation rate of approximately 7 rpm.

[00052] Following the stretching, the non-woven sheet was soaked in acetone, allowed to air dry, and then baked in air at a temperature of 350° C for about 3 hours.

[00053] Samples of this stretched non-woven sheet were taken from which property measurements were made. The results of the measurements are provided in Table 3.

Table 3

Property	Before	After
Resistivity	8 $X10^{-4}$ Ω-cm	2 X 10^{-4} Ω-cm
Tensile Strength	200 MPa	800 MPa
Seebeck Coefficient	6 μV/°K	43 μV/°K

Example II

[00054] A partially spun yarn made of single wall carbon nanotubes was produced by a CVD process, similar to that described in U.S. Patent Application Serial No. 11/488,387, incorporated herein by reference.

[00055] With reference now to Fig. 5, under steady-state production using a CVD process of the present invention, nanotubes 51 may be collected from within a synthesis chamber 52 and a yarn 53 may thereafter be formed. Specifically, as the nanotubes 51 emerge from the synthesis chamber 52, they may be collected into a bundle 54, fed into intake end 55 of a spindle 56, and subsequently spun or twisted into yarn 53 therewithin. It should be noted that a continual twist to the yarn 53 can build up sufficient angular stress to cause rotation near a point where new nanotubes 51 arrive at the spindle 56 to further the yarn formation process. Moreover, a continual tension may be applied to the yarn 53 or its advancement into collection chamber 58 may be permitted at a controlled rate, so as to allow its uptake circumferentially about a spool 57.

[00056] Typically, the formation of the yarn results from a bundling of nanotubes that may subsequently be tightly spun into a twisting yarn. Alternatively, a main twist of the yarn may be anchored at some point within system 10 and the collected nanotubes may be wound on to the twisting yarn. Both of these growth modes can be implemented in connection with the present invention.

[00057] The yarn generated can be immersed in an aniline solution, then stretched by hand by about 500 percent (i.e., 5 times its initial length). In an embodiment, the yarn can be soaked for a period of approximately 1 hour then stretched. A sample of the stretched material was taken for property measurements and these results are shown below in Table 4.

Table 4

Property	Before	After
Resistivity	3.0 X10^{-4} Ω-cm	1.6 X 10^{-4} Ω-cm
Tensile Strength	1000 MPa	1600 MPa

[00058] It should be appreciated that the observed differences in properties between the extensible structure having substantially aligned nanotubes and increased contact points between adjacent nanotubes (After) and the extensible structure having substantially non-aligned nanotubes (Before) in both Example I (non-woven sheet) and Example II (yarn) are profound. For example, the tensile strength of the non-aligned nanotubes in the non-woven sheet changes from about 200 MPa to 800 MPa upon alignment, whereas the Seebeck coefficient changes from about 5 micro-Vs per degree K to about 50 micro-Vs per degree K. In addition, the resistivity, and thus conductivity, changes from about 8×10^{-4} Ω-cm to about 2×10^{-4} Ω-cm.

[00059] As for the yarn, although the nanotubes in the yarn are more aligned than the non-woven sheet at the start, an improvement in tensile strength, from about 1000 MPa to about 1600 MPa, and resistivity, from about 3.0×10^{-4} Ω-cm to about 1.6×10^{-4} Ω-cm were also observed upon alignment of the nanotubes.

[00060] While the present invention has been described with reference to certain embodiments thereof, it should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the invention. In addition, many modifications may be made to adapt to a particular situation, indication, material and composition of matter, process step or steps, without departing from the spirit and scope of the present invention. All such modifications are intended to be within the scope of the claims appended hereto.

What is claimed is:

1. A method for aligning nanotubes within an extensible structure, the method comprising:

providing an extensible structure having a plurality of substantially non-aligned nanotubes;

adding a chemical mixture to the extensible structure, so as to wet the extensible structure; and

stretching the extensible structure, so as to substantially align the nanotubes within the extensible structure relative to one another.

2. A method as set forth in claim 1, wherein, in the step of providing, the extensible structure is a non-woven sheet of non-aligned nanotubes.

3. A method as set forth in claim 1, wherein, in the step of providing, the extensible structure is a yarn comprising a plurality of twisted nanotubes.

4. A method as set forth in claim 1, wherein, in the step of providing, the nanotubes include one of carbon nanotubes, boron nanotubes, or a combination thereof.

5. A method as set forth in claim 1, wherein, in the step of providing, the nanotubes include one of single wall nanotubes, multiwall nanotubes, or a combination thereof.

6. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes a solvent.

7. A method as set forth in claim 6, wherein, in the step of adding, the solvent includes one of Aniline (Phenyl amine, Amino benzene), DMF (Dimethyl formamide), NMP (N-methylpyrrolidone), Toluene (methylbenzene), Acetone (Dimethyl ketone), or Dichlorobenzene.

8. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes a surfactant.

9. A method as set forth in claim 8, wherein, in the step of adding the surfactant includes one of an anionic surfactant, a cationic surfactant, an anionic/cationic surfactant, or a non-ionic surfactant.

10. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixtures includes (i) a solvent, including, Aniline (Phenyl amine, Amino benzene), DMF (Dimethyl formamide), NMP (N-methylpyrrolidone), Toluene (methylbenzene), Acetone (Dimethyl ketone), or Dichlorobenzene, and (ii) a surfactant, including an anionic surfactant, a cationic surfactant, an anionic/cationic surfactant, or a non-ionic surfactant, in any combination.

11. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes aniline or in combination with one of Sodium dodecyl sulfate (SDS), Sodium dodecylbenzenesulfonate (SDBS, NaDDBS), Sodium dodecylsulfonate (SDSA), Sodium sodium *n*-lauroylsarcosinate (Sarkosyl), Sodium alkyl allyl sulfosuccinate (TREM), Polystyrene sulfonate (PSS), Sodium cholate, Dodecyltrimethylammonium bromide (DTAB), Cetyltrimethylammonium bromide (CTAB), ZetaSperse 2300, Brij Series, Tween Series, Triton X Series, Poly(vinylpyrrolidone) (PVP), PEO-PBO-PEO triblock polymer (EBE), PEO-PPO-PEO triblock polymers (Pluronic® Series), or similar surfactants.

12. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes neat aniline in combination with ZetaSperse.

13. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes DMF or in combination with one of Sodium dodecyl sulfate (SDS), Sodium dodecylbenzenesulfonate (SDBS, NaDDBS), Sodium dodecylsulfonate (SDSA), Sodium sodium *n*-lauroylsarcosinate (Sarkosyl), Sodium alkyl allyl sulfosuccinate (TREM), Polystyrene sulfonate (PSS), Sodium cholate,

Dodecyltrimethylammonium bromide (DTAB), Cetyltrimethylammonium bromide (CTAB), ZetaSperse 2300, Brij Series, Tween Series, Triton X Series, Poly(vinylpyrrolidone) (PVP), PEO-PBO-PEO triblock polymer (EBE), PEO-PPO-PEO triblock polymers (Pluronic® Series), or similar surfactants.

14. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes neat DMF in combination with ZetaSperse.

15. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes neat DMF in combination with SDS.

16. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes acetone or in combination with one of Sodium dodecyl sulfate (SDS), Sodium dodecylbenzenesulfonate (SDBS, NaDDBS), Sodium dodecylsulfonate (SDSA), Sodium sodium *n*-lauroylsarcosinate (Sarkosyl), Sodium alkyl allyl sulfosuccinate (TREM), Polystyrene sulfonate (PSS), Sodium cholate, Dodecyltrimethylammonium bromide (DTAB), Cetyltrimethylammonium bromide (CTAB), ZetaSperse 2300, Brij Series, Tween Series, Triton X Series, Poly(vinylpyrrolidone) (PVP), PEO-PBO-PEO triblock polymer (EBE), PEO-PPO-PEO triblock polymers (Pluronic® Series), or similar surfactants.

17. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes of neat acetone in combination with Zetasperse.

18. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes neat acetone in combination with SDS.

19. A method as set forth in claim 1, wherein, in the step of adding, the chemical mixture includes o-Dichlorobenzene or in combination with one of Sodium dodecyl sulfate (SDS), Sodium dodecylbenzenesulfonate (SDBS, NaDDBS), Sodium dodecylsulfonate (SDSA), Sodium sodium *n*-lauroylsarcosinate (Sarkosyl), Sodium alkyl allyl sulfosuccinate (TREM), Polystyrene sulfonate (PSS), Sodium cholate,

Dodecyltrimethylammonium bromide (DTAB), Cetyltrimethylammonium bromide (CTAB), ZetaSperse 2300, Brij Series, Tween Series, Triton X Series, Poly(vinylpyrrolidone) (PVP), PEO-PBO-PEO triblock polymer (EBE), PEO-PPO-PEO triblock polymers (Pluronic® Series), or similar surfactants.

20. A method as set forth in claims 1, wherein, in the step of adding, the chemical mixture includes ZetaSperse surfactant at a concentration between about 0.1 % and about 5% by volume.

21. A method as set forth in claims 1, wherein, in the step of adding, the chemical mixture includes ZetaSperse surfactant at a concentration of about 1% by volume.

22. A method as set forth in claim 1, wherein the step of adding includes performing the wetting at the temperature range from about 20 degrees centigrade to about 50 degrees centigrade.

23. A method as set forth in claim 1, wherein the step of adding includes performing the wetting at the temperature of about 23 degrees centigrade.

24. A method as set forth in claim 1, wherein the step of stretching is done in a mechanical apparatus.

25. A method as set forth in claim 1, wherein the step of stretching is done by one of by hand, by pressurized gas blowing on the fabric, by vacuum, or a combination thereof.

26. A method as set forth in claim 1, further including washing the stretched extensible structure in a solvent to remove any residue.

27. A method as set forth in claim 26, wherein the step of washing includes one of a thermal treatment, a chemical treatment, an electrochemical treatment, or a combination thereof.

28. A method as set forth in claim 26, further including exposing the washed extensible structure to a temperature less than about 400° C.

29. An extensible structure comprising:

a plurality of extended length nanotubes in substantial alignment relative to one another; and

a plurality of contact points between adjacent nanotubes, the contact points allowing for a relative increase in conductivity of the extensible structure in comparison to an extensible structure with substantially non-aligned nanotubes.

30. An extensible structure as set forth in claim 29, wherein the increase in conductivity includes increase in electrical conductivity.

31. An extensible structure as set forth in claim 29, wherein the increase in conductivity includes increase in thermal conductivity.

32. An extensible structure as set forth in claim 29, wherein the plurality of contact pointes between adjacent nanotubes allow for a relative increase in tensile strength of the extensible structure in comparison to an extensible structure with substantially non-aligned nanotubes.

33. An extensible structure as set forth in claim 29, wherein the nanotubes are capable of being stretched to allow the extensible to increase to at least about 5% or more of its original length.

34. An extensible structure as set forth in claim 29, wherein the structure is one of a non-woven sheet or a yarn.

35. A system for aligning nanotubes within an extensible structure, the system comprising:

opposing rollers around which an extensible structure may be wrapped;

a mechanism to rotate the rollers;

means to permit the rollers to move away from one another as they rotate to stretch the extensible structure; and

a reservoir from which a chemical mixture may be dispensed to wet the extensible structure to help in the stretching process.

36. A system as set forth in claim 35, wherein the opposing rollers are designed to permit the extensible structure to be mounted in a loop about the rollers.

37. A system for aligning nanotubes within an extensible structure, the system comprising:

a first and second set of pinch rollers adjacent one another, and being designed to permit the extensible structure to be fed between the pinch rollers of each set;

a mechanism to permit each set of pinch rollers to rotate independently of one another so as to stretch the extensible structure being fed; and

a reservoir from which a chemical mixture may be dispensed to wet the extensible structure to help in the stretching process.

38. A system as set forth in claim 37, wherein one set of pinch rollers is designed to move at a slightly faster velocity than other set of pinch rollers.

39. A system as set forth in claim 38, wherein a difference in velocity between the set of pinch rollers ranges from about 1% to about 30%.

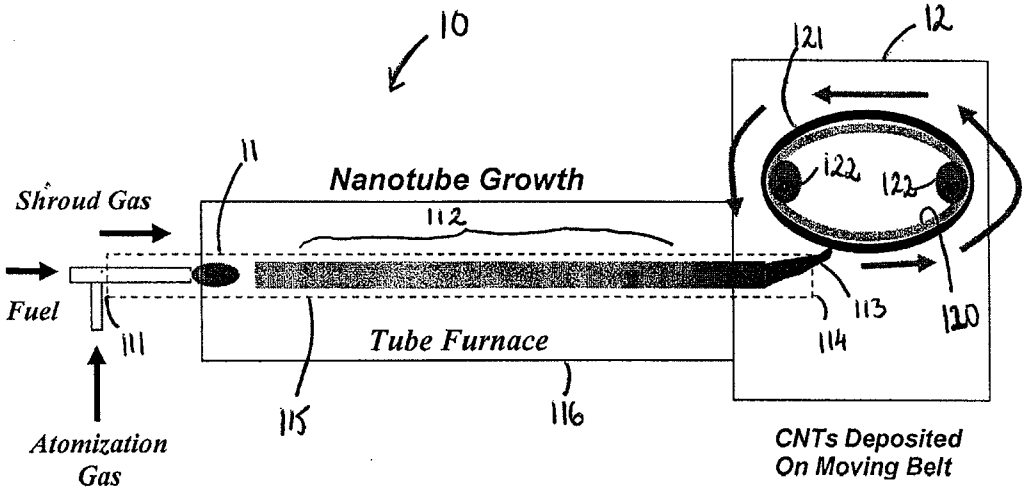

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Nanotube Growth
112
Shroud Gas
Fuel
111
Tube Furnace
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114
120
115
116
Atomization Gas
CNTs Deposited On Moving Belt

Fig. 1A

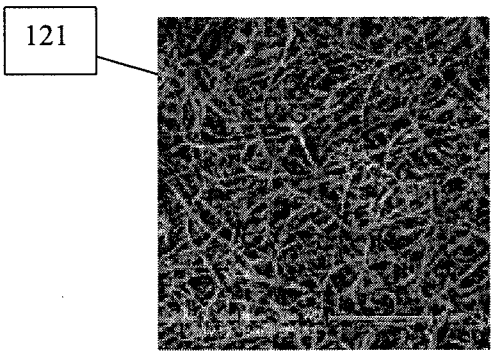

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Fig. 1B

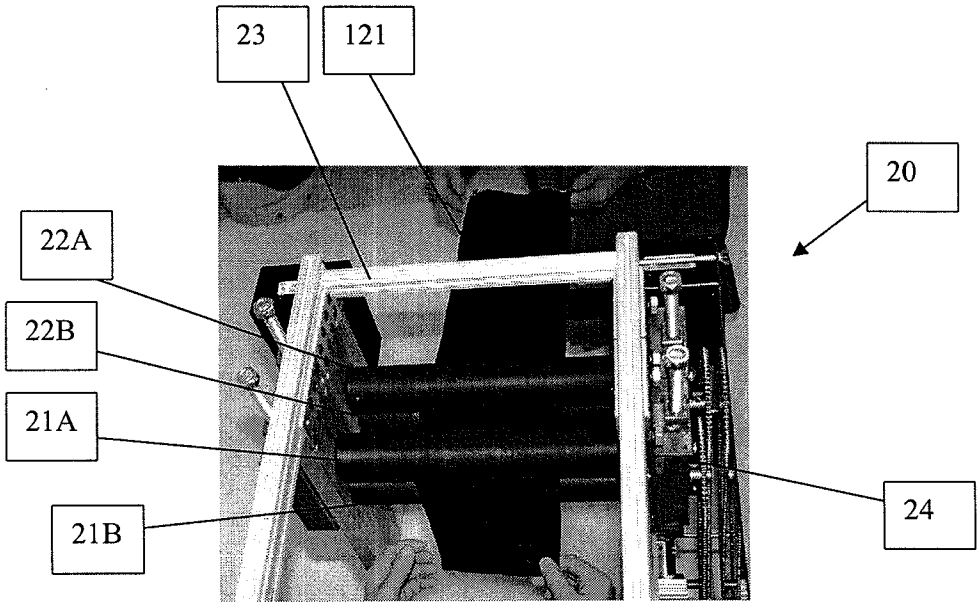


Fig. 2

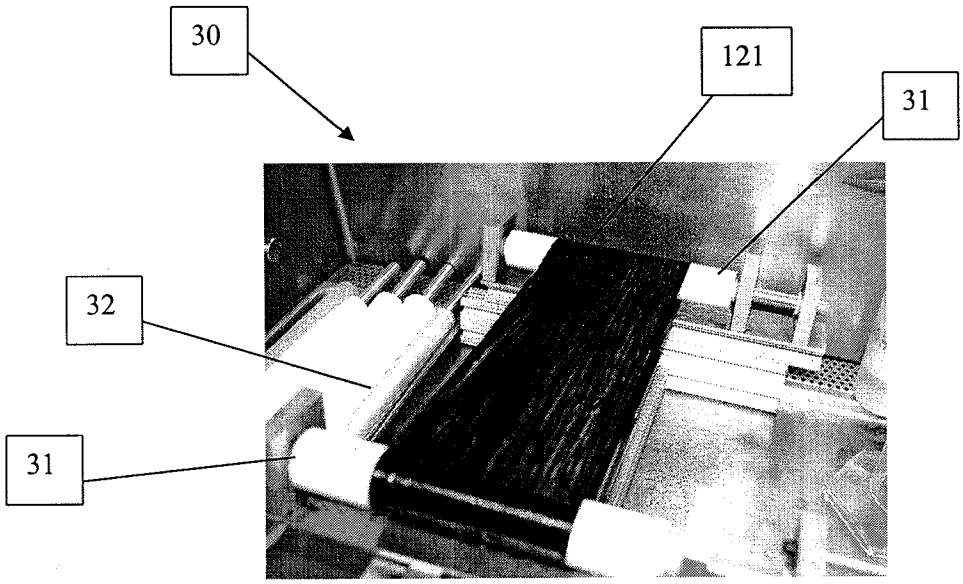


Fig. 3

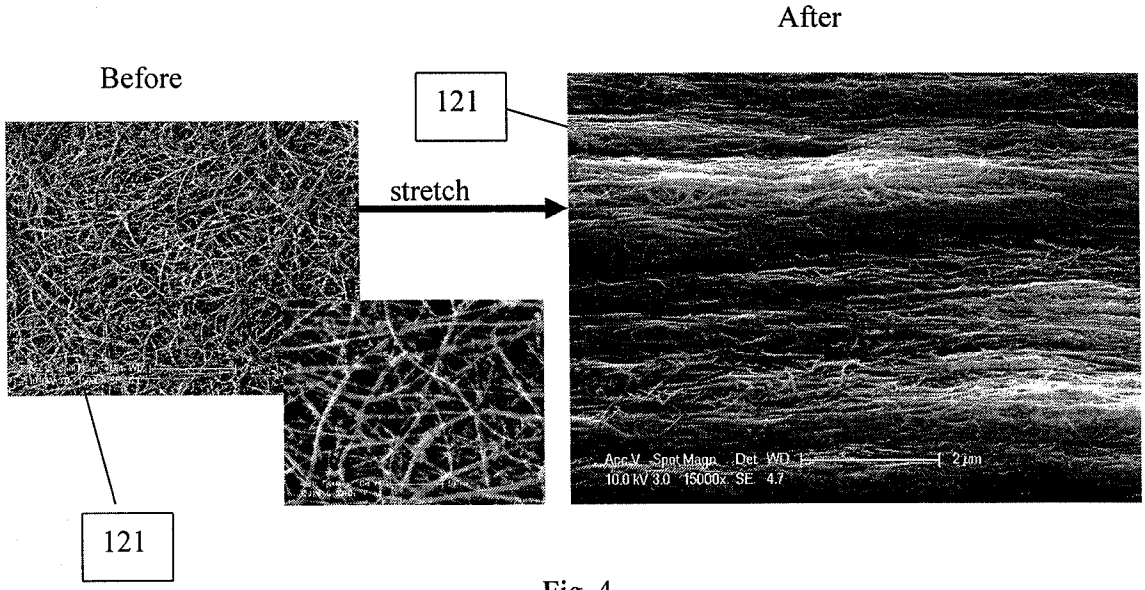

After
Before
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stretch
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Acc.V Spot Magn Det WD 2 µm
10.0 kV 3.0 15000x SE 4.7

Fig. 4

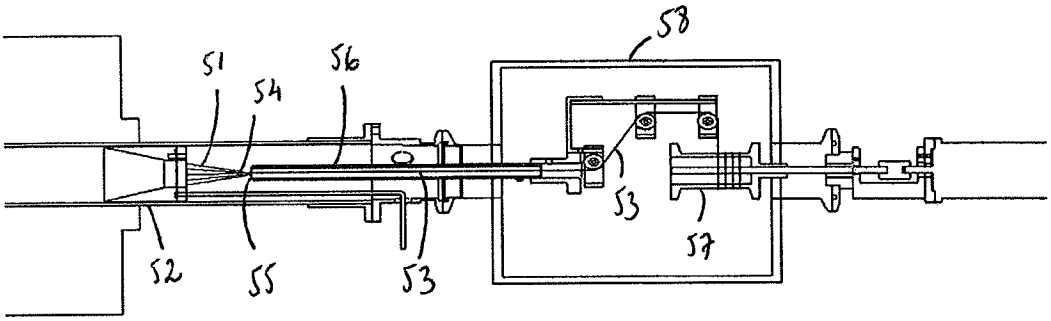

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Fig. 5