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(54) FUNCTIONALIZATION OF CARBON NANOTUBES

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(57) ABSTRACT
Method and system for functionalizing a collection of carbon nanotubes (CNTs). A selected precursor gas (e.g., H₂ or F₂) is irradiated to provide a cold plasma of selected target particles, such as atomic H or F, in a first chamber. The target particles are directed toward an array of CNTs located in a second chamber. An array of CNTs is functionalized with the target particles, at or below room temperature, to a point of saturation in an exposure time interval no longer than about 30 sec.
FIG. 3

Absorbance vs. Wavenumber (cm⁻¹)

Control

FIG. 4

Absorbance vs. Wavelength (nm)

Control
Irradiate a Precursor Gas to Provide Selected Target Particles in First Chamber

Provide a Collection of CNT's on a Substrate in a Second Chamber That Communicates With The First Chamber

Transport Target Particles to Second Chamber, Optionally Suppressing Transport of Ultraviolet Radiation From First to Second Chamber

Allow One or More Target Particles to Become Chemically Attached to One or More of The CNT's in The Second Chamber

FIG. 5
FUNCTIONALIZATION OF CARBON NANOTUBES

FIELD OF THE INVENTION

This invention is related to addition of functional groups to collections of carbon nanotubes.

BACKGROUND OF THE INVENTION

Carbon nanotubes (CNTs) have attracted much attention, due to their extraordinary mechanical properties and their unique electronic properties. A CNT is topologically equivalent to a two-dimensional graphite sheet rolled into a cylinder, with a cylinder diameter as small as 0.7 nanometers (nm) and with a cylinder length up to several microns (μm). A CNT can be single walled (SW) or multiple walled (MW) and can also be fabricated as a nanofiber or other CNT structure. A CNT can be characterized by its chiral vector components (n,m), which helps determine tube diameter, electronic properties and other properties. Depending upon the chirality (n-m divisible by 3 or otherwise), a CNT can be conducting (metal-like) or semi-conducting.

CNTs are being studied for applications in high strength/low weight composites, membranes, mechanical filters, body armor, space suits, electronics, nano-electro-mechanical systems, heat exchange systems, radiators, chemical sensors, physical sensors, actuators, data storage, computers and other applications. In some of these applications, chemical functionalization (addition of one or more specified chemical groups to a basic structure) may be necessary to alter the CNT properties for particular applications. For example, functionalization of the CNT tip or the side walls with suitable probe molecules can provide chemical sensors that recognize certain target species and ignore all others. Development of functional composites may require functionalization of a collection of CNTs to allow the tubes to be dispersed more easily in a host matrix.

An ideal functionalization process should be clean, produce relatively little residue for disposal, should be efficient, selective, and reasonably fast, should be scalable to large scale production, should not require use of complex apparatus to produce the target species or attach the species to the CNTs, and should not require complex chemical processing.

The CNT functionalization processes reported in the literature use wet chemical procedures and work with liquids or vapors, to which the CNTs are exposed. An example is use of hot flowing fluorine to attach fluorine atoms to CNTs, as reported by E. T. Michelson et al in Chem. Phys. Lett. vol 296 (1998) 188. Large quantities of wet chemicals are often required, with most of the chemicals becoming residues that must be disposed of under hazardous substance guidelines. Recycling of the chemicals used is seldom an option.

What is needed is a CNT functionalization process that is "dry", produces relatively little residue for clean-up, is flexible enough to be used for large numbers of chemical functional groups, is reasonably selective, is scalable, and does not require use of complex apparatus or complex processing to achieve functionalization of a collection of CNTs.

SUMMARY OF THE INVENTION

These needs are met by the present invention, which provides a selective, scalable approach, not involving "wet" chemistry, for functionalization of a collection of CNTs with any of a large class of elements and compounds, including hydrogen, the alkali metals, selected hydrocarbons, selected organic species, and the halogens. Taking hydrogen as an example of a target species, atomic hydrogen is produced by applying a glow discharge to a molecular hydrogen source to provide a cold plasma, and using a strong pressure differential to direct the atomic hydrogen thus produced toward the CNTs. Atomic hydrogen that is not received by the CNTs can be allowed to recombine and can be recovered for another glow discharge cycle.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1, 6 and 7 illustrate systems for practicing the invention.

FIG. 2 graphically illustrates FTIR spectra of non-functionalized CNTs and CNTs functionalized according to the invention.

FIG. 3 graphically illustrates saturation of CNT functionalization, using hydrogen, at various times.

FIG. 4 graphically illustrates absorption of the samples from FIG. 2 in portions of the ultraviolet, visible and infrared spectrum.

FIG. 5 is a flow chart of a procedure for practicing the invention.

DESCRIPTION OF PREFERRED MODES OF THE INVENTION

FIG. 1 illustrates a system 11 for practicing the invention to provide hydrogen as the species for functionalization of the CNTs. The system 11 includes a precursor source 13 that feeds hydrogen (e.g., molecular hydrogen, with a purity of 99.9999 percent or better) to a partially evacuated precursor chamber 15. Molecular hydrogen in the precursor chamber 15 is irradiated by a microwave source or other suitable radiation source 17, for example, a McCarroll cavity operating at 2.45 GHz and powered by an Optimos microwave generator. The radiation source 17 provides sufficient radiant energy to produce a cold plasma, in which the free electrons, with typical temperatures T_e=500-1000 K. This discharge produces electrons by ionization and radicals, especially atomic hydrogen as a precursor particle, by dissociation.

Part of the atomic hydrogen thus produced is received in an aperture 19 in a plug 21 of TEFLOm or other suitable material having an outer diameter of 5-25 mm, where the aperture 19 has a selected diameter (e.g., d(ap)=1 mm), has a selected length (e.g., 5-25 mm, or greater if desired), and connects the precursor chamber 15 with a target chamber 23 that contains a collection of CNTs 27, assembled in an array on a substrate 29, such as CaF₂. The substrate 29 is located adjacent to an aperture exit AE of the aperture 19, is oriented substantially perpendicular to the particle flow direction within the aperture at the aperture exit, and coated with purified CNTs. At appropriate time intervals, the substrate 29 can be removed from the target chamber 23 to harvest the functionalized CNTs and can be replaced by another substrate including non-functionalized CNTs. Purity of the CNTs used here is monitored using transmission electron microscopy, which verifies that troublesome substances, such as Fe nano-particle, are removed by the purification process (described in Khare et al., Nano Lett. vol. 2 (2002) pp. 73-77, incorporated by reference herein).

The precursor chamber 15 and the target chamber 23 are maintained at pressures of 100-1000 μm Hg and 1-10 μm Hg.
(optionally including an inert carrier gas, such as including N₂, Ne or Ar), respectively, using a vacuum pump 25 for the chamber 23, so that a large pressure ratio (100:1 to 500:1) exists between the two chambers. This large pressure ratio will encourage most of the atomic hydrogen produced in the precursor chamber 15 to move relatively quickly into and along the aperture 19 and to collide, react with and functionalize the CNTs 27. This functionalization process has been performed at room temperature and at temperatures down to liquid nitrogen temperatures.

FIG. 2 shows FTIR spectra for wavenumbers \( v' = 1300-1800 \text{ cm}^{-1} \), illustrating relative transmission for a CNT array (i) exposed to \( \text{H}_2 \) plus atomic \( \text{H} \) produced by a glow discharge and (ii) exposed to only \( \text{H}_2 \) (no discharge). C–H bending modes at wavenumbers of about \( v' = 1370 \text{ cm}^{-1} \) and \( v' = 1459 \text{ cm}^{-1} \) are manifest in the glow discharge curve, as expected from other experimental data. Two other spectral features occur at \( v' = 1566 \text{ cm}^{-1} \) and \( v' = 1727 \text{ cm}^{-1} \), which may correspond to C–C interaction in unfunctionalized CNTs and to C=C or C=O interaction in any carbonyl groups that are present. CNTs are known to absorb O atoms and \( \text{CH}_x \) molecules easily, even at very low pressures, and O atoms and/or \( \text{CH}_x \) molecules may be present as trace impurities in the hydrogen. The intensities of the extrema in the discharge curve did not change for exposure times intervals produced the same peaks, but at peak intensities several orders of magnitude smaller. Therefore, the absorption results in FIG. 3 can be attributed to functionalization of SWCNTs with atomic hydrogen, exposed to the plasma.

Experiments to demonstrate substantial functionalization of single wall CNTs (SWCNTs) with atomic hydrogen have been performed. Molecular hydrogen gas (\( \text{H}_2 \), 99.9999 percent purity) was passed through a liquid nitrogen trap to eliminate water and hydrocarbon impurities, with an \( \text{H}_2 \) pressure of about 500 \( \mu \text{m Hg} \) in the precursor chamber 13. The pressure in the CNT chamber 23 was about 1 \( \mu \text{m Hg} \). The \( \text{H}_2 \) precursor gas was irradiated, and a beam of \( \text{H} \) particles was directed along a central axis CA of the aperture 19 toward an array of SWCNTs on the substrate 29 in the CNT chamber 23. The SWCNTs were produced by the HiPCO process and were purified, as described in the Khare et al. article, op cit. The approach extends to other procedures, in addition to HiPCO, for producing SWCNTs and MWNTs.

Before functionalization with H, the SWCNTs were baked in a vacuum for 30 minutes at a temperature \( T = 810^\circ \text{C} \) to remove hydrocarbon impurities. A Thermo Nicolet Nexus 670 Fourier transform infrared (FTIR) spectrometer at 4 \( \text{cm}^{-1} \) resolution and a Perkin Elmer UV-VIS-NIR spectrometer (model Lambda 900) were used to analyze control (non-functionalized) and functionalized SWCNT samples.

Recombination of atomic hydrogen to produce molecular hydrogen, as well as other reactions, will also produce ultraviolet radiation within the precursor chamber 15, and such radiation is known to break C–H bonds in hydrogenated structures such as hydrogenated CNTs. For this reason, the aperture 19 in the plug 21 is aligned with an initial and/or final aperture segment that is curvilinear (referred to herein as “off-axis alignment”), or is otherwise configured so that little or no UV radiation is received by the target chamber 23 from the precursor chamber 15.

Recent theoretical studies by Bauschlicher et al., reported in Nan0 Lett. vol. 1 (2001) pp. 223 and in Nano Lett. vol. 2 (2002) p. 337, indicate that the maximum hydrogen coverage on the outside of a CNT is about 50 percent, due to \( \text{sp}^3 \) hybridization. Ultraviolet absorption, arising from \( \pi^* \pi^* \) excitations in a CNT covered with H atoms, are expected to be reduced to about half the absorption values found for “bare” CNTs with no H atoms present. FIG. 4 shows UV-VIS-NIR absorption data for the same samples as shown in FIGS. 2 and 3. The spectra are featureless for CNTs having varying diameters and bandgaps. The decrease in UV absorption intensity is consistent with decrease in the fraction of C–C bonds present, as would be expected. These UV-VIS-NIR data are consistent with the IR results of FIG. 3 and support the hypothesis that the SWCNT data, shown in FIG. 3, indicate substantial functionalization of these CNTs with atomic hydrogen.

This approach uses a glow discharge or cold plasma irradiation of the precursor molecules (here, \( \text{H}_2 \)) to provide functionalization of CNTs. The procedure is a clean, low temperature process that requires a relatively small amount of precursor gas (here, \( \text{H}_2 \)) and uses relatively high efficiency plasma production. A cold plasma process can be used for production of single species atomic halogens, beginning with a precursor gas such as \( \text{F}_2 \), \( \text{Cl}_2 \), \( \text{Br}_2 \) or \( \text{I}_2 \). A cold plasma process can be used for production of single species atomic alkali metals (single valence), such as Li, Na, K, Rb and Cs. A cold plasma process can also be used for
A method for functionalizing a collection of carbon nanotubes (CNTs), the method comprising:

1. A method for functionalizing a collection of carbon nanotubes (CNTs), the method comprising:

   1. Irradiating a precursor gas to provide a plurality of selected target particles in a first chamber having a first selected chamber pressure p1;
   2. Providing a collection of CNTs on a substrate in a second chamber having a second selected pressure p2, where p2 lies in a range of about between p1/100 ≤ p2 ≤ p1/100;
   3. Providing a particle communication mechanism that allows transport of at least a portion of the target particles from the first chamber to the second chamber, wherein the mechanism is configured so that transport of ultraviolet radiation from the first chamber to the second chamber is suppressed by providing an elongated aperture, having an aperture central axis and an aperture side wall and connecting the first and second chambers; wherein at least one of the following present: (i) the aperture central axis is aligned off-axis so that substantially no ultraviolet radiation that is produced within the first chamber can move in a single straight line from the first chamber to the second chamber, (ii) the aperture central axis is curvilinear, and is provided with sufficient curvature so that substantially no ultraviolet radiation that is produced within the first chamber can move in a single straight line from the first chamber to the second chamber, and (iii) allowing at least one of the target particles to become chemically attached to at least one of the CNTs in the second chamber; and
   4. The method of claim 1, further comprising providing at functionalized CNTs.

2. The method of claim 1, further comprising choosing the target particles from a group of target particle species consisting of H, Li, Na, K, Rb, Cs, F, Cl, Br, I, dichlorocarbene, C2H2Cl2, C3H7Cl, and CnH2n+2 with n=1, 2 and 3.

3. The method of claim 1, wherein said step of irradiating said precursor gas comprises providing a particle communication mechanism that allows transport of at least a portion of the target particles from the first chamber to the second chamber, wherein the mechanism is configured so that transport of ultraviolet radiation from the first chamber to the second chamber is suppressed by providing an elongated aperture, having an aperture central axis and an aperture side wall and connecting the first and second chambers; wherein at least one of the following present: (i) the aperture central axis is aligned off-axis so that substantially no ultraviolet radiation that is produced within the first chamber can move in a single straight line from the first chamber to the second chamber, (ii) the aperture central axis is curvilinear, and is provided with sufficient curvature so that substantially no ultraviolet radiation that is produced within the first chamber can move in a single straight line from the first chamber to the second chamber, and (iii) allowing at least one of the target particles to become chemically attached to at least one of the CNTs in the second chamber; and
   5. The method of claim 1, further comprising choosing the target particles from a group of target particle species consisting of H, Li, Na, K, Rb, Cs, F, Cl, Br, I, dichlorocarbene, C2H2Cl2, C3H7Cl, and CnH2n+2 with n=1, 2 and 3.

4. The method of claim 1, further comprising choosing the target particles from a group of target particle species consisting of H, Li, Na, K, Rb, Cs, F, Cl, Br, I, dichlorocarbene, C2H2Cl2, C3H7Cl, and CnH2n+2 with n=1, 2 and 3.

5. The method of claim 1, further comprising choosing the target particles from a group of target particle species consisting of H, Li, Na, K, Rb, Cs, F, Cl, Br, I, dichlorocarbene, C2H2Cl2, C3H7Cl, and CnH2n+2 with n=1, 2 and 3.

6. The method of claim 1, further comprising choosing the target particles from a group of target particle species consisting of H, Li, Na, K, Rb, Cs, F, Cl, Br, I, dichlorocarbene, C2H2Cl2, C3H7Cl, and CnH2n+2 with n=1, 2 and 3.