US009301401B2

(12) United States Patent
Humfeld

(10) Patent No.: US 9,301,401 B2
(45) Date of Patent: Mar. 29, 2016

(54) **NANOTUBE ELECTRONICS TEMPLATED SELF-ASSEMBLY**

(71) Applicant: **The Boeing Company**, Chicago, IL (US)

(72) Inventor: **Keith Daniel Humfeld**, Federal Way, WA (US)

(73) Assignee: **THE BOEING COMPANY**, Chicago, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/819,972**

(22) Filed: **Aug. 6, 2015**

(65) **Prior Publication Data**

US 2015/0342059 A1 Nov. 26, 2015

Related U.S. Application Data

(62) Division of application No. 13/897,480, filed on May 20, 2013, now Pat. No. 9,117,883, which is a division of application No. 12/874,319, filed on Sep. 2, 2010, now Pat. No. 8,450,202.

(60) Provisional application No. 61/258,375, filed on Nov. 5, 2009.

(51) **Int. Cl.**
H05K 3/22 (2006.01)
H01L 23/532 (2006.01)

(52) **U.S. Cl.**
CPC ***H05K 3/222*** (2013.01); ***H01L 23/53276*** (2013.01)

(58) **Field of Classification Search**
CPC H05K 3/222; H01L 21/76838; H01L 23/53276
USPC 257/746; 438/610; 118/612, 58
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,870,361 B2 * 3/2005 Chopra B82Y 15/00 257/798
8,450,202 B1 5/2013 Humfeld
9,117,883 B2 8/2015 Humfeld
2006/0281306 A1 * 12/2006 Gstrein H01L 21/76877 438/666
2007/0278448 A1 12/2007 Chari et al.

(Continued)

FOREIGN PATENT DOCUMENTS

DE 102006048537 A1 4/2008

OTHER PUBLICATIONS

Makaram et al., "Scalable nanotemplate assisted directed assembly of single walled carbon nanotubes for nanoscale devices," Applied Physics Letters, vol. 90, No. 243108, Jun. 2007, 3 pages.

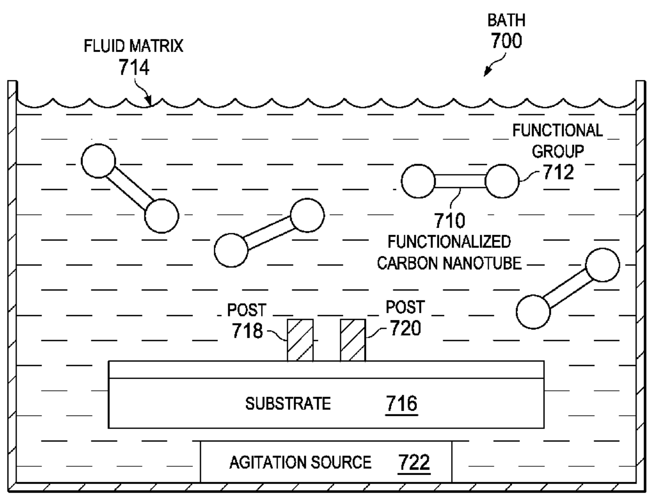
(Continued)

Primary Examiner — Walter H Swanson
(74) *Attorney, Agent, or Firm* — Yee & Associates, P.C.

(57) **ABSTRACT**

A fabricated substrate has at least one plurality of posts. The plurality is fabricated such that the two posts are located at a predetermined distance from one another. The substrate is exposed to a fluid matrix containing functionalized carbon nanotubes. The functionalized carbon nanotubes preferentially adhere to the plurality of posts rather than the remainder of the substrate. A connection between posts of the at least one plurality of posts is induced by adhering one end of the functionalized nanotube to one post and a second end of the functionalized carbon nanotube to a second post.

19 Claims, 5 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2009/0239338	A1*	9/2009	Zhou	B82Y 10/00 438/108
2011/0057717	A1	3/2011	Manning et al.	
2011/0156109	A1	6/2011	Gazit et al.	
2011/0180427	A1	7/2011	Matsumoto et al.	
2013/0264711	A1	10/2013	Humfeld	

OTHER PUBLICATIONS

Wei et al., "Directed Assembly of Polymer Blends Using Nanopatterned Templates," Advanced Materials, vol. 21, No. 7, Feb. 2009, pp. 794-798.

Xiong et al., "Building Highly Organized Single-Walled-Carbon-Nanotube Networks Using Template-Guided Fluidic Assembly," Small, vol. 3, No. 12, Dec. 2007, pp. 2006-2010.

Xiong et al., "Directed assembly of gold nanoparticle nanowires and networks for nanodevices," Applied Physics Letters, vol. 91, No. 063101, Aug. 2007, 3 pages.

Office Action, dated Sep. 25, 2012, regarding U.S. Appl. No. 12/874,319, 14 pages.

Notice of Allowance, dated Jan. 30, 2013, regarding U.S. Appl. No. 12/874,319, 8 pages.

Office Action, dated Feb. 21, 2014, regarding U.S. Appl. No. 13/897,480, 18 pages.

Final Office Action, dated Mar. 24, 2014, regarding U.S. Appl. No. 13/897,480, 19 pages.

Office Action, dated Jul. 7, 2014, regarding U.S. Appl. No. 13/897,480, 19 pages.

Notice of Allowance, dated Apr. 21, 2015, regarding U.S. Appl. No. 13/897,480, 11 pages.

* cited by examiner

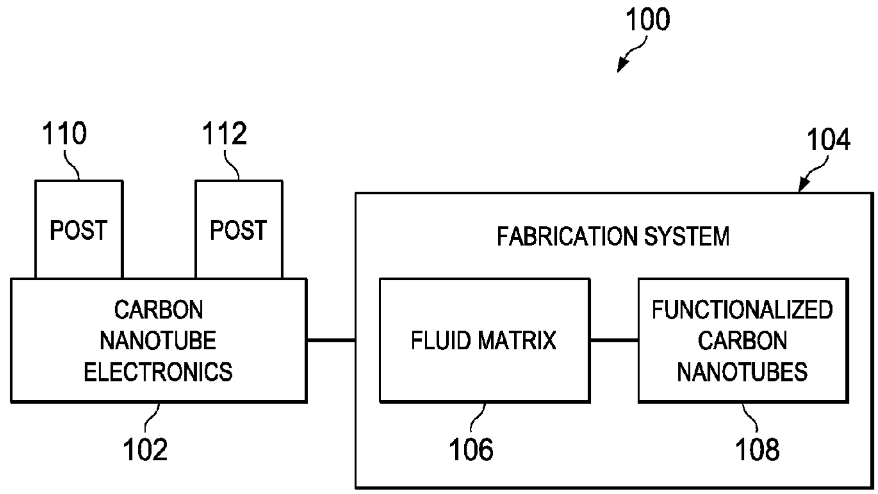

100
110
112
104
POST
POST
FABRICATION SYSTEM
CARBON NANOTUBE ELECTRONICS
FLUID MATRIX
FUNCTIONALIZED CARBON NANOTUBES
102
106
108

FIG. 1

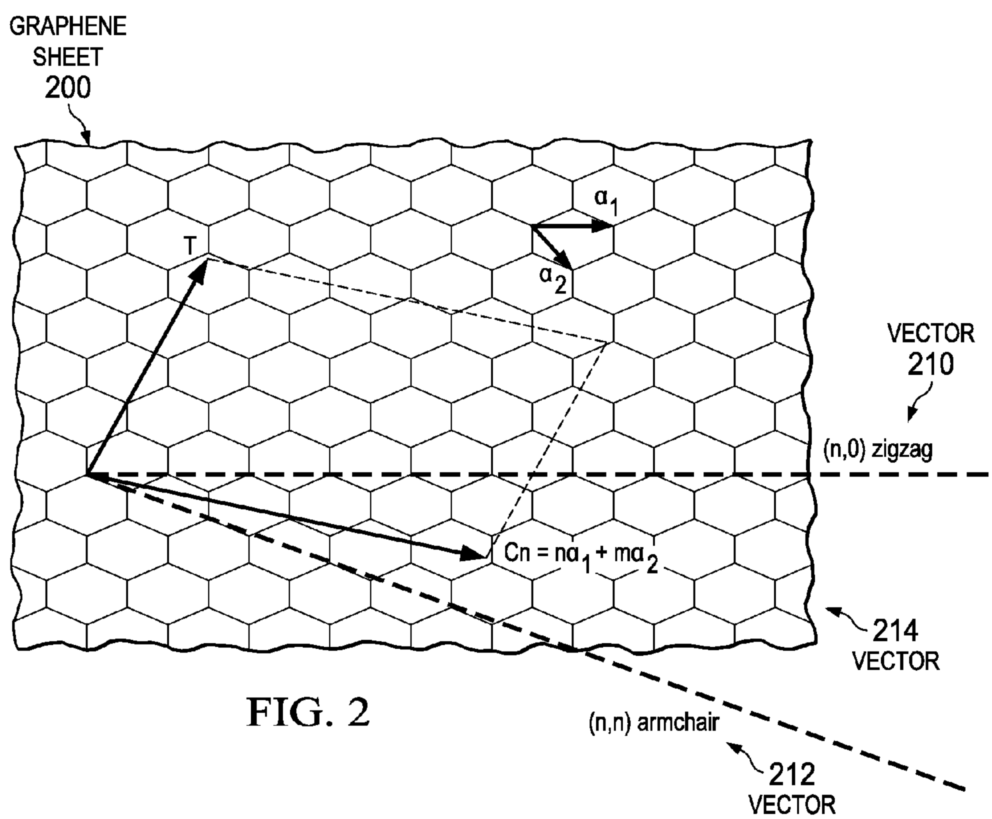

GRAPHENE SHEET 200
T
α1
α2
VECTOR 210
(n,0) zigzag
Cn = nα1 + mα2
214 VECTOR
(n,n) armchair
212 VECTOR

FIG. 2

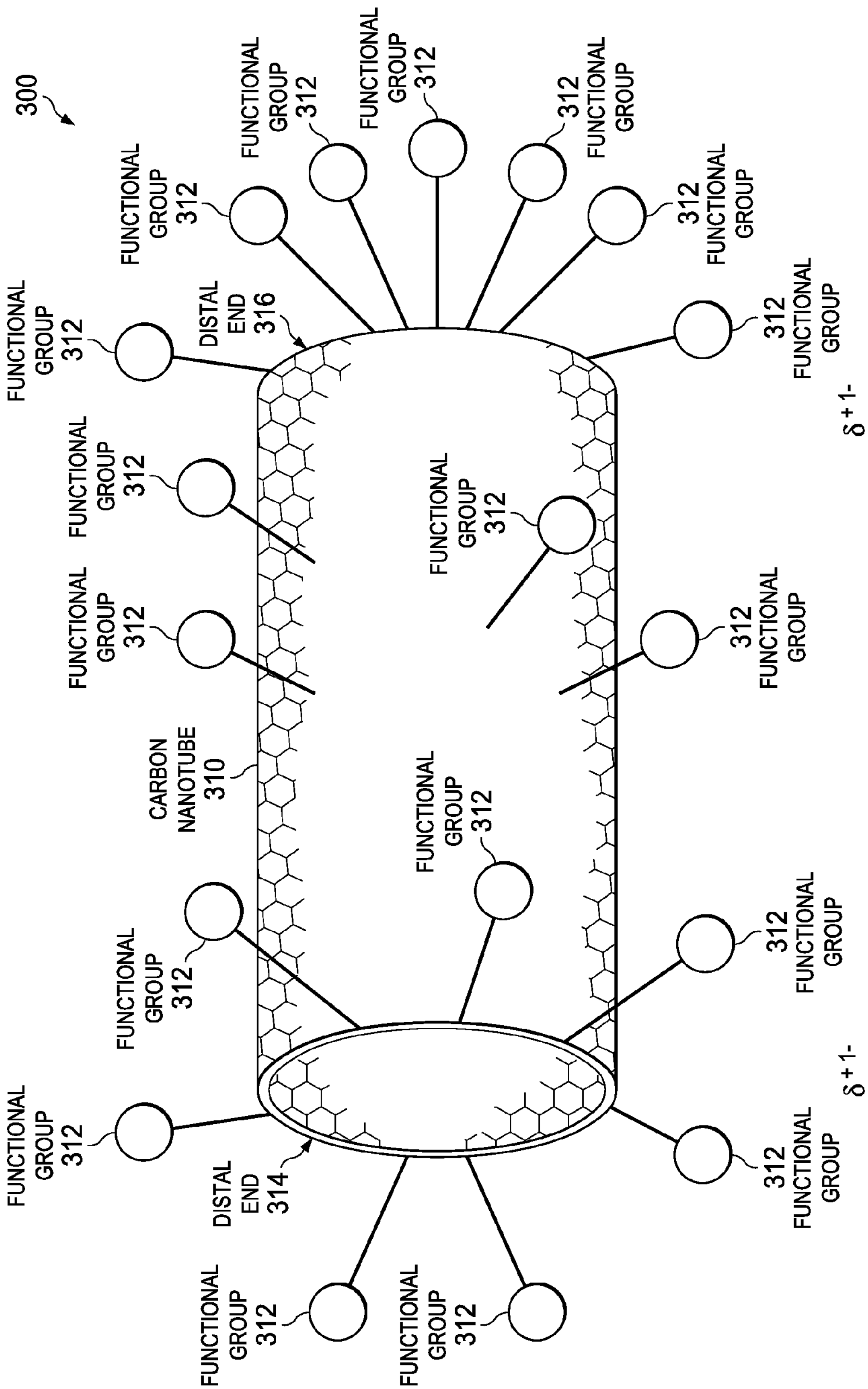

300
FUNCTIONAL GROUP 312
CARBON NANOTUBE 310
DISTAL END 314
DISTAL END 316
δ+1-
δ+1-

FIG. 3

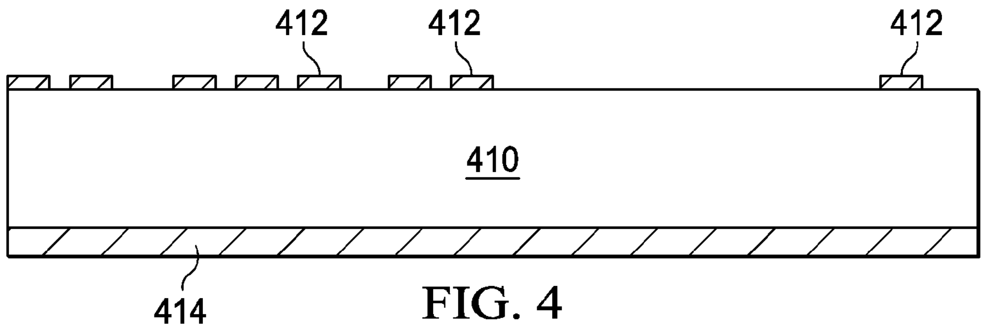


FIG. 4

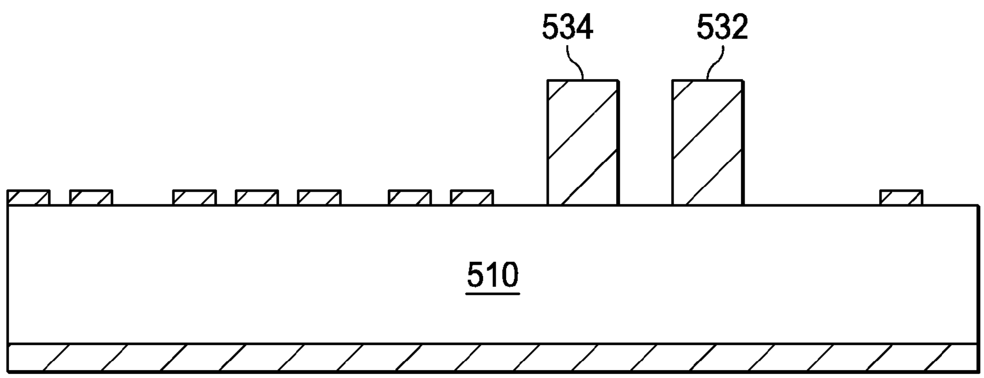


FIG. 5

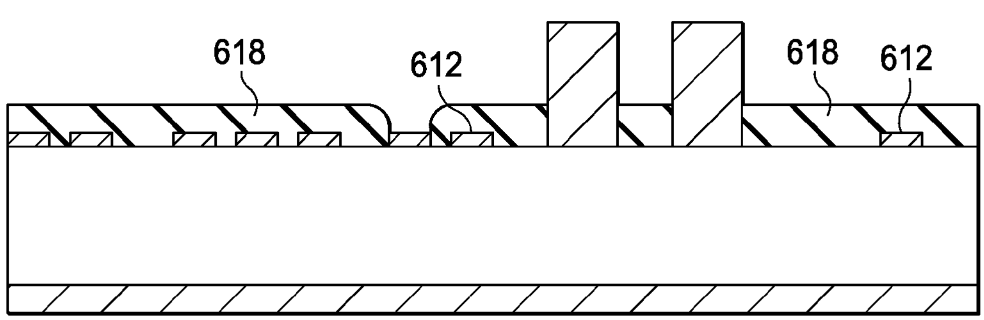


FIG. 6

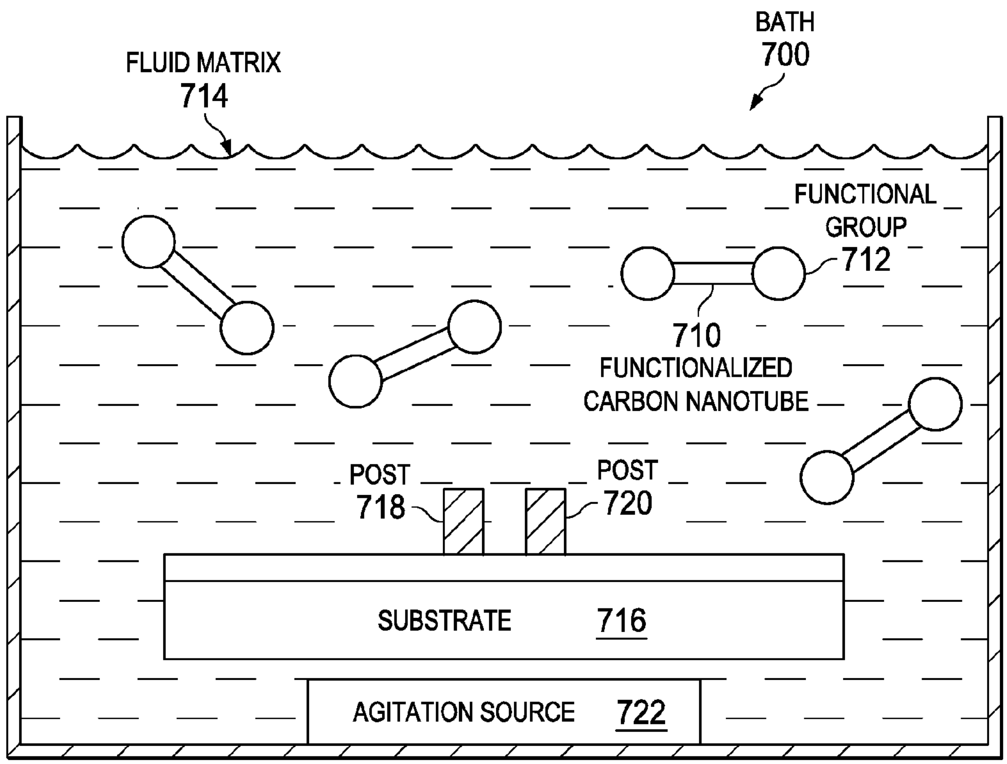

BATH
700
FLUID MATRIX
714
FUNCTIONAL
GROUP
712
710
FUNCTIONALIZED
CARBON NANOTUBE
POST
718
POST
720
SUBSTRATE 716
AGITATION SOURCE 722

FIG. 7

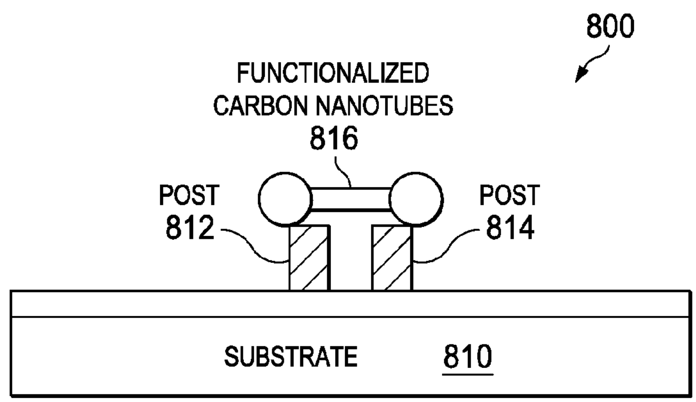

800
FUNCTIONALIZED
CARBON NANOTUBES
816
POST
812
POST
814
SUBSTRATE 810

FIG. 8

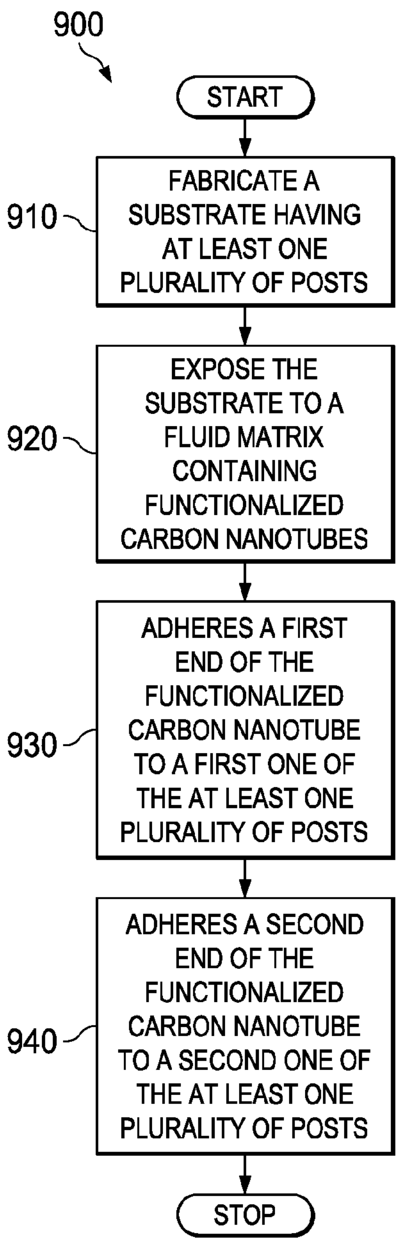

900
START
FABRICATE A SUBSTRATE HAVING AT LEAST ONE PLURALITY OF POSTS
910
EXPOSE THE SUBSTRATE TO A FLUID MATRIX CONTAINING FUNCTIONALIZED CARBON NANOTUBES
920
ADHERES A FIRST END OF THE FUNCTIONALIZED CARBON NANOTUBE TO A FIRST ONE OF THE AT LEAST ONE PLURALITY OF POSTS
930
ADHERES A SECOND END OF THE FUNCTIONALIZED CARBON NANOTUBE TO A SECOND ONE OF THE AT LEAST ONE PLURALITY OF POSTS
940
STOP

FIG. 9

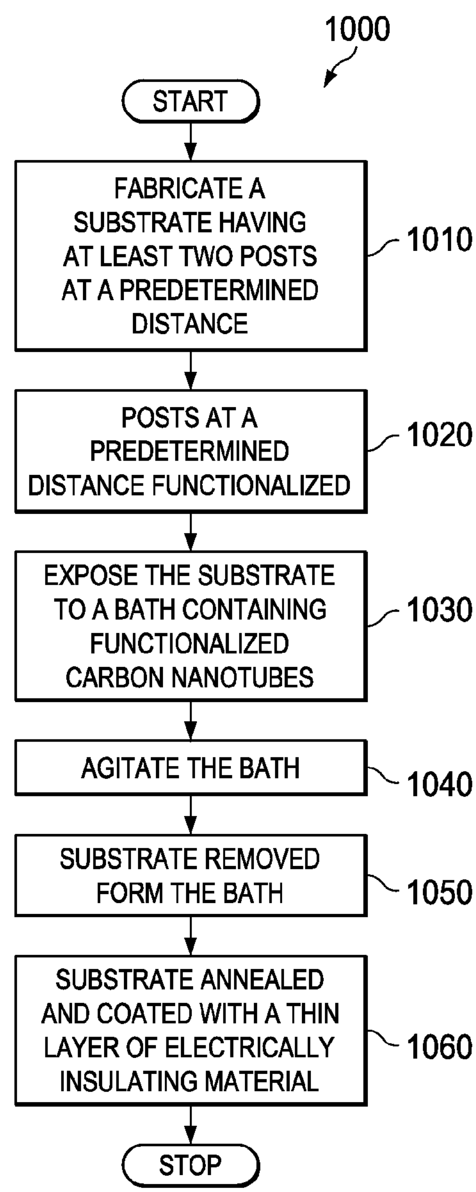

1000
START
FABRICATE A SUBSTRATE HAVING AT LEAST TWO POSTS AT A PREDETERMINED DISTANCE
1010
POSTS AT A PREDETERMINED DISTANCE FUNCTIONALIZED
1020
EXPOSE THE SUBSTRATE TO A BATH CONTAINING FUNCTIONALIZED CARBON NANOTUBES
1030
AGITATE THE BATH
1040
SUBSTRATE REMOVED FORM THE BATH
1050
SUBSTRATE ANNEALED AND COATED WITH A THIN LAYER OF ELECTRICALLY INSULATING MATERIAL
1060
STOP

FIG. 10

NANOTUBE ELECTRONICS TEMPLATED SELF-ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of, and claims the benefit of priority of, U.S. patent application Ser. No. 13/897,480, filed May 20, 2013; which is a divisional of, and claims the benefit of priority of, U.S. patent application Ser. No. 12/874,319, filed Sep. 2, 2010; all of which are related to, and claim the benefit of priority of, provisional U.S. patent application Ser. No. 61/258,375, filed Nov. 5, 2009, entitled "Nanotube Electronics Templated Self-Assembly"; all of the aforementioned applications are incorporated herein by reference.

BACKGROUND INFORMATION

1. Field

The present disclosure relates generally to methods and systems for production of electronic devices, and devices produced therefrom. More specifically, the present disclosure relates to methods and systems for production of circuits containing nanotubes.

2. Background

Modern processor chip designs often include one or more caches on the same integrated circuit chip as the processor, and in some cases include multiple processors on a single integrated circuit chip. Despite the enormous improvement in speed obtained from integrated circuitry, the demand for even faster computer systems has continued. With this demand comes a need for even further size reduction in the logic circuitry within an integrated circuit chip.

A typical integrated circuit chip is constructed in multiple layers. Many active and passive elements are formed on a substrate (usually silicon). A dielectric layer is placed over the elements, and multiple conductive layers, each separated by another dielectric layer, are formed over the elements. The conductive layers carry power and ground potentials, as well as numerous signal interconnects running among active elements. Each conductive layer comprises multiple discrete conductors, often running substantially in parallel. Conductive interconnects between conductive layers, or between a conductive layer and an active or passive element, are formed as holes in the dielectric layers, called vias, into which a conductive metal, such as aluminum or copper, is introduced.

The number of active elements in a typical processor dictates a very large number of interconnections, and since these must be packaged within a small area, the size of individual interconnections is limited. Conductors, whether in the conductive layer or the via between conductive layers, have a small, finite resistance, which grows as the cross-sectional area of the conductor shrinks. Increasing the number of logic elements on a chip requires a larger number of conductors, which in turn reduces the amount of space available for each individual conductor. If all other design parameters remain the same, this has the effect of increasing the resistances of the individual conductors.

Recently, carbon nanotubes have been used to form conductive pathways in integrated circuits. Carbon nanotubes are cylindrically structured carbon allotropes composed entirely of sp^2-hybridized bonding between carbon atoms. A single walled carbon nanotube is conceptually a one-atom-thick layer of graphene wrapped into a seamless cylinder.

Manufacturing of carbon nanotube-based electronics requires the positioning of each individual nanotube, which is prohibitive in terms of time and cost. While carbon nanotube-based electronics can be fabricated, individual nanotubes must be directly placed to create the carbon nanotube-based electronics. The direct placement of nanotubes requires an atomic force microscopy tip or similar microscope tip to position each of the nanotubes to form each electrical connection. The required time and cost of manually positioning each of the nanotubes to form each electrical connection is prohibitive of production scale manufacturing of carbon nanotube-based electronics.

Therefore, it would be advantageous to have a method and apparatus that takes into account at least one of the issues discussed above, as well as possibly other issues.

SUMMARY

An embodiment of the present disclosure provides methods and systems for production of nanotube-enabled circuits that do not rely on manual positioning of the nanotubes. Carbon nanotubes self-assemble on a metal-templated surface to form electrical connections including semiconducting connections that define a circuit.

A fabricated substrate has at least one plurality of posts. The plurality is fabricated such that the centers of two posts are located at a predetermined distance from one another.

Due to the available bond sites on the carbon atoms along the end of a nanotube, or due to the increased energy of the carbon bonds when stretched under curvature in two dimensions, functional groups preferentially adhere to distal ends of the carbon nanotube. The relative concentration of functional groups at the distal ends of functionalized carbon nanotubes creates a concentration of electrical charges.

The substrate is exposed to a fluid matrix containing functionalized carbon nanotubes. The ends of the functionalized carbon nanotubes preferentially adhere to the plurality of posts rather than the remainder of the substrate. A connection between posts of the at least one plurality of posts is induced by adhering a second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts.

The lengths and chiralities of the functionalized carbon nanotubes are preselected. The length of the functionalized carbon nanotubes matches the predetermined distance between the centers of posts of the plurality of posts. The chirality of the functionalized carbon nanotubes is selected to impart the desired electrical properties to the created circuit.

Carbon nanotubes are cylindrically structured carbon allotropes composed entirely of sp^2-hybridized bonding between carbon atoms. The chirality of the carbon nanotubes is denoted by a pair of indices (n, m). The values of n and m determine the chirality, or "twist" of the nanotube. The chirality, in turn, affects the conductance of the nanotube, its density, its lattice structure, and other properties. For a given (n, m) nanotube, if n=m, that is, the carbon nanotube has an "armchair" chirality, the carbon nanotube is conducting. If n−m is a multiple of three, then the nanotube is semiconducting with zero band gap such that the nanotube is considered semi-metallic. Otherwise, the nanotube is a moderate semiconductor. The band gap of a semiconducting carbon nanotube is determined uniquely by the chiral indices (n, m).

An embodiment of the present disclosure provides a method for assembling carbon nanotube electronics. A substrate is fabricated, wherein the substrate has at least one plurality of posts, the at least one plurality of posts being fabricated at a predetermined distance from one another. The substrate is then exposed to a fluid matrix containing functionalized carbon nanotubes. A first end of the functionalized carbon nanotube adheres to a first one of the at least one plurality of posts. A second end of the functionalized carbon

nanotube adheres to a second one of the at least one plurality of posts, wherein a connection is formed between posts of the at least one plurality of posts.

An embodiment of the present disclosure provides a system for assembling carbon nanotube electronics. The system comprises a substrate, wherein the substrate has at least one plurality of posts, the at least one plurality of posts being fabricated at a predetermined distance from one another. The system also comprises a fluid matrix containing functionalized carbon nanotubes, wherein the substrate is exposed to the fluid matrix. Agitation of the fluid matrix adheres a first end of at least one of the functionalized carbon nanotubes to a first one of the at least one plurality of posts, and induces a connection between posts of the at least one plurality of posts by adhering a second end of the at least one of the functionalized carbon nanotube, to a second one of the at least one plurality of posts.

The features, functions, and advantages can be achieved independently in various embodiments of the present disclosure, or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the advantageous embodiments are set forth in the appended claims. The advantageous embodiments, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an advantageous embodiment of the present disclosure when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is a carbon nanotube electronics assembly environment depicted in accordance with an advantageous embodiment;

FIG. **2** is a graphene sheet depicting several vectors along which a single walled carbon nanotube can be created in accordance with an advantageous embodiment;

FIG. **3** is a carbon nanotube that has been exposed to a fluid containing functional groups in accordance with an advantageous embodiment;

FIG. **4** is a fabrication technique of a printed circuit board in accordance with an advantageous embodiment;

FIG. **5** is a fabrication technique of a printed circuit board in accordance with an advantageous embodiment;

FIG. **6** is a fabrication technique of a printed circuit board in accordance with an advantageous embodiment;

FIG. **7** is a functionalized carbon nanotube bath for creating pathways in accordance with an advantageous embodiment;

FIG. **8** is a completed circuit having a carbon nanotube pathway in accordance with an advantageous embodiment;

FIG. **9** is a flowchart of a method for assembling carbon nanotube electronics in accordance with an advantageous embodiment; and

FIG. **10** is a flowchart of the processing steps for the self-assembly of a carbon nanotube electronic circuit in accordance with an advantageous embodiment.

DETAILED DESCRIPTION

The different advantageous embodiments provide a method and system for production of nanotube-enabled circuits that do not rely on manual positioning of the nanotubes. Carbon nanotubes self-assemble on a metallic templated surface to form electrical connections. These electrical connections include, for example, without limitation, semiconducting connections that define a circuit.

A substrate has at least one plurality of posts. The plurality of posts is fabricated such that the center of two posts are located at a predetermined distance from one another.

Other pluralities of posts might be fabricated at other predetermined distances.

The substrate is exposed to a fluid matrix containing functionalized carbon nanotubes. The ends of the functionalized carbon nanotubes preferentially adhere to the plurality of posts rather than the remainder of the substrate. A connection between posts of the at least one plurality of posts is induced by adhering a second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts.

The lengths and chiralities of the functionalized carbon nanotubes are preselected. The length of the functionalized carbon nanotubes matches the predetermined distance between the centers of the posts of the plurality of posts. The chirality of the functionalized carbon nanotubes is selected to impart the desired electrical properties to the created circuit.

With reference now to FIG. **1**, carbon nanotube assembly environment is depicted in accordance with an advantageous embodiment. Carbon nanotube assembly environment **100** is an exemplary environment in which carbon nanotube electronics **102** may be fabricated. In these examples, Fabrication system **104** is used to fabricate carbon nanotube electronics **102**.

In the illustrative example fabrication system **104** comprises fluid matrix **106** and functionalized carbon nanotubes **108**. Fluid matrix **106** is a matrix capable of suspending functionalized carbon nanotubes **108** in solution, without dissolving functionalized carbon nanotubes **108**. Fluid matrix **106** acts as a carrier system for delivering and suspending functionalized carbon nanotubes **108** during assembly of carbon nanotube electronics **102**. In one advantageous embodiment, fluid matrix **106** is an aqueous solution.

Functionalized carbon nanotubes **108** are carbon nanotubes having functional groups attached thereto. Carbon nanotubes are cylindrically structured carbon allotropes composed entirely of sp^2-hybridized bonding between carbon atoms. Functionalized carbon nanotubes **108** are formed by exposing carbon nanotubes to a source of functional groups under favorable reaction conditions.

Due to the available bond sites on the carbon atoms along the end of a nanotube, or due to the increased energy of the carbon bonds when stretched under curvature in two dimensions, functional groups preferentially adhere to distal ends of the carbon nanotube. The relative concentration of functional groups at the distal ends of functionalized carbon nanotubes **108** creates a concentration of electrical charges.

Carbon nanotube electronics **102** is a chip, circuit board, or other electronic device that includes circuits, pathways, or electrical connections formed from carbon nanotubes. Carbon nanotube electronics **102** includes posts **110** and **112**. Posts **110** and **112** are points on carbon nanotube electronics **102** that are to be connected by a carbon nanotube. Posts **110** and **112** are fabricated such that the centers of the two posts are located at a predetermined distance from one another.

The lengths and chiralities of functionalized carbon nanotubes **108** are preselected. The length of functionalized carbon nanotubes **108** matches the predetermined distance between the centers of posts of posts **110** and **112**. The chirality of the functionalized carbon nanotubes is selected to impart desired electrical properties to carbon nanotube electronics **102**.

Carbon nanotube electronics **102** is exposed to fluid matrix **106**. Upon exposure, an end of the functionalized carbon nanotubes **108** preferentially adheres to the plurality of posts rather than the remainder of the substrate. A connection between posts of the at least one plurality of posts is induced by adhering a second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts.

The illustration of carbon nanotube assembly environment **100** in FIG. **1** is not meant to imply physical or architectural limitations to the manner in which different advantageous embodiments may be implemented. Other components in addition to, and/or in place of, the ones illustrated may be used. Some components may be unnecessary in some advantageous embodiments. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined and/or divided into different blocks when implemented in different advantageous embodiments.

Referring now to FIG. **2**, a graphene sheet is shown depicting several vectors along which a single walled carbon nanotube can be created, according to an advantageous embodiment. Graphene sheet **200** is conceptually an unrolled single walled carbon nanotube showing the various chiralities that can be formed.

Carbon nanotubes are cylindrically structured carbon allotropes composed entirely of sp^2-hybridized bonding between carbon atoms. A single walled carbon nanotube is conceptually a one-atom-thick layer of graphene wrapped into a seamless cylinder. The chirality of the wrapped graphene sheet is wrapped in the chiral vector, denoted by a pair of indices (n, m). The integers n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. The values of n and m determine the chirality, or "twist" of the nanotube. The chirality, in turn, affects the conductance of the nanotube, its density, its lattice structure, and other properties.

Vector **210** is represented by an indices of (n, 0). Vectors having an "m" value equal to zero (0) are said to have a "zigzag" pattern that is non-chiral. Vector **212** is represented by an indices of (n, n), that is, the "n" and "m" values are equal. Vector **212** having an "n" value equal to the "m" is said to have an "armchair" pattern that is non-chiral. Vector **214** is represented by an indices of (n, m), wherein the "n" and "m" values are not equal.

The different chiral structures of carbon nanotubes strongly affect the electrical properties of the nanotube. For a given (n, m) nanotube, if n=m, that is, the carbon nanotube has an "armchair" chirality, the carbon nanotube is conducting. If n−m is a multiple of three, then the nanotube is semiconducting with zero band gap such that the nanotube is considered semi-metallic. Otherwise, the nanotube is a moderate semiconductor. The band gap of a semiconducting carbon nanotube is determined uniquely by the chiral indices (n, m).

Referring now to FIG. **3**, a carbon nanotube that has been exposed to a fluid containing functional groups is shown in accordance with an advantageous embodiment. Carbon nanotube **310** is a carbon nanotube having a chirality such described in FIG. **2**.

Functional groups **312** preferentially attract to, and concentrate at, the distal ends of carbon nanotube **310**. Functional groups **312** are chemical functional groups capable of adhering to the surface and ends of carbon nanotube **310**. In one advantageous embodiment, functional groups **312** are carboxylic acid functional groups.

Due to the available bond sites on the carbon atoms along the end of a nanotube, or due to the increased energy of the carbon bonds when stretched under curvature in two dimensions, functional groups **312** preferentially adhere to distal ends **314** and **316** of carbon nanotube **310**. The relative concentration of functional groups at distal ends **314** and **316** of carbon nanotube **310** creates a concentration of electrical charges.

Carbon nanotube **310** is pictured with "open" ends. Nanotubes with open ends will experience functionalization preferentially along their ends, due to the available bond sites at the carbons along the edge.

While not shown, Carbon nanotube **310** may also be a "capped" nanotube. A capped nanotube will experience functionalization preferentially along its end caps, due to the increased energy due to the curvature in two dimensions.

Distal ends **314** and **316** therefore exhibit a relative charge different from that of the middle of carbon nanotube **310**. Depending on what specific functional group is adhered to distal ends **314** and **316**, this relative charge can be either a partial delta negative charge or a partial delta positive charge. Other reasons that the functionalized groups cause preferential attachment of the nanotubes besides the charge imbalance include, for example, but are not limited to polarity of functional group, hydrogen bonding, and modification of Van der Waals forces.

FIGS. **4-6** depict the fabrication of a printed circuit board according to an advantageous embodiment.

Referring now to FIG. **4**, there is shown an electrically insulating substrate **410**. Electrically insulating substrate **410** is a base or supporting material to which additional layers or materials are applied. Electrically insulating substrate **410** is, for example, but not limited to, an epoxy substrate.

In these examples, signal-wiring conductors **412** and **414** can be selectively deposited into a connection pattern by a dry-film dielectric with laser via process on selected surface portions of electrically insulating substrate **410**, signal wiring conductors **412** and **414** are an electrically conductive material. This material may be, for example, but not limited to, copper, molybdenum, and tungsten. Each of the layers **412** and **414** has a weight of, for example, about 0.5 ounces and a thickness of, for example, about 18 micrometers.

Signal wiring conductors **412** and **414** can be patterned by direct selective deposition, selective etching, or other suitable techniques. Signal wiring conductor **414** on the other side can be utilized as a power supply layer. However, it should be clear to those skilled in the art, that signal wiring conductor **414** can also be patterned and segmented into a power mesh with signal pads distributed within the power mesh, but not necessarily connected to the power mesh.

As shown in FIG. **5**, post **532** and post **534** are formed on substrate **510** at a location where a connection is to be established. Post **532** and post **534** are fabricated at a predetermined distance from one another that matches a known length of a carbon nanotube that will be utilized to span the distance between post **532** and post **534**. The coupled carbon nanotube can form useful circuits when the substrate is designed with knowledge of nanotube length and desired electrical properties (chiralities).

While post **532** and post **534** are shown as being formed early in the fabrication process, it is appreciated that post **532** and post **534** can be similarly fabricated at other points during fabrication of a printed circuit board. Post **532** and post **534** can be formed, for example, but not limited to, prior to deposition of any signal wiring connectors, after deposition of signal wiring connectors, and at any other point during the build up of various layers of the printed circuit boards.

Next, in FIG. **6**, layer **618** of electrically insulating material, preferably a layer of photosensitive resin, is applied to cover the signal-wiring conductors **612** in the first wiring layer, and the photosensitive resin is then exposed and developed. The photosensitive resin can be a negative type photosensitive epoxy resin applied to the surface of the substrate by curtain coating, and then precured. The photosensitive resin is then developed with a developer. This developer may be, for example, a mixture of propylene carbonate, cyclohexanone, and gamma-butyrolactone.

After being developed, the surface of the epoxy resin layer **618** is roughened by etching with a solution of potassium permanganate, and is then activated with a seeding chemical. This seeding chemical is a solution including colloidal tin and palladium in this illustrative example.

It is appreciated that signal wiring conductors **612** can be patterned by other methods known in the art, such as for example, by a dry-film dielectric with laser via process by selective etching to form a second wiring layer or wiring level which includes signal wiring conductors **612**. Additional layers may be added to one or both sides of the circuit board in subsequent steps not shown here.

Referring now to FIG. **7**, a functionalized carbon nanotube bath for creating pathways is shown in accordance with an advantageous embodiment. Bath **700** contains functionalized carbon nanotubes **710** which can be carbon nanotube **310** of FIG. **3**. Substrate **716** can be a printed circuit board, such as the electrically insulating substrate **510** of FIG. **5** that is formed into a printed circuit board as described in relation to FIG. **7**.

Functionalized carbon nanotubes **710** are suspended in fluid matrix **714**. Functionalized carbon nanotubes **710** have been filtered or otherwise segregated such that each of functionalized carbon nanotubes **710** have similar chiralities and lengths. In one advantageous embodiment, each of functionalized carbon nanotubes **710** is narrowly dispersed around a given length, such as, but not limited to 80+/−1 nanometers, 100+/−1 nanometers, and 120+/−1 nanometers. In one advantageous embodiment, each of functionalized carbon nanotubes **710** have similar chiral vectors (or non-chiral vectors), such that each of functionalized carbon nanotubes **710** within fluid matrix **714** have similar or identical indices (n, m).

It is appreciated that functional groups **712**, attached to functionalized carbon nanotubes **710**, may be present along the shaft of functionalized carbon nanotubes **710** in addition to the shown locations at distal ends of the functionalized carbon nanotubes **710**. However, as shown in FIG. **3** above, functional groups **712** preferentially adhere to distal ends of functionalized carbon nanotubes **710**. The relative concentration of functional groups at distal ends of functionalized carbon nanotubes **710** creates a relative charge at each of the distal ends of functionalized carbon nanotubes **710**.

Bath **700** also contains fluid matrix **714**. Fluid matrix **714** is a matrix capable of suspending functionalized carbon nanotubes **710** in solution, without dissolving functionalized carbon nanotubes **710**. In one advantageous embodiment, fluid matrix **714** is an aqueous solution.

Substrate **716** is submerged in fluid matrix **714**. Substrate **716** includes post **718** and post **720**. Post **718** and post **720** are fabricated on substrate **716** such that the linear distance between the center of post **718** and the center of post **720** matches the known length of functionalized carbon nanotubes **710**. Thus, in one advantageous embodiment, the linear distance between the center of post **718** and the center of post **720** can be one of 80+/−1 nanometers, 100+/−1 nanometers, and 120+/−1 nanometers.

In one advantageous embodiment, post **718** and post **720** are functionalized prior to immersion in fluid matrix **714**.

Functional groups **712** of functionalized carbon nanotubes **710** preferentially adhere to post **718** and post **720** rather than the remainder of substrate **716**. Because the functionalized carbon nanotubes **710** have previously been filtered according to a desired size, functionalized carbon nanotubes **710** will energetically prefer to attach themselves in a manner that spans the linear distance between post **718** and post **720**, thus creating an electrical pathway along functionalized carbon nanotubes **710**.

Bath **700** also contains, or is functionally coupled to, agitation source **722**. Agitation source **722** is a source of disturbance to bath **700**. Once substrate **716** is submerged within bath **700**, agitation source **722** provides gentle agitation to fluid matrix **714**.

The agitation of fluid matrix **714** provides the motion and energy required to remove nanotubes that may have adhered to post **718** or post **720** along the shaft rather than at functional groups **712** of functionalized carbon nanotubes **710**. The agitation of fluid matrix **714** further provides the necessary turbulence to impart motion to distal ends of functionalized carbon nanotubes **710** that have adhered to one of, but not yet the other of, post **718** and post **720**.

Motion of the ends distal from an attached end of functionalized carbon nanotubes **710** allows the distal end the opportunity to adhere to posts that are located at the predetermined linear distance.

Referring now to FIG. **8**, a completed circuit having a carbon nanotube pathway is shown according to an advantageous embodiment. Circuit **800** is a circuit formed from the preferential adherence of a functionalized carbon nanotube to posts within a bath, such as bath **700** of FIG. **7**.

Substrate **810** can be a printed circuit board, such as the electrically insulating substrate **716** of FIG. **7** that is formed into a printed circuit board as described in relation to FIG. **7**. Substrate **810** includes post **812** and post **814**. Functionalized carbon nanotubes **816** spans the linear distance between post **812** and post **814**.

The self-assembly of circuit **800** results in functionalized carbon nanotubes **816** being anchored to both post **812** and post **814**. Thus, the coupled carbon nanotube can form useful circuits when the substrate is designed with knowledge of nanotube length and desired electrical properties as determined by the chirality of the coupled carbon nanotubes.

After removing the substrate from the bath, the substrate can be annealed to remove functionalization from functionalized carbon nanotubes **816**, as well as any functionalization on post **812** and post **814**. Annealing may also enhance electrical connections between posts **812** and **814** to adhered carbon nanotubes.

In one advantageous embodiment, circuit **800** can be coated with a thin layer of electrically insulating material. The insulating material also serves to hold functionalized carbon nanotubes **816** in place between post **812** and post **814**. Annealing may remove the functionalization that caused the preferential adhesion. Therefore, the thin layer of electrically insulating material may be needed to preserve the physical connections between functionalized carbon nanotubes **816** and post **812**, and functionalized carbon nanotubes **816** and post **814**.

Referring now to FIG. **9**, a flowchart of a method for assembling carbon nanotube electronics is shown in accordance with an advantageous embodiment.

Process **900** begins by providing a substrate having at least one plurality of posts (step **910**). The at least one plurality of posts are fabricated such that the center of the posts are located at a predetermined distance from one another. The predetermined distance is chosen to match the known length of a functionalized carbon nanotube that will be used to span between the two posts.

Process **900** then exposes the substrate to a fluid matrix containing functionalized carbon nanotubes (step **920**). The fluid matrix can be an aqueous bath or other liquid capable of suspending the functionalized carbon nanotubes. The functionalized carbon nanotubes within the fluid matrix have been presorted based on both the chirality and the length of the functionalized carbon nanotubes. The chirality of the functionalized carbon nanotubes is chosen to impart desired electrical properties to the carbon nanotube electronics. The length of the functionalized carbon nanotubes is chosen to match the predetermined distance between the two posts of the substrate.

Process **900** then adheres a first end of the functionalized carbon nanotube to a first one of the at least one plurality of posts (step **930**). The first end of the nanotube is either distal end of the carbon nanotube having a relatively higher concentration of functional groups than does the shaft of the carbon nanotube. Due to the relative charge of the distal end, the functionalized carbon nanotubes will self assemble to the posts.

Process **900** then adheres a second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts (step **940**), with the process terminating thereafter. Because each of the functionalized carbon nanotubes within the fluid matrix have the desired chirality and length, the functionalized carbon nanotube will form a pathway between the two posts. The pathway will have the desired electrical properties based on the chirality of the functionalized carbon nanotube.

Referring now to FIG. **10**, a flowchart of the processing steps for the self-assembly of a carbon nanotube electronic circuit is shown according to an advantageous embodiment. Process **1000** is a physical process that occurs within a bath, such as bath **700** of FIG. **7**.

Process **1000** begins by providing a substrate having at least two posts at a predetermined distance (step **1010**). The substrate can be substrate **716** of FIG. **7**, and can be fabricated according to a method similar to that described with regard to FIG. **7**. The at least two posts at a predetermined distance are fabricated on the substrate at a predetermined distance chosen to match the length of carbon nanotubes that will be used to span the predetermined distance between the centers of the two posts.

Optionally, the at least two posts at a predetermined distance can be functionalized (step **1020**). Functionalization of the posts may enhance the affinity of nanotube ends to adhere to the posts.

Process **1000** continues by exposing the substrate to a bath containing functionalized carbon nanotubes (step **1030**). The bath can be bath **700** of FIG. **7**. The functionalized carbon nanotubes can be carbon nanotube **310** of FIG. **3**. The functionalized carbon nanotubes in the bath have been filtered or otherwise segregated such that each of the functionalized carbon nanotubes has similar chiralities and lengths. In one advantageous embodiment, each of the functionalized carbon nanotubes is narrowly dispersed around a given length, such as, but not limited to 80+/−1 nanometers, 100+/−1 nanometers, and 120+/−1 nanometers. In one advantageous embodiment, each of the functionalized carbon nanotubes have similar chiral vectors (or non-chiral vectors), such that each of the functionalized carbon nanotubes within the bath have similar or identical indices (n, m).

The functional groups of the functionalized carbon nanotubes preferentially adhere to posts of the submerged substrate, rather than the remainder of substrate. Because the functionalized carbon nanotubes have previously been filtered according to a desired size, functionalized carbon nanotubes will energetically prefer to attach themselves in a manner that spans the linear distance between adjacent posts separated by the predetermined distance, thus creating an electrical pathway along the functionalized carbon nanotube.

Process **1000** continues by agitating the bath (step **1040**). Agitation of the bath provides the motion and energy required to remove nanotubes that may have adhered to post **718** or post **720** of FIG. **7** along the nanotube shaft rather than at the distal ends of the functionalized carbon nanotubes. The agitation of fluid matrix further provides the necessary turbulence to impart motion to distal ends of functionalized carbon nanotubes that have adhered to one of, but not yet the other of, adjacent posts separated by the predetermined distance. Motion of the ends distal from an attached end of functionalized carbon nanotubes allows the distal end the opportunity to adhere to posts that are located at the predetermined linear distance.

The substrate is then removed from the bath (step **1050**). The self-assembly of the circuit results in functionalized carbon nanotubes being anchored to adjacent posts separated by the predetermined distance. Thus, the coupled carbon nanotube can form useful circuits when the substrate is designed with knowledge of nanotube length and desired electrical properties, as determined by the chirality of the functionalized carbon nanotube.

Optionally, after removing the substrate from the bath, the substrate can be annealed and coated with a thin layer of electrically insulating material (step **1060**). Annealing the substrate can remove functionalization from functionalized carbon nanotubes, as well as any functionalization on posts. Annealing may also enhance electrical connections between posts to the adhered carbon nanotubes. The insulating material also serves to hold the functionalized carbon nanotubes in place between the posts. Because annealing may remove the functionalization that caused the preferential adhesion, the thin layer of electrically insulating material may be needed to preserve the physical connections between functionalized carbon nanotubes and the posts.

The advantageous embodiments provide a method and system for production of nanotube-enabled circuits that do not rely on manual positioning of the nanotubes. Carbon nanotubes self-assemble on a metal-templated surface to form electrical connections including semiconducting connections that define a circuit.

A fabricated substrate has at least one plurality of posts. The plurality is fabricated such that the two posts are located at a predetermined distance from one another.

The substrate is exposed to a fluid matrix containing functionalized carbon nanotubes. The functionalized carbon nanotubes preferentially adhere to the plurality of posts rather than the remainder of the substrate. A connection between posts of the at least one plurality of posts is induced by adhering a second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts.

The lengths and chiralities of the functionalized carbon nanotubes are preselected. The length of the functionalized carbon nanotubes matches the predetermined distance between the centers of posts of the plurality of posts. The chirality of the functionalized carbon nanotubes is selected to impart the desired electrical properties to the created circuit.

Advantageous embodiments herein provide a system for production level manufacturing of nanotube-enabled circuits that do not rely on manual positioning of the nanotubes. Producing carbon nanotube electronics according to the disclosed method can substantially decrease production time and costs associated with the manufacture of carbon nanotube electronics, resulting in the feasibility of production scale manufacturing of carbon nanotube-based electronics.

The description of the different advantageous embodiments has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different advantageous embodiments may provide different advantages as compared to other advantageous embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A system for assembling carbon nanotube electronics, the system comprising:

a substrate, wherein the substrate has at least one plurality of posts, the at least one plurality of posts being fabricated at a predetermined distance from one another;

a fluid matrix containing functionalized carbon nanotubes, wherein the functionalized carbon nanotubes comprise a first end, a middle, and a second end, wherein the first end and the second end have a relative concentration of functional groups different from that of the middle such that the functionalized carbon nanotubes exhibit relative electrical charges at the first end and the second end;

an agitation source, wherein providing agitation of the fluid matrix to preferentially adhere the first end of a functionalized carbon nanotube to a first one of the at least one plurality of posts and adheres the second end of the functionalized carbon nanotube to a second one of the at least one plurality of posts due to the relative electrical charges at the first end and the second end, wherein a connection is formed between the first one and the second one of the at least one plurality of posts.

2. The system of claim **1** further comprising:

the fluid matrix containing the functionalized carbon nanotubes, wherein the fluid matrix contains the functionalized carbon nanotubes having similar lengths and similar chiralities.

3. The system of claim **2**, wherein the similar lengths of the functionalized carbon nanotubes are selected to correspond to the predetermined distance between the first one and the second one of the at least one plurality of posts.

4. The system of claim **2**, wherein the similar lengths of the functionalized carbon nanotubes are selected from the group consisting of 80+/−1 nanometers, 100+/−1 nanometers, and 120+/−1 nanometers.

5. The system of claim **1**, wherein the similar chiralities of the functionalized carbon nanotubes are selected based on desired electrical properties of the functionalized carbon nanotubes.

6. The system of claim **5**, wherein the desired electrical properties of the functionalized carbon nanotubes is a conductance of the functionalized carbon nanotubes.

7. The system of claim **5**, wherein each of the functionalized carbon nanotubes have similar or identical chiral vectors.

8. The system of claim **1**, wherein the fluid matrix is an aqueous matrix.

9. The system of claim **1** further comprising:

the agitation source, wherein the agitation source agitates the fluid matrix to induce removal of functionalized carbon nanotubes that may have adhered to the first one and the second one of the at least one plurality of posts along a shaft of the functionalized carbon nanotubes.

10. The system of claim **1** further comprising:

the agitation source, wherein the agitation source agitates the fluid matrix to impart motion to distal ends of functionalized carbon nanotubes that have adhered to one of, but not yet the other of, the first one and the second one of the at least one plurality of posts.

11. The system of claim **1**, wherein the functionalized carbon nanotubes comprise carboxylic acid functional groups.

12. The system of claim **1** further comprising:

a heat source, wherein the heat source anneals the substrate to remove functional groups from the functionalized carbon nanotubes.

13. The system of claim **12** further comprising:

the heat source, wherein the heat source anneals the substrate to remove functional groups from the first one and the second one of the at least one plurality of posts.

14. The system of claim **1** further comprising:

an electrically insulating material, wherein the electrically insulating material comprises a coating applied to the substrate.

15. The system of claim **13**, wherein the electrically insulating material comprises a layer of photosensitive resin applied to cover the connection formed between the first one and the second one of the at least one plurality of posts.

16. The system of claim **1**, wherein the substrate is a printed circuit board.

17. The system of claim **1**, wherein the functionalized carbon nanotubes are selected from the group consisting of open ended carbon nanotubes and capped carbon nanotubes.

18. The system of claim **1**, wherein the first one and the second one of the at least one plurality of posts are functionalized prior to immersion in the fluid matrix.

19. The system of claim **1**, wherein the connection formed by the functionalized carbon nanotube spans a linear distance between the first one and the second one of the at least one plurality of posts.

* * * * *