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(54) **THREE-DIMENSIONAL NANOTUBE STRUCTURE**

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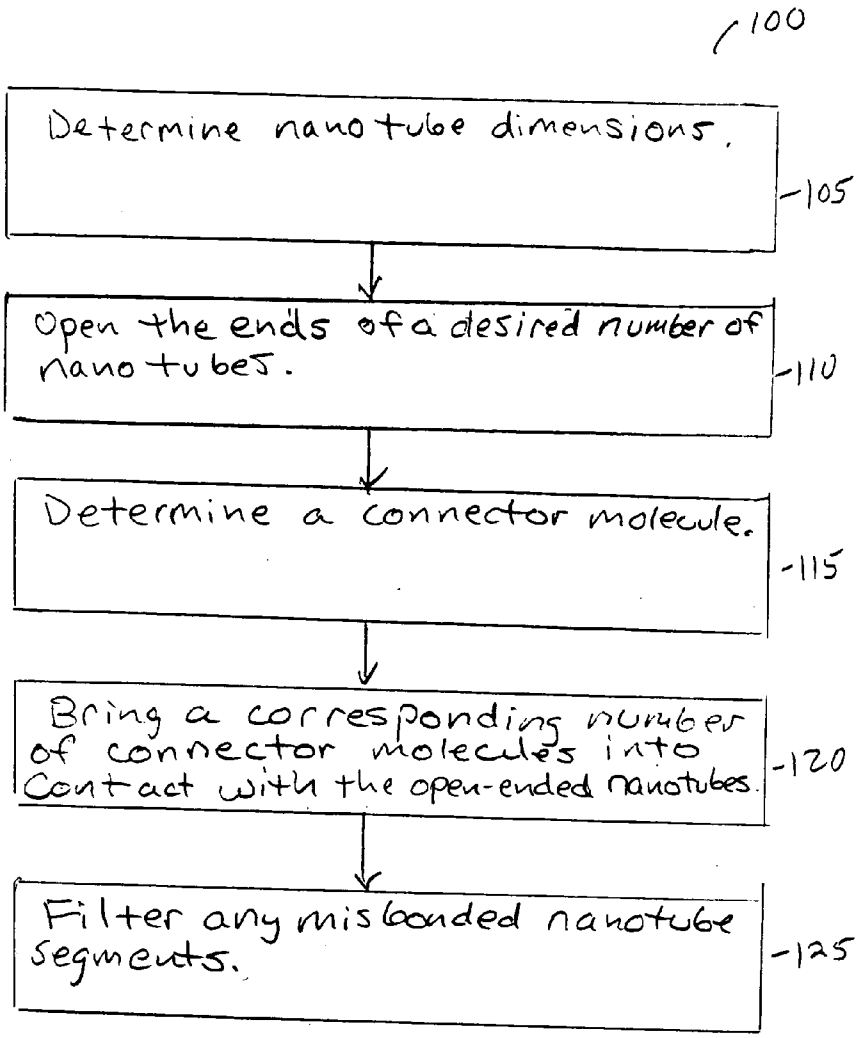
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(57) **ABSTRACT**

Embodiments of the invention provide a three-dimensional nanotube structure. For one embodiment, a connector molecule is created that has bonding sites capable of bonding with one end of an open-ended nanotube segment and bonding sites capable of bonding with the corresponding bonding sites of a plurality of other connector molecules. For one embodiment, the connector molecule is cone-shaped, with base of the cone determined so as to bond with the edge of the open-ended nanotube and the point of the cone comprising a single molecule capable of bonding with the corresponding molecules of two or more other connector molecules. In one embodiment, the three-dimensional nanotube structures are incorporated into a polymer matrix to form a composite polymer having improved thermal conductivity. For one embodiment, the composite polymer is used to form efficient and cost-effective heat dissipation devices.



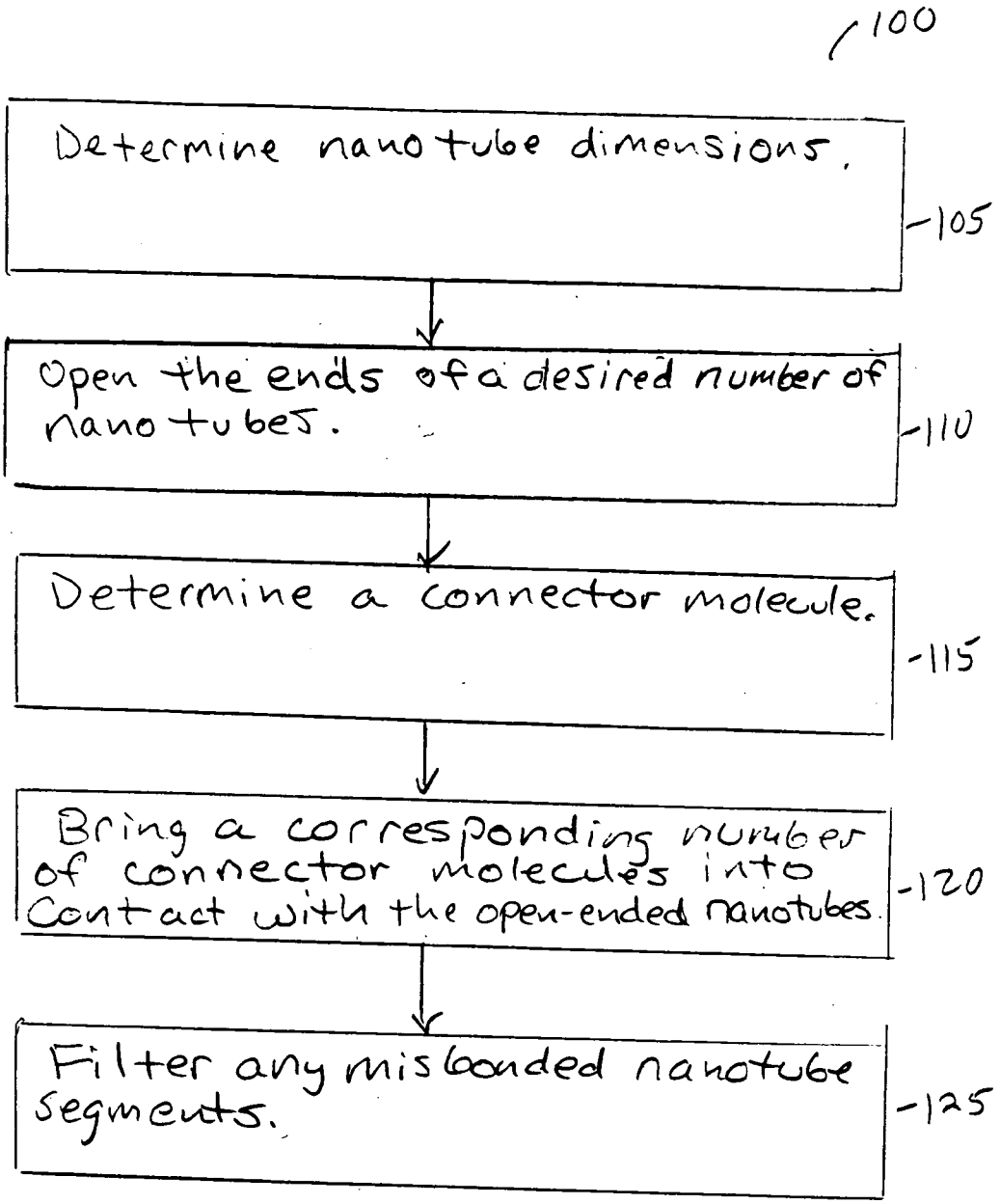

100
Determine nanotube dimensions.
105
Open the ends of a desired number of nanotubes.
110
Determine a connector molecule.
115
Bring a corresponding number of connector molecules into contact with the open-ended nanotubes.
120
Filter any misbonded nanotube segments.
125

Fig. 1

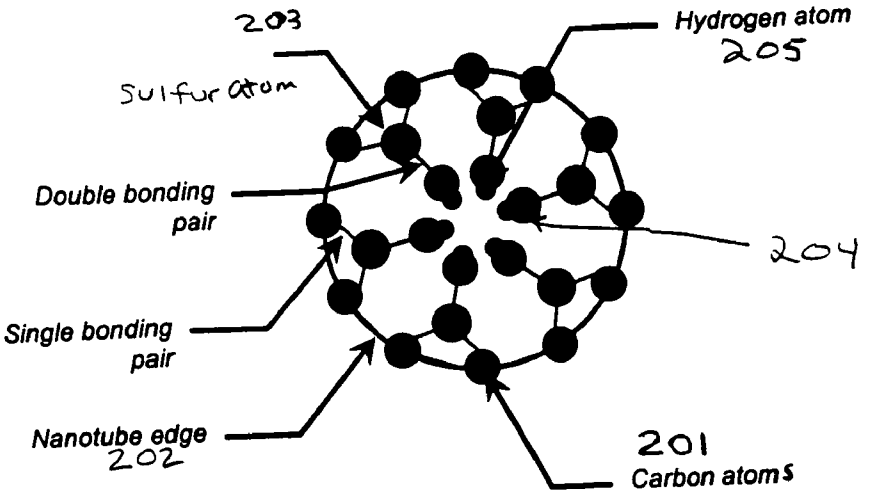

203
Sulfur atom
Hydrogen atom
205
Double bonding pair
204
Single bonding pair
Nanotube edge
202
201
Carbon atoms

Fig. 2A

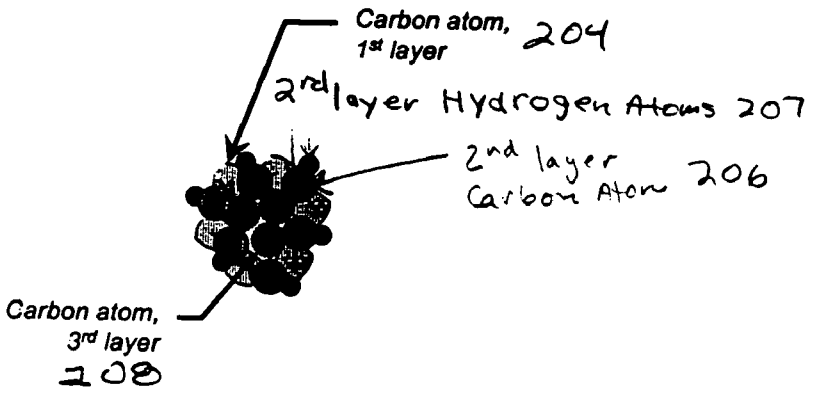

Carbon atom, 1st layer
204
2nd layer Hydrogen Atoms 207
2nd layer Carbon Atom 206
Carbon atom, 3rd layer
208

Fig. 2B

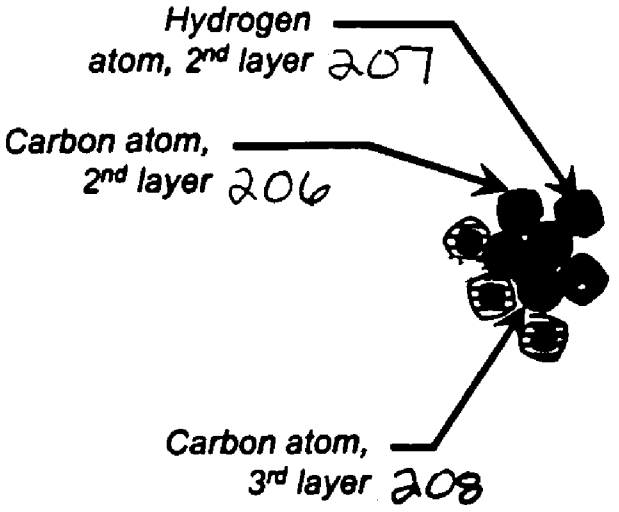

Hydrogen atom, 2nd layer 207
Carbon atom, 2nd layer 206
Carbon atom, 3rd layer 208

Fig 2C

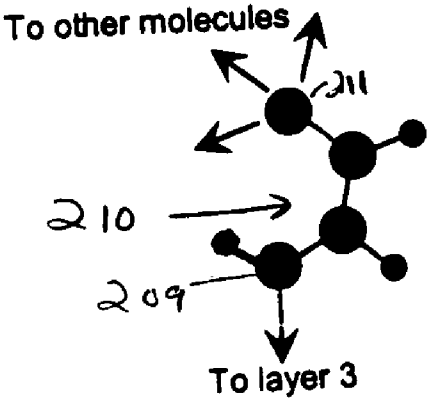
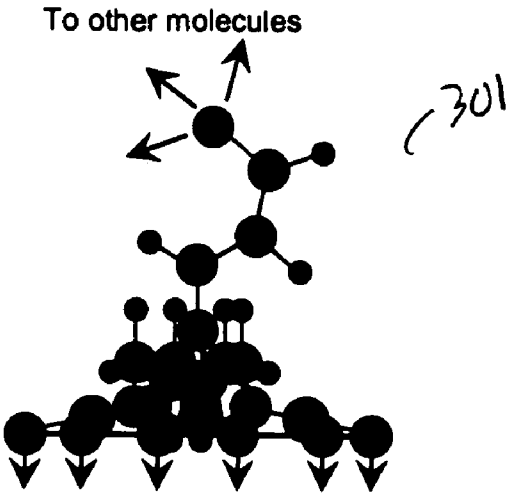
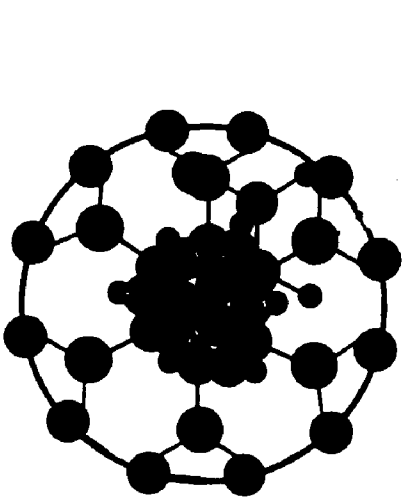

To other molecules
211
210
209
To layer 3

Fig. 2D



Completed molecule, side view
$C_{19}S_6H_{24}$

Fig. 3A



Completed molecule, top view
$C_{19}S_6H_{24}$

3B

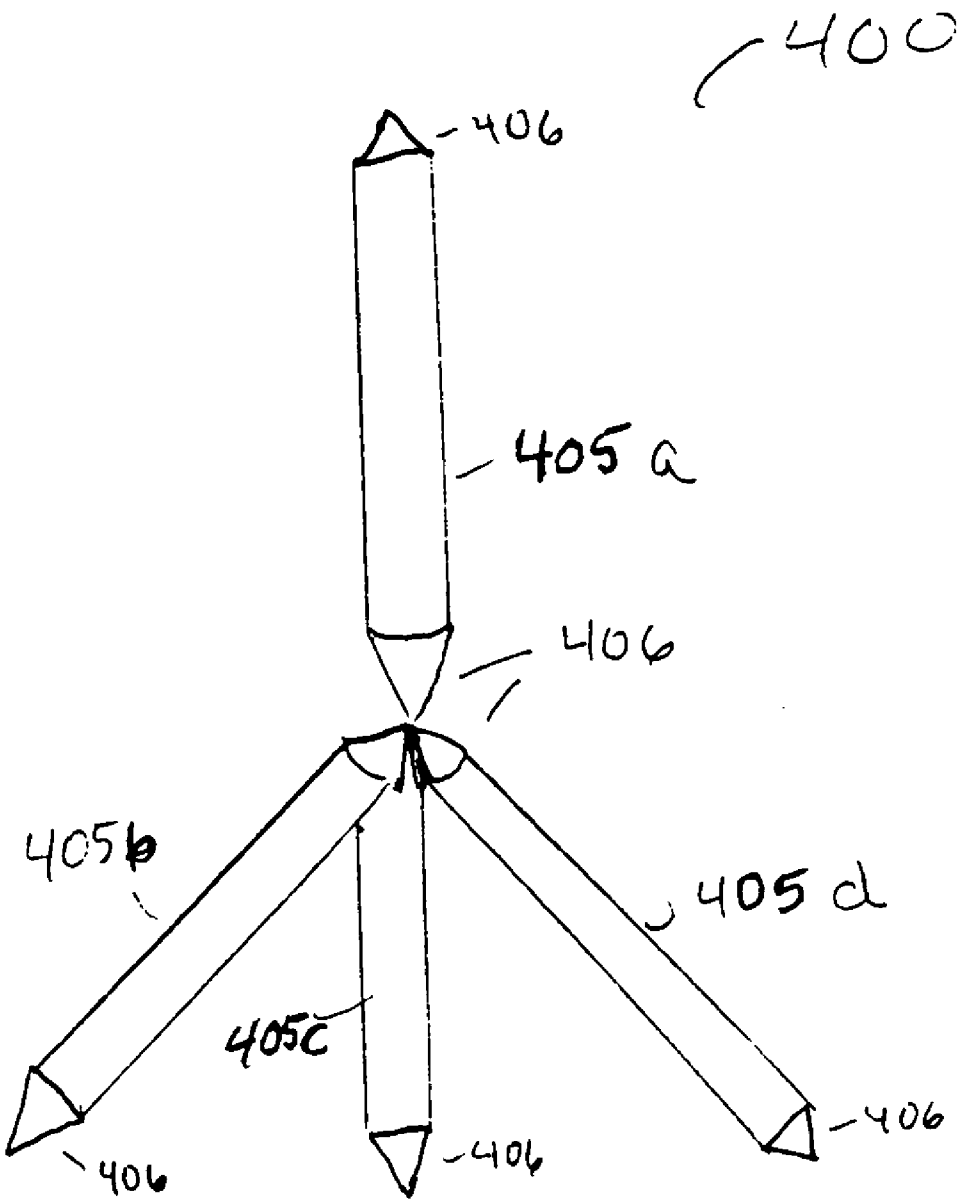


Fig. 4

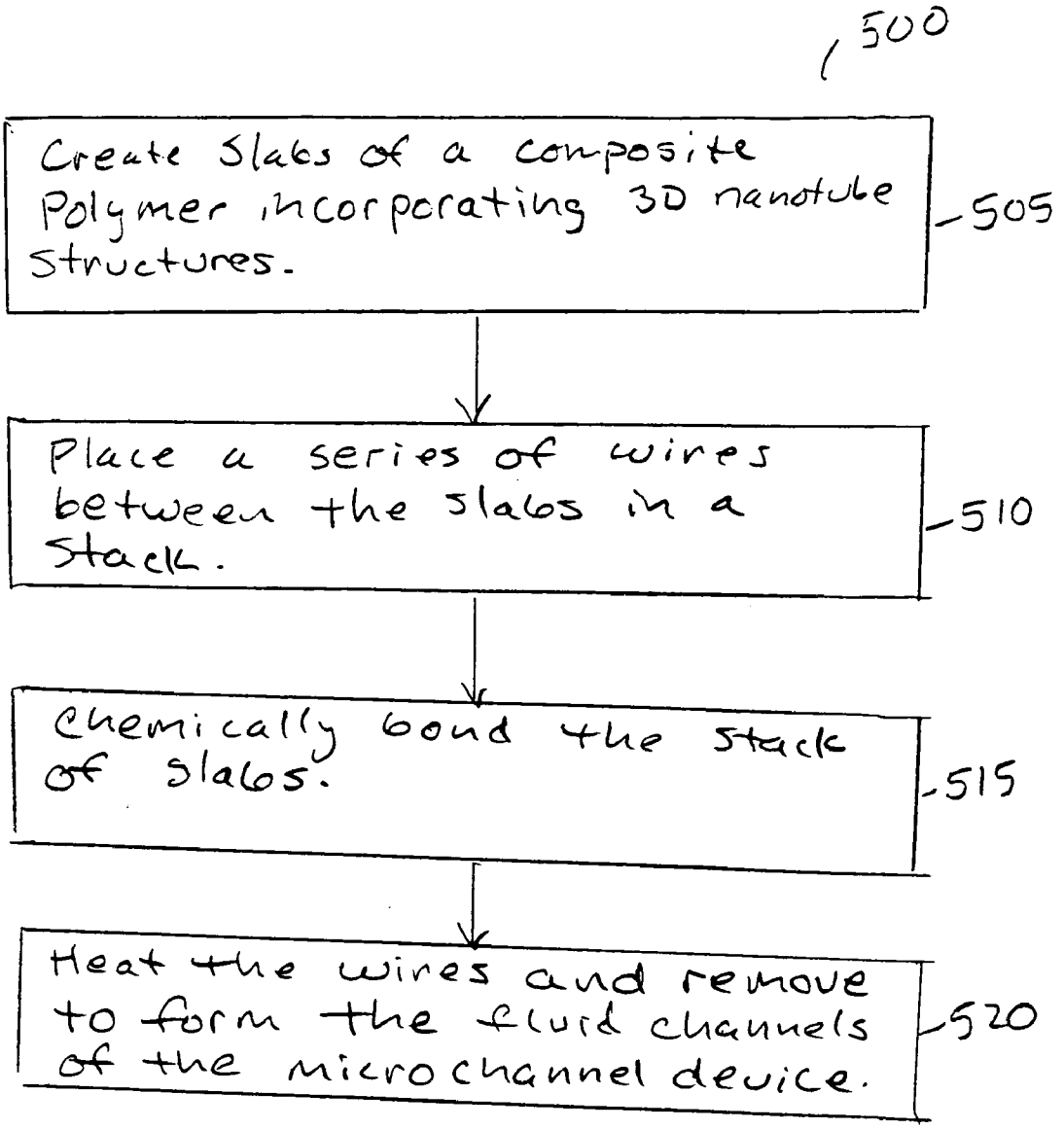

500
Create Slabs of a composite Polymer incorporating 3D nanotube structures.
505
Place a series of wires between the slabs in a stack.
510
Chemically bond the stack of slabs.
515
Heat the wires and remove to form the fluid channels of the microchannel device.
520

Fig. 5

THREE-DIMENSIONAL NANOTUBE STRUCTURE

FIELD

[0001] Embodiments of the invention relate, generally, to the field of nanotechnology and, more specifically, to nanotubes.

BACKGROUND

[0002] Nanotubes (e.g., carbon nanotubes (CNTs)) are tubular molecules that exhibit high thermal and electrical conductivity. CNTs have a cylindrical structure with a diameter ranging from approximately 1-100 nanometers and a length of several microns or more. Each end of the cylindrical structure is capped with a half fullerene molecule.

[0003] The theoretical applications for CNTs include miniature cathode ray tubes (CRTs), to provide a thin, low energy, lightweight display, high strength composite materials, electronic circuitry, as well as superconductor and biotechnology applications.

[0004] Currently, applications for CNTs are developing that take advantage of their light-weight, high-strength, and electrical and thermal properties. Many such applications involve mixing the CNTs with other materials, for example, polymers. However, because CNTs are not readily soluble in many types of polymers and solvents, they tend to clump together making it difficult to obtain a uniform material with the desired uniform property.

[0005] For some applications, a random orientation of the CNTs is not desirable. For example, the excellent thermal conductive properties of the CNTs are extremely directionally dependent. That is, the tubular structure acts as a conduit for the heat so the heat moves readily along the orientation of the tube. Or for example, the CNTs may be used to form electrical interconnects. For such applications, a specific orientation may be desired. Some progress has been made toward linking the individual CNTs together to facilitate orientation. Linking the individual CNTs allows for a greater ability to orient them in a desired direction.

[0006] Currently, the CNTs can be linked, one-dimensionally, by using an acid to sever each end of the tube. That is, the half fullerene molecule at the end of each tube is removed, resulting in an open-ended tubular structure. Each end of the open-ended tubular structure will have molecular bonding sites. Connector molecules are then provided that will attract two open-ended tubes and bond with the exposed bonding sites, thus providing a linked CNT structure. This process can be used to create ropelike CNT structures. Such ropelike CNT structures tend to tangle, so, here too, the limited ability to orient the CNT structures is a significant impediment to application development.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The invention may be best understood by referring to the following description and accompanying drawings that are used to illustrate embodiments of the invention. In the drawings:

[0008] **FIG. 1** illustrates a process for producing 3D nanotube structures in accordance with one embodiment of the invention;

[0009] **FIGS. 2A-2D** illustrate the layers of a cone-shaped connector molecule that can be used to connect CNTs to form a 3D nanotube structure in accordance with one embodiment of the invention;

[0010] **FIGS. 3A and 3B** illustrate respective views of a $C_{19}S_6H_{24}$, molecule that can be used as a connector molecule to produce 3D nanotube structures in accordance with one embodiment of the invention;

[0011] **FIG. 4** illustrates the connection of coned-topped nanotube segments to form a 3D nanotube structure in accordance with one embodiment of the invention; and

[0012] **FIG. 5** illustrates a process for fabricating a microchannel device from a composite polymer incorporating 3D nanotube structures in accordance with one embodiment of the invention.

DETAILED DESCRIPTION

[0013] In the following description, numerous specific details are set forth. However, it is understood that embodiments of the invention may be practiced without these specific details. In other instances, well-known circuits, structures and techniques have not been shown in detail in order not to obscure the understanding of this description.

[0014] Reference throughout the specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, the appearance of the phrases "in one embodiment" or "in an embodiment" in various places throughout the specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

[0015] Moreover, inventive aspects lie in less than all features of a single disclosed embodiment. Thus, the claims following the Detailed Description are hereby expressly incorporated into this Detailed Description, with each claim standing on its own as a separate embodiment of this invention.

[0016] In accordance with one embodiment of the invention, a connector molecule is provided that bonds with nanotubes to form a three-dimensional (3D) nanotube structure.

[0017] **FIG. 1** illustrates a process for producing 3D nanotube structures in accordance with one embodiment of the invention. Process **100**, shown in **FIG. 1**, begins at operation **105** in which nanotube dimensions (e.g., diameter and length) are determined. The nanotube dimensions may be determined based upon a specific application, commercially available nanotubes, or other considerations, including those discussed below.

[0018] At operation **110**, a desired number of nanotubes are opened to produce open-ended nanotube segments (segments). Opening the nanotubes may be accomplished through an acid washing process (e.g., exposure to nitric acid), as known in the art.

[0019] At operation **115**, a connector molecule is determined, such that the shape of the connector molecules allows for the formation of a 3D nanotube structure. For one

embodiment, the connector molecules used have one dimension corresponding to the diameter of the nanotubes and another dimension tapered to a significantly smaller size. Therefore, it may be practical to select the nanotube diameter based upon the dimensions of the desired, or available, connector molecules, or vice versa.

[0020] At operation **120**, a corresponding number of connector molecules are brought in to contact with the segments. The segments will bond with the connector molecules to form 3D nanotube structures.

[0021] At operation **125**, any misbonded segments are filtered. That is, the bonding process may not be completely optimal, resulting in segments and/or connector molecules not bonding, or bonding in an undesired manner.

[0022] Connector Molecule

[0023] For one embodiment, the connector molecule is a cone-shaped molecule, chemically and geometrically matched to a particular nanotube. For example, for one embodiment, the connector molecule for a CNT is cone-shaped, with a ring of carbon atoms forming the base of the cone. The diameter of the base of the cone is matched to the diameter of the CNT. For one embodiment, the point of the cone is a single molecule, which is capable of bonding to the single molecule points of other cone-shape connector capped nanotube segments.

[0024] **FIGS. 2A-2D** illustrate the layers of a cone-shaped connector molecule, $C_{19}S_6H_{24}$, that can be used to connect CNTs to form a 3D nanotube structure in accordance with one embodiment of the invention.

[0025] **FIG. 2A** illustrates the base, or first layer, of the cone-shaped connector molecule. As shown in **FIG. 2**, the connector molecule has a base ring of sulfur atoms **203**, each of which is bonded to two of the carbon atoms **201** that form the edge of CNT segment **202**. The base ring of sulfur atoms **203** is matched to the diameter of the nanotube edge **202**. In the case illustrated in **FIG. 2A**, the CNT segment has twelve carbon atoms resulting in a CNT diameter of approximately 1.4 nm diameter. Each of the sulfur atoms **203** is double bonded to one of the carbon atoms **204**. Each of the carbon atoms **204** is also bonded to one hydrogen atom **205**, and also has one remaining bonding pair.

[0026] **FIG. 2B** illustrates the second layer of the cone-shaped connector molecule. Each of the second layer carbon atoms **206** is bonded to a first layer carbon atom **204** and two second layer hydrogen atoms **207**. Each of the second layer carbon atoms **206** is also bonded to one of three third layer carbon atoms **208**. The third layer carbon atoms **208** are below the second layer carbon atoms **206** and form an inverted tetrahedral structure.

[0027] **FIG. 2C** illustrates the third layer of the cone-shaped connector molecule. The third layer has three carbon atoms **208** and three hydrogen atoms (not shown). Each carbon atom **208** is bonded to two second layer carbon atoms, as discussed above in reference to **FIG. 2B**, and also to a one hydrogen atom. This leaves one bonding pair per carbon atom free (tetrahedral, inverted). This free bond from each of the three third layer carbon atoms is joined to a single carbon atom (fourth layer, discussed below).

[0028] **FIG. 2D** illustrates the fourth layer of the cone-shaped connector molecule. A single carbon atom **209** is bound to three third layer carbon atoms (not shown) and to a C_3H_3 group **210**. The final (point) carbon atom **211** may be bound to any other group or cone-capped nanotube segment to produce a 3D nanotube structure. Since the point carbon atom **211** has only two of its eight valence electrons engaged in the bonding to C_3H_3 group **210**, it can accommodate a bonding with the point carbon atoms from three other cone-shaped connector molecules.

[0029] **FIGS. 3A and 3B** illustrate respective views of a $C_{19}S_6H_{24}$, molecule that can be used as a connector molecule to produce 3D nanotube structures in accordance with one embodiment of the invention. **FIG. 3A** shows the side view of cone-shaped connector molecule **301**. **FIG. 3B** shows the top view of cone-shaped connector molecule **301**.

[0030] **FIG. 4** illustrates the connection of coned-topped nanotube segments to form a 3D nanotube structure in accordance with one embodiment of the invention. 3D nanotube structure **400**, shown in **FIG. 4**, includes four nanotube segments **405***a*-**405***d*. The end of each nanotube segment has been cut and a cone-shaped connector molecule has been attached to each end as described above. For one embodiment, as shown in **FIG. 4**, the connector molecules **406**, which need not be cone-shaped, are shaped to provide enough physical space for the connection of multiple nanotube segments **405***a*-**405***d*. Additionally, the connector molecules **406** are chemically constituted to provide bonding sites to connect multiple connector molecules.

[0031] For one embodiment, the cone-shaped connector molecule has a base equal to the diameter of the nanotube and tapers to a single molecule point, which can be connected to the points of other cone-shaped connector molecules. For one embodiment, the dimensions of the connector molecule are based, not only upon the diameter of the nanotubes, but on the length of the nanotubes as well.

[0032] When the 3D nanotube structure has reached a desired size, the connection process can be halted, by providing an atom or molecule to cap the open ends of remaining nanotube segments. That is, for example, an atom without sufficient additional bonding sites to promote continued connections is used to cap the open ends of the remaining nanotube segments.

Exemplary Applications

[0033] The 3D nanotube structure, in accordance with various embodiments, has many applications. For one embodiment, the 3D nanotube structures may be incorporated into a base material (e.g., a polymer or ceramic) to provide a material with improved thermal conductivity. That is, because thermally conductive materials are more efficient if heat is conducted in all directions (as opposed to along a path), the 3D nanotube structure, when incorporated into a material, in accordance with various embodiments of the invention, provide greatly improved thermal conductivity. Additionally, the thermal conductivity of a polymer can be adjusted by the addition of more or less 3D nanotube structures, in accordance with one embodiment of the invention.

[0034] Microchannel

[0035] A microchannel cold plate (microchannel) is a heat dissipation device used to cool integrated circuits (ICs). Microchannel devices have a series of very small channels

through which a fluid (coolant) is flowed to dissipate heat. The fluid channels are typically 50-60 microns in diameter. Currently, the microchannel devices are made by chemically etching silicon to form the fluid channels, or alternatively, by laser drilling, or acid-etching copper. Such processes are relatively costly, often employ harsh chemicals, and provide limited flexibility in fluid channel design. Moreover, a thermal interface material (TIM) must be used to bond the microchannel to the IC package.

[0036] In accordance with one embodiment of the invention, a thermally conductive polymer incorporating 3D nanotube structures is used to form a microchannel. The microchannel device can be formed by molding, casting, or extruding the polymer and the fluid channels can be formed by a wet etch process. For one embodiment, the microchannel device is cast directly on the IC package, thus eliminating the need for the TIM at that interface.

[0037] Use of a polymer incorporating 3D nanotube structures to form a microchannel also allows the thermal conductivity to be adjusted by varying the volume percentage of 3D nanotube structures in the polymer matrix.

[0038] **FIG. 5** illustrates a process for fabricating a microchannel device from a composite polymer incorporating 3D nanotube structures in accordance with one embodiment of the invention. Process **500**, shown in **FIG. 5**, begins at operation **505** in which a number of slabs of a composite polymer/3D nanotube structure material are formed. The slabs can be of varying thickness.

[0039] At operation **510**, a series of wires are placed between stacked slabs. The wires, which will form the fluid channels of the microchannel device, can be of varying diameter and may be patterned as desired.

[0040] At operation **515**, the stack of slabs, with the wires positioned between each slab, are bonded such that the wires are embedded in a continuous slab that forms the microchannel device. In one embodiment, the stack of slabs may be chemically bonded.

[0041] At operation **520**, the wires are heated and removed from the continuous slab. For one embodiment, a voltage is applied and an electrical current passed through the wires to locally soften or melt the polymer so that the wires can be removed. In an alternative embodiment, the polymer may be heated to conform to the wires or to allow removal of the wires.

[0042] The removal of the wires leaves fluid channels that may be any desired shape or size without extensive processing or retooling. This allows for a great deal of flexibility in designing the microchannel device. With such flexibility, and the ability to adjust the thermal conductivity of the composite material, the microchannel can be designed to closely match the heat signature of a given IC device.

[0043] Cold Plate and Heat Exchanger

[0044] Cold plates also are liquid cooled heat dissipation devices for ICs, but with much larger channels than a microchannel device. In a typical configuration, an IC device chip package is thermally coupled to an integrated heat spreader (IHS) using a TIM. The cold plate is on top of the (IHS) with another layer of TIM between them. A coolant (e.g., water or water/propylene glycol mixture) is pumped into the cold plate. Heat is transferred from the chip package through the IHS to the coolant of the cold plate. The coolant is pumped out of the cold plate to a liquid/air heat exchanger where it is dissipated.

[0045] Typically, cold plates are made of copper or aluminum and are machined or stamped. To achieve desired heat removal, several thin fins are bundled closely together. The desired fin proximity may make machining difficult, or preclude it entirely. In the latter case, the fins are typically attached to a separate base plate. Where the fins are brazed, there is additional thermal resistance.

[0046] In accordance with one embodiment of the invention, a cold plate and heat exchanger are formed from a composite polymer incorporating 3D nanotube structures. For one embodiment, the cold plate may be formed by molding, casting, or extruding the polymer. The heat exchanger, owing to its more complicated form, may be molded or built from smaller pieces of the polymer. Because it may be molded or cast, it is possible to design more intricate cold plates. The coolant tube and the fins can be cast as one piece, thus reducing fabrication costs and complexity. The TIM material can be eliminated because the cold plate can be chemically bonded to the IHS or the silicon directly.

[0047] Heat Sink and Integrated Heat Spreader

[0048] Heat sinks are larger heat dissipation devices that are typically made of machined metal (e.g., copper). Machining is an expensive process that does not lend itself to intricate design. The IHS is also typically copper and is thermally coupled with the IC device with a TIM (e.g., thermal grease). The TIMs may be poor thermal conductors and be the cause of thermal bottleneck in the overall heat dissipation stack-up. Also, the IHS typically has a rough surface that makes it difficult to mate with the heat sink surface.

[0049] In accordance with one embodiment of the invention, a heat sink and IHS are formed from a composite polymer incorporating 3D nanotube structures. For one embodiment, either the heat sink, the IHS, or both, may be formed by molding, casting, or extruding the polymer. Heat sinks formed from such a polymer are lighter and can be formed in more intricate shapes. Again, the thermal conductivity can be adjusted by varying the amount of 3D nanotube structures present in the composite polymer, as discussed above, in reference to the microchannel device.

[0050] For one embodiment, a composite polymer IHS can be bonded directly to the IC package or the heat sink, thus eliminating the need for, and the difficulties associated with, the TIM. Also, in accordance with one embodiment, a localized liquid solvent may be used at the interface between the heat sink and the IHS to liquefy the composite polymer. As the solvent evaporates, the composite polymer solidifies in direct contact with the bonding surface allowing the composite polymer to more fully conform to the bonding surface, thus eliminating the need for the TIM.

[0051] General Matters

[0052] Embodiments of the invention provide molecular structures and methods to create 3D nanotube structures. That is, by creating or determining an appropriate connector molecule, nanotubes (e.g., carbon nanotubes) may be connected in 3D shapes that provide desired electrical, thermal, and mechanical properties.

[0053] Embodiments of the invention have been described in which the connector molecule is cone-shaped. For various alternative embodiments, the connector molecule may be some other shape that allows the formation of a 3D nanotube structure.

[0054] Embodiments of the invention have been described in terms of various applications that take advantage of the improved thermal conductivity provided by composite polymers containing a 3D nanotube structure. It is apparent to one skilled in the art that embodiments of the invention have wide-ranging application, beyond composite polymers, that use additional or alternative characteristics of the 3D nanotube structure.

[0055] Embodiments of the invention include various operations. Many of the methods are described in their most basic form, but operations can be added to or deleted from any of the methods without departing from the basic scope of the invention.

[0056] While the invention has been described in terms of several embodiments, those skilled in the art will recognize that the invention is not limited to the embodiments described, but can be practiced with modification and alteration within the spirit and scope of the appended claims. The description is thus to be regarded as illustrative instead of limiting.

What is claimed is:

1. A method comprising:

opening a number of nanotubes to create open-ended nanotube segments; and

bringing a corresponding number of connector molecules into contact with the nanotube segments, each connector molecule providing first bonding sites capable of bonding with one end of the nanotube segments and second bonding sites capable of bonding with corresponding bonding sites of a plurality of other connector molecules, such that bonding occurs forming three-dimensional nanotube structures.

2. The method of claim 1 wherein the nanotubes are carbon nanotubes.

3. The method of claim 2 wherein the connector molecule is in the shape of a cone.

4. The method of claim 3 wherein the base of the cone is comprised of a ring of atoms capable of binding to an edge of an open-ended nanotube segment.

5. The method of claim 3 wherein the point of the cone is comprised of a single point atom capable of binding with a corresponding point atom of each of two or more other connector molecules.

6. The method of claim 2 further comprising:

allowing bonding to occur; and

filtering at least some of any misbonded nanotube segments or connector molecules.

7. The method of claim 6 further comprising:

mixing the three-dimensional nanotube structures with a polymer matrix material to form a composite polymer material.

8. The method of claim 6 further comprising:

forming a heat dissipation device from the composite polymer material.

9. The method of claim 8 wherein the heat dissipation device is a heat dissipation device selected from the group consisting of a microchannel device, a cold plate, an integrated heat spreader, and a heat sink.

10. The method of claim 8 wherein a method of forming the heat dissipation device is selected from the group consisting of molding, casting, and extruding.

11. A composite polymer comprising:

a polymer matrix material; and

one or more three-dimensional nanotube structures incorporated within the polymer matrix material.

12. The composite polymer of claim 11 wherein each three-dimensional nanotube structure is comprised of a number of open-ended nanotube segments each having at least one connector molecule bonded thereto, at least some of the connector molecules bonded to two or more other connector molecules.

13. The composite polymer of claim 12 wherein the nanotube segments are carbon nanotube segments.

14. The composite polymer of claim 13 wherein the connector molecules are in the shape of a cone.

15. The composite polymer of claim 14 wherein the base of the cone is comprised of a ring of atoms capable of binding to an edge of each of the open-ended nanotube segments.

16. The composite polymer of claim 14 wherein the point of the cone is comprised of a single point atom capable of binding with a corresponding point atom of each of two or more other connector molecules.

17. A connector molecule comprising:

one or more atoms providing a plurality of binding sites capable of binding to one end of an open-ended nanotube segment; and

one or more additional atoms providing one or more binding sites capable of binding to a corresponding one or more additional atoms of more than one other connector molecules.

18. The connector molecule of claim 17 wherein the connector molecule is in the shape of a cone.

19. The connector molecule of claim 18 wherein the base of the cone is comprised of a ring of atoms capable of binding to an edge of an open-ended nanotube segment.

20. The connector molecule of claim 18 wherein the point of the cone is comprised of a single point atom capable of binding with a corresponding point atom of each of two or more other connector molecules.

21. The connector molecule of claim 17 wherein the nanotube segment is a carbon nanotube segment.

22. A system comprising:

an integrated circuit device; and

a heat dissipation device thermally coupled thereto, the heat dissipation device formed of a composite polymer comprised of a polymer matrix and one or more three-dimensional nanotube structures incorporated within the polymer matrix.

23. The system of claim 22 wherein each of the one or more three-dimensional nanotube structure is comprised of a number of open-ended nanotube segments each having at least one connector molecule bonded thereto, at least some of the connector molecules bonded to two or more other connector molecules.

24. The system of claim 23 wherein the nanotube segments are carbon nanotube segments.

25. The system of claim 22 wherein the heat dissipation device is a heat dissipation device selected from the group consisting of a microchannel device, a cold plate, an integrated heat spreader, and a heat sink.

26. The system of claim 25 wherein a method of forming the heat dissipation device is selected from the group consisting of molding, casting, and extruding.

27. The system of claim 26 wherein the heat dissipation device is a microchannel device formed by pressing wires between one or more stacked slabs of the polymer matrix such that the polymer matrix conforms to a shape of the wire and subsequently removing the wire to form one or more fluid channels for the microchannel device.

* * * * *