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(54) **ELECTRON BEAM INDUCED DEPOSITION OF INTERFACE TO CARBON NANOTUBE**

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(52) **U.S. Cl.** **438/618**; 438/626; 438/691; 438/800; 257/E21.589

(58) **Field of Classification Search** 438/618, 438/626, 691, 800; 257/E21.589
See application file for complete search history.

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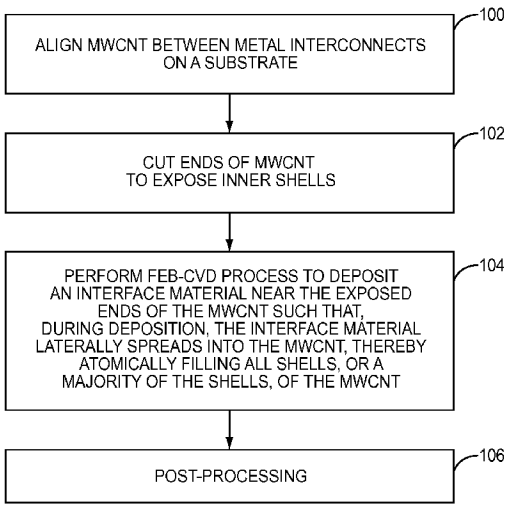
(57) **ABSTRACT**

A system and method are provided for fabricating a low electric resistance ohmic contact, or interface, between a Carbon Nanotube (CNT) and a desired node on a substrate. In one embodiment, the CNT is a Multiwalled, or Multiwall, Carbon Nanotube (MWCNT), and the interface provides a low electric resistance ohmic contact between all conduction shells, or at least a majority of conduction shells, of the MWCNT and the desired node on the substrate. In one embodiment, a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process is used to deposit an interface material near an exposed end of the MWCNT in such a manner that surface diffusion of precursor molecules used in the FEB-CVD process induces lateral spread of the deposited interface material into the exposed end of the MWCNT, thereby providing a contact to all conduction shells, or at least a majority of the conduction shells, of the MWCNT.

16 Claims, 5 Drawing Sheets



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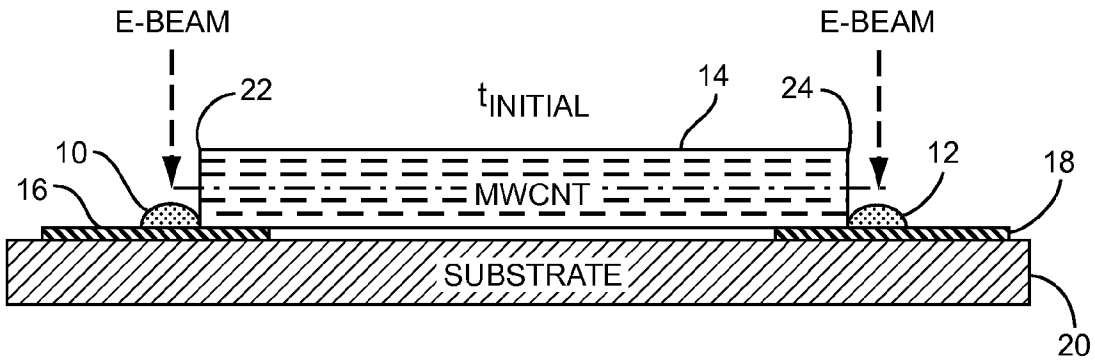

FIG. 1A

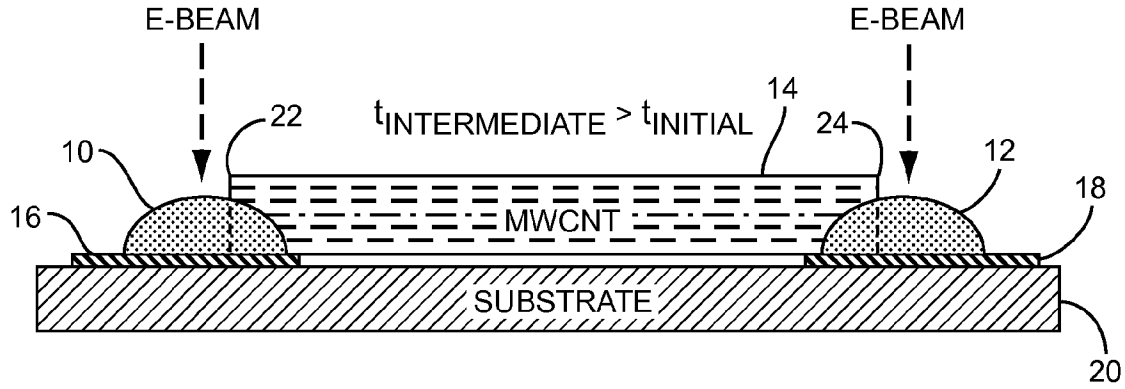

FIG. 1B

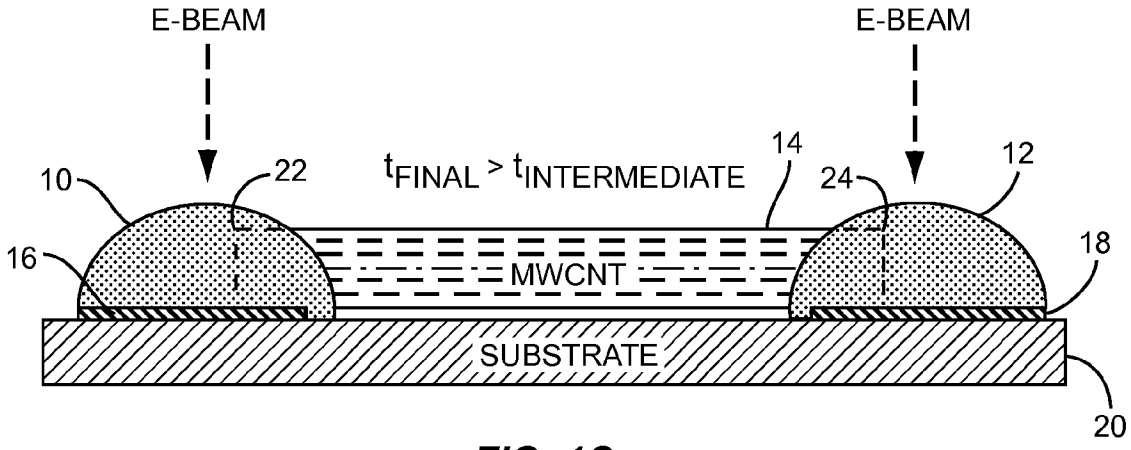

FIG. 1C

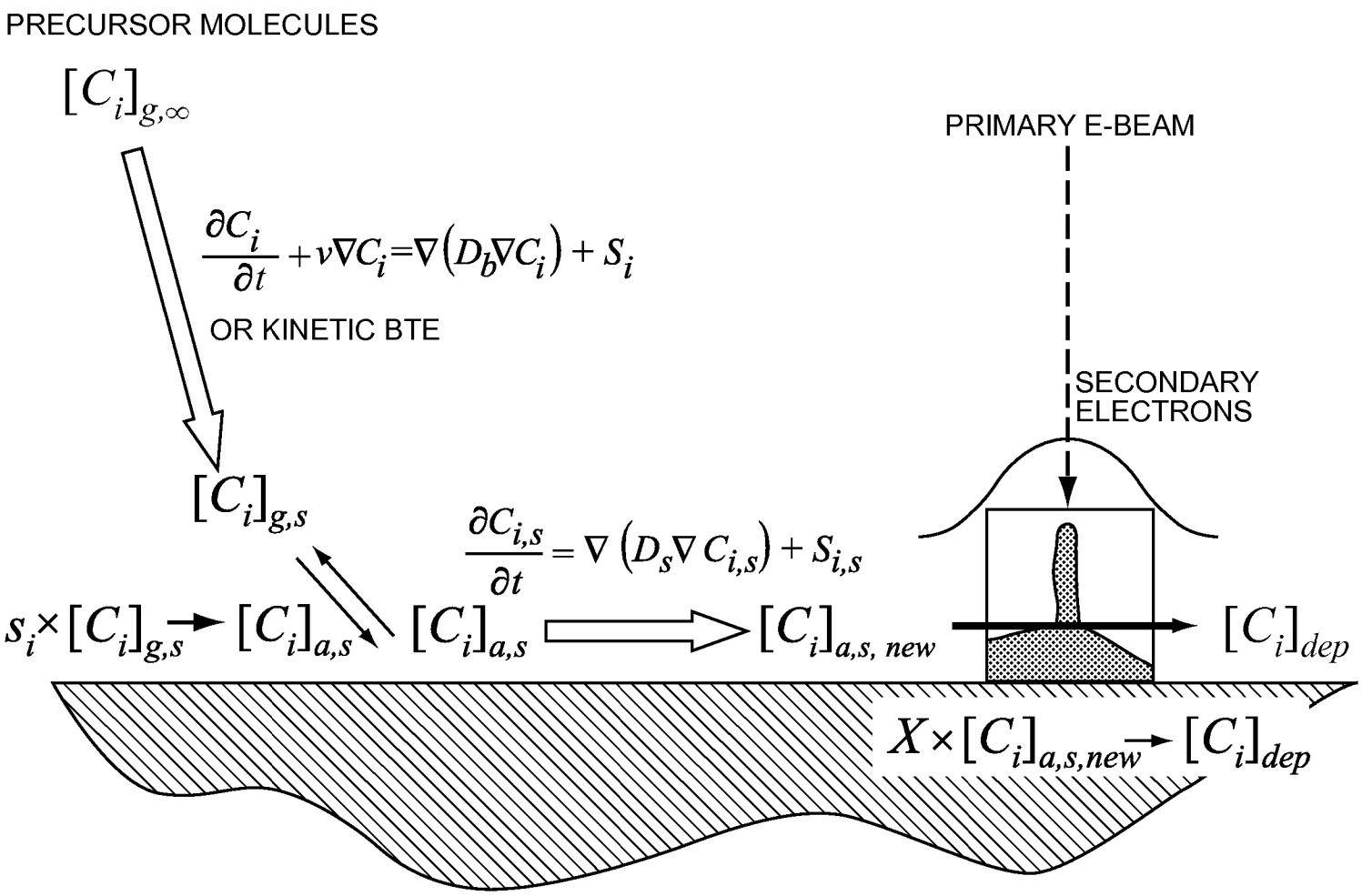
PRECURSOR MOLECULES
$[C_i]_{g,\infty}$
$\frac{\partial C_i}{\partial t} + v\nabla C_i = \nabla\left(D_b \nabla C_i\right) + S_i$
OR KINETIC BTE
PRIMARY E-BEAM
SECONDARY ELECTRONS
$[C_i]_{g,s}$
$\frac{\partial C_{i,s}}{\partial t} = \nabla\left(D_s \nabla C_{i,s}\right) + S_{i,s}$
$s_i \times [C_i]_{g,s} \rightarrow [C_i]_{a,s}$
$[C_i]_{a,s}$
$[C_i]_{a,s,\,new}$
$[C_i]_{dep}$
$X \times [C_i]_{a,s,new} \rightarrow [C_i]_{dep}$

FIG. 2

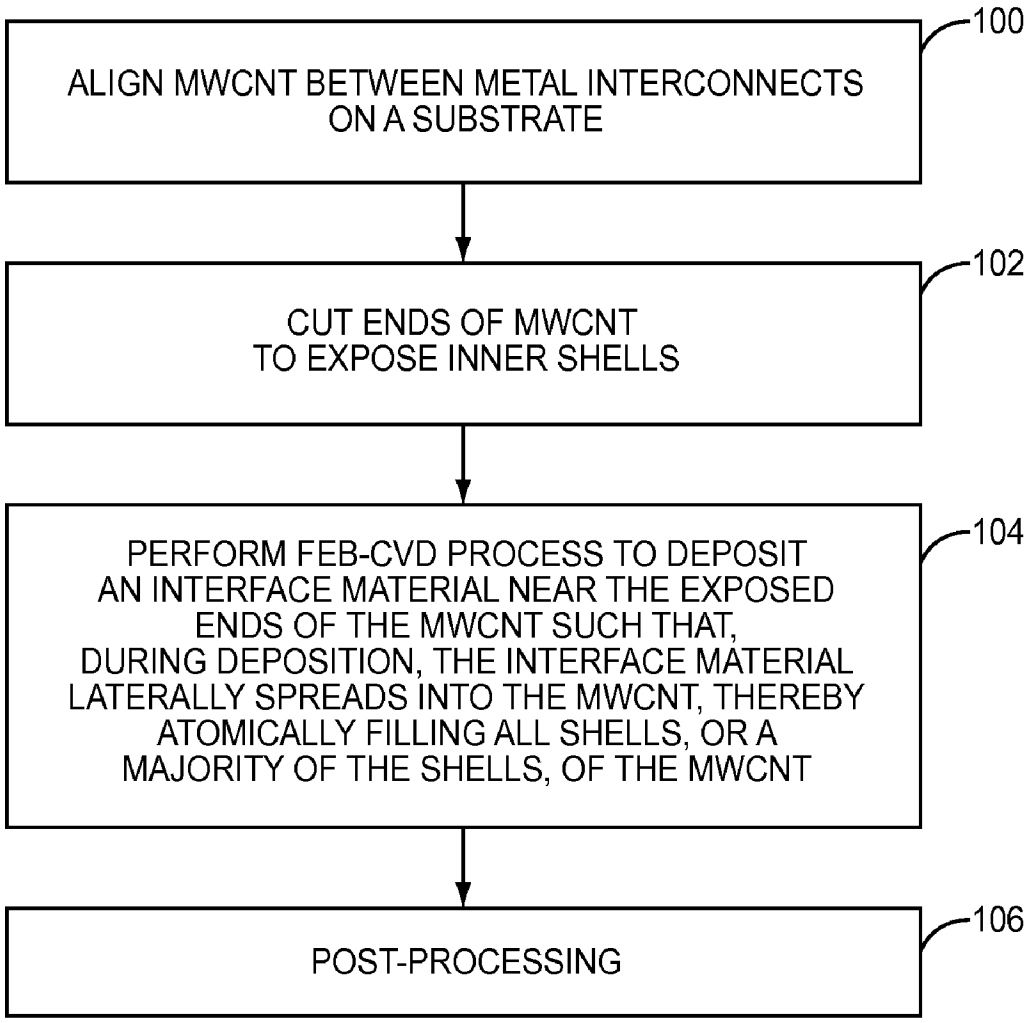
ALIGN MWCNT BETWEEN METAL INTERCONNECTS ON A SUBSTRATE
100
CUT ENDS OF MWCNT TO EXPOSE INNER SHELLS
102
PERFORM FEB-CVD PROCESS TO DEPOSIT AN INTERFACE MATERIAL NEAR THE EXPOSED ENDS OF THE MWCNT SUCH THAT, DURING DEPOSITION, THE INTERFACE MATERIAL LATERALLY SPREADS INTO THE MWCNT, THEREBY ATOMICALLY FILLING ALL SHELLS, OR A MAJORITY OF THE SHELLS, OF THE MWCNT
104
POST-PROCESSING
106

FIG. 3

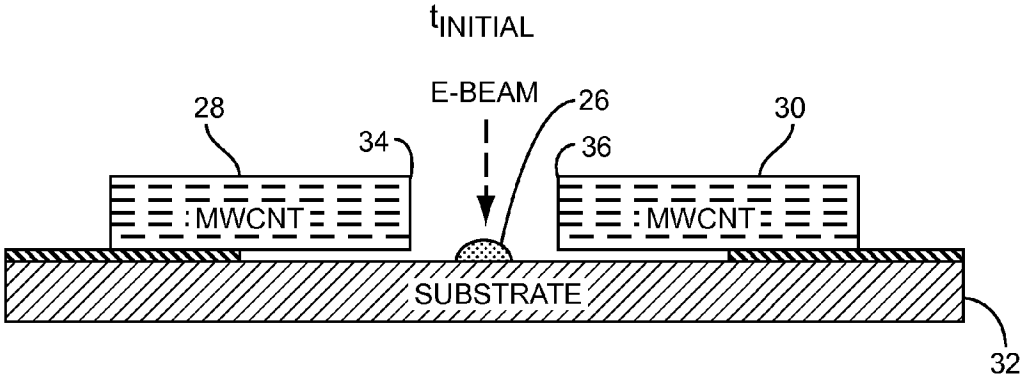

FIG. 4A

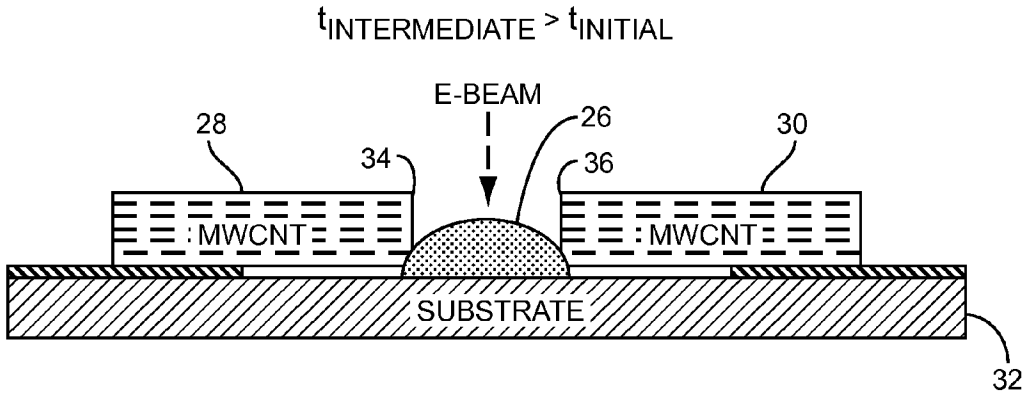

FIG. 4B

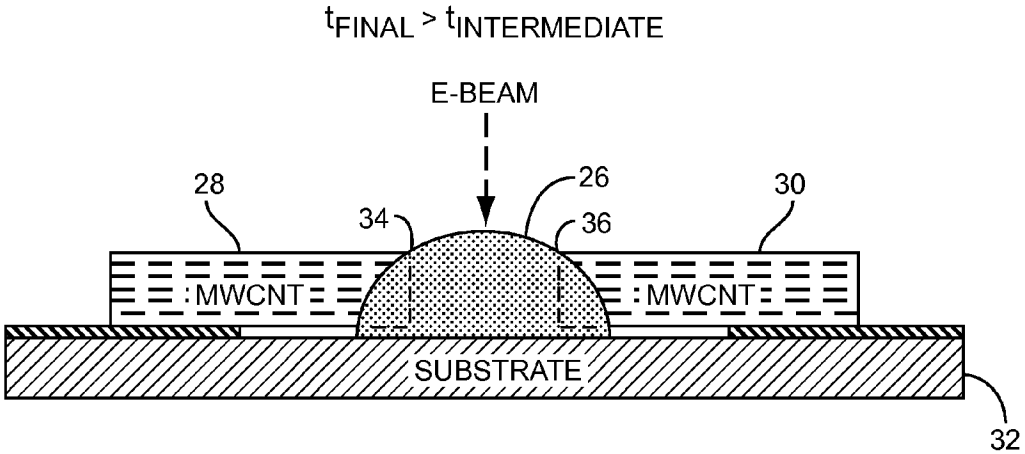

FIG. 4C

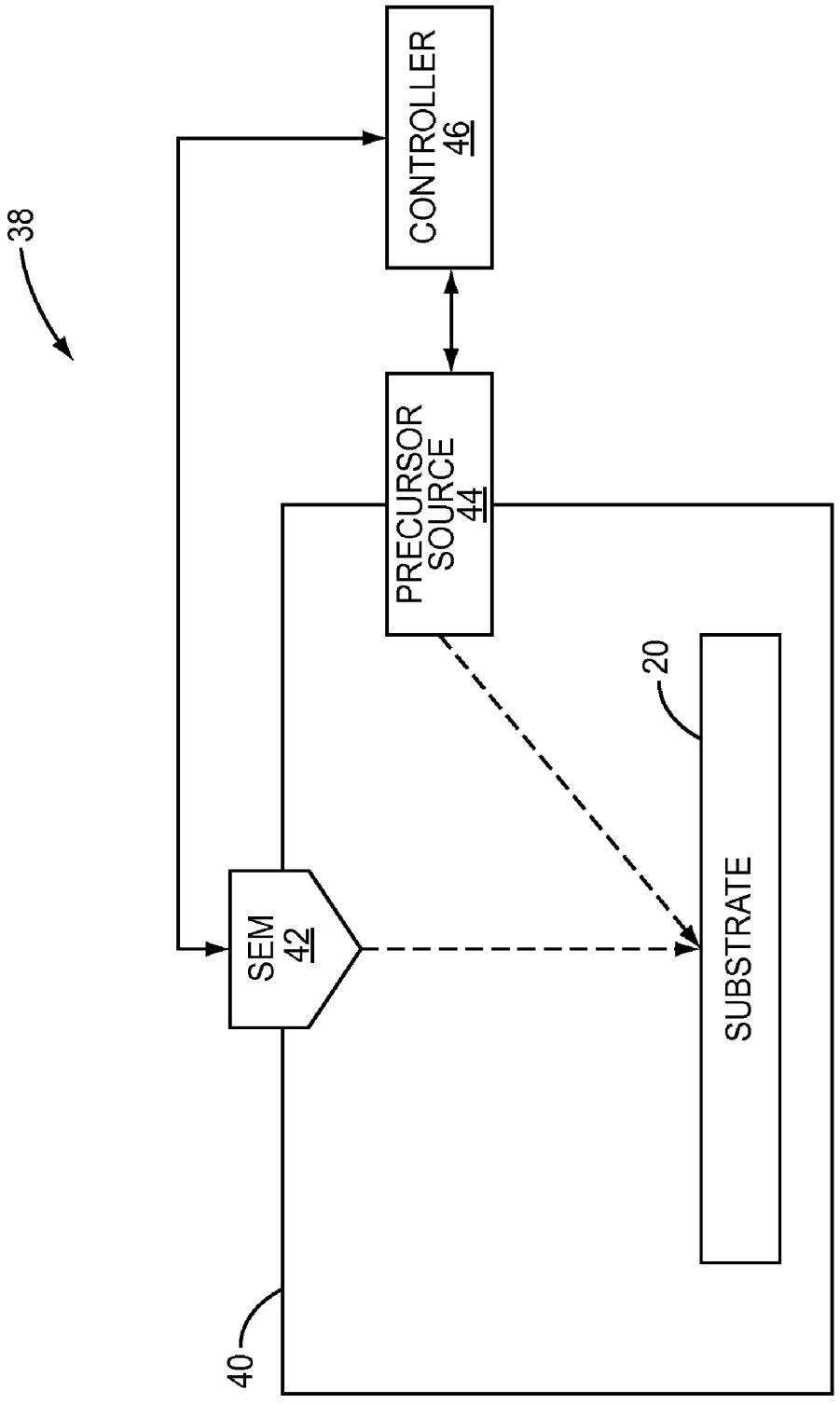

FIG. 5

ELECTRON BEAM INDUCED DEPOSITION OF INTERFACE TO CARBON NANOTUBE

FIELD OF THE DISCLOSURE

This disclosure relates to fabrication of an interface between a Carbon Nanotube (CNT) and a desired node on a substrate.

BACKGROUND

Low-resistance, stable contacts are critical for the performance and reliability of integrated circuits. As such, the preparation and characterization of contacts for integrated circuits demand major efforts in circuit fabrication. Conventional techniques for fabricating contacts are fundamentally flawed in making low resistance contacts between Multiwalled Carbon Nanotubes (MWCNTs) or MWCNT-based devices and metal pads or wires. Specifically, conventional techniques lack the level of control on nanoscale required for making a precise connection to MWCNTs and, most importantly, can only be used to establish electric contact to the outer conduction shell of the MWCNT. As such, a majority of the conduction channels through the inner shells of the MWCNT cannot be utilized, thus negating a key advantage of MWCNTs as highly efficient multi-channel electric conductors.

SUMMARY

The present disclosure describes a system and method for fabricating a low electric resistance ohmic contact, or interface, between a Carbon Nanotube (CNT) and a desired node on a substrate. In one embodiment, the CNT is a Multiwalled, or Multiwall, Carbon Nanotube (MWCNT), and the interface provides a low electric resistance ohmic contact between all conduction shells, or at least a majority of conduction shells, of the MWCNT and the desired node on the substrate. In one embodiment, a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process, which is also referred to as Electron Beam Induced Deposition (EBID) process, is used to deposit an interface material near an exposed end of the MWCNT in such a manner that surface diffusion of precursor molecules used in the FEB-CVD process induces lateral spread of the deposited interface material into the exposed end of the MWCNT. As a result of the lateral spread of the deposited interface material into the exposed end of the MWCNT, the interface material provides a contact to all conduction shells, or at least a majority of the conduction shells, of the MWCNT. The deposited interface material provides a low electric resistance ohmic contact between the MWCNT and the desired node on the substrate.

More specifically, in one embodiment, a MWCNT is first aligned between two electrically conducting interconnects on a substrate. Each of the electrically conducting interconnects may be, for example, a metallic interconnect, an electrically conducting polymer interconnect, a graphene interconnect, or the like. The substrate may be, for example, a semiconductor substrate, a dielectric substrate, or the like. If the ends of the MWCNT do not expose inner shells of the MWCNT, the ends of the MWCNT are cut to expose the inner shells of the MWCNT using a technique such as, for example, Focused Ion Beam (FIB) milling. Next, for each of the exposed ends of the MWCNT, a FEB-CVD process is performed wherein a primary electron beam is focused near the exposed end of the MWCNT. As a result, an interface material is deposited near the exposed end of the MWCNT such that, during deposition, the interface material laterally spreads into the exposed end of the MWCNT and makes contact to all of the conduction shells, or at least a majority of the conduction shells, of the MWCNT. Further, in one embodiment, a timing of an on/off regime of the primary electron beam is controlled such that surface diffusion of precursor molecules used in the FEB-CVD process has sufficient time to induce lateral spread of the deposited interface material into the exposed end of the MWCNT. A shape and size of the deposited interface material may be controlled via parameters of the FEB-CVD process. The shape of the deposited interface as well as the size of the contact area of the interface material to both the MWCNT and the electrically conducting interconnect define the interface thermal resistance between the MWCNT and the electrically conducting interconnect.

In another embodiment, one end of the MWCNT is aligned with an end of a second MWCNT. If the aligned ends of the MWCNTs do not expose inner shells of the MWCNTs, the aligned ends of the MWCNTs are cut to expose the inner shells of the MWCNTs using a technique such as, for example, FIB milling. Next, a FEB-CVD process is performed wherein a primary electron beam is focused near the aligned exposed ends of the MWCNTs. As a result, an interface material is deposited near the aligned exposed ends of the MWCNTs such that, during deposition, the interface material laterally spreads into the aligned exposed ends of the MWCNTs and makes contact to all of the conduction shells, or at least a majority of the conduction shells, of the MWCNTs. Further, in one embodiment, a timing of an ON/OFF regime of the primary electron beam is controlled such that surface diffusion of precursor molecules used in the FEB-CVD process has sufficient time to induce lateral spread of the deposited interface material into the aligned exposed ends of the MWCNTs. A shape and size of the deposited interface material may be controlled via parameters of the FEB-CVD process. The shape of the deposited interface as well as the size of the contact area of the interface material to the MWCNTs define the interface thermal resistance between the MWCNTs.

In one embodiment, the deposited interface material is amorphous carbon (a-C), and post-processing is used to lower an electric resistance of the deposited interface material while maintaining contact between the metal pad/wire and the MWCNT. More specifically, an annealing process induced by either direct heating (thermal) or by passing an electric current through the interface (electric) may be performed to provide total or partial graphitization of the deposited carbon interface material, thereby substantially reducing the electric resistance of the deposited carbon interface material. In another embodiment, the deposited interface material is a metallic material and the precursor molecule is an organometallic compound.

Those skilled in the art will appreciate the scope of the present invention and realize additional aspects thereof after reading the following detailed description in association with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings incorporated in and forming a part of this specification illustrate several aspects of the invention, and together with the description serve to explain the principles of the invention.

FIGS. **1**A-**1**C graphically illustrate fabrication of interfaces between a Multiwalled Carbon Nanotube (MWCNT) and electrically conducting interconnects on a substrate according to one embodiment of the present disclosure;

FIG. **2** graphically illustrates a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process, which is also referred to as an Electron Beam Induced Deposition (EBID) process, that is preferably utilized to fabricate the interfaces for a MWCNT of FIG. **1** according to one embodiment of the present disclosure;

FIG. **3** is a flow chart illustrating a process for fabricating an interface for a MWCNT according to one embodiment of the present disclosure;

FIGS. **4**A through **4**C graphically illustrate fabrication of an interface between MWCNTs according to another embodiment of the present disclosure; and

FIG. **5** illustrates a FEB-CVD system for fabricating an interface for a MWCNT on a substrate according to one embodiment of the present disclosure.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the invention and illustrate the best mode of practicing the invention. Upon reading the following description in light of the accompanying drawings, those skilled in the art will understand the concepts of the invention and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

FIGS. **1**A through **1**C graphically illustrate a process for fabricating interfaces **10** and **12** between a Carbon Nanotube (CNT) **14** and electrically conducting interconnects **16** and **18** (hereinafter interconnects **16** and **18**) on a substrate **20** according to one embodiment of this disclosure. Preferably, the CNT **14** is a Multiwalled, or Multiwall, Carbon Nanotube (MWCNT) **14** and will be referred to as such for much of this disclosure. However, in an alternative embodiment, the CNT **14** is a Single Walled CNT. As will be appreciated by one of ordinary skill in the art, the MWCNT **14** includes multiple conduction shells, or conduction layers, of carbon, which is typically in the form of graphite. The multiple conduction shells may be in a spiral pattern such that a cross-section of the MWCNT **14** is a spiral pattern. Alternatively, the multiple conduction shells in the MWCNT **14** may be concentric tubes such that a cross-section of the MWCNT **14** is a set of concentric circles. Each of the interconnects **16** and **18** is formed of an electrically conducting material and may be, for example, a metallic interconnect (e.g., a metal pad or wire), an electrically conducting polymer interconnect, a graphene interconnect, or the like. The substrate **20** may be any type of suitable substrate such as, for example, a semiconductor substrate, a dielectric substrate, or the like.

In this embodiment, a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process, which may also be referred to as an Electron Beam Induced Deposition (EBID) process, is used to form the interfaces **10** and **12** between the MWCNT **14** and the interconnects **16** and **18** on the substrate **20**. By taking advantage of surface diffusion of precursor molecules and controlling a location of a primary, or high energy, electron beam (e-beam) used in the FEB-CVD process, the interfaces **10** and **12** are fabricated with nanometer resolution such that there are low electric resistance ohmic contacts formed between all conduction shells, or at least a majority of the conduction shells, of the MWCNT **14** and the interconnects **16** and **18** on the substrate **20**.

Before continuing with the discussion of FIGS. **1**A through **1**C, a discussion of FED-CVD is beneficial. FIG. **2** graphically illustrates an exemplary FEB-CVD process. In this FEB-CVD process, a tightly-focused, high-energy primary e-beam impinges on a substrate. High energy primary electrons from the primary e-beam interact with the substrate to produce low energy secondary electrons. A precursor gas is introduced into a reaction chamber either via flooding from a smaller reaction cell within the reaction chamber with the precursor gas, local injection of the precursor gas using very a fine needle, or as a residual species pre-adsorbed on the substrate which is commonly referred to as a substrate contamination.

Once adsorbed on the substrate surface, precursor molecules from the precursor gas continuously redistribute on the substrate by surface diffusion. Interactions of adsorbed precursor molecules with back-scattered primary and secondary electrons of the appropriate energy result in dissociation of the precursor molecules and formation of a deposit. As will be appreciated by one of ordinary skill in the art, the precursor gas is selected such that the deposit is formed of a desired material. For example, methane may be selected as the precursor gas in an embodiment where the deposit is desired to be carbon. Note that a variety of materials such as carbon, metals, and like may be deposited via FEB-CVD by selection of the appropriate precursor gas, as will be appreciated by one of ordinary skill in the art upon reading this disclosure. Note that the FEB-CVD process is a room temperature process and is therefore compatible with electronics fabrication processes such as Complementary Metal Oxide Semiconductor (CMOS) fabrication processes.

Returning to FIGS. **1**A through **1**C, FIG. **1**A illustrates the fabrication of the interfaces **10** and **12** at an initial point in time ($t_{initial}$) during the fabrication process. As illustrated, the MWCNT **14** is aligned between the interconnects **16** and **18**. In this embodiment, the interconnects **16** and **18** are, for example, contact pads or wires formed of an electrically conducting material. The interfaces **10** and **12** are formed at exposed ends **22** and **24**, respectively, of the MWCNT **14**. The exposed ends **22** and **24** of the MWCNT **14** expose the inner conduction shells of the MWNCT **14**. For the interface **10**, the primary e-beam used for the FEB-CVD process is focused near the exposed end **22** of the MWCNT **14**. Preferably, the primary e-beam is focused approximately 0 nanometers (nm) (i.e., right at the edge of the exposed end **22** of the MWNT **14**) to 500 nm from the exposed end **22** of the MWCNT **14**. Likewise, for the interface **12**, the primary e-beam used for the FEB-CVD process is focused near the exposed end **24** of the MWCNT **14**. Preferably, the primary e-beam is focused approximately 0 nm (i.e., right at the edge of the exposed end **24** of the MWNT **14**) to 500 nm from the exposed end **24** of the MWCNT **14**. By focusing the primary e-beam near the exposed ends **22** and **24** of the MWCNT **14**, an interface material is deposited near the exposed ends **22** and **24** of the MWCNT **14** and, in this embodiment, over the interconnects **16** and **18**. In one embodiment, the interface material is a-C. In another embodiment, the interface material is a metal such as, for example, Copper, Platinum, Tungsten, or the like. Again, the interface material can be selected by utilizing the appropriate precursor compound.

FIG. **1**B illustrates the interfaces **10** and **12** at an intermediate time ($t_{intermediate}$) in the fabrication process. As illustrated, surface diffusion of the precursor molecules has induced lateral spread of the deposited interface material into the MWCNT **14** at the exposed ends **22** and **24** of the MWCNT **14**. In one embodiment, timing of an ON/OFF regime, or sequence, for the primary e-beam is controlled such that surface diffusion of the precursor molecules is given sufficient time to induce lateral spread of the deposited interface material into the exposed ends **22** and **24** of the MWCNT

14. As will be appreciated by one of ordinary skill in the art upon reading this disclosure, the amount of time that is sufficient to induce lateral spread of the deposited interface material into the exposed ends **22** and **24** may vary depending on various parameters such as, but not limited to, a surface diffusion coefficient for the precursor molecules on the surface of the substrate **20**, the physico-chemical nature of the precursor molecule and the substrate **20**, the deposition conditions (pressure, temperature), among other factors and a distance between the primary e-beam and the exposed ends **22** and **24** of the MWCNT **14**.

FIG. **1**C illustrates the interfaces **10** and **12** at a final time (t_{final}) in the fabrication process. At this point, deposition of the interface material is complete. As illustrated, surface diffusion of the precursor molecules has continued to induce lateral spread of the deposited interface material into the MWCNT **14** such that the deposited interface material atomically fills and establishes an electric contact to all conduction shells (both inner and outer), or at least a majority of the conduction shells, of the MWCNT **14** at the exposed ends **22** and **24** of the MWCNT **14**. Again, in one embodiment, timing of an ON/OFF regime, or sequence, for the primary e-beam is controlled such that surface diffusion of the precursor molecules is given sufficient time to induce lateral spread of the deposited interface material into the exposed ends **22** and **24** of the MWCNT **14**.

In one embodiment, fabrication of the interfaces **10** and **12** is completed via post processing. More specifically, the interfaces **10** and **12** may be annealed by either direct heating (thermal) or by passing an electric current through the interface (electric). For example, in one embodiment, the deposited interface material is a-C, which, due to its amorphous structure, is an insulator rather than a conductor. By thermally or electrically annealing the deposited interface material, the a-C is partially or totally graphitized. In other words, via thermal or electric annealing, the deposited carbon transitions from a-C, which is insulating, to partially or totally graphitized carbon, which is conducting. As a result, after post processing, the interfaces **10** and **12** are ohmic contacts having low electric resistivity. Note that in the embodiment where the deposited interface material is a-C, after post processing, the electric resistivity of the interfaces **10** and **12** is low both because of the conductivity of the partially or totally graphitized carbon interfaces **10** and **12** and because the partially or totally graphitized carbon interfaces **10** and **12** have a crystalline structure that is the same as, or similar to, that of the conduction shells of the MWCNT **14**.

FIG. **3** is a flow chart illustrating a process for fabricating the interfaces **10** and **12** between the MWCNT **14** and the interconnects **16** and **18** on the substrate **20** according to one embodiment of this disclosure. First, the MWCNT **14** is aligned between the interconnects **16** and **18** (step **100**). The MWCNT **14** may be aligned between the interconnects **16** and **18** using any suitable technique. In one embodiment, a droplet of MWCNT solution is placed on a region of the substrate **20** containing the interconnects **16** and **18**. A Direct Current (DC), Alternating Current (AC), or DC-AC potential is then applied on one of the interconnects **16** and **18**, the other one of the interconnects **16** and **18** is allowed to remain floating, and a third interconnect (not shown) in the region is grounded. A strength of the resulting non-uniform interelectrode electric field is controlled to overcome Brownian motion such that the MWCNT **14**, which is within the MWCNT solution, aligns between the interconnects **16** and **18**. While not essential, for a more detailed discussion of an exemplary process for aligning the MWCNT **14** between the interconnects **16** and **18**, the interested reader is directed to J. W. Song et al., "Characterization and air pressure sensing of doubly clamped multi-walled carbon nanotubes," 19 Nanotechnology 4 (2008), which is hereby incorporated herein by reference for its teaching relating to aligning a MWCNT between electrodes.

Next, the ends of the MWCNT **14** are cut to expose the inner conductive shells of the MWCNT **14**, thereby providing the exposed ends **22** and **24** of the MWCNT **14** (step **102**). Note that some MWCNTs may already have exposed ends and therefore do not need to be cut. As such, step **102** may not be needed for all types of MWCNTs. Any suitable process for cutting the ends of the MWCNT **14**, or otherwise opening the ends of the MWCNT **14** to expose the inner conduction shells, may be used. In one embodiment, localized water assisted electron beam etching and Focused Ion Beam (FIB) cutting is used to cut the ends of the MWCNT **14** to expose the inner conduction shells. More specifically, if small amounts of water vapor are introduced into the microscope chamber, the MWCNT **14** may be cut by focusing the primary e-beam at the desired location to perform an etching process. The carbon forming the MWCNT **14** may be etched as a result of the reaction $C+2H_2O \rightarrow CO_2+2H_2$ with $\Delta H=-82.4$ kilojoules per mole (kJ/mol). Carbon can also be removed from the MWCNT **14** by exothermic reactions $C+O_2 \rightarrow CO_2$ and $C+\frac{1}{2}H_2 \rightarrow CH$ with oxygen and hydrogen originating either from the environment or the water reaction.

A FEB-CVD process is then performed to deposit a desired interface material near the exposed ends **22** and **24** of the MWCNT **14** such that, during deposition, the interface material laterally spreads into the MWCNT **14**, thereby atomically filling and making contact to all conduction shells (both inner and outer), or at least a majority of the conduction shells, of the MWCNT **14** at the exposed ends **22** and **24** of the MWCNT **14** (step **104**). As discussed above, the primary e-beam used for the FEB-CVD process is focused near the exposed end **22** of the MWCNT **14**. During deposition of the desired interface material, surface diffusion of the precursor molecules induces lateral spread of the interface material into the MWCNT **14** such that the interface **10** connects to all conduction shells, or at least most conduction shells, of the MWCNT **14**. Likewise, the primary e-beam used for the FEB-CVD process is focused near the exposed end **24** of the MWCNT **14**. During deposition of the desired interface material, surface diffusion of the precursor molecules induces lateral spread of the interface material into the MWCNT **14** such that the interface **12** connects to all conduction shells, or at least most conduction shells, of the MWCNT **14**.

Note that various parameters of the FEB-CVD process may be adjusted to control a size and shape of the interfaces **10** and **12** to an arbitrary degree as well as to control the growth rate of the interfaces **10** and **12**. For instance, primary e-beam current, primary e-beam energy, primary e-beam diameter, deposition chamber pressure and temperature, deposition time, precursor delivery scheme, or any combination thereof may be controlled to grow the interfaces **10** and **12** in a desired shape and size at an acceptable growth rate. As an example, the interfaces **10** and **12** may be grown using a Scanning Electron Microscope (SEM) as the source of the primary e-beam in a high vacuum of 10-6 Torr with no additional precursor gases introduced by keeping the primary e-beam focused for a time period between 2.5 minutes and 25 minutes with a e-beam accelerating voltage or energy in the range of 15-30 kiloelectron volts (keV) and with a primary e-beam current in the range of approximately 350-450 picoamps (pA). While not essential, for more information regarding the effects of the FEB-CVD process parameters on the size and shape of the interfaces **10** and **12** and the growth rate of the

interfaces **10** and **12**, the interested reader is directed to Andrei G. Fedorov et al., "Transport issues in focused electron beam chemical vapor deposition," 201 Surface & Coatings Technology 8808 (2007), Konrad Rykaczewski et al., "Analysis of electron beam induced deposition (EBID) of residual hydrocarbons in electron microscopy," 101 Journal of Applied Physics 054307 (2007), Konrad Rykaczewski et al. "Dynamic growth of carbon nanopillars and microrings in electron beam induced dissociation of residual hydrocarbons," 108 Ultramicroscopy 989 (2008), and William B. White et al., "What Controls Deposition Rate in Electron-Beam Chemical Vapor Deposition?," 97 Physical Review Letters 086101 (2006), each of which is incorporated herein by reference for their teachings on the effect of FEB-CVD parameters on the size and shape of the deposit and the growth rate of the deposit.

Once the interfaces **10** and **12** are deposited, post-processing may be performed (step **106**). Note that post-processing may not be needed for all types of interface materials. In one embodiment, the deposited interface material is a-C. For a-C, thermal or electric annealing is used to provide total or partial graphitization of the a-C thereby causing the interfaces **10** and **12** to transition from insulating to conducting. At this point, the carbon interfaces **10** and **12** have a low-electric resistance as a result of the post-processing and the fact that the crystalline structure of the carbon interfaces **10** and **12** is the same as, or similar to, that of the conduction shells of the MWCNT **14**. Once post-processing is complete, the interfaces **10** and **12** provide low electric resistance ohmic contacts to all of the conduction shells, or at least a majority of the conduction shells, of the MWCNT **14**.

FIGS. **4**A through **4**C graphically illustrate a process for fabricating an interface **26** between CNTs **28** and **30** on a substrate **32** according to another embodiment of the present disclosure. Preferably, the CNTs **28** and **30** are MWCNTs **28** and **30** and, therefore, will be referred to as such for much of this disclosure. However, in an alternative embodiment, the CNTs **28** and **30** are Single Walled CNTs. Note that while FIGS. **4**A through **4**C illustrate two MWCNTs **28** and **30**, this process may be used to create an interface between more than two MWCNTs such that the interface **26** connects aligned ends of the more than two MWCNTs. For example, one end of each of three MWCNTs may be aligned such that the interface **26** connects the aligned ends of the three MWCNTs.

The process of FIGS. **4**A through **4**C is substantially the same as that described above. FIG. **4**A illustrates the fabrication of the interface **26** at an initial point in time ($t_{initial}$). As illustrated, an end **34** of MWCNT **28** has been aligned with an end **36** of the MWCNT **30** using any suitable technique. Depending on whether the ends **34** and **36** of the MWCNTs **28** and **30**, respectively, are already exposed, the ends **34** and **36** may be cut using, for example, an FIB cutting process to expose the inner shells of the MWCNTs **28** and **30**, which are hereinafter referred to as exposed ends **34** and **36**. A primary e-beam used for the FED-CVD process is focused near the exposed ends **34** and **36** of the MWCNTs **28** and **30**. Preferably, the primary e-beam is focused in the range of and including approximately 0 nm (i.e., right at the edge of the exposed end of the MWNT) to 500 nm from each of the exposed ends **34** and **36** of the MWCNTs **28** and **30**. By focusing the primary e-beam near the exposed ends **34** and **36** of the MWCNTs **28** and **30**, an interface material is deposited near the exposed ends **34** and **36** of the MWCNTs **28** and **30**. In one embodiment, the interface material is a-C. In another embodiment, the interface material is a metal such as, for example, Copper, Platinum, Tungsten, or the others. Again, the interface material can be selected by utilizing the appropriate precursor compound.

FIG. **4**B illustrates the interface **26** at an intermediate time ($t_{intermediate}$) in the fabrication process. As illustrated, surface diffusion of the precursor molecules has induced lateral spread of the deposited interface material into the exposed ends **34** and **36** of the MWCNTs **28** and **30**. In one embodiment, timing of an ON/OFF regime, or sequence, for the primary e-beam is controlled such that surface diffusion of the precursor molecules is given sufficient time to induce lateral spread of the deposited interface material into the exposed ends **34** and **36** of the MWCNTs **28** and **30**. As will be appreciated by one of ordinary skill in the art upon reading this disclosure, the amount of time that is sufficient to induce lateral spread of the deposited interface material into the exposed ends **34** and **36** of the MWCNTs **28** and **30** may vary depending on various parameters such as, but not limited to, a surface diffusion coefficient for the precursor molecules on the surface of the substrate **32**, the physico-chemical nature of the precursor molecule and the substrate **32**, the deposition conditions (pressure, temperature), among other factors and a distance between the primary e-beam and the exposed ends **34** and **36** of the MWCNTs and **30**.

FIG. **4**C illustrates the interface **26** at a final time (t_{final}) in the fabrication process. At this point, deposition of the interface material is complete. As illustrated, surface diffusion of the precursor molecules has continued to induce lateral spread of the deposited interface material into the exposed ends **34** and **36** of the MWCNTs **28** and **30** such that the deposited interface material atomically fills and establishes an electric contact to all conduction shells (both inner and outer), or at least a majority of the conduction shells, of the MWCNTs **28** and **30** at the exposed ends **34** and **36** of the MWCNTs **28** and **30**. Again, in one embodiment, timing of an ON/OFF regime, or sequence, for the primary e-beam is controlled such that surface diffusion of the precursor molecules is given sufficient time to induce lateral spread of the deposited interface material into the exposed ends **34** and **36** of the MWCNTs **28** and **30**.

In one embodiment, fabrication of the interface **26** is completed via post processing. More specifically, the interface **26** may be annealed by either direct heating (thermal) or by passing an electric current through the interface (electric). For example, in one embodiment, the deposited interface material is a-C, which, due to its amorphous structure, is an insulator rather than a conductor. By thermally or electrically annealing the deposited interface material, the a-C is partially or totally graphitized. In other words, via thermal or electric annealing, the deposited carbon transitions from a-C, which is insulating, to partially or totally graphitized carbon, which is conducting. As a result, after post processing, the interface **26** is an ohmic contact having low electric resistivity. Note that in the embodiment where the deposited interface material is a-C, after post processing, the electric resistivity of the interface **26** is low both because of the conductivity of the partially or totally graphitized carbon interface **26** and because the partially or totally graphitized carbon interface **26** has a crystalline structure that is the same as, or similar to, that of the conduction shells of the MWCNTs **28** and **30**.

FIG. **5** illustrates a system **38** for fabricating the interfaces **10** and **12** between the MWCNT **14** and the interconnects **16** and **18** on the substrate **20** according to one embodiment of the present disclosure. Note that this discussion is equally applicable to the fabrication of the interface **26** between the MWCNTs **28** and **30** as described above in FIGS. **4**A through **4**C. As illustrated, the substrate **20** is located within a reaction

chamber **40**. A primary e-beam source, which in this embodiment is a Scanning Electron Microscope (SEM) **42**, provides the primary e-beam for the FEB-CVD process. The system **38** may also include a precursor source **44**. The precursor source **44** may operate to flood the reaction chamber **40** with the precursor gas or provide the precursor gas to a localized region of the substrate **20** via an associated needle. Note that the precursor source **44** is optional. In another embodiment, the precursor gas is pre-adsorbed on the surface of the substrate **20** from the contamination or exposure to environment. Lastly, the system **38** includes a controller **46**. The controller **34** is a hardware device such as, for example, a personal computer. The controller **46** includes one or more hardware components, one or more software components, or a combination thereof that enable the controller **46** to control the SEM **42** and optionally the precursor source **44** and substrate **20** to fabricate the interfaces **10** and **12** as described above. Note that the system **38** may include additional components that are not illustrated in FIG. **5**, as will be appreciated by one of ordinary skill in the art upon reading this disclosure. For example, the system **38** may include a vacuum pump that operates to control the pressure within the reaction chamber **40**.

Those skilled in the art will recognize improvements and modifications to the embodiments of the present invention. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A method comprising:

aligning a multiwalled carbon nanotube (MWCNT) between two desired nodes on a substrate, the MWCNT comprising a plurality of conduction shells; and

fabricating an interface between an exposed end of the MWCNT and one of the two desired nodes on the substrate such that the interface forms a contact with at least a majority of the plurality of conduction shells of the MWCNT at the exposed end of the MWCNT;

wherein fabricating the interface comprises performing a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process wherein a primary electron beam used for the FEB-CVD process is focused near the exposed end of the MWCNT such that, during deposition of a desired interface material for the interface, surface diffusion of precursor molecules used for the FEB-CVD process induces spread of the desired interface material into the exposed end of the MWCNT thereby making connections with the at least a majority of the plurality of conduction shells of the MWCNT.

2. The method of claim **1** wherein the interface forms a contact with all of the plurality of conduction shells of the MWCNT.

3. The method of claim **1** wherein the primary electron beam is focused at a location that is less than or equal to 500 nanometers (nm) from the exposed end of the MWCNT.

4. The method of claim **1** wherein performing the FEB-CVD process comprises controlling an ON/OFF timing of the primary electron beam during deposition of the desired interface material such that surface diffusion of the precursor molecules is provided sufficient time to induce spread of the desired interface material into the exposed end of the MWCNT.

5. The method of claim **1** wherein the desired interface material is amorphous Carbon (a-C).

6. The method of claim **5** further comprising performing post-processing to provide at least partial graphitization of the a-C such that the interface transitions from insulating to conducting.

7. The method of claim **1** wherein the desired interface material is a metallic material.

8. The method of claim **1** wherein fabricating the interface comprises fabricating the interface at room temperature.

9. The method of claim **1** wherein the MWCNT initially has a closed end, and the method further comprises opening the closed end of the MWCNT to provide the exposed end of the MWCNT.

10. The method of claim **1** wherein the interface is a low electric resistance ohmic contact between the at least a majority of the plurality of conduction shells of the MWCNT and the one of the two desired nodes on the substrate.

11. The method of claim **1** wherein the two desired nodes are two electrically conducting interconnects on the substrate.

12. The method of claim **1** wherein the one of the two desired nodes is an exposed end of a second MWCNT such that the interface connects at least a majority of the plurality of conduction shells of the MWCNT at the exposed end of the MWCNT and at least a majority of a plurality of conduction shells of the second MWCNT at the exposed end of the second MWCNT.

13. A method comprising:

aligning a carbon nanotube (CNT) between two desired nodes on a substrate; and

performing a Focused Electron Beam Chemical Vapor Deposition (FEB-CVD) process to deposit an interface between an end of the CNT and one of the two desired nodes on the substrate, wherein a primary electron beam used for the FEB-CVD process is focused near the end of the CNT such that, during deposition of a desired interface material for the interface, surface diffusion of precursor molecules used for the FEB-CVD process induces spread of the desired interface material to make contact with the CNT.

14. The method of claim **13** wherein the CNT is a Multiwalled Carbon Nanotube (MWCNT) and the interface provides a contact between at least a majority of a plurality of conduction shells of the MWCNT and the one of the two desired nodes on the substrate.

15. The method of claim **13** wherein the CNT is a Single Walled Carbon Nanotube (SWCNT).

16. The method of claim **13** wherein the primary electron beam is focused at a location that is less than or equal to 500 nanometers (nm) from the end of the CNT.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 8,207,058 B1
APPLICATION NO. : 12/493278
DATED : June 26, 2012
INVENTOR(S) : Fedorov et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Please insert the following as the first paragraph of the specification:

--This invention was made with support from the U.S. government under grant number 0403671, awarded by the National Science Foundation. The Government has certain rights in the invention.--

Signed and Sealed this
Twenty-ninth Day of January, 2013

David J. Kappos

David J. Kappos
Director of the United States Patent and Trademark Office