

# US Patent & Trademark Office

## Patent Public Search | Text View

---

United States Patent	12396235
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Dhanyakumar; Mahaveer Sathaiya et al.

---

### Semiconductor device and method for forming the same

---

#### Abstract

A method includes forming a dielectric layer over a substrate; forming a carbon nanotube (CNT) over the dielectric layer; forming a dummy gate structure over the CNT; forming gate spacers on opposite sidewalls of the dummy gate structure; forming source/drain epitaxy structures on opposite sides of the dummy gate structure and in contact with opposite sidewalls of the CNT; replacing the dummy gate structure with a metal gate structure; and forming source/drain contacts over the source/drain epitaxy structures, respectively.

---

**Inventors:** Dhanyakumar; Mahaveer Sathaiya (Hsinchu, TW), Chung; Cheng-Ting (Hsinchu, TW), Chen; Chien-Hong (Hsinchu County, TW), Cai; Jin (Hsinchu, TW), Wu; Chung-Wei (Hsinchu County, TW)

**Applicant:** TAIWAN SEMICONDUCTOR MANUFACTURING COMPANY, LTD.  
(Hsinchu, TW)

**Family ID:** 1000008765806

**Assignee:** TAIWAN SEMICONDUCTOR MANUFACTURING COMPANY, LTD.  
(Hsinchu, TW)

**Appl. No.:** 17/724434

**Filed:** April 19, 2022

#### Prior Publication Data

Document Identifier	Publication Date
US 20230335617 A1	Oct. 19, 2023

---

#### Publication Classification

**Int. Cl.:** H10D64/01 (20250101); H10D30/01 (20250101); H10D30/67 (20250101); H10D84/01 (20250101); H10D84/03 (20250101)

## U.S. Cl.:

CPC     **H10D64/017** (20250101); **H10D30/031** (20250101); **H10D30/6715** (20250101);  
**H10D30/6729** (20250101); **H10D30/6735** (20250101); **H10D30/6757** (20250101);  
**H10D64/021** (20250101); **H10D84/0128** (20250101); **H10D84/013** (20250101);  
**H10D84/0147** (20250101); **H10D84/038** (20250101);

## Field of Classification Search

USPC:   None

---

## References Cited

### U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
2020/0075875	12/2019	Vasen	N/A	H10K 10/481
2020/0161574	12/2019	Vasen	N/A	H10K 10/84
2020/0357911	12/2019	Frougier	N/A	H01L 29/775

### OTHER PUBLICATIONS

Dirk König et al., “Modulation Doping of Silicon using Aluminium-induced Acceptor States in Silicon Dioxide”, Scientific Reports, vol. 7, 2017, pp. 1-8. cited by applicant

Zuzana Melnikova-Kominkova et al., “Strong and efficient doping of monolayer MoS2 by a graphene electrode”, Physical Chemistry Chemical Physics, vol. 21, 2019, pp. 25700-25706. cited by applicant

Carter T. White et al., “Fundamental Properties of Single-Wall Carbon Nanotubes”, The Journal of Physical Chemistry B, vol. 109, No. 1, 2005, pp. 52-65. cited by applicant

U.S. Appl. No. 17/527,723, filed Nov. 16, 2021. cited by applicant

---

*Primary Examiner:* Amer; Mounir S

*Attorney, Agent or Firm:* Maschoff Brennan

---

## Background/Summary

### BACKGROUND

(1) As the semiconductor industry has progressed into nanometer technology process nodes in pursuit of higher device density, higher performance, and lower costs, challenges from both fabrication and design issues have resulted in the development of three-dimensional designs, such as gate all around (GAA) structures. Non-Si based low-dimensional materials are promising candidates to provide superior electrostatics (e.g., for short-channel effect) and higher performance (e.g., less surface scattering). Carbon nanotubes (CNTs) are considered one such promising candidate due to their high carrier mobility and substantially one dimensional structure.

---

## Description

## BRIEF DESCRIPTION OF THE DRAWINGS

- (1) Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.
- (2) FIG. 1A is a top view of a semiconductor device in accordance with some embodiments of the present disclosure.
- (3) FIG. 1B is a cross-sectional view of a semiconductor device in accordance with some embodiments of the present disclosure.
- (4) FIG. 1C is a schematic view of a semiconductor device in accordance with some embodiments of the present disclosure.
- (5) FIG. 2 illustrates band structures of a semiconductor device in accordance with some embodiments of the present disclosure.
- (6) FIG. 3A is a top view of a semiconductor device in accordance with some embodiments of the present disclosure.
- (7) FIGS. 3B to 3C are cross-sectional views of semiconductor devices in accordance with some embodiments of the present disclosure.
- (8) FIGS. 4 to 13 show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure.
- (9) FIGS. 14 to 19 show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure.
- (10) FIGS. 20 to 25 show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure.

## DETAILED DESCRIPTION

- (11) The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.
- (12) Further, spatially relative terms, such as “beneath,” “below,” “lower,” “above,” “upper” and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.
- (13) FIG. 1A is a top view of a semiconductor device in accordance with some embodiments of the present disclosure. FIG. 1B is a cross-sectional view of a semiconductor device in accordance with some embodiments of the present disclosure. In greater details, FIG. 1B is the cross-sectional view along line B-B of FIG. 1A. It is noted that some elements of FIG. 1B are not illustrated in FIG. 1A for clarity. Moreover, it is noted that the embodiments, of FIGS. 1A and 1B use a front-gate device as an example, while the structure can also be a back-gate device in other embodiments.
- (14) Reference is made to FIGS. 1A and 1B. Shown there is a substrate 100. The substrate 100 is

made of a suitable elemental crystalline semiconductor, such as silicon, diamond or germanium; a suitable alloy or compound crystalline semiconductor, such as Group-IV compound semiconductors (e.g., silicon germanium (SiGe), silicon carbide (SiC), silicon germanium carbide (SiGeC), GeSn, SiSn, SiGeSn), Group III-V compound semiconductors (e.g., gallium arsenide, indium gallium arsenide (InGaAs), indium arsenide, indium phosphide, indium antimonide, gallium arsenic phosphide, or gallium indium phosphide), or the like. In some embodiments, crystalline silicon is used as the substrate **100**.

(15) In FIG. **1A**, the substrate **100** includes a first region **100A** and a second region **100B**. In some embodiments, an N-type device (e.g., NFET) is disposed over the first region **100A**, while a P-type device (e.g., PFET) is disposed over the second region **100B**. Alternatively, in some other embodiments, a P-type device (e.g., PFET) is disposed over the first region **100A**, while an N-type device (e.g., NFET) is disposed over the second region **100B**.

(16) In FIG. **1B**, a dielectric layer **105** is disposed over the substrate **100**. The dielectric layer **105** may be an insulating material, which is utilized to isolate devices formed on the substrate **100**. In some embodiments, the dielectric layer **105** is a dielectric material such as silicon oxide, aluminum oxide, combinations thereof, or the like. In some embodiments, the thickness of the dielectric layer **105** is in a range from about 10 nm to about 100 nm.

(17) One or more carbon nanotubes (CNTs) **110** are arranged over the substrate **100** and are disposed on the dielectric layer **105**. Each of the CNTs **110** may serve as channel region in a semiconductor device, and thus the CNTs **110** can also be referred to CNT channel. As shown in FIG. **1A**, the CNTs are arranged over the substrate and aligned with substantially the same direction (e.g., Y direction). The CNTs **110** are laterally stacked over the substrate **100** along a direction (e.g., Y direction) that is perpendicular to the lengthwise direction of the CNTs **110** (e.g., X direction). In FIG. **1B**, the CNTs **110** are disposed over the dielectric layer **105**, and are vertically separated from the substrate **100** by the dielectric layer **105**. In some embodiments, the average diameter of the CNTs **110** is in a range from about 0.7 nm to about 2.0 nm, or may be in a range from about 0.5 nm to about 2.0 nm. In some embodiments of FIG. **1B**, the CNTs **110** and the dielectric layer **105** may include substantially the same width. For example, sidewalls of the CNTs **110** may be aligned with sidewalls of the dielectric layer **105**. In some other embodiments, the CNTs **110** and the dielectric layer **105** may include different widths.

(18) Gate structures **140** are disposed over the substrate **100**. As shown in FIG. **1A**, each of the gate structures **140** may cross over the CNTs **110**. FIG. **1C** shows embodiments that each of the gate structures **140** may wrap around the CNTs **110**. It is noted that although the embodiments of FIGS. **1A** to **1C** illustrate that the CNTs **110** are laterally stacked over the substrate **100**, the CNTs **110** may also be vertically stacked over the substrate **100** in some embodiments.

(19) The gate structures **140** may include a gate dielectric layer **142** and a gate electrode **144** over the gate dielectric layer **142**. In some embodiments, the gate dielectric layer **142** includes one layer of high-k dielectric. In some other embodiments, the gate dielectric layer **142** includes multi-layer structure, such as an interfacial layer and a high-k dielectric material. Examples of high-k dielectric material include HfO<sub>2</sub>, HfSiO, HfSiON, HfTaO, HfTiO, HfZrO, zirconium oxide, aluminum oxide, titanium oxide, hafnium dioxide-alumina (HfO<sub>2</sub>—Al<sub>2</sub>O<sub>3</sub>) alloy, other suitable high-k dielectric materials, and/or combinations thereof. The thickness of the high-k dielectric material may be in a range from about 1 nm to about 10 nm. Examples of interfacial layer include silicon oxide (SiO<sub>2</sub>), silicon nitride (SiN), silicon oxynitride (SiON), hBN, aluminum oxide (Al<sub>2</sub>O<sub>3</sub>), other suitable dielectric material, and/or combinations thereof. The thickness of the interfacial layer may be in a range from about 0.5 nm to about 2 nm. The gate dielectric layer **142** may be formed by CVD, ALD or any suitable method. In one embodiment, the gate dielectric layer **142** is formed using a highly conformal deposition process such as ALD in order to ensure the formation of a gate dielectric layer having a uniform thickness around each of the CNTs **110**.

(20) In some embodiments, the gate electrode **144** includes a conductive material and may be

selected from a group comprising of polycrystalline-silicon (poly-Si), poly-crystalline silicon-germanium (poly-SiGe), metallic nitrides, metallic silicides, metallic oxides, and metals. Examples of metallic nitrides include tungsten nitride, molybdenum nitride, titanium nitride, and tantalum nitride, or their combinations. Examples of metallic silicide include tungsten silicide, titanium silicide, cobalt silicide, nickel silicide, platinum silicide, erbium silicide, or their combinations. Examples of metallic oxides include ruthenium oxide, indium tin oxide, or their combinations. Examples of metals include tantalum, tungsten, titanium, aluminum, copper, molybdenum, nickel, platinum, etc. In some embodiments, the gate electrode **144** may be deposited by CVD, ALD, sputter deposition, or other techniques known and used in the art for depositing conductive materials. The thickness of the gate electrode **144** may be in a range from about 5 nm to about 40 nm.

(21) As shown in FIG. **1B**, gate spacers **150** are disposed on opposite sidewalls of each of the gate structures **140**. In some embodiments, the gate spacers **150** may be formed by insulating dielectric material, such as a silicon nitride-based material. Examples of the silicon nitride-based material can be SiN, SiON, SiOCN or SiCN and combinations thereof. In some other embodiments, the insulating material is one of SiOC, SiCON and SiCN. In some embodiments, the thickness of the gate spacers **150** is in a range from about 2 nm to about 10 nm.

(22) Source/drain epitaxy structures **160** are disposed over the substrate **100** and on opposite sides of the gate structure **140**. As shown in FIG. **1B**, the source/drain epitaxy structures **160** may be in contact with the dielectric layer **105** and the CNTs **110**. In some embodiments of FIG. **1B**, the source/drain epitaxy structures **160** may be in contact with bottom surfaces of the gate spacers **150**. Stated another way, the source/drain epitaxy structures **160** may extend to positions that are vertically under the corresponding gate spacers **150**.

(23) In FIG. **1B**, each of the source/drain epitaxy structures **160** may include a wider portion **160W** and a narrower portion **160N** over the wider portion **160W**. The wider portion **160W** of the source/drain epitaxy structures **160** is below the bottom surfaces of the gate spacers **150** and is in contact with the substrate **100**, the CNTs **110**, and the dielectric layer **105**. On the other hand, the narrower portion **160N** of the source/drain epitaxy structures **160** is in contact with sidewalls of the gate spacers **150**.

(24) In some embodiments, the source/drain epitaxy structures **160** may include lightly-doped regions **160LDD**. In some embodiments, the lightly-doped regions **160LDD** are located in the wider portion **160W** of the source/drain epitaxy structures **160**, and are in contact with the CNTs **110**. In some other embodiments, the lightly-doped regions **160LDD** may be in contact with the bottom surfaces of the corresponding gate spacers **150**. Here, the lightly-doped regions **160LDD** may be referred to as regions of the source/drain epitaxy structures **160** that have lower dopant concentration than other regions of the source/drain epitaxy structures **160**. For example, the lightly-doped regions **160LDD** may include lower dopant concentration than the narrower portion **160N** of the source/drain epitaxy structures **160**. As a result, the narrower portion **160N** of the source/drain epitaxy structures **160** can also be referred to as a heavily-doped region.

(25) In some embodiments, the source/drain epitaxy structures **160** may include Si, SiGe, Ge, III-V materials, or the like. In some embodiments, the source/drain epitaxy structures **160** may include epitaxial material for N-type device (e.g., NFET), such as SiP, SiAs, SiC, or the like. On the other hand, the source/drain epitaxy structures **160** may include epitaxial material for P-type device (e.g., PFET), such as SiGeB, SiCB, or the like. In some embodiments, the source/drain epitaxy structures **160** may include dopant such as Ge, C, P, As, B, or the like.

(26) Source/drain contacts **170** are disposed over and in contact with the source/drain epitaxy structures **160**. In some embodiments, the source/drain contacts **170** may include conductive material such as W, Co, Ru, TiN, Ti, TaN, Ta, Al, Mo, Ag, Sc, Hf, Sn, Au, Pt, Pd, or combinations thereof. The source/drain contacts **170** may include single layer structure or multi-layer structure. In some embodiments where each of the source/drain contacts **170** is a multi-layer structure, the

source/drain contacts **170** each may include a liner and a filling metal over the liner. Examples of the liner can be TiN, Ti, TaN, Ta, or the like. Examples of the filling metal can be W, Cu and Co, or the like.

(27) As shown in FIG. **1B**, contact etch stop layer (CESL) **165** may be disposed over the Source/drain contacts **170** are disposed over and in contact with the source/drain epitaxy structures **160** and extending to sidewalls of the gate spacers **150**. In some embodiments, the CESL **165** may also extend along sidewalls of the source/drain contacts **170**. The CESL **165** may be made of a dielectric material, such as silicon nitride, silicon carbide, or the like, or a combination thereof.

(28) FIG. **2** illustrates band structures of a semiconductor device in accordance with some embodiments of the present disclosure. In greater detail, FIG. **2** shows the band structure along the source/drain contact **170**, the source/drain epitaxy structure **160**, the lightly-doped region **160LDD**, the CNT **110**, the lightly-doped region **160LDD**, the source/drain epitaxy structure **160**, and the source/drain contact **170** of the device of FIG. **1B**. In some embodiments, the source/drain epitaxy structure **160** on the left side of FIG. **2** can be referred to as source epitaxy structure **160**, and thus the source/drain contact **170** on the left side of FIG. **2** can be referred to as source contact **170**. On the other hand, the source/drain epitaxy structure **160** on the right side of FIG. **2** can be referred to as drain epitaxy structure **160**, and thus the source/drain contact **170** on the right side of FIG. **2** can be referred to as drain contact **170**.

(29) In condition A of FIG. **2**, the band structure under a flat band condition is illustrated. In condition A, the voltage  $V_s$  applied to the source contact **170** (left side) and the voltage  $V_D$  applied to the drain contact **170** (right side) are set to 0V. The gate voltage  $V_G$  is set to flat band voltage  $V_{sub.FB}$ . It can be seen that the conduction band of the CNT **110** is aligned with the conduction bands of lightly-doped regions **160LDD** on opposite sides of the CNT **110**.

(30) In condition B of FIG. **2**, when the voltage  $V_D$  applied to the drain contact **170** (right side) and the gate voltage  $V_{sub.G}$  are set to  $V_{sub.DD}$ , the conduction band of the CNT **110** is also aligned with the conduction bands of lightly-doped regions **160LDD** on opposite sides of the CNT **110**.

(31) The band alignment can reduce the contact resistance at CNT **110**, and will improve the device performance. This is due to the present of the source/drain epitaxy structures **160**, which are located between the CNT **110** and the source/drain contacts **170**. The conduction bands of the source/drain epitaxy structures **160**, which are made of semiconductor material, such as silicon-based or germanium-based materials, can be tuned by doping the source/drain epitaxy structures **160**, and thus the band alignment can be achieved. However, if the source/drain epitaxy structures **160** are omitted, the CNT **110** will be in direct contact with the source/drain contacts **170**, which in turn will increase the contact resistance at the interfaces between the CNT **110** and the source/drain contacts **170**. In some embodiments, the estimated contact resistance between the CNT **110** and the source/drain epitaxy structures **160** is about 0.72 K $\Omega$ , while the estimated contact resistance between the CNT **110** and the source/drain contacts **170** (when the source/drain epitaxy structures **160** are omitted) is about 4.5 K $\Omega$ . Accordingly, by inserting the source/drain epitaxy structures **160** between the CNT **110** and the source/drain contacts **170**, the contact resistance at the CNT **110** can be significantly reduced.

(32) In some embodiments, the band alignment of the CNT **110** and the source/drain epitaxy structures **160** can be achieved by several ways. First, doping the source/drain epitaxy structures **160** will create shallow states in the band-gap, in which the shallow states have small ionisation energies. In some embodiments, if the dopant concentration is high, the dopant states will create a band that is close to the conduction band, which will effectively decrease the band-gap of the source/drain epitaxy structures **160**. Moreover, the lightly-doped regions **160LDD** of the source/drain epitaxy structures **160** are formed in contact with opposite sides of the CNT **110**, and will facilitate band alignment with the CNT **110**. In some embodiments where the lightly-doped regions **160LDD** are omitted in FIG. **1B**, the estimated drain current  $I_{sub.deff}$  may be degraded by about 30%.

(33) Moreover, the conduction band of the CNT **110** can be tuned by adjusting the diameter of CNT **110**. Generally, there are three types of CNT structures based on chirality: armchair, zigzag, and chiral. Chirality can be used to adjust the diameter of the CNT **110**. In some embodiments, the average diameter of the CNT **110** is in a range from about 0.7 nm to about 2.0 nm, such range will result in a satisfied band-gap of the CNT **110** for band alignment with the source/drain epitaxy structures **160**.

(34) It is noted that the discussion of FIG. 2 uses an N-type device as an example. If the device is a P-type device, the band alignment can be achieved by tuning the valence bands of the CNT **110** and the source/drain epitaxy structures **160**.

(35) As mentioned above, the substrate **100** includes a first region **100A** and a second region **100B**. An N-type device (e.g., NFET) is disposed over the first region **100A**, while a P-type device (e.g., PFET) is disposed over the second region **100B**. Alternatively, in some other embodiments, a P-type device (e.g., PFET) is disposed over the first region **100A**, while an N-type device (e.g., NFET) is disposed over the second region **100B**. Here, the N-type device is referred to as a device using electrons as majority carriers in channel, while the P-type device is referred to as a device using holes as majority carriers in channel. In some embodiments, the N-type device can be formed by doping the source/drain epitaxy structures **160** with N-type dopants, while the P-type device can be formed by doping the source/drain epitaxy structures **160** with P-type dopants. In some embodiments, the CNTs **110** of an N-type device (e.g., NFET) over the substrate **100** and the CNTs **110** of a P-type device (e.g., PFET) over the substrate **100** may include single diameter. That is, diameter of the CNTs **110** of an N-type device (e.g., NFET) over the substrate **100** may be substantially the same as diameter of the CNTs **110** of a P-type device (e.g., PFET).

(36) FIG. 3A is a top view of a semiconductor device in accordance with some embodiments of the present disclosure. FIGS. 3B and 3C are cross-sectional views of a semiconductor device in accordance with some embodiments of the present disclosure. In greater details, FIGS. 3B and 3C are different embodiments of cross-sectional views along line B-B of FIG. 3A. It is noted that some elements of FIGS. 3B and 3C are not illustrated in FIG. 3A for clarity. Moreover, some elements of FIGS. 3A to 3C may be similar to those described in FIGS. 1A and 1B, such elements are labeled the same, and relevant details will not be repeated for brevity.

(37) The embodiments of FIGS. 3A to 3C are different from the embodiments of FIGS. 1A and 1B, in that each of the CNTs **110** of FIGS. 3A to 3C is longer than the gate structures **140** along the lengthwise direction of CNTs **110**. For example, as shown in FIGS. 3B and 3C, the CNTs **110** may be wider than the gate structure **140**, and may extend to bottom surfaces of the gate spacers **150**. In such embodiments, opposite ends of the CNTs **110** may be vertically aligned with outer sidewall of the respective gate spacers **150**.

(38) In some embodiments of FIGS. 3A to 3C, each of the CNTs **110** may include lightly-doped regions **110LLD** on opposite sides of each of the CNTs **110**. For example, as shown in FIGS. 3B and 3C, the lightly-doped regions **110LLD** may be located at opposite portions of each of the CNTs **110** that are under the gate spacers **150**, while portion of each of the CNTs **110** that is under the gate structure **140** may be un-doped region. In some embodiments, the portion of each of the CNTs **110** that is under the gate structure **140** may also be referred to as a channel portion. In some embodiments, the dopant concentration of the lightly-doped regions **110LLD** of the CNTs **110** is higher than the channel portion of the CNTs **110**.

(39) Furthermore, the embodiments of FIGS. 3A to 3C are different from the embodiments of FIGS. 1A and 1B, in that the epitaxy structures **160** of FIGS. 3A to 3C do not include lightly-doped region (e.g., the lightly-doped regions **160LDD** of FIG. 1B).

(40) In the embodiments of FIG. 3B, the dielectric layer **105** and the CNTs **110** has substantially the same width. As a result, sidewalls of the CNTs **110** may be aligned with sidewalls of the dielectric layer **105**. Furthermore, different from embodiments of FIG. 1B, each of the epitaxy structures **160** in FIG. 3B may include substantially uniform width. For example, the gate spacers

**150** may not overlap the epitaxy structures **160** along the vertical direction.

(41) In the embodiments of FIG. 3C, the dielectric layer **105** is narrower than the CNTs **110**. That is, portions of the epitaxy structures **160** may extend to positions that are vertically under the CNTs **110**. For example, the epitaxy structures **160** of FIG. 3C may be similar to the epitaxy structures **160** described in FIG. 1B, which includes a wider portion **160W** and a narrower portion **160N** over the wider portion **160W**. However, in the cross-sectional view of FIG. 3C, the wider portion **160W** of the epitaxy structures **160** may be vertically separated from the bottom surfaces of the gate spacers **150** by the CNTs **110**.

(42) Embodiments of FIGS. 3A to 3C provide another way to reduce contact resistance at the CNTs **100**. For example, the opposite ends of each CNT **110** are doped to form lightly-doped regions **110LLD**, and will facilitate band alignment between the CNT **110** and the source/drain epitaxy structures **160**. In some embodiments, the estimated contact resistance between the CNT **110** and the source/drain epitaxy structures **160** is about 0.72 K $\Omega$ , while the estimated contact resistance between the CNT **110** and the source/drain contacts **170** (when the source/drain epitaxy structures **160** are omitted) is about 4.5 K $\Omega$ . Accordingly, by inserting the source/drain epitaxy structures **160** between the CNT **110** and the source/drain contacts **170**, and by further forming lightly-doped regions in the CNT **110**, the contact resistance at the CNT **100** can be significantly reduced.

(43) FIGS. 4 to 13 show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure. In greater details, FIGS. 4 to 13 illustrate a method for forming the structure shown in FIG. 3B. It is noted that relevant structural details will not be repeated for brevity.

(44) Reference is made to FIG. 4. A dielectric layer **105** is deposited over a substrate **100**, and a CNT **110** is formed over the dielectric layer **105**. It is noted that, although one CNT **110** is illustrated in FIG. 4, numbers of CNTs **110** may be formed over the substrate **100** as shown in FIG. 3A. The dielectric layer **105** may be deposited onto the substrate **100** using a deposition process such as chemical vapor deposition, sputtering, atomic layer deposition, combinations of these, or the like. However, any suitable material and any suitable deposition process may be utilized.

(45) The CNT **110** can be formed by various methods, such as arc-discharge or laser ablation methods, or a templated CVD method on a substrate. The formed CNTs can be dispersed in a solvent, such as sodium dodecyl sulfate (SDS). The CNTs can be transferred to and disposed on a substrate using various methods, such as a floating evaporative self-assembly method in some embodiments.

(46) Reference is made to FIG. 5. A gate dielectric layer **132**, which includes silicon oxide, silicon nitride, or the like, may be deposited over the CNT **110**. Next, a dummy gate layer **134**, such as amorphous silicon, polycrystalline silicon, or the like, may be deposited over the gate dielectric layer **132** and then planarized (e.g., by CMP). A hard mask **136**, such as silicon nitride, silicon carbide, or the like, may be formed over the dummy gate layer **134**. The materials used to form the gate dielectric layer **132**, the dummy gate layer **134**, and hard mask **136** may be deposited using any suitable method such as CVD, plasma-enhanced CVD (PECVD), atomic layer deposition (ALD), plasma-enhanced ALD (PEALD) or the like, or combinations thereof.

(47) Reference is made to FIG. 6. The gate dielectric layer **132**, the dummy gate layer **134**, and hard mask **136** may be patterned to form dummy gate structures **130**. In some embodiments, the dummy gate structures **130** may be formed by, for example, forming a patterned photoresist layer over the hard mask **136**, which includes openings that expose unwanted portions of the gate dielectric layer **132**, the dummy gate layer **134**, and hard mask **136**, and then performing an etching process to remove the unwanted portions of the gate dielectric layer **132**, the dummy gate layer **134**, and hard mask **136** through the openings of the patterned photoresist layer. Each of the dummy gate structures **130** includes remaining portions of the gate dielectric layer **132**, the dummy gate layer **134**, and hard mask **136**.

(48) In some embodiments, after the gate structures **130** are formed, lightly-doped regions **110LDD**



may be formed in the CNT **110** by doping portions of the CNT **110** that are uncovered by the gate structures **130**. In some embodiments, the CNT **110** can be doped by suitable process, such as molecular doping, ion implantation, or the like.

(49) Reference is made to FIG. 7. A spacer layer **151** is deposited blanket over the structure of FIG. 6. In greater details, the spacer layer **151** is formed lining exposed surfaces of the dummy gate structures **130** and lining exposed surfaces of the CNT **110**. In some embodiments, the spacer layer **151** may be deposited using any suitable method such as CVD, plasma-enhanced CVD (PECVD), atomic layer deposition (ALD), plasma-enhanced ALD (PEALD) or the like, or combinations thereof.

(50) In some embodiments, the lightly-doped regions **110LDD** are not formed in the stage of FIG. 6. Instead, the lightly-doped regions **110LDD** may be formed after the spacer layer **150** are deposited over the structure of FIG. 6. In some embodiments, the lightly-doped regions **110LDD** may be formed by using charged spacer. For example, the spacer layer **150** may be doped, such that the spacer layer **150** becomes a donor type spacer or an acceptor type spacer. If the spacer layer **150** is an acceptor type spacer (doped with B, Al, Ga, In, or the like), the spacer layer **150** may include acceptor states that can capture electrons from portions of the CNT **110**, while leaving holes to the portions of CNT **110** as majority charge carriers for P-type device. Similarly, if the spacer layer **150** is a donor type spacer (doped with P, As, Sb, or the like), the spacer layer **150** may include donor states that can capture holes from portions of the CNT **110**, while leaving electrons to the portions of CNT **110** as majority charge carriers for N-type device. Here, the portions of the CNT **110** with charge carriers can be referred to as the lightly-doped regions **110LDD**.

(51) Reference is made to FIG. 8. An etching process is performed to remove horizontal portions of the spacer layer **151** (see FIG. 7), while leaving vertical portions of the spacer layer **151** remaining on sidewalls of the dummy gate structures **130**. The remaining portions of the spacer layer **151** may be referred to as gate spacers **150**.

(52) The etching process further removes portions of the CNT **110** and portions of the dielectric layer **105** that are not covered by the dummy gate structures **130** and the gate spacers **150** until top surface of the substrate **100** is exposed. As a result, openings **O1** are formed in the dielectric layer **105**. In some embodiments, the etching process may include an anisotropic etching process, such as dry etch. Accordingly, after the etching process, sidewalls of the gate spacers **150**, the CNT **110**, and the dielectric layer **105** may be aligned with each other.

(53) Reference is made to FIG. 9. Source/drain epitaxy structures **160** are formed in the openings **O1** of the dielectric layer **105**. In some embodiments, the source/drain epitaxy structures **160** may overfill the openings **O1** of the dielectric layer **105** such that top surfaces of the source/drain epitaxy structures **160** may be higher than top surface of the CNT **110**, such that the source/drain epitaxy structures **160** are in contact with sidewalls of the gate spaces **150**. In some embodiments, the source/drain epitaxy structures **160** may be formed by selective epitaxial growth (SEG). In some embodiments, the epitaxy structures **160** may be doped with p-type dopants or n-type dopants.

(54) Reference is made to FIG. 10. A contact etch stop layer (CESL) **165** is deposited blanket over the structure of FIG. 9. Afterward, an interlayer dielectric (ILD) layer **166** is deposited over the CESL **165**. In some embodiments, the ILD layer **166** may include silicon oxide, silicon nitride, silicon oxynitride, tetraethoxysilane (TEOS), phosphosilicate glass (PSG), borophosphosilicate glass (BPSG), low-k dielectric material, and/or other suitable dielectric materials. Examples of low-k dielectric materials include, but are not limited to, fluorinated silica glass (FSG), carbon doped silicon oxide, amorphous fluorinated carbon, parylene, bis-benzocyclobutenes (BCB), or polyimide. In some embodiments, the CESL **165** and the ILD layer **166** can be deposited by CVD, plasma-enhanced CVD (PECVD), atomic layer deposition (ALD), plasma-enhanced ALD (PEALD) or the like, or combinations thereof.

(55) Reference is made to FIG. 11. A chemical mechanism polishing (CMP) process is performed

to remove excess materials of the CESL **165** and the ILD layer **166** until top surfaces of the dummy gate structures **130** (see FIG. **10**) are exposed. Afterward, an etching process is performed to remove the dummy gate structures **130** to expose the CNT **110**. As a result of the etching process, gate trenches TR1 are formed between the gate spacers **150**. In some embodiments, the dummy gate structures **130** may be removed by a suitable process, such as wet etch, dry etch, or combinations thereof.

(56) Reference is made to FIG. **12**. Metal gate structures **140**, which include a gate dielectric layer **142** and a gate electrode **144**, are formed in the gate trenches TR1. In some embodiments, the metal gate structures **140** can be formed by, for example, depositing material(s) of the gate dielectric layer **142**, depositing material(s) of the gate electrode **144** over the material(s) of the gate dielectric layer **142**, and subsequently performing a CMP process until the top surface of the ILD layer **166** is exposed. The gate dielectric layer **142** may be formed by PVD, CVD, ALD, or other suitable deposition processes. The gate electrode **144** may be formed by PVD, CVD, ALD, or other suitable deposition processes.

(57) Reference is made to FIG. **13**. An etching process is performed to remove portions of the ILD layer **166** and the CESL **165** (see FIG. **12**) to form openings that expose top surfaces of the source/drain epitaxy structures **160**. Afterwards, source/drain contacts **170** are formed in the openings. In the cross-sectional view of FIG. **13**, the etching process may remove an entirety of the ILD layer **166**, such that the source/drain contacts **170** may be in contact with the CESL **165**. However, in some other embodiments, portions of the ILD layer **166** may remain in the cross-sectional view of FIG. **13**, and the remaining ILD layer **166** may be in contact with sidewalls of the source/drain contacts **170**. In some embodiments, the source/drain contacts **170** may be formed by PVD, CVD, ALD, or other suitable deposition processes. In some embodiments, prior to forming the source/drain contacts **170**, silicide layers (not shown) may be formed over the exposed surfaces of the source/drain epitaxy structures **160**. The silicide layers may include NiSi, CoSi and WSi, or the like.

(58) FIGS. **14** to **19** show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure. In greater details, FIGS. **14** to **19** illustrate a method for forming the structure shown in FIG. **3C**. It is noted that relevant structural details will not be repeated for brevity.

(59) Reference is made to FIG. **14**, in which FIG. **14** is a cross-sectional view following the cross-sectional view of FIG. **8**. In greater detail, another etching process is performed to the structure shown in FIG. **8**, so as to laterally trim the dielectric layer **105**. As a result, the openings O1 in the dielectric layer **105** may be enlarged as a result of the etching process, and the openings O1 may expose bottom surfaces of the CNT **100**. In some embodiments, during the etching process of FIG. **14**, the CNT **110** and the gate spacers **150** may include higher etching resistance to the etching process than the dielectric layer **105**. As a result, the dielectric layer **105** may be trimmed while leaving the CNT **110** and the gate spacers **150** substantially intact (or negligible etched) after the etching process is completed. In some embodiments the etching process may be a wet etch. In some embodiments, the dielectric layer **105** may be laterally trimmed by about 1 nm to about 20 nm.

(60) Reference is made to FIG. **15**. Source/drain epitaxy structures **160** are formed in the openings O1 of the dielectric layer **105**. The source/drain epitaxy structures **160** may be formed in contact with the exposed bottom surfaces of the CNT **100**. In some embodiments, the source/drain epitaxy structures **160** may be formed by selective epitaxial growth (SEG). In some embodiments, the epitaxy structures **160** may be doped with p-type dopants or n-type dopants.

(61) Reference is made to FIG. **16**. A contact etch stop layer (CESL) **165** is deposited blanket over the structure of FIG. **15**. Afterward, an interlayer dielectric (ILD) layer **166** is deposited over the CESL **165**.

(62) Reference is made to FIG. **17**. A chemical mechanism polishing (CMP) process is performed to remove excess materials of the CESL **165** and the ILD layer **166** until top surfaces of the dummy

gate structures **130** (see FIG. **16**) are exposed. Afterward, an etching process is performed to remove the dummy gate structures **130** to expose the CNT **110**. As a result of the etching process, gate trenches TR1 are formed between the gate spacers **150**.

(63) Reference is made to FIG. **18**. Metal gate structures **140**, which include a gate dielectric layer **142** and a gate electrode **144**, are formed in the gate trenches TR1. In some embodiments, the metal gate structures **140** can be formed by, for example, depositing material(s) of the gate dielectric layer **142**, depositing material(s) of the gate electrode **144** over the material(s) of the gate dielectric layer **142**, and subsequently performing a CMP process until the top surface of the ILD layer **166** is exposed.

(64) Reference is made to FIG. **19**. An etching process is performed to remove portions of the ILD layer **166** and the CESL **165** (see FIG. **18**) to form openings that expose top surfaces of the source/drain epitaxy structures **160**. Afterwards, source/drain contacts **170** are formed in the openings.

(65) FIGS. **20** to **25** show various stages of a sequential manufacturing operation of a semiconductor device in accordance with some embodiments of the present disclosure. In greater details, FIGS. **20** to **25** illustrate a method for forming the structure shown in FIG. **1B**. It is noted that relevant structural details will not be repeated for brevity.

(66) Reference is made to FIG. **20**, in which FIG. **20** is a cross-sectional view following the cross-sectional view of FIG. **8**. In greater detail, another etching process is performed to the structure shown in FIG. **8**, so as to laterally trim the dielectric layer **105** and to laterally trim the CNT **110**. As a result, the openings O1 in the dielectric layer **105** may be enlarged and the bottom surfaces of the gate spacers **150** may be exposed as a result of the etching process. In some embodiments, the dielectric layer **105** and the CNT **110** may be laterally trimmed by about 1 nm to about 20 nm.

(67) In some embodiments, the etching process may include a first step and a second step. For example the first step may include using a first etchant that has a higher etching rate to the CNT **100** than to the dielectric layer **105**, so as to trim the CNT **100** while leaving the dielectric layer **105** substantially intact (or negligible etched). The second step may include using a second etchant that has a higher etching rate to the dielectric layer **105** than to the CNT **100**, so as to trim dielectric layer **105** while leaving the CNT substantially intact (or negligible etched). The first step may be performed prior to or after the second step. Although in the embodiments of FIG. **20**, the dielectric layer **105** and the CNT **100** are trimmed equally, the dielectric layer **105** and the CNT **100** may be trimmed non-equally in other embodiments.

(68) Reference is made to FIG. **21**. Source/drain epitaxy structures **160** are formed in the openings O1 of the dielectric layer **105**. The source/drain epitaxy structures **160** may be formed in contact with the exposed bottom surfaces of the gate spacers **150**. In some embodiments, the source/drain epitaxy structures **160** may be formed by selective epitaxial growth (SEG). In some embodiments, the epitaxy structures **160** may be doped with p-type dopants or n-type dopants. Examples of p-type dopants can be B, Al, Ga, In, or the like. Examples of n-type dopants can be P, As, Sb, or the like.

(69) In some embodiments, an implantation process may be performed during forming the epitaxy structures **160** to dope the epitaxy structures **160** from top surfaces of the epitaxy structures **160**. Accordingly, heavily doped region may be formed in the narrower portion **160N** of the epitaxy structures **160**. Afterward, an annealing process may be performed to diffuse the dopants in the narrower portion **160N** of the epitaxy structures **160** laterally, so as to form lightly-doped region **160LDD** under the gate spacers **150**.

(70) Reference is made to FIG. **22**. A contact etch stop layer (CESL) **165** is deposited blanket over the structure of FIG. **15**. Afterward, an interlayer dielectric (ILD) layer **166** is deposited over the CESL **165**.

(71) Reference is made to FIG. **23**. A chemical mechanism polishing (CMP) process is performed to remove excess materials of the CESL **165** and the ILD layer **166** until top surfaces of the dummy

gate structures **130** (see FIG. **22**) are exposed. Afterward, an etching process is performed to remove the dummy gate structures **130** to expose the CNT **110**. As a result of the etching process, gate trenches TR1 are formed between the gate spacers **150**.

(72) Reference is made to FIG. **24**. Metal gate structures **140**, which include a gate dielectric layer **142** and a gate electrode **144**, are formed in the gate trenches TR1. In some embodiments, the metal gate structures **140** can be formed by, for example, depositing material(s) of the gate dielectric layer **142**, depositing material(s) of the gate electrode **144** over the material(s) of the gate dielectric layer **142**, and subsequently performing a CMP process until the top surface of the ILD layer **166** is exposed.

(73) Reference is made to FIG. **25**. An etching process is performed to remove portions of the ILD layer **166** and the CESL **165** (see FIG. **24**) to form openings that expose top surfaces of the source/drain epitaxy structures **160**. Afterwards, source/drain contacts **170** are formed in the openings.

(74) Based on the above discussions, it can be seen that the present disclosure offers advantages. It is understood, however, that other embodiments may offer additional advantages, and not all advantages are necessarily disclosed herein, and that no particular advantage is required for all embodiments. One advantage is that by forming source/drain epitaxy structures on opposite sides of a CNT channel, the contact resistance can be reduced. Moreover, by tuning a diameter of the CNT channel, by forming lightly-doped regions in the source/drain epitaxy structures, or by forming lightly-doped regions in the CNT channel can further achieve band alignment between the CNT channel and the source/drain epitaxy structures, which will further reduce the contact resistance, and will further improve the device performance.

(75) In some embodiments of the present disclosure, a method includes forming a dielectric layer over a substrate; forming a carbon nanotube (CNT) over the dielectric layer; forming a dummy gate structure over the CNT; forming gate spacers on opposite sidewalls of the dummy gate structure; forming source/drain epitaxy structures on opposite sides of the dummy gate structure and in contact with opposite sidewalls of the CNT; replacing the dummy gate structure with a metal gate structure; and forming source/drain contacts over the source/drain epitaxy structures, respectively.

(76) In some embodiments, the method further includes etching the CNT to expose bottom surfaces of the gate spacers, in which the source/drain epitaxy structures are formed in contact with the bottom surfaces of the gate spacers.

(77) In some embodiments, the method further includes performing an annealing process to diffuse dopants of the source/drain epitaxy structures to form lightly-doped regions in the source/drain epitaxy structures, in which the lightly-doped regions are vertically under the gate spacers and are in contact with the CNT.

(78) In some embodiments, the method further includes forming lightly-doped regions in opposite ends of the CNT that are uncovered by the dummy gate structure.

(79) In some embodiments, the method further includes etching the dielectric layer to expose a bottom surface of the CNT, in which the source/drain epitaxy structures are formed in contact with the bottom surface of the CNT.

(80) In some embodiments, etching the dielectric layer is performed to expose a top surface of the substrate.

(81) In some embodiments, the method further includes etching the CNT and the dielectric layer to shorten the CNT and the dielectric layer after forming the gate spacers and prior to forming the source/drain epitaxy structures.

(82) In some embodiments of the present disclosure, a method includes forming a dielectric layer over a substrate; forming a carbon nanotube (CNT) over the dielectric layer; forming a dummy gate structure over the CNT; forming source/drain epitaxy structures on opposite sides of the dummy gate structure and on opposite sides of the CNT, in which forming the CNT and forming the source/drain epitaxy structures includes tuning a conduction band of the CNT and conduction

bands of the source/drain epitaxy structures, such that the conduction band of the CNT is aligned with the conduction bands of the source/drain epitaxy structures; and replacing the dummy gate structure with a metal gate structure.

(83) In some embodiments, a diameter of the CNT is in a range from about 0.7 nm to about 2.0 nm.

(84) In some embodiments, tuning the conduction band of the CNT includes forming lightly doped regions in opposite ends of the CNT that are uncovered by the gate spacers.

(85) In some embodiments, tuning the conduction bands of the source/drain epitaxy structures includes doping the source/drain epitaxy structures.

(86) In some embodiments, tuning the conduction bands of the source/drain epitaxy structures further includes performing an annealing process to form lightly doped regions in the source/drain epitaxy structures and in contact with the CNT.

(87) In some embodiments, the method further includes etching the CNT to expose bottom surfaces of the gate spacers, in which each of the source/drain structures has a wider portion in contact with the bottom surface of a corresponding one of the gate spacers, and a narrower portion in contact with a sidewall of the corresponding one of the gate spacers, in which the narrower portion has a smaller width than the wider portion.

(88) In some embodiments, the method further includes etching the dielectric layer to expose a bottom surface of the CNT, in which each of the source/drain structures has a wider portion in contact with the bottom surface of the CNT, and has a narrower portion in contact with a sidewall of the CNT, in which the narrower portion has a smaller width than the wider portion.

(89) In some embodiments of the present disclosure, a device includes a substrate, a dielectric layer, carbon nanotubes (CNTs), a gate structure, gate spacers, source/drain epitaxy structures, and source/drain contacts. The dielectric layer is over the substrate. The CNTs are over the dielectric layer. The gate structure is over the substrate, in which the gate structure covers the CNTs from a top view. The gate spacers are on opposite sidewalls of the gate structure. The source/drain epitaxy structures are over the substrate and on opposite sides of the gate structure, in which in a cross-sectional view, the source/drain epitaxy structures are in contact with opposite ends of the CNTs and opposite sidewalls of the dielectric layer. The source/drain contacts are over the source/drain epitaxy structures, respectively.

(90) In some embodiments, the source/drain epitaxy structures are in contact with bottom surfaces of the gate spacers, respectively.

(91) In some embodiments, each of the CNTs is wider than the dielectric layer.

(92) In some embodiments, the source/drain epitaxy structures are in contact with the substrate.

(93) In some embodiments, the source/drain epitaxy structures include lightly-doped regions under the gate spacers.

(94) In some embodiments, a diameter of each of the CNTs is in a range from about 0.7 nm to about 2.0 nm.

(95) The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

## Claims

1. A method, comprising: forming a dielectric layer over a substrate; forming a carbon nanotube (CNT) over the dielectric layer; forming a dummy gate structure over the CNT; forming gate

spacers on opposite sidewalls of the dummy gate structure; after forming the gate spacers, etching the CNT and the dielectric layer to shorten the CNT and the dielectric layer; after etching the CNT and the dielectric layer, forming source/drain epitaxy structures on opposite sides of the dummy gate structure and in contact with opposite sidewalls of the CNT; replacing the dummy gate structure with a metal gate structure; and forming source/drain contacts over the source/drain epitaxy structures, respectively.

2. The method of claim 1, wherein etching the CNT and the dielectric layer is performed to expose bottom surfaces of the gate spacers, wherein the source/drain epitaxy structures are formed in contact with the bottom surfaces of the gate spacers.

3. The method of claim 2, further comprising performing an annealing process to diffuse dopants of the source/drain epitaxy structures to form lightly-doped regions in the source/drain epitaxy structures, wherein the lightly-doped regions are vertically under the gate spacers and are in contact with the CNT.

4. The method of claim 1, further comprising forming lightly-doped regions in opposite ends of the CNT that are uncovered by the dummy gate structure.

5. The method of claim 1, wherein etching the CNT and the dielectric layer is performed to expose a top surface of the substrate.

6. A method, comprising: forming a dielectric layer over a substrate; forming a carbon nanotube (CNT) over the dielectric layer; forming a dummy gate structure over the CNT; forming gate spacers on opposite sidewalls of the dummy gate structure; etching the dielectric layer to expose a bottom surface of the CNT; forming source/drain epitaxy structures on opposite sides of the dummy gate structure and on opposite sides of the CNT, wherein forming the CNT and forming the source/drain epitaxy structures comprises tuning a conduction band of the CNT and conduction bands of the source/drain epitaxy structures, such that the conduction band of the CNT is aligned with the conduction bands of the source/drain epitaxy structures, wherein one of the source/drain epitaxy structures has a wider portion under the bottom surface of the CNT or a bottom surface of one of the gate spacers, and has a narrower portion alongside a sidewall of the CNT or a sidewall of one of the gate spacers, wherein the narrower portion has a smaller width than the wider portion; and replacing the dummy gate structure with a metal gate structure.

7. The method of claim 6, wherein a diameter of the CNT is in a range from about 0.7 nm to about 2.0 nm.

8. The method of claim 6, wherein tuning the conduction band of the CNT comprises forming lightly doped regions in opposite ends of the CNT that are uncovered by the gate spacers.

9. The method of claim 6, wherein tuning the conduction bands of the source/drain epitaxy structures comprises doping the source/drain epitaxy structures.

10. The method of claim 9, wherein tuning the conduction bands of the source/drain epitaxy structures further comprises performing an annealing process to form lightly doped regions in the source/drain epitaxy structures and in contact with the CNT.

11. A method, comprising: forming carbon nanotubes (CNTs) over a dielectric layer on a substrate; forming a dummy gate structure over the substrate and covering the CNTs; forming gate spacers on opposite sidewalls of the dummy gate structure; after forming the gate spacers, etching the CNTs and the dielectric layer; after etching the CNTs and the dielectric layer, forming source/drain structures over the substrate, wherein in a cross-sectional view, the source/drain structures are in contact with opposite ends of the CNTs and opposite sidewalls of the dielectric layer; and forming a gate structure over the substrate and covering the CNTs.

12. The method of claim 11, wherein the CNTs are arranged along a horizontal direction.

13. The method of claim 11, wherein in the cross-sectional view, one of the CNTs is wider than the dielectric layer.

14. The method of claim 11, wherein the source/drain structures are in contact with the substrate.

15. The method of claim 11, wherein a diameter of each of the CNTs is in a range from about 0.7

nm to about 2.0 nm.

16. The method of claim 11, wherein etching the CNTs and the dielectric layer is performed to expose bottom surfaces of the gate spacers.

17. The method of claim 11, wherein etching the CNTs and the dielectric layer is performed to expose a top surface of the substrate.

18. The method of claim 11, wherein in the cross-sectional view, one of the source/drain structures has a wider portion under a bottom surface of one of the CNTs, and has a narrower portion alongside a sidewall of the one of the CNTs, wherein the narrower portion has a smaller width than the wider portion.

19. The method of claim 11, wherein in the cross-sectional view, one of the source/drain structures has a wider portion under a bottom surface of a corresponding one of the gate spacers, and a narrower portion alongside a sidewall of the corresponding one of the gate spacers, wherein the narrower portion has a smaller width than the wider portion.

20. The method of claim 11, further comprising forming source/drain contacts over the source/drain structures, respectively.

---