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OVERVIEW OF CARBON NANOTUBE FIELD-EFFECT TRANSISTORS

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Abstract: An overview of the different types of CNTFET which have large potential to semiconductor industry and microelectronic systems is presented. The present paper is focused on the structure of the various types of CNTFET and their technology characteristics depending on the specific CNT used: single-walled or multi-walled.

Keywords: CNTFET, nanotube, nanowire, semiconductor quantum wires, carrier mobility

1. Introduction

Device scaling is critical for continuing trend of more functionality in a chip. As the scaling of Si MOSFET approaches towards its limiting value, new alternatives are coming up to overcome these limitations. Many types of transistors with nanomaterials in the channel are studied so far, e.g. Carbon NanoTube Field-Effect Transistor, Silicon (Si) nanowire transistors, Gallium Antimonite (GaSb) nanowire transistors, Gallium Nitride (GN) nanowire transistors (GN), Zinc oxide (ZnO) nanowire transistor, etc. The carbon nanotubes (CNT) are one of the most important new materials with excellent mechanical and electrical properties. The progress of Carbon NanoTube Field-Effect Transistor (CNTFET) technology and the understanding of its device physics has been very dynamic.

2. Carbon nanotubes

Fullerene, graphene and CNT are of major importance among nanostructures. Graphene is a 2D graphite sheet. It is monocrystal SP_2 bonding monolayer in hexagonal flat carbon atomic net. The length of the covalent bonding between two neighboring atoms in the lattice bond is apporx. 0.142 nm. Graphene is the basic structure element of the CNT and fullerenes. The electron transport characteristics in graphene are determined by the high mobility of carriers in the CNT at room temperature which enables the fast signal switching of graphene based devices. The mobility values are above 15 000-20 000 cm^2V^{-1} S^{-1}. Electrons and holes have approximately the same mobility and the doping does not affect conductor mobility [1]. Carbon nanotubes (CNTs) are nanometer-diameter sized tubes consisting of a single graphene sheet wrapped up to form a cylinder. The nanotube diameter is some few nanometres wide while the tube itself may reach a few millimeters. These cylinders can have either metal electrical properties or semiconductor electrical properties and these properties can rival or even exceed the best known metals or semiconductors. CNT can be either single-walled (SW-

CNTs) or multi-walled (MW-CNTs). The SW-CNT structure can be best described as a tube wrapping up one-atom-thick layer of graphite (called grapheme) into a seamless cylinder. Multi-walled nanotubes (MW-CNT) consist of multiple rolled layers (concentric tubes) of graphite. Graphene applications are diverse but they are mostly used as MOSFET channels. The main advantage of a MOSFET with grapheme channel is its high carrier mobility. Graphene is also used in gas sensors. Different gas types generate electrons and holes in graphene and thus change the sensor's resistance [1].

The manufacturing of carbon nanotubes is constantly increasing. The expectation for the upcoming 5-10 years is that the demand for CNTs will continue to grow steadily, as long as cost/quality, purity and production yield issues are overcome. The cost of carbon nanotubes has been changing considerably in the past few years, being dependent on their purity and type as well as the supplier. Depending on the size and morphology of the fibrous carbons, the applications vary a lot. When the diameter is large, they are used in energy devices such as fuel cells, lithium ion secondary batteries, and electric double-layer capacitors. Large fibers can also be used in composites as a filler material, for reinforcing the composites, and as a thermal conductor. As the diameter of the fibrous carbon decreases, the applications also scale down in size. Smaller fibrous carbons can be used as a filler of three-phase composites, such as the resin/large carbon fiber/small carbon nanotube composite. In this composite, nanotubes fill and reinforce the resin that exists around the fiber. The nanotubes in the resin also act as an interconnection between the fibers to enhance the electrical and thermal conductivity of the composite. Nanotubes are used as field emitters and optical polarizers as well [2].

3. Carbon Nanotube FETs (CNTFETs)

The Carbon nanotube field effect transistor (CNTFET) is one of the most promising candidates for next generation electronics and sensors. The first carbon nanotube field-effect transistors were reported in 1998. These were simple devices fabricated by depositing single-wall CNTs (synthesized by laser ablation) from solution onto oxidized Si wafers which had been treated with gold or platinum electrodes. The electrodes served as source and drain, connected via the nanotube channel, and the doped Si substrate served as the gate [3]. CNTFET so far can be classified into: Back-gated CNTFET's, Top-gated CNTFET's, Wrap-around gate CNTFET's, Suspended CNTFET's, Multi-Wall CNTFET, Vertical CNTFET. One device fabricated with CNTs that has been highly examined is the carbon nanotube field-effect transistor (CNTFET), comprised of single-wall CNTs (SWCNTs) as the active element between two metal source and drain contacts. Even though there are many advantages to the CNTFET, such as size, high sub-threshold slope, and low power consumption. There are two main method for CNT creation: CVD Growth и CNT Solution Deposition [4].

3.1 Single-Wall CNTFETs

There are a few types of architecture of Single-wall Carbon Nanotube FET - (SWNT-FET): Back-gated CNTFET's, Top-gated CNTFET's, Wrap-around gate CNTFET's, Suspended CNTFET's, Vertical CNTFET, Local-gated single-walled CNTFET. Single device architecture cannot be suitable for all applications. Hereinafter is an overview of single-wall nanotube devices depending on their architecture.

Back-gated CNTFETs

Type 1 – Carbon Nanotube Field Effect transistor has been fabricated using single-walled carbon nanotube and back-gated architecture. Hydrophobic self-assembled monolayer (SAM) was used to restrict the catalyst-supporting area after the fabrication of an electrode array.

Since it is known that droplets are trapped at rough edges of a hydrophobic surface, the deposition of a liquid-based catalyst, followed by alcohol catalytic chemical vapor deposition (ACCVD) produced SWNTs that grew only at the corners of electrode edges. This method is compatible with scalable and cost-effective liquid-based catalyst preparation. Furthermore, development and lift-off processes are not required. The characterization of the SWNT-FETs showed that, for a channel width of 40 nm, 98% of the 60 devices were electrically connected, and more than 50% of these devices worked as functional FETs. The localized catalyst supporting method presented here will provide an easy batch fabrication method for CNT-FET arrays and may realize the large-scale integration of CNT based FET devices [5].

Type 2 – Carbon nanotubes are quasi one-dimensional nanostructures with unique electrical properties that make them prime candidates for applications in nanoelectronics.1 One of the most important findings in this respect is that they can be used as the channel of nanotube field-effect transistors. Individual CNTFETs, and, more recently, arrays of CNTFETs with good switching characteristics have been produced. The next critical step in assessing the suitability of these devices for computer electronics involves the integration of individual CNTFETs to form logic gates. Two type transistors with different conductivity are created. Intramolecular logic gate was created with them (Figure 1). Using vacuum annealing or doping to make n-type CNTFETs, are fabricated complementary devices, i.e., p- and n-CNTFETs on the same substrate. These complementary CNTFETs are then assembled to form intermolecular logic gates. In particular, we demonstrate the fabrication of a "NOT" gate or voltage inverter. Most importantly, using is more than 3 orders of magnitude, which is sufficient for use in logic circuits. Similar results have been obtained from more than 20 independent devices composed of either one single nanotube or a small bundle of nanotubes [6].

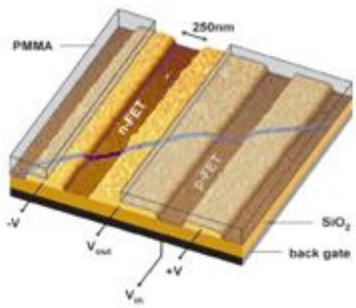

Figure 1. AFM image showing the design of an intramolecular logic gate [6].

Top-gated CNTFET

Type 1 – In typical inverter designs, both n - and p-channel devices are placed side by side to form a complementary circuit. A much more compact configuration can be achieved by placing them on top of each other. First, an n-channel MOSFET device was fabricated using a traditional silicon very large-scale-integration (VLSI) process. A thin gate dielectric layer (150 Å) for the back-gated CNTFET is grown on the exposed polysilicon through thermal oxidation (900 °C). Red dashed lines indicate approximate position of the underlying nMOSFET (Figure 2). Such a configuration offers many advantages for high-density electronics and ultra-sensitive detection [7].

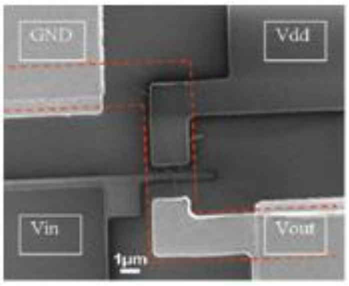

Figure 2. Top view of the hybrid inverter structure obtained by SEM [7].

Type 2 – High performance complementary inverters have been fabricated using single-walled carbon nanotubes. The Al_2O_3 top-gate dielectric is grown via first depositing an Al film followed by complete oxidation of the film. It is shown that the quality of the Al_2O_3 film can be significantly improved by annealing at 400 °C, and stable *p*-type and *n*-type carbon nanotube field-effect transistors (CNTFETs) may be fabricated using either Pd (*p*-type) or Al (*n*-type) electrodes. High performance complementary inverter is demonstrated by integrating the *p*-type and *n*-type CNTFETs on the same carbon nanotube, and a gain of about 3.5 is achieved. Demonstration of a simple process for fabricating stable p-type and n-type top-gate CNTFETs with Al_2O_3 being the gate oxide. The performance of the top-gate CNTFETs is shown to be much better than that of corresponding back-gate CNTFETs, and high performance complementary inverters with gain of about 3.5 are obtained by integrating the *p*- and *n*-type CNTFETs fabricated on the same SWCNT [8].

Wrap-around gate

Type 1 – Demonstration of a gate-all-around single-wall carbon nanotube field-effect transistor. This is the first successful experimental implementation of an off-chip gate and gate dielectric assembly with subsequent deposition on a suitable substrate. In general, a gate all-around (GAA) structure is expected to be the ideal geometry that maximizes electrostatic gate control in FETs. Combining the ultrathin body of a CN with a GAA device geometry is a natural choice for ultimate device design. However, a real GAA layout requires both the dielectric and the gate metal to completely wrap around the semiconducting channel. In this paper, are demonstrated for the first time a GAA-CNFET, consisting of a functionalized nanotube wrapped by an Al_2O_3 dielectric and tungsten nitride (WN) gate metal using atomic layer deposition (ALD). Figure 3 shows the schematic of the GAA-CNFET. The WN and Al_2O_3 are removed everywhere from the CN by wet chemical etching, 1 except in the gate area. Source/drain (S/D) contacts are made at the ends of the CN, leaving uncovered tube segments for chemical or electrostatic doping. The part of the CN under the gate is kept undoped. Depending on the type of doping in the outer segments, we can create a *p*/*i*/*p* or *n*/*i*/*n* profile [9].

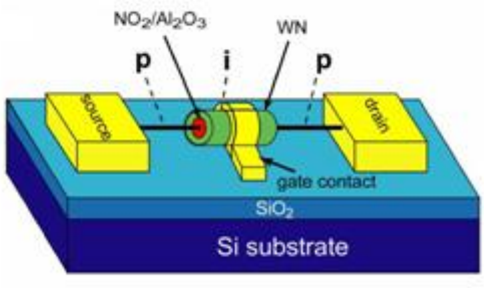

Figure 3. Schematic of a GAA-CNFET [9].

Vertical CNTFET

Type 1 - A schematic for a SG SWCNT-FET is shown in Figure 4. Process for fabricating beginning with a thermally evaporated thin film of 100 nm Ti/100 nm Al/1 nm Fe/300 nm Al (bottom to top) on a thermally oxidized Si wafer, PAA is formed by anodizing the Al in 0.3*M* oxalic acid at 40 V relative to a counter Pt gauze electrode at a constant temperature of 5 °C. The resulting template contains pores with an average diameter of 20 nm at a spacing of approximately 100 nm. The v-SWCNTs are synthesized in a microwave plasma chemical vapor deposition (MPCVD) system flowing 50 SCCM (SCCM denotes cubic centimeter per minute at STP) hydrogen and 10 SCCM methane gases with a 300 W plasma at 10 torr and a substrate temperature of 900 °C as monitored from an embedded thermocouple. The SWCNTs grow vertically from the Fe layer embedded in the PAA, and extend beyond the top of the PAA, at a yield of no more than one SWCNT per pore. The percentage of pores that contain a SWCNT has not been determined, but this characteristic can be adjusted by varying the MPCVD growth conditions and can range from a few percent to more than 50%. SG SWCNT devices offer several advantages, including the ability to scale channel length more aggressively without incurring degrading short channel effects.

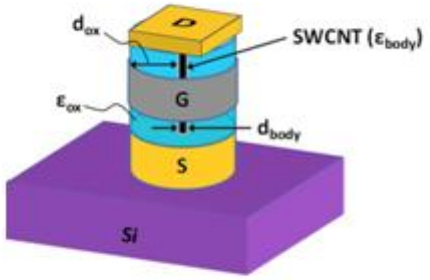

Figure 4. SG configuration [10].

Local-gated single-walled CNTFET

Type 1 – Manifactures Local gated CNTFET devices (figure 5). The approach is based on directed assembly of individual single wall carbon nanotube from dichloroethane via AC dielectrophoresis (DEP) onto pre-patterned source and drain electrodes with a local aluminum gate in the middle. Local gated CNTFET devices display superior performance compared to global back gate with on-off ratios > 10^4 and maximum subthreshold swings of 170 mV/dec. The local bottom-gated DEP assembled CNTFETs will facilitate large scale fabrication of complementary metal-oxide semiconductor (CMOS) compatible nanoelectronic devices.

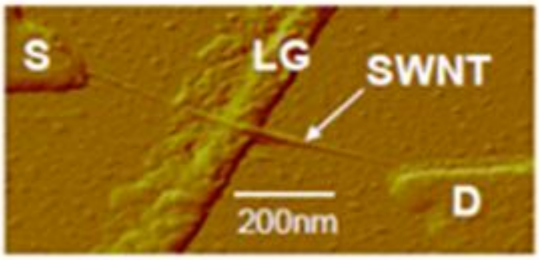

Figure 5. Local gated CNT - FET device [11].

Type 2 – This is other type single-well CNTFET transistor with local gate (figure 6). The CNT gated CNT transistor devices are fabricated using a two-step chemical vapor deposition technique. The measured transfer characteristics are in very good agreement with theoretical modeling results that provide confirmation of the operating principle of the transistors. Gate delays below 2 ps should be readily achievable by reducing the thickness of the gate dielectric.

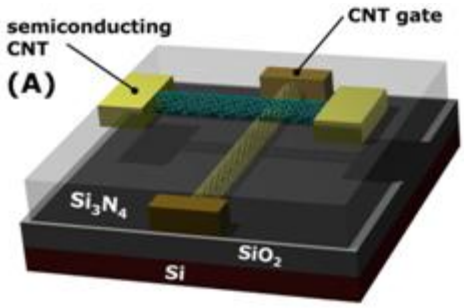

Figure 6. CNTFET with a CNT gate [12].

Multichannel Carbon-Nanotube FET

Type 1 - A high-performance multichannel carbon-nanotube field-effect transistor (MC CNTFET) has been built by applying an array of parallel nanowelded single-walled carbon nanotubes (SWCNTs) as the channels. The SWCNT channel array with good directional and spatial control was obtained by the ac electric-field alignment of SWCNTs on a specially designed electrode. An ultrasonic nanowelding technique was utilized to achieve the reliable and highly transparent contacts between SWCNT channels and electrodes. Both *p*- and *n*-MC-CNTFETs fabricated exhibit high performance. Key transistor performance parameters, transconductance and carrier mobility reach 50.2 μS and 7160 $cm^2 \cdot V^{-1}.S^{-1}$ for p- MC-CNTFETs, and 36.5 μS and 5311 $cm^2. V^{-1}. S^{-1}$ for n- MC-CNTFETs, respectively. Using the authors' techniques, complementary inverters with a high gain of up to 31.2 have also been demonstrated [13].

3.2 Multi-Wall CNTFET

The multiwall carbon nanotubes structure is complex. So they are not studied in detail. Each multiwall carbon nanotube can be metal or semiconductor with different chirality [3].

Type 1 - This study demonstrates the electrical detection of protein binding by the introduction of Au nanoparticle–antibody conjugates in a carbon nanotube field effect transistor (CNTFET), in which the nanoparticle-functionalized carbon nanotube serves as the electrical conducting channel (figure 7). Antibody (anti-horseradish peroxidase) and antigen (horseradish peroxidase) binding events lead to the amplitude change in the drain current, which can be sensitively detected by FET measurements. The sensor shows negligible response to mismatched proteins such as Immunoglobulin G (IgG), confirming the specificity of the biosensor. The reported CNTFET-based biosensor could be adapted to detect a variety of proteins for in vitro diagnostics.

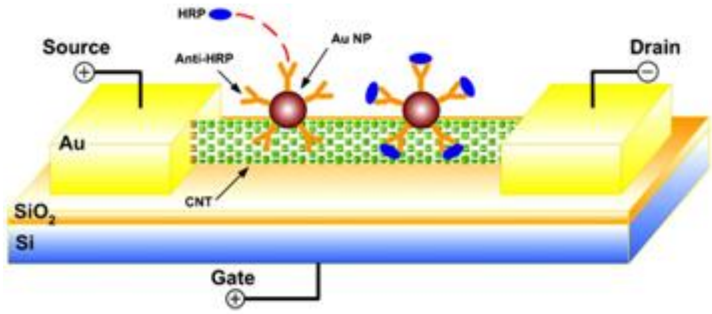

Figure 7. Diagram of a CNTFET. Anti-HRP is anchored to the CNT surface through Au NPs and functions as a specific recognition group for HRP binding [14].

4. Conclusion

This paper presented an overview of the Carbon Nanotubes types and the Carbon Nanotube Field Effect Transistors structures depending on the type of nanotube and device architecture. Carbon nanotubes offer a wide range of attractive properties and could enhance many coatings applications – today there are plenty of CNT devices such as composites, energy devices, electronic applications, and medical applications. Carbon nanotubes are viewed as the most promising carbon nanostructure material for the upcoming nanoelectronic transistors. CNTFETs present an opportunity to sustain the Moore’s Law of scaling should their practical and manufacturing problems be overcome. However, the carbon nanotube field is still in early stage of development.

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