Development, Challenges and Prospects of Carbon Nanotube Transistors in Sensors

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Abstract. Carbon nanotubes are a new type of nanomaterial discovered at the end of the last century. Carbon nanotube have great potential in many fields due to their excellent electrical properties. Carbon nanotube transistor, as one of the most important applications of carbon nanotube, has become a research hotspot in semiconductor field. The technology of carbon nanotube transistor-based sensors has gradually matured in recent years. However, there are still great challenges including the stability of electrical properties. This work outlines the progression of carbon nanotube transistors and their applications in sensors. The basic principles of carbon nanosensors are introduced. In this part, the construction of carbon nanotubes are discussed. In addition, the construction and principles of chemiresistor and back-gated chemical field effect transistor (ChemFET) are highlighted. Moreover, the specific applications of chemiresistor and ChemFET are introduced respectively. Finally, the problems faced by the future development of carbon nanotube sensors have also been raised.

Keywords: Carbon nanotube transistor; sensors; applications.

1. Introduction

Nowadays, sensors are widely used in various fields in the world. There are a variety of sensors including gas sensors, chemical sensors, biological sensors and so on. Among them, gas sensors play a vital role in fire prevention and detection of atmospheric composition. Chemical sensors and biosensors are also important in the areas of medicine and health care. With the progress of society, the demand for sensors is increasing. So far, many materials have been used in sensors. For example, SnO_2, ZnO. Fe_2O_3, WO_3 and Co_3O_4 are often used in gas sensors [1].

Carbon nanotubes (CNTs) is a new material that may be a good candidate of the mainstream materials in the field of sensors. CNTs are seamless nanotubes made of graphene sheets rolled around a central axis. They are lightweight, small in size and have a perfect hexagonal connectivity structure. CNTs can be classified as single-layer CNTs or multilayer CNTs depending on whether they are made of single-layer or multi-layer graphene sheets [2]. Its excellent structural characteristics as well as electron transport properties give it an ultra-high sensitivity when being used as sensors. Carbon nanotube field effect transistor (CNTFET) is reported to be promising due to its small dimension, high stability and selectivity. Therefore, the applications of CNTs in sensors are very attractive to researchers.

In this work, CNTs, CNTFET and their applications in sensors are reviewed. The reason why CNTs have ultra-high sensitivity are discussed. The breakthroughs and applications of CNTs in sensors are then summarized. After that, the breakthroughs in chemical and biosensors are highlighted. Besides, the difficulties and challenges of carbon nanotube transistors in sensors and fabrication are also discussed. Finally, an outlook on the application of carbon nanotube transistors in chemical and biological sensors are given.

2. Carbon Nanotubes and Carbon Nanotube Field Effect Transistor

2.1. The structure and properties of CNTs

CNTs are seamless nanotubes formed by graphene sheets rolled around a central axis with diameters of 2-20 nm. A carbon nanotube consists of one or more concentric hollow carbon cylinders.

Carbon nanotubes composed of single-layer graphene sheets are single-walled carbon nanotubes (SWCNTs). Carbon nanotubes composed of multilayer graphene sheets become multi-walled carbon nanotubes (MWCNTs). SWCNTs have semiconductor properties and are p-type semiconductors by nature [3]. Due to their special structural characteristics, carbon nanotubes have outstanding mechanical, electrical, thermal, and optical properties. Due to their excellent conductivity, SWCNTs exhibit semiconductor characteristics and can be used in the manufacture of sensors.

2.2. Carbon Nanotube Field Effect Transistors

CNTFET consist of source, drain and gate terminals. The drain current which flowed through the channel between drain-source is controlled by the reverse-biased gate terminals together with the source and drain terminal voltages. The simple structure of CNTFET can be seen in Figure 1. However, the fact that CNTs are one-dimensional materials. Their high carrier transport mobility makes them superior candidate to traditional silicon FET [4]. In summary, utilizing CNTFETs in chemical and biological sensors would contribute to the enhancement of the performances.

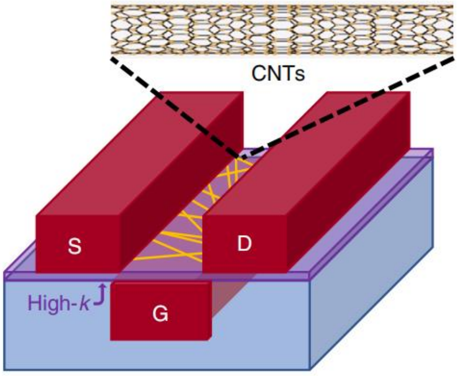

Fig. 1 Schematic diagram of a CNFET with a geometrically structured bottom gate, wherein the FET channel consists of a plurality of parallel carbon nanotubes and has a drain, a source, and a gate in the conventional sense [4].

3. Applications of CNTs as Chemical and Biological Sensors

3.1. Development of Carbon Nanotube Transistor Gas Sensors

Firstly, it is essential to understand the principle of sensors. Carbon nanotransitors are highly sensitive to changes in charge. When molecules combine with carbon nanotubes, the hole density in the nanotube’s changes. Resistance and conductivity of CNTs change accordingly. In this way, the concentration of the gas to be measured can be converted into an electrical signal, realizing the role of a gas sensor.

In general, there are two types of CNT based gas sensors. They are chemiresistor and back-gated chemical field effect transistor (ChemFET) [5]. Their structures are shown in Figure 2. As it is shown in this figure, functionalized carbon nanotubes come into contact with two electrodes in these two types of sensors.

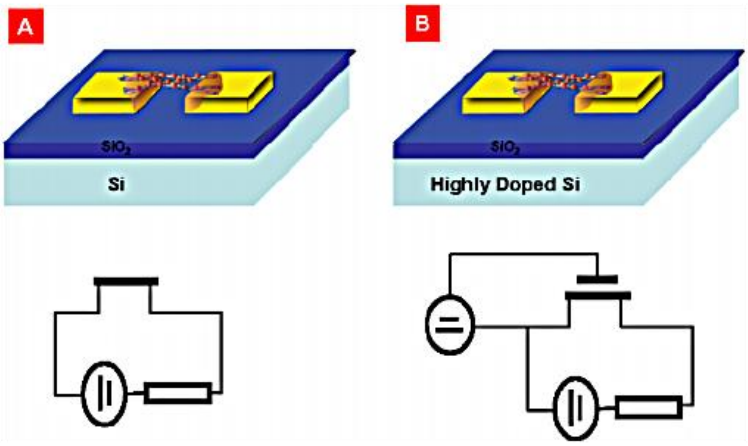

Fig. 2 Schematic structure of a chemoresistor (A) and a chemical field effect tube (B), wherein a functionalized carbon nanotube is in contact with two electrodes [5].

It is well known that FET is widely used as the central sensing unit. In addition, the mechanism that different gas molecules act to enhance the inductive sensing is worthy of exploring. Recent research suggests that a permeation network composed of carbon nanotube transistors with high concentration (99% or more) may be one of the solutions. Minsu Jeon and his team, using pre-separated 99.9% pure carbon nanotubes to make the carbon nano-channels. P-doping process and thermal growth are employed to make a CNT-based FET gas sensor. The results indicate that the average current of sensors prepared using ultra-high purity carbon nanotubes is better than previous results. This proves that high purity carbon nanotubes may be a great solution to improve the sensitivity of gas sensors [6].

However, the weak interaction between gas molecules and carbon nanotubes makes the performance of carbon nanotube transistor gas sensors reduced to a certain extent. Nowadays, some research teams use acid treatment, oxygen plasma treatment, and fluorine plasma treatment to cause defects on the wall of carbon nanotubes. They introduce chemical groups (eg. hydroxyl, carboxyl) to realize the functionalization of carbon nanotube walls. Functionalization of the carbon nanotube wall reduces the gas adsorption on the carbon nanotube wall and avoid the dispersion of CNTs in the liquid [7,8].

3.2. Development of CNT-based Biosensors

Carbon nanotube transistors also have very broad prospects as biosensors. The basic working principle of CNT-based biosensors is also to functionalize carbon nanotubes through chemical means so that they can recognize biometric originals. Chemical means of functionalization are mainly divided into the direct covalent coupling and non-covalent coupling of the two categories. In recent years, in order to improve the performance of SWCNT-based FET biosensors many researchers have made great efforts [9].

One of the most representative improvements in the improvement of protein-based analytes in biosensors is that Kim et al. changed the conductivity by decreasing the distance between the proteins and the channel. They added spacers in the functionalization of CNTFETs. It is easier for charged antigens to approach the surface of SWCNT, which reduced the impact of charge screening by the electrical double layer. Thus, it is easier to influence the conductivity of the CNT. This enhances the sensitivity of the sensor.

In addition, it has been reported that carbon nanotubes used in sensors can help reduce the impact of charge screening. Some researchers combine larger analytes with smaller aptamers which are functionalized on the surface of CNTs to achieve a reduction in the distance between the analyte and the surface of the sensor.

There has also been some progress in the detection of nucleic acid-based analytes for SWCNTS biosensors. FET biosensors generally detect DNA and RNA by functionalizing the complementary DNA and RNA strands on the surface of the sensor so that the sensor can complement the target strand and generate electrical signals. In recent years, Star's team has developed a label-free SWCNT-based FET [11]. Instead of using single-stranded DNA (ssDNA) to covalently attach to the tube wall of SWCNTs, this biosensor uses nucleotide groups to interact with the Π-stack on the tube wall of SWCNTs. In this way, ssDNA encapsulates SWCNTs to form non-covalent attachment. Complementary DNA chains can hybridize to ssDNA on the walls of SWCNTs, resulting in a change in conductivity. This enables polymorphism discrimination of single nucleotides [9].

In recent years, breath analysis has become a new method of detecting human conditions. It has great potential due to its non-invasive advantages. The basic principle of breath analysis is that a sensor detects the volatile molecular components of a person's breath to determine his or her health status (which can be effective in detecting conditions such as prostate cancer, breast cancer, Parkinson's disease, etc.). Due to the excellent chemical properties of CNTs, which make them ideal for breath analysis, Haick and his team constructed a sensor array by coating semiconducting SWCNTs with a variety of non-polymerized organic materials, which were able to successfully differentiate between healthy subjects and those suffering from lung cancer and chronic kidney failure. In a follow-up study Haick's team used a combination of molecularly modified gold nanoparticles and replaced chemoresistance with FET (which was intended to minimize the effect of humidity on the detection results). It finally succeeded in detecting all 17 diseases in more than 1,400 subjects with a correct diagnosis rate of more than 86% [12].

3.3. Challenges and Prospects

Although carbon nanotube-based sensor technology has made great progress, there are still some challenges and difficulties waiting for researchers to overcome. Currently, finding new modified additives that can improve the parameters of nanotube sensors is of vital importance. In addition, the quality of carbon nanotube materials especially different purification schemes should be explored. Besides, the prevention of interferences is another important research topic.

Completely overcoming these challenges is not yet realistic for the current technology. But the cutting-edge advances in CNT sensors in recent years are evidence enough that this field holds great potential.

4. Conclusion

Carbon nanotubes are a modern material with excellent structural and conductive properties. In this work, the progression of carbon nanotubes and carbon nanotube transistor-based sensors were reviewed. This paper focuses on the structures of carbon nanotube transistor-based sensors. Chemiresistor and back-gated chemical field effect transistor were discussed. After that, the paper introduces their cutting-edge applications of gas sensors and biochemical sensors, respectively. Finally, the difficulties and challenges that lie ahead in the advancement of carbon nanotubes are also highlighted.

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