Carbon Nanotube and Its Application in Transistor and Sensor

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Abstract. Carbon nanotubes (CNTs), a new type of nanomaterial, exhibits typical circular tube structure. CNTs have excellent mechanical, electrical, and chemical properties. CNTs have excellent mechanical, electrical, and chemical properties. With the deepening of research on nanomaterials, their application fields have been expanded in recent years. It has become one of the most commonly used functional materials in the semiconductor field. The use of CNTs for modification in transistors has become a research hotspot. At the same time, as a key material for improving the performance of sensors, CNTs are also receiving increasing attention. In this article, the main electrical properties of CNTs were discussed. In addition, the current-voltage relation is also studied in different transistors. For CNT-based transistor, MOSFET and Schottky barrier field effect transistor (SB FET) were highlighted. The application of CNTs in sensors has also been introduced. Bare CNTs used for sensors were reviewed. Several different modification methods are introduced for this type of sensor. Metal particles, organic groups, and aromatic hydrocarbon for modification of CNT sensors have been discussed. According to different characters, they could be applied in real-time detecting and biochemical environment detecting.

Keywords: Carbon Nanotube, Transistor, Sensor, Semiconductor, Integrated Circuits.

1. Introduction

Silicon based circuits have already made a great progress in recent years. In recent years, Artificial Intelligent (AI) technology has developed rapidly with the arrival of the big data era. As an important foundation for the development of this technology, obtaining high-performance transistors has become a key research topic. Classical transistors is composed of silicon, which can be doped by other elements to form PN junction. In order to decrease the energy consumption, increase integration level and arithmetic speed, research have been done to reduce the length of transistor (often refers to the gate length) and decrease the shelter voltage. However, it is a great challenge to adhere to Moore's law. Traditional silicon-based circuits are facing its limits. Short channel effects limit the further development of silicon-based transistor. Therefore, researchers put their eyes onto other materials with excellent properties. Carbon nanotube is one of them.

At the same time, the development and application of artificial intelligence technology cannot be separated from the progress of sensing technology. Exploring high-performance sensors has become a key issue in supporting the development of AI technology. Nowadays, using nanomaterials to modify sensors is acknowledged to be one of the main ways which can improve the performance of sensor. Among numerous high-performance nanomaterials, carbon nanotube is one of them.

Carbon nanotube is a kind of nanomaterial which was reported by Sumlo lijima in 1991 C60. Carbon nanotubes have attracted the interest of many researchers due to their excellent physical, chemical, mechanical, and electrical properties. The potential of carbon nanotubes in transistor modification has been discovered. Meanwhile, it can also find an application in sensor due to its low shelter voltage. A lower shelter voltage means more sensitive to concentration change. Due to the importance of carbon nanotubes in modification of transistor and sensor, a large amount of research has been conducted on this topic in recent years. This study aims to give insight into the recent research of carbon nanotubes and their applications in transistors and sensors.

2. Carbon Nanotube Based Transistor

2.1. Electrical Properties of Carbon Nanotube

The electrical properties of carbon nanotubes affect their application in transistors directly. Therefore, discussing the electrical properties of carbon nanotubes is of great significance. The conductivity of carbon nanotubes is influenced by their structure. According to the characteristics of the structure, carbon nanotubes can be divided into armchair and zigzag. It is interesting that only carbon nanotube with zigzag structure presents the properties of semiconductors [1]. Generally, chirality isomers are difficult to depart from each other. Nevertheless, it has been reported that a gel column chromatography method can separate zigzag carbon nanotube from the mixture of single walled carbon nanotubes [2].

The conductivity of carbon nanotubes is affected by their adsorption. It is well known that carbon nanotubes have high specific surface area and excellent adsorption performance. Carbon nanotube can absorb some small molecule while crystalline silicon cannot. The influence mechanism of adsorption on carbon nanotubes has been discussed. Initially, the adsorbed small molecules were believed to be dopants of carbon nanotubes. However, the mechanism by which adsorption affects the electrical properties of carbon nanotubes cannot be well elucidated through doping mechanisms. The properties cannot to be explained well by doping theory. Therefore, a new mechanism has been proposed to explain this phenomenon. It was reported that the gas absorbed (mainly O2 in air) changed the work function, thus the height of Schottky Barrier was changed correspondingly [3]. Therefore, adsorbing different types of small molecules may achieve adjustable gate voltage. This approach helps to broaden the performance range of carbon nanotubes and achieve modification of carbon nanotubes.

The height of the Schottky barrier also has an impact on the performance of carbon nanotransitors [4]. It has potential to work with an extremely small dimension, candidate for traditional silicon transistors [5]. Identifying the factors that affect the Schottky barrier height can help design specific transistors that meet our needs. The height of the Schottky barrier is influenced by the geometry of the electrode [3]. For example, the needle like contact between the electrode and carbon nanotubes can help reduce the gate voltage.

The carrier transport speed of carbon nanotubes affects their application in transistors. The implementation of high switching speed depends on the high transport speed of charge carriers. High switching speed is another advantage of CNFETs. With a special structure and tiny dimension, carbon nanotube transport electrons via a special way named quasi-ballistic transport. Ultra high carrier mobility can be achieved, reaching $8000cm^2V^{-1}sec^{-1}$ [6].

2.2. CNFET in ICs

The main application of transistors is in digital circuits. There is still a long way to go for CNFET before its commercialization. Nevertheless, researchers can estimate the performance of CNT-based transistor from the applicating view. In a circuit, designer mainly cares about the length of gate electrode, noise margin, voltage swing, delay and etc. There are two main types of CNT transistors, MOS CNFET and SB CNFET. They have different properties and may be applicated in different areas. SB CNFET is much more scalable than Si-based MOSFET. For a fixed gate electrode, the delay of CNFET is smaller. In addition, CNFET has a shorter gate electrode for a fixed delay. That means circuits based on CNT have a higher integrity and a better performance [7].

3. Sensor

Sensors can receive the measured information and transform it into electrical signals or other required forms of information according to certain rules. Therefore, carbon nanotube transistors have important applications in the field of sensors.

3.1. Working Principle: An Interesting Example

Compared with traditional methods, carbon nanotube transistors have a lower energy consumption, higher sensitivity and smaller dimension. This would contribute to the applications in wearable devices. It is reported that carbon nanotube transistor can be used as a glucose biosensor [8]. However, glucose molecules are electrically neutral which can hardly cause the change of electronic field.

To make the current change with the concentration of glucose, glucose aptamers are situated near the gate electrode. After binding with glucose, the receptor undergoes morphological change. In this case, the electrical field will be slightly changed, and the tiny difference would be detected by the carbon nanotube.

Considering the application environment of the sensor, the thickness of the transistor needs to be limited. It is well known that covalent bonds have high bond energy. In carbon nanotubes, the atoms are held together by covalent bonds. This is why carbon nanotubes have good mechanical properties. Good mechanical properties determine the broad application prospects of carbon nanotubes in sensors.

The sensor, to some extent, is a transistor controlled by the concentration of matter. Because of the low gate voltage, carbon nanotube-based sensors tend to have lower detection limits and energy consumption.

The example mentioned above could explain how nanotubes convert concentrations of specific substances into electronic signals. In fact, there are many different mechanisms in different design methods. The performance of sensors is often evaluated from the following aspects, selectivity, detection limits, recovery time, and so on. Different types of carbon nanotube sensors have different advantages and disadvantages, which can be explained from the perspective of structure and composition.

3.2. Bare CNT-based Sensor

For some chemicals, such as ammonia and nitrogen dioxide, they can combine with carbon nanotube and have an impact on the electron cloud density. Dai's team try to explain it by using Molecule Orbital Theory [9], the exact mechanism of this reaction is still debated. This kind of sensor is quite easy to prepare compared to other sensors. However, poor selectivity and sensitivity restrict its application. The poor selectivity results from the entirely random absorbing progress. In other words, CNT could react with all the molecule that have similar structures. For example, an ammonia sensor may react to other polar molecules such as water vapor in humidity conditions.

3.3. Metal Particles Modified CNT-based Sensor

To solve the selectivity problems in bare carbon nanotube, one idea is attaching some material to it. It is widely known the application of Pd in hydrogen catalyze area. And the catalyzing progress is quite similar to the sensor mechanism. Pd draws hydrogen molecules on the surface and depart it into single atoms. Thus, Pd itself becomes a good hydrogen solvent. For the Pd particle attached to carbon nanotube, the first step is the same. With dissociative hydrogen atoms being absorbed, the work function of Pd will be decreased and electron will be injected into CNT [10]. Once the gas of hydrogen is removed from the system, the unstable hydrogen atoms will react with oxygen to form water. The balance is broken, and the conductivity is back to normal.

3.4. Organic Groups Modified CNT-based Sensor

For detecting a complex organic molecule with bioactivity, attach an aptamer is a good way. Aptamer is similar to antibody that can combine with a specific molecule. Compared to antibody, aptamer is synthetic. As to selectivity, the rate of accuracy can reach a very high level. The aptamer can combine with organic molecules with specific polarity and in specific position in three dimensions. It has specificity and recognition, which is similar to fingerprints. Once combined with the target molecule, the aptamer's structure would change in one way or another. And this change would stimulate electron injected into CNT from metal particles.

3.5. CNT-based Sensors Decorated with Aromatic Hydrocarbon

It is necessary to distinguish aromatic groups from other group modifications. In the above-mentioned section, the detection process took place between molecules. For the aromatic modified group sensor, the aromatic group is directly covalent to the carbon nanotubes. In addition, a conjugated system was formed between carbon nanotubes and aromatic groups. In this case, electrons are free to move between the π bonds of the carbon nanotubes and the aromatic compound. Carbon nanotubes can quickly respond to changes in charge, in order to diminish detection delay [11].

4. Conclusion

CNTs, as a research hotspot in nanomaterials, have excellent properties. CNTs have a wide range of applications. Among them, the application in sensors and diodes has developed rapidly in recent years. In this work, some key properties of carbon nanotube and its applications as sensors were discussed. CNTs display tunable properties, so CNFET or CNT-based sensor could be designed to reach the optical performance. SB CNFET and MOS CNFET are discussed. They tend to have different voltage-current characters, noise margin and other characters. They may be used in different field. Several designing methods of sensors are introduced for different target molecule. Carbon nanotube is an excellent semiconductor for its good mechanical properties, high carrier mobility, and low shelter voltage. Carbon nanotube-based devices, including transistors and sensors, have much higher performance than ordinary devices. However, there are still limitations. Exploring techniques of manufacture in the future would help for further applications. In addition, clarifying the underlying mechanism of utilizing CNTs to enhance device performance will also contribute to further development in this field.

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