Diodes made from carbon nanotubes

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Abstract: Carbon nanotube diodes are an important part of nanotechnology and a key component of the nanotechnology revolution that could have major implications for the future. Nanotechnology is a discipline that deals with the design, manufacture and manipulation of materials at the nanometer scale. Carbon nanotubes, on the other hand, are among the nanomaterials that stand out and attract great attention in this field.

Keywords: Carbon nanotube, Nano diode, Single-walled carbon nanotubes (SWCNT), Multi-walled carbon nanotubes (MWCNT), Electrical conductivity.

1.INTRODUCTİON

Diodes prepared from carbon nanotubes are diodes in which carbon nanotube material is used as electronic components.

Carbon nanotubes can be thought of as cylindrical structures formed by bending graphene sheets. These nanotubes can have electrical and optical properties and potentially be used in semiconductor components [1-31].

The crystallinity of carbon nanotubes depends on the structural arrangement of the nanotubes and the position of their atomic planes. Carbon nanotubes are formed by bending graphene sheets in a specific way.

There are two main types of carbon nanotubes: single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT).

1. Single-Walled Carbon Nanotubes (SWCNT):

Single-walled carbon nanotubes are formed by bending a single sheet of graphene into a cylindrical shape. Such nanotubes are highly ordered in crystallinity. The bonds between atoms are regular and nearly perfect, resulting in high electrical conductivity and mechanical properties.

SWCNTs usually have chirality (spiral structure) expressed with (n, m) indices, and these indices determine the properties of the nanotube.

Table 1. Common features of semiconductor diodes and carbon nanotube diodes

General properties	Semiconductor diodes	Carbon nanotube diodes
Semiconductor material	Usually silicon, germanium, etc.	Carbon nanotubes
Diode function	Passes electrical current in one direction	Conducts electrical current in one direction
Band structure	Valence band and transmission band	Electronic band structure
Principle of operation	Transmission of electrons in the band structure	Transmission of electrons in the electronic band structure
Electronic applications	Transistors, solar panels, diodes	Optoelectronic devices, photoelectric sensors, nanoscale electronic devices, etc.
Material Flexibility	Standard silicon semiconductors	Carbon nanotubes, mechanically flexible

Mechanical resistance	Good wear resistance	Mechanically strong
Applications	Electronic devices, solar cells, sensors, etc.	Nanotechnology, optoelectronic devices, advanced applications of nanotubes, etc.

2.Multi-Walled Multi-Walled Carbon Nanotubes (MWCNT):

Multi-walled carbon nanotubes are formed by wrapping multiple layers of graphene around each other. [5, 6, 17-19]There may be gaps and irregularities between these layers. The positions and degrees of bending of the layers in MWCNTs can vary, resulting in less crystal order. Therefore, MWCNTs may have lower electrical and mechanical properties compared to SWCNTs.

The crystallinity of carbon nanotubes exhibits different properties depending on the atomic arrangement in their structure. Single-walled carbon nanotubes tend to have higher conductivity, strength, and other mechanical properties due to their crystal arrangement. [4,30] However, both types of nanotubes have unique properties that can be used in a variety of applications.

The table 1. shows the general aspects of semiconductor diodes and carbon nanotube diodes.[1,7,9,29,31]

The electrical conductivity of diodes prepared frm carbon nanotubes is based on their physical structure. Carbon nanotubes can be thought of as cylindrical structures formed by bending graphene sheets. These structures have a graphite-like structure with unique electronic properties. Diodes prepared from carbon nanotubes basically come about by designing structures containing p-n junctions. Diodes are semiconductor devices that allow electric current to flow in only one direction. Some of the carbon nanotubes may have p-type semiconductor properties, while others may have n-type semiconductor properties. This makes it possible to use carbon nanotubes as diodes.

Semiconductor diodes and some carbon nanotube diodes may have n-type or p-type structures, and these structures significantly affect the diode characteristics. [3-6,22,27,28] The characteristics and operation of N and P type diodes have the basic features described below:

N Type Carbon Nanotube Diodes:

- ⇒ In n-type carbon nanotube diodes, a foreign atom (for example, boron or nitrogen) is added to the structure of the nanotubes.

these diodes, free electrons act as carriers.

- ⇒ Current flows when the anode (P side) is applied negative and the cathode (N side) is applied positive.
- ⇒ In N-type diodes, electrons move towards the anode side and current is generated.

P Type Carbon Nanotube Diodes:

- ⇒ In p-type carbon nanotube diodes, a foreign atom is added to the structure of the nanotubes, this time creating an electron deficiency and turning the nanotube into a p-type semiconductor. In these diodes, holes (lack of electrons) act as carriers.
- ⇒ Current flows when the anode (N side) is applied positive and the cathode (P side) is applied negative.
- ⇒ In P-type diodes, the holes move towards the cathode side and current is generated.

The n-type or p-type structures of carbon nanotube diodes determine the current-voltage (I-V) characteristics of the diode and control in which direction current can flow.[2,5] The conductivity of the diode can vary depending on the applied voltage and therefore diodes can be used in different applications.

N and P type carbon nanotube diodes have potential applications in many fields such as solar cells, sensors, radiation sensors and other optoelectronic devices. The selection of diodes must be done carefully to obtain the appropriate operation and characteristics for a particular application.

The exact mathematical formula of carbon nanotube diodes is difficult to pinpoint, especially given the complexity and different variations of such diodes. However, there are mathematical formulations that express the working principle of diodes in general. Carbon nanotube diodes are based on the electronic properties of semiconductor materials. These diodes are formed by joining semiconductor materials called a p-n junction. P-n junction is the joining of positively charged (p-type) and negatively charged (n-type) semiconductor regions. It is expressed by Ohm's Law and diode equations. For carbon nanotube diodes, the following mathematical formulas can be used:

Diode current voltage relationship (Diode equation):

Here:

I is the current of the diode

I_0, saturation current (non-linear diode characteristic)

e, Euler number (approximately 2.71828)
q, electron charge (approximately $1.602 \cdot 10^{-19}$C)
V is the voltage across the diode
k is Boltzmann's constant (approximately $1.381 \cdot 10^{-23}$J/K)
T is the temperature of the diode (in Kelvin)
Modeling electrical properties of carbon nanotube:
There are several models that fully express the electrical properties of carbon nanotubes, for example the Brenner, Tersoff or Stillinger-Weber potentials.[25-31, 36,37]These models are used to explain the energy band structures, energy levels and electron transfer of nanotubes. However, the exact mathematical formulations of these models are quite complex, and these models are often used with computational methods or simulations.
By 2023, diodes made from carbon nanotubes are generally in laboratory-level research and development and are not widely used in commercial applications. However, due to the potential of carbon nanotubes, it is thought that they could be used in a number of applications in the future. Here are some of the potential consumer and industrial application areas:

1. Electronic Devices: Carbon nanotube diodes can be used in high speed and low power consumption electronic devices. In particular, they can play an important role in the development of high-frequency and high-performance transistors.[1,8,10,11,37-39]
2. Optoelectronic Devices: Carbon nanotubes can be used in optical communication and sensing systems. They have significant potential in the development of optoelectronic devices, especially photodiodes and phototransistors.[12,13-27]
3. Energy Storage and Conversion: Carbon nanotubes can be used in energy storage and conversion technologies such as batteries and supercapacitors, thanks to their high surface area and good conductivity.[14]
4. Biomedical Applications: Carbon nanotubes also have potential applications in biomedical fields such as biosensors, drug carriers and imaging technologies.
5. Sensors: Carbon nanotubes can be used in the development of gas, chemical, radiation and biological sensors. High surface area and sensitivity characteristics can improve sensor performance.

However, to achieve these potential applications, significant challenges such as fabrication methods, scalability and cost of carbon nanotube diodes must be overcome. In addition, the functional properties of diodes such as reliability, stability and repeatability need to be improved

3. CONCLUSİON

Diodes prepared from carbon nanotubes have the potential to have important results in many applications in the future. However, the usability and performance of carbon nanotube diodes in practical applications is still an active research topic. Some laboratory studies and experimental studies have shown that carbon nanotube diodes give some positive results. For example, the high mobility and good electrical conductivity of carbon nanotubes make diodes potentially usable in fast switching and high frequency applications.[9-13] Moreover, the use of carbon nanotubes in optoelectronic devices (for example, photodiodes) may offer advantages such as high sensitivity and fast response times. However, there are some difficulties in the usability of carbon nanotube diodes in practical applications. For example, there are technical difficulties in the production, control and sequencing of carbon nanotubes. In addition, the problems of carbon nanotubes such as surface defects, contact resistance and functional stability are also issues to be resolved.
Therefore, further research and development studies are required for the transition of carbon nanotube diodes to commercial applications and their wide availability. With advances in nanotechnology, it may be possible to realize the potential of carbon nanotube diodes and evolve into further optimized, high-performance diodes. This could open new opportunities for the development of faster, more powerful and more energy efficient electronic devices.

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