Application of CNTs Based on Their Unique Electrical Properties

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Abstract. Ever since carbon nanotubes (CNTs) were discovered, because of their exceptionally impressive mechanical, chemical, and electrical properties, CNTs have garnered considerable interest and investigation from experts throughout the world, accelerating the development of nanoscience and technology. The unique tubular structure of CNTs enables them to have excellent electrical properties and can be used in all aspects of electrical devices. Therefore, this paper collects all aspects of applications and applicable optimization schemes based on the electrical properties of CNTs. The main applications of the electrical properties of nanotubes are summarized. It is discovered that CNTs' electrical characteristics are primarily reflected in the electrochemical devices, photoelectric devices as well as electronic devices. CNTs have tremendous potential for applications in these fields and can greatly improve the performance of related devices and devices. The large-scale production and application of CNTs in related fields will benefit the development of energy, photoelectric and electronic devices worldwide.

Keywords: CNTs, Electrical properties, Electrochemical device, electronic device, Photoelectric device.

1. Introduction

With the rapid development of the new era economy, energy consumption is increasing. However, due to the shortage of global resources and serious environmental pollution, efficient and clean energy technologies are urgently needed to meet the global sustainable energy needs. At the same time, with the rapid development of electronic information technology, electronic devices need to be updated, increasing the demand for devices and devices with ultra-high performance, miniaturization and low energy consumption, making it an inevitable trend to speed up the corresponding electronic device research.

At present, electric power is the most likely clean new energy to replace fossil energy. With the rise of the global electric vehicle, smartphone and other industries, the requirements for energy density, power density, recyclability, reversible capacity and safety of the corresponding batteries are also increasing. CNTs have been one of the hottest nanomaterials in the field of new energy. CNTs have strong interaction with lithium ions. The application of CNTs in lithium battery electrodes can greatly improve the energy density and power density of batteries, greatly enhance the performance of electric vehicles or other electronic devices, and promote the development of related industries. CNTs have attracted considerable attention in the application of supercapacitors due to their good conductivity and ion migration channels, as well as their unique cylindrical structure which does not collapse after multiple charge-discharge cycles, and good cycling performance.

At the same time, solar cells are also a hot spot in the field of energy research in recent years. As is known to all, solar energy is an inexhaustible and inexhaustible clean auxiliary energy. In addition to inorganic solar cells, organic solar cells as a new type of photovoltaic device, have the characteristics of flexibility, light quality, adjustable light absorption, solution processibility, large-area printing preparation, etc. However, low efficiency is the main factor that limits its large-scale application. Doping modification of the interface of single-walled CNTs can solve these problems and improve device performance.

In addition, with the rapid development of electronic information technology, the requirements for microelectronic devices are increasing: integrated circuit chips with high integration to achieve more powerful, lower power consumption, faster and lower cost. Among them, traditional silicon transistors encounter bottlenecks in minimization. Carbon nanotubes, as one of the one-dimensional quantum materials, become the most potential candidates for future transistors. Carbon nanotubes have a large number of favorable electrons moving along the tube wall. Due to its unique structural characteristics, carbon nanotube transistors can be fabricated through doping to obtain both metal conductivity and semiconductor properties. Liquid metals can also be filled into carbon nanotubes by capillary action to prepare nano-metal wires, which upgrade micro-electronic devices to nano-electronic devices, and realize the rapid development of nano-electronic devices.

In summary, carbon nanotubes have considerable research and application value in electrochemical devices, photoelectric devices, and electronic devices because of their remarkable electrical properties. Therefore, a summary of the study on the electrical characteristics of carbon nanotubes is crucial. This study is based on the excellent electrical properties of nanotubes, their applications in electrochemical devices, optoelectronic devices and electronic devices, and their corresponding optimization schemes.

2. Structure and Electrical Properties of Carbon Nanotubes

2.1. Carbon Nanotube Structure

CNTs are seamless nanotube structures made of a single or several layers of graphite sheets twisted at a specific spiral angle around a common central axis. Typically, hemispherical fullerenes with five and seven members surround the ends of CNTs. Each layer of nanotubes has a tube wall that is produced by a hexagonal network plane on which three nearby carbon atoms are completely bound to the central carbon atom by sp^2 hybridization. CNT can be divided into single-walled carbon nanotubes (SWNTs) and multi-walled carbon nanotubes (MWNTs) according to the number of graphite sheets in the tube, as shown in Fig. 1.

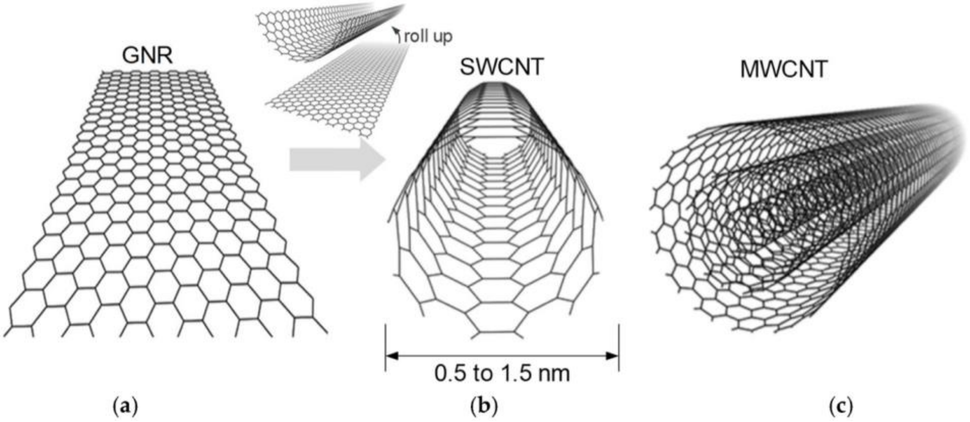

Figure 1. Schematic of Graphene nanoribbon (GNR), SWNT and MWCNT [1]

2.1.1. Structure of MWNT

SWNTs are a coaxial multilayer tubular Fuller carbon structure unexpectedly discovered by IijimaS., which is about 1μm, a multilayered graphite tube with a diameter of 4~30 nm. It is another allotrope of carbon elements through structural studies. The layer count ranges from 2 to 50, and the layers are dispersed randomly. The layer spacing is (0.34 ±0.01) nm, which is equivalent to the layer spacing of 0.335 nm graphite. MWCNTs typically have a diameter of 2 to 30 nm and a length of 0.1 to 50 μm [2]. Defect centers, such as five-membered rings or seven-membered rings, are easily produced during the creation of MWCNTs at the tube's end, the layer's surface, and between the layers. Carbon nanotubes will protrude and seven-membered rings will become concave when five-membered rings develop [2]. If five-membered rings or seven-membered rings appear at the top of carbon nanotubes, they will become caps of carbon nanotubes [2].

2.1.2. Structure of SWNT

With the discovery of MWNT, a large number of researchers conducted extensive research on the characteristics and uses of carbon nanotubes, which furthered the advancement of this field of study.SWNTs are the optimal fiberic material because they have a smaller diameter dispersion, fewer flaws, and greater homogeneity than unrolled graphene. SWNT is 1-50 μm long and has a diameter of 0.7-3.0 nm [2]. One layer of graphene sheets may be imagined as curling up SWNT. The dangling bonds at the border subsequently bind when the graphene sheets coil into a cylinder, leading to the randomness of the carbon nanotube's axis orientation.

The hexagonal lattice of carbon atoms is twisted into a spiral pattern in the overall structure of carbon nanotubes. Helicity is present in carbon nanotubes to a certain extent [2] (Fig. 2). The structure parameters of carbon nanotubes can be determined by the chiral vector (n, m) index. Different (n, m) corresponds to different chiral vectors and chiral angles (Fig. 2). θ), structural parameters such as curling mode, diameter and perimeter.

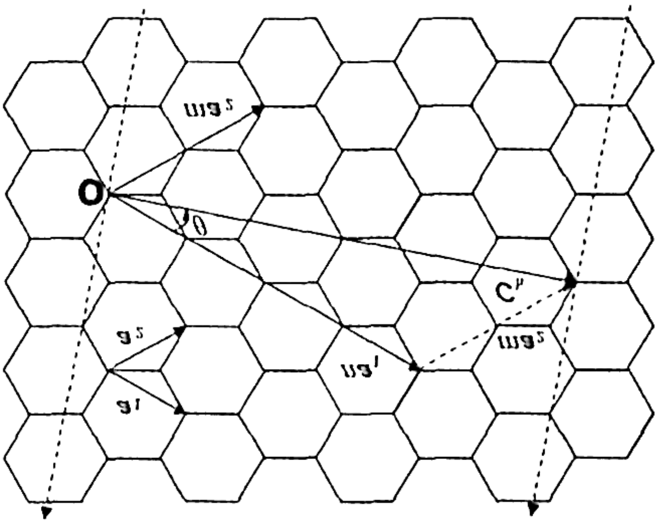

Figure 2. Schematic diagram showing how a hexagonal sheet of graphite is rolled to form a carbon nanotube [3]

Depending on the rolled up direction vectors (i.e., chirality of carbon tubes) (n, m), SWNTs can be roughly metallic (metal, n-m=3k, K is integer, no gap) or semiconductive (semiconductive, n-m≠3k, K is integer, with gap). Depending on the external shape of the fold up, SWNTs can be divided into armchair, zigzag and chiral, as shown in Fig. 3. Generally, when m=n, SWNT can be categorized as chiral, zigzag, and armchair. θ= At 30 degrees, it is called armchair tube. When n(m)= 0, θ= 0 degrees, called serrated tube; Others are commonly referred to as chiral (spiral) tubes.

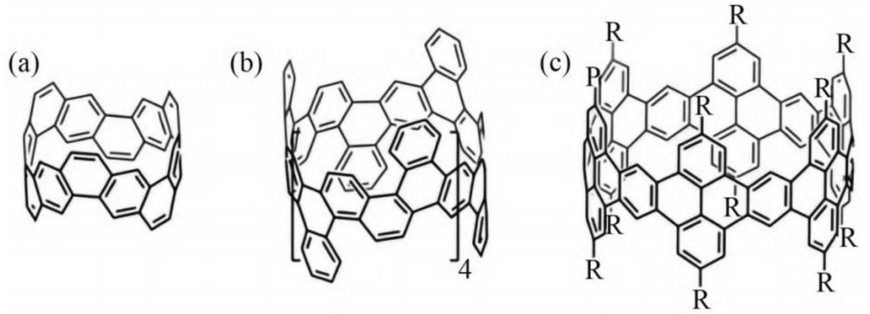

Figure 3. Schematic diagram of different orientations of carbon hexagons along the axial direction in CNTs [4].

(a) Armchair type; (b) Helical type; (c) Zigzag type.

2.2. Electrical Properties of Carbon Nanotubes

2.2.1. Electrical Properties

The electrochemical properties of nano-carbon materials depend on the morphology and micro-structure of the carbon materials, which make them have extraordinary semiconductor properties, and their conductivity is several orders of magnitude higher than any one of the high conductive molecules [5]. This conductivity can even be comparable to copper and silicon. Experiments show that single-walled carbon nanotubes are easy to accept electrons whose conductivity is between semiconductors and metals and changes with the chiral angle and diameter of the tube body. MWCNTs are cylindrical multilayered graphite sheet layers whose outermost shell determines their performance as metal or semiconductor. Besides the properties of electron acceptors, their height-to-diameter ratio fits perfectly with the charge migration along the tube axis. In practical applications, SWCNTs can be used to fabricate electrodes or doped with conjugated macromolecules to form bulk heterojunctions to act as active layers of devices. They can also be used as translucent, flexible hole collectors [5].

2.2.2. Structual Principle in Microscale

Chiral vector (n, m) values, i.e., diameter and chiral angle θ Because the quantum-domain effect electrons can only move along the axis of the tube, the electrical properties of carbon nanotubes change dramatically with the change of the molecular structure. This is a unique structural electrical property of carbon nanotubes, which makes them have completely different properties in different molecular structures. When $|n-m|=3q$ and Q is an integer, (n, m) carbon nanotubes are metallic (no energy bandgap). Therefore, single-arm carbon nanotubes are metallic (n=m); A small part of the chiral and serrated carbon nanotubes are metallic. Many of the chiral and serrated carbon nanotubes are flat conductors with limited band gaps. As the diameter of the carbon nanotubes increases, the band gaps will decrease. For example, the energy gaps of the serrated carbon nanotubes are inversely proportional to the square of the tube radius, so the large-diameter carbon nanotubes are all metallic. Semiconductor-metal carbon nanotube pairs are structurally stable.

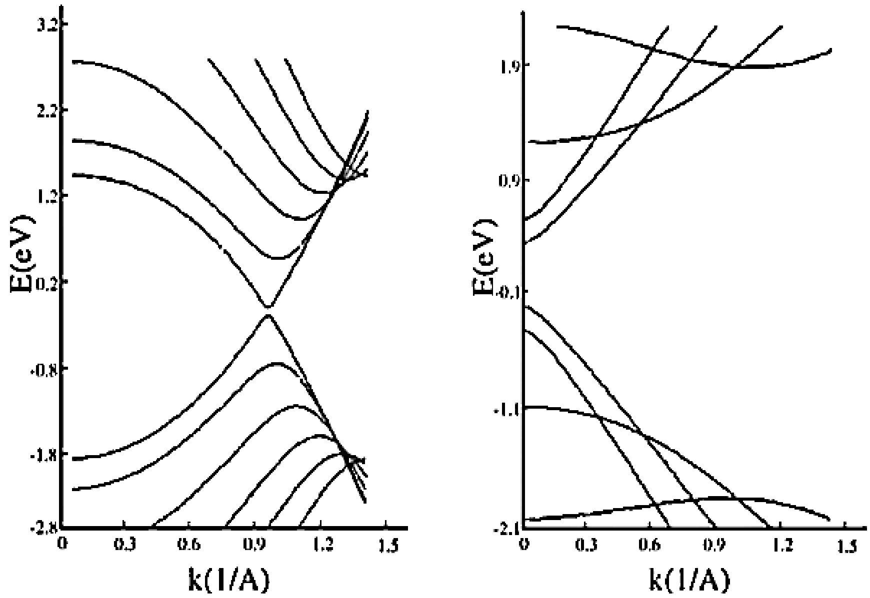

Figure 4. Energy band diagram of metal and semi-conducting CNT.
(L)Metal (R)semi-conductin [6]

CNTs are derived from graphite and have a large number of electrons that move along the wall of the tube, both metal conductivity and semiconductor performance (Fig. 4). By introducing defects in the CNTs (such as pentagonal and heptagonal structures in a hexagonal grid), the same CNTs have both metal and semiconductor properties [6]. This is a molecular diode, in which the current flows from the semiconductor to the metal. In addition, a semiconductor heterojunction can be formed when two carbon nanotubes of different sizes are docked. A third electrode in the vicinity of the heterojunction inside the carbon nanotube can form a conductive channel controlled by a grid. Carbon nanotube transistors made from this principle can operate at room temperature and have a high switching speed by adjusting the grid voltage. The discovery of three-electrode single-molecule transistors is a major advance in molecular electronics, where the resistance of carbon nanotubes can vary over a wide range from semiconductors to insulators [6].

To sum up, because of the special structure of CNT, it has excellent electrical performance and excellent semiconductor properties, making it an excellent representative of carbon materials, and can be used in electrochemical devices, photoelectric devices, electronic devices, to achieve high performance, low energy consumption, miniaturization of corresponding devices and devices.

3. Applications of Electrical Properties of Carbon Nanotubes

3.1. Electrochemical Device

3.1.1. Lithium Ion battery

Due to their high working voltage, high specific energy density, extended cycle life, lack of memory effect, and environmental friendliness, lithium-ion batteries have been used in many facets of life. However, with the popularity of electric vehicles, the performance of existing lithium-ion batteries cannot fully meet the market demand. In addition, the electrodes of lithium-ion batteries can expand and shrink several times during charging and discharging (lithium intercalation and deintercalation), which will lead to the breakage of the electrodes and seriously affect the performance and lifetime of the batteries. Therefore, it is urgent to upgrade and optimize the performance of lithium-ion batteries to meet the market demand. Due to the special one-dimensional structure of carbon nanotubes, excellent mechanical strength and good conductive performance, It can be used as a scaffold for these materials to alleviate strain due to drastic volume changes. In addition, due to the good electrical conductivity of carbon nanotubes, it can enhance the transmission speed of electrons in these materials. These unique micro-structure characteristics make them have excellent lithium-inserting properties. Lithium ions can not only be embedded in the tube, but also embedded in the gap between the tubes or layers, which provides ample storage space and transport channels for lithium ions. In addition, the stable tubular structure of carbon nanotubes will not collapse, crack or powder after multiple charge-discharge cycles. As a result, the performance and cycle life of lithium-ion batteries are greatly improved [2]. Moreover, carbon nanotubes interwoven with the electrode materials can absorb the stress caused by volume changes caused by the deinsertion of lithium ions during the charging and discharging process. As a result, the electrodes are stable and not easily damaged, and their cycle performance is better than that of ordinary carbon electrodes. CNTs have great advantages in the research field of lithium-ion batteries because of their excellent thermal conductivity and high rate charge-discharge performance and safety [2].

As a negative material for lithium-ion batteries, the capacity of carbon nanotubes largely depends on their structure and morphology (ranging from 300 to 1500mA.h/g) [7]. The differences in capacities between different carbon nanotubes can be attributed to structural factors such as chirality, diameter, length, defects, etc. The reversible capacity of the electrode materials can reach 116mA.h/g by post-treatment such as ball milling, acid oxidation and metal oxide cutting. Due to the large structural defects and high voltage lag of carbon nanotubes, it is still challenging to use single carbon nanotubes as electrode materials to achieve high Coulomb efficiency [7]. In order to obtain better electrochemical and physical properties, it is possible to combine carbon nanotubes with active materials to form composite structures or to dope heteroatoms [7].

It is found that when carbon nanotubes were integrated with Fe_2O_3/C composites and a 3-D network structure was formed by cold spraying (see Fig. 5), the lithium storage capacity reached 1598 mA/h/g at 100 mA/g current density. After 1000 charge-discharge cycles, the structure retained 88% capacity. Carbon nanotubes were used as the conductive framework of MoS2 and titanium dioxide is used as the surface coating of MoS_2. A multi-functional carbon nanotube was prepared [7]. After

1000 cycles at current densities of 1000mA/g and 2000 mA/g, the multi-functional carbon nanotube/MoS_2 composite had excellent long cycle performance (528.5mA/h/g and 455.2mA/h/g). Yang et al. composited the carbon nanotube aerogel with $CoFe_2O_4$, which effectively solved the problems of poor conductivity, large volume expansion and severe powdering of $CoFe_2O_4$ [7]. This method not only improved the electrochemical performance, but also increased the safety of the battery. Carbon nanotube aerogel/$CoFeO_4$ composites exhibited a high reversible capacity of 1033 mA/h/g (0.1A/g current density), excellent cycle stability (874 mA/h/g, 160 cycles at 1 A/g), and a capacity of 516 mA/h/g at high current density (5A/g). This demonstrates that the introduction of carbon nanotubes can effectively improve the electron and ion transport, enhance the utilization of highly active materials, and improve the reaction kinetics performance.

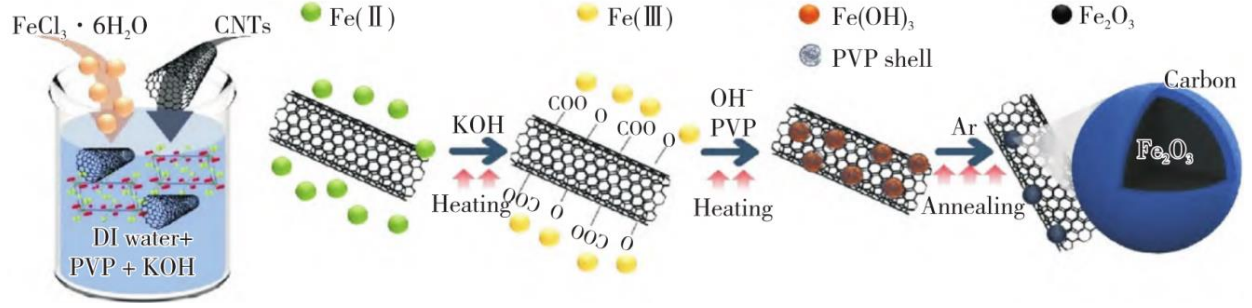

Figure 5. Integration process of carbon nanotubes and Fe2O3/C composites [7]

In addition to the preparation of composite electrodes, heteroatom doping is also a method to improve the properties of carbon nanotube materials.Carbon nanotubes' chemical and physical characteristics may be altered by doping them with boron, nitrogen, and phosphorus atoms. However, a single doping modification has not significantly improved the electrochemical properties. More emphasis is placed on doping at the same time of hybridization with other active phases. Li et al. compounded nitrogen-doped carbon nanotubes with silicon and used them as negative electrodes for lithium-ion batteries [7]. The battery showed a high capacity of 1640 mA.h/g for 500 cycles at 500 mA/g and a capacity retention rate of 70% for 750 cycles at 1 A/g high current density. It is due to the high capacity of silicon and the unique structure of carbon nanotubes that the volume expansion of the material during lithium removal was alleviated. This indicates that nitrogen doping of CNTs improves the capacity and magnification characteristics, resulting in a synergistic effect [7].

3.1.2. Supercapacitor

Supercapacitors are a new kind of green energy storage device that have gained recognition for its high levels of safety, good durability, and quick charging and discharging rates. However, its low energy density makes it urgent to select ideal electrode material as one of the most critical ways to improve the energy density of supercapacitor [8]. CNT has good conductivity, special tubular structure and pore channels to promote ion transport. The application of supercapacitors has been greatly favored, but due to the easy accumulation of CNT in the carbon structure matrix, the energy density and specific capacitance of CNT are limited, which leads to some limitations in the field of supercapacitors. In order to solve this problem, researchers are committed to research and prepare CNT structures with good conductivity. The electrochemical performance of composite electrode materials is also being improved by investigating CNT composited with conductive polymers, transition metal oxides, graphene, and metal organic frameworks in order to fully integrate the benefits of each component and make use of the synergistic effects of various materials.

RuO_2, MnO_x, NiO_x, and CoOx are examples of transition metal oxides and related hydrate electrode materials. These materials have extremely high pseudocapacitance. They are anticipated to be employed as the electrode material for supercapacitors because the Faraday quasi-capacitance generated by the reaction at the electrode/solution interface is significantly greater than the double layer capacitance of the carbon material [8]. However, the low conductivity of these oxides will also reduce the power density of the electrode material. When the transition metal oxides (TMOs) are combined with CNT, the Faraday quasi-capacitance of the TMOs will be reduced. Transition oxide electrodes can undergo fast and reversible electrode reactions. The large specific surface area of CNT mesh structure and good conductivity of CNT make electron transfer more accessible to the inside of the electrodes, so that the energy can be stored in three-dimensional space, which ultimately improves the specific capacitance and energy density of the electrodes [8]. Therefore, to improve the capacitive properties of the electrodes, The composite of CNT and transition metal oxides has attracted much attention in recent years as electrode materials for supercapacitors. There have been many reports on ruthenium oxides and hydrates in the composite materials of CNT and transition metal oxides. Although the electrode materials of CNT and ruthenium oxides have good supercapacitive properties and good performance, ruthenium oxides are precious metal oxides with high cost, toxicity and environmental pollution. It is not conducive to large-scale industrial production. In the study on preparation and electrochemical properties of non-precious transition metal materials of Quanyufei, CNT/Nixene (Mxene) materials with high specific capacitance were prepared through hydrothermal method instead of ruthenium oxides [9]. The specific capacitance of CNT/Mxene//NiCoO4ASC at 1A/g reached up to 291F/g, and 5000 cycles of charging and discharging at 5A/g have a capacity retention rate of 90.85%. As the cathode material of supercapacitor, it had excellent performance [9]. Lai et al. synthesized CNT/NiO composite through hydrothermal method [10]. The tubular conductive CNT was used as the supporting structure and the path of electron transfer. NiO grew on the surface of CNT and provided higher pseudocapacitance through redox reaction, which formed a synergistic effect [10]. The composite electrode material showed 713.9 F/g high specific capacitance at 2 mV/s sweep speed. When applied to asymmetric supercapacitors, 88.2% of the capacity was retained after 3000 charge-discharge cycles, and the stability was good. In transition metal oxides, MnO_2 also has the advantages of high specific capacity and low preparation cost, and is considered to be one of the most potential electrode materials. Lei et al. used Chemical vapor deposition (CVD) method to grow CNT in situ on stainless steel substrate and annealed it [10]. Then, Lei used $KMnO_4$ as the precursor and uniformly deposited MnO_2 on CNT substrates by hydrothermal method to construct core-shell heterostructures MnO_2@CNTs Compound material. Core CNT acted as a stable structural framework, and shell MnO_2 shortened the ion diffusion path. The CNT@MnO_2 based supercapacitor obtained a current density of 0.5 mA/cm^2, an area specific capacity of 274 mF/cm^2, and a capacity retention rate of 93% after 6000 cycles due to the synergistic impact of CNT and MnO_2.

In addition, conductive polymer is a new type of electrode material for supercapacitor. It has the advantages of high operating voltage, high energy storage capacity, good plasticity, easy fabrication of thin-layer electrodes, low internal resistance and low cost. Polyaniline (PANI) was deposited on CNT thin films by electrochemical deposition, and CNT/PANI composite was prepared. The specific capacitance of CNT/PANI composite was 541F/g when the scanning rate was 20mV/s. Polypyrrole/MWCNT (PPy/MWCNT) composite with core-shell structure was prepared by in situ polymerization using a mixture of $H_5Mo_{12}O_{41}P$ and $H_3O_{40}PW_{12}$ as oxidant. Carboxylated CNT provided rich functional groups, interactd with the mixture of $H_5Mo_{12}O_{41}P$ and $H_3O_{40}PW_{12}$, and then attached to the surface of MWCNT by in situ polymerization. The final PPy was decorated on the surface of MWCNT to form a clear core-shell structure [10]. The electrochemical performance tests showed that the PPy/MWCNT composite could provide a high specific capacitance of 570F/g at current density of 1A/g. In addition, using $FeCl_3$, MO, SDBS as oxidant and dopant, Liu et al.synthesized PPy/MWCNT composite by oxidative in-situ polymerization [10]. When the mass ratio of PPy to MWCNT was 9:1, the initial specific capacitance of PPy/MWCNT composite electrodes was 374.6F/g. After 10,000 charge and discharge cycles, the material still had 88% capacity retention, indicating excellent cycle stability.

In addition to the above mentioned materials, the preparation of supercapacitor electrodes from graphene (GN) has received considerable attention recently. Jiang et al. obtained graphene oxide/CNT (GO/CNT) materials by oxidative peeling of CNT with modified Hummers method, using CNT as raw material, and then L-ascorbic acid as reducing agent [10]. Reduced graphene oxide/CNT (rGO/CNT) composites were prepared by freeze-drying and high-temperature treatment. The prepared composites had a maximum specific surface area of 581.4 m^2/g, a large number of mesoporouss. The specific capacitance of rGO/CNT in 1 mol/L tetraethyltetrafluoroboric acid/acetonitrile (Et_4NBF_4/PC) organic electrolyte was 128F/g, and only 4.37% capacitance decayed rate after 2000 cycles, showing superior potential in the field of electrochemical energy storage [10].

3.2. Photoelectric Device

3.2.1. Photovoltaic (PV)/Solar cell (SC)

Solar energy has great potential to meet the demand for renewable energy. Solar cells include first-generation solar cells, second-generation solar cells and third-generation solar cells [11]. The third-generation solar cells mainly include dye-sensitive solar cells (DSSCs), organic photovoltaic/ organic solar cells (OPV/OSCs), etc. Third-generation solar cells have lower costs. Carbon nanotubes (CNTs), which can be used for photoelectric conversion, have broad application prospects in the development and research of solar cells. By using the excellent flexibility and good conductivity of CNTs, they can replace precious metals such as platinum to serve as counter electrodes of DSSCs to reduce the cost of solar cells [11]. They can also be used as flexible electrodes of OSCs to expand the application of solar cells [11].

Pt-based materials are the most commonly used catalysts in DSSCs [12]. However, due to the shortage of resources, high cost and easy corrosion by electrolytes of iodine system, the application of Pt-based catalysts is limited. The development of efficient and durable non-precious metals is very important for the development of DSSCs. The conductivity and morphology of carbon skeleton also play a key role in the electron transfer ability and electrochemical stability of the catalysts [10]. Carbon nanotubes (CNTs) have abundant wrinkles, which can greatly increase the number of active sites of the catalysts. In addition, Fe is often used as a metal element to control the doping of melamine-derived nitrogen into carbon to form CNT [12]. Li et al. prepared bamboo-shaped CNT by introducing Fe into melamine-derived nitrogen-doped carbon [12]. Yang et al. prepared tubular CNT/Fe_3C composites from melamine and iron nitrate by controlling annealing temperature. Compared with commercial Pt/C catalysts, they showed higher (oxygen reduction reaction)ORR activity, better stability and better methanol tolerance in 0.1mol/L KOH solution [12]. It mainly depends on the ability of Fe to absorb carbon atoms/clusters. The ability of Fe to absorb carbon atoms/clusters depends on its size. Fe catalyst particles with appropriate size can balance the incorporation and precipitation of carbon atoms/clusters on the surface of carbon-based materials to form CNT [12].

OSCs generally consist of active layer materials, interfacial layer materials and electrode materials. The active layer materials can be divided into donor materials and acceptor materials, and interfacial layer materials can be divided into hole transport material and electron transport layer. The material classification of OSCs is shown in Fig. 6.

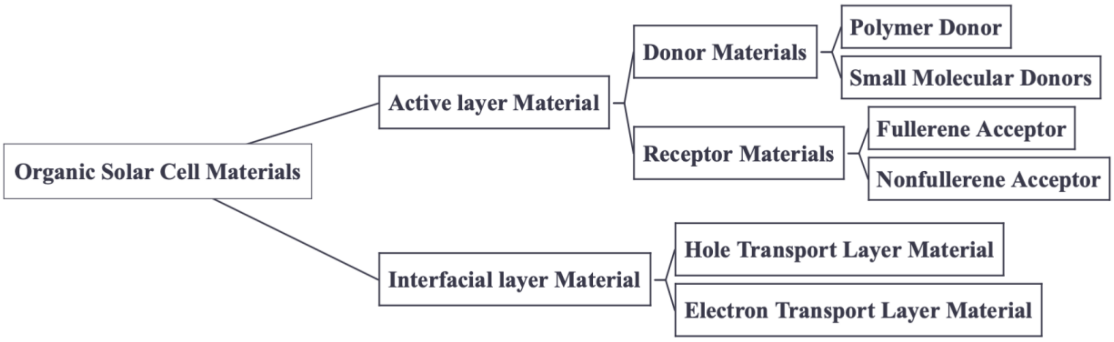

Figure 6. diagram of organic solar cell materials.

Currently, the methods to obtain high-performance OSCs are more focused on finding new high-performance acceptor materials, optimizing device structure and preparation process. As an important part of OSCs, the interface modification layer is also important to improve the device performance because it can alleviate the interface barrier, ensure the normal transport of carriers, control the morphology of active layer and improve the device stability.

Due to the excellent transparency, high conductivity, excellent carrier mobility, and solution treatment compatibility of SWCNTs. In Huang Junhua's study, PDINN was selected as the electron transport layer (ETL) of OSCs, and the high conductive substances NG and SWCNT were doped into it, respectively, to study the modification of the interface. doping of SWCNT in PDINN improved the conductivity of the interface, thus promoting the charge transfer and collection. Therefore, when it was dispersed into PDINN, the optimal doping ratio of SWCNT was 4%, the maximum PCE of OSCs was 16.36% [13]. The valence band and composition of N-doped ESR results in the process of SWCNT doping PDINN were characterized according to EXPS. As shown in Fig. 7, for PDINN, the binding energy of N1s could occur at 399 eV and 400 eV. According to the results of the peak plot, with the doping of SWCNT, the binding of amino groups can transfer from 399 eV to 400 eV [13]. Amino group at 399 eV binding energy and -N-CO group at 400 eV binding energy. Thus, the method of doping SWCNT in PDINN is the N-doping of electrons transferred from PDINN to SWCNT. This shows that N-doping ETL can increase the conductivity of OSCs, regulate the power function of negative electrodes, reduce charge recombination, increase the charge extraction rate, and ultimately improve the photovoltaic performance of OSCs. It also proves that SWCNT can improve the conductivity and charge mobility of ETLs in PDINN. It is concluded that doping ETL is feasible and applicable [13].

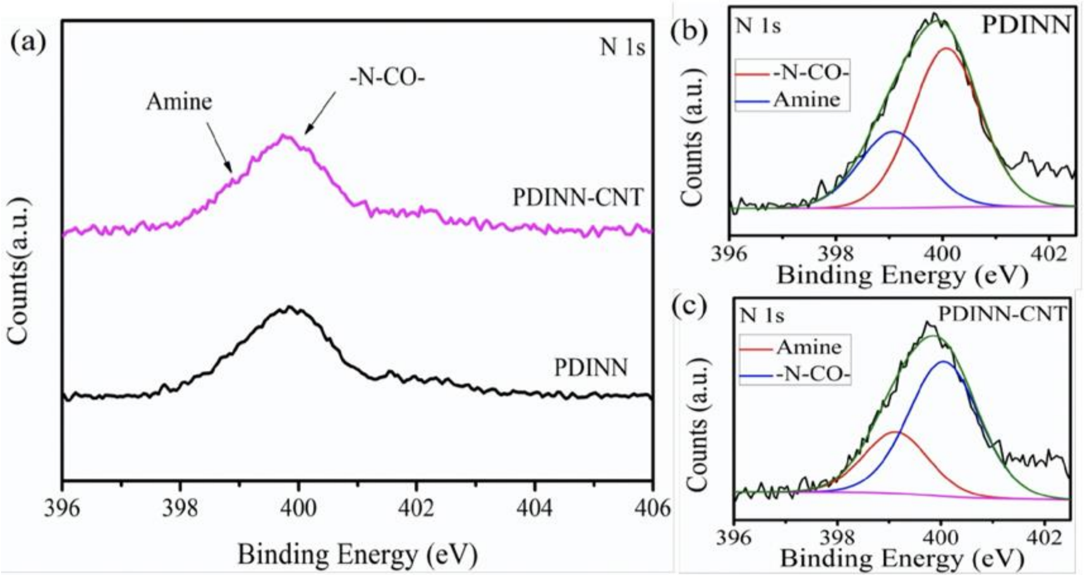

Figure 7. N1s XPS spectra of pure PDINN and 4% single-walled carbon nanotube doped PDINN [13]

Table 1. XPS quantitative measurement of the ratio of pure PDINN to PDINN doped with single-walled carbon nanotubes

	The ratio of N 1s (400eV)/N 1s (399eV)
PDINN	2.09
PDINN-CNT	2.41

3.2.2. Organic Light Emitting Diodes (OLEDs)

Organic light-emitting diodes (OLEDs) are the most competitive display technologies due to their self-luminescence, ultra-thin, energy-saving, large area, easy flexibility and three-dimensional display. Flexible transparent electrode materials are essential for flexible OLEDs that can be bent, folded and worn. However, traditional indium-tin oxide (ITO) electrodes are fragile, raw materials are scarce and the price is increasing year by year, which is not suitable for the wide application of flexible OLEDs in the future [14].

In general, the elastic modulus of a single CNT is up to 1 TPa, the tensile strength is up to 100 GPa, and is more than 10 times higher than that of industrial fibers. The T of a CNT film electrode is about 90%, and the Rs is about 100 Ω·SQ-1 [14]. These properties are affected by the concentration of CNT solution and the thickness of the film electrodes. For example, Baugan et al. prepared 5 cm wide, 5 cm wide by CVD method. 1 m long CNT array thin-film electrodes, as shown in Fig. 8, have up to 85% T in the visible light range and good mechanical properties. The conductivity does not change significantly after 100% stretching, but Rs is about 700 sq^{-1}. Bao etc. The stretchable CNT film electrodes were prepared by spraying CNT solution on the flexible polydimethylsiloxane (PDMS) substrate [15]. Thin film electrodes up to 2200 S·cm^{-1} (Rs=328 Ω·sq^{-1}) and light transmittance T=79%. The conductivity of the obtained thin film electrodes hardly changes after 10,000 biaxial stretches [15].

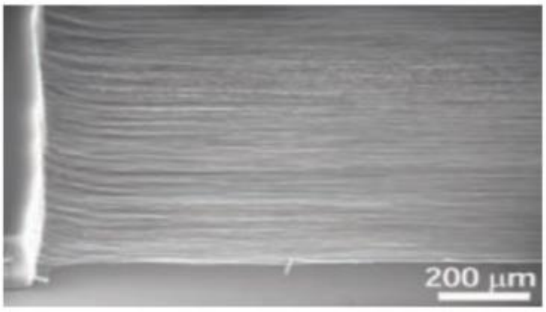

Figure 8. CNT array thin electrode [15]

At the same time, with the development of OLED technology, active matrix organic light emitting diode (AMOLED) appears [16]. AMOLED has the characteristics of self-luminescence, fast response, high color saturation and flexible preparation compared with traditional LCD display, which meets the requirements of various future display devices. However, due to the insufficient carrier mobility of current traditional materials, the uniformity of device performance is also a problem. Because of the high cost of device processing and the stability of devices under flexible conditions, AMOLED flexible drive circuits can be prepared by utilizing the excellent mechanical and electrical properties of CNT [16].

3.3. Electronic Device

3.3.1. Field Effect Transistor (FET)

Modern electronic information technology is based on integrated circuit chips, and almost all the components that make up the integrated chip are made up of silicon-based CMOS field effect transistors [17]. Field effect transistors (FETs) are components of a voltage-controlled current source. They control the current size between sources and drains through gate modulation to make them open and closed. Thus, the core part of logic 1 and logic 0 is the channel part modulated by the gate. The traditional channel of field effect transistors is single crystal silicon. For decades, the industry's development strategy for silicon-based CMOS devices has been based on Moore's Law to reduce key sizes and improve integration, resulting in more powerful, lower power consumption, faster and lower cost integrated circuit chips [17]. However, as CMOS transistor technology develops today, there is an unavoidable fact that it is approaching its physical limit [17]. This requires a switch to alternative materials and the development of new semiconductor integrated circuit technologies.

The selection criteria for the next generation of sub^{-10} nm FET channel materials are very stringent and need to be considered from several perspectives: First, the semiconductor materials must be sufficiently thin, however the Short Channel Effect will result in decreased transistor performance when the channel length is too short. Increasing the gate capacitance is one efficient technique to get rid of the short channel effect. The quantum tunnel effect's limitations, however, provide little possibility for the gate capacitance to be improved. Thin the channel as another option for doing this.

The grid can regulate a channel more readily and has a better immunity to the short channel effect the thinner it is. Second, the channel material should have sufficient electron and hole mobility. Ballistic transfer should be made simpler by semiconductor channel materials having a longer average carrier free route. Carbon nanotubes (CNTs) with their ultra-small size (1-3nm in diameter), ultra-high intrinsic mobility to electrons and holes (greater than $1\times10^5\text{cm}^2/\ (\text{Vs})$) and the average free path of the extra-long carrier (generally greater than 1) [17]. Therefore, carbon nanotube field effect transistors (CNTFETs) designed with carbon nanotubes (CNTs) have received considerable attention [17].

Semiconductor carbon nanotubes (CNTs) possess the electrical properties of traditional semiconductors, which have poor conductivity at room temperature and can be considered as insulators [18]. However, if a bias is applied to the diameter direction of the tube, the conductivity will be generated inside the CNTs. With the increase of radial bias, the concentration of carriers will also increase, which is much higher than that of conventional silicon transistors. In addition to the above similar properties to traditional semiconductors, CNTs have the same conductivity as traditional semiconductors. Semiconductive carbon nanotubes (CNTs) also have their own unique characteristics, that is, the conduction mode will change according to the same bias applied in the radial direction: when positive bias is applied, the charge carriers inside the CNTs are electrons, and the conduction type is n-type; When negative bias is applied, the charge carriers inside the tube are holes, and the conduction type is p-type [18]. Therefore, the semiconductor carbon nanotubes have voltage-controlled switching characteristics, which is the key to realize field-effect transistor function using semiconductor carbon nanotubes. Especially, single-walled semiconductive carbon nanotubes have narrow bandgap and better gate voltage modulation characteristics. This is also a valuable aspect of using single-walled carbon nanotubes as transistor conduction channel materials [18].

4. Conclusion

Through the research, it is found that the applications of the electrical properties of carbon nanotubes are mainly reflected in the electrochemical devices such as lithium batteries, supercapacitors, organic solar cells, organic light emitting diodes, and field effect transistors. In the process of this study, it was also found that the optimization schemes of the corresponding applications overlap in some aspects, such as the preparation of carbon nanotube composite materials, doping modification of active substances, etc. This provides a new direction for future research on the optimization of carbon nanotubes for other applications.

In general, carbon nanotubes' exceptional electrical capabilities depend on their distinctive structural features. The majority of carbon nanotube compositions and dopings are based on modifications to their microstructures, which significantly enhance the relevant electrical characteristics. Therefore, they can be used in batteries, capacitors, photoelectric devices and electronic components. Although the primary application techniques based on the electrical characteristics of carbon nanotubes are thoroughly reviewed in this study, the optimization schemes for each application direction are only chosen for a more representative list, and there are numerous additional novel and distinctive optimization techniques that have not been presented. Therefore, in future research, various optimization schemes can be further compared and analyzed to obtain corresponding application laws, providing ideas for future research and innovation of carbon nanotubes in various aspects.

Finally, the applications of the electrical properties of carbon nanotubes have great application value. It is believed that in the future, with more in-depth research on the electrical properties of carbon nanotubes, carbon nanotubes will have a more profound impact in more fields and promote the development of global energy, electronic information technology and other fields.

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