REVIEWS

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Preparation and application of carbon nanotubes flexible sensors

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Abstract: Based on the good extensibility and conductivity, the flexible sensors (FSs) have a wide range of applications in the field of the electrochemical energy storage and variable stress sensors, which causes that the preparation of FSs also become a hot spot of research. Among the materials for preparing the FSs, the flexible carbon matrix composites (FCMCs) have become the widely used material since the good performance in the properties of electrochemistry and mechanics, which could be divided into three types: the carbon nanofibers (CNFs), the carbon nanospheres (CNSs) and the carbon nanotubes (CNTs). Compared with CNFs and CNSs, the CNTs wrapped by the polydimethylsiloxane (PDMS) have the advantages of the excellent extensibility and electrochemical stability. Therefore, the CNTs flexible sensor (CFS) could be well used in the field of the FSs. The purpose of this review is summarizing the preparation methods and application fields of CFS and proposing the research direction of CFS in the future. In this paper, two methods for fabricating the CFS have been designed by consulting the methods mentioned in the literature in recent years, and the advantages and disadvantages between the two methods have been explained. The application fields of CFS in recent years are enumerated, and the conclusion that the application fields of CFS are very wide is drawn. At the end of this paper, the review concludes with an overview of key remaining challenges in the application fields of the CFS.

Key words: CNTs; PDMS; CFS; preparation methods; application fields

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1. Introduction

With the development of various industries, including electronic industry, material industry, and medical industry, the quality requirements of electronic products are higher. How to ensure the high flexibility, high energy density, high power density and good stability of electronic products has become a research hotspot in the electronic field. As a new type of electrodes, compared with the traditional electrodes, the flexible sensors (FSs) that are made of flexible materials have the advantages of the good elastic strain, the excellent conductivity and the fantastic durability, which enables FSs to satisfy the requirements mentioned above and lets FSs be widely used in the two-stage matrix converter, the single polyaniline tube, the electrodes in lithium-ion batteries, solar cells and other energy storage components[1–3].

As for the materials consisting of FSs, in order to guarantee the good of mechanical flexibility and the good of electrical conduction, materials of FSs mainly include the graphene, the electrospinning, the oxides of transition metal and the conductive polymers[4, 5]. Among those kinds of materials, based on the excellent electrical conductivity, the high thermal conductivity, the high strength, the low expansion coefficient, the good friction performance, the high dimensional stability and the good performance of resisting thermal shock, the research and the application of the flexible carbon matrix composites (FCMCs), which are made of the matrix of the material of carbon element and the reinforcement of material of carbon fiber or silicon carbide, are more extensive[6–9]. The several application fields of FCMCs are as follow[10–14]:

(1) FCMCs can be used as the electronic transmission channels in FSs because of their excellent electrical conductivity.

(2) FCMCs can be used as the materials of supporting the electrodes in FSs since their excellent properties of bending and folding.

(3) Because of the strong plasticity of the material of carbon element, FCMCs can be easily shaped into various shapes, including the nanostructures of one-dimensional, two-dimensional and three-dimensional, which could have a positive effect on the transmission of current and improve the conductivity of FCMCs.

In summary, the FCMCs play an important role in FSs and become one of the most popular materials which consisting of FSs. In the field of FCMCs, the material of nano-carbon (NC) has become the popular material due to its small size and strong plasticity. According to the forming structure, NC materials are divided into three types[15–19].

1.1. Carbon nanofibers

Carbon nanofibers (CNFs) are made of the flaky materials of the polyacrylonitrile fibers, the asphalt fibers, the viscose filaments or the phenolic fibers, which are stacked along the axial direction of the fibers and then carbonized and graph-

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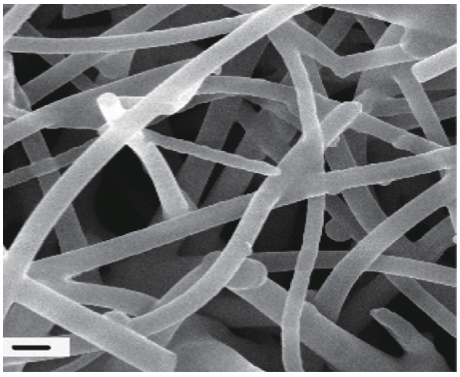

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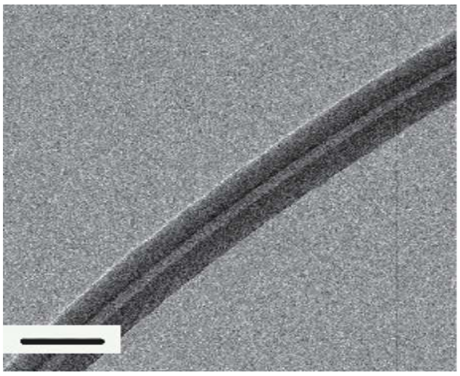


(b)

Fig. 1. Structure characterization of the CNFs. (a) Image of the CNFs under the SEM. (b) Image of the CNFs under the TEM. (Reproduced with permission from Ref. [15].)

itized. CNFs are a kind of inorganic material made entirely by manual intervention. The structure characterization of the CNFs made by Yang *et al.* is shown in the Fig. 1[15].

The advantages of CNFs include the high strength, the high modulus, the low density, the ultra-high temperature resistance in non-oxidation environment, the low thermal expansion coefficient, the good anisotropy and the good corrosion resistance. The disadvantage of CNFs is the high cost, because the production of carbon nanofibers requires the plenty of the manpower, the raw materials and the time, which restricts the production of the FSs of CNFs[16].

1.2. Carbon nanospheres

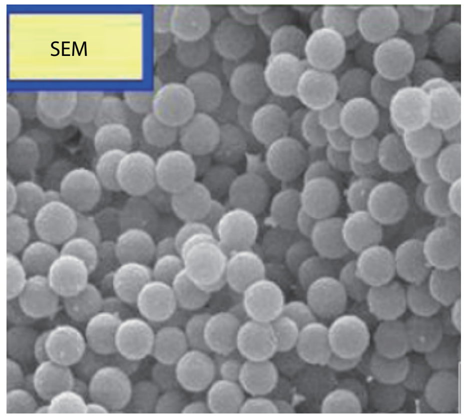
Carbon nanospheres (CNSs) can be obtained by the mixture of carbon raw materials and catalysts, which experience the program of heating at the constant temperature and the program of cooling respectively[17].

Park *et al.* fabricated the CNSs by using the porous hollow microcapsules, whose structure is shown as the Fig. 2[18]. The CNSs have the same advantages as CNFs except the anisotropy. However, for FSs, the CNSs cannot satisfy the characteristics that FSs need to be folded freely.

1.3. Carbon nanotubes

Carbon nanotubes (CNTs) are the hollow tubular carbon materials which are seamless, which are made of graphite sheets of single or multi-layer that curled around the left at a certain angle[19]. CNTs not only have the same advantages as CNFs, but also have the advantage of low cost of production, which is suitable for the preparation of FSs.

Although CNTs can be used to fabricate FSs, CNTs fabricated from powders cannot be directly used as FSs installed in



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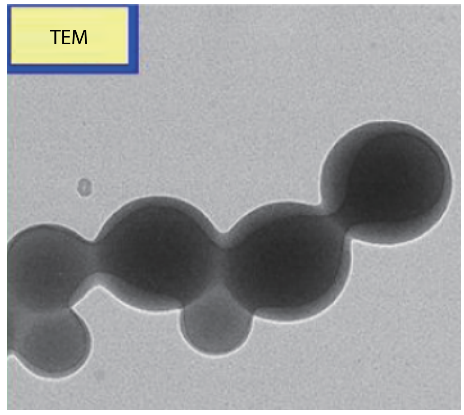

(b)

Fig. 2. Structure characterization of the CNSs. (a) Image of the CNSs under the SEM. (b) Image of the CNSs under the TEM. (Reproduced with permission from Ref. [18].)

batteries, and must be attached to a carrier. In theory, materials that can fix the shape of CNTs, such as the material of SiO_2, Au and Pd, can be used as the carriers of CNTs[20–24]. However, in order to ensure that the ductility and conductivity of CNTs are not affected, the carriers of CNTs must have the good insulation and ductility.

The polydimethylsiloxane (PDMS) is a kind of the hydrophobic silicone material, which has the color of colorless or pale yellow, the taste of tasteless, the high transparency and the non-toxic. PDMS shows the excellent performance in ductility, heat resistance, cold resistance, hydrophobicity, thermal conductivity, insulation, physiological inertia and chemical stability[25–27]. Based on the advantages of it, PDMS can be used as a kind of the material of the carrier of CNTs. The CNTs/PDMS composite can be obtained by coating and fastening CNTs with PDMS[26–28]. The CNTs flexible sensor (CFS) can be obtained by inserting two conductive metal strips into the area of CNTs in the CNTs/PDMS composite.

Starting from the structure and properties of the CNTs, this paper introduces in detail the preparation methods and the application fields of the CFS in recent years, expounds the advantages and disadvantages of the preparation methods of the CFS, and shows the application prospects of the CFS in the future.

2. The structure of the CNTs flexible sensor

2.1. The structure and characterization of CNTs

As a kind of the materials of the one-dimensional

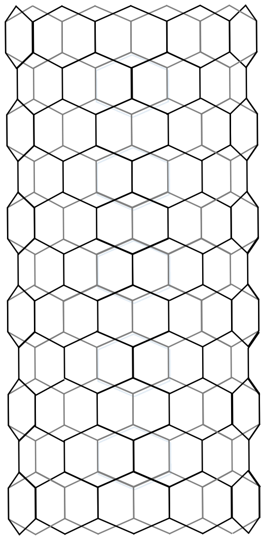

Fig. 3. Theory model of the CNTs.

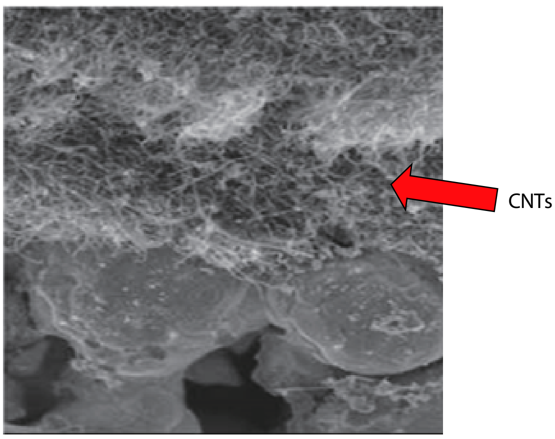

Fig. 4. Structure characterization of the CNTs. (Reproduced with permission from Ref. [29].)

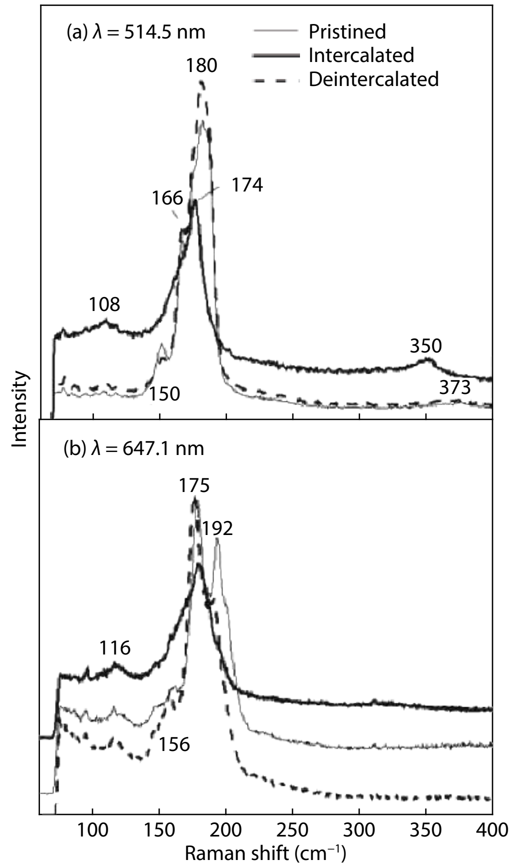

Fig. 5. Raman spectra of pristine (thin solid), I_2-intercalated (thick solid), and deintercalated (dashed) SWNTs in the low Raman shift range taken by: (a) the 514.5-nm line of an Ar-ion laser and by (b) the 647.1-nm line of Kr-ion laser. (Reproduced with permission from Ref. [33].)

quantum with special structures, the CNTs are mainly composed of coaxial tubes with several to dozens of layers of carbon atoms arranged in a hexagonal arrangement. The theory model of the CNTs is shown as the Fig. 3.

About the method of obtaining the CNTs structure characterization, Liao *et al.* transferred the silver paste/CNTs film on an indium tin oxide (ITO) glass using a single laser shot, which obtained the structure characterization that showed under the scanning electron microscope (SEM) as shown in the Fig. 4[29].

According to the different orientation of the carbon hexagon along the axis, CNTs can be divided into three types: zigzag, armchair and spiral. The spiral CNTs have the chirality, while the CNTs of zigzag and armchair have no chirality[30].

According to the number of layers of carbon atoms, CNTs can be divided into the single-walled carbon nanotubes (SWCNTs) and the multi-walled carbon nanotubes (MWCNTs). The SWCNTs are formed by one layer of carbon atoms curling around the left of rotation, which causes the good uniformity and stability since the differences in the size and shape between each carbon atom in SWCNTs are little[31]. The MWCNTs are made of two or more layers of carbon atoms curled around the left of rotation. Compared with SWCNTs, the advantage of MWCNTs is that they can carry more catalysts, because there are sandwiches between the layers of carbon atoms that make up the MWCNTs, which can store additional materials. Nevertheless, the uniformity and stability of MWCNTs are not as good as that of SWCNTs, because of the van der Waals force between each layer of carbon atoms, which will weaken the bonding force between each layer of carbon atoms and further interfere with the stability of MWCNTs[32].

In order to reflect the levels of the rotational energy and the vibrational energy of molecules and reflect dipole moments of chemical molecules inside the CNTs, it is necessary to test the Raman characterization and the UV–vis spectroscopy characterization of the CNTs. In the work of Nguyen *et al.*, under the interference of different materials, the CNTs showed different Raman spectra. And the Raman spectra of pristine (thin solid), I_2-intercalated (thick solid), and deintercalated (dashed) SWNTs taken by the 514.5-nm line of Ar-ion laser was shown in Fig. 5[33].

In the work of Tsai *et al.*, the UV–vis spectroscopy of the SWCNT with the 9 anthracene carboxylic acid in deionized water (DI water) was shown in Fig. 6[34].

Based on the internal structure, CNTs can be used as the structural materials and the functional materials. As the structural materials, CNTs have high strength because of the covalent bonds between carbon atoms in CNTs. As a functional material, CNTs have good electrical conductivity, thermal conductivity, ductility and other properties, and can be applied in many fields (such as the composite materials and nanomechanical).

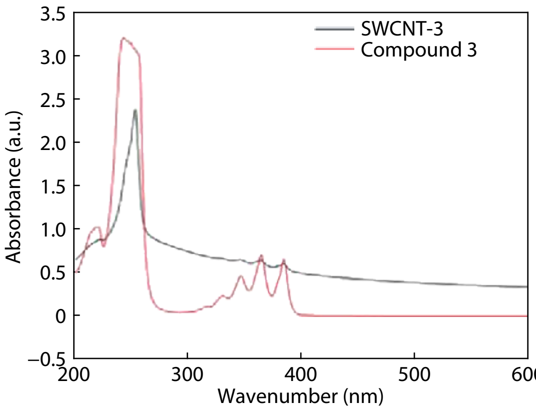

Fig. 6. (Color online) UV–vis spectroscopy of SWCNT-3 with 9 anthracene carboxylic acid in DI water. (Reproduced with permission from Ref. [34].)

2.2. The structure and function of PDMS

PDMS is an organic material composed of dimethyl siloxane, which has good biocompatibility. The adhesion of PDMS varies little under the changes of temperature, the surface tension of PDMS is small, and the shear resistance of PDMS is very high. Based on these advantages, PDMS is widely used in the fields of the thin film and the physical carrier[27].

3. Preparation of CNTs flexible sensors

3.1. The hydrothermal auxiliary method

The hydrothermal auxiliary method, which promote the combination between the CNTs and PDMS, could be used for preparing the CFS. Tang *et al.* provide a method using the hydrothermal assistance for preparing the redox graphene (RG)/PDMS composite flexible sensor, which can be used to fabricate the CFS[35]. The steps of hydrothermal auxiliary method of preparing the RG/PDMS composite flexible sensor are shown in Fig. 7. Several important equipment and their specification used in this method are as follow in Table 1.

The improved preparation method of the CFS is as follows:

(1) The copper mesh is pretreated by the hydrochloric acid/acetone solution to remove various impurities such as oxides adhering to the surface of copper mesh.

(2) The CNTs dispersions are diluted with water.

(3) The copper mesh, whose specification parameters have been shown in Table 1, is placed in a 50 ml autoclave, and then the 35 ml of the CNTs diluted water dispersion is added into the autoclave. After standing for a period of time, CNTs dispersions would deposit on the copper mesh and form a mixture of CNTs and copper mesh (CNTs/Cu).

(4) The solution containing CNTs/Cu in a high-pressure autoclave is put into the oven and heat-treated for 12 h at 180 °C.

(5) Remove the autoclave from the oven and add deionized water into the autoclave. Carefully clean the CNTs/Cu with deionized water in order to eliminate the CNTs powder which do not attach to the copper mesh.

(6) CNTs/Cu cleaned with deionized water is dried in an oven at 50 °C. This step be not completed until all of the water in the autoclave evaporates.

(7) CNTs/Cu removed from the autoclave are divided into two areas: the electrode area and the protected area. The electrode region serves as a connection between CNTs and electrodes, which will not be covered by PDMS because of the good insulation of PDMS. Protected areas protect the CNTs from external interference, which will be covered by PDMS.

Table 1. Several equipment and specification in the hydrothermal auxiliary method.

Equipment	Specification
Copper mesh	8 cm of length
	3 cm of width
	80 of mesh number
	50 μm of copper diameter
Hydrochloric acid/acetone solution	1/5 of volume ratio of hydrochloric acid/acetone
Mixed solution of PDMS	30/10/1 of mass ratio of n-hexane/PDMS monomer/curing agent
$FeCl_3$/HCl solution	0.5 mol/L of amount of the substance of $FeCl_3$
	0.5 mol/L of amount of the substance of HCl

(8) The mixed solution of PDMS which is pulled out by dropper was stirred for more than 30 min to achieve the purpose of fully mixing the components in the solution.

(9) The mixed solution of PDMS whose components have been mixed fully is dripped into the protective area of CNTs/Cu. In this step the mixture of CNTs/PDMS/Cu could be obtained.

(10) The CNTs/PDMS/Cu is dried for 2.5 h in a vacuum environment at 120 °C, which ensured that the PDMS monomer is initially polymerized in the protective area of CNTs/PDMS/Cu.

(11) Under the room temperature, the protected region of CNTs/PDMS/Cu has been immersed in the mixed solution of $FeCl_3$/HCl for 12 h. In this solution, the copper mesh can be oxidized to Cu^{2+} by Fe^{3+} that exists in $FeCl_3$, which can be dissolved into the solution. The expressions involved are:

$$2Fe^{3+} + Cu = 2Fe^{2+} + Cu^{2+}. \tag{1}$$

In this step, the CNTs/PDMS could be obtained.

(12) CNTs/PDMS obtained by step (11) is carefully cleaned several times with ionic water to remove the remaining etching solution and dry in air.

(13) The CCFS can be obtained by installing an electrode in the electrode region of the CNTs/PDMS.

3.2. The chemical vapor deposition method

The chemical vapor deposition (CVD) is a chemical technology, which forms thin films by chemical reaction on the substrate surface by using gas phase compounds or simple substances containing thin film elements. Jeong *et al.* provide a method for making the strain sensors by using the CVD technology to mix the graphene foams (GF) and PDMS, which could be used for preparing the CFS[36]. The steps of CVD method of preparing the GF/PDMS composite flexible sensor are shown in Fig. 8. Several important equipment and their specification used in this method are as follow in Table 2.

The preparation scheme of CFS improved by this method is as follows:

(1) Using the chemical vapor deposition technology, the CNTs is adhered to the foam nickel template.

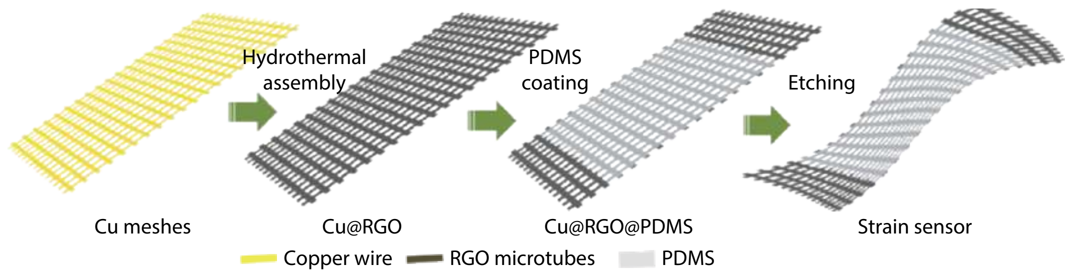

Fig. 7. (Color online) Fabrication steps of the RG/PDMS composite flexible sensor. (Reproduced with permission from Ref. [35].)

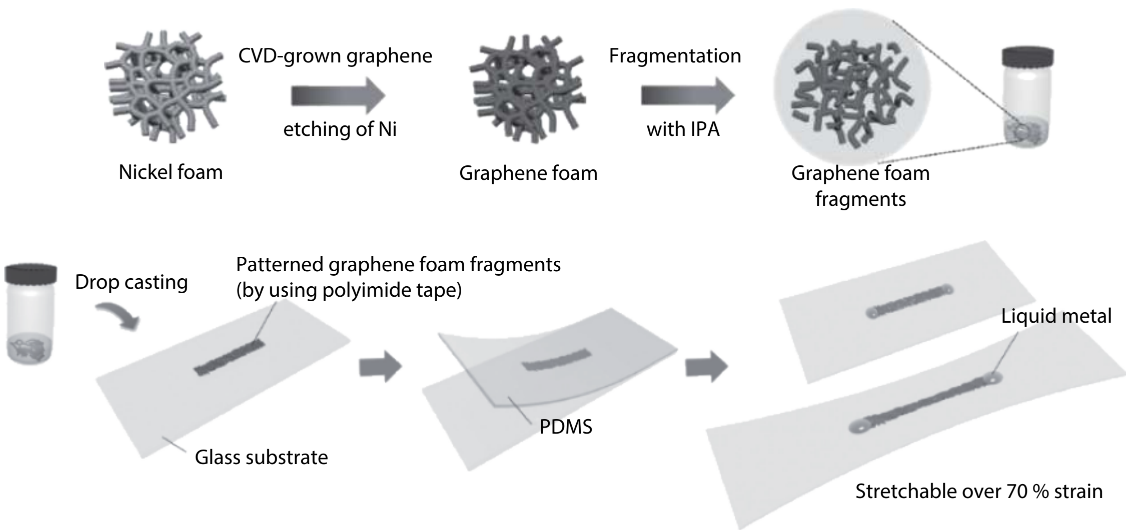

Fig. 8. Schematic of the process of CVD method of preparing the GF/PDMS strain sensors. (Reproduced with permission from Ref. [36].)

Table 2. Several equipment and specification in the method of CVD.

Equipment	Specification
Nickel foam template	2 × 2 cm^2 of size
Glass slide	3 × 20 mm^2 of size of the rectangular shape
FGF/isopropyl alcohol (IPA) solution	4.9 mg/ml of the concentration
Galinstan eutectic alloy	68.5%/21.5%/10% of atomic percentage of Ga/In/Sn

(2) Etching the nickel foam template with hot solution of HCl.

(3) The CNTs is immersed in a small bottle containing isopropanol solution, and is broken for 20 min by an edd *y* current mixer, which causes that the flake of CNTs is dispersed in isopropanol.

(4) Stewing the mixed solution of CNTs/isopropanol for 24 h to make the plate-like CNTs precipitate.

(5) Using the micropipette to inlay CNTs/isopropanol onto glass sheets which are arranged in a rectangular (3 × 20 mm^2) pattern with polyimide tape to rearrange CNTs. Because the cost of making electrode pattern with polyimide tape is low, the electrodes with various shapes and sizes can be conveniently designed[32]. Because the concentration of CNTs/isopropanol is constant, the amount of CNTs used to make CFS could be controlled by the volume of micropipette.

(6) Put the glass sheet containing the CNTs/isopropanol in the oven with a temperature of 50 °C to evaporate the isopropanol and take out the glass sheet from the oven after finishing evaporating the isopropanol.

(7) Polyimide tape is removed from glass slide and PDMS

Table 3. Comparison between hydrothermal auxiliary method and CVD method.

Aspect	Hydrothermal auxiliary method	CVD method
Time (h)	12	26
Steps number	13	7
Equipment number	14	14
Complexity degree	Normal	Hard
Reference	35	36

is poured onto glass slide. After curing and peeling, a composite strain sensor film of CNTs/PDMS is prepared.

The comparison between two methods is shown in Table 3.

As shown in the preparation process of two methods and the Table 3, compared with the CFS prepared by the CVD method, the CFS prepared by the hydrothermal auxiliary method has several advantages, which are shown as follow:

(1) short preparation time,

(2) materials that be got easily (such as the solution of hydrochloric acid/acetone and the solution of $FeCl_3$/HCl), which could reduce the cost and the difficulty of preparation.

The disadvantage of the hydrothermal auxiliary method is the need for more experimental steps, which leads to more details to pay attention to.

4. Application fields of CNTs composite flexible sensors

CFS have been used in various fields for the excellent sta-

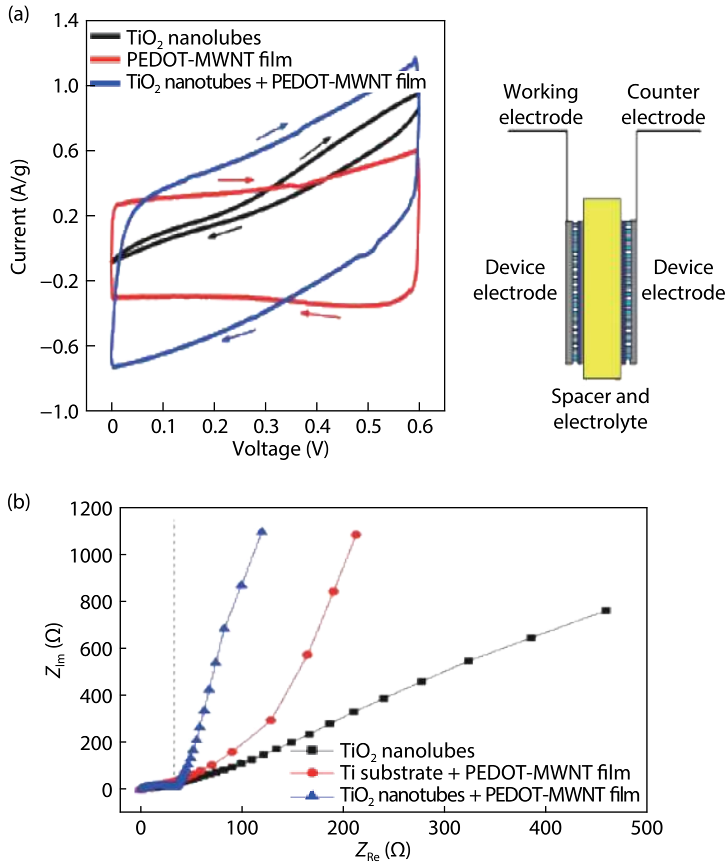

Fig. 9. (Color online) (a) Respective cyclic voltammograms of TiO_2 nanotube supercapacitor, PEDOT–MWNT film supercapacitor and TiO_2 nanotube + PEDOT–MWNT film supercapacitor in 1 M H_2SO_4 aqueous electrolyte. (b) Nyquist plots of TiO_2 nanotube supercapacitor, PEDOT–MWNT film supercapacitor, and TiO_2 nanotube + PEDOT–MWNT film supercapacitor from high frequency to low frequency. (Reproduced with permission from Ref. [8].)

bility, ductility and conductivity. At present, there are two application forms of carbon nanotube flexible sensors:

(1) Other materials are added into the CFS to form the CNTs composite flexible sensor (CCFS).

(2) A new system is composed of CFS or CCFS and other devices.

Both of these two methods could improve the conductivity and electrochemical performance of CFS, and expand the application field of CFS, including the fields of electronics, micromechanical, and thermal management.

4.1. Application in the field of electronics

A flexible symmetric supercapacitor based on TiO_2 and CNTs was invented, and a hybrid electrode design was introduced in the work of Chien *et al.*[8]. The specific capacitance was further improved by combining titanium dioxide nanotubes with CNTs. Vertically oriented titanium dioxide nanotube arrays were prepared by anodic oxidation and used as the porous pseudo electrodes with small density and large surface area. A conductive multi-walled carbon nanotube (MWNT) network was coated on the titanium dioxide nanotubes to form a composite electrode. Fig. 9(a) showed the cyclic voltammograms of supercapacitors of TiO_2 nanotube, PEDOT–MWNT film and TiO_2 nanotube with PEDOT–MWNT film in 1 M aqueous electrolyte of H_2SO_4. As shown in the Fig. 9, compared with pure CNTs electrodes, the specific capacitance of these electrodes which used the electrolyte of H_2SO_4 were increased by about 30%. The good capacitance characteristics of them were shown by the electrochemical impedance spectroscopy (EIS), whose figures were shown in Fig. 9(b).

High-speed DC circuit breaker played a very important role in the circuit, and the optimization of the contact material of high-speed DC circuit breaker became the cornerstone of the reliable function of high-speed DC circuit breaker. Among many materials, pure metal materials had high affinity for welding. The Ag/CdO materials did not meet the requirements of European Union. The SnO_2, ZnO and the graphite, which worked normally at low current, had not been optimized for high current applications (such as the railway industry). Based on the situation, a kind of material of Ag/CNTs was designed in the work of Jaüimoviül *et al.*[37]. Ag/CNTs was chemically similar to Ag/graphite, but the uniform distribution of CNTs could reduce the combustion rate, which could prevent or reduce the occurrence of re-arc. As shown in Fig. 10, the test results of welding tendency tester for electrical contact materials showed that the composite of Ag/CNTs with a small amount of solid lubricant had the solid potential as electrical contacts in high-speed DC circuit breakers because they exhibited high welding resistance in a new state.

Chang *et al.* demonstrated the superior performance of thin film transistors with a functionalized SWCNTs-blended poly (3-hexylthiophene) (F-SWCNT-P3HT) channel and multi-

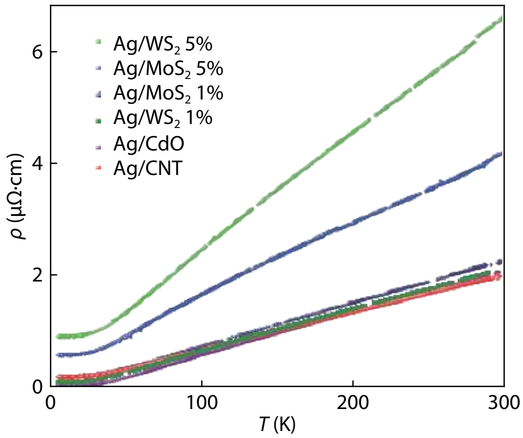

Fig. 10. (Color online) Temperature dependence of resistivity of several materials. (Reproduced with permission from Ref. [37].)

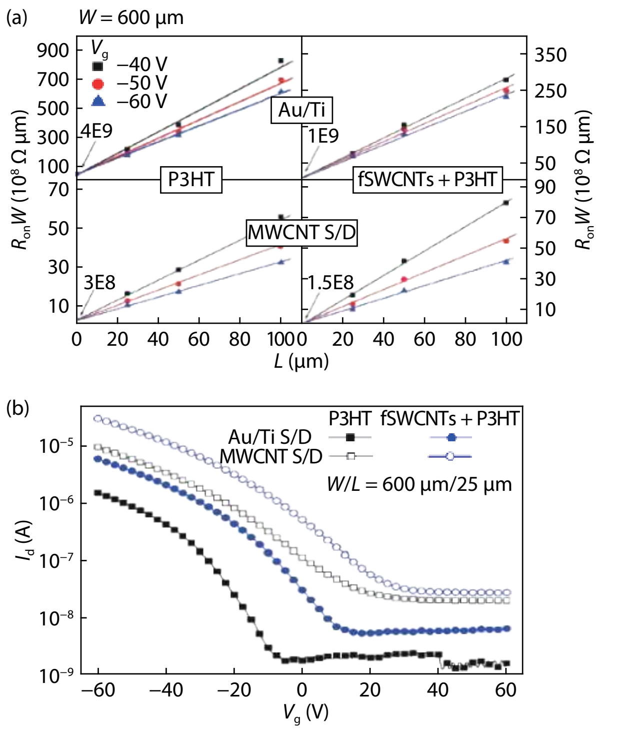

Fig. 11. (Color online) (a) The values of contact resistance. (b) Characteristics of drain current versus gate voltage of transistors with a P3HT or F-SWCNT-P3HT channel and gold or MWCNT S/Ds. (Reproduced with permission from Ref. [38].)

walled CNTs source and drain electrodes[38]. The effects of F-SWCNT-hybrid P3HT channel and MWCNTs/DS devices were systematically researched. As shown in Figs. 11(a) and 11(b), the contact resistance of devices using F-SWCNT-P3HT and MWCNTs/DS decreased, and the mobility increased. It was proved that transistors with F-SWCNT-P3HT channel and MW-CNTs/DS had excellent performance. Mobility has been improved by an order of magnitude or more.

On the structure of digitized gold electrode, for the detection of CO, NH_3, CO_2 and other gases, the gas sensor of sulfonated CNTs (s-CNTs) and the mixture gas sensor of CNTs/polyaniline (PANI) were prepared respectively[39]. The electrochemical performance and the structural stability of two kinds of gas sensing micro-sensors were also described. As shown in Fig. 12, the experimental results showed that the sensors not only had different resistivity values for various gases, but also

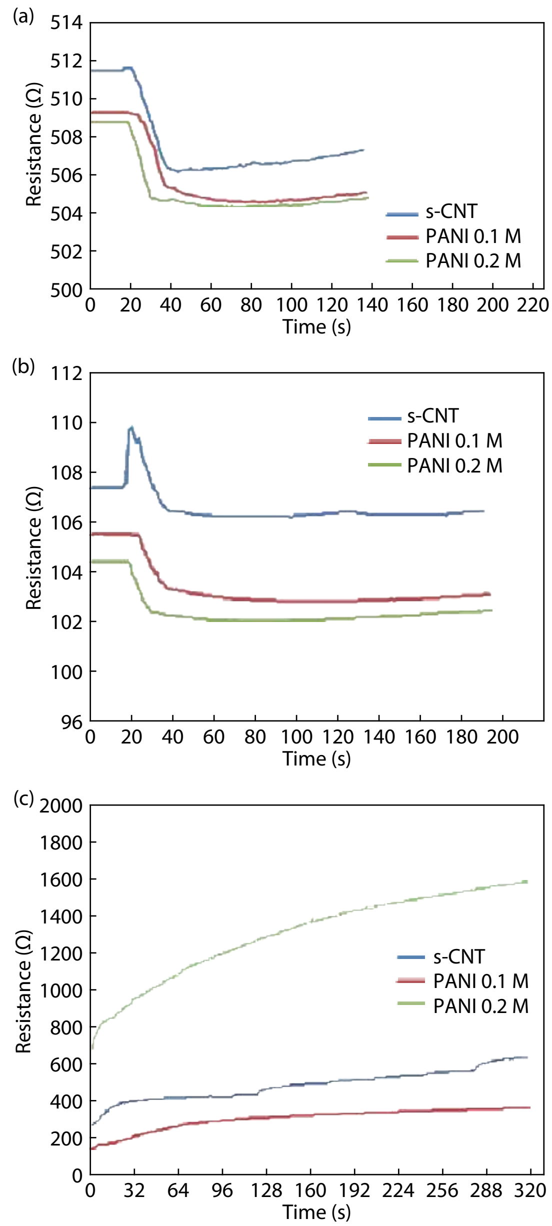

Fig. 12. (Color online) Resistance evolution of resulting structures as a function of gas concentrations. (a) CO. (b) CO_2. (c) NH_3. (Reproduced with permission from Ref. [39].)

had the high sensitivity and selective potential for the measured chemical analytes. In addition, the two kinds of gas micro-sensors had the advantages of high sensitivity, small size, light weight, and long service life, which could be applied to improve the life of sensor batteries and other fields.

Carbon nanotube flexible sensors could also detect chemical gases. Based on the flexible carbon nanotube sensor and using the non-equilibrium Green's function, a kind of tunnel type carbon nanotube field effect transistor (CNTFET) which could be used to detect the toxic gas in the tunnel was designed, which was shown in Fig. 13[40]. At the temperature of 200, 300, and 400 K, respectively, the conductivity of the CNTs was measured in different gases (SO_2, acetonitrile, sarin and carbonyl chloride). From the Fig. 14, the experimental results showed that the higher the temperature was, the higher the dielectric constant was. As shown in Fig. 15, at the same temperature, the higher the gas concentration, the greater the conduction current of the transistor. Therefore, the nano

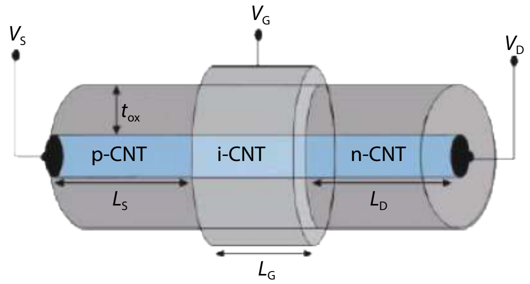

Fig. 13. (Color online) Two-dimensional circuit model for ballistic CNT-FET. (Reproduced with permission from Ref. [40].)

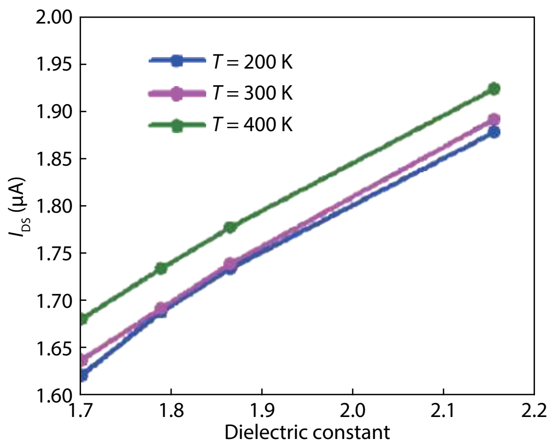

Fig. 14. (Color online) Drain-source current diagram versus dielectric constant. (Reproduced with permission from Ref. [40].)

sensor is suitable for toxic gas detection under different temperature conditions.

4.2. Application in the micromechanical system

Sha *et al.* invented electroplated Ni-CNT nanocomposites for micromechanical resonator applications[41]. In this paper, the electroplated Ni-CNT nanocomposites were synthesized and used as structural materials for micromechanical resonators. As shown in Fig. 16, CNTs were well dispersed in electrolytes and could be incorporated into Ni films by sodium sulfate dodecyl pretreatment.

4.3. Application in the electron field

Wu *et al.* provided the idea of applying CNTs to the emission devices in the cold cathode electron field and described the cathode ray tubes[42]. Driven by the direct mode of grid CNTs emitters and the transistor feeding applications, a method based on the technology of laser-induced forward transmission (LIFT) was proposed to realize the concepts of the cold cathode electron field emission devices of CNTs and the cathode ray tubes of CNTs. Based on this idea, a new kind of scheme of laser material transfer (SLM) was proposed, which could deposit both of CNTs and silver slurry layer at the same time. This method confined the transferable area to the laser irradiated area, which proved the feasibility of transferring materials in the mask protection area. The results show that the prepared double-layer CNTs/silver slurry CNTs emitters had good characteristics of the field emission.

A MEMS/NEMS electron impact gas ion generator based on the CNTs, which had an integrated extractor gate for portable mass spectrometry, was constructed in the work of Hu *et al.*[43]. The ion generator used the sparse forest of CNTs

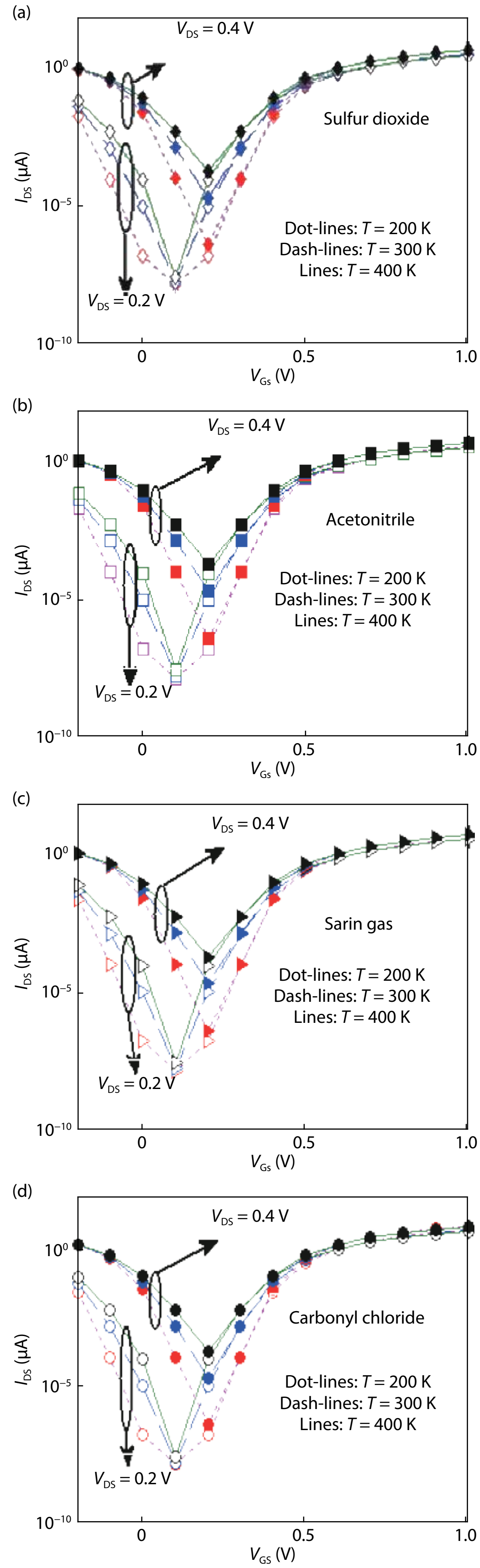

Fig. 15. (Color online) Transport features. (a) Sulfur Dioxide. (b) Acetonitrile. (c) Sarin Gas. (d) Carbonyl Chloride at logarithmic scale for V_{DS} = 0.2, 0.4 V. (Reproduced with permission from Ref. [40].)

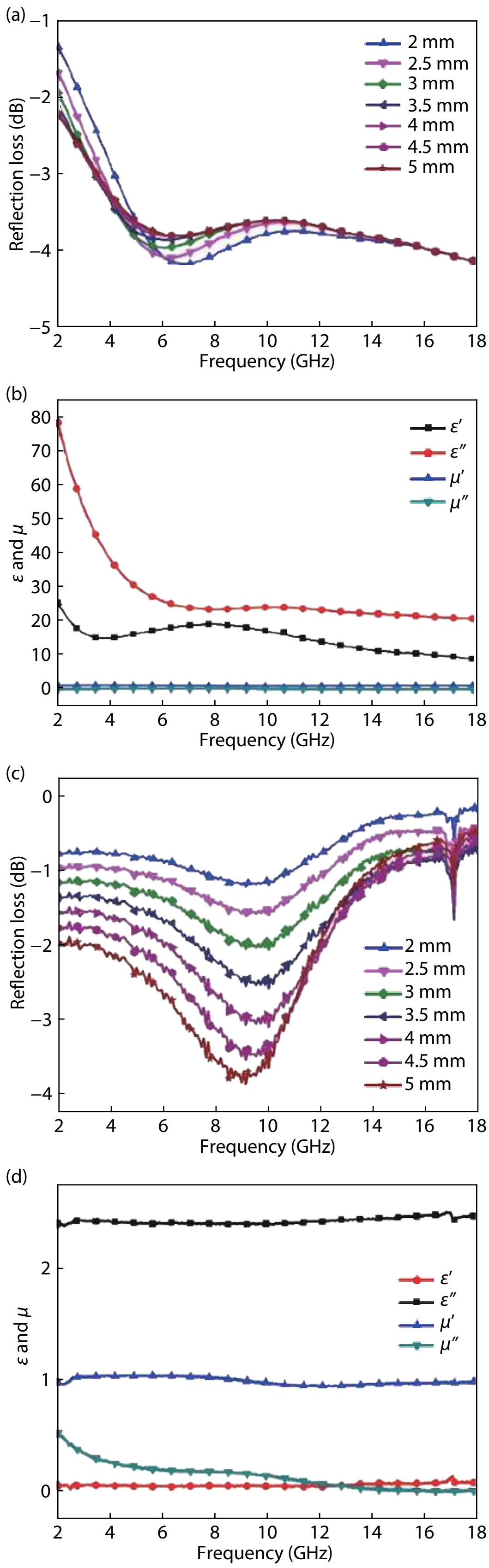

Fig. 16. (Color online) (a) and (c) Reflection losses of raw CNTs and Ni with 2–5 mm thickness. (b) and (d) Complex permittivity ε and permeability μ of the raw CNTs and Ni. (Reproduced with permission from Ref. [41].)

that were produced by the plasma enhanced chemical vapor deposition (PECVD) as the grid of field emitter and proximal extractor to realize low voltage ionization. The extractor gate was integrated into the ionizer using a high-voltage MEMS packaging technology based on the definition of deep reactive ion etching (DRI) silicon spring. The ion generator also included a high aspect ratio silicon structure, which contributed to the sparse CNTs growth and enabled uniform current emission.

4.4. Application in the back-end interconnection

Liang *et al.* introduced the method of combining electrical measurement with atomic pair circuit simulation, studied the conductivity of doped SWCNTs and doped MWCNTs, and provided a feasible choice for the next generation of back-end interconnection[44]. The initio simulation predicted the doping-related displacement of Fermi level. By converting the semiconductor shell into metal, the chiral variability of the shell could be reduced and the resistivity could be increased by 90%. The electrical testing of platinum salt doped CNTs provided up to 50% of the reduction of resistance, which was a milestone in the future of the technology of CNTs interconnection.

4.5. Application in the thermal management

Because of the thermodynamic properties, CNTs materials were also widely used in the field of thermal management applications. In the process of thermal management applications, it was necessary to estimate the thermal properties of CNTs. For the estimation of the thermal properties of CNTs, CNTs were arranged vertically on the mounted Pt/Si micro-hot plate in the work of Silvestri *et al.,* and then the thermal properties of CNTs were estimated directly[45]. In addition, the electrothermal simulation (finite element modeling) was also carried out to evaluate the experimental results and generate valuable instruments for the design of customized fitting geometric structures with specific power dissipation constraints. The simulation was consistent with the experimental results in the whole temperature range. Therefore, the tool could predict the optimal design and geometry of chip-level heat dissipation in microdevices encapsulated by CNTs.

4.6. Application in the medicine and the anthroponomy

Jung *et al.* prepared a kind of the dry ECG electrode of the CNTs/PDMS composite, which could be easily connected to the traditional ECG equipment, and showed the long-term wearable monitoring ability and the robustness to exercise[46]. It was proved that this dry ECG electrode overcame the limitations of traditional dry or wet electrodes. Even after a week of continuous use, the electrode did not have any obvious side effects, such as itching or irritation. Compared with Ag/AgCl electrode, the signal quality did not decrease with the passage of time. The experimental results showed that the composite electrode had good biocompatibility and robustness under the condition of exercise and sweating, and was suitable for long-term electrocardiogram monitoring.

Rezaei *et al.* provided an application of the mixed electrodes of MWCNTs/modified carbon quantum dots/pencil graphite in the field of electrochemical determination of dextromethorphan (DXM)[47]. Through this application, we could know that the MWCNTs composites modified by the nanoparticles of carbon quantum dots could be used as a suitable modifier in the electrochemical method for the determination of DXM. And the platinum group elements modified by the MWCNTs/modified carbon quantum dots/pencil graphite had good synergistic effect on DXM oxidation.

Xie *et al.* pointed out a kind of CNTs water dispersion which was used in the thermal effect of microwave[48]. The water dispersion took the H_2SO_4:HNO_3 as the functional group, successfully realized the functionalization of the functional group, ensured the stability and the high concentration of CNTs. After ultrasonic treatment, the water dispersant had very high dielectric properties and could be applied in clinical related fields. In addition, the length of CNTs would affect their water dispersion. The shorter the length of CNTs, the better their biocompatibility and dispersion stability.

CNTs/PDMS composite film which is the part of CCFS could also be used in single monitoring of human body. Yang *et al.* provided a kind of flexible Ag/CNTs/PDMS composite membrane sensor[49]. The mechanism of force-electricity was based on the micro-crack of silver film in the process of external forcing, which resulted in the change of resistance. The sensor had the advantages of high sensitivity, wide strain range, good stability and good durability, low cost and suitable for large-scale production because of the use of the wrinkled film of CNTs. Preliminary application in human monitoring showed that the sensor could detect weak tremor, breathing depth, breathing frequency as well as the corresponding heartbeat response. In addition, as a kind of electromechanical sensor, it was expected to be widely used in many fields, such as human-computer cooperation and the robotic systems.

5. Conclusion

In this paper, the preparation methods of the CFS are proposed, and several cases of the application of CFS and CCFS which containing CNTs and other materials in recent years are described, which could prove that either CFS or CCFS has a wide use in various fields, such as the energy storage systems, the artificial skin and the nanocomposites. However, there are several remaining challenges in the application fields of the CFS. That the CFS is improved on the basis of the existing technology in order to be used as the elastic electromyogram (EMG) sensor could control the muscle activity in the human body easily. Being used as the material support for the flexible electronic devices with flexibility, the CFS could promote the development of the wearable devices. In addition, based on the good ductility and electric conductivity, CFS could be used as the carrier devices for the human-computer interactive motion monitoring, which could promote the development of automatic control.

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