

## Research Article

# Influence of MWCNTs Doping on the Structure and Properties of PEDOT:PSS Films

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Poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS) doped with multi-walled carbon nanotubes (MWCNTs) films is fabricated on quartz substrates by spin coating method. The effects of MWCNTs on the structure and properties of PEDOT:PSS film have been investigated. X-ray diffractometer (XRD) and Fourier transform Raman spectroscopy (FTRM) show that the crystallization behavior and the main chain of PEDOT:PSS are not changed. Atomic force microscopy (AFM) shows that individual nanotubes are well dispersed in the PEDOT:PSS matrix. Moreover, some nanotubes overlap into a net-like structure, forming new conductive channels, which can enhance efficiently the film conductivity. The conductivity of PEDOT:PSS film doped with a lower percentage of MWCNTs (0.2 wt%) is 9.16 S/cm, higher than that of pure PEDOT:PSS film (0.28 S/cm), although the optical transmission of PEDOT:PSS decreases a little after the addition of MWCNTs. The interaction between MWCNTs and PEDOT:PSS during melt mixing is also given a possible explanation.

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## 1. Introduction

In the recent years, films fabricated from commercially available poly(3,4-ethylenedioxythiophene):poly(4-styrenesulfonate) (PEDOT:PSS) aqueous dispersions have attracted a lot of attention mainly due to their exceptional advantages of high transparency in the visible range, excellent thermal stability, and aqueous solution processibility [1, 2]. With all these properties, PEDOT:PSS is now widely used in optoelectronic devices. For example, it can be used as a hole transporter layer in organic light-emitting diodes (OLED) [3–5], or as a buffer layer between the ITO and active layers in organic solar cells (OSC) [6–8]. However, the film also suffers low conductivity with about 0.05 ~ 0.8 S/cm [9, 10], which directly affects the performance of the device [11, 12]. Therefore, the improvement of the film conductivity has been considered to be an urgent work.

Recently, several strategies have been applied to increase the conductivity of PEDOT:PSS [10, 13–15]. Kim et al. [10] reported that the enhancement of the PEDOT:PSS conductivity could be achieved by adding organic solvent

dimethyl sulfoxide or N,N-dimethylformamide. Ouyang et al. [13, 14] reported that the addition of ethylene glycol to the aqueous PEDOT:PSS dispersion could induce the change of conductivity, and they proposed that the conductivity enhancement results from the conversion of the PEDOT molecular conformation from “ben structure” to “quoid structure”.

Nanotubes can serve as a good filler for conducting polymer. It has been reported that incorporating of nanotubes into conventional conducting polymers improves the conductivity of nanotubes/polymer composites by many orders of magnitude [15–20], which could be attributed to nanotubes' large contact area, high dimensional aspect ratio, and exceptional electrical conductivity [21].

In this work, the PEDOT:PSS doped with multiwalled carbon nanotubes (MWCNTs) transparent conducting film was fabricated on quartz substrates by spin coating method. The pristine and doped PEDOT:PSS films were characterized by XRD, FTRM, AFM, UV-Vis spectroscopy, and four-point measurement. The effects of MWCNTs on the structure and properties of the PEDOT:PSS film were also investigated.

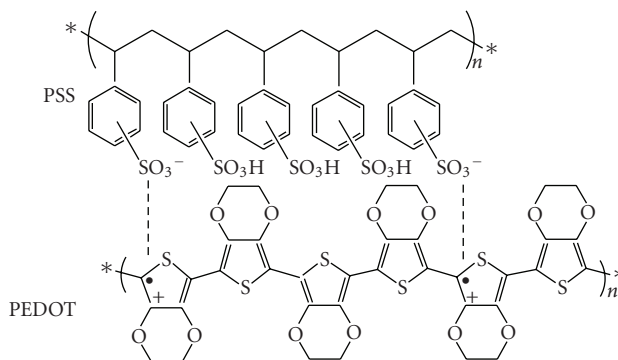


FIGURE 1: Chemical structure of PEDOT:PSS. The “dot” and “plus” represent the unpaired electron and positive charge on the PEDOT chain, respectively.

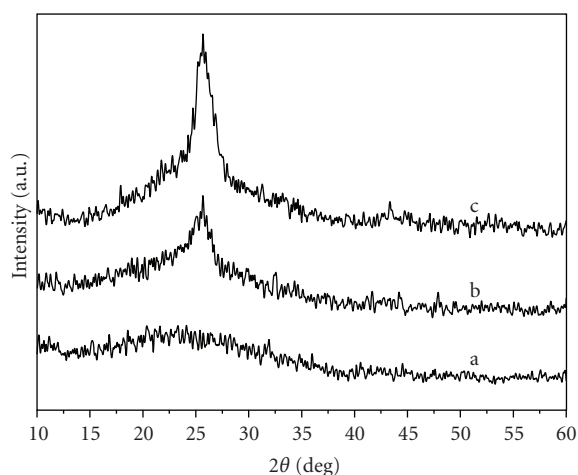


FIGURE 2: XRD patterns of (a) pure PEDOT:PSS, (b) M-PEDOT:PSS (0.1 wt%), and (c) MWCNTs films.

## 2. Experimental

Multiwalled carbon nanotubes (diameter: 10 ~ 30 nm, length: 5 ~ 15  $\mu\text{m}$ , purity: >95%) were purchased from Beijing Nachen Nanotech Co., Ltd and were further acid-treated by the previously established methods [22, 23]. The MWCNTs after acid-treatment can be dispersed into aqueous PEDOT:PSS solution and no precipitation is observed in the solution after several weeks. PEDOT:PSS aqueous solution (1.3 wt% dispersed in  $\text{H}_2\text{O}$ ) was from Aldrich. Other reagents and solvents were of analytical grade.

The chemical structure of PEDOT:PSS is shown in Figure 1. In the PEDOT:PSS dispersion, PEDOT is the charge transporting species [9, 10]. PSS acts as a charge-compensating counterion to stabilize the p-doped conducting polymer, and forms a processable water-borne dispersion of negatively charged swollen colloidal particles consisting of PEDOT and excess PSS [24, 25].

All the quartz substrates (20 mm  $\times$  20 mm) were ultrasonically cleaned with a series of organic solvents (ethanol, methanol, and acetone), then rinsed in ultrasonic bath with deionized water, and dried in a vacuum oven. Residual

organic contaminations were subsequently removed by exposing to a UV-ozone lamp for 30 min. Prior to spin coating, the precursor solution of PEDOT:PSS with appropriate mass of MWCNTs was prepared. Some amount of acid treated-MWCNTs were added to the PEDOT:PSS aqueous dispersion in ultrasonic bath for about 12 hours. The PEDOT:PSS and acid treated-MWCNTs-doped PEDOT:PSS films (PEDOT:PSS and M-PEDOT:PSS, separately) with a thickness of 95–100 nm, as determined with scanning electron microscopy, were fabricated on transparent quartz substrates by spin coating method. The spin coating procedure included 20 seconds of 2000 rpm followed by 30 seconds of 5000 rpm. Then these films were dried at 110° for 60 minutes in the vacuum oven before any further characterization.

The molecular structure analysis of all the samples was carried out with Fourier transform Raman spectroscopy, which was recorded with a RFS 100 Bruker spectrometer (excitation wavelength 1064 nm). Sample structures were analyzed with D8 Advance Bruker AXS X-ray diffractometer, with  $\text{Cu K}\alpha_1$  radiation. The dispersion of acid-treated MWCNTs in PEDOT:PSS matrix was investigated with atomic force microscopy, which was performed with Digital Instruments Nanoscope III operating in tapping mode. The optical properties were characterized with a TU-1901 Dual-beam UV-Visible spectrophotometer. The conductivity of the films was measured by the four-point probe technique with a Keithley 2400 Source Meter. All the measurements were performed at room temperature.

## 3. Results and Discussion

The XRD patterns of pure MWCNTs, PEDOT:PSS, and M-PEDOT:PSS films are shown in Figure 2. There are not any sharp peaks in the pristine PEDOT:PSS profile (Figure 2(a)), which indicates substantial amorphous nature of the PEDOT:PSS film. Similar results were also obtained by different research groups [26, 27]. The pure MWCNTs film shows a sharp peak centered on  $2\theta$  value of 25.6° corresponding to the (002) planes of MWCNTs (Figure 2(c)). The composite film (Figure 2(b)) shows the characteristic peaks of both MWCNTs and PEDOT:PSS without any additional

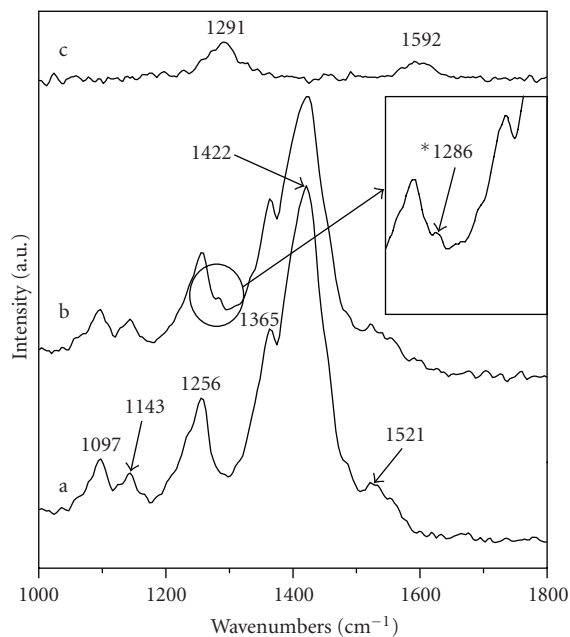


FIGURE 3: Raman spectra of (a) pure PEDOT:PSS, (b) M-PEDOT:PSS (0.1 wt%), and (c) MWCNTs films. \*The inset curve shows clearly the peak of  $1286\text{ cm}^{-1}$ .

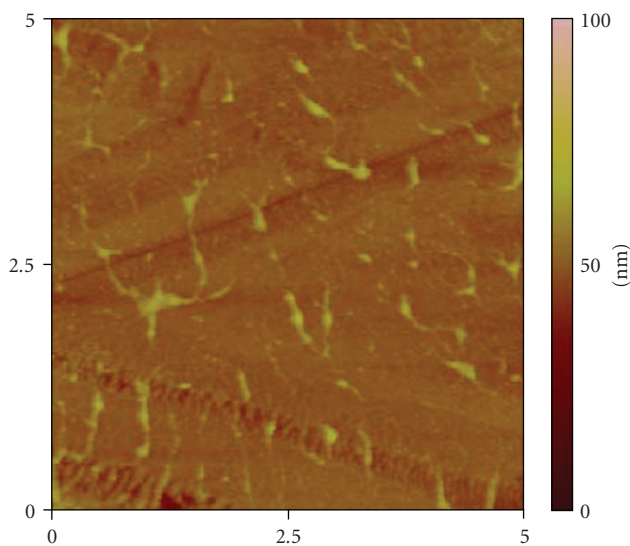


FIGURE 4: AFM image ( $5 \times 5\text{ }\mu\text{m}$ ) of M-PEDOT:PSS (0.1 wt%) film.

bands, which represents the absence of covalent interactions between the phases. Moreover, the crystallization behavior of the PEDOT:PSS film is not changed.

The Raman spectrum of pure PEDOT:PSS film is identified in [28–30] (Figure 3(a)). Raman spectrum shows six dominant principal peaks of PEDOT. The peak at  $1521\text{ cm}^{-1}$  represents  $C_{\alpha}=C_{\beta}$  asymmetric vibrations;  $1421\text{ cm}^{-1}$  can be assigned to  $C_{\alpha}=C_{\beta}$  symmetric vibrations,  $1365\text{ cm}^{-1}$  to C–C stretching deformations,  $1256\text{ cm}^{-1}$  to C–C in-plane symmetric stretching, and  $1143\text{ cm}^{-1}$  and  $1097\text{ cm}^{-1}$  to C–C in-plane bending. As shown in Figure 3(c), there are

mainly two optically active phonon modes in the first-order Raman spectrum of MWCNTs film, and two peaks at  $1592\text{ cm}^{-1}$  and  $1291\text{ cm}^{-1}$  represent a graphite  $E_{2g}$  mode and an MWCNTs disordered  $A_{1g}$  mode, respectively. The disordered  $A_{1g}$  mode indicates the imperfection of the  $sp^2$  hybridization of MWCNTs, which may occur during the production process or the acid-treated process [31]. Raman spectrum of the M-PEDOT:PSS film is essentially the same as that of PEDOT:PSS film except one additional peak centered at  $1286\text{ cm}^{-1}$  (Figure 3(b)).

Chemical and physical interactions between some materials and MWCNTs often occur during melt mixing, and these interactions can affect the Raman spectrum of MWCNTs. These phenomena have been confirmed by both theoretical and experimental researches [32, 33]. Combining with the results of XRD, we speculate that there may be some noncovalent interactions, which might stem from the  $\pi$ - $\pi$  interaction between the delocalized  $\pi$  bond network of MWCNTs and the thiophene rings of PEDOT backbone. This conjugated interaction would affect the electronic density among MWCNTs. Therefore, the peak of MWCNTs at  $1291\text{ cm}^{-1}$ , which shifts red from  $1291\text{ cm}^{-1}$  to  $1286\text{ cm}^{-1}$ , may result from the change of electronic density of MWCNTs. While the peak of MWCNTs at  $1592\text{ cm}^{-1}$  is so weak that it cannot be observed (Figure 3(b)). However, the mechanism of the interactions between MWCNTs and PEDOT:PSS during melt mixing is still an assumption and needs to be further studied.

AFM image ( $5 \times 5\text{ }\mu\text{m}$ ) in Figure 4 shows that individual nanotubes are well dispersed in the PEDOT:PSS matrix. Some nanotubes overlap into a net-like structure, which implies that some continuous channels are embedded in the PEDOT:PSS matrix.

When PEDOT:PSS is applied in OLED or OSC devices, it is always important to keep its transmittance high. Figure 5 shows the wavelength dependence of the optical transparency of PEDOT:PSS and M-PEDOT:PSS thin films on the wavelength range from  $550\text{ nm}$  to  $950\text{ nm}$ , which corresponds to the power density of ambient sunlight on the Earth's surface [34]. The PEDOT:PSS film gives a good optical transmittance in the above wavelength range (93.2% average) (Figure 5(a)). Moreover, The transmittance increases from  $950\text{ nm}$  to  $550\text{ nm}$ , which is mainly because of more absorptions in the infrared region for the PEDOT:PSS film [5, 35], as shown in Figure 5(b). Transmittance curve of M-PEDOT:PSS film is about 88.5% average, about 5% less than that of pure PEDOT:PSS film. This may result from the formation of the conductive network of MWCNTs and some absorptions of MWCNTs in the above wavelength range [24, 36].

As shown in Figure 6, the conductivity of pure PEDOT:PSS film is  $0.28\text{ S/cm}$ . While the conductivity increases drastically when MWCNTs doping concentration increases from  $0.04\text{ wt\%}$  to  $0.12\text{ wt\%}$ , and then increases moderately at loading levels in excess of  $0.12\text{ wt\%}$ . When MWCNTs content reaches about  $0.2\text{ wt\%}$ , the conductivity of composite film is  $9.16\text{ S/cm}$ . These indicate that the percolation threshold of the nanocomposite films resides between  $0.04\text{ wt\%}$  and  $0.12\text{ wt\%}$ , where some conductive

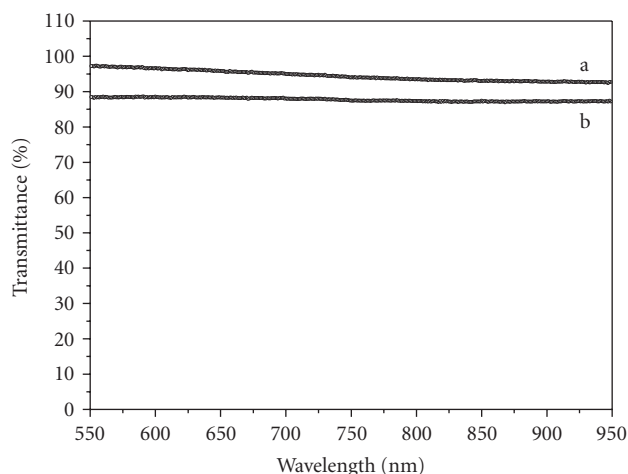


FIGURE 5: Transmittance of (a) pure PEDOT:PSS and (b) M-PEDOT:PSS (0.1 wt%) films.

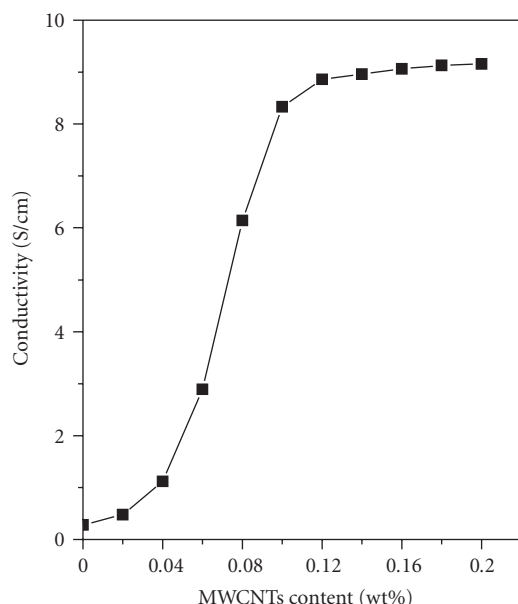


FIGURE 6: The electrical conductivity of composite films as a function of weight fraction of MWCNTs.

MWCNT channels in the PEDOT:PSS matrix might form, as shown in AFM (Figure 4), which can help charge transport and enhance the conductivity of films [37, 38].

## 4. Conclusion

In summary, influences of MWCNTs doping on the structure and properties of PEDOT:PSS films have been investigated. XRD and FTRM show that the crystallization behavior and the main chain of PEDOT:PSS are not changed. AFM shows that individual nanotubes are well dispersed in the PEDOT:PSS matrix. Moreover, some nanotubes overlap into a net-like structure, forming new conductive channels, which can enhance efficiently the film conductivity.

The conductivity of PEDOT:PSS film doped with a lower percentage of MWCNTs (0.2 wt%) is 9.16 S/cm, higher than that of pure PEDOT:PSS film (0.28 S/cm), although the optical transmission of PEDOT:PSS decreases a little after the addition of MWCNTs. The interaction between MWCNTs and PEDOT:PSS during melt mixing is also given a possible explanation. However, this explanation is still an assumption and needs to be further studied.

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