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Highly conductive PEDOT:PSS films prepared through a treatment with geminal diols or amphiphilic fluoro compounds

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ABSTRACT

Poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) films with high conductivity can have important application as the transparent electrode of optoelectronic devices. In this paper, we report the significant conductivity enhancement of PEDOT:PSS through a treatment with germinal diols which have two hydroxyl groups connected to one carbon atom or amphiphilic fluoro compounds which have hydrophobic fluorocarbon groups and hydrophilic hydroxyl or carboxylic groups. Several compounds, including hexafluoroacetone, cyclohexanehexone, formaldehyde, acetaldehyde, and perfluorobenzophenone, which could convert into geminal diols, were used to treat PEDOT:PSS films. The conductivity enhancements are generally consistent with the equilibrium constants for the conversion of these compounds into geminal diols. PEDOT:PSS films were also treated with several amphiphilic fluoro compounds. The conductivity was significantly enhanced when PEDOT:PSS films were treated with hexafluoroisopropanol, trifluroacetic acid and heptafluorobutyric acid, while it hardly changed when they were treated with 2,2,2-trifluoroethanol. Conductivities of more than 1000 S cm⁻¹ were observed on the treated PEDOT:PSS films. The mechanism for the conductivity enhancement of PEDOT:PSS through the treatment with geminal diols or amphiphilic fluoro compounds is attributed to the phase segregation of PSSH from PEDOT:PSS and conformational change of the PEDOT chains as the results of the compounds-induced reduction in the Coulombic attraction between the positively charged PEDOT and negatively charged PSS chains.

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1. Introduction

Optoelectronic devices, such as liquid crystal displays (LCDs), light-emitting diodes (LEDs), solar cells, touch panel displays, lasers, and detectors, have important application in our life. They are indispensable units for many technologies. The market for optoelectronic devices has been huge and is still rapidly expanding. At least one electrode of an optoelectronic device is required to be transparent in order to emit or harvest light. Conventionally, indium tin oxide (ITO) is the most popular material as the transparent electrode of optoelectronic devices.

* Corresponding author. E-mail address: mseoj@nus.edu.sg (J. Ouyang). However, ITO has problems of high price, scarcity of indium on earth and high mechanical brittleness. These problems cause ITO unsuitable for flexible electronic devices that are regarded as the next-generation electronic devices and bring a concern of the long-term availability [1,2]. Hence, new transparent conductive materials are urgently needed. Many materials have been proposed as the transparent electrode of optoelectronic devices, including conducting polymers [3–15], carbon nanotubes [16– 19], graphenes [20,21], and metal wires [22–24]. Among them, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, chemical structure shown in Scheme 1) is promising as the next-generation transparent electrode material. PEDOT:PSS is the most successful conducting polymer in terms of the practical application thanks to





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Scheme 1. Chemical structure of PEDOT:PSS.

its advantages in processability, mechanical and optical properties. It can be dispersed in water and some organic solvents, and high-quality PEDOT:PSS films can be readily prepared by conventional solution processing techniques, such as spin coating and printing [25–27]. Moreover, PEDOT:PSS films have high transparency in the visible range, high mechanical flexibility, and excellent thermal stability. However, PEDOT:PSS does suffer a problem of low conductivity. As-prepared PEDOT:PSS films from aqueous PEDOT:PSS solution usually have a conductivity below 1 S cm⁻¹, which is saliently lower than that of ITO [26,28]. It is thus important to significantly enhance the conductivity ity of PEDOT:PSS films for their application as the transparent electrode of optoelectronic devices.

Several methods have been developed to significantly enhance the conductivity of PEDOT:PSS since the report by Kim et al. by adding dimethyl sulfoxide (DMSO) or dimethylformamide (DMF) into PEDOT:PSS aqueous solution [29]. The addition of other organic compounds, including ethylene glycol (EG), glycerol, other polyols (compounds with two or more OH groups), ionic liquids, anionic surfactants, and dimethyl sulfate, into PEDOT:PSS aqueous solution can also significantly improve the conductivity of PEDOT:PSS [13,30-38]. Similar conductivity enhancement was also observed by treating PEDOT:PSS films with polar organic compounds, salts, zwitterions, carboxylic or inorganic acids, or cosolvents [9,39-45]. Most of the research works have been carried out on PEDOT:PSS aqueous solutions commercially supplied by H.C. Starck, which was taken over by Heraeus, or Agfa, and the conductivity of the treated PEDOT:PSS films depends on the grade of the PEDOT:PSS aqueous solutions. The conductivity of PEDOT: PSS prepared from Clevios P is usually below 200 S cm⁻¹ after a treatment, while the conductivity of PEDOT: PSS films prepared from Clevios PH1000 can be enhanced to $680 \pm 50 \text{ S cm}^{-1}$ or higher after a treatment with EG or DMSO [46]. Recently, Kim et al. prepared PEDOT:PSS films from Clevios PH1000 solution added with EG and then treated the PEDOT:PSS films in EG bath again [47]. The conductivity could be enhanced up to 1418 S cm^{-1} .

Recently, we reported the treatment of PEDOT:PSS films prepared from pristine Clevios PH1000 aqueous solution with a fluoro compound, hexafluoroacetone (HFA, chemical structure shown in Scheme 2) [48]. The conductivity of the PEDOT:PSS films is enhanced to 1164 S cm⁻¹ after treated with HFA for one time, which is even higher than that of PEDOT:PSS films treated with EG or DMSO for one

time. HFA hydrolyzes into 1,1,1,3,3,3-hexafluoropropane-2,2-diol (HFP2OH) with water, which is a geminal diol with two -OH groups connected to one C atom. Because normal polyols can significantly enhance the conductivity of PEDPT:PSS and geminal diols are special polyols, it is expected that the conductivity of PEDOT:PSS can be enhanced by other geminal diols and the conductivity enhancement should be related to the structure of the geminal diols. In addition, HFP2OH is an amphiphilic compounds owning to the two highly hydrophilic -OH groups and the two highly hydrophobic -CF₃ groups. An amphiphilic compound can strongly interact with PEDOT:PSS, as PEDOT is highly hydrophobic while PSS is highly hydrophilic. Due to the high hydrophobicity of fluorocarbon groups, such as $-CF_3$, it is reasonably expected that other amphiphilic fluoro compounds can significantly enhance the conductivity of PEDOT:PSS as well. In this paper, we report the conductivity enhancements of PEDOT:PSS films through a treatment with various geminal diols and amphiphilic fluoro compounds. The conductivity of PEDOT:PSS can be enhanced from 0.3 S cm⁻¹ to more than 1000 S cm⁻¹, and the conductivity enhancement depends on the structure of these compounds.

2. Experimental

2.1. Treatment of PEDOT:PSS films

PEDOT:PSS aqueous solution (Clevios[™] PH 1000) was purchased from H.C. Starck. The concentration of PEDOT:PSS was 1.3% by weight, and the weight ratio of PSS to PEDOT was 2.5 in solution. All other chemicals were obtained from Sigma–Aldrich. All the materials were used without further purification.

PEDOT:PSS films were prepared by spin coating the CleviosTM PH 1000 aqueous solution on 1.3×1.3 cm² glass substrates, which were pre-cleaned sequentially with detergent, de-ionized (DI) water, acetone and isopropyl alcohol. The PEDOT:PSS films were dried at 120 °C on a hot plate for 15 min. The treatment was performed by dropping 100 µL geminal diol or fluoro compound or aqueous solution of a compound on a PEDOT:PSS film on a hot plate at 140 °C. The films dried after about 5 min. They were cooled down to room temperature, and then were rinsed with deionized water and dried at 140 °C again.

2.2. Characterization of PEDOT:PSS films

The conductivities of dried polymer films were measured by the van der Pauw four-point probe technique with a Keithley 2400 source/meter. The electrical contacts were made by pressing indium on the four corners of each PEDOT:PSS film on glass substrate. The temperature dependences of the resistivities of the untreated and treated PEDOT:PSS films were tested using a Janis Research VPF-475 dewar with liquid nitrogen as coolant and a Conductus LTC-11 temperature controller. The UV–Vis-NIR absorption spectra of the polymer films were taken with a Varian Cary 5000 UV–Vis-NIR spectrometer, and the AFM images were obtained using a Veeco NanoScope



hexafluoroacetone



cyclohexanehexone



CH₃COCH₃

acetone

HCHO

formadehyde



hexafluoroisopropanol

perfluorobenzophenone

CH₃CHO

acetaldehyde

CF₃CH₂OH

2,2,2-trifluoroethanol



CF₃COOH

trifluoroacetic acid

heptafluorobutyric acid

Scheme 2. chemical structure of some germinal diols and amphiphilic fluoro compounds.

IV Multi-Mode AFM with the tapping mode. The X-ray photoelectron spectroscopy (XPS) spectra were collected with an Axis Ultra DLD X-ray photoelectron spectrometer equipped with an Al K_{α} X-ray source (1486.6 eV). The thicknesses of the polymer films were determined with an Alpha 500 step profiler.

3. Results and discussion

3.1. Conductivity enhancement of PEDOT:PSS films by geminal diols

The conductivity of PEDOT:PSS can be significantly enhanced by EG and other polyols, while the conductivity is negligible when alcohols with only one OH group are used [32]. This suggests that a geminal diol, which has two –OH groups connected to one C atom and can be considered as a special polyol, can significantly enhance the conductivity of PEDOT:PSS. This is evidenced by our recent observation

that the conductivity of PEDOT:PSS could be significantly enhanced through a treatment with HFA [48]. HFA hydrolyzes into HFP2OH, a geminal diol,

$CF_3COCF_3 + H_2O \rightarrow CF_3 - C(OH)_2 - CF_3.$

Other geminal diols may improve the conductivity of PEDOT:PSS as well. Geminal diols are usually generated through the hydrolysis of ketones or aldehydes. Chemical structures of some molecules which can convert into geminal diols are listed in Scheme 2. The equilibrium constant for the conversion of a ketone or aldehyde into a geminal diol depends on the molecular structure. It is about 10^6 for the conversion of HFA into HPF2OH. Such a high conversion constant is related to the strong electron-with-drawing ability of the two $-CF_3$ groups, which causes the middle C atom of HFA to be partially positively charged so that the hydrolysis can take place. The equilibrium constant decreases with the decrease in the positive charge on

the middle C atoms. For example, it becomes 10^3 for the conversion of formaldehyde into its geminal diol, $H-C(OH)_2-H$,

 $HCHO + H_2O \rightarrow H_2C(OH)_2.$

It further decreases to 10^{-3} for the conversion of acetone into CH₃-C(OH)₂-CH₃,

 $CF_3COCF_3 + H_2O \rightarrow CH_3 - C(OH)_2 - CF_3.$

The conductivities of PEDOT:PSS films treated with HFA. formaldehyde and acetone are consistent with the equilibrium constants for the conversion of these compounds into geminal diols (Table 1). The melting points and boiling points of these compounds are also listed in Table 1. A treatment of PEDOPT:PSS films with 12.2 M formaldehvde aqueous solution, which corresponds to the concentration of 36.7% by weight, enhances the conductivity from 0.3 to 862 S cm⁻¹, while a treatment with acetone hardly improve the conductivity. The conductivity of the PEDOT:PSS films treated with acetaldehyde is 83 S cm⁻¹, which is higher than that treated with acetone but lower than that treated with formaldehyde. This can be understood in terms of the chemical structures of these compounds. It is inferred that the equilibrium constant for the conversion of acetaldehyde into geminal diol should be between those of formaldehyde and acetone.

We also investigated the treatment of PEDOT:PSS with cyclohexanehexone. Only its geminal diol structure, dodecahydroxycyclohexane, exists in water [49]. Cyclohexanehexone is a solid at room temperature, and it has limit solubility in water. We found that the conductivity of PED-OT:PSS films was enhanced to 349 S cm⁻¹ after a treatment with 0.1 M cycloehexanehexone aqueous solution. This conductivity is even higher than the conductivity (177 S cm⁻¹) of PEDOT:PSS films treated with 0.1 M HFA.

In addition, we investigated the treatment of PEDOT:PSS with perfluorobenzophenone which has a carbonyl group connected with two fluorobenzene rings. It is a solid at room temperature. Its aqueous solution gives rise to no change in the conductivity of PEDOT:PSS. It may be difficult for this molecule to convert into geminal diol because the attachment of two –OH groups to the C atom of the carbonyl group with the two fluorobenzene rings.

Table 1

Conductivities of PEDOT:PSS films treated with geminal diols.

Name	Melting point (°C)	Boiling point (°C)	Conductivity $(S \text{ cm}^{-1})^{a}$
Cyclohexanehexone octahydrate	99	345	349 (0.1 M)
HFA trihydrate	-129	-28	1164
Formaldehyde	-92	-19	862 (12.2 M)
Acetaldehyde	-124	20	83 (18.2 M)
Acetone	-95	56	1
Perfluorobenzophenone	90–95	359	0.3 (1 M)

^a Conductivity of PEDOT:PSS after treated with a neat compound or aqueous solution of a compound with the highest concentration. The numbers in parentheses indicate the compound concentrations of aqueous solutions used for the treatments.

Table 2

Conductivities of PEDOT:PSS films treated with amphiphilic fluoro compounds.

Compounds	Melting point (°C)	Boiling point (°C)	Conductivity $(S \text{ cm}^{-1})^{a}$
HFA hydrate	-129	-28	1164
Hexafluoroisopropanol	-3	58	1022
2,2,2-Trifluoroethanol	-45	74	11
Heptafluorobutyric acid	-18	120	578 (5.6 M)
Trifluoroacetic acid	-15	72	473

^a Conductivity of PEDOT:PSS after treated with a neat compound or aqueous solution of a compound with the highest concentration. The number in parenthesis indicates the concentration of the aqueous solution used for the treatment.

3.2. Conductivity enhancement of PEDOT:PSS films by amphiphilic fluoro compounds

The geminal diol, HFP2OH, is also an amphiphilic molecule. Amphiphilic compounds can shield the Coulombic attraction between PEDOT and PSS and lead to the conductivity enhancement of PEDOT:PSS, since PEDOT is hydrophobic while PSS is hydrophilic. Fluorocarbon groups are highly hydrophobic. These inspire us to investigate the treatment of PEDOT:PSS with other amphiphilic fluoro compounds. The chemical structures of the fluoro compounds are listed in Scheme 2 as well.

Table 2 lists the conductivities of the PEDOT:PSS films treated with various fluoro compounds. Their melting points and boiling points are listed as well. All these fluoro compounds are liquid at room temperature. Conductivity as high as 1022 S cm^{-1} was observed on the PEDOT:PSS films treated with hexafluoroisopropanol (HFP). This conductivity is quite close to that treated with HFA [48]. The conductivity enhancement cannot be attributed to the effect by geminal diol, because HFP does not convert to a geminal diol in water. But HFP has the amphiphilicity similar to HFP2OH owing to the two $-CF_3$ groups and the -OH group.



Fig. 1. Transmittance spectra of PEDOT:PSS films treated with HFA, HFP and 12.2 M formaldehyde solution.



Fig. 2. Temperature dependences of the normalized resistances of PEDOT:PSS films. (a) Normalized resistances of untreated and treated PEDOT:PSS films versus temperature. (b) Analyses of resistance-temperature relationships of untreated and treated PEDOT:PSS films with the one-dimensional VRH model. The resistances are normalized to those of the corresponding PEDOT:PSS films at 110 K.

However, the conductivity enhancement became less significant when 2,2,2-trifluoroethanol was used for the treatment. The conductivity was only 11 S cm^{-1} after a treatment with 2,2,2-trifluoroethanol. It seems that the presence of two hydrophobic groups or two hydrophilic groups in the molecule is important for the significant conductivity enhancement.

This assumption was further confirmed by the investigation on the treatments of PEDOT:PSS films with trifluoroacetic acid and heptafluorobutyric acid. The carboxylic group can be considered as two polar groups, a carbonyl group and a hydroxyl group. Though trifluoroacetic acid is different from 2,2,2-trifluoroethanol only by the carbonyl group, the former can enhance the conductivity to 473 S cm⁻¹, much more significant than the latter. The conductivity enhancement becomes even more significant for heptafluorobutyric acid, which has more fluoro atoms on the molecule.

3.3. Optical and electrical properties of treated PEDOT:PSS films

Though a treatment with a geminal diol or an amphiphilic fluoro compound can significantly enhance the conductivity of PEDOT:PSS films, the treatment does not affect the transparency of the polymer films in the visible range. Fig. 1 presents the transmittance spectra of PED-OT:PSS films treated with HFA, HFP and formaldehyde. These PEDOT:PSS films are about 50 nm thick. Their transmittances are more than 90% in the visible range from 400 to 700 nm. As we observed that the HFA-treated PED-OT:PSS films could have transmittance and surface resistance comparable to ITO on plastic [48], the HFP- and formaldehyde-treated PEDOT:PSS films can have comparable transmittance and surface resistance to ITO on plastic as well.

The conduction mechanism of PEDOT:PSS films treated with HFA, HFP and formaldehyde were studies by measuring their resistances from room temperature down to 110 K (Fig. 2a). At temperature below 200 K, the resistances of these PEDOT:PSS films monotonically increase with the lowering temperature, which is similar to that of untreated PEDOT:PSS films. But the temperature dependences of the resistances of these treated PEDOT:PSS films are different from that of untreated PEDOT:PSS films when the temperature is higher than 200 K. The resistances are almost constant, especially for the PEDOT:PSS films treated with HFA and HFP.

Fig. 2b shows the analysis of the temperature dependences of the resistances with the one-dimensional variable range hopping (VRH) model [29,34,50],

$$R(T) = R_0 \exp\left[\left(\frac{T_0}{T}\right)^{1/2}\right],$$

where $T_0 = 16/k_B N(E_F) L_{//} L_{\perp}^2$ is the energy barrier between localized states, $N(E_{\rm F})$ is the density of the states at the Fermi level, and $L_{l/l}(L_{\perp})$ is the localization length in the parallel (perpendicular) direction. The untreated PEDOT:PSS film has a linear log R vs $T^{-1/2}$ in the whole temperature range from 110 to 310 K, and the T_0 value estimated from this linear relationship is 1901 K. The $\log R$ vs $T^{-1/2}$ data of the HFA- and HFP-treated PEDOT:PSS films have a linear relationship only at the low temperature range below 200 K, and the T_0 value estimated from the linear relationships are 99 and 127 K, respectively. The T_0 value of formaldehyde-treated PEDOT:PSS film at T < 200 K is 194 K. The T_0 values in the low temperature range are consistent with the conductivities of these PEDOT:PSS films at room temperature, which are 0.3, 1164, 1022, and 862 S cm^{-1} for the untreated, HFA-, HFP-, and formaldehyde-treated PEDOT:PSS films, respectively. T_0 decreases with the increasing conductivity. It thus suggests that the treatment with a geminal diol or an amphiphilic fluoro compound can lower the energy barrier for the interchain and interdomain charge hopping.

The $\log R - T^{-1/2}$ curves of the PEDOT:PSS films treated with HFA, HFP and formaldehyde suggest that the polymer films experience a phase transition at around 230 K. The T_0 value of PEDOT:PSS treated with formaldehyde decreases to 54 K at the temperature range from 230 to 310 K. The resistances of the PEDOT:PSS films treated with HFA and HFP are almost insensitive to temperature at the temperature range of more than 230 K. Thus, the phase transition at around 230 K for the PEDOT:PSS films treated with HFA and HFP can be an insulator-to-metal phase transition. Similar insulator-to-metal phase transition was also observed on polyaniline by Lee et al. [51]. The phase transition of polyaniline is related to the crystalline structure of the polymer. However, we did not observe any X-ray diffraction band for untreated PEDOT:PSS films and PEDOT:PSS films treated with HFA, HFP and formaldehyde.

3.4. Mechanism for the conductivity enhancements

The mechanism for the conductivity enhancements of PEDOT:PSS though the treatment with geminal diols and amphiphilic fluoro compounds was studied by various chemical and physical characterizations. The UV absorption spectra of PEDOT:PSS films are shown in Fig. 3. The intensities of the two absorption bands, which originate from the aromatic rings of PSS, drop after a treatment with HFA or HFP. This change indicates the decrease of the PSSH amount in PEDOT:PSS after the treatment. On the other hand, the intensities of the two absorption bands hardly change after a treatment with 2,2,2-trifluoroethanol. It suggests that the treatment with 2,2,2-trifluoroethanol does not give rise to remarkable change in the composition of PEDOT: PSS. The changes in the UV absorption spectra of PEDOT:PSS films after the treatment with different compounds are consistent with the effects of these compounds on conductivity of PEDOT:PSS.

The reduction of PSSH from the PEDOT:PSS films after a treatment is confirmed by the XPS spectra of the PED-OT:PSS films (Fig. 4). The two XPS bands with binding energies between 166 and 172 eV are the S 2p bands of the sulfur atoms in PSS, whereas the two XPS bands with binding energies between 162 and 166 eV are the S 2p bands of the sulfur atoms in PEDOT [52,53]. The S 2p XPS intensity ratio of PEDOT to PSS increases after the HFA and HFP treatment, while it only slightly changes after the treatment with 2,2,2-trifluoroethanol.

Moreover, no fluorine XPS signal was detected on PEDOT:PSS films treated with HFA and other fluoro compounds. Hence, these compounds do not remain in the PEDOT:PSS films after the treatment. They may completely

1.0 untreated 0.8 2,2,2-trifluoroethanol treated Absorbance (A. U.) HFP treated HFA treated 0.6 0.4 0.2 0.0 200 250 300 350 Wavelength (nm)

Fig. 3. UV absorption spectra of PEDOT:PSS films untreated and treated with HFA, HFP, and 2,2,2-trifluoroethanol.

vaporize during the treatment and/or be rinsed away by water.

These results suggest that the mechanism for the conductivity enhancement of PEDOT:PSS by these geminal diols and amphiphilic fluoro compounds can be similar to that by HFA and polyols. It has been understood that the polyol treatment of PEDOT:PSS can give rise to the phase segregation of PSSH chains from PEDOT:PSS and the conformational change of the PEDOT chains [32,33]. The amphiphilic fluoro compounds can also give rise to changes in the composition and structure of PEDOT:PSS. The amphiphilic fluoro compound-induced phase segregation of the PSSH chains can be ascribed to the shielding of the Coulombic attraction between PEDOT and PSS by the amphiphilic flruoro compounds. Some of these PSSH chains can be removed from the polymer films by the rinse with water. The wash-away of some PSSH chains from the PEDOT:PSS films can reduce the less conductive shell for the conductive PEDOT chains and lead to the conductivity enhancement. The phase segregation can not only reduce the amount of insulator PSSH in the polymer film but also the conformation of the PEDOT chains [54].

The surface morphology of the PEDOT:PSS films changed after the treatment with geminal diols and fluoro compounds as studied by AFM (Fig. 5). The rms roughnesses are 1.63 nm, 1.68 nm, 1.44 nm, and 2.27 nm for the untreated, HFA-, HFP-, and formaldehyde-treated PEDOT:PSS films. The apparent rms roughness increases to 4.88 nm for the PEDOT:PSS film treated with 2,2,2-trifluoroethanol. Obviously, that is mainly due to the appearance of pores in the 2,2,2-trifluoroethanol-treated PEDOT:PSS film, which may be due to the swelling of the polymer chains in 2,2,2-trifluoroethanol and the vaporization of 2,2,2-trifluoroethanol. A close-up look on the AFM image can find the change in the morphology of the PEDOT:PSS films after the treatments. Fibrous structures can be observed on the PEDOT:PSS films treated with HFA, HFP and formaldehyde, while they are absent for the untreated and 2,2,2-trifluoroethanol-treated PEDOT:PSS films. The change in the AFM images can be attributed to the phase segregation of PSSH chains from



Fig. 4. S_{2p} XPS spectra of PEDOT:PSS films untreated and treated with HFA, HFP, and 2,2,2-trifluoroethanol.



Fig. 5. AFM images of PEDOT:PSS films (a) untreated and treated with (b) HFA, (c) HFP, (d) formaldehyde solution, and (e) 2,2,2-trifluoroethanol. The unit for the AFM images is μ m.

PEDOT:PSS films after the treatment. It also suggests the conformational change of the PEDOT chains during the treatment.

4. Conclusions

In conclusion, the conductivity of PEDOT:PSS films can be significantly enhanced through a treatment with a geminal diol or amphiphilic fluoro compound. The conductivity can be enhanced to more than 1000 S cm⁻¹. The conductivity enhancement is related to the equilibrium constants for the conversion of the compounds into geminal diols or the chemical structure of the amphiphilic fluoro compounds. The treatment does not affect the transmittance of PEDOT:PSS films in the visible range, so that PEDOT:PSS films with high transparency and low sheet resistance can be obtained. The conductivity enhancement is attributed to the phase segregation of PSSH from PEDOT:PSS and conformational change of the PEDOT chains, induced by the geminal diols and amphiphilic fluoro compounds.

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