Research progress on a novel conductive polymer —poly(3,4-ethylenedioxythiophene) (PEDOT)

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Abstract In this paper the progress in study on a new organic conducting polymer—poly(3,4-ethylenedioxythiophene) (PEDOT) is reviewed. Its ground-state structure, excellent advantages and morphology are presented. Then the modification ways such as its copolymers and composites are introduced in detail. Moreover, the applications of PEDOT are also summarized.

Keywords: poly(3,4-ethylenedioxythiophene) (PEDOT), structure, advantages, composites, copolymers, applications

1. Introduction

Although polythiophene is relatively stable compared with other conducting polymers, the decrease of its conductivity over a long period limits its industrial applications. The stability of polythiophene may be improved by decreasing its oxidising potential. This can be realised by introducing an alkoxyl group (such as ether group), which has electron-donating character. Substituted thiophene can be polymerised at a considerably lower potential than thiophene and the resulting polymers are more stable in the anion-doped state especially when the side chain is not too long. Ether substituted thiophene mainly includes 3-alkoxy thiophenes, 3,4-alkoxy thiophenes and 3,4-(crown ether) thiophene or pseudocrown ether thiophene. However, study of polythiophenes with long side chain substituents shows that the polymer chain is distorted thereby giving lower conductivities. Therefore, a shorter chain ether substituted thiophene, 3,4-(crown ether) thiophene, has attracted many scientists’ attention and many results about PEDOT have been achieved and reported. Therefore, the research progress on PEDOT is reviewed in many aspects in this paper.

2. Ground-state structures of PEDOT

In many publications, the structure of PEDOT is usually described as Figure 1. However, two possible structures for neutral PEDOT: aromatic-like (Figure 2 (B)) and quinoid-like (Figure 2 (C)). In the earlier study, it was proposed by Lapkowski and Pron that the ground state of PEDOT was quinoid, based on the spectroscopic data. However, a theoretical investigation carried out by A.
Dkhissi et al.\textsuperscript{2} along two lines suggested that the ground state of neutral PEDOT was aromatic-like. They evaluated the energy per repeat unit ($E_{\text{pru}}$) of the aromatic and quinoid forms from quantum-chemical calculation by both RHF (restricted Hartree-Fock) and DFT (density functional theory) techniques. On the other hand, to confirm the conclusion, the vibration spectra of the two forms were calculated and compared to the experimental spectra recorded by Kvarnström et al.\textsuperscript{3-4}. Finally, a conclusion was drawn that PEDOT had aromatic character in the ground state, which was also the case for unsubstituted PT (Figure 2 (A)) but in contrast to polyisothianaphthene (PITN) (Figure 2 (D)).

![Figure 1. Structure of PEDOT.](image1)

![Figure 2. Ground-state structures of PEDOT.](image2)

### 3. Excellent characteristics of PEDOT

PEDOT is one of the most promising materials for practical applications due to its following characteristics:

#### 3.1. Reversible doping state

PEDOT can be repeatedly doped and undoped. PEDOT is almost transparent and light blue in the oxidized state and can be easily changed into opaque and dark blue appearance in the neutral state. Thus its color changes visibly when its doped state changes and may be suitable for optical applications, such as electrochromic displays\textsuperscript{5}.

#### 3.2. Excellent stability

PEDOT has improved chemical and thermal stability. Thermal studies show that a continuous degradation occurs above 150 °C and complete decomposition above 390 °C.\textsuperscript{6} Electrical conducting properties appear to remain almost unaltered after aging in environmental conditions. Its high stability is attributed to favorable ring geometry and the electron-donating effect of the oxygen atoms at the 3,4-positions stabilizing the positive charge in the polymer backbone\textsuperscript{7}.

#### 3.3. Regular structure

Due to the structure of the monomer, competing polymerizations through 3- and 4- positions as in thiophene are avoided. Thus, only the 2,5-couplings of the 3,4-ethylenedioxythiophene are expected. Therefore, PEDOT is expected to have fewer defects than the thiophene analogues.

#### 3.4. Low band-gap (High conductivity)

PEDOT has a low band gap of 1.5-1.6 eV\textsuperscript{8}. The lower band-gap relative to polythiophene is thought to originate from the influence of the electron-donor ethylene dioxy groups on the energies of the frontier levels of the $\pi$ system\textsuperscript{9}. Experimental results show that after doping, PEDOT exhibits reduced absorption in the visible: the oscillator strength shifts from around 1.5 eV (lowest $\pi-\pi^*$ transition) to below 1 eV in the metallic state\textsuperscript{10}. Thus it shows a high electrical conductivity (up to 550 S/cm) in the doped state.

#### 3.5. Effect of temperature on conductivity

DC conductivity measurements\textsuperscript{11} show that PEDOT has a resistivity ratio $\rho_T < 2$. But for the samples with $\rho_T = \rho(1.4K)/\rho(291K) = 1.5-2.8$, the temperature coefficient of resistivity, TCR, changes signs
below 10K from negative to positive which is characteristic of normal metals. For negative and positive TCR, the $\delta(T)$ is isotropic and proportional to $T^{1/2}$. The increase in conductivity below the transition temperature is approximately 2-3%.

3.6. Electrochemical properties
Compared to other conducting polymers, electrochemically synthesized films of PEDOT have a low redox potential and excellent stability in their doped state\textsuperscript{12}. Studied by cyclic voltammetry, it is found that the redox peaks at approximately 0 mV (oxidation) and –400 mV (reduction) remain almost unaffected during cycling. However, only under an applied negative potential of –700 mV were the neutral films found to be stable. Open circuit potential measurements show that the neutral films are rapidly oxidized\textsuperscript{13}.

4. Morphology of PEDOT
The high electrical conductivity measured for PEDOT agrees well with metallic state behaviour in the surface plane of the film. Determined by variable-angle spectroscopic ellipsometry together with intensity reflectance and transmission spectrophotometry, the optical anisotropy of PEDOT films are of uniaxial character with the optic axis normal to the film surface. The (ordinary) index of refraction in the plane shows a metallic state behaviour while the out-of-plane (extraordinary) index of refraction was character similar to that of a dielectric\textsuperscript{14}.

![Figure 3. Structural model of tosylate-doped PEDOT.](image)

Based on diffraction peak positions and intensities, K. E. Aasmundtveit et al.\textsuperscript{15-16} presented a structural model of thin-film tosylate-doped PEDOT which corroborated with the optical anisotropy. As shown in Figure 3, the structural model has a pseudo-orthorhombic unit cell with four monomers and one tosylate ion per cell and lattice parameters $a=14.0$ Å, $b=6.8$ Å and $c=7.8$ Å. The thiophene backbone of the polymer chain along the c-axis is flat and the polymer repeat distance is assumed to be 7.8 Å. The chains stack on top of each other with a stacking distance of $b/2 = 3.4$ Å. These bc-layers are separated along the a-axis by layers of tosylate ions. Therefore, the orientation of the material is such that the a-axis is preferably oriented along the surface normal so that the thin films are highly anisotropic, which is in good agreement with an observed optical anisotropy of the materials\textsuperscript{17}. In the plane of the film, the b- and c-axes are randomly distributed, ensuring cylindrical symmetry, giving a picture where the bc-layers (alternate polymer and dopant layers) lie flat down on the substrate. The structure is described as a paracrystalline one, where the lattice parameters represent
only mean values of probability distributions, implying also that the crystalline order decays with increasing distance. The width of the a-axis distribution is estimated to 2 %, and the size of individual paracrystalline domains in this direction to 50 Å. It is noteworthy that hardly any amorphous scattering was observed, so the paracrystalline state accounts for the entire volume of the material. This fact may be important for explaining the high conductivity of PEDOT, because insulating barriers formed by amorphous regions have been proposed as the limiting factor for the conductivity of conducting polymers.

5. PEDOT composites

5.1. PEDOT nanocomposites
A step forward with respect to ‘simple’ modification with pristine CPs consists in the inclusion of metal functionalities inside the polymeric matrix, in order to further increase the performances of the resulting composite material. In particular, inclusion of noble metal nanoparticles (NPs), whose catalytic properties are well known, constitutes one of the most interesting possibilities.

Au nano-PEDOT nanocomposites were successfully prepared using chemical and electrochemical routes and the AuNPs were found to attach stably to the polymer nanofibrillar matrix. The advantages of these films were demonstrated for sensing biologically important compounds such as dopamine (DA) and uric acid (UA) in presence of excess ascorbic acid, with superior selectivity and sensitivity when compared to the polymer film alone. The PEDOT matrix was recognized to be responsible for the peak separation (selectivity) while also favoring catalytic oxidation of the above compounds and the nanometer-sized gold particles allowed nanomolar sensing of DA and UA (sensitivity). Thus, it is possible to detect nanomolar levels of DA and UA in presence of excess of AA.

Composite materials consisting of PEDOT including Au nanoparticles encapsulated by bulky anionic species could also be electrogenerated. Notable chemical and morphological differences of the CP/NP composites were obtained with respect to the pure organic materials and reflected on the electrochemical performances of the various PEDOT-based coatings with respect to the oxidation of suitably chosen electroactive species. The sensitivity and selectivity of the electrochemical responses depended on the presence and density of the nanoparticles and the nature of the relevant encapsulating agent. The selectivity exhibited by the PEDOT/Au-Tann electrode system constitutes quite an interesting feature to exploit in electroanalysis. And this electrode coating is stable under subsequent DPV scans in the presence of DP, which is of key importance for possible analytical applications.

A new type of layered PEDOT/VS₂ nanocomposite were prepared by in situ oxidative polymerization of EDOT with VS₂ as a host material in the presence of an external oxidizing agent. The polymerization proceeded concomitantly with intercalation so that there was considerable bonding interaction between the organic and inorganic components, probably due to hydrogen bonding. Compared with pristine VS₂, the improvement of electrochemical performance with reversible specific capacities up to ~130 mAh/g was attributed to higher electric conductivity and enhanced bidimensionality. The influence of intercalants on Li⁺ diffusion rates and charge capacity in the PEDOT/VS₂ nanocomposite was increased relative to that for VS₂, therefore, the polymer nanocomposite acts as a better cathode material than the pristine VS₂ material by enhancing lithium diffusion.

5.2. PEDOT composites including carbon materials
Composite films of carbon nanotubes (CNTs)/PEDOT were prepared via electrochemical co-deposition from solutions containing acid treated CNTs and the corresponding monomer. CNTs served as the charge carriers during electro-deposition, and also acted as both the backbone of a three-dimensional micro-and nano-porous structure and the effective charge-balancing dopant within the polymer. All the composites showed improved mechanical integrity, higher electronic and ionic
conductivity (even when the polymer was reduced), and exhibited larger electrode specific capacitance and greater stability in charge–discharge cycling compared with the pure conducting polymers.

Moreover, transparent conductive films were fabricated using a composite of PEDOT and the acid-treated various CNTs by the bar coating method. The dispersion stability of acid-treated CNTs is very stable in PEDOT solution. Compared with the raw PEDOT film with a transmission of 87.8% and a sheet resistance of 1182 V/sq, electrical and optical properties of CNTs/PEDOT film was improved so that a sheet resistance of 249.2 V/sq and a transmission of 82.7% were obtained when the concentration of the t-MWNTs was 0.01 wt.%. In addition, these films showed robust flexibility and did not break down upon bending and folding in contrast with commercial films such as ITO. A further improvement in the various properties of the transparent conductive film, such as its electrical conductivity and optical transmission, should be possible by enhancing the degree of dispersion of the CNTs in the PEDOT solution. These CNT/PEDOT thin films may be obtained, permitting one to fabricate transparent electronic devices such as a flexible display, solar cell and sensors, etc. It will be able to lead to important advances in developments of flexible optoelectronic devices and especially to alternatives to approach for transparent and conductive coatings such as commercial ITO films.

The PEDOT/LiCoO$_2$–KB(Ketjenblack) cathodes were made by electrochemical deposition of 3,4-ethylendioxythiophene (EDOT) monomer on the pre-formed LiCoO$_2$–KB electrodes with 1 and 5 wt% of KB content. The PEDOT layer was successfully coated on the LiCoO$_2$ and KB components. Homogeneity of the KB component and the presence of conductive PEDOT layer were found to be important factors in controlling the cathode properties such as the involved capacity, cycle ability, intercalation/de-intercalation rate and rate capability. Electrochemical characterizations on the LiCoO$_2$–KB and PEDOT/LiCoO$_2$–KB cathodes suggested that incorporation of the conductive PEDOT into cathode enhanced the intercalation/deintercalation of Li ion and also the rate capability.

5.3. PEDOT composites with other polymers

PEDOT/polypyrrole(Ppy) composite electrodes were prepared by electropolymerization of EDOT on the surface of Ppy modified tantalum electrodes to obtain the PEDOT/Ppy composite with its rapid response like PEDOT while its specific capacitance and cost close to those of Ppy. The specific capacitance of composite electrodes, due to the synergic effect of PEDOT and Ppy, was much higher than the values of either pure PEDOT or pure Ppy electrodes. Moreover, the composites prepared on the surface of Ppy with horn-like structure allowed the specific capacitance up to more than 200 F g$^{-1}$ and had a good cycleability. This implies that PEDOT/Ppy composites are promising to be used as electrode material of supercapacitors.

In order to improve the repeatability of the responses on the PEDOT modified electrode, different kinds of surfactants were included into the polymer during the polymerization. The fouling effect was strongly alleviated when the polymerization of EDOT was carried out in the presence of poly(sodium 4-styrenesulphonate) (NaPSS). PEDOT:PSS composite films were successfully prepared by LB inducing deposition method. There is an intense electrostatic force between SO$_3$ functional group of PSS and NH$_3^+$ functional group of aliphatic amines. ODA–SA/PEDOT:PSS composite film had higher film-forming ability than ODA/PEDOT–PSS composite film. From the electrical conductivity investigation, this kind of composite LB film exhibited a very potential application for organic electronic devices and the research focusing on this aspect is underway now.

PEDOT/silk fibroin (SF) composite fibers were fabricated successfully and expediently by in situ polymerization without any modification of silk fibroin surface. SEM observation and elements analysis confirmed that PEDOT molecules had been coated successfully by such polymerization process without destroying SF in nature and the composite fibers still possessed their former fibrillar morphology and strength properties. Structural analysis (IR, XRD and DSC) implied that PEDOT molecules had different interactions to certain extent with SF chains. These composite fibers exhibited better electrical and thermal properties and may have potential applications in textile, biological and other novel functional materials.
Composite materials containing nanoparticulate PEDOT in a polymer electrolyte matrix (PEO) containing either a Cu–Cu$^{2+}$ or Fe$^{2+}$–Fe$^{3+}$ redox couples showed rapid and reversible decreases of up to 500-fold in their electrical and microwave impedances when small DC or AC electric fields were applied across coaxial line and strip samples from their edges, which were much larger than microparticulate PEDOT composites and made significant progress in this field$^{27}$. The composites showed large field-dependent resistances at low applied fields and good electrochemical stability. Changes in microwave impedance from $350 \Omega^{-1}$ at 0.01 V to $24 \Omega^{-1}$ at 12 V, both measured at 1 GHz proved unequivocally that the changes observed occurred in the bulk samples and not just in a region within the immediate vicinity of the electrode–composite interface.

6. PEDOT copolymers and their electrochromic devices

Copolymerization is a powerful tool to enhance the electrochemical, optical, and electrochromic properties of the parent homopolymers. To reduce its band gap, shorten switching time, enhance its capacity stability, many efforts were dedicated to copolymerize EDOT and other monomers and the copolymers were assembled into electrochromic devices and measured in many aspects as follows.

Copolymer of 4-(2,5-di(thiophen-2-yl)-1H-pyrrol-1-yl)benzenamine (SNS-NH$_2$) and EDOT was achieved in acetonitrile NaClO$_4$/LiClO$_4$ (0.1 M:0.1 M) solvent–electrolyte couple$^{28}$. Copolymer revealed multichromatic property with five different colors at different applied potentials. Colorimetry studies for P(SNS-NH$_2$-co-EDOT) proved that it is possible to provide fine tuning of these colors by varying applied potential during synthesis. The band gap of the copolymer was calculated as 1.7 eV and 0.6 s was found as the time required to attain 95% of the total transmittance difference. A dual-type complementary ECD was assembled with a configuration of ITO/P(SNS-NH$_2$-co-EDOT)/gel electrolyte/PEDOT/ITO and characterized for its performance. Suitable potential range for operating the device between purple to blue was found to be between -1.5 and +1.5 V. Electrochromic switching study results revealed that optical contrast (%)DT and switching time were 11% and 0.8 s at 491 nm, respectively. In addition, the device showed good open circuit memory and stability. Copolymer of SNS-NH$_2$ with EDOT can be thought as a feasible nominee for anodically coloring electrochromic layers in ECDs.

Electropolymerizations (EPs) of the mixed monomers of Th and EDOT in 0.05M Et$_4$NClO$_4$/propylene carbonate (PC) solution were performed to prepare polymer films$^{29}$. The incorporation of EDOT units into pure polythiophene (PTh) chain leads to large alternations on the experimental conditions of EPs and the properties of the resulting polymer films. The resulting copolymer films further served as cathode materials to test their applicability in lithium ion battery. With incorporation of EDOT units, the corresponding polymers showed the enhancement of reversibility compared to PTh, i.e. during the repeatedly positive and negative sweeps, no considerable overoxidation was observed. With varying scanning rate, PTh–EDOT copolymers also exhibited faster responses than PTh. Advantages of EDOT incorporation also reflects in the better capacity stability toward successive cycling. Almost 100% recovery on the capacity was observed for PTh–EDOT (1/1) copolymer, which is different from the 40% loss on PTh after 25 times of cycling.

The synthesis of a new copolymer utilizing 2,5-di(thiophen-2-yl)-1-p-tolyl-1H-pyrrole (DTTP) and EDOT was successfully achieved in ACN/LiClO$_4$/NaClO$_4$ (0.1 M) solvent–electrolyte couple$^{30}$. The copolymerization with EDOT not only decreases the band gap $E_g$, but also enhanced the electrochromic properties such as optical contrast and switching time. The copolymer has an electronic band gap of 1.65 eV. The contrast was measured as the difference between %T in the reduced and oxidized forms and noted as 20% at 487 nm. Then dual-type complementary colored polymer ECD were assembled with a configuration of ITO/P(NTP-co-EDOT)||gel electrolyte||PEDOT/ITO and electrochromic switching study results showed that its optical contrast (%)T and switching time were 18% and 1.5 s at 615 nm. In addition, the device has good environmental and redox stability.

1-benzyl-2,5-di(thiophen-2-yl)-1H-pyrrole (SNBS) and EDOT was electrochemically copolymerized$^{31}$. The resulting copolymer displayed exclusive color changes between claret red, yellow, green, and blue upon applied potential and a full switch in 1 s with an optical contrast of 40%.
As an application, absorption/transmission type electrochromic device with indium tin oxide (ITO)/copolymer/gel electrolyte PEDOT/ITO configuration was constructed, where copolymer and PEDOT functioned as the anodically and the cathodically coloring layers, respectively. Results implied the successive use of this copolymer in electrochromic device applications, since the device exhibited short switching times with a wide color variation upon applied potential.

7. Applications of PEDOT

Since PEDOT has so many excellent properties, it inspires much great interest of research and a wide range of potential applications. Its high conductivity and stability in the doped state cause it to be of major interest for applications such as antistatic and electrostatic coatings, for metallization of insulators, and as electrodes for capacitors or photodiodes. If the durability of the capacitors using PEDOT is enhanced, they will have a wider range of applications such as in electronic circuits for cars and man-made satellites. Due to its property of being repeatedly doped and de-doped, it is very attractive for electrochromic applications. With proper choice of counter-ions, PEDOT is also of interest for applications as an electrochemical actuator. PEDOT has been a successful commercial product due to the accessibility of the monomer and the possibility of producing the conducting material as a water dispersion by using a water-soluble polymeric counterion poly(styrene sulphonate). It has been extensively used as an antistatic coating on photographic films and as an electrode layer in flexible displays and organic light-emitting devices. Further progress has been achieved through recent studies on the application of PEDOT in the electrochemical field such as actuators, capacitors, OLED, photovoltaic cells, sensors etc.

7.1. Actuators

PEDOT has very high conductivity, particularly high stability in the doped state and the reversibility of the doping process. The expulsion/inclusion of ions during its doping/de-doping processes results in the dimensional change properties, leading to interesting potential applications in the design of actuator with large mechanical stress and strain values for robotics, prosthetics, microvalves. For trilayer actuators with the configuration of Ppy(DBS)/PEDOT(DBS)/Ppy(DBS), the addition of the PEDOT(DBS) layer produced significant improvements in the strain and force difference between reduced and oxidized states at faster scan rates without any negative effects or delamination. Additionally, the dispersion of PEDOT in the interpenetrating polymer networks (IPNs) of poly(ethylene oxide) and polybutadiene with a room temperature ionic liquid, 1-ethyl-3-methylimidazolium bis-(trifluoromethylsulfonyl)imide (EMITFSI) could enhance the actuation result of the actuator based on them. By adjusting the PEDOT mass quantity loaded in the conducting IPN, the electrical resistance along the surface was improved at least 1000 times compared with that in the bulk. Moreover, solid actuators were prepared based on PEDOT/NBR films with the absorption of room temperature ionic liquids (RTIL) including imidazolium salts, e.g. 1-butyl-3-methyl imidazolium X [where X=BF$_4$-, PF$_6$-, (CF$_3$SO$_2$)$_2$N$^-$] into the composite films. The PEDOT content was gradually decreased from the outside towards the center of the matrix film in order to yield a similar structure to that of an interpenetrating polymer network (IPN). The conformational effects of the polymer chains influenced their actuation and the displacement of the actuator increased with increasing the anion-size of the ionic liquids. The (CF$_3$SO$_2$)$_2$N$^-$-doped PEDOT actuator showed a large displacement with a maximum displacement generated electrically of 5.49 mm, which was much higher than that of the films doped with BF$_4$-(1.10 mm) or PF$_6$-(3.09 mm).

7.2. Capacitors

The highly stable polymer electrode material PEDOT is of particular interest for being used to develop high-performance supercapacitor owing to the combination of high energy density, high specific power density, lower cost, easy to be prepared and fabricated on needs. PEDOT electropolymerized in neat [bmim][BF$_4$] for actuators possessed nearly ideal capacitive characteristic of 130 F/g and
especially excellent level of stability with a long time of redox cycling up to 70,000 cycles, close to that of carbon electrode material with a general lifetime of 100,000 cycles. The developed Ta/PEDOT capacitor showed the advantages of high capacitance per unit volume, excellent frequency characteristics greatly improved in high-frequency range in comparison with Ta/MnO₂ one, as well as superior durability without any deterioration for more than 1000 h at 125°C in air and at 85°C/85%RH due to the environmental stability of PEDOT. Therefore, the commercialization of the Ta/PEDOT capacitor will give rise to further wide-ranging applications. Introduction of crosslinked HBPSi onto the aluminum oxide/PEDOT counter electrode for capacitor resulted in a large number of vinyl groups to improve the interfacial affinity between aluminum oxide and PEDOT so that it is effective in improving the capacitance and equivalent series resistance of the capacitor as compared with linear, vinyl terminated polydimethylsiloxanes. The specific capacitance of the PEDOT-PSS-RuO₂·xH₂O for supercapacitor increased with increasing loading of RuO₂·xH₂O particles embedded into the porous PEDOT-PSS matrix with a uniform dispersion and excellent incorporation and a maximum specific capacitance of 653 F/g was achieved.

7.3. Photovoltaic cell
Compared with the conventional electrodes such as expensive Pt or C with poor quality and relatively low conductivity, PEDOT:PSS has high room temperature conductivity, much better film-forming ability, relatively low cost, remarkable stabilities and the electronically catalytic activity, expected to have improved performances as the counter electrodes for dye-sensitized solar cells (DSSCs). PEDOT:PSS counter electrodes for highly transparent DSSCs with PMMA/PC gel polymer electrolyte showed similar I³⁻/I⁻ catalytic activities to Pt based counter electrodes. The best performance obtained gave a short circuit current of 2mAcm⁻² and an open circuit voltage of 625mV in quasi-solid-state construction assemblies and had a longer lifetime, which is a prerequisite for any future application. The transparent thin graphene/PEDOT:PSS film as a counter electrode in DSSC possessed high transmittance (>80%) at visible wavelengths and the high electrocatalytic activity of graphene and PEDOT:PSS. As a result, the DSSC with the counter electrode of graphene/PEDOT:PSS composite film containing 1 wt% or more graphene showed a high energy conversion efficiency of 4.5% under irradiation of 100mWAM 1.5 white light. Thus the high transmittance of the films provides them with potential applications in power-producing windows or metal-foil-supported DSSC. The conductivity of the PEDOT:PSS films treated with DMSO exhibited high conductivity of 85±15 S/cm due to the increased surface roughness. The DSSC using carbon black (0.1 wt%)-modified DMSO-PEDOT:PSS conductive coating as a counter electrode reached a cell efficiency of 5.81% under 100 mW/cm², which is attributed to the low charge-transfer resistance and the low Nernstian diffusion resistance.

7.4. OLED
PEDOT anodes for OLED substantially reduce the turn-on voltage and made current injection almost linear after turn-on, attributed to the reduced barrier at the organic-organic interface in PEDOT, the ‘ladder’ effect of stepping the band offset over several interfaces, and the favorable PEDOT film morphology. The benefit of the PEDOT anode is clearly seen in the improvement in device brightness and the high external quantum efficiency obtained. The best performance achieved for OLED based on Alq₃/TPD active regions with PEDOT:PSS as an anode layer yielded a brightness of 1720 cd/m² at 25 V, a turn-on voltage of 3 V, and electroluminescence (EL) efficiency and external quantum efficiency of 8.2 cd/A and 2%, respectively, at a brightness of 100 cd/m² and 5 V. The metal or semimetal properties of the MWCNTs might contribute to the improved electric properties of the nanocomposites of PEDOT:PSS and MWCNTs, which leads to the improvement of the OLEDs such as the improved luminance intensity and decrease of turn-on voltage. The appropriate mild oxygen plasma treatment of PEDOT:PSS layers could form uniformly distributed nanoislands on the surface of PEDOT:PSS layers, which may improve the contact between PEDOT:PSS anode buffer layer and hole transport layer, leading to improvement of device performance. The OLEDs with PEDOT:PSS after mild oxygen plasma treatment as anode buffer layer exhibited significantly enhanced lifetime and...
decreased driving voltage. An electrophilic addition reaction involving the PPV vinylene bond and protons from PEDOT:PSS occurred between PEDOT:PSS layer and PPV layer for OLED and PEDOT:PSS has a considerable effect on molecular dopants dispersed in the polymeric host. Defect states in an interface region between them were created by the interaction and resulted in a considerable quenching of the PPV photoluminescence so that the photoluminescence intensity of PPV in a working device under operating conditions can be quenched by at least 20% with respect to the intensity at zero applied volt. Chemical interactions between layers in the light-emitting device can result in the occurrence of additional quenching mechanisms that influence both the host polymer and molecular dopants dispersed in the host.

7.5. Sensors
PEDOT is an attractive candidate for sensing material in ion selective electrodes because it shows high selectivity toward the dopant ion in its oxidized state, a selectivity which depends more on the size of the ion than its lyophobicity. And PEDOT-based ion selective sensors are expected to deteriorate more slowly than other CP-based electrodes due to its environmental stability in the oxidized state. PEDOT was successfully used for sensing perchlorate in a new solid-state potentiometric sensor for perchlorate ion. Over the 8 month period of this study, the PEDOT(ClO$_4^-$) sensors exhibited a stable, linear response spanning at least five orders of magnitude in concentration (1M to 1×10$^{-5}$M perchlorate) with near-Nernstian slopes approaching -59 mV/decade of ClO$_4^-$ concentration and a limit of detection of 5×10$^{-6}$ M. The GC/PEDOT(CB$_{11}$H$_6$Br$_6^-$) electrode for sensors is sensitive to Ag$^+$ in the concentration range of 10$^{-1}$-10$^{-5}$ M AgNO$_3$ solutions with sub-Nernstian slope. A significant enhancement of the potentiometric response was achieved after the electrodes were pretreated maybe due to a decrease in the amount of elemental silver (Ag$^0$/Ag$^+$ ratio) present in the polymer film, thereby facilitating ion transfer at the polymer/solution interface. The electrode showed high selectivity to Ag$^+$ in comparison to many alkali-, alkaline-earth, and transition-metal cations except for Hg$^{2+}$. For simple pressure sensors based on polyimide membrane and a PEDOT/PSS strain sensor, an approximate value of 0.8 for the strain gauge factor could be derived from membrane mechanics, clearly demonstrating the potential of PEDOT/PSS as a mechanical sensor material and might lead to completely organic MEMS.

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