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Enhanced thermoelectric performance of PEDOT: PSS films via ionic liquid post-treatment

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Thermoelectric (TE) energy harvesting can effectively convert waste heat into electricity, which is a crucial technology to solve energy concerns. As a promising candidate for energy conversion, poly(3,4-ethylenedioxythiophene): poly (styrene sulfonate) (PEDOT:PSS) has gained significant attention owing to its easy doping, high transparency, and solution processability. However, the TE performance of PEDOT:PSS still needs to be further enhanced. Herein, different approaches have been applied for tuning the TE properties: (i) direct dipping PEDOT:PSS thin films in ionic liquid; (ii) post-treatment of the films with concentrated sulfuric acid (H_2SO_4), and then dipping in ionic liquid. Besides, the same bis(trifluoromethanesulfonyl)amide (TFSI) anion and different cation salts, including 1-ethyl-3-methylimidazolium ($EMIM^+$) and lithium (Li^+), are selected to study the influence of varying cation types on the TE properties of PEDOT:PSS. The Seebeck coefficient and electrical conductivity of the PEDOT:PSS film treated with H_2SO_4EMIM:TFSI increase simultaneously, and the resulting maximum power factor is 46.7 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$, which may be attributed to the ionic liquid facilitating the rearrangement of the molecular chain of PEDOT. The work provides a reference for the development of organic films with high TE properties.

Keywords: PEDOT:PSS, ionic liquid, thermoelectric performance

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1. Introduction

Approximately 90% of the world's energy is produced by burning fossil fuels. The world requirement for energy has led to a dramatic escalation of social and political turmoil. Furthermore, fossil energy technologies cannot meet the rapidly growing demand for electricity worldwide. The development of new energy conversion technologies is urgently needed to solve these problems. Thermoelectric (TE) material is a sort of green energy conversion material, which can directly realize the mutual conversion of heat energy and electric energy using the directional transport of charge carriers inside the material.[1–5] Domestic heating, automobile exhaust, and industrial processes generate large amounts of unutilized waste heat, which can be converted into electricity by a TE generator. In general, the performance of TE materials can be evaluated by both the figure-of-merit ZT value ($ZT = S^2\sigma T/\kappa$) and power factor ($PF = S^2\sigma$), where S and σ respectively represent the Seebeck coefficient and electrical conductivity of the material, T is the absolute temperature, and κ stands for the thermal conductivity.[6,7]

Recently, organic TE materials, such as polypyrrole (PPy),[8,9] polyaniline (PANI),[10,11] and poly(3,4-ethylenecdioxythiophene) (PEDOT),[12–16] have shown promise as competitive substitutes for inorganic TE materials due to their low toxicity, flexibility, and low thermal conductivity. Among organic TE materials, poly(4-styrenesulfonate)-doped PEDOT (PEDOT:PSS) has attracted extensive attention because of its easy doping, high transparency, excellent thermal stability, and solution processability.[17–19] However, the pristine PEDOT:PSS film has the disadvantage of σ lower than 1 $S{\cdot}cm^{-1}$, resulting in its power factor of only 0.01 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$.[20,21] Currently, there are varieties of ways to enhance the TE performance of PEDOT:PSS, including removing excess PSS,[22–24] optimizing PEDOT oxidation levels,[25–27] and regulating the order of the PEDOT molecular chain.[28,29] Luo *et al.*[22] reported that the σ of PEDOT:PSS films increased from 0.2 $S{\cdot}cm^{-1}$ to 90 $S{\cdot}cm^{-1}$ with dimethyl sulfoxide (DMSO) and ethylene glycol (EG) as secondary dopants, and the S did not change significantly. The increase in conductivity is due to the shielding effect caused by the polar solvent, which reduces the Coulomb interaction between PEDOT and counter-anion PSS. Li *et al.*[25] investigated the combination of polyethylenimine ethoxylated (PEIE) and sulfuric acid (H_2SO_4) to adjust the oxidation level of PEDOT:PSS and to improve the TE performance. Nonetheless, the regulation of oxidation level will not result in the simultaneous increase of S and σ, and the two always change in inverse proportion.

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Ionic liquids (ILs) have received particular attention due to their high thermal stability, unique structure, and electrochemical properties.[30,31] Especially, ILs combine the ion-exchange effect and the high-boiling solvent effect to provide σ enhancement while also improving S. Liu *et al.*[32] studied the simultaneous improvement of σ and S of PEDOT:PSS films with two kinds of 1-butyl-3-methylimidazolium (BMIM) cationic-based ILs as dopants. The increase in the Seebeck coefficient may be due to ion exchange reactions similar to inorganic salt additives.[33,34] Subsequently, Kee *et al.*[35] reported the composite films of PEDOT:PSS and a series of ILs based on the same 1-ethyl-3-methylimidazolium (EMIM) cation and revealed that ILs with small binding energy make the counter-ion exchange reaction thermodynamically stable in the mixed solution. The substitution of counter-ions alters the environment for molecular interaction around the PEDOT chain, resulting in molecular stacking and rearrangement, forming a highly ordered PEDOT chain with nanofibrillar structure, and promoting electron transfer. However, to our knowledge, the effect of PEDOT:PSS film post-treatment with ILs of different cations on its TE properties has not been explored yet.

In this work, the PEDOT:PSS film was prepared by direct dilution-filtration. To study the influence of different cation types on the TE properties of PEDOT:PSS, the same bis(trifluoromethanesulfonyl)amide (TFSI) anion and two other cation salts, including $EMIM^+$ and lithium (Li^+), were selected, as shown in Fig. 1. The effects of dipping ILs at various times on the TE performance of the PEDOT:PSS films before and after concentrated sulfuric acid treatment were investigated. The changes in the microstructure, electronic structure, and chemical composition of the films were detected by atomic force microscopy (AFM), ultraviolet-visible (UV-vis), and x-ray photoelectron spectroscopy (XPS), respectively. This work provides a reference for the development of organic films with high thermoelectric properties.

2. Experimental details

2.1. Materials

PEDOT:PSS (Clevios PH 1000) aqueous solution, anhydrous ethanol, and sulfuric acid (H_2SO_4; 98%) were obtained from HC Stark, Sinopharm Chemical Reagent Co. Ltd, and Xilong Chemical Co., Ltd., respectively. EMIM:TFSI and Li:TFSI were acquired from J&K Scientific Ltd.

2.2. Preparation of PEDOT:PSS film

PEDOT:PSS film was fabricated via the dilution-filtration method based on our previous report.[36] In short, anhydrous ethanol was selected as the dilution solvent, 200 μL PEDOT:PSS and 5 mL ethanol were mixed, and the PEDOT:PSS film was obtained by vacuum filtration of poly (vinylidene fluoride) membrane (pore size: 0.45 μW).

2.3. ILs post-treatment

EMIM:TFSI and Li:TFSI aqueous solutions with a concentration of 5 $g{\cdot}L^{-1}$ were prepared, and the PEDOT:PSS films were immersed in two solutions for different treatment time (1, 2.5, 5, and 10 min). Subsequently, after rinsing with deionized water three times, it was dried at 120 °C for 15 min.

To further promote the TE performance of the films, post-treatment of the filtering PEDOT:PSS films with concentrated sulfuric acid (H_2SO_4) for 15 min, after washing three times with deionized water, and then dipping in ionic liquid. The above ILs post-treatment steps were repeated.

2.4. Characterizations

The microstructure, electronic structure, and chemical composition of the as-prepared products were detected by AFM (Veeco Multimode, and Plainview, NY), UV-vis spectra (Agilent 8454 spectrophotometer), and XPS (Thermo Fisher Scientific: Escalab 250Xi), respectively. All characterizations were performed on PEDOT:PSS films dipped in ionic liquid for 2.5 min. The thickness of the sample was measured with a digital thickness gauge. The film thickness was 459.3 ± 25.5 nm. The S and σ of the PEDOT:PSS films were investigated with Keithley 2401 systems and the four-probe method. The Seebeck coefficient can be evaluated according to $S = -\Delta V/\Delta T$ (ΔT and ΔV respectively represent the temperature gradient and voltage difference of the films in the axial direction).

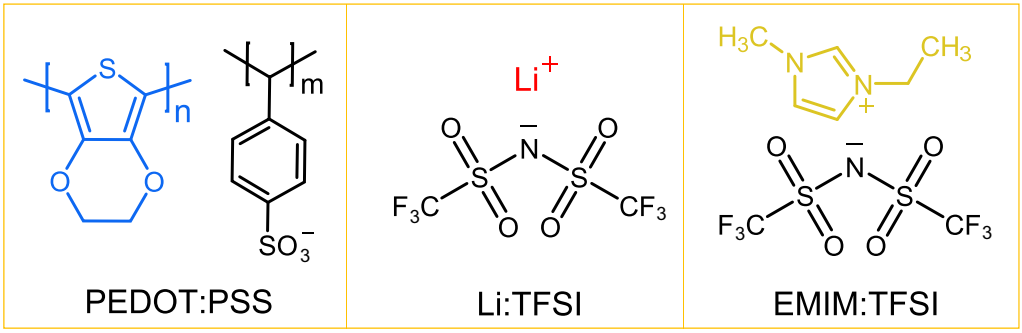


Fig. 1. Chemical structures of PEDOT:PSS and ILs.

3. Results and discussion

3.1. Material characterizations

The micromorphology of PEDOT:PSS film is characterized by AFM. The organic solvent makes the PEDOT:PSS film prepared by dilution-filtration to show good phase separation (Figs. 2(a) and 2(f)). The conductive particle distribution is relatively uniform (RMS = 1.55 nm), showing a relatively smooth film surface consistent with the previous report.[36] After Li:TFSI and EMIM:TFSI dipping, the surface of the corresponding films is flatter and smoother with reduced roughness of 1.35 nm and 1.42 nm, which may be attributed to PEDOT:PSS molecular chain rearrangement caused by the ionic liquid. The PEDOT:PSS film treated with H_2SO_4-Li:TFSI has a significant increase in roughness to RMS = 1.95 nm, and the surface of the film presents a fibrous structure with many fine particles (Figs. 2(d) and 2(i)). This is because the PSS enriched on the surface is partially removed after H_2SO_4 post-treatment, which leads to exposure of more PEDOT molecular chains.[37] H_2SO_4-EMIM:TFSI post-treated film (RMS = 1.94 nm) has similar roughness to the film after H_2SO_4-Li:TFSI treatment, while it can be seen from Figs. 2(e) and 2(j) that H_2SO_4-EMIM:TFSI post-treated PEDOT:PSS film has a more obvious aggregation of conductive PEDOT particles, which is beneficial to the transport of carriers.

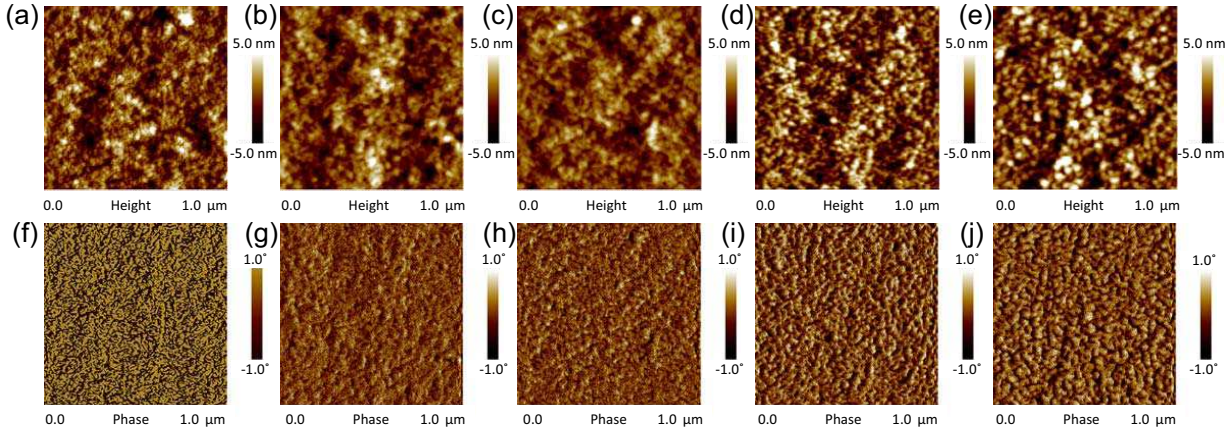


Fig. 2. AFM images of PEDOT:PSS nanofilms obtained by direct filtration (a), (f); TFSI:Li dipping (b), (g), EMIM:TFSI dipping (c), (h), H_2SO_4-TFSI:Li dipping (d), (i), and H_2SO_4-EMIM:TFSI dipping (e), (j). (a)–(e) topographic images and (f)–(j) phase images.

In addition to the investigation of AFM, UV-vis spectroscopy is another effective way to investigate the effect of ILs post-treatment. The two absorption bands at 195.8 nm and 226.4 nm in Fig. 3(a) are attributed to the electronic transitions of $-SO_3^-$ and C=C in PSS. The decrease in their strength indicates the loss of PSS of the PEDOT:PSS film.[38] Note that, a significantly decreased absorption intensity from PSS for H_2SO_4 post-treated PEDOT:PSS films is presented, illustrating the part removal of PSS from PEDOT:PSS thin films after post-treated with H_2SO_4. Interestingly, this phenomenon is more evident for H_2SO_4-TFSI:Li (H_2SO_4-EMIM:TFSI) post-treated PEDOT:PSS films, which may be attributed to the exchange of anions between ILs and PEDOT:PSS. Further, changes in the oxidation levels of PEDOT are also discovered in Fig. 3(b). The broad absorption peak in the near-infrared region is the bipolaron state of the PEDOT chain ($PEDOT^{2+}$), which can be gradually dedoping to the polaron state ($PEDOT^+$) with absorption at about 900 nm and the neutral state (PEDOT) with absorption at about 600 nm.[39] For the filtering PEDOT:PSS films, a broad absorption peak at the nearinfrared region is presented from the absorption of $PEDOT^{2+}$, but another absorption from $PEDOT^+$ can also be observed for the only ILs post-treated PEDOT:PSS thin films, meaning reduced oxidation level. Following, H_2SO_4 and H_2SO_4TFSI:Li treated PEDOT:PSS films exhibit both polaronic and neutral species. In contrast to this, the absorption behavior of PEDOT:PSS film after H_2SO_4-EMIM: TFSI treatment has no change. A possible explanation for these trends may be given by the characteristics of the cations used. Compared with EMIM cations, the monoatomic properties of Li cations lead to smaller sizes. Salts with small size and high cation mobility are expected to change molecular structure significantly.[40]

The changes of the surface chemical composition of the PEDOT:PSS films are studied by XPS. Survey scans (Fig. 4(a)) of the as-prepared samples show the presence of F, O, N, C, and S elements, and further, the N 1s intensity is higher for the films treated with EMIM:TFSI. This observation confirms the interaction between imidazolium cation and PEDOT:PSS. Furthermore, no TFSI anions remain in the films treated with EMIM:TFSI (TFSI:Li). The intensity of F 1s in Fig. 4(b) also confirms that the films treated with ILs have no residual anions. After H_2SO_4 treatment, the Coulomb interaction between PEDOT and PSS is weakened, making anion exchange easier. According to the intensity of F 1s, it can be inferred that the anion exchange degree of the film treated with H_2SO_4-TFSI:Li

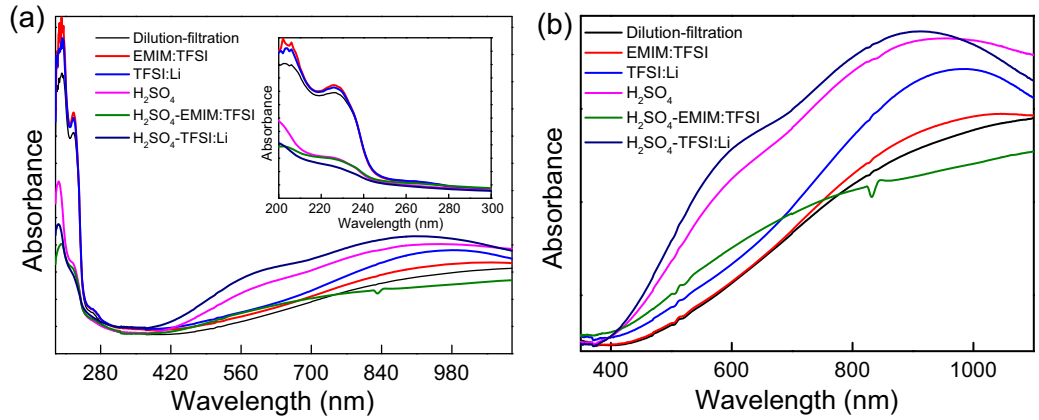


Fig. 3. UV-vis spectra of the PEDOT:PSS nanofilms with different dipping methods.

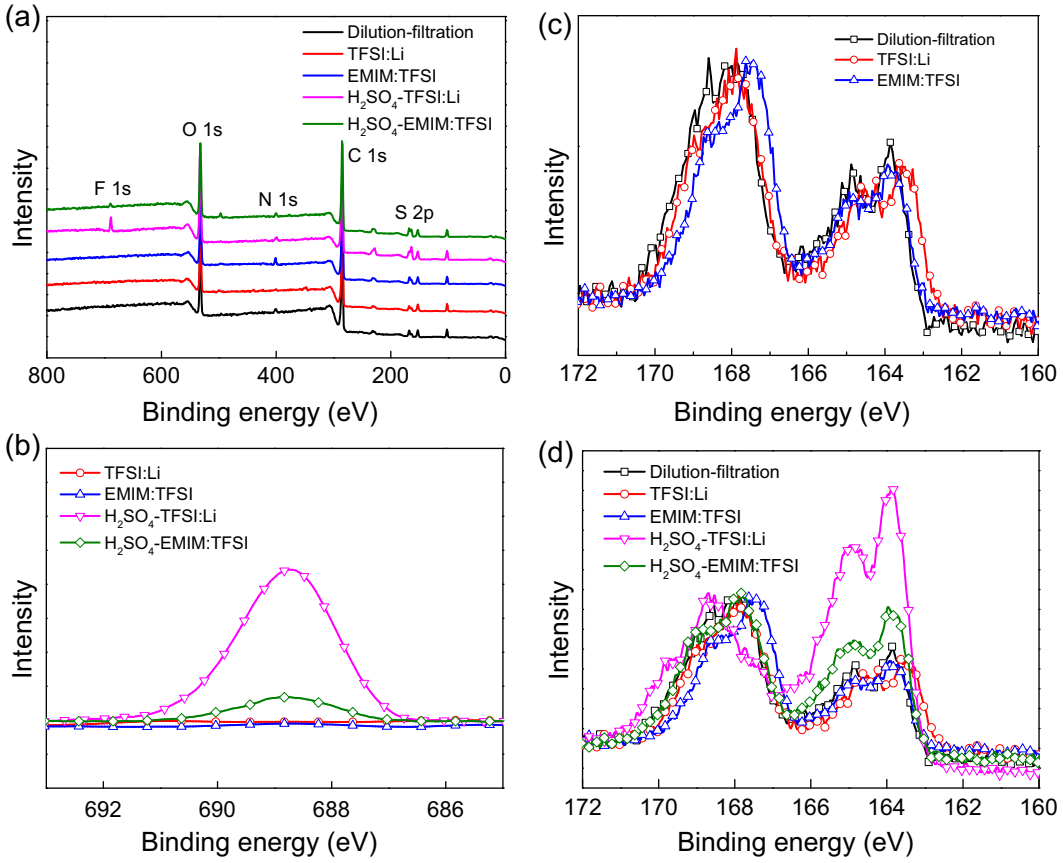


Fig. 4. XPS of the PEDOT:PSS nanofilms with different dipping methods. (a) XPS general scan; (b) F 1s spectra; and (c), (d) S 2p spectra.

is greater than that of the film treated with H_2SO_4-EMIM:TFSI, which may be due to the easy realization of effective anion exchange in the ILs composed of small cations.[41] Figures 4(c) and 4(d) show that the XPS peaks at $\sim$ 164.9 eV correspond to the S atoms in PEDOT, and higher binding energies at 168.2 eV and 169.3 eV correspond to the S atom in the PSS.[42,43] After the ionic liquid treatment, the proportion of PEDOT and PSS did not alter. Still, the peaks of PEDOT and PSS moved to the higher binding energy, suggesting the reduction in the doping level by ILs treatment, which is consistent with the results of UV-vis spectra. This shift has also been observed in the study of Yemata *et al.*[44] Compared with the one-step treatment with ILs, the PEDOT peak intensity of the films treated with H_2SO_4-EMIM:TFSI or H_2SO_4-TFSI:Li increases, indicating that the PSS is partially removed.

3.2. TE performance of PEDOT:PSS film

Figure 5 shows the TE properties of the films treated by TFSI:Li, EMIM:TFSI, H_2SO_4-TFSI:Li, and H_2SO_4-EMIM:TFSI, respectively. The ionic liquid treatment presents very similar results (Figs. 5(a) and 5(b)). The decrease of σ is accompanied by the increase of S, which is consistent with the reduction of oxidation level of PEDOT:PSS after ionic liquid post-treatment confirmed by UV-vis spectra. The power factor of the PEDOT:PSS films reaches the optimal value un-

der a specific oxidation state, and σ tends to decrease with the increase of S at a lower oxidation level, similar to the previous report.[45] At a dipping time of 2.5 min, the optimized power is 25.3 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$ for the TFSI:Li treated film and 21 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$ for the EMIM:TFSI. Additionally, the σ of PEDOT:PSS films after EMIM:TFSI post-treatment decreased first and then increased slightly. The increase in σ may be because the ionic liquid promotes the rearrangement of the PEDOT molecular chain.[40] To make the ILs interact with PEDOT:PSS more obviously, PEDOT:PSS films are pre-immersed with H_2SO_4. After H_2SO_4 treatment, the Coulombic effect between PEDOT and PSS is weakened, making it easier to achieve ion exchange. Subsequently, the σ of the film decreases remarkably after being treated in TFSI:Li and improves notably with the increase of the dipping time in Fig. 5(c). The best treatment time is 5 min, σ and S reach 1057 $S{\cdot}cm^{-1}$ and 18.9 $\mu V{\cdot}K^{-1}$, respectively. And the maximum power factor can achieve 40.2 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$, which is about two times higher than that without H_2SO_4 pretreatment. The simultaneous increase of σ and S for H_2SO_4-EMIM:TFSI treated PEDOT:PSS films is consistent with previous reports.[46,47] The maximum power factor is increased to 46.7 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$, which may be attributed to the IL facilitating the rearrangement of the molecular chain of PEDOT.

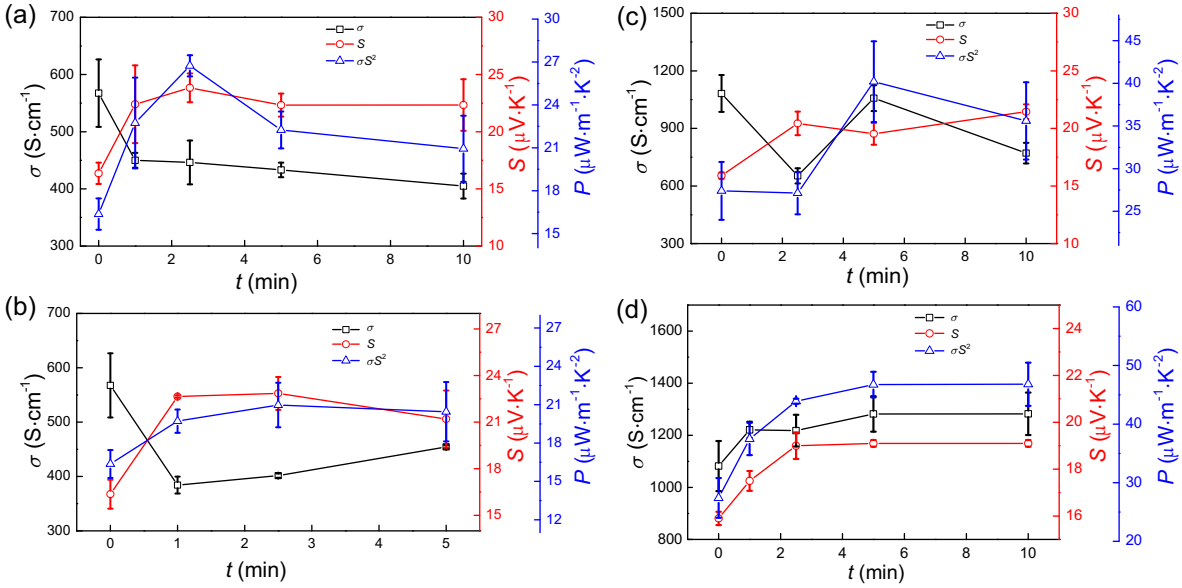


Fig. 5. TE performance of PEDOT:PSS nanofilms depending on the dipping time in TFSI:Li (a), EMIM:TFSI (b), H_2SO_4-TFSI:Li (c), and H_2SO_4-EMIM:TFSI (d).

4. Conclusions

In summary, PEDOT:PSS film was prepared via vacuum filtration and H_2SO_4 treatment. TFSI:Li and EMIM:TFSI with the same anion were selected as ionexchange agents to explore the effects of ILs with different cations on the TE properties of PEDOT:PSS. Further, the TE performance of the films depending on the dipping time at room temperature was measured. The results show that the influence of ILs on the TE properties of PEDOT:PSS is dissimilar due to the different degree of ion exchange between diverse cation types of ILs and PEDOT:PSS. Furthermore, the σ and S of the PEDOT:PSS film treated with H_2SO_4-EMIM:TFSI increase simultaneously, and the resulting maximum power factor is 46.7 $\mu W{\cdot}m^{-1}{\cdot}K^{-2}$. The current work will contribute to developing high-performance thin films and TE materials in the future.

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References

[1] He J and Tritt T M 2017 *Science* **357** 1369
[2] Snyder G J and Toberer E S 2008 *Nat. Mater.* **7** 105
[3] Jiang Q L, Sun H D, Zhao D K, Zhang F L, Hu D H, Jiao F, Qin L Q, Linseis V, Fabiano S and Crispin X 2020 *Adv. Mater.* **32** 2070335
[4] Li C C, Jiang F X, Liu C C, Liu P P and Xu J K 2019 *Applied Materials Today* **15** 543
[5] Li X, Wang T Z, Jiang F X, Liu J, Liu P, Liu G Q, Xu J K, Liu C C and Jiang Q L 2019 *J. Alloys Compd.* **781** 744
[6] Du Y, Chen J G, Meng Q F, Dou Y C, Xu J Y and Shen S Z 2020 *Vacuum* **178** 109384
[7] Zou Q, Shang H J, Huang D X, Li T G, Xie B W, Gu H W and Ding F Z 2021 *Soft Sci.* **1** 2
[8] Li M, Luo C, Zhang J, Yang J J, Xu J K, Yao W Q, Tan R R, Duan X M and Jiang F X 2020 *Surf. and Interfaces* **21** 100759
[9] Liang L R, Chen G M and Guo C Y 2017 *Mater. Chem. Front.* **1** 380
[10] Yang J J, Jiang Q L, Zhang J, Xu J K, Liu J, Liu P P, Liu G Q, Wang Y Y and Jiang F X 2020 *Synth. Met.* **269** 116546
[11] Wang L M, Yao Q, Xiao J X, Zeng K Y, Shi W, Qu S Y and Chen L D 2016 *Chem. Asian J.* **11** 1955
[12] Jia Y H, Liu C, Liu J, Liu C C, Xu J K, Li X J, Shen L L, Jiang Q L, Wang X D, Yang J and Jiang F X 2019 *J. Polym. Sci., Part B: Polym. Phys.* **57** 257

[13] Bubnova O, Khan Z U, Malti A, Braun S, Fahlman M, Berggren M and Crispin X 2011 *Nat. Mater.* **10** 429

[14] Wu M Y, Duan J S, Feng K, Yu H Y and Xu L 2021 *Org. Electron.* **90** 106068

[15] Xiong J H, Wang L Y, Xu J K, Liu C C, Zhou W Q, Shi H, Jiang Q L and Jiang F X 2016 *J. Mater. Sci.: Mater. Electron.* **27** 1769

[16] Wang X D, Meng F L, Tang H T, Gao Z M, Li S, Jin S, Jiang Q L, Jiang F X and Xu J K 2018 *Synth. Met.* **235** 42

[17] Fan Z and Ouyang J Y 2019 *Adv. Electron. Mater.* **5** 1800769

[18] Bubnova O, Khan Z U, Wang H, Braun S, Evans D R, Fabretto M, Hojati-Talemi P, Dagnelund D, Arlin J B, Geerts Y H, Desbief S, Breiby D W, Andreasen J W, Lazzaroni R, Chen W M, Zozoulenko I, Fahlman M, Murphy P J, Berggren M and Crispin X 2013 *Nat. Mater.* **13** 190

[19] Xu Y W, Jia Y H, Liu P P, Jiang Q L, Hu D H and Ma Y G 2021 *Chem. Eng. J.* **404** 126552

[20] Ouyang J Y 2013 *ACS Appl. Mater. Interfaces* **5** 13082

[21] Li Q K, Deng M J, Zhang S M, Zhao D K, Jiang Q L, Guo C F, Zhou Q and Liu W S 2019 *J. Mater. Chem. C* **7** 4374

[22] Luo J J, Billep D, Blaudeck T, Sheremet E, Rodriguez R D, Zahn D R, Toader M, Hietschold M, Otto T and Gessner T 2014 *J. Appl. Phys.* **115** 054908

[23] Kim J Y, Jung J H, Lee D E and Joo J 2002 *Synth. Met.* **126** 311

[24] Jiang F X, Xu J K, Lu B Y, Xie Y, Huang R J and Li L F 2008 *Chin. Phys. Lett.* **25** 2202

[25] Li X J, Liu C C, Zhou W Q, Duan X M, Du Y K, Xu J K, Li C C, Liu J, Jia Y H, Liu P P, Jiang Q L, Luo C, Liu C and Jiang F X 2019 *ACS Appl. Mater. Interfaces* **11** 8138

[26] Park H, Lee S H, Kim F S, Choi H H, Cheong I W and Kim J H 2014 *J. Mater. Chem. A* **2** 6532

[27] Feng K, Xu L, Xiong Y, Sun L, Yu H Y, Wu M Y, Thant A A and Hu B 2020 *J. Mater. Chem. C* **8** 3914

[28] Li Q K, Zhou Q, Wen L and Liu W S 2020 *J. Materiomics* **6** 119

[29] Wei Q S, Mukaida M, Naitoh Y and Ishida T 2013 *Adv. Mater.* **25** 2831

[30] Teo M Y, Kim N, Kee S, Kim B S, Kim G, Hong S, Jung S and Lee K 2017 *ACS Appl. Mater. Interfaces* **9** 819

[31] Li X, Liu Z, Zhou Z K, Gao H Y, Liang G D, Rauber D, Kay C W and Zhang P 2021 *ACS Appl. Polym. Mater.* **3** 98

[32] Liu C C, Xu J K, Lu B Y, Yue R R and Kong F F 2012 *J. Electron. Mater.* **41** 639

[33] Shu Y, Odunmbaku G O, He Y J, Zhou Y L, Cheng H L, Ouyang J Y and Sun K 2021 *Appl. Phys. Lett.* **118** 103902

[34] Fan Z, Du D H, Yu Z M, Li P C, Xia Y J and Ouyang J Y 2016 *ACS Appl. Mater. Interfaces* **8** 23204

[35] Kee S, Kim N, Kim B S, Park S, Jang Y H, Lee S H, Kim J, Kim J, Kwon S and Lee K 2016 *Adv. Mater.* **28** 8625

[36] Xiong J H, Jiang F X, Zhou W Q, Liu C C and Xu J K 2015 *RSC Adv.* **5** 60708

[37] Kim N, Kee S, Lee S H, Lee B H, Kahng Y H, Jo Y R, Kim B J and Lee K 2014 *Adv. Mater.* **26** 2268

[38] Fan Z, Li P C, Du D H and Ouyang J Y 2017 *Adv. Energy Mater.* **7** 1602116

[39] Saxena N, Pretzl B, Lamprecht X, Biessmann L, Yang D, Li N, Bilko C, Bernstorff S and Muller P 2019 *ACS Appl. Mater. Interfaces* **11** 8060

[40] Li X, Liu Z, Zhou Z K, Gao H Y, Liang G D, Rauber D, Kay W M and Zhang P 2020 *ACS Appl. Polym. Mater.* **3** 98

[41] Yamashita Y, Tsurumi J, Ohno M, Fujimoto R, Kumagai S, Kurosawa T, Okamoto T, Takeya J and Watanabe S 2019 *Nature* **572** 634

[42] Lee H M, Anoop G, Lee H J, Kim W S and Jo J Y 2019 *RSC Adv.* **9** 11595

[43] Jiang Q L, Lan X Q, Liu C C, Shi H, Zhu Z Y, Zhao F, Xu J K and Jiang F X 2018 *Mater. Chem. Front.* **2** 679

[44] Yemata T A, Zheng Y, Kyaw A K K, Wang X Z, Song J, Chin W S and Xu J W 2020 *RSC Adv.* **10** 1786

[45] Lee S H, Park H, Kim S, Son W, Cheong I W and Kim J H 2014 *J. Mater. Chem. A* **2** 7288

[46] Jonathan A, Matthew R B, James M G and Matthew J C 2020 *Polymers* **12** 559

[47] Yun D J, Jung J, Kim K H, Ra H, Kim J M, Choi B S, Jang J, Seol M and Jeong Y J 2021 *Appl. Surf. Sci.* **553** 149584