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ARTICLE

Poly(vinylidene fluoride) nanofibrous mats with covalently attached SiO₂ nanoparticles as ionic liquid host: enhanced ion transport for electrochromic device and lithium-ion battery

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In this article, it is demonstrated that electrospun poly(vinylidene fluoride-co-hexafluoropropylene) (P(VDF-HFP)) nanofibrous mat functionalized with (3-aminopropyl)triethoxysilane is a versatile platform for fabrication of hybrid nanofibrous mats by covalently attaching various types of inorganic oxide nanoparticles on the nanofiber surface via sol-gel process. In particular, SiO₂-on-P(VDF-HFP) nanofibrous mat synthesized using this method is an excellent ionic liquid (IL) host for electrolyte applications. The IL-based electrolytes in the form of free-standing mats are obtained by immersing the SiO₂-on-P(VDF-HFP) mats in two types of liquid electrolytes, namely LiClO₄/1-butyl-3-methylimidazolium tetrafluoroborate and bis(trifluoromethane)sulfonimide lithium salt/1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide, respectively. It is found that the surface attached SiO₂ nanoparticles can effectively serve as salt dissociation promoters by interacting with the anions of both ILs and lithium salts through Lewis acid-base interactions. They dramatically enhance the ionic conductivity and lithium transference number of the electrolytes. In addition, better compatibility of the electrolytes with lithium electrode is also observed in the presence of surface-attached SiO₂. Using IL-loaded SiO₂-on-P(VDF-HFP) nanofibrous mats as the electrolytes, electrochromic devices display higher transmittance contrast, while Li/LiCoO₂ batteries show significantly improved C-rate performance and cycling stability. This class of novel non-volatile electrolytes with high ionic conductivity also has the potential to be used in other electrochemical devices.

1. Introduction

Room-temperature ionic liquids, a class of ionic materials having melting points lower than 25 °C, have attracted much attention over the past decade.^{1, 2} The development of ionic liquid (IL)-based electrolytes has been recognized as a viable solution to the safety problems faced by a range of electrochemical devices, including fuel cells, lithium ion batteries, supercapacitors and electrochromic devices.³⁻⁷ The attractiveness of the ILs for the use in electrolytes lies upon their non-flammability and non-volatility as well as excellent electrochemical and thermal stability.⁸ Meanwhile, ILs are frequently doped with lithium salts to compensate for their large ion size to further improve the device performance.⁹ However, the potential problem caused by the liquid nature of the ILs, such as leakage, is considered as one of the critical factors limiting the long-term performance and practical use of the ILs. Thus, IL-based gel polymer electrolytes (GPEs), which consist of IL immobilized in a

polymer matrix, is an attractive alternative to the IL-based liquid electrolytes.¹⁰⁻¹³ Among many IL-based polymer electrolytes, IL-loaded electrospun mats have garnered increasing interest because in the mats there are interconnected pores between the randomly laid fibers, which facilitate electrolyte uptake and transport of ions.^{14, 15} Nevertheless, the IL-loaded electrospun polymer mats also have some inherent limitations, namely, they have relatively weak mechanical strength, and their ionic conductivity and lithium-ion mobility are significantly lower than that of the traditional liquid electrolytes.

To address the aforementioned shortcomings of the IL-based polymer electrolytes, vigorous efforts have been undertaken, among which an effective approach is to incorporate inorganic fillers, such as SiO₂,¹⁶ TiO₂¹⁷ and polyhedral oligomeric silsesquioxane (POSS)¹⁸ into the electrospun polymer nanofibers. It has been reported that these nanofillers can facilitate the dissociation of both ILs and lithium salts by Lewis acid-base interactions, giving enhanced ionic

conductivity and lithium-ion mobility.¹⁸⁻²¹ The addition of the nanoparticles also leads to enhanced mechanical property and compatibility with the lithium electrode.^{22, 23} Using this approach, the active fillers are, however, mainly embedded in the IL-swollen nanofibers and hence not directly accessible to liquid electrolytes in the pores, whereas the liquid phase is the major contributor to the overall ion transport properties.²⁴ Thus, a more appealing strategy is to attach inorganic nanoparticles on the surface of the nanofibers. This would allow the nanoparticles to have extensive Lewis acid-base interactions with the ionic species in the liquid electrolytes in the pores, and further improve the ionic conductivity and lithium electrode/electrolyte interfacial stability. Indeed, Yanilmaz *et al.* reported a method to produce SiO₂-on-poly(vinylidene fluoride) (PVDF) nanofibrous hybrid mats by combining electrospinning with electrospinning techniques, which allowed SiO₂ nanoparticles be physically attached onto electrospun PVDF mats.²⁵ The obtained hybrid mats showed higher ionic conductivities, lower interfacial resistance with lithium electrode and better C-rate performance in Li/LiFeO₄ batteries compared with that of neat PVDF mats.

In this article, for the first time we report a novel approach to grow SiO₂ nanoparticles on ethoxysilane-functionalized surface of electrospun poly(vinylidene fluoride-co-hexafluoropropylene) (P(VDF-HFP)) nanofibrous mats. This gives covalently attached SiO₂ nanoparticles uniformly distributed on the P(VDF-HFP) nanofiber surface (SiO₂-on-P(VDF-HFP)), preventing de-bonding at the fiber-nanoparticle interface during long-term cycling of electrochemical devices. To demonstrate the unique advantages of such novel organic-inorganic core-shell hybrid nanofibers, the SiO₂-on-P(VDF-HFP) nanofibrous mats were used as the hosts for two types of ILs doped with lithium salts, namely LiClO₄/1-butyl-3-methylimidazolium tetrafluoroborate (BMIM⁺BF₄⁻) and bis(trifluoromethane)sulfonimide lithium (LiTFSI)/1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide (PYR₁₄⁺TFSI⁻). The former was applied in electrochromic devices, while the latter was employed in lithium-ion batteries. Herein, we demonstrate that with optimized SiO₂ content, the mechanical strength, ionic conductivity and lithium transport property of the electrolytes all exhibit substantial enhancements, and both the electrochromic device and lithium ion battery show significantly improved performance. Furthermore, the synthesis method presented here is generic. The ethoxysilane groups grafted on the nanofiber surface can also facilitate the growth of many other types of oxide nanoparticles such as Al₂O₃, ZnO and TiO₂ via sol-gel process, and the obtained hybrid materials may be used for a wide variety of applications.

2. Experimental

2.1. Materials

LiClO₄, BMIM⁺BF₄⁻, LiTFSI, PYR₁₄⁺TFSI⁻, 1,3-diaminopropane, (3-aminopropyl)triethoxysilane (APTES), tetraethoxysilane (TEOS), aniline, 4-dodecylbenzene sulfonic acid (DBSA), titanium butoxide, xylene, N,N-dimethylformamide (DMF), ethanol and acetone were obtained from Sigma-Aldrich Corporation (USA). LiClO₄ was dried in vacuum at 100 °C for 24 h prior to usage. P(VDF-HFP) powder (solef 11008, M_w = 115,000) was purchased from Solvay Solexis Inc. (USA) and used as received. DBSA-doped polyaniline (PANI)-TiO₂ hybrid was prepared via a sol-gel process involving the reaction of titanium butoxide and a hybrid bridging compound, followed by oxidative emulsion copolymerization of aniline in the presence of the hybrid gel and DBSA.²⁶ Conducting indium tin oxide (ITO) glass (5-15 Ω □⁻¹) were purchased from Delta Technologies Co. (USA) and cleaned by ultrasonication in a series of solvents

including detergent, deionized water and acetone for 10 min each prior to usage.

2.2. Preparation of SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats

Chemically cross-linked electrospun P(VDF-HFP) mats with 1 wt% 1,3-diaminopropane were prepared according to our previous publication.⁶ A two-step method was adopted to attach SiO₂ nanoparticles on the surface of the P(VDF-HFP) nanofibers. In the first step, silane groups were grafted onto the fiber surface by immersing the electrospun mats in 5 wt% APTES ethanol solution at 70 °C for 1, 3, 5 and 10 h, respectively. The product obtained was denoted as silane-on-P(VDF-HFP). In the second step, the silane-on-P(VDF-HFP) nanofibrous electrospun mats were transferred into TEOS, DI water and ethanol solution with the molar ratio of 1: 3: 8.5 under vigorous shaking. NH₄OH was added dropwise to achieve a final pH value of 11. The above process was conducted for 0.5, 1, 3, 5 and 10 h, respectively to achieve different SiO₂ contents. After thoroughly washing with ethanol and deionized water, the SiO₂-attached electrospun mats were dried at 60 °C under vacuum. The product obtained was denoted as SiO₂-on-P(VDF-HFP). The SiO₂ contents in the final mats were calculated based on the weights of the electrospun mats before and after SiO₂ attachment.

2.3. Preparation of IL-based polymer and hybrid electrolytes

The IL-based electrolytes were obtained by soaking the electrospun mats with and without SiO₂ in BMIM⁺BF₄⁻ and 1 mol kg⁻¹ LiClO₄/BMIM⁺BF₄⁻ solutions for 12 h at 60 °C, respectively. The mats were then placed onto a piece of cellulose paper and pressed by 20 g weight to absorb excess IL. The electrolyte uptake (ϵ) was calculated using equation (1)

$$\epsilon(\%) = \frac{M - M_0}{M_0} \times 100 \quad (1)$$

where M_0 is the mass of dry electrospun mats and M the mass after soaking with IL electrolytes.

2.4. Characterization

The Raman spectra of the electrospun mats were taken using a Witec confocal Raman spectrometer with an excitation light of 488 nm. Fourier transform infrared (FTIR) spectra were obtained using the attenuated total reflection (ATR) attachment on a Perkin Elmer Spectrum GX FTIR spectrometer with a wave number range from 600 to 4000 cm⁻¹. Wide angle X-ray diffraction (WAXD) patterns of the electrospun mats were recorded on a Bruker GADDS X-ray diffractometer using Cu K α radiation (λ = 0.154 nm) generated at 40 kV and 40 mA. The morphologies of the electrospun nanofibrous mats were investigated using a field-emission scanning electron microscope (FESEM, JEOL 7600F). Tensile tests were performed on Instron Tester 5567 with a 500 N load cell at a crosshead speed of 5 mm min⁻¹. Dumb-bell-shaped specimens were prepared according to the ASTM D638 standard with dimensions of 25 mm × 3.2 mm × 0.1 mm. Each reported value was the average of five specimens.

The ionic conductivities were determined by AC impedance spectroscopy in the frequency range of 10⁵-10 Hz using the cell inserted electrolytes into parallel stainless steel electrodes. Lithium transference numbers (T_{Li^+}) were measured using the method of chronoamperometry in the Li/electrolytes/Li cells with a polarization voltage of 30 mV (ΔV) according to our previous publication.¹⁸ In brief, the initial current, I_0 , and the steady-state current, I_{ss} , that flowed through the cell were measured. The same cell was also

monitored by impedance spectroscopy in frequency range of 10^6 – 10^{-1} Hz to obtain the initial, R_0 , and the steady-state, R_{ss} , Li/electrolyte resistance. The lithium transference numbers (T_{Li+}) were given by equation (2)

$$T_{Li+} = \frac{I_{ss}(\Delta V - R_0 I_0)}{I_0(\Delta V - R_{ss} I_{ss})} \quad (2)$$

The interface resistance (R_{int}) between the IL-loaded electrospun mats and lithium-metal electrode were examined using the impedance response of the Li/electrolytes/Li cells.

2.5. Fabrication and testing of electrochromic device

PANI-TiO₂ emulsion in xylene was spin-coated onto cleaned ITO-coated glass to form thin film. Single-active-layer electrochromic devices with configuration of ITO glass/electrochromic layer (PANI-TiO₂)/electrolyte/ITO glass were fabricated. The visible transmittance spectra and switching kinetics of the devices were recorded on a UV-vis spectrophotometer (Shimadzu UV-2501 PC), by applying constant potentials and square-wave potentials using the Autolab PGSTAT 302 potentiostat/galvanostat analyzer, respectively. The switching kinetics of the devices was determined at the wavelength of 650 nm (λ_{max}), at which maximum transmittance contrast was achieved under the constant potentials. For the dynamic switching, the potential was stepped between -2.0 V and +2.0 V with step intervals of 40 s.²⁷

2.6. Assembly and testing of lithium-ion battery cathode

A standard CR2032 coin cell with lithium metal as counter electrode was used for testing the electrochemical properties of the cathode. The working electrode was prepared by spreading a mixture of LiCoO₂ (80 wt%), Super-P (10 wt%) and PVDF (10 wt%) dispersed in N-methyl pyrrolidone (NMP) onto an aluminium foil current collector. IL-based electrolytes were prepared by soaking commercial Celgard 2325 membrane, neat P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous electrospun mats in 0.3 mol kg⁻¹ LiTFSI/PYR₁₄⁺TFSI⁻ for 24 h in an argon filled glove box. The electrochemical tests were performed on a NEWARE-CT3008 battery test system (Neware Technology Limited, Shenzhen, China). The cells were cycled between 2.8–4.2 V vs Li⁺/Li.

3. Results and Discussion

3.1. Structures and morphologies of the SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats

Scheme 1 shows the route for preparation of SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats. To grow SiO₂ nanoparticles on the P(VDF-HFP) nanofiber surface, the fibers were firstly treated with an amine-terminated silane (APTES). Owing to the strong polarity of C-F bond, nucleophiles such as amines, phenols and thiolene are effective reagents for the introduction of functional groups onto fluoropolymer main chains.²⁸ As shown in Scheme 1, the reaction with APTES creates C=N double bond, leading to covalent tethering of APTES onto P(VDF-HFP). Raman spectra are used to verify the reaction. As illustrated in Fig. 1a, neat P(VDF-HFP) has no Raman signal in the range of 2000–1000 cm⁻¹.²⁹ By contrast, new bands corresponding to C=N and C-N stretching vibration appear at 1541 and 1141 cm⁻¹ after silane attachment, signifying the covalent tethering of APTES on the surface of the nanofibers. Fig. 1b shows the FTIR spectra of P(VDF-HFP), silane-on-P(VDF-HFP) and SiO₂-on-P(VDF-HFP) nanofibrous mats, respectively. The absorption band at 1640 cm⁻¹ for both Silane-on-P(VDF-HFP) and SiO₂-on-

P(VDF-HFP) can be attributed to C=N stretching vibration, which is in accordance with the Raman spectra. In addition, by comparing the spectra of P(VDF-HFP) before and after modification, the intensity of the broad band centred at 1070 cm⁻¹ clearly increases for SiO₂-on-P(VDF-HFP) (using C-F symmetric stretching band at 879 cm⁻¹ as reference). This is due to the overlap of band from F-C-F symmetric stretching vibration (at 1072 cm⁻¹)³⁰ and the band from Si-O-Si antisymmetric stretching vibration (at 1070 cm⁻¹),³¹ indicating the successful attachment of SiO₂ on the fiber surface. WAXD studies were also performed to investigate the structures of the hybrid mats. As illustrated in Fig. S1†, no diffraction peak corresponding to crystalline SiO₂ phase is observed for all the hybrid mats, indicating the amorphous nature of the attached SiO₂ nanoparticles.

Fig. 2a shows that with the attachment of SiO₂ nanoparticles, the nanofibrous mat retains its flexibility. FESEM studies indicate that the attachment of SiO₂ does not block the interpenetrating pores of the mats (Fig. 2b). Most SiO₂ nanoparticles have size of 10–20 nm, while the slightly larger ones are likely to be the aggregates of the smaller ones as they have irregular shapes. These nanoparticles are uniformly distributed on the fiber surface (Figs. 2c, 2d, 2e). By contrast, without the APTES treatment, relatively smooth fiber surface (Fig. S2a†) is observed for the neat P(VDF-HFP) electrospun mats after the sol-gel process, and FTIR spectrum shows no SiO₂ signal (Fig. S2b†). The combination of FESEM and FTIR studies confirms that the attachment of APTES on the fiber surface is an indispensable step to effectively grow covalently bonded SiO₂ nanoparticles on the fiber surface. Cross-sectional SEM micrographs for the hybrid nanofibers are provided in Fig. S3†. It shows the thickness of the SiO₂ layer on the P(VDF-HFP) nanofiber surface is approximately 10–20 nm. More FESEM images taken from the SiO₂-on-P(VDF-HFP) mats with different SiO₂ contents are provided in Fig. S4†. The SiO₂ contents in the hybrid mats for different silane (APTES) grafting time and sol-gel processing time are also presented in Fig. S5†.

3.2. Mechanical properties of the SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats

Since the hybrid electrolytes must withstand the forces applied during device fabrication and cycling stress, their mechanical properties are important parameters in determining their long-term performance. The apparent Young's modulus and tensile strength of SiO₂-on-P(VDF-HFP) nanofibrous mats with different SiO₂ contents are shown in Fig. 3. Both apparent Young's modulus and ultimate tensile strength show a sharp increase at the SiO₂ content of 12.6 wt%, which is presumably due to the load transfer from the polymer fibers to inter-connected SiO₂ nanoparticles. The apparent tensile strength decreases with the further increase of SiO₂ content, which can be explained by the increased brittleness, causing a decrease in strain at break. It is worth noting that at similar SiO₂ loadings, the apparent modulus values of the SiO₂-on-P(VDF-HFP) mats are significantly higher than that of the hybrid mats prepared by simply incorporating SiO₂ nanoparticles into polymer nanofibers.^{16, 32, 33}

3.3. Effects of SiO₂ on ionic conductivity and salt dissociation

Table 1 summarizes the electrolyte uptake and ionic conductivity of SiO₂-on-P(VDF-HFP) nanofibrous mats after loading with BMIM⁺BF₄⁻ and LiClO₄/BMIM⁺BF₄⁻, respectively. The electrolyte uptake is due to swelling of the polymer and filling the pores of the mats by the ILs. For the SiO₂-on-P(VDF-HFP) nanofibrous mats loaded with neat IL, both the electrolyte uptake and ionic conductivity increase with SiO₂ content up to 1.4 wt%, followed by a drop. The increased electrolyte uptake can be attributed to the large

surface area and hydrophilic nature of SiO₂ nanoparticles, which help to trap more liquid electrolyte. The subsequent decrease of electrolyte uptake can be explained by the decreased porosity resulting from larger fiber diameters. The highest ionic conductivity of 7.8 mS cm⁻¹ is achieved at 1.4 wt% SiO₂ content, which is much higher than that of neat BMIM⁺BF₄⁻ (3.5 mS cm⁻¹).³⁴ The -OH groups on the SiO₂ surfaces can act as Lewis acid centres, interacting with the anions (BF₄⁻) of the IL through Lewis acid-base interaction, and hence leading to enhanced dissociation of the IL and more free ions. The combination of the increased electrolyte uptake and increased number of free ions leads to the significant improvement of ionic conductivity.

FTIR spectroscopy is used to verify the interactions between BF₄⁻ and -OH groups on the SiO₂ surfaces. As shown in Fig. 4, the triplet bands at 1058, 1039 and 1022 cm⁻¹ in neat BMIM⁺BF₄⁻ are ascribed to the antisymmetric B-F stretching vibration.³⁵ The triplet bands shift to lower frequencies for the IL-loaded electrospun P(VDF-HFP) mats, which is presumable caused by the complexation of the polymer backbone with the IL. Moreover, it is clearly visible that the triplet bands further shift to 1047, 1034 and 1017 cm⁻¹, respectively, for the IL-loaded electrospun mats with SiO₂. A lower wavenumber indicates relatively stronger interactions, signifying the formation of Lewis acid-base interaction between hydroxyl groups of SiO₂ and BF₄⁻ anions. This favourable interaction promotes the dissociation of the IL, and results in improved ionic conductivity demonstrated earlier.

In order to address the low ion mobility issue caused by the large cation size of the ILs, LiClO₄ was introduced into BMIM⁺BF₄⁻. The electrolyte uptake of SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats shows the same trend as those loaded with neat BMIM⁺BF₄⁻, whereas the ionic conductivity monotonically increases with SiO₂ content. The mat with 15.4 wt% SiO₂ exhibits the highest ionic conductivity of 8.6 mS cm⁻¹, which is comparable to that of traditional organic solvent-based electrolytes.¹⁶ For the mats with 1.4 wt% and lower SiO₂ content, the introduction of LiClO₄ into BMIM⁺BF₄⁻ leads to slight decrease in conductivity. This is due to the formation of stiffer ionic aggregates, provoking an increase in viscosity and a diminution in the self-diffusion coefficients and conductivity.³⁶ For the mats with higher SiO₂ content, the conductivity increases with the incorporation of LiClO₄. The enhanced conductivity at higher SiO₂ content is due to increased salt dissociation, as the larger amounts of hydroxyl groups effectively interact with both types of anions (ClO₄⁻ and BF₄⁻), breaking the interactions between the ion pairs and boosting the concentration of free conducting ions. Additionally, the addition of the lithium salt increases charge density, and hence requires more active functional groups to effectively interact with them, which explains the monotonic increase of conductivity with SiO₂ content. The above results demonstrate that the surface-tethered SiO₂ is very effective in improving the ionic conductivity of the IL-based electrolytes.

To obtain direct evidence for the interactions between ClO₄⁻ and -OH group on the SiO₂ surfaces, Raman spectroscopy is conducted. As shown in Fig. 5, a band at 934 cm⁻¹ is accompanied by a shoulder on the high frequency side (942 cm⁻¹), which are attributed to the symmetric stretching vibration of ClO₄⁻. The former arises from free ClO₄⁻ anions, while the latter originates from contact-ion pairs or the ClO₄⁻ anions bound with -OH group of SiO₂.³⁷ The intensity of the shoulder peak at 942 cm⁻¹ clearly increases after the incorporation of SiO₂. The increase in the high frequency component reveals that the -OH groups on SiO₂ surfaces function as Lewis acidic centres, interacting with ClO₄⁻ anions through Lewis acid-base interactions. The interaction of ClO₄⁻ anions with SiO₂ promotes the dissociation of LiClO₄ and thus frees up Li⁺ ions.

To confirm the effect of SiO₂ on the migration of Li⁺ ions in the electrolytes, their lithium transference numbers (T_{Li^+}) were measured using DC polarization method combined with impedance techniques. Fig. 6 shows the current-time data and impedance spectra for LiClO₄/BMIM⁺BF₄⁻ loaded in neat P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) mats, respectively. The current flowing through the cell drops sharply within a few minutes, and then decreases gradually with time. The resistance of Li/electrolyte interface is obtained from impedance spectra, and T_{Li^+} values are calculated using equation (2). With the incorporation of SiO₂, the T_{Li^+} value increases from 0.25 to 0.41, which is due to the improved lithium salt dissociation as discussed above. However, this increase is not as significant as that of ionic conductivity because the hydroxyl groups interact with both types of anions (ClO₄⁻ and BF₄⁻), facilitating the transport of both BMIM⁺ and Li⁺ cations. Thus BMIM⁺ transference number may also increase, affecting the degree of enhancement in T_{Li^+} value.

3.4. Performance of the electrolytes in electrochromic devices

Electrochromic devices have found a wide range of applications including smart windows and display panels owing to their energy-saving potentials. However, the problems associated with solvent volatility and electrolyte leakage would cause safety concerns and lead to poor long-term durability.³⁸ Thereby, to make electrochromic devices safer and more durable, the choice of the electrolyte is crucial. IL-based electrolytes stand out in this regard due to their unique advantages. Additionally, in order to fabricate electrochromic device capable of delivering higher optical contrast, lithium salt is commonly introduced into IL-based electrolytes, which greatly facilitates the doping and dedoping process of the electrochromic layer due to its much smaller ion size.⁹ To demonstrate the effects of attaching SiO₂ on P(VDF-HFP) on the performance of the IL-based electrolytes, devices using P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻ and SiO₂ (15.4 wt%)-on-P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻ as electrolytes, respectively, were fabricated and tested under the same conditions. Fig. 7 shows the switching behaviours of the devices under the applied step potential between +2.0 V and -2.0 V at the wavelength of 650 nm (λ_{max} , at which maximum transmittance contrast was achieved under constant potentials). The device with SiO₂-on-P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻ electrolyte exhibits transmittance contrast of 72 %, which is 20 % higher than that with P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻. The higher contrast achieved may be attributed to the increased number of free ions, especially Li⁺ ions. Consequently, more ions can easily diffuse into the active layer and more active units can be effectively switched.

3.5. Performance of the electrolytes in lithium-ion batteries

IL-based electrolytes are presently considered as promising materials with great potentials for a variety of electrochemical devices, among which lithium-ion battery is one of the most challenging application area. Despite the unique advantages of the IL-based electrolytes, their rather low Li⁺ ion conductivity due to the relatively high viscosity and ion complexes formed among ions may cause concentration gradient within the battery and deteriorate the battery performance under high current density.³⁹ To demonstrate the effectiveness of the P(VDF-HFP) electrospun mats tethered with SiO₂ nanoparticles in improving Li⁺ transport properties, three IL hosts were evaluated, namely commercial Celgard membrane, neat P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mats, which were all loaded with 0.3 mol kg⁻¹ LiTFSI/PYR₁₄⁺TFSI⁻ to provide high ionic conductivity, wide electrochemical window and good compatibility toward the lithium electrode. The T_{Li^+} values of Celgard membrane, neat P(VDF-HFP) and SiO₂ (15.4 wt%)-on-

P(VDF-HFP) nanofibrous mats are 0.23, 0.31 and 0.68, respectively. In comparison with Celgard membrane, the T_{Li^+} value of P(VDF-HFP) electrospun mat shows a slight increase. It indicates that P(VDF-HFP) polymer chains can solvate anions (TFSI⁻) and hinder their motions to some extent. It is striking to see that with the attachment of SiO₂ on the fiber surface, the T_{Li^+} value increases drastically. It is attributed to the interactions between the Lewis acid sites on SiO₂ and TFSI⁻ anions that impede the formation of ionic complexes and release more free Li⁺. A high T_{Li^+} value would decrease the electrolyte polarization caused by anion accumulation and suppresses the concentration gradient to facilitate lithium-ion transport, which is beneficial for the rate performance of lithium-ion batteries.

The chemical stabilities of these IL electrolytes against lithium anode are important for the cycle life, power density and safety of lithium-ion batteries, which can be characterized by the interfacial resistance between the electrolytes and lithium electrode. The interfacial resistance is associated with the passivation layer on the lithium electrode and the associated charge transfer resistances, which can be investigated by the electrochemical impedance spectra (EIS) using the Li/electrolyte/Li symmetric cells. Due to the low electrochemical potential of lithium metal, the electrolyte undergoes reduction on its surface, leading to the growing of an electronically insulating but ionically conducting solid electrolyte interphase (SEI) on the anode surface.⁴⁰ The passivating SEI layer can protect the electrode from further reaction with the electrolyte, thereby limit the degradation of the electrolyte, whereas also leads to irreversible capacity loss since the SEI layer contains lithium compounds.^{41, 42} Therefore, a thin and stable SEI layer is essential for achieving high-performance lithium-ion battery. As shown in Fig. 8a, for the three LiTFSI/PYR₁₄⁺TFSI⁻-loaded membranes, the interfacial resistance increases initially, then a dynamic equilibrium state is achieved. The increase in interfacial resistance with the storage time may be associated with the growth of the passivation layer on the lithium electrode surface and degradation of the direct physical contact between the electrode and membrane. For membranes without nanoparticles, the stabilization takes a few days. Whereas, P(VDF-HFP) electrospun mats exhibit lower interfacial resistance compared with commercial Celgard membrane. It can be attributed to larger porosity, higher electrolyte uptake, and better electrolyte/lithium electrode affinity of the P(VDF-HFP) mats, which facilitate the migration of Li⁺ at the electrolyte/electrode interface and cause a decrease in interfacial resistance.¹⁴ The introduction of covalently bonded SiO₂ nanoparticles onto the P(VDF-HFP) nanofibrous mats further reduces the interfacial resistance. There is only a very small initial surge in the first few hours and the resistance keeps almost constant afterwards. This suggests that the presence of SiO₂ nanoparticles may lead to thinner and more stable SEI.²⁵ The SiO₂ nanoparticles, which have large surface area and high hydrophilicity, can effectively hold the liquid electrolyte by capillary force and help to trap residual trace of moistures and impurities. This would inhibit the reactions of the electrolyte and impurities with the lithium metal, resulting in smaller and more stable interfacial resistance.²⁵

In order to evaluate the effectiveness of the SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mats in improving the rate performance of lithium-ion batteries, Li/LiCoO₂ cells using this membrane loaded with 0.3 mol kg⁻¹ LiTFSI/PYR₁₄⁺TFSI⁻ as electrolytes were fabricated and tested. For comparison, cells using commercial Celgard membrane and neat P(VDF-HFP) mat loaded with the same amount of LiTFSI/PYR₁₄⁺TFSI⁻ were also tested. Fig. 8b shows the discharge C-rate capabilities of the Li/LiCoO₂ cells containing the aforementioned three electrolyte systems. It is clear that the SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mat exhibits the highest discharge capacity at each C-rate, and the differences become larger

at higher current density where the influence of Li⁺ ion conductivity is more significant. The notable improvement in the rate performance of Li-ion battery can be attributed to the unique advantages of this novel SiO₂-on-P(VDF-HFP) nanofibrous mat, which provides higher T_{Li^+} value, and better compatibility with lithium electrode as demonstrated above. The discharge capacities at 0.5 C as a function of cycle number of the three systems are also compared, and the results are shown in Fig. 8c. It is observed that the cell based on SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mat delivers a high initial discharge capacity of 121 mA h g⁻¹, and shows a capacity retention of 95 % after 50th cycle. The superior cyclability of the SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mat is associated with its high Li⁺ ion conductivity and better compatibility with lithium electrode.

3.6. Covalently attaching metal oxide nanoparticles on polymer nanofibers

Herein we report that ethoxysilane groups grafted on the P(VDF-HFP) nanofiber surface can also facilitate the covalent attachment of metal oxide nanoparticles via sol-gel process. Fig. S6[†] shows SEM images of APTES-modified P(VDF-HFP) mats after treated with TiO₂ and Al₂O₃ precursor solutions. It is clear that both TiO₂ and Al₂O₃ nanoparticles have been successfully attached on the nanofiber surface. This demonstrates that the ethoxysilane-functionalized P(VDF-HFP) nanofibrous mats are versatile platform for synthesis of a wide variety of hybrid nanofibrous mats with metal oxide nanoparticles covalently attached on nanofiber surface.

Both TiO₂ and Al₂O₃ attached P(VDF-HFP) electrospun mats were loaded with BMIM⁺BF₄⁻, and their corresponding ionic conductivity are listed in Table S1[†]. It shows that the incorporation of TiO₂ and Al₂O₃ nanoparticles both leads to higher ionic conductivity compared with that of neat P(VDF-HFP) mat, whereas the extent of increase is smaller than that given by the attachment of the same amount of SiO₂. It may be explained by the stronger Lewis acidity of SiO₂ nanoparticles, which may interact with BF₄⁻ anions more strongly, hence releasing more BMIM⁺ cations. Nevertheless it is believed that TiO₂-on-P(VDF-HFP), Al₂O₃-on-P(VDF-HFP) and other metal oxide-on-P(VDF-HFP) nanofibrous mats that may be synthesized using this method may find a wide range of applications in areas such as filtration, UV protection and environmental applications.

4. Conclusion

SiO₂-on-P(VDF-HFP) nanofibrous mats have been successfully prepared by a combination surface functionalization of electrospun mats and sol-gel protocol. SiO₂ nanoparticles with size of 10-20 nm are uniformly distributed on the fiber surface through covalent tethering, without blocking the pores in the electrospun mats. The attachment of SiO₂ nanoparticles results in remarkable improvement in mechanical property of the nanofibrous mats. IL-based polymer electrolytes can be facilely prepared by immersing the SiO₂-on-P(VDF-HFP) nanofibrous mats in BMIM⁺BF₄⁻ and LiClO₄/BMIM⁺BF₄⁻ liquid electrolytes, respectively. Significant enhancement of ionic conductivity and lithium transference number is achieved, which is attributed to the enhanced salt dissociation caused by Lewis acid-base interactions of SiO₂ with BF₄⁻ and ClO₄⁻. The electrochromic device using the IL-loaded SiO₂-on-P(VDF-HFP) nanofibrous mats as the electrolyte layer shows enhanced contrast, as a result of increased number of free lithium ions. The hybrid mats are also loaded with LiTFSI/PYR₁₄⁺TFSI⁻, and the resultant electrolytes are tested in Li/LiCoO₂ cells. The

incorporation of SiO₂ improves the lithium transference number and compatibility with the lithium electrode, leading to much enhanced rate capacity and good cycling stability of the cells. We believe that this approach may also be adopted to prepare non-volatile electrolytes for other types of devices, such as supercapacitors and fuel cells. Furthermore, it also paved the way for tethering other types of inorganic nanoparticles onto PVDF-based nanofibers for a wide variety of applications.

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Notes and references

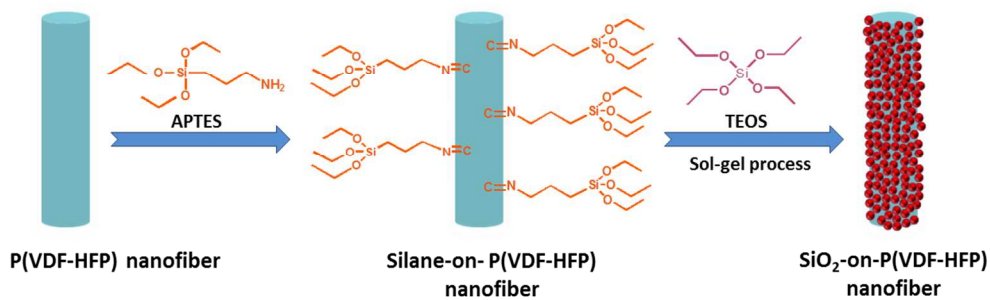
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† Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/b000000x/

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Scheme 1. The schematic showing the preparation route of SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats.

Table 1. Electrolyte uptake and ionic conductivity of SiO₂-on-P(VDF-HFP) nanofibrous mats with different SiO₂ contents (measured at 20 °C).

SiO ₂ content	BMIM ⁺ BF ₄ ⁻		LiClO ₄ /BMIM ⁺ BF ₄ ⁻ (1 mol kg ⁻¹)	
	Electrolyte uptake (%)	Ionic conductivity (mS cm ⁻¹)	Electrolyte uptake (%)	Ionic conductivity (mS cm ⁻¹)
0 wt%	440	2.6±0.2	460	2.3±0.1
0.9 wt%	440	6.5±0.3	460	4.3±0.1
1.1 wt%	450	6.6±0.3	480	4.5±0.2
1.4 wt%	500	7.8±0.4	510	4.8±0.2
2.1 wt%	420	5.6±0.2	400	6.2±0.3
8.6 wt%	360	5.6±0.2	320	6.2±0.2
12.6 wt%	330	5.4±0.1	310	6.5±0.2
15.4 wt%	300	5.2±0.2	290	8.6±0.2

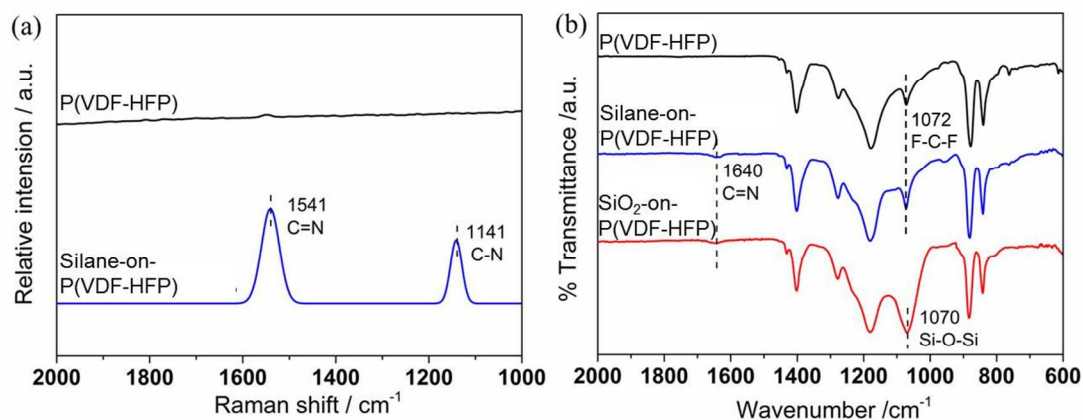


Fig. 1. (a) Raman spectra of P(VDF-HFP) and Silane-on-P(VDF-HFP) nanofibrous electrospun mats; (b) FTIR spectra of P(VDF-HFP), Silane-on-P(VDF-HFP) and SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats, respectively.

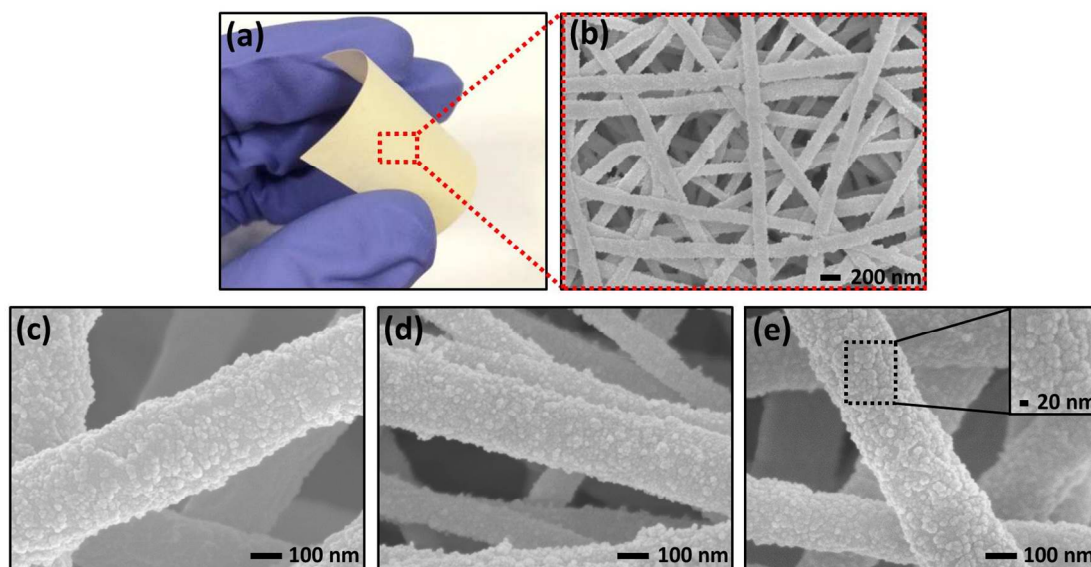


Fig. 2. (a) Photograph of the SiO₂-on-P(VDF-HFP) nanofibrous electrospun mats and (b) the corresponding SEM image at low magnification; SEM images of the hybrid mats with (c) 1.4 wt%, (d) 8.6 wt% and (e) 15.4 wt% SiO₂ at high magnification with an enlarged inset.

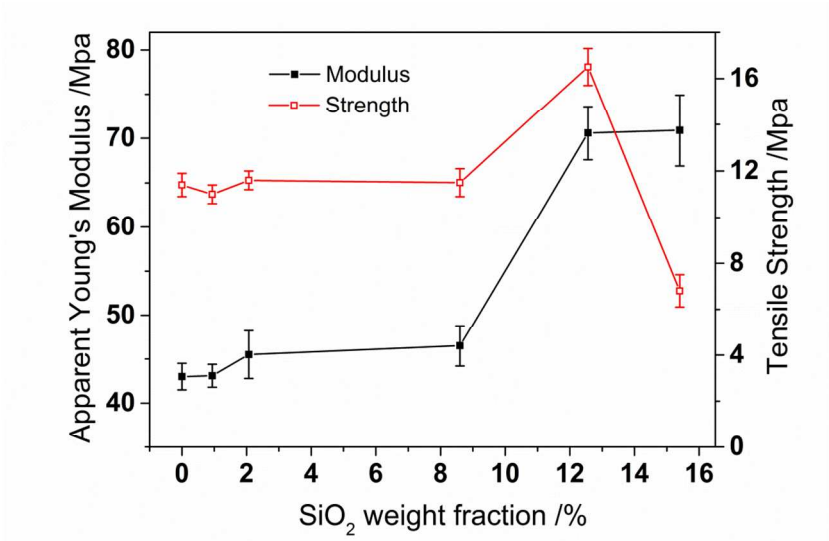


Fig. 3. The apparent Young's Modulus and tensile strength of the SiO₂-on-P(VDF-HFP) nanofibrous mats with different SiO₂ contents.

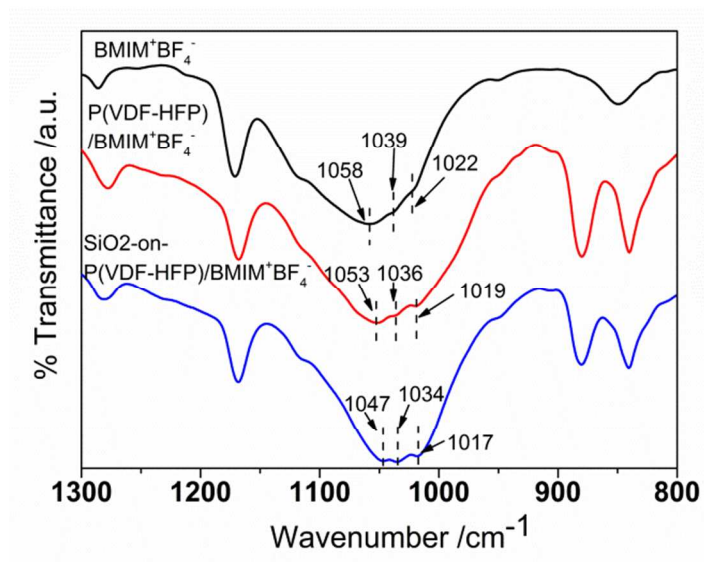


Fig. 4. FTIR spectra of neat $\text{BMIM}^+\text{BF}_4^-$, P(VDF-HFP) and SiO_2 (15.4 wt%)-on- P(VDF-HFP) nanofibrous electrospun mats after loading with $\text{BMIM}^+\text{BF}_4^-$.

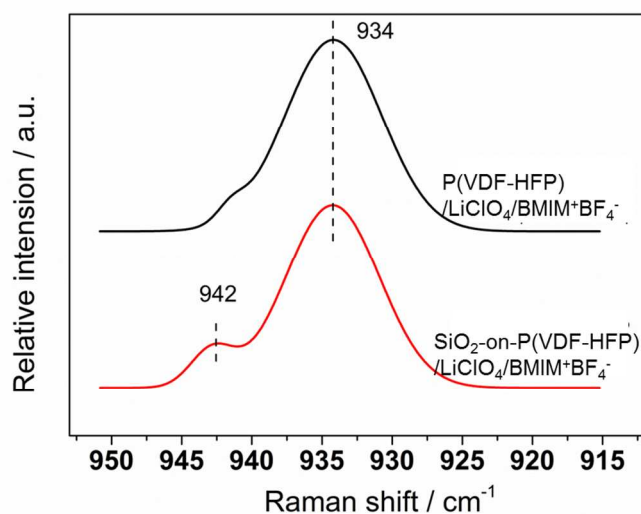


Fig. 5. Raman spectra of P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous electrospun mats loaded with LiClO₄/BMIM⁺BF₄⁻.

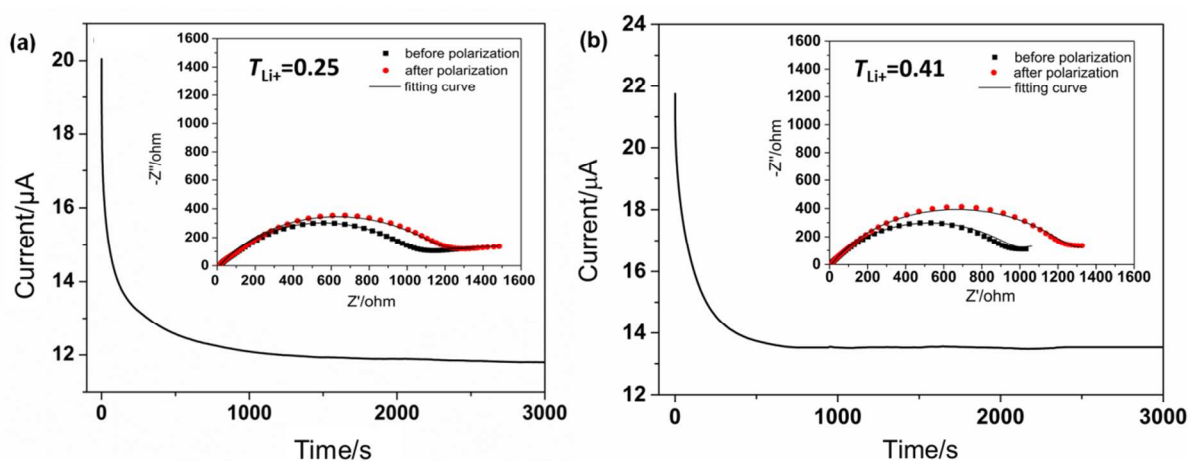


Fig. 6. Chronoamperometric curves of Li/electrolyte/Li symmetric cells with P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous mats loaded with LiClO₄/BMIM⁺BF₄⁻ as electrolytes, at 30 mV DC. Insets show the impedance response of the same cell before and after the DC polarization.

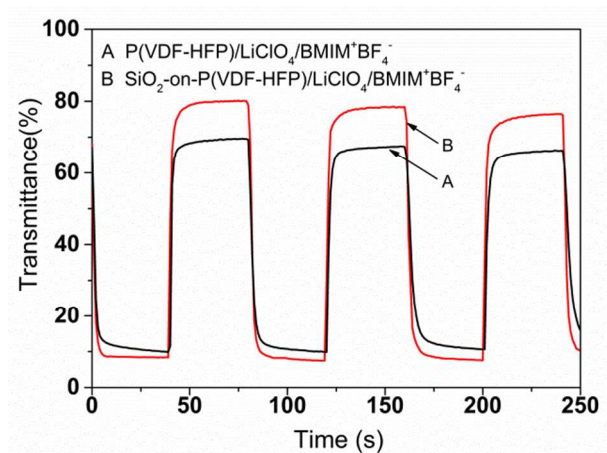


Fig. 7. Switching curves of PANI-TiO₂-based single-layer electrochromic devices with P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻ and SiO₂ (15.4 wt%)-on-P(VDF-HFP)/LiClO₄/BMIM⁺BF₄⁻ as electrolytes under square-wave potentials oscillating between +2.0 V and -2.0 V.

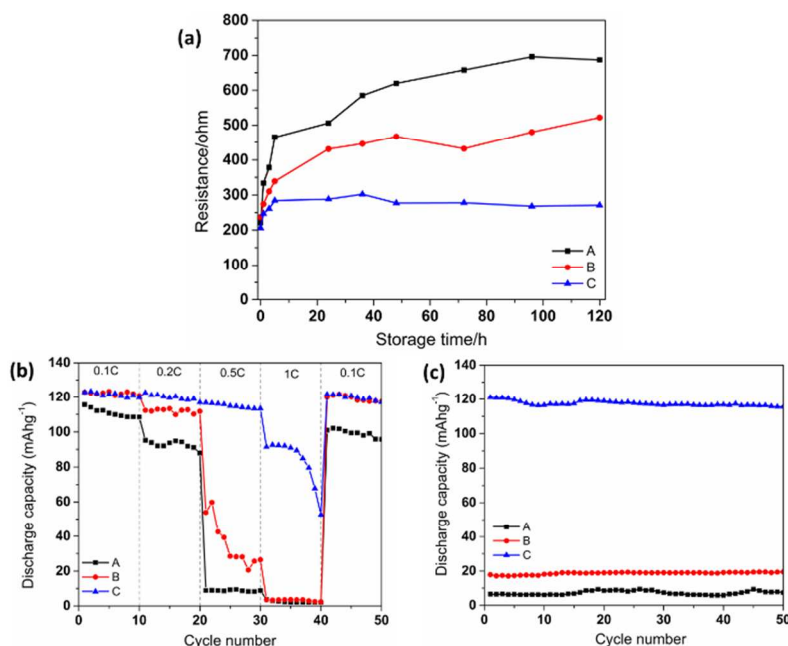
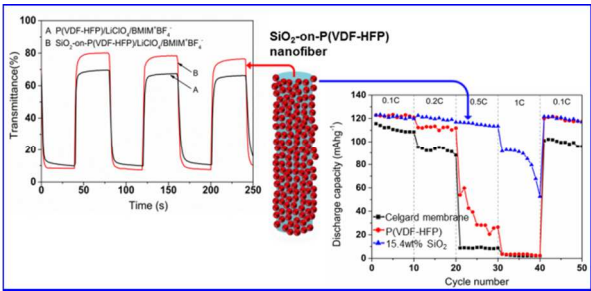


Fig. 8. (a) Time dependence of the electrolyte/lithium electrode interfacial resistance at room temperature; (b) rate discharge capacity of Li/LiCoO₂ cells under difference current density; (c) cycling stability at 0.5 C (A, B and C represent for commercial Celgard membrane, P(VDF-HFP) and SiO₂ (15.4 wt%)-on-P(VDF-HFP) nanofibrous electrospun mats after loading with 0.3 mol kg⁻¹ LiTFSI/PYR₁₄⁺TFSI⁻).

Graphical abstract:



Using ionic liquid-loaded SiO₂-on-P(VDF-HFP) nanofibrous mats as electrolytes, both electrochromic device and Li/LiCoO₂ battery exhibit significantly improved performance.