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Electrochemical behavior of PEDOT/Lignin in Ionic Liquid Electrolytes: Suitable Cathode/Electrolyte System for Sodium Batteries

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Abstract: Biomass derived polymers, such as lignin, contain redox quinone/hydroquinone redox moieties that can be used to store charge. Composites based on the biopolymer lignin and several conjugated polymers have shown good charge storage properties. However, their performance has been just studied in acidic aqueous media limiting the applications mainly to supercapacitors. Here we show that PEDOT/Lignin biopolymers are electroactive in aprotic ionic liquids and we move a step further by assembling sodium full cell batteries using PEDOT/Lignin as electrode material and ionic liquid electrolytes. Thus, the electrochemical activity and cycling of PEDOT/Lignin electrodes is investigated in 1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide (BMPyTFSI), 1-butyl-1-methylpyrrolidinium bis(fluorosulfonyl)imide (BMPyFSI), 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (EMImTFSI) and 1-ethyl-3-methylimidazolium bis(fluorosulfonyl)imide (EMImFSI) ionic liquid electrolytes. The effects of water and sodium salt addition to the ionic liquids are investigated in order to obtain optimum electrolyte systems for sodium batteries. Finally, sodium batteries based on PEDOT/Lignin cathode with imidazolium based ionic liquid electrolyte showed higher capacity values than pyridinium ones, reaching 70 mAhg⁻¹. Our results demonstrate that PEDOT/Lignin composites can serve as low cost and sustainable cathode materials for sodium batteries.

Introduction

Organic electrode materials, made of redox active polymers are promising candidates for novel energy storage, since they are relatively inexpensive and diverse. [1] Organic materials exhibit higher rate capability than the current oxides and inorganic phosphates materials. [2] Moreover, they present low toxicity, processability and recyclability, which make them good candidates to meet the challenging demand of green batteries. However, they also present some drawbacks such as low energy density, self-discharge and low cyclability. Regardless, redox active polymers synthesized from biomass or recycled sources [3] offer a promising solution in terms of sustainable energy storage and conversion devices.

Small molecules and biopolymers containing carbonyl groups such as quinone have gained great attention due to their good redox reversibility, high theoretical capacity and low price. [4] For instance, lignin, which is the second most abundant biopolymer in the world is also a renewable and cheap source of quinone/hydroquinone groups. [5] In general, lignins are polyphenolic compounds with no exact regular structure and varying chemical and physical properties depending on the biological source. [6] Unfortunately, lignin is non-conductive and therefore requires a conductive additive to allow electron transfer. One approach to overcome this limitation is the incorporation of a conducting material into the matrix, such as graphene [7] and carbon nanotubes. [8] Recently, Inganäs et al. pioneered the synergic combination of conducting polymers and lignin biocomposites to be used as electrodes. [9]

Polypyrrole/lignin cathodes were prepared by electrochemical polymerization of pyrrole in lignin based solutions, which were used as cathodes with a charge capacity of 75 mAhg⁻¹ close to the estimated theoretical value of 80 mAhg⁻¹. [10] This system’s capacity was further improved up to 186 mAhg⁻¹ by doping the conducting polymer with additional redox active compounds such as anthraquinone sulfonate. [11] However, polypyrrole/lignin electrodes suffer from strong loss of charge capacity upon long cycling. Therefore, other conducting polymers, such as polyaniline and poly(3,4-ethylenedioxythiophene) (PEDOT), have been used as alternatives to prepare electrodes with lignosulfonates by electrochemical techniques. [12] Recently, high performance PEDOT/Lignin electrodes have been synthesized by oxidative polymerization which opens up the possibility of scaling up the production of this material for future commercial applications. [13]

Although many studies have focused on the improvement of charge storage properties of these conducting polymer/lignin composites, [11-14] their electrochemical behavior has been just investigated in aqueous acidic media such as 0.1 M HClO₄ and 0.5 M H₂SO₄. [15] For this reason, these materials have only been applied so far in supercapacitors [14] and electrochemical sensors. [15]

Ionic liquids (ILs) have been widely investigated as electrolyte materials for batteries due to the outstanding properties and structure versatility. In general ionic liquids show good ionic conductivity, low vapor pressure, low flammability, excellent chemical and thermal stability and wide electrochemical window. [16] They are being investigated as electrolytes not only in lithium batteries but also in other technologies such as...
supercapacitors, sodium batteries, flow batteries or metal air batteries.

Sodium secondary batteries have gained great interest due to the lower price and significantly greater abundance of sodium compared to lithium. Imidazolium and pyrrolidinium based ionic liquids have been studied as potential electrolytes for sodium batteries, which demonstrated sodium deposition and dissolution with good efficiency. Moreover, conducting polymers have been proven to be good electro-active materials for sodium batteries due to their flexible structure to reversibly host Na ions.

The goal of the present study is to investigate the electrochemical behavior of PEDOT/Lignin biopolymers in a series of imidazolium and pyrrolidinium-based ionic liquids. The effects of the nature of the ionic liquid, type of cation/anion, water and sodium salt addition are also investigated in detail. It is expected that the use of ionic liquids as electrolyte in comparison to the studied aqueous acidic solutions will provide lower ionic conductivity but an enhancement of the electrochemical and thermal stability of the device as well as a higher output voltage. Previous works indicate a good electrochemical behavior of both PEDOT and quinone/hydroquinone moieties in ionic liquids, showing reversible redox processes in aprotic ionic liquids. The final goal is to demonstrate the concept of a new battery cell using PEDOT/Lignin as cathode material, the optimized ionic liquid as electrolyte and a sodium anode. To the best of our knowledge this is the first conducting polymer/lignin sodium battery. We envisioned that this cell configuration could lead to high cycling stabilities and satisfactory storage capacities, with an average voltage higher than 2.5 V.

Results and Discussion

Electrochemical characterization of PEDOT/Lignin in ionic liquids

The chemical structure of the polymer and the ionic liquids investigated in this article are represented in Scheme 1. PEDOT/lignin composites were obtained by oxidative polymerization as reported before. Thus, the electrochemical behavior of PEDOT/Lignin composites in two different weight ratios, 80/20 (PEDOT:Lign8020) and 60/40 (PEDOT:Lign6040), have been investigated in a series of 4 ionic liquids composed of the combination of an imidazolium (EMIm+) and pyrrolidinium (BMPyr+) cation with bis(trifluoromethylsulfonyl)imide (TFSI) and bis(fluorosulfonyl)imide (FSI) anion.

First, the electrochemical properties of the PEDOT/Lignin composites were compared to their single constituents, PEDOT and lignin, in BMPyrTFSI ionic liquid. Cyclic voltammograms are shown in Figure 1. Electrochemical stability of the biocomposites was studied by subsequent scans. Figure 1 shows the 20th cycle corresponding to PEDOT:Lign8020, PEDOT:Lign6040, PEDOT and lignin in BMPyrTFSI ionic liquid. PEDOT/Lignin composites exhibit three oxidation peaks, A1-A3, and three reduction processes C1-C3. The first oxidation process for PEDOT:Lign8020 at -0.90 V (A1) is not very pronounced, which is followed by another at -0.30 V (A2) and the third one at 0.90 V (A3). Comparing to the single constituents we can observe that A2 corresponds to the oxidation of PEDOT chains, while A3 is attributed to the oxidation of quinone/hydroquinone groups in lignin. The anodic process A1, which is not presented in the single constituents CVs, is attributed to the oxidation of PEDOT as it was observed previously in EMImTFSI. In the cathodic scan, the peak at 0.5 V (C1) corresponds to the reduction of hydroquinone groups, while the peaks at -0.3 V (C2) and -1.1 V (C3) are related to the reduction of PEDOT chains in the composite. PEDOT presents a broad oxidation and reduction peak at -0.3 V and -0.5 V, respectively. In this case, the potential was limited to 0.5 V to avoid oxidative breakdown of PEDOT polymer. Lignin shows an oxidation peak at 0.7 V and two reduction peaks at 0.45 V and -0.6 V, confirming that the reaction mechanism of quinone/hydroquinone groups in lignin can take place in aprotic ionic liquid such as BMPyrTFSI. These redox potentials are similar to the ones reported for hydroquinone in BMImBF4 ionic liquid. Both PEDOT/Lignin composites present enhanced electroactivity and electrostability as compared to both constituents. A similar electrochemical response was obtained in EMImFSI ionic liquid (Figure S1). This result demonstrates that the synergic combination between lignin and conducting polymers is also seen when ionic liquids are used as electrolytes as observed with acidic aqueous electrolyte.
Due to the superior redox activity in terms of current density, PEDOTLig8020 was chosen to study its electrochemical behavior in a series of 4 different ionic liquids. Figure 3 shows the cyclic voltammograms of PEDOTLig8020 in pyrrolidinium and imidazolium-based ionic liquids with TFSI\(^-\) and FSI\(^-\) anions. In all the cases, PEDOTLig8020 presents three redox processes in pyrrolidinium ionic liquids (oxidation reactions at -0.90 V, -0.35 V and 0.90 V and reduction reactions at 0.5 V, -0.3 V and -1.1 V) at first glance, an increase of the current density is observed in every cycle. This is clearly seen in Figure 3 when comparing cycles 1, 4, 12 and 20, where an increased current density is noticeable. This is associated, as discussed below, to the activation of the film layer during the ion exchange occurring throughout the electrochemical cycling. This behavior was previously observed for PEDOT in ionic liquids.\(^{[22]}\) This increase of electroactivity of the PEDOT films should be due to an expansion of the closed polymer structure that it is provoked by the consecutive redox processes. This indicates better swelling of the polymer and faster ion transport after long cycling. It is well known that during oxidation and reduction the polymer swells due to the transport of cations or anions of the ionic liquid that should enter the structure to compensate the charge. In all the cases, PEDOTLig8020 presents a series of redox processes at 0.5 V, -0.3 V and -1.1 V. This behavior was previously observed for PEDOT in ionic liquids.\(^{[22]}\) This increase of electroactivity of the PEDOT films should be due to an expansion of the closed polymer structure that it is provoked by the consecutive redox processes. This indicates better swelling of the polymer and faster ion transport after long cycling. It is well known that during oxidation and reduction the polymer swells due to the transport of cations or anions of the ionic liquid that should enter the structure to compensate the charge. So the swelling of the PEDOT/Lignin biocomposites by resting in the ionic liquid for three hours without cycling is not enough to activate the material (Figure S3).

As clearly observed, the presence of lignin in the biocomposites provides an extra redox process increasing the specific capacity of the PEDOT electrodes. However, it is noticeable that the current density of PEDOTLig8020 is considerably higher than PEDOTLig6040. In order to explain this result, it needs to be taken into account that the morphology and surface area can also play an important role affecting the electrochemical properties. Thus, Scanning Electron Microscopy (SEM) was used to study the surface morphology of the composites, and compared to the single constituents PEDOT and lignin (Figure 2). PEDOT (Figure 2a) presents granular-cauliflower type morphology, while a smoother solid like morphology was observed for lignin (Figure 2b, S2). The morphology of the PEDOT/Lignin composites depends on the weight ratio of the constituents and thus a more granular-cauliflower morphology is attained for PEDOTLig8020 (Figure 2c) as compared to PEDOTLig6040 (Figure 2d). Therefore, two competitive effects were observed in our PEDOT/Lignin composites. On the one hand, the presence of lignin provides an extra redox process increasing the specific capacity of the electrodes. On the other hand, an increase of lignin in the composites leads to lower surface area, decreasing the accessible electroactive sites of the biocomposite.

### Table of the anodic and cathodic potentials of the polymers

<table>
<thead>
<tr>
<th>Polymer</th>
<th>(A_1) (V)</th>
<th>(A_2) (V)</th>
<th>(A_3) (V)</th>
<th>(A_4) (V)</th>
<th>(B_1) (V)</th>
<th>(B_2) (V)</th>
<th>(B_3) (V)</th>
<th>(B_4) (V)</th>
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</thead>
<tbody>
<tr>
<td>PEDOTLig8020</td>
<td>-0.98</td>
<td>-0.30</td>
<td>1.10</td>
<td>-0.20</td>
<td>0.50</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PEDOTLig6040</td>
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<td>0.00</td>
<td>0.93</td>
<td>-0.95</td>
<td>-0.15</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEDOT</td>
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<td>-0.50</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Lignin</td>
<td>0.70</td>
<td>-0.60</td>
<td>0.45</td>
<td></td>
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**Figure 1.** a) Cyclic voltammograms of PEDOTLig8020, PEDOTLig6040, PEDOT and Lignin-modified GC electrodes in BMPyrTFSI. b) Magnification of Lignin and PEDOT cyclic voltammograms. Cycle number 20, Scan rate: 20 mV s\(^{-1}\). c) Table of the anodic and cathodic potentials of the polymers investigated in BMPyrTFSI.

**Figure 2.** SEM images of a) PEDOT; b) Lignin; c) PEDOTLig8020 and d) PEDOTLig6040 powders.
where P is the neutral polymer, $P^\text{ox}$ the oxidized polymer, C$^\text{+}$ the cation and A$^-$ the anion. Several studies have proved that redox mechanism involves either the egress of cations and also the ingress of anions which strongly depends on the size of the ions.\cite{23} During the oxidation process of the polymer, anions from the bulk are incorporated into the polymer, compensating the charge along the polymeric backbone.\cite{24} In the case of big cations and small anions, the cation exchange is unexpected. Thus, due to the big size of pyrrolidinium cation (1.1 nm radius),\cite{25} an anionic exchange will happen in the case of BMPyrTFSI and BMPyrFSI ionic liquids; given that the TFSI$^-$ (0.8 nm radius)\cite{26-28} anions are bigger than FSI$^-$ (0.3 nm radius)\cite{26} (Table S1), they create more accessible sites during this exchange and as a result, the current increases in greater steps with TFSI$^-$ anion. In the case of ionic liquids, the transport mechanism of the ion exchange also depends on the symmetry of the ionic liquid. Although, those mechanisms are not completely understood, it is known that in the case of imidazolium-based IL due to the planarity of the cation the intercalation into the conducting polymer is easier.\cite{27} Moreover, the EMIm$^+$ cation has a smaller size (0.3 nm radius)\cite{28} compared with the pyrrolidinium cation and TFSI$^-$ anions and it has been reported as the main diffusing species for one of the redox mechanisms of PEDOT\cite{21}. Therefore, in the case of pure EMImTFSI, the small EMIm$^+$ cation will be exchanged to establish the electroneutrality in the polymer. On the other hand, pyrrolidinium-based ionic liquid is less planar and bigger in size, and therefore we hypothesise that such cation will not be involved in the electroneutrality of the conducting polymer. Thus, the TFSI$^-$ and FSI$^-$ anions will be responsible for the ion exchange leading to lower current density, in comparison with the imidazolium-based systems. Furthermore, as shown in Figure 3b, the redox peaks are sharper and the current intensity is higher in EMImFSI than in EMImTFSI ionic liquid. This behavior can be attributed to the higher fluidity and ionic conductivity of EMImFSI ionic liquid and the smaller ionic radius of FSI$^-$, which makes it a more mobile species.

**Effect of water and sodium salts in the electrochemical behavior of PEDOT/Lignin in ionic liquids**

Considering the higher current density, BMPyrTFSI and EMImFSI ionic liquids combined with PEDOTLig8020 were studied in further detail. It is known that quinone/hydroquinone electrochemistry is largely affected by the presence of protic compounds such as water.\cite{29} Therefore, the influence of water on the electrochemical performance of PEDOTLig8020 was investigated by saturating the ionic liquid with water. The cyclic voltamograms obtained in dry (<75 ppm H$_2$O) and wet (5100 ppm H$_2$O) EMImFSI are shown in Figure 4. The presence of water reduces the electrochemical window by 0.5 V while the current density is doubled. The polymer film is swollen during the first cycles due to the water presence which increases the electrode active area. After the 5th cycle delamination and subsequent dissolution diminishes the performance beyond this point (see inset in Figure 4). As dissolution of the electrode material in the electrolyte is a drawback to obtain good battery cycling performances, wet conditions were dismissed.

![Figure 3. Cyclic voltammograms of PEDOTLig8020 modified GC electrodes in a) BMPyrTFSI and BMPyrFSI; b) EMImTFSI and EMImFSI ionic liquids. Cycle number 1, 4, 12 and 20. Scan rate: 20 mV s$^{-1}$.](image-url)
The effect of sodium salt on the electrochemical properties of the biocomposites is crucial for well performing sodium batteries. Thus, different concentrations of sodium salts were dissolved in BMPyrTFSI and EMImFSI matching the IL anion (e.g. NaTFSI and NaFSI). Figure 5a depicts the 1st and 20th cyclic voltammograms of PEDOTLig8020 in BMPyrTFSI with 0, 10 and 20 mol% of NaTFSI. It is apparent that the current density decreases in presence of the salt, probably due to less favored physicochemical performance.\(^{17a}\) However, the electrochemical properties of NaTFSI/BMPyrTFSI have been reported in the literature\(^{17a}\) exemplifying its feasibility for secondary sodium batteries even in the presence of large amount of sodium metal cation (e.g. 0.5 M NaTFSI). Redox potentials of PEDOTLig8020 are maintained and a slightly higher current density is obtained for higher NaTFSI content (20 mol%) in comparison with 10 mol% NaTFSI.

EMImFSI dissolves a larger amount of NaFSI; therefore, mixtures containing 20 and 30 mol% NaFSI were studied (Figure 5b). The same current density is observed for the 20 and 30 mol% NaFSI mixtures. However, the two redox potentials (A₁, A₂), which are related to PEDOT, are shifted to lower potentials only in the presence of 30 mol % NaFSI, while the process related to lignin is barely modified. Upon increasing the concentration of NaFSI in EMImFSI, the FSI⁻ molar concentration remains constant but the EMIm⁺ concentration is reduced. Thus, this differences in the potential may be due to the decrease of concentration of the mobile EMIm⁺ cation, which is consistent with the exchangeability of EMIm⁺ during charging and discharging of the polymer.

The cycling stability of PEDOTLig8020 in sodium-ion conducting electrolytes was investigated by cyclic voltammetry, running 150 cycles for each sample. Figure 6 shows the cyclability of PEDOTLig8020 over several cycles in BMPyrTFSI:NaTFSI and EMImFSI:NaFSI-based electrolytes. The current density increases gradually upon cycling in BMPyrTFSI based electrolytes over the measured 150 cycles. The current density also increases upon cycling for the EMImFSI electrolyte, but it gets to a stable value after the 75th cycle. Therefore, redox activity and stability of PEDOTLig8020 is kept at least over 150 cycles in the studied sodium ion conducting electrolytes, which makes PEDOTLig8020 a good candidate for use as a cathode material in sodium batteries.
Figure 6. Cyclic voltammograms of PEDOTLig8020 modified GC electrodes in a) NaTFSI/BMPyrTFSI and b) NaFSI/EMImFSI electrolytes. Scans 25, 50, 75, 100, 125 and 150.

Full cell characterization having a PEDOT/Lignin cathode, ionic liquid electrolyte and sodium anode

To further verify the potential of PEDOTLig8020 as cathode material, sodium coin cells were prepared using BMPyrTFSI:NaTFSI (20 mol%) and EMImFSI:NaFSI (20 mol%) electrolytes. The cathode was composed of 65 wt% PEDOTLig8020, 25 wt% PDADMA-TFSI and 10 wt% C-65, while the anode was sodium metal (Scheme 2). It has to be mentioned that the capacities are calculated per gram of PEDOT/Lignin polymer, thus, the values are related to the different redox processes in the composite material and not just the quinone/hydroquinone process taking part in lignin, which would lead to higher capacity values.

Figure 7 shows the charge and discharge profiles of pyrrolidinium (Fig. 7a) and imidazolium based (Fig. 7b) cells at various scan rates. The discharge profiles exhibit an almost linear decrease in potential due to the high content of PEDOT, demonstrating a capacitor-like discharge behavior. The polymer electrodes show an average discharge potential of 2.6 V and 2.8 V for pyrrolidinium and imidazolium based devices respectively, suitably serving as cathode active materials for sodium batteries. The long term cycling data is presented in Figure 8. Interestingly, the capacity of the imidazolium electrolyte device stabilises rather rapidly after only 20 cycles at a capacity of 70 mAh g\(^{-1}\), while the capacity increase is much slower for the pyrrolidinium sample (80 cycles, 46 mAh g\(^{-1}\)). This behaviour is in good agreement with that observed from the cyclic voltammetry experiments (see above) where the voltammograms in the pyrrolidinium-based electrolyte increases with cycling while in the imidazolium IL it stabilises more rapidly. This behaviour is believed to be due to the different ionic species exchanged during the charge and discharge of the polymer. There is a slight capacity loss of 6% observed upon long term cycling in case of the imidazolium electrolyte. The nature of this capacity fade is unclear and still under investigation. In the case of current scan experiments (Figure 9), the capacity also increases with cycle number. It should be mentioned that imidazolium device was conditioned for 20 cycles at 25 mAg\(^{-1}\) until stable capacities were observed. As expected, with increasing current the capacity drops when the imidazolium electrolyte is used although higher capacities are attained as compared to the pyrrolidinium system (in agreement with CV and long term cycling results). As suggested before, the reason for this is mainly the higher fluidity and intrinsic ionic conductivity of the EMImFSI compared to BMPyrTFSI (Table S1). Also after running the samples at high current rates and then switching back to the initial low current shows the capacity has regained its initial value (imidazolium sample) or shows an even larger value as a result of conditioning (pyrrolidinium), suggesting that the device performance is not compromised while exposing it to high currents.
different h), iron (III) chloride (FeCl₃, Aldrich), sodium persulfate (Na₃S₂O₈, Aldrich) and poly(diallyldimethylammonium) chloride (p-DADMAC, Aldrich, average Mw 400,000–500,000, 20 wt.% in H₂O) with lithium bis(trifluoromethanesulfonyl)imide (LiTFSI, Solvionic, 99.9%). The synthetic procedure has previously been reported elsewhere.[31]

**Synthesis of p-DADMA-TFSI binder**

p-DADMA-TFSI binder was synthesized by anionic exchange reaction from the commercially available polymer poly(diallyldimethylammonium) chloride (p-DADMAC, Aldrich, average Mw 400,000–500,000, 20 wt.% in H₂O) with lithium bis(trifluoromethanesulfonyl)imide (LiTFSI, Solvionic, 99.9%). The synthetic procedure has previously been reported elsewhere.[31]
Preparation of GC modified electrodes

Redox active polymer (0.0136 g) and carbon black (0.0017 g, Timcal C65) were gently mixed in a hand mortar and added to a solution of PDADMA-TFSI (0.0017g, Solvent) in NMP to obtain a composition of 80 wt % of redox active polymer, 10 wt % of C65 and 10 wt % of PDADMA-TFSI binder. The dispersion was stirred at r.t. for 2h and 0.3 µL of the slurry were drop-casted into the 1 mm GC electrode. The electrode was allowed to dry in the fume hood for 30 min and further drying at 50 °C vacuum for 12h.

Electrochemical measurements

Electrochemical measurements were performed on a Biologic SP-200 potentiostat in an Ar-filled glove box in a conventional 3 electrode set up. A platinum wire (99.95%, APS) was used as counter electrode and a glassy carbon electrode (GC, 1mm diameter, ALS Co., Ltd. Japan) as working electrode, which was modified with a slurry of the redox active polymer. The reference electrodes were fabricated by immersing a silver wire into 5 mL AgOTf BMPyrTFSI and 5 mL AgOTf EMImDCA solutions, both separated from the bulk by a glass frit and used respectively for pyrrolidinium and imidazolium based electrolytes. The reference electrodes were calibrated against ferrocene/ferrocenium couple and all potentials were referenced against FoFc⁺ couple. The slurry modified working electrodes were allowed to rest for 30 min inside the Ionic liquid before running the electrochemical measurements.

Sodium cells assembly

Coin cell prototypes were prepared using CR2032 Hohsen setup (2x 0.3 mm spacer, 1.4 mm spring). Sodium electrodes were prepared rolling sodium metal (Merck) in a glovebox and cutting out 0.9 cm diameter discs using a hole puncher. Cathodes were prepared by applying a formulation of 65% PEDOT:Lignin, 25% PDADMA-TFSI, and 10% C65 (Timcal) in N-methyl-2-pyrrolidone (Sigma Aldrich) onto battery grade aluminium substrate (Targray) using a #40 wire coating bar. After cutting using a 7/16 inch puncher (Timcal) in N₂, discs were cut using a 7/16 inch hole puncher. The weight of each individual electrode was determined. Before assembly the cathodes were vacuum dried inside the glovebox. A solupor separator was used (Lydall). Sodium electrodes were prepared rolling sodium methyl (0.0017 g, Timcal C65) in N₂, 65% PEDOT:Lignin biopolymer in the electrode.

Scanning Electron Microscopy (SEM)

SEM images were acquired on a JSM IT 300 series SEM at an accelerating voltage of 2 kV.

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Keywords: Energy Storage • Ionic Liquids • Lignin • Poly(3,4-ethylenedioxythiophene) • Sodium Batteries

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FULL PAPER

Electroactivity of PEDOT/Lignin biopolymer is studied in aprotic ionic liquids, demonstrating an effective cathode/electrolyte system that has been applied to develop sustainable sodium batteries. These results open up the possibility to use other lignin derived cathodes in sodium batteries as well as PEDOT/Lignin in other electrochemical devices using ionic liquids as electrolytes.