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Comparison of the thermally stable conducting polymers PEDOT, PANi, and PPy using sulfonated poly(imide) templates

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ABSTRACT

We showed that it is possible to use sulfonated poly(amic acid)s (SPAA) to template polymerize 3,4ethylenedioxythiophene (EDOT) to PEDOT, resulting in an aqueous dispersion of conducting polymer. This study compares PEDOT with poly(aniline) (PANi) and poly(pyrrole) PPy using the same and another, more rigid, poly(amic acid) template. A variety of system parameters, including reaction time, conductivity, and overall thermal stability, were noted to change systematically depending on the systems chosen. PANi-SPAA takes less than one tenth of the reaction time of PEDOT-SPAA (12 h versus 7 days), and results in higher conductivities at room temperature (*ca.* 10 S/cm). However, it is not as thermally stable as the PEDOT-SPAA system; conductivity is not measureable after annealing at 300 °C. PPy-SPAA was found to be more thermally stable than PANi-SPAA (less mass lost at 300 °C), but it was still more conductive than un-doped PEDOT-SPAA by a factor of 1000 (*ca.* 1.0 S/cm).

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1. Introduction

Conducting polymers (CPs) are of increasing interest, especially in areas such as electronic devices. They are used as a transparent anode in the field of optical electronics, demonstrating applications such as light detection [1], electrochromic displays [2], organic light emitting diodes (OLEDs) [3], and optical displays [4]. Of the many interesting conducting polymers that have been developed over the past decade, those based on poly(aniline) or PANi [5], poly(3,4ethylenedioxythiophene) or PEDOT [6,7], and poly(pyrrole) or PPy [8] are of significant importance due to their low costs [9], low densities [10], and their light weights [10] (in comparison to metals or other inorganic materials). As a result, these conducting polymers have attracted much attention in organic electronics. PEDOT is among the most popular conducting polymers. It has shown high conductivity, ranging from 10^{-2} to 10^{5} S/cm [11]. The issue with PEDOT alone is that it is an insoluble polymer, like many CPs. The use of template polymerization in the presence of a polyanion template, such as poly(styrene sulfonic acid) (PSSA), is one solution for this issue. It results in the formation of a colloidal dispersion of PEDOT-PSS nanoparticles that can then be cast as a thin, conductive

film. However, conducting polymer polymerizations with this traditional template show degradation after annealing above 200 °C. particularly resulting in a decrease or total loss of conductivity. This is a problem for high-temperature processing conditions, such as melt-coating with polycarbonate. Applications where devices use layers of PEDOT-PSS, such as photovoltaic cells or skyscraper windows, will experience losses of function over time or complete device failure if subjected to high temperatures over long periods of time, as well. To address these obstacles, new templates which can resist higher temperatures for annealing and that can also anneal for longer times than traditional templates were studied in this work. Sulfonated poly(amic acid) templates were used, which were subsequently converted to the polyimide upon annealing. The systems studied within use two different chemical structures for the poly(amic acid), as well as three different conducting polymers, to assess the function and benefits of one system over another.

Poly(imide)s are well-known high-temperature polymers because they have several advantages, including thermal stability [12], mechanical properties [13] thermoxidative stability [14], and superior chemical resistance [15]. The success of Kapton by DuPont was the first well-known commercial poly(imide) film which can remain stable over a wide range of temperatures, from 273 °C to 400 °C. It has been used in the manufacture of integrated circuits [16] and also in gas membrane separators [16]. Kapton is produced



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from the condensation of pyromellitic dianhydride (PMDA) and 4,4'-diaminodiphenyl ether (4,4'-ODA), which is a rigid structure for a polyimide. Pineri and co-workers [17] first synthesized sequenced five-membered and six-membered ring sulfonated polyimides from 4,4'-diaminobiphenyl-2,2'-disulfonic acid (BDSA), 4,4'-oxydianiline (ODA), and two types of dianhydrides, oxydiphthalic dianhydride (O-DDPA) and 1.4.5.8-naphthalenetetracarboxylic dianhydride (NTDA), respectively. Okamoto et al. have studied sulfonated poly(imide)s which use 4,4'-ODADS as a diamine for proton exchange membrane (PEM) fuel cell systems [18]. We used this diamine, along with a more flexible dianhydride, to synthesize a new sulfonated poly(amic acid) that can be used as a template to form PEDOT. This template can then undergo a conversion to the thermally stable sulfonated poly(imide) form by annealing at greater than 150 °C for a short time. This form of the conductive composite resisted higher temperatures than traditional PEDOT-PSS [19]. This work is an expansion of this principle and has studied two different templates to investigate the effect of the structure of poly(imide) on the properties of a variety of popular conducting polymers.

Herein, the template polymerization of conducting polymers has been accomplished using three different conducting polymers (PEDOT, PANi, and PPy) as well as two sulfonated poly(amic acid)s (SPAA1 and SPAA2). The chemical structures of each system are shown in Fig. 1. These CPs represent three of the broadest and most popular classes of materials. Polymers based on anilines, pyrroles, and thiophenes have all seen commercialized success in some form. The templates were chosen because of their differences in rigidity. The result of each template polymerization was a colloidal dispersion in water. These systems were explored in terms of reaction time, thermal stability, mass loss with time, and conductivity response to common dopants and annealing temperatures. Controls for all systems were prepared in the form of in-house polymerizations using the PSSA template for each CP that was used.

2. Experimental

2.1. Materials

4,4'-Diaminodiphenyl ether (4,4'-ODA), 4,4'-oxydiphthalic anhydride (O-DPDA), triethylamine (Et₃N), m-cresol, fuming sulfuric acid (SO₃, 20%), poly(styrene sulfonic acid) (18 wt.% in water), iron (III) ptoluene sulfonate hexahydrate, 3,4-ethylenedioxythiophene (EDOT), lithium trifluoromethanesulfonate, *N*,*N*-dimethylformamide (DMF), and aniline were purchased from Sigma–Aldrich. EDOT was distilled before use. 4,4'-Hexafluoroisopropylideneoxydiphthalic anhydride (6FDA) was purchased from TCI America. Pyrrole, ammonium persulfate, concentrated sulfuric acid (95%), sodium hydroxide (NaOH), hydrochloric acid (HCI), and acetone were purchased from Fisher Scientific and were used as received. Surfynol[®] 2502 surfactant was purchased from Air Products, Inc. d-Sorbitol 97%, ion-exchange resin DOWEX 50W × 8 50–100 mesh, and Amberlite* IR-120 (Na⁺ form) were purchased from Acros Organics. Sodium poly(styrenesulfonate) was purchased from Polysciences, Inc. Dialysis tubes (Molecular weight cut off [MWCO] = 3.5–5 kDa) were purchased from Spectrum Laboratories Inc.

2.2. Preparation of monomers and sulfonated poly(amic acid)s

2.2.1. Synthesis of 4,4'-diaminodiphenyl ether-2,2'-disulfonic acid (4,4'-ODADS)

To a 100 mL three-neck flask with a stirring device was added 2.00 g (10.0 mmol) of 4,4'-diaminodiphenyl ether (4,4'-ODA). The flask was cooled in an ice bath, and then 1.7 mL of concentrated (95%) sulfuric acid was slowly added with stirring. After 4,4'-ODA was completely dissolved, 10.5 mL of fuming (SO₃ 20%) sulfuric acid was slowly added to the flask. The reaction mixture was stirred at 0 °C for 2 h and then slowly heated to 80 °C and kept at this temperature for an additional 3 h. After cooling to room temperature, the slurry solution mixture was carefully poured onto 20 g of crushed ice. The resulting white precipitate was filtered off and then re-dissolved in a sodium hydroxide solution. The basic solution was filtered, and the filtrate was acidified with concentrated hydrochloric acid. The solid was filtered off, washed with water and methanol successively, and dried at 80 °C in vacuum oven overnight [18]. (87.17% yield).

2.2.2. Synthesis of sulfonated poly(amic acid)s (SPAA1, SPAA2)

To a 100 mL three-neck flask with N2 inlet and outlet was added 0.5405 g (1.5 mmol) of 4,4'-ODADS, 6 mL of m-cresol, and 0.3643 g (3.6 mmol) of triethylamine. After 4,4'-ODADS was completely dissolved, 0.4653 g (1.5 mmol) of O-DPDA for SPAA1 or 0.6664 g



Fig. 1. Chemical structures of the various conducting polymers and the various templates used in this study, with their corresponding abbreviations ($R = H^+$ for PEDOT and PPy, Na⁺ for PANi).

(1.5 mmol) of 6FDA for SPAA2 were added and then stirred at room temperature for 24 h. When the reaction was complete, the reaction mixture was decanted into acetone (75 mL), filtered, washed with acetone (25 mL, 2 times), and dried at 50 °C in a vacuum oven overnight [18]. (1.1463 g, 83.66% yield for SPAA1 and 1.3404 g, 85.31% yield for SPAA2).

2.2.3. Purification

The sulfonated poly(amic acid)s were purified via dialysis tube. SPAAs dissolved in water were loaded inside the dialysis tube and soaked in DI water for 24 h, changing the water twice (2 times at 12 h each).

2.2.4. Ion exchange

The purified SPAAs salt form were changed to SPAAs acid form with an ion exchange resin of strong acid type DOWEX 50W × 8 (cation exchange) in case using for polymerization with EDOT and purified with Amberlite* IR-120 (Na⁺ form) ion exchange resin in case using for polymerization with aniline. The SPAAs salt form were stirred in DI water with the ion exchange resin for 1 h to convert them to the free acid form (SO₃H) and sulfonated poly(amic acid) sodium form (Na⁺); they were centrifuged and filtered in a crucible filter and then dried at 50 °C in vacuum oven overnight. Molecular weight and molecular weight distributions of SPAA1 and SPAA2 were $M_{n1} = 20,769$, $M_{w1} = 35,502$, PDI₁ = 1.71 and $M_{n2} = 18,627$, $M_{w2} = 39,442$, PDI₂ = 2.12.

2.3. Template polymerization of EDOT and poly(styrenesulfonic acid) (PEDOT-PSS)

To a 25 mL one neck flask, 21.3 mg (0.15 mmol) of EDOT and 290.4 mg of 18 wt.% PSSA aqueous solution was added. To this suspension 108.4 mg (0.16 mmol) of iron (III) p-toluene sulfonate hexahydrate was added. The total mass of all the reactants was adjusted to 10 g by adding an appropriate amount of de-ionized water. The reaction mixture was stirred vigorously for 24 h at room temperature leading to a dark blue dispersion, purified according to literature procedure [20].

2.4. Template polymerization of EDOT and sulfonated poly(amic acid) (PEDOT-SPAA1, PEDOT-SPAA2)

To a 25 mL one neck flask, 21.3 mg (0.15 mmol) of EDOT and 200.0 mg (0.30 mmol) of SPAA1 or 230.6 mg (0.30 mmol) of SPAA2 were added. To this suspension 108.4 mg (0.16 mmol) of iron (III) p-toluene sulfonate hexahydrate was added for both polymerizations. The total mass of all the reactants was adjusted to 10 g by adding appropriate amount of de-ionized water. The reaction mixtures were stirred vigorously for 7 days, 5 days for PEDOT-SPAA1 and PEDOT-SPAA2, respectively at room temperature leading to a dark blue dispersion, purified according to literature procedure [19].

2.5. Template polymerization of ANi and poly(styrenesulfonic acid) (PANi-PSS)

To a 100 mL one neck flask, 49.36 mg (0.53 mmol) of ANi was introduced dropwise in 0.5 M aqueous HCl solution 40 mL and was stirred for 1 h. Then, 600.0 mg (0.07 mmol) of PSS⁻Na⁺ was added to the mixed solution and was stirred for 1 h. The polymerization of ANi was conducted with 157.46 mg (0.69 mmol) of APS as an oxidizing agent. The reaction mixtures were stirred vigorously for 12 h at room temperature leading to a dark green dispersion [21].

2.6. Template polymerization of ANi and sulfonated poly(amic acid) (PANi-SPAA1, PANi-SPAA2)

To a 100 mL one neck flask, 49.36 mg (0.53 mmol) of ANi was introduced dropwise in 0.5 M aqueous HCl solution 40 mL and was stirred for 1 h. Then, 47.34 mg (0.07 mmol) of SPAA1 Na⁺ form or 54.32 mg (0.07 mmol) of SPAA2 Na⁺ form were added to the mixed solution and were stirred for 1 h. The both polymerizations of ANi were conducted with 157.46 mg (0.69 mmol) of APS. The reaction mixtures were stirred vigorously for 12 h at room temperature leading to a dark green dispersion [21].

2.7. Template polymerization of Py and poly(styrenesulfonic acid) (PPy-PSS)

To a 25 mL one neck flask, 10.06 mg (0.15 mmol) of Py and 290.4 mg of 18 wt.% PSSA aqueous solution were added. To this suspension 108.40 mg (0.16 mmol) of iron (III) p-toluene sulfonate hexahydrate was added. The total mass of all the reactants was adjusted to 10 g by adding an appropriate amount of de-ionized water. The reaction mixture was stirred vigorously for 24 h at room temperature leading to a black dispersion [22,23].

2.8. Template polymerization of Py and sulfonated poly(amic acid) (PPy-SPAA1, PPy-SPAA2)

To a 25 mL one neck flask, 10.06 mg (0.15 mmol) of Py and 200.0 mg (0.30 mmol) of SPAA1 or 230.6 mg (0.30 mmol) of SPAA2 were added. To this suspension 108.40 mg (0.16 mmol) of iron (III) p-toluene sulfonate hexahydrate was added for both polymerizations. The total mass of all the reactants was adjusted to 10 g by adding appropriate amount of de-ionized water. The reaction mixtures were stirred vigorously for 5 days at room temperature leading to a black dispersion [22,23].

2.9. Preparation of PEDOT, PANi, PPy with SPAA1 and SPAA2 films

Films were prepared by drop casting pristine films and doped films onto glass slides at room temperature. The films were annealed at 180 °C for 10 or 90 min, and 300 °C for 10 min for improving conductivities with thermal treatment. Separate films of each material were evaluated for conductivity at room temperature after annealing. All films were also prepared with 5 wt.% of d-sorbitol, 0.1 wt.% DMF, 0.1 wt.% Surfynol[®] 2502, and with all three components simultaneously.

2.10. Measurements

Fourier transform infrared spectroscopy (FTIR) was performed using a MAGNA-IR560. Spectra was taken on ground powder in a KBr matrix with a scanning range of 500-4000 cm⁻¹, 64 scans at a resolution of 4 cm⁻¹. Thermogravimetric Analysis (TGA) was performed by a Perkin-Elmer TGA 7 series analysis system at a heating rate of 20 °C/min under air at a flow rate of 60 mL/min. Gel Permeation Chromatography (GPC) was done using a millipore model 150-C GPC system; DMAC was used as the mobile phase. The results were calibrated by standards of poly(methyl methacrylate). Nuclear Magnetic Resonance (NMR)¹H NMR spectra were recorded on a Bruker DMX-500 NMR Spectrometer. Conductivities were measured using a four-line collinear array utilizing a Keithley Instruments 224 constant current source and a 2700 Multimeter. The polymer was coated on the glass substrate having four gold coated leads on the surface across the entire width of the polymer and 0.25 cm apart from each other. The current was applied across the outer leads and voltage was measured across the inner leads.

3. Results and discussion

3.1. Diamine monomer and PEDOT, PANi, PPy with sulfonated poly (amic acid) templates

Firstly, we have synthesized the diamine monomer, 4.4'-diaminodiphenvl ether-2.2'-disulfonic acid (4.4'-ODADS) for use as a material used to make the sulfonated poly(amic acid). Fuming sulfuric acid was used as a sulfonated agent. The monomer structure was confirmed by ¹H NMR and FTIR. The FTIR spectrum shows absorptions at a) 1031.8 and b) 1088.3 cm⁻¹ for the sulfonic acid group, and at c) 3481.7 cm⁻¹ assigned to NH₂ of the diamime. The new template, sulfonated poly(amic acid) was synthesized with two different dianhydrides. The first template (SPAA1), 4,4'-oxydiphthalic anhydride (O-DPDA) is a dianhydride which has an ether bond (R-O-R) between two aromatic positions. It is a flexible system. The second template (SPAA2), 4,4'-hexafluoroisopropylideneoxydiphthalic anhydride (6FDA) is more thermally stable than the first template. The structure of poly(amic acid) was confirmed with FTIR. The broad absorption band at 3476.9 cm⁻¹ is assigned to the absorbed water in the sample (the sulfonic acid groups are highly hydrophilic). The peak at 1663.3 cm⁻¹ indicates the absorption bands of carbonyl group (CONH) and peak at *ca.* 2500-3500 cm⁻¹ indicate the absorption bands of the carboxylic acid (COOH). The sulfonic acid groups (SO₃H) appears at 1029.0 cm⁻¹, which confirmed formation of the prepared sulfonated poly(amic acid). After annealing at 180 °C for short curing time, the strong absorption band around 1719.7 cm^{-1} is assigned to the symmetric imide C=O stretching, and also the peak at 1778.6 cm^{-1} indicates the asymmetric imide C=O stretching, which confirmed the complete imidization to sulfonated poly(imide) (details in Supporting Information).

The conducting polymers were chosen due to their broad popularity in academia and industry. The templates were chosen on the basis of differences in rigidity. If a too-rigid template is chosen, either it will not be soluble in water when sulfonated or it will not allow for the templating of a conducting polymer. We have observed a failure to template polymerize when using sulfonated Kapton, for example, which is more rigid than our SPAA1 or SPAA2 systems when converted to their imide forms. The system chosen for SPAA2 was more rigid than SPAA1, but it was not so rigid as to disallow formation of the templated CP in any case. Balancing this issue is a key element to obtaining a usable template system. Further, reaction times have varied with the different systems. The control reaction for each CP takes 24 h (PSSA template). PEDOT-SPAA1 takes 7 days, but using SPAA2 required 5 days. PANi was much faster, overall, taking on the order of 12 h, regardless of the template. PPy systems achieved templating in 5 days, as well.

3.2. Conductivity

The conductivity of PEDOT, PANi, and PPy each with SPAA1, SPAA2, and PSS were all measured. In the cases where annealing was performed, the form of the template is actually the imide, SPI1 and SPI2, because only 5–10 min is needed to convert these films from the amic acid state. The second template (SPAA2) is less water soluble than the first template (SPAA1), this was attributed as the cause for a slight decrease in conductivity for systems using this template. However, it became a dark blue dispersion faster than PEDOT-SPAA1 (5 days as opposed to 7 days) indicating that the reaction is still viable. Comparison of the same template (SPAA1) at room temperature, the conductivities of PANi-SPAA1, PPy-SPAA1 and PEDOT-SPAA1 were 7.74 S/cm, 3.47 × 10⁻² S/cm and 2.04 × 10⁻⁴ S/cm, respectively. For SPAA2, the conductivities of PANi-SPAA2, PPy-SPAA2 and PEDOT-SPAA2 were 7.34 × 10⁻¹ S/cm, 3.63 × 10⁻³ S/cm and 1.96 × 10⁻⁴ S/cm, respectively. This shows

that PANi systems have higher conductivities than PPy and PEDOT systems, at room temperature.

After heat treatment, the chain alignment in the films will change due to the differences in rigidity of the poly(amic acid) and the poly(imide), leading to modified morphologies, which causes the observed conductivity enhancement. For example, after annealing at 180 °C for 10 min. the conductivity of PEDOT-SPI1 was increased from 2.04 \times 10⁻⁴ S/cm to 5.83 \times 10⁻³ S/cm, a 10-fold enhancement, but the conductivity of PANi-SPI1 decreased slightly from 7.74 S/cm to 2.88 S/cm. PPy-SPI1 did not significantly change, however, (from 3.47 \times 10⁻² to 5.00 \times 10⁻², which is within the standard deviation for these measurements). The chain rearrangements that caused a more marked increase for the PEDOT system appear to have less of an affect on PANi and PPy. The exhaustive results of all conductivities measured are shown in the Supporting Information, including all annealing and doping studies using d-sorbitol and other common additives. For ease of comparison, the highest achieved conductivity for each material synthesized herein is shown in Fig. 2. We found that the PANi systems had higher conductivities than PPy and PEDOT systems. The conductivities of PEDOT systems were increased from 2.04 \times 10⁻⁴ to 5.83×10^{-3} S/cm, after annealing at 180 °C for 10 min and increased from 2.04×10^{-4} to 6.47×10^{-4} S/cm, after annealing at 300 °C for 10 min. In the PPy systems, conductivities were increased from 3.47×10^{-2} to 5.00×10^{-2} S/cm only annealing at 180 °C for 10 min, but at 300 °C for 10 min the conductivities decreased from 3.47×10^{-2} to 8.33×10^{-3} S/cm. In the case of the PANi systems, conductivities were decreased by increasing temperature, but PEDOT-based films exhibited a 3-fold improvement after annealing at 180 °C for 90 min and also a 3-fold improvement for the SPI1 template (from 1.02×10^{-4} S/cm to 2.96×10^{-4} S/cm), and a 6-fold increase from 1.02×10^{-4} S/cm to 6.06×10^{-4} S/cm after annealing at 300 °C for 10 min (PEDOT-SPI1). PANi-SPI1 and PANi-SPI2 could no longer be measured after annealing at 300 °C, whereas PPy-SPI1 and PPy-SPI2 showed slightly lower conductivities. The conductivities of PPy-SPI1 and PPy-SPI2 at room temperature were 3.47×10^{-2} S/cm and 3.63×10^{-3} S/cm, respectively, whereas PPy-PSS was measured to be 2.47 S/cm. The highest value for PEDOT-SPAA1 was 8.99×10^{-2} S/cm, which was doped with DMF (0.1 wt.%) and annealed at 180 °C for 10 min (so, in reality, it was the PEDOT-SPI1). The highest value for PEDOT-SPAA2 was 6.44×10^{-2} S/cm, which was doped with d-sorbitol (5 wt.%). This means that the PEDOT-SPAA systems had the highest increases in conductivity (accomplished with 180 °C annealed samples upon secondary doping with common additives). For PANi systems, PANi-SPAA1 had the highest value, 7.74 S/cm, which was without heat treatment



Fig. 2. Conductivities of each system. (P1 = PEDOT-SP11 doped with DMF 0.1 wt.% at 180 °C, P2 = PEDOT-SPAA2 doped with d-sorbitol 5 wt.% at 20 °C, A1 = PANi-SPAA1 at 20 °C, A2 = PANi-SPAA2 doped with DMF 0.1 wt.% at 20 °C, Y1 = PPy-SPAA1 doped with DMF 0.1 wt.% at 20 °C, Y2 = PPy-SP12 doped with DMF 0.1 wt.% at 180 °C).



Fig. 3. Overlaid TGAs of a) PEDOT, PANi, PPy with SPI1 and b) PEDOT, PANi, PPy with SPI2.

or addition of a secondary dopant; but PANi-SPAA2 exhibited its highest value, 1.47 S/cm, when doped with DMF (0.1 wt.%). The result of PPy systems showed similar trends to the PEDOT systems: the conductivities were increased when doped with a secondary substance and also were annealed for a short time. The highest value for PPy-SPI1 was 3.97×10^{-1} S/cm and the highest value for PPy-SPI2 was 1.36×10^{-1} S/cm, which were doped with DMF (0.1 wt.%) and d-sorbitol (5 wt.%, respectively), and were both annealed at 180 °C for 10 min. The highest conductivities for all of the various samples are summarized in Fig. 2.

3.3. Thermal stability of films

A comparison of the thermal properties of PEDOT-SPI, PANi-SPI and PPy-SPI is shown in Fig. 3. Thermal stability of PEDOT-SPI1 was higher than that of PPy-SPI1 and PANi-SPI1, respectively. The SPI2 template exhibited a higher thermal stability than any of the other systems using the SPI1. This was an expected result due to the increased thermal stability of SPI2 as compared to SPI1 when not used as a template. This retention of properties should extend to other such poly(imide) systems as well. The initial weight loss for both (around 100 °C) is due to absorbed water. The weight loss at 250 °C is due to the decomposition of the sulfonic acid groups; the degradation of the polyimide backbone begins around 420 °C. By comparison, the PANi system has the lowest thermal stability, as seen from the TGA results, and could not retain its conductivity with high-temperature or long term curing. Isothermal TGAs were also run for each system, showing longer-term mass stabilities (see Supporting Information).

4. Conclusion

We have successfully demonstrated the versatility of our earlier system [19]. We have shown that sulfonated poly(amic acid)

templating is possible for three classes of conducting polymers: anilines, pyrroles, and thiophenes. Further, the resulting thermal stabilities upon imidization of the template could lead to their use in a variety of high-temperature applications or processing steps. The rigidification of the template backbone causes a rearrangement of the template conductor, resulting in a 10-fold increase in conductivity for PEDOT systems. As expected, certain systems possessed advantages over others. PANi-SPAA took far less time to synthesize and was more conductive overall, but did not survive higher temperatures than its PSSA-based control. PEDOT-SPI exhibited the highest thermal stability but had fairly low intrinsic conductivity. Secondary doping was able to enhance it by two orders of magnitude, however. It also takes seven days to synthesize, which could be a drawback for scalability. PPy systems seemed to balance these advantages and constraints, allowing for better thermal stability than PANi with slightly lower conductivities, yet higher conductivities than PEDOT-SPAA with lower thermal stability. It is clear that, depending on the desired use of these organic conductors, one has the ability to choose a class of materials that will suit their needs. Finally, we have observed that the more rigid the initial template, the lower the conductivity of the final sample. By choosing a more rigid second template, SPAA2, we were able to achieve higher thermal stability at a slight cost to the conductivity. The trends observed here serve to display the obvious tunability of this approach.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.polymer.2010.08.008.

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