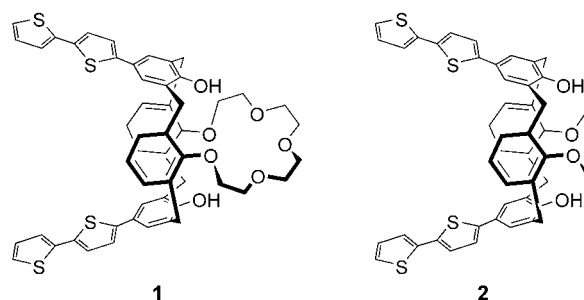


## Charge-Specific Interactions in Segmented Conducting Polymers: An Approach to Selective Ionoresistive Responses\*\*

Hsiao-hua Yu, Anthony E. Pullen, Michael G. Büschel, and Timothy M. Swager\*

Conductivity-based sensory devices built on electrically conductive polymers have proved to offer great promise towards the detection of a wide variety of analytes.<sup>[1]</sup> Selective chemoresistive responses have been demonstrated with charge localization,<sup>[2]</sup> planarization/twist of the polymer backbone to modify conjugation length,<sup>[3]</sup> and segmental energy matching/mismatching of the polymer backbone.<sup>[4]</sup> We have been interested in developing new chemoresistive methods to determine blood electrolyte levels that are diagnostic in determining the physiological condition of individuals. In particular, the determination of Ca<sup>2+</sup> ion concentration has attracted interest as a growing number of ionochromic sensors for this ion have been developed.<sup>[5]</sup> However, in view of the importance of this analyte new systems with enhanced specificity, better signal/noise ratios, and alternative sensory platforms remain a topic of interest. Herein, we report a new approach to produce a selective ionoresistivity resulting from a charge-specific interaction between the segmented conducting-polymer backbone and the bound metal ion.

We have previously reported a proton-doped calix[4]arene-based conducting polymer, formed by oxidative polymerization of monomer **2**.<sup>[6]</sup> The conductivity of the polymer film relies on rapid self-exchange between the discrete electroactive units attached to the upper (wider) rim of the calix[4]arene. To have this process be sufficiently fast, a condition for high conductivity, all of the phenolic oxygen atoms need to be maintained in their protonated state to ensure that the redox centers have equivalent energy levels and chemical structures. The high sensitivity of the resistivity to the chemical state of lower-rim phenolic oxygen atoms suggested to us that new sensory materials could be produced by designing specific cationic interactions with these centers. Herein we report our investigation of related polymers derived from monomer **1** (Scheme 1) which integrate a recognition site through the calix[4]arene-crown-5 moiety, a motif that has been demonstrated to provide differential



Scheme 1. Structures of calix[4]arene-based monomers **1** and **2**.

binding of metal cations.<sup>[7–10]</sup> Monomer **1** was synthesized by a pathway similar to that we reported for **2** by using palladium-catalyzed cross-coupling methodology.<sup>[6,11,12]</sup> To determine the binding of various metal ions, we treated monomer **1** with 10 equivalents of the respective salts, and the proton NMR spectra of the solutions revealed significant changes, as summarized in Table 1. To assert that these effects are the

Table 1: Proton NMR signals from bridge -CH<sub>2</sub>- of the calix[4]arene moiety and free O-H of monomer **1** in the presence of different Group 1 and Group 2 metal salts.<sup>[a]</sup>

Metal Ions	Bridge Ar-CH <sub>2</sub> -Ar [ppm] chemical shifts	$\Delta\delta$ <sup>[b]</sup>	O-H [ppm]
none <sup>[c]</sup>	3.50, 4.43	0.93	8.42
Li <sup>+</sup>	3.60, 4.32	0.72	8.28
Na <sup>+</sup>	3.65 <sup>[d]</sup> , 4.22	0.57	7.86
K <sup>+</sup>	3.65, 4.25 <sup>[d]</sup>	0.60	none <sup>[e]</sup>
Mg <sup>2+</sup>	3.51, 4.39	0.88	8.16
Ca <sup>2+</sup>	3.67, 4.34	0.67	7.96

[a] The spectra were obtained in the presence of 10 equivalents of the corresponding PF<sub>6</sub><sup>-</sup> or ClO<sub>4</sub><sup>-</sup> salt. [b] The difference between the pairs of high and low resonance signals. [c] Addition of the electrolyte, (nBu)<sub>4</sub>NPF<sub>6</sub>, resulted in no difference in the NMR spectrum. [d] The resonance signals overlap with the signals assigned to the ethylene-oxo bridge (-OCH<sub>2</sub>CH<sub>2</sub>O-). [e] No NMR signal associated with free OH is observed.

result of metal-ion binding, we confirmed that there was no change to the proton NMR spectra of **1** on the addition of (nBu)<sub>4</sub>NPF<sub>6</sub>, a non-binding electrolyte. In addition, we observed that solutions of **2** displayed no spectroscopic differences with these metal-ion salts, which indicates that the difference in the NMR shifts is not simply due to an enhanced ionic strength.

The resonances assigned to the -CH<sub>2</sub>- bridge (Ar-CH<sub>2</sub>-Ar) of the calix[4]arene remain a pair of doublets in the presence of alkali-metal ions, but their relative chemical shifts ( $\Delta\delta$ ) changes. The initial  $\Delta\delta$  for the ion-free calix[4]arene-crown is 0.93 ppm. When metal ions are introduced, we observed a diagnostic decrease in  $\Delta\delta$  ranging from 0.57 to 0.88 ppm, suggestive of a “flattened-cone” conformation.<sup>[13]</sup> The characteristic shifts of the ethylene-oxo bridge resonances (-OCH<sub>2</sub>CH<sub>2</sub>O-) between  $\delta = 3.50$  and 4.50 ppm confirm that the alkali-metal ions bind to the crown moiety at the lower rim. This is further supported by the fact that there are no significant changes of the upper-rim aromatic-ring resonance

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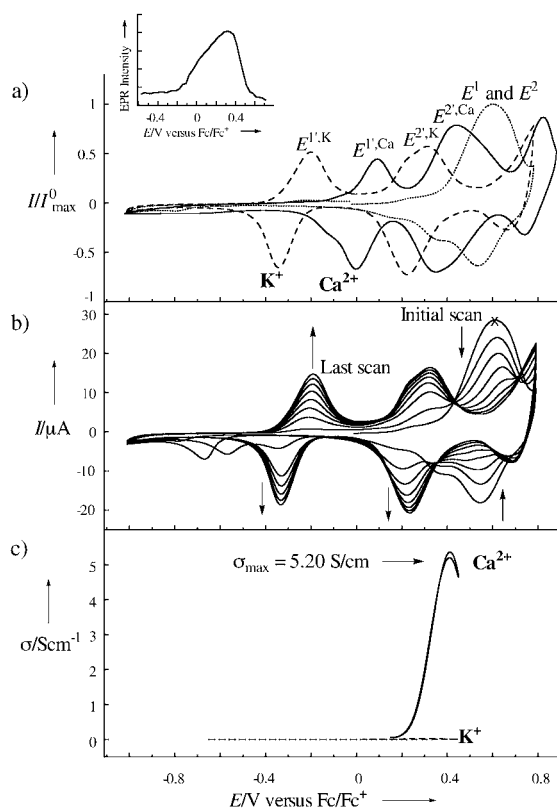
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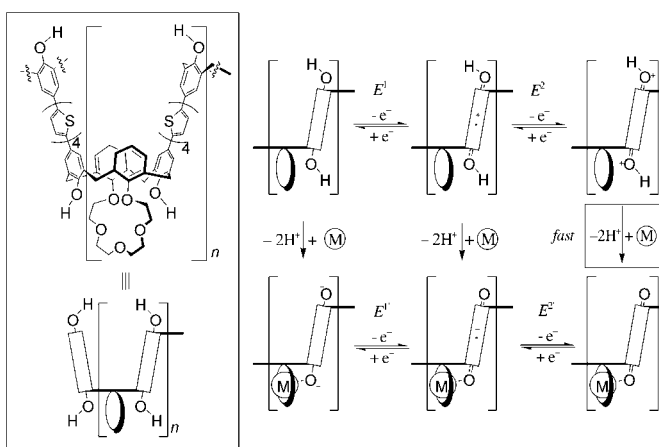
signals on ion binding. In contrast, we found that for free phenol the  $\delta = 8.42$  ppm  $^1\text{H}$  NMR signal shifts upfield and decreases in intensity or completely disappears in the case of  $\text{K}^+$ , indicating rapid proton exchange.

Monomers **1** and **2** were subjected to anodic electropolymerization to form films of Poly(**1**) and Poly(**2**) on the surface of the electrode.<sup>[14]</sup> Both films display a quasireversible two-electron wave with a half-wave potential ( $E_{1/2}$ ) around 0.55 V ( $E^1$  and  $E^2$  in Figure 1 a).<sup>[15,16]</sup> While non-bonding Poly(**2**) films are completely insensitive to the presence of metal ions, the voltammetric responses of Poly(**1**) films in solution containing the different metal ions ( $\text{PF}_6^-$  or  $\text{ClO}_4^-$  salts) display significant differences. Smaller ions ( $\text{Na}^+$ ,  $\text{Li}^+$ ) only produced minor shifts of the cathodic peak potentials ( $E_{p,c}$ ) and this limited response is attributed to the low binding constant between these ions and the calix[4]arene-crown-5 system.<sup>[7]</sup> In contrast, cycling in an electrolyte containing  $\text{K}^+$  ions transforms the voltammogram

from a single two-electron wave to two new waves with  $E_{1/2}^{1,K} = 0.28$  V and  $E_{1/2}^{2,K} = -0.26$  V (Figure 1 a). The steady-state voltammogram evolves with continued cycling (Figure 1 b). The development of electroactivity at more negative potentials is probably the result of proton loss from the oxidized phenol units to give an extended *p*-diquinone-like redox system.<sup>[17,18]</sup> We had previously observed small amounts of proton loss in Poly(**2**) in  $\text{CH}_3\text{CN}$ , however it appears that in the case of Poly(**1**) the deprotonation is driven to completion by the presence of  $\text{K}^+$  ions under oxidizing potentials and the resulting dianions are stabilized by the binding of the metal ions. Therefore the evolution of the voltammograms not only can be explained by the coupling between electrochemical process and proton–metal-ion exchange but also suggests that the exchange is accelerated by the applied potential (Scheme 2). This explanation is also consistent with the



**Figure 1.** Cyclic voltammograms and in situ conductivity measurement of Poly(**1**) film in 0.1 M  $(n\text{Bu})_4\text{NPF}_6/\text{CH}_3\text{CN}$  containing 10 mM  $\text{K}^+$  or  $\text{Ca}^{2+}$  ions at a scan rate of  $50 \text{ mVs}^{-1}$ . a) Comparison of the original cyclic voltammogram (dotted line) and voltammetric responses toward  $\text{K}^+$  (dashed line), and  $\text{Ca}^{2+}$  (solid line) ions.  $I_{\text{max}}^0$  is the maximum current obtained in the initial scan (e.g. marked with an X in Figure 1 b). Inset: In situ EPR spectroscopy of Poly(**1**) after the film is saturated with  $\text{K}^+$  ions. b) Scan-by-scan transformation of Poly(**1**) film on Pt button electrode ( $2 \text{ mm}^2$  surface area) as the  $\text{K}^+$  ions diffuse into the binding sites of the polymer film; X marks the initial scan. c) In situ conductivity measurements for Poly(**1**) films with  $\text{K}^+$  and  $\text{Ca}^{2+}$  ions. Measurements made on a  $5 \mu\text{m}$  interdigitated microelectrode at a sweep rate of  $5 \text{ mVs}^{-1}$  with a 40 mV offset potential between adjacent electrodes.



**Scheme 2.** Coupling equilibria between electrochemical process and proton–ion exchange of Poly(**1**) and Poly(**2**). The exchange occurs fastest once the complex has undergone a two-electron oxidation.

transient more negative reduction wave at  $-0.67$  V ( $E_{p,c}$ ) that is present in the initial cycles before shifting to a less negative potential at  $-0.33$  V. The  $-0.67$  V wave in the initial scans is attributed to an incomplete distribution of  $\text{K}^+$  ions throughout all of the receptor sites, which leads to the formation of higher energy anions. When Poly(**1**) films are immersed in electrolyte solution containing  $\text{Ca}^{2+}$ , we see a similar behavior, however, both waves ( $E_{1/2}^{1,\text{Ca}} = 0.06$  V and  $E_{1/2}^{2,\text{Ca}} = 0.41$  V) are shifted to values that are positive relative to the  $\text{K}^+$  complex, consistent with the higher charge of the  $\text{Ca}^{2+}$  ion.

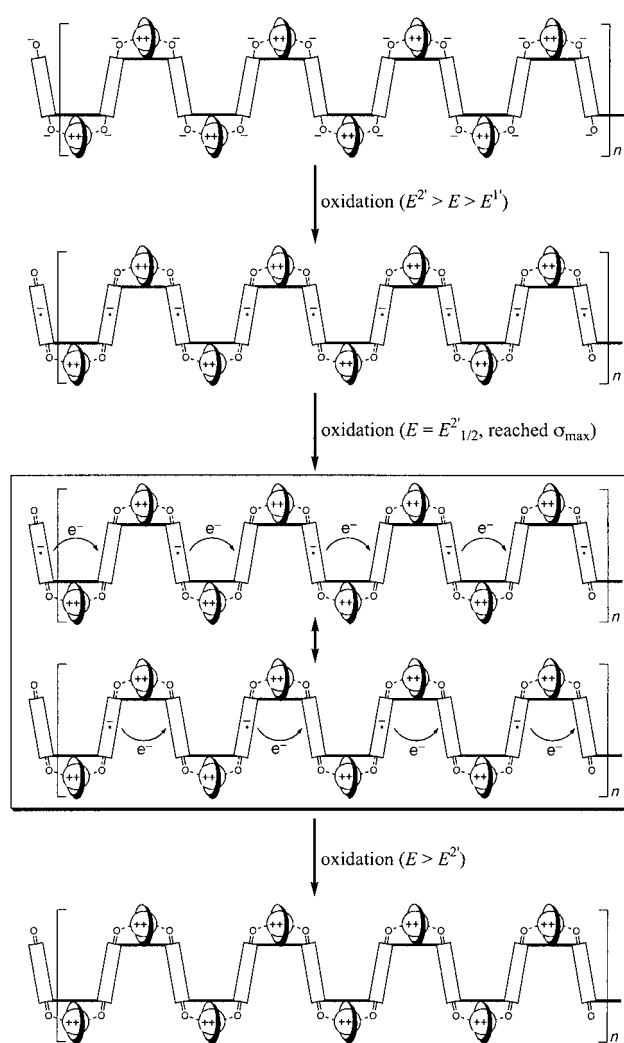
In situ EPR spectroscopy revealed a maximum signal ( $g = 2.005$  and constant peak-to-peak width of ca. 5 G) at  $E = 0.11$  V, which is positioned midway between the two principle redox waves (Figure 1 a, inset). This profile is consistent with weakly interacting electroactive segments that undergo single-electron redox processes. A similar profile is observed for material complexed with  $\text{Ca}^{2+}$  ion. To find further support for the proton–metal-ion exchange mechanism, a small amount of methylviolate was added to the solution.<sup>[19]</sup> After cycling in electrolyte solution containing  $\text{K}^+$  or  $\text{Ca}^{2+}$  ions, an increase of absorption intensity from the indicator's acid form ( $\lambda_{\text{max}} = 442 \text{ nm}$ ) was displayed (see Supporting Information), identi-

fying the release of protons from the polymer to the solution. In addition,  $K^+$ -ion recognition of Poly(**1**) film is also examined in the presence of trifluoroacetic acid, which hinders the deprotonation of the calixarene. In contrast to the negative shift observed without the acid (Figure 1 a), the incorporation of metal ion results in a positive shift of the oxidation potential of the extended *p*-dihydroquinone ( $E_{1/2} = 0.77$  V, see Supporting Information), which is due to the positively charged ion bound to the protonated phenol unit.

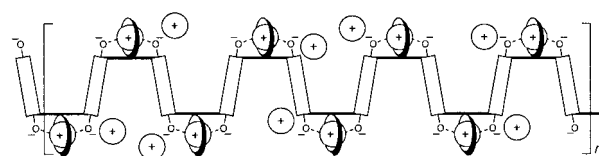
Given the localized behavior of the redox segments of Poly(**1**) in the presence of  $K^+$  and  $Ca^{2+}$  ions, it is clear that electrical conduction is best considered to be by a hopping (self-exchange) mechanism. The hopping rate will be optimal when each segment has the same environment to ensure isoenergetic character. The maximum conductivity ( $\sigma_{\max}$ ) of Poly(**1**) is  $0.6 \text{ S cm}^{-1}$  (not shown) when oxidized in  $\text{CH}_2\text{Cl}_2$  or acidic  $\text{CH}_3\text{CN}$  solutions,<sup>[20]</sup> however, upon addition of  $K^+$  ions, the conductivity is reduced to  $<1\%$  of its original value (Figure 1 c). In contrast, subjecting Poly(**1**) films to similar conditions but in the presence of  $Ca^{2+}$  ions gives very different results. The maximum conductivity raises to  $5.2 \text{ S cm}^{-1}$ , almost an order of magnitude increase over the as-synthesized film.

There are several ways in which  $Ca^{2+}$ -ion complexation can influence the rate of electron transfer (conductivity). The conductivity maximum at  $0.41$  V ( $E_{1/2}^{2+,Ca}$ ) for the  $Ca^{2+}$ -Poly(**1**) complex corresponds to a state where there is an equal amount radical anion segments and neutral *p*-diquinone segments (Figure 2, boxed section). As is the case with bound protons in the conductive Poly(**2**) film, bound  $Ca^{2+}$  ions located near the *p*-diquinone units enhance the electron delocalization of these electroactive segments. Therefore a lower energy barrier for electron hopping results. However, in the case of the  $K^+$  ions, the fact that the calix[4]arene crown receptor can only precisely bind one monovalent cation creates a situation wherein there are net negative charges on the polymer backbone (Figure 3). To compensate the charges, there are unbound  $K^+$  and/or small numbers of protons in the  $K^+$ -Poly(**1**) film. The presence of disordered unbound ions results in nondegenerate energy levels of individual electroactive segments. In addition, the dissociation of unbound  $K^+$  ions with partial oxidation results in even greater inequivalence and hopping becomes a more activated process. It is also possible that the interaction of the receptor with ions can produce a geometry change in the calix[4]arene that places the redox-active segments closer to each other and thereby increases the intersegment electron-transfer rate. As was mentioned above, solution  $^1\text{H NMR}$  spectroscopy measurements suggest a flattened-cone conformation that potentially reduces the interchain distance between redoxactive segments.

Of all the potential mechanisms by which  $Ca^{2+}$  ions can enhance the conductivity of Poly(**1**), we believe that charge balance between the polymer backbone and the bound metal ion is dominant. Our rationale for this statement is supported by the general trends observed when Poly(**1**) is exposed to different monovalent and divalent metal ions. Specifically, treatment of Poly(**1**) films with solutions containing monovalent cations  $\text{Na}^+$  and  $\text{Li}^+$ , similar to  $\text{K}^+$ , resulted in insulating films, even though NMR spectroscopic measure-



**Figure 2.** Schematic representation of the conducting mechanism of  $Ca^{2+}$ -Poly(**1**) film.



**Figure 3.** Schematic representation of  $K^+$ -Poly(**1**) film at fully reduced state.

ments suggest similar perturbations to the calixarene's conformation. To further support our charge-balancing model we found that treatment with  $10$  mM of divalent  $\text{Mg}^{2+}$  and  $\text{Ba}^{2+}$  also provide high conductivity films ( $\sigma_{\max} = 0.48 \text{ S cm}^{-1}$  for  $\text{Mg}^{2+}$  and  $1.71 \text{ S cm}^{-1}$  for  $\text{Ba}^{2+}$ ).

In summary, we have demonstrated a new conceptual approach to selective ionoresistive sensing. Although the binding of monovalent  $\text{K}^+$  and divalent  $\text{Ca}^{2+}$  ions to the calixarene crown produces extremely similar NMR spectroscopic and cyclic voltammetric behaviors, the conductivities show more than three orders of magnitude difference. We propose that this profound sensitivity to the charge state of

the metal ion is related to the need for charge balancing between the redox segments and the metal ions, which is essential for efficient hopping conductivity. This charge-balancing principle is general and will be applied to other sensor designs.

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- [1] a) D. T. McQuade, A. E. Pullen, T. M. Swager, *Chem. Rev.* **2000**, *100*, 2537; b) T. M. Swager, *Acc. Chem. Res.* **1998**, *31*, 201.
- [2] M. J. Marsella, P. J. Carroll, T. M. Swager, *J. Am. Chem. Soc.* **1994**, *116*, 9347.
- [3] a) M. J. Marsella, T. M. Swager, *J. Am. Chem. Soc.* **1993**, *115*, 12214; b) M. J. Marsella, R. J. Newland, P. J. Carroll, T. M. Swager, *J. Am. Chem. Soc.* **1995**, *117*, 9842.
- [4] a) S. S. Zhu, T. M. Swager, *J. Am. Chem. Soc.* **1997**, *119*, 12568; b) R. P. Kingsborough, T. M. Swager, *Adv. Mater.* **1998**, *10*, 1100; c) T. Shioya, T. M. Swager, *Chem. Commun.* **2002**, 1364.
- [5] a) Y. H. Kim, N. R. Cha, S.-K. Chang, *Tetrahedron Lett.* **2002**, *43*, 3883; b) Y. Kubo, S. Tokita, Y. Kojima, Y. T. Osano, T. Matsuzaki, *J. Org. Chem.* **1996**, *61*, 3758; c) Y. Kubo, S. Obara, S. Tokita, *Chem. Commun.* **1999**, 2399.
- [6] H.-h. Yu, B. Xu, T. M. Swager, *J. Am. Chem. Soc.* **2003**, *125*, 1142.
- [7] Similar compounds with calix[4]arene-crown-5 moiety have been found with the binding free energy:  $K^+ > Na^+ > Li^+$ , see A. Casnati, A. Pochini, R. Ungaro, C. Bocchi, F. Ugozzoli, R. J. M. Egberink, H. Struijk, R. Lugtenberg, F. deJong, D. N. Reinhoudt, *Chem. Eur. J.* **1996**, *2*, 436.
- [8] Other compounds with calix[4]arene-crown-5 moiety have also been found binding  $Ca^{2+}$  and  $Ba^{2+}$  ions, respectively, see reference [5a] and R. Cacciapaglia, A. Casnati, L. Mandolini, R. Ungaro, *J. Am. Chem. Soc.* **1992**, *114*, 10956.
- [9] a) P. J. Dijkstra, J. A. J. Brunink, K. E. Bugge, D. N. Reinhoudt, S. Harkema, R. Ungaro, F. Ugozzoli, E. Ghidini, *J. Am. Chem. Soc.* **1989**, *111*, 7567; b) E. Ghidini, F. Ugozzoli, R. Ungaro, S. Harkema, A. A. El-Fadl, D. N. Reinhoudt, *J. Am. Chem. Soc.* **1990**, *112*, 6979; c) K. Takahashi, A. Gunji, D. Guillaumont, F. Pichierri, S. Nakamura, *Angew. Chem.* **2000**, *112*, 3047; *Angew. Chem. Int. Ed.* **2000**, *39*, 2925.
- [10] For reports of cyclic voltammetric studies of polythiophene with pendant crown ether moieties see: a) J. Roncali, R. Garreau, M. Lemaire, *J. Electroanal. Chem.* **1990**, *278*, 373; b) P. Bäuerle, S. Scheib, *Acta Polym.* **1995**, *46*, 124; c) H. K. Yousoufi, M. Hmyene, F. Garnier, D. Delabouglise, *J. Chem. Soc. Chem. Commun.* **1993**, 1550.
- [11] Detailed experimental conditions and material preparations are available in the Supporting Information. Monomer **1**: m.p. 181–182 °C;  $^1H$  NMR (500 MHz,  $CDCl_3$ ):  $\delta$  = 7.93 (s, 2H), 7.33 (s, 4H), 7.19 (dd, 2H,  $J$  = 5.0, 1.0 Hz), 7.17 (dd, 2H,  $J$  = 3.5, 1.0 Hz), 7.12 (d, 2H,  $J$  = 3.5 Hz), 7.09 (d, 2H,  $J$  = 3.5 Hz), 7.01 (dd, 2H,  $J$  = 5.0, 3.5 Hz), 6.93 (d, 4H,  $J$  = 8.0 Hz), 6.77 (t, 2H,  $J$  = 8.0 Hz), 4.46 (d, 4H,  $J$  = 13.5 Hz), 4.12 (bm, 8H), 3.96 (t, 4H,  $J$  = 5.5 Hz), 3.85 (t, 4H,  $J$  = 5.5 Hz), 3.42 ppm (d, 4H,  $J$  = 13.5 Hz);  $^{13}C$  NMR (125 MHz,  $CDCl_3$ ):  $\delta$  = 153.6, 152.0, 143.9, 137.8, 135.0, 132.7, 129.1, 128.5, 127.8, 126.0, 125.4, 125.1, 124.5, 123.9, 123.1, 122.1, 76.8, 71.1, 71.0, 70.2, 31.1 ppm. FT-IR (KBr):  $\tilde{\nu}$  = 3500–3100 (broad, OH), 2919, 2361, 2339, 1484, 1456, 1250, 1202, 1136, 1081, 1051, 796, 694  $cm^{-1}$ . HR-MS (ESI): calcd for  $C_{52}H_{46}O_7S_4 + NH_4^+$  928.2464 [( $M + NH_4^+$ )]<sup>+</sup>; found 928.2461.
- [12] A. F. Littke, G. C. Fu, *Angew. Chem.* **2002**, *114*, 4350; *Angew. Chem. Int. Ed.* **2002**, *41*, 4176.
- [13] C. D. Gutsche, *Calixarenes, Monographs in Supramolecular Chemistry* (Ed.: J. F. Stoddart), The Royal Society of Chemistry, Cambridge, UK, **1989**.
- [14] Electropolymerizations were performed in  $CH_2Cl_2$  containing 1 mM of monomer **1** or **2** and 0.1M  $(nBu)_4NPF_6$  by repeated cycling of the electrode between  $-0.4$  V and  $0.8$  V at a scan rate of  $100$   $mVs^{-1}$ .
- [15] All potentials are referenced to  $Fc/Fc^+$  ( $Fc$  = ferrocene). A standard three-electrode setup was used for all electrochemical studies: Pt button working electrode, Pt coil counter electrode, and  $Ag/Ag^+$  reference electrode. Ferrocene is used as an external standard.
- [16] In situ EPR experiments confirm the redox wave as a two-electron transition. A build up of intensity ( $g = 2.002$ ) was displayed as the polymer oxidized and reached a maximum at anodic peak potential ( $E_{pa} = 0.58$  V), indicating the formation of a state with unpaired electrons. The spin density decreased as the film was further oxidized. This is evidence of the formation of another spinless state. This build up and decay is consistent with a two-electron transition.
- [17] The coupling equilibria of electroactivity and proton-ion exchange from the repeating unit is similar to what was reported by Echegoyan and co-workers, see a) D. A. Gustowski, M. Delgado, V. J. Gatto, L. Echegoyan, G. W. Gokel, *J. Am. Chem. Soc.* **1986**, *108*, 7553; b) M. Delgado, D. A. Gustowski, H. K. Yoo, V. J. Gatto, G. W. Gokel, L. Echegoyan, *J. Am. Chem. Soc.* **1988**, *110*, 119.
- [18] Electrochemical properties of thiophene-extended *p*-diquinone have been studied, see K. Takahashi, T. Suzuki, *J. Am. Chem. Soc.* **1989**, *111*, 5483.
- [19] M. Lapkowski, E. M. Genies, *J. Electroanal. Chem.* **1990**, *284*, 127.
- [20] A method originally designed by Wrighton and co-workers (G. P. Kittlesen, H. S. White, M. S. Wrighton, *J. Am. Chem. Soc.* **1984**, *106*, 7389) was used for the measurement.