(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
16 October 2014 (16.10.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/169122 A1

(51) International Patent Classification:
H01M 10/28 (2006.01) *H01M 4/24* (2006.01)
H01M 4/60 (2006.01) *H01M 10/36* (2010.01)

(21) International Application Number:
PCT/US2014/033652

(22) International Filing Date:
10 April 2014 (10.04.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/810,599 10 April 2013 (10.04.2013) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) Title: AQUEOUS ENERGY STORAGE DEVICES WITH ORGANIC ELECTRODE MATERIALS

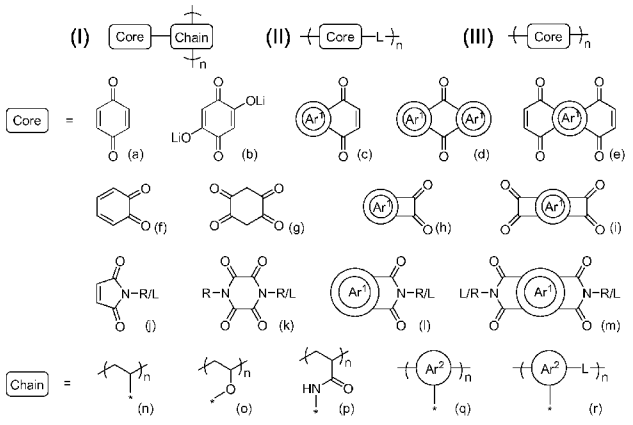


FIGURE 1

(57) Abstract: An aqueous metal-ion battery and a method for constructing same. In one embodiment, the battery includes an aqueous electrolyte and at least one electrode comprising at least one organic electrode material. A method comprises incorporating an organic electrode material into the electrode of an aqueous metal-ion battery. The organic electrode material further comprises at least one material chosen from carbonyl compounds.

WO 2014/169122 A1

AQUEOUS ENERGY STORAGE DEVICES WITH ORGANIC ELECTRODE MATERIALS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/810,599 filed on April 10, 2013 and titled "Aqueous Batteries with Organic Electrode Materials," the application in its entirety being incorporated herein by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made in part with Government support under award titled “Aqueous lithium-ion batteries with high-energy novel organic anodes for safe and robust energy storage" by The U.S. Department of Energy (award number: DE-AR0000380). The Government has certain rights in this invention.

BACKGROUND

Field of the Disclosure

[0003] This disclosure relates to a secondary or rechargeable battery, specifically to a battery with an aqueous electrolyte and at least one organic material used for an electrode.

Background

[0004] Generally, aqueous metal-ion batteries (AMIBs) represent a potential improvement in battery technology for commercial and industrial applications, particularly in vehicular designs. Prototype aqueous batteries have previously demonstrated ~75 Wh/kg of energy density based on the weight of electrodes. However, this parameter remains below the effective specific energy densities required to meet various governmental and regulatory recommended metrics, as well as certain application-specific demands. Further, it has been demonstrated that some cathode materials employed in some non-aqueous lithium-ion batteries (LIBs) are generally stable in aqueous electrolytes. Exemplary lithium-based cathode materials such as layered $LiCoO_2$ and spinel $LiMn_2O_4$ have shown capacities approaching their theoretical values with good reversibility at high charge/discharge rates. However, the intercalation compound-based anodes have demonstrated unsatisfactory cyclability in AMIBs, including aqueous lithium ion batteries (ALIB), due to material dissolution into the bulk electrolyte and oxidation by O_2 at the discharged state. Currently, creating an anode material with satisfactory cyclability for operation in high energy density batteries represents a technological hurdle to commercial implementation of AMIBs as a whole.

SUMMARY

[0005] The disclosure includes an AMIB having at least one electrode comprising at least one organic electrode material, wherein the organic electrode material comprises an organic electroactive compound. Further disclosed is an AMIB comprising a first electrode comprising at least one organic electrode material, an aqueous electrolyte, and a second electrode capable of metal-ion (de)intercalation/(un-)coordination. The first electrode comprises at least one organic electrode material chosen from carbonyl compounds.

[0006] Also disclosed is a method of constructing an aqueous battery comprising preparing an electrode capable of metal-ion (de)intercalation/(un-)coordination, contacting the electrode capable of metal-ion (de)intercalation/(un-)coordination with an aqueous electrolyte, preparing an electrode comprising at least one organic electrode material, contacting the electrode comprising at least one organic electrode material with the aqueous electrolyte, and applying an electric current to the two electrodes. The electrode comprising at least one organic electrode material comprises one or a mixture of organic electrode materials bearing electroactive carbonyl groups.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] For a detailed description of the disclosed embodiments, reference will now be made to the accompanying drawings in which:

[0008] FIGURE 1 illustrates representative molecular structures of the organic electrode materials (OEMs) for implementation as electrode materials for an AMIB;

[0009] FIGURE 2 illustrates O_2/H_2 evolution potential of water as a function of pH as compared to the potential and capacity of state-of-the-art anode materials for ALIBs (on the left) and the disclosed organic carbonyl compounds (OCCs) (on the right);

[0010] FIGURE 3 illustrates molecular structures of exemplary OEMs;

[0011] FIGURE 4 illustrates the charge–discharge profile of PAQS in a 2.0 M Li_2SO_4 aqueous solution at pH 14 measured in a three-electrode cell at a rate for charge and discharge of 1C (Coulomb);

[0012] FIGURE 5 illustrates the comparison of the capacity and cycling stability of PAQS in alkaline metal salt-based electrolytes ($[M^+]$ = 5 M) at neutral (pH 7) and basic (pH 14) conditions at a rate for charge and discharge of 1C;

[0013] FIGURE 6 illustrates the cycling performance of PAQS in a 2.0 M TEACl aqueous solution at pH 14 at a rate for charge and discharge of 1C;

[0014] FIGURE 7 illustrates the charge–discharge profile of PBDTD in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell at a rate for charge and discharge of 1C;

[0015] FIGURE 8 illustrates the cycling performance of PBDTD in a 2.5 M Li_2SO_4 aqueous solution at pH 7 at a rate for charge and discharge of 1C;

[0016] FIGURE 9 illustrates the charge–discharge profile of a full cell comprising PBDTD as the anode and $LiMn_2O_4$ as the cathode with a 2.5 M Li_2SO_4 aqueous solution (pH 7) as the electrolyte at a rate for charge and discharge of 1C;

[0017] FIGURE 10 illustrates the comparison of the capacity and cycling stability of PBDTD in sodium/alkaline earth metal salt-based electrolytes ($[Na^+]$ = 5 M and $[M^{2+}]$ = 2.5M, respectively) at pH 7 at a rate for charge and discharge of 1C;

[0018] FIGURE 11 illustrates the rate capability of PBDTD in a 2.5 M Li_2SO_4 aqueous solution at pH 7at the same rate for both charge and discharge;

[0019] FIGURE 12 illustrates the charge–discharge profile of PBDTDS in a 2.5 M Li_2SO_4 aqueous solution at pH 13 measured in a three-electrode cell at a rate for charge and discharge of 1C;

[0020] FIGURE 13 illustrates the rate capability of PBDTDS in a 2.5 M Li_2SO_4 aqueous solution at pH 13 at the same rate for both charge and discharge;

[0021] FIGURE 14 illustrates the cycling performance of PBDTDS in a 2.5 M Li_2SO_4 aqueous solution at pH 13 at a rate for charge and discharge of 10C;

[0022] FIGURE 15 illustrates the charge–discharge profile of a full cell comprising PBDTDS as the anode and $LiCoO_2$ as the cathode with a 2.5 M Li_2SO_4 aqueous solution (pH 13) as the electrolyte at a rate for charge and discharge of 5C;

[0023] FIGURE 16 illustrates the comparison of the capacity and cycling stability of PBDTDS in lithium salt-based electrolytes ($[Li^+]$ = 5 M) at neutral (pH 7) and basic (pH 13) conditions at a rate for charge and discharge of 1C;

[0024] FIGURE 17 illustrates the charge–discharge profile of PBFFD in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell at a rate for charge and discharge of 1C;

[0025] FIGURE 18 illustrates the charge–discharge profile of PBFFDS in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell at a rate for charge and discharge of 1C;

[0026] FIGURE 19 illustrates the charge–discharge profile of PPQ in a 2.5 M Li_2SO_4 aqueous solution at pH 13 measured in a three-electrode cell at a rate for charge and discharge of 1C;

[0027] FIGURE 20 illustrates the cycling performance of PPQ in a 2.5 M Li_2SO_4 aqueous solution at pH 13 at a rate for charge and discharge of 1C;

[0028] FIGURE 21 illustrates the charge–discharge profile of PPTO in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell. Rate for charge and discharge: 1C;

[0029] FIGURE 22 illustrates the charge–discharge profile of PNDI in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell. Rate for charge and discharge: 1C;

[0030] FIGURE 23 illustrates the charge–discharge profile of PNDIE in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell. Rate for charge and discharge: 1C;

[0031] FIGURE 24 illustrates the rate capability of PNDIE in a 2.5 M Li_2SO_4 aqueous solution at pH 7. Same rate for both charge and discharge;

[0032] FIGURE 25 illustrates the cycling performance of PNDIE in a 2.5 M Li_2SO_4 aqueous solution at pH 7. Rate for charge and discharge: 10C;

[0033] FIGURE 26 illustrates the comparison of the capacity and cycling stability of PNDIE in sodium/magnesium salt-based electrolytes ($[Na^+]$ = 5 M and $[Mg^{2+}]$ = 2.5M, respectively) at pH 7. Rate for charge and discharge: 1C;

[0034] FIGURE 27 illustrates the charge–discharge profile of PNDIB in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell. Rate for charge and discharge: 1C;

[0035] FIGURE 28 illustrates the charge–discharge profile of PPDIE in a 2.5 M Li_2SO_4 aqueous solution at pH 7 measured in a three-electrode cell. Rate for charge and discharge: 1C.

DETAILED DESCRIPTION

[0036] OVERVIEW: Generally, electrical energy storage devices include capacitors and batteries. While both have various applications, batteries are preferred in the computer and electric vehicle industries for their cyclability and energy/power density. Batteries and particularly secondary or rechargeable batteries are configured as one or more electrochemical cells capable of converting electrical energy into chemical energy during charging and converting chemical energy into electric energy during discharging. In operation of most conventional batteries, the cathode and anode undergo compositional changes during discharging that are restored during charging. The medium through which the electrodes are electrically coupled is the electrolyte. Currently, solutions of salts, bases, and acids in aqueous/non-aqueous solvents are used as electrolytes in secondary batteries.

[0037] The present disclosure relates to configurations of aqueous electrolyte batteries. Aqueous electrolyte batteries may provide design options that are not available in organic electrolyte-based battery configurations, such as but not limited to LIBs. More specifically, AMIBs have improved safety and flexibility in vehicle design at reduced system costs compared to LIBs because AMIBs including aqueous lithium-ion batteries (ALIB) use the highly reversible ion-intercalation principle of conventional LIBs but with lower-cost, nonflammable aqueous electrolytes.

[0038] Further, the present disclosure relates to battery configurations including at least one electrode comprising OEMs including but not limited to, OCCs. The OEMs of the present disclosure are configurable to operate as both the anode and cathode or to couple with existing cathodic and anodic materials, including but not limited to lithium mixed oxides. In these configurations, the OEM applications in AMIBs demonstrate inorganic and organic hybrid redox couples. As disclosed herein, these redox couples appear to satisfy certain technical performance targets for energy density both in weight and in volume. Further, these properties are maintained in AMIB configurations comprising at least one organic electrode. Thus, organic electrode AMIB configurations disclosed herein represent an additional reduction in the cost of producing a battery, without reduction in cyclability and energy/power density.

[0039] ORGANIC ELECTRODE MATERIALS: Figure 1 illustrates representative molecular structures of the exemplary OEMs for implementation as electrode materials for an AMIB. Generally, OCCs are used as the anodic material for an AMIB. The OCCs are characterized by reversibly reducible R–C(=O)–R' groups. Suitable OCCs comprise at least one structural formula illustrated in Figure 1. The three structural formulas comprise (I) structures where electroactive cores are attached to a poly-/oligomer segment, (II) structures where electroactive cores are linked with linkers in-between, and (III) structures where electroactive cores are directly connected to one another. In the structural formulas (I), (II), and (III), the core comprises carbonyl group. With respect to the structural formula (I) the chain comprises any polymer or oligomer. Likewise, in structural formula (II), L comprises a moiety chosen from the group consisting of dicarbonyl, NH, O, S, CH_2, $(CH_2)_2$, $(CH_2)_3$, $(CH_2)_4$, $(CH_2)_6$, optionally substituted 5–6 membered aryl/heteroaryl groups, and biaryls consisted of two identical or different optionally substituted 5–6 membered aryl/heteroaryl groups. Without limitation, "n" indicates the average number of repeating units in the formula. The average number of repeats is at least 2.

[0040] Figure 1 likewise illustrates exemplary core structures (a) through (m) that fit within the

three OCC structural formulas (I)–(III). In the core structures (a) through (m), Ar^1 comprises at least one moiety chosen from the group consisting of naphthalene, perylene, optionally substituted 5–6 membered aryl/heteroaryl groups, and biaryls consisted of two identical or different optionally substituted 5–6 membered aryl/heteroaryl groups. Likewise, in the core structures (a)–(m), R comprises at least one moiety chosen from H, CH_3, or C_2H_5.

[0041] These OCCs are generally insoluble even at the reduced state and show stable capacity retention in both organic and aqueous electrolytes. The employed electroactive moieties without limitation include 1,4-benzoquinone, 1,2-benzoquinone, 1,2-bicarbonyl, diimide, and their derivatives. Aromatic rings can be incorporated to fine-tune the properties of the OCCs. Without limitation by any particular theory, the structural variety and design strategy of organic compounds permit predictable tuning of their redox potential in a wide range in order to fulfill specific device requirements. The reduced form of these structures coordinated to metal-ions, which are prepared via (electro)chemical reduction or formed in situ during charge–discharge, are also within the scope of the disclosure. The disclosed OCCs can demonstrate the characteristics for implementation as electrode materials for ALIBs. As noted hereinabove, these OEMs are merely representative and related configurations of the OEMs are considered within the scope of the present disclosure.

[0042] ORGANIC ELECTRODE POTENTIALS: Referring now to Figure 2, the O_2/H_2 evolution potential of an exemplary aqueous electrolyte model, in this case water, as a function of pH is illustrated. More specifically, the thermodynamic stability of water is illustrated by solid lines and the dashed lines show the kinetic stability range for aqueous electrolytes considering the over-potentials for gas evolution. In exemplary embodiments of the present disclosure, the organic electrode materials are selected and configured to have a potential within the range of the kinetic stability, including the gas evolution over-potentials, at a pH 7.

[0043] The electrochemical characteristics of the OCCs illustrated in Figure 1 are summarized in TABLE 1. Exemplary OCCs include anthraquinone (AQ), benzofuro[5,6-*b*]furan-4,8-dione (BFFD), 2,5-dimethoxy-1,4-benzoquinone (DMBQ), poly(2,5-dihydroxy-1,4-benzoquinonyl sulfide (PDBS), poly(pyromellitic diimide) (PI), 5,7,12,14-pentacenetetrone (PT), and pyrene-4,5,9,10-tetraone (PTO), without limitation.

[0044] TABLE 1: OCC Electrochemical Characteristics

Name	MW	Number of carbonyls	Theoretical Specific Capacity (mAh/g)	Observed Specific Capacity (mAh/g)	Average Reduction Potential (V vs. Li/Li^+)

AQ	208.2	2	257	239	2.27
BFFD	188.1	2	285	257	2.45
DMBQ	168.2	2	319	312	2.60
PDBS	170.1	2	315	228	2.05
PI	257.2	4	417	237	2.08
PT	338.3	4	319	300	2.10
PTO	262.2	4	409	360	2.59

[0045] Referring still to Figure 2, the potentials of known metal oxide electrodes and exemplary OEMs as a function of specific capacity are illustrated. Generally speaking metal oxide electrodes exhibit specific capacities that do not exceed 200 mAh/g. The metal oxide electrodes are conventionally found in ALIBs. However, the specific capacities of the OEMs are greater than 200 mAh/g. In Figure 1, the exemplary OEMs include the previously discussed OCCs. Thus, a battery configured with the OEMs disclosed herein provides a method of increasing the specific capacity of a battery.

[0046] TABLE 2: OEM Electrochemical Characteristics

Name	MW	Number of Active Carbonyls	Theoretical Specific Capacity (mAh/g)	Average Reduction Potential (V vs. Ag/AgCl)
PAQS	238	2	225	–0.80
PBDTD	218	2	246	–0.45
PBDTDS	250	2	214	–0.42
PBFFD	186	2	288	–0.38
PBFFDS	218	2	246	–0.34
PPQ	206	2	260	–0.45
PPTO	260	4	412	–0.46
PNDI	264	2	203	–0.44
PNDIE	292	2	183	–0.56
PNDIB	340	2	158	–0.55
PPDIE	242	2	221	–0.79

[0047] ELECTRODE AND CELL FABRICATION: The OEM electrodes are fabricated by coating a support with a mixture containing at least one OEM. Generally, the mixture is coated onto a support and pressed and/or dried to form the electrode. Alternatively, the mixture may be compressed in contact with a foil, foam, or mesh. More specifically, the mixture comprises a dispersion of at least one OEM, conductive carbon, and at least one fluoropolymer. In certain configurations, the mixture comprises a polar solvent such as but not limited to N-methyl-2-pyrrolidone (NMP), ethanol, and isopropanol. The electrochemical characteristics of some exemplary OEMs are summarized in TABLE 2.

[0048] The mixture comprises a dispersion of OEM, conductive carbon, and a fluoropolymer. The concentration of the OEM is between about 20 wt.% and about 90 wt.%, and in certain configurations between about 30 wt.% and about 80 wt.%. The conductive carbon

concentration is between about 5 wt.% and about 75 wt.%, and in certain configurations between about 10 wt.% and about 60 wt.%. The fluorpolymer concentration is between about 1 wt.% and about 30 wt.% and in certain configurations between about 5 wt.% and about 25 wt.%. The fluoropolymer may comprise at least one chosen from polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE).

[0049] The support is configured to be a current collector. Non-limiting examples of current collectors comprise a metallic foam, foil, or mesh. The metal of the foam, foil, or mesh comprises at least one transition metal, including Group VIB, VIIB, VIII, IB, IIB, and IIIA metals. In configurations, the foam, foil, or mesh comprises a Group VIII metal, such as but not limited to nickel (Ni); alternatively, the foam, foil, or mesh comprises a Group IIIA metal such as but not limited to aluminum (Al). Further, the foam, foil, or mesh may be coated by a second metal chosen from the transition metal groups listed hereinabove. Likewise, the second metal is a Group VIII metal, such as but not limited to nickel (Ni). In alternative configurations, the foam, foil, or mesh may comprise stainless steel.

[0050] Generally, the mixture coats the support and is pressed and/or dried to form the OEM electrode. Alternatively, the mixture may be forced into the support prior to drying. Occasionally, pressure is used to force the mixture into the foam or mesh supports. In certain instances, the pressure comprises mixture injections, compression of the mesh or foam, and the compression of mesh or foam loaded with the (dried) mixture. Pressure may include 0.3–2.0 MPa without limitation.

[0051] ORGANIC-METAL ION HYBRIDS BATTERIES: In some configurations, the disclosed electrode materials are configurable for implementation in AMIBs. In these configurations, the batteries comprise an electrode capable of intercalation by/coordination to at least one metal-ion chosen from the group comprising lithium (Li), sodium (Na), magnesium (Mg), calcium (Ca), and in certain instances aluminum (Al). Again, without limitation by any particular theory, the batteries configured thusly use a group of electrochemical redox couples that leverage metal-ion battery electrode chemistry characteristics to potentially provide a reliable and high capacity electrode material to meet certain technical performance parameters for AMIBs in commercial applications.

[0052] COUNTER ELECTRODE FABRICATION: Counter electrodes containing compounds capable of metal-ion (de)intercalation/(un-)coordination may be utilized. Generally, the counter electrodes comprise between about 50 wt.% and about 100 wt.% of compounds capable of metal-ion (de)intercalation/(un-)coordination; alternatively the counter electrodes comprise between about 60 wt.% and about 95 wt.% metal-containing compounds.

For the fabrication of aqueous lithium-ion batteries, non-limiting exemplary compounds capable of metal-ion (de)intercalation/(un-)coordination include $LiCoO_2$, $LiMn_2O_4$, $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, lithium-rich mixed oxides, $LiNi_{0.5}Mn_{1.5}O_4$ $Ni(OH)_2$, MnO_2, carbonyl compounds, organosulfur compounds, radical compounds, non-conjugated polymers, and combinations thereof. In instances, the counter-electrodes are fabricated in a mixture method as described hereinabove. Additionally, aqueous solutions of one or a mixture of lithium salts such as but not limited to $LiNO_3$, Li_2SO_4, LiCl, and LiOH ($[Li^+] = 0.5–14.0$ M) are used as the electrolyte.

[0053] In certain configurations, the disclosed batteries uses a group of electrochemical redox couples that leverage lithium-ion battery cathode chemistry characteristics to potentially provide a reliable and high capacity anode material to meet certain technical performance parameters for ALIBs in commercial applications. Certain exemplary OEMs that are sustainable, low-cost, and high-energy are illustrated in Figure 3. One exemplary electrochemical redox couple of $LiMn_2O_4$/PAQS has the following reactions illustrated in Equation 1 [EQ 1] and Equation 2 [EQ 2].

[EQ 1] Anode: $C_{14}H_6O_2S$ (PAQS) + $xLi^+ + xe^- \Leftrightarrow C_{14}H_6O_2SLi_x$ (~ –0.8 V vs. Ag/AgCl)

[EQ 2] Cathode: $LiMn_2O_4 \Leftrightarrow Li_{1-x}Mn_2O_4 + xLi^+ + xe^-$ (~1.0 V vs. Ag/AgCl)

[0054] Specifically, the aqueous electrolytes are composed of at least one metal salt as solute and an aqueous solvent which comprises at least 90 wt.% of water. The aqueous electrolytes may have a pH between about pH 2 and about pH 15. Alternatively, the aqueous electrolytes may have a pH between about pH 6 and about pH 14. In further configurations, the electrolytes may be chosen to most stably support the operation of the electrodes, including a cathode capable of metal-ion (de)intercalation/(un-)coordination and an OEM electrode.

[0055] Further, manipulation of the chemical structure, molecular weight, and degree of crystallinity of the OEMs provides increased stability and robustness, particularly in the instances of mechanical trauma or thermal runaway. Thus, the disclosed OEMs may be incorporated into an AMIB such that special protection is unneeded in commercial applications, including vehicular and industrial applications. Additionally, in the present disclosure, the battery configurations are multifunctional. Relating to the stability of the OEMs and the tunability of the electrolytes in the secondary or rechargeable, aqueous, metal-ion battery, the battery may be configurable as a structural member. Exemplary structural members

may comprise frames, supports, trusses, chassis, or other components of electrical and mechanical equipment.

[0056] To further illustrate various illustrative embodiments of the present invention, the following examples are provided.

EXAMPLES

[0057] Example 1: PAQS (see Figure 3a) A mixture of PAQS (70 wt.%), Super-P carbon (20 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.0 M) and LiOH (1.0 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.80 V vs Ag/AgCl (Figure 4). PAQS delivers reversible cycling performance when working in sodium (2.0 M NaCl + 1.0 M NaOH)/potassium (2.0 M KCl + 1.0 M KOH) salt-based electrolytes (Figure 5). In particular, when tetraethylammonium (TEA) (2.0 M TEACl + 1.0 M TEAOH) was used, no noticeable capacity decrease was observed after 50 cycles at 1C rate (for both charge and discharge) (Figure 6). A lower capacity was obtained when a neutral lithium salt-based electrolyte (2.5 M Li_2SO_4) was used.

[0058] Example 2: PBDTD (see Figure 3b) A mixture of PBDTD (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.45 V vs Ag/AgCl (Figure 7). Rate performance tested in two-electrode coin cells showed a 93% capacity retention at 10C compared to that obtained at 1C (Figure 8). At 1C rate (for both charge and discharge), no noticeable capacity decrease was observed after 50 cycles (Figure 9). Alternatively, a mixture of $LiMn_2O_4$ (80 wt.%), Super-P carbon (10 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the counter electrode. Coin cells are fabricated to demonstrate an average discharge potential of 1.02 V (Figure 10). PBDTD also delivered stable cycling performance when working in sodium (5 M $NaNO_3$)/calcium (2.5 M $Ca(NO_3)_2$) salt-based electrolytes (Figure 11). When a magnesium salt-based electrolyte was used, a lower capacity but similar cycling stability was obtained.

[0059] Example 3: PBDTDS (see Figure 3c) PBDTDS was synthesized with a similar method as that for PAQS. A mixture of PBDTDS (30 wt.%), Super-P carbon (60 wt.%), and

polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) and LiOH (0.1 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.42 V vs Ag/AgCl (Figure 12). Rate performance tested in two-electrode coin cells showed 91 % and 60% of capacity retention at 10C and 100C, respectively (Figure 13). At 10C rate (for both charge and discharge), 93% of the original capacity was maintained after 2000 cycles (Figure 14). Alternatively, a mixture of $LiCoO_2$ (80 wt.%), Super-P carbon (10 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the counter electrode. Coin cells are fabricated to demonstrate an average discharge potential of 0.96 V (Figure 15). When a neutral electrolyte was used, a lower capacity was obtained (Figure 16).

[0060] Example 4: PBFFD (see Figure 3d) PBFFD was synthesized with a similar method as that for PBDTD. A mixture of PBFFD (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.38 V vs Ag/AgCl (Figure 17).

[0061] Example 5: PBFFDS (see Figure 3e) PBFFDS was synthesized with a similar method as that for PAQS. A mixture of PBFFDS (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.34 V vs Ag/AgCl (Figure 18).

[0062] Example 6: PPQ (see Figure 3f) PPQ was synthesized with a similar method as that for PBDTD. A mixture of PPQ (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) of LiOH (0.1 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction

potential of –0.45 V vs Ag/AgCl (Figure 19). At 1C rate (for both charge and discharge), no capacity degradation was observed after 200 cycles (Figure 20).

[0063] Example 7: PPTO (see Figure 3g) PPTO was synthesized with a similar method as that for PBDTD. A mixture of PPTO (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.46 V vs Ag/AgCl (Figure 21).

[0064] Example 8: PNDI (see Figure 3h) A mixture of PNDI (30 wt.%), Super-P carbon (60 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.44 V vs Ag/AgCl (Figure 22).

[0065] Example 9: PNDIE (see Figure 3i) A mixture of PNDIE (60 wt.%), Super-P carbon (30 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.56 V vs Ag/AgCl (Figure 23). Rate performance tested in two-electrode coin cells showed a 84 % capacity retention at 10C compared to that obtained at 1C (Figure 24). At 10C rate (for both charge and discharge), no noticeable capacity decrease was observed after 2000 cycles (Figure 25). PNDIE also delivered stable cycling performance when working in sodium (5 M $NaNO_3$)/magnesium (2.5 M $Mg(NO_3)_2$) salt-based electrolytes (Figure 26).

[0066] Example 10: PNDIB (see Figure 3j) A mixture of PNDIB (60 wt.%), Super-P carbon (30 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.55 V vs Ag/AgCl (Figure 27).

[0067] Example 11: PPDIE (see Figure 3k) A mixture of PPDIE (60 wt.%), Super-P carbon (30 wt.%), and polytetrafluoroethylene (10 wt.%) was pressed into a stainless steel mesh to

form the working electrode. A glass fiber paper wet with an aqueous solution of Li_2SO_4 (2.5 M) is placed between the working electrode and a piece of activated carbon cloth serving as the counter electrode. Three-electrode coin cells are fabricated to demonstrate an average reduction potential of –0.79 V vs Ag/AgCl (Figure 28).

[0068] Variations, combinations, and/or modifications of the embodiment(s) and/or features of the embodiment(s) disclosed herein made by a person having ordinary skill in the art are within the scope of the disclosure. Alternative embodiments that result from combining, integrating, and/or omitting features of the embodiment(s) are also within the scope of the disclosure. Where numerical ranges or limitations are expressly stated, such express ranges or limitations should be understood to include ranges or limitations of like magnitude falling within the expressly stated ranges or limitations (e.g., from about 1 to about 10 includes, 2, 3, 4, etc.; greater than 0.10 includes 0.11, 0.12, 0.13, etc.). For example, whenever a numerical range with a lower limit, R_l, and an upper limit, R_u, is disclosed, any number falling within the range is specifically disclosed. In particular, the following numbers within the range are specifically disclosed: $R=R_l+k*(R_u-R_l)$, wherein k is a variable ranging from 1 percent to 100 percent with a 1 percent increment, i.e., k is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent, ….. 50 percent, 51 percent, 52 percent... 95 percent, 96 percent, 97 percent, 98 percent, 99 percent, or 100 percent. Moreover, any numerical range defined by two R numbers as defined in the above is also specifically disclosed. Use of the term "optionally" with respect to any element of a claim means that the element is required, or alternatively, the element is not required, both alternatives being within the scope of the claim. Use of broader terms such as “comprises”, “includes”, and “having” means “including but not limited to” and should be understood to also provide support for narrower terms such as “consisting of”, “consisting essentially of”, and “comprised substantially of”. Accordingly, the scope of protection is not limited by the description set out above but is defined by the claims that follow, that scope including all equivalents of the subject matter of the claims. Each and every claim is incorporated as further disclosure into the specification and the claims are exemplary embodiment(s) of the present invention. The discussion of a reference in the disclosure is not an admission that it is prior art, especially any reference that has a publication date after the priority date of this application. The disclosure of all patents, patent applications, and publications cited in the disclosure are hereby incorporated by reference, to the extent that they provide exemplary, procedural or other details supplementary to the disclosure.

CLAIMS

What is claimed is:

1. An aqueous metal-ion battery comprising:

an aqueous electrolyte; and

at least one electrode comprising at least one organic electrode material.

2. The battery of claim 1, wherein at least one organic electrode material comprises an organic carbonyl compound.

3. The battery of claim 2, wherein the organic carbonyl compound comprises a structural formula chosen from the group consisting of (I), (II), and (III).

4. The battery of claim 3, wherein the organic carbonyl compound comprises a core having at least one structural formula chosen from the group consisting of (a), (b), (c), (d), (e), (f), (g), (h), (i), (j), (k), (l), and (m).

5. The battery of claim 4, wherein the core is coupled to at least one chemical group chosen from the group consisting of a polymer chain, an oligomer chain, dicarbonyl, NH, O, S, CH_2, $(CH_2)_2$, $(CH_2)_3$, $(CH_2)_4$, $(CH_2)_6$, optionally substituted 5–6 membered aryl/heteroaryl groups, and another core.

6. The battery of claim 4, wherein the core comprises at least one chemical group chosen from the group consisting of naphthalene, perylene, optionally substituted 5–6 membered aryl/heteroaryl groups, biaryls having optionally substituted 5–6 membered aryl/heteroaryl groups, H, CH_3, and C_2H_5

7. The battery of claim 2, wherein the carbonyls in the core are reduced and coordinated to metal-ions.

8. The battery of claim 1, comprising a counter electrode consisting of at least one organic or inorganic electrode material.

9. The battery of claim 8, wherein the counter electrode is capable of intercalation

by/coordination to at least one metal-ion chosen from the group consisting of lithium (Li), sodium (Na), magnesium (Mg), calcium (Ca), and aluminum (Al), and combinations thereof.

10. The battery of claim 8, wherein the organic counter electrode comprises at least one organic electrode material chosen from the group consisting of carbonyl compounds, organosulfur compounds, radical compounds, non-conjugated polymers, and combinations thereof.

11. A battery electrode comprising:

a support; and

an organic electrode material.

12. The electrode of claim 11, wherein the electrode comprises at least one structure chosen from the group consisting of foam, foil, or mesh constructed of at least one metal chosen from the group consisting of Group VIB, VIIB, VIII, IB, IIB, and IIIA metals.

13. The electrode of claim 11, wherein the organic electrode material comprises an organic carbonyl compound.

14. The electrode of claim 13, wherein the organic carbonyl compound comprises a structural formula chosen from the group consisting of (I), (II), and (III).

15. The electrode of claim 14, wherein the organic carbonyl compound comprises a core having at least one structural formula chosen from the group consisting of (a), (b), (c), (d), (e), (f), (g), (h), (i), (j), (k), (l), and (m).

16. The electrode of claim 15, wherein the core is coupled to at least one chemical group chosen from the group consisting of a polymer chain, an oligomer chain, dicarbonyl, NH, O, S, CH_2, $(CH_2)_2$, $(CH_2)_3$, $(CH_2)_4$, $(CH_2)_6$, optionally substituted 5–6 membered aryl/heteroaryl groups, and biaryls having two identical or different optionally substituted 5–6 membered aryl/heteroaryl groups.

17. The electrode of claim 15, wherein the core comprises at least one chemical group comprising naphthalene, perylene, optionally substituted 5–6 membered aryl/heteroaryl

groups, biaryls having two identical or different optionally substituted 5–6 membered aryl/heteroaryl groups, H, CH_3, and C_2H_5

18. A method of constructing an aqueous battery comprising:

preparing a first electrode consisting of at least one organic electrode material;

preparing a second electrode; and

contacting the two electrodes with an aqueous electrolyte.

19. The method of claim 18, wherein the first electrode comprises a support coated with a mixture containing at least one organic carbonyl compound having a structural formula chosen from the group consisting of (I), (II), and (III).

20. The method of claim 18, wherein the second electrode comprises an inorganic or organic compound capable of intercalation by/coordination to at least one metal-ion chosen from the group consisting of lithium (Li), sodium (Na), magnesium (Mg), calcium (Ca), and aluminum (Al), and combinations thereof.

21. The method of claim 18, wherein the aqueous electrolyte comprises at least one metal salt as solute and an aqueous solvent which comprises at least 90 wt.% of water.

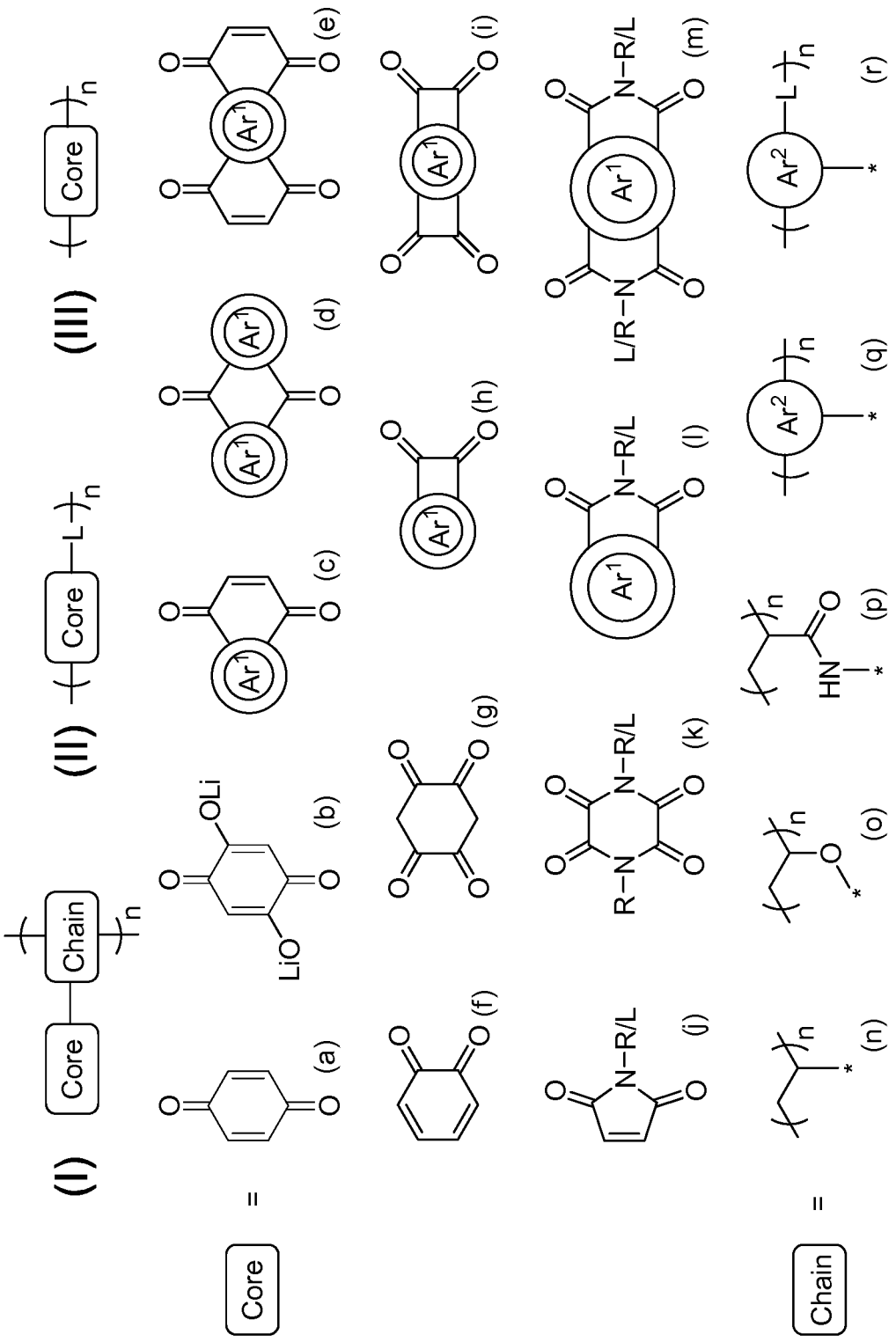

(I)
Core
Chain
n
(II)
Core
L
n
(III)
Core
n
=
(a)
(b)
OLi
LiO
(c)
(d)
(e)
Ar1
(f)
(g)
(h)
(i)
N–R/L
R–N
(j)
(k)
(l)
(m)
L/R–N
Ar2
(n)
(o)
HN
(p)
(q)
(r)
Core
Chain

FIGURE 1

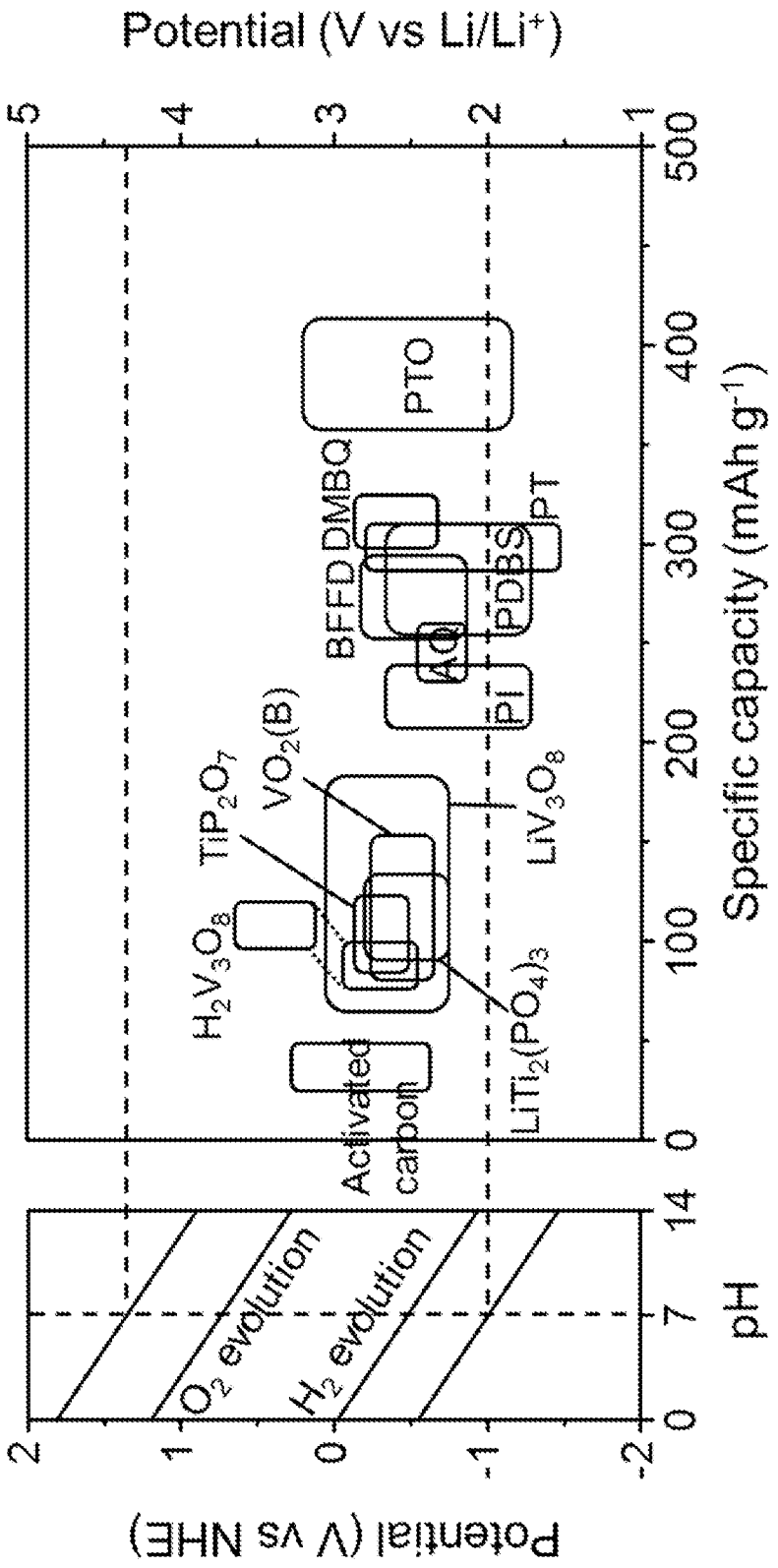

Potential (V vs Li/Li+)
Specific capacity (mAh g-1)
pH
Potential (V vs NHE)
O2 evolution
H2 evolution
Activated carbon
H2V3O8
TiP2O7
VO2(B)
LiTi2(PO4)3
LiV3O8
BFFD
DMBQ
PTO
AQ
PI
PDBS
PT

FIGURE 2

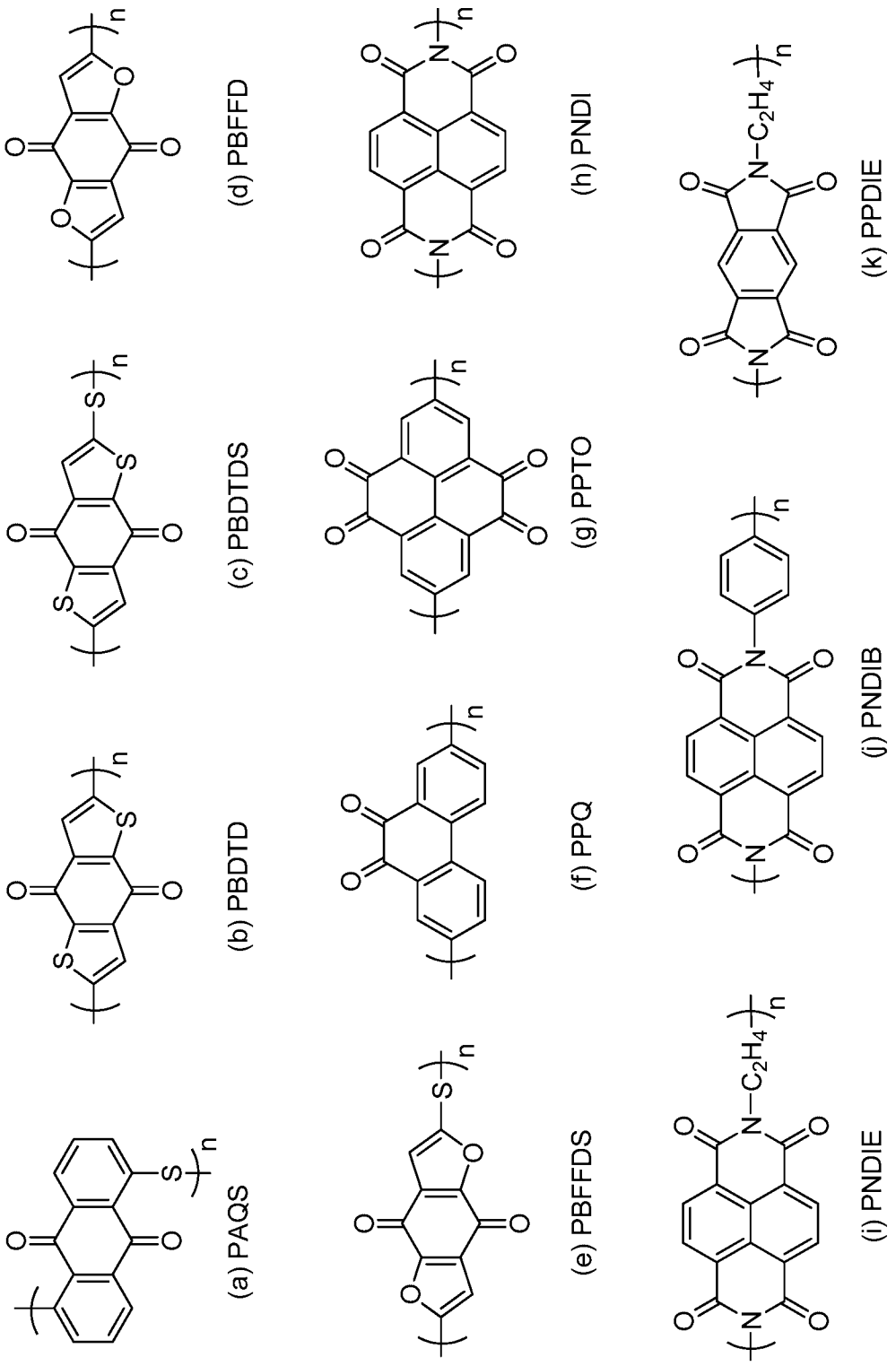

(a) PAQS
(b) PBDTD
(c) PBDTDS
(d) PBFFD
(e) PBFFDS
(f) PPQ
(g) PPTO
(h) PNDI
(i) PNDIE
(j) PNDIB
(k) PPDIE

FIGURE 3

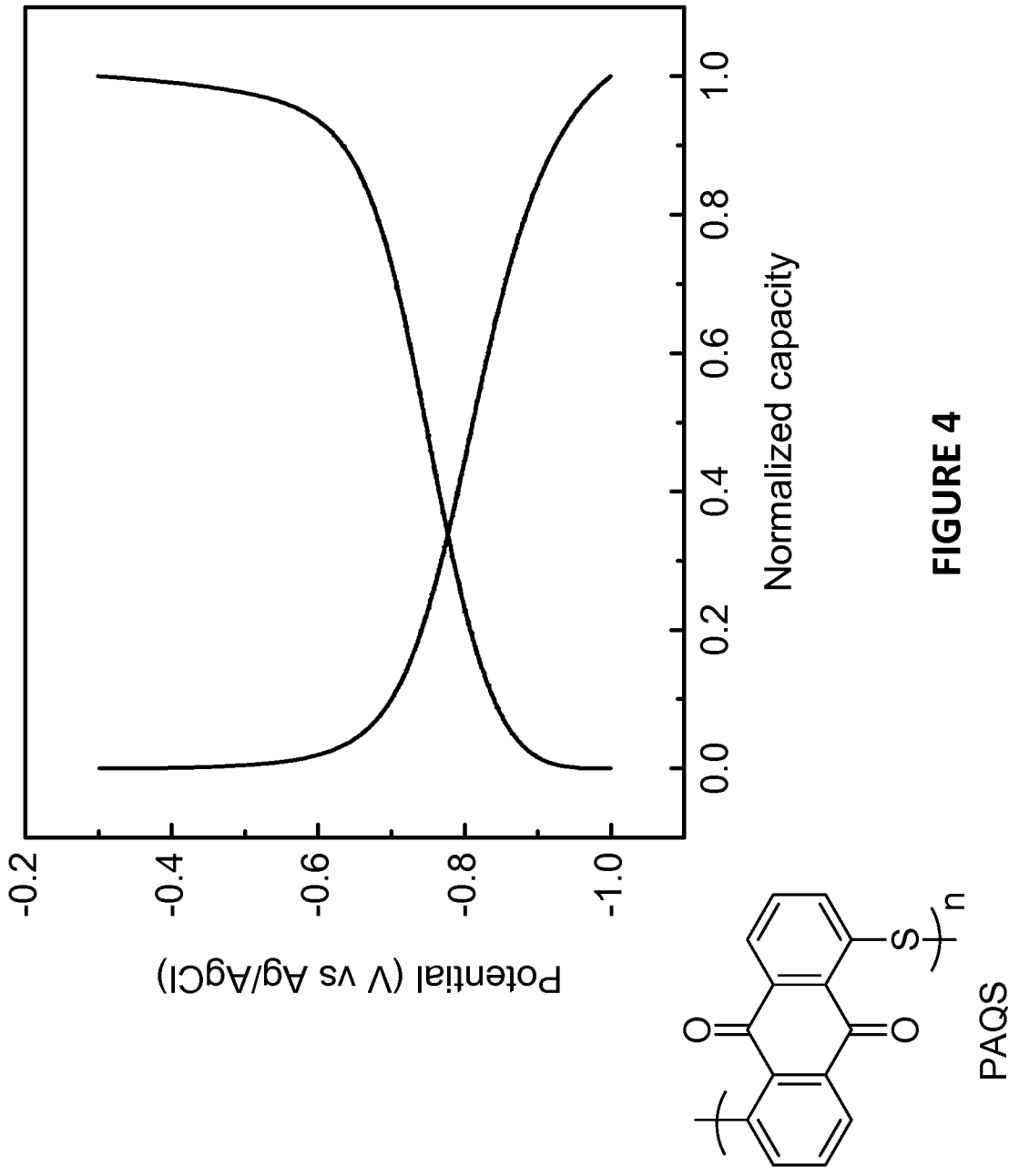

Potential (V vs Ag/AgCl)
-0.2
-0.4
-0.6
-0.8
-1.0
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
S
n
PAQS

FIGURE 4

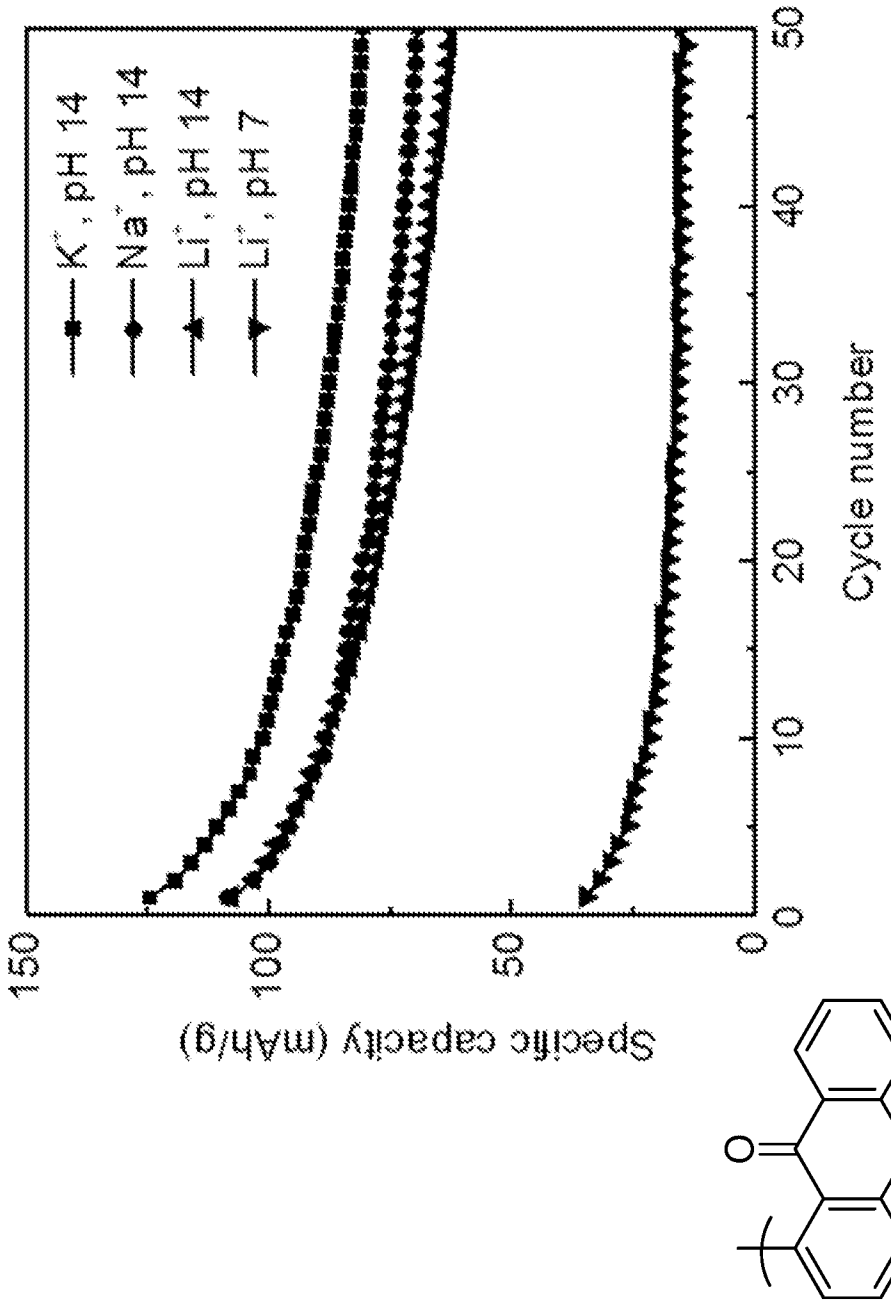

Specific capacity (mAh/g)
150
100
50
0
0
10
20
30
40
50
Cycle number
K+, pH 14
Na+, pH 14
Li+, pH 14
Li+, pH 7
O
O
S
n
PAQS

FIGURE 5

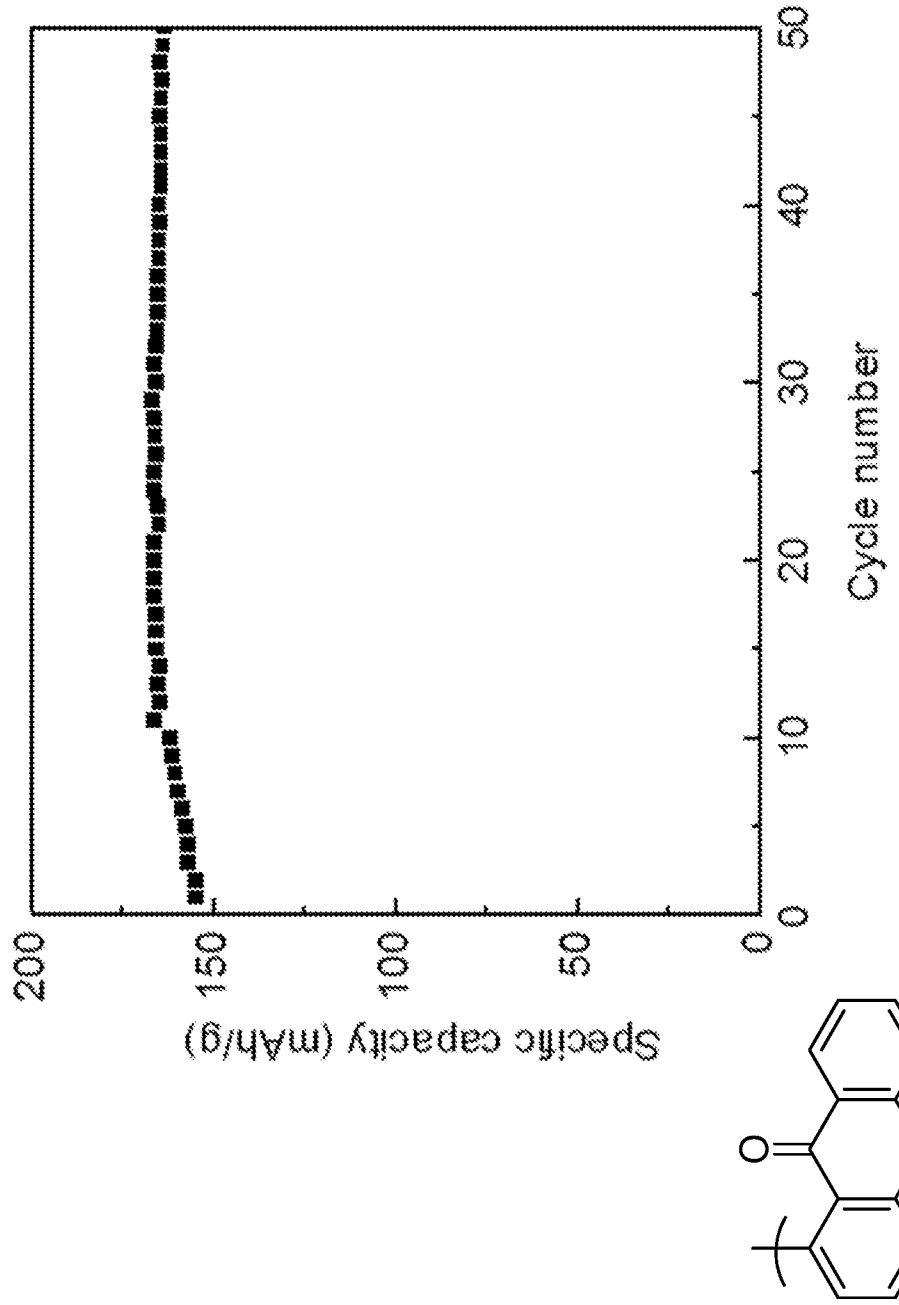

Specific capacity (mAh/g)
200
150
100
50
0
0
10
20
30
40
50
Cycle number
O
O
S
n
PAQS

FIGURE 6

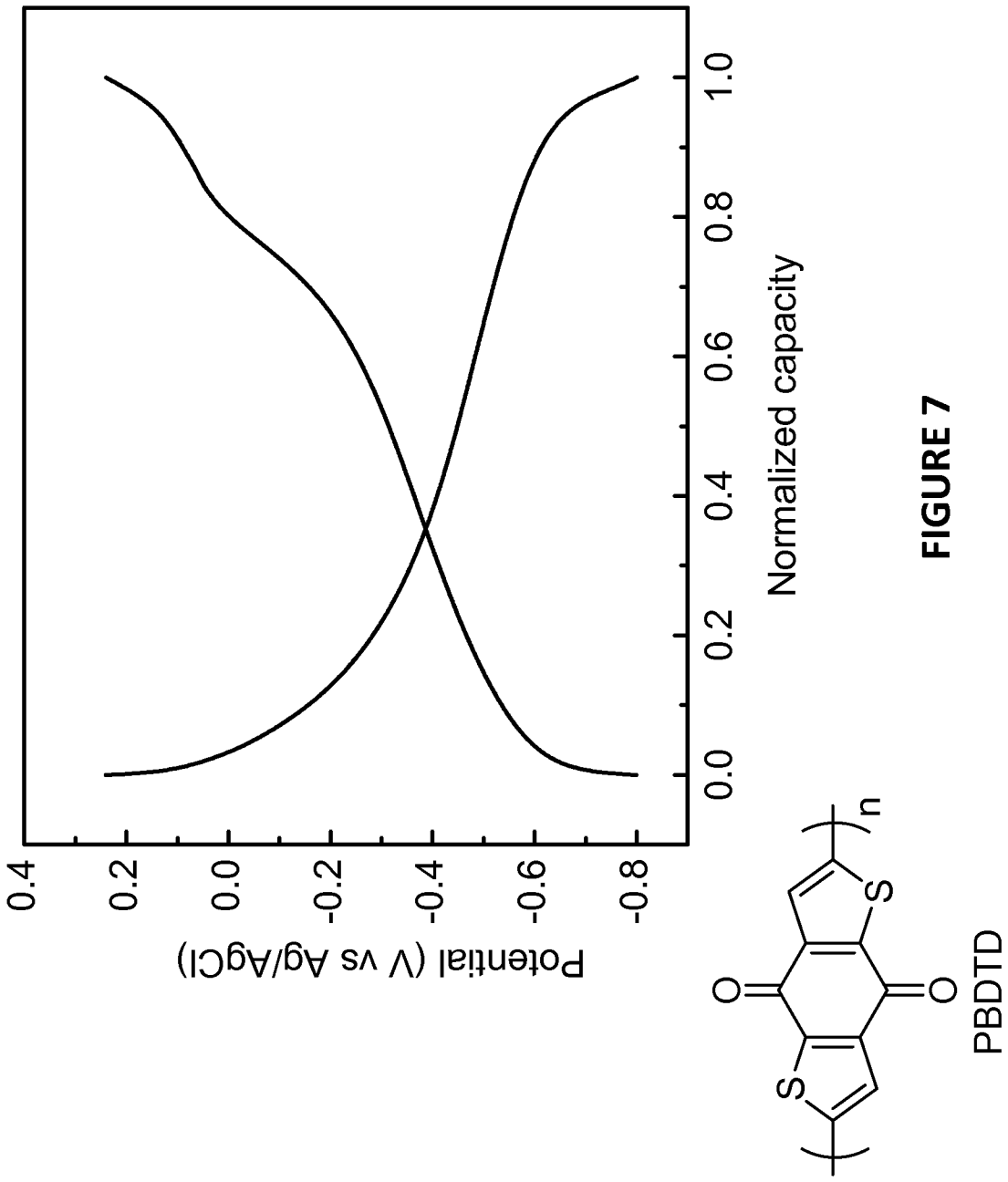

Potential (V vs Ag/AgCl)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
S
S
n
PBDTD

FIGURE 7

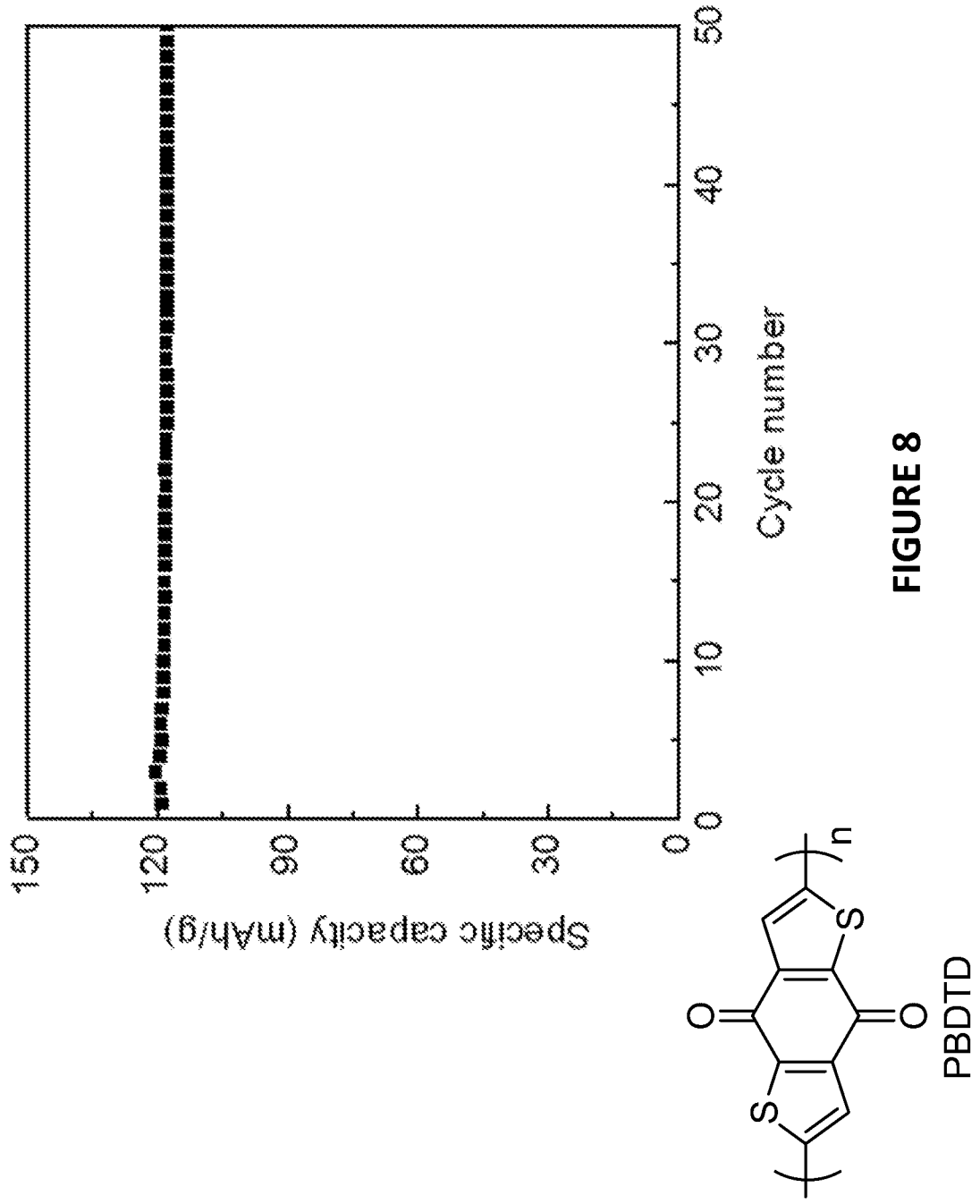

Specific capacity (mAh/g)
150
120
90
60
30
0
0
10
20
30
40
50
Cycle number
O
O
S
S
n
PBDTD

FIGURE 8

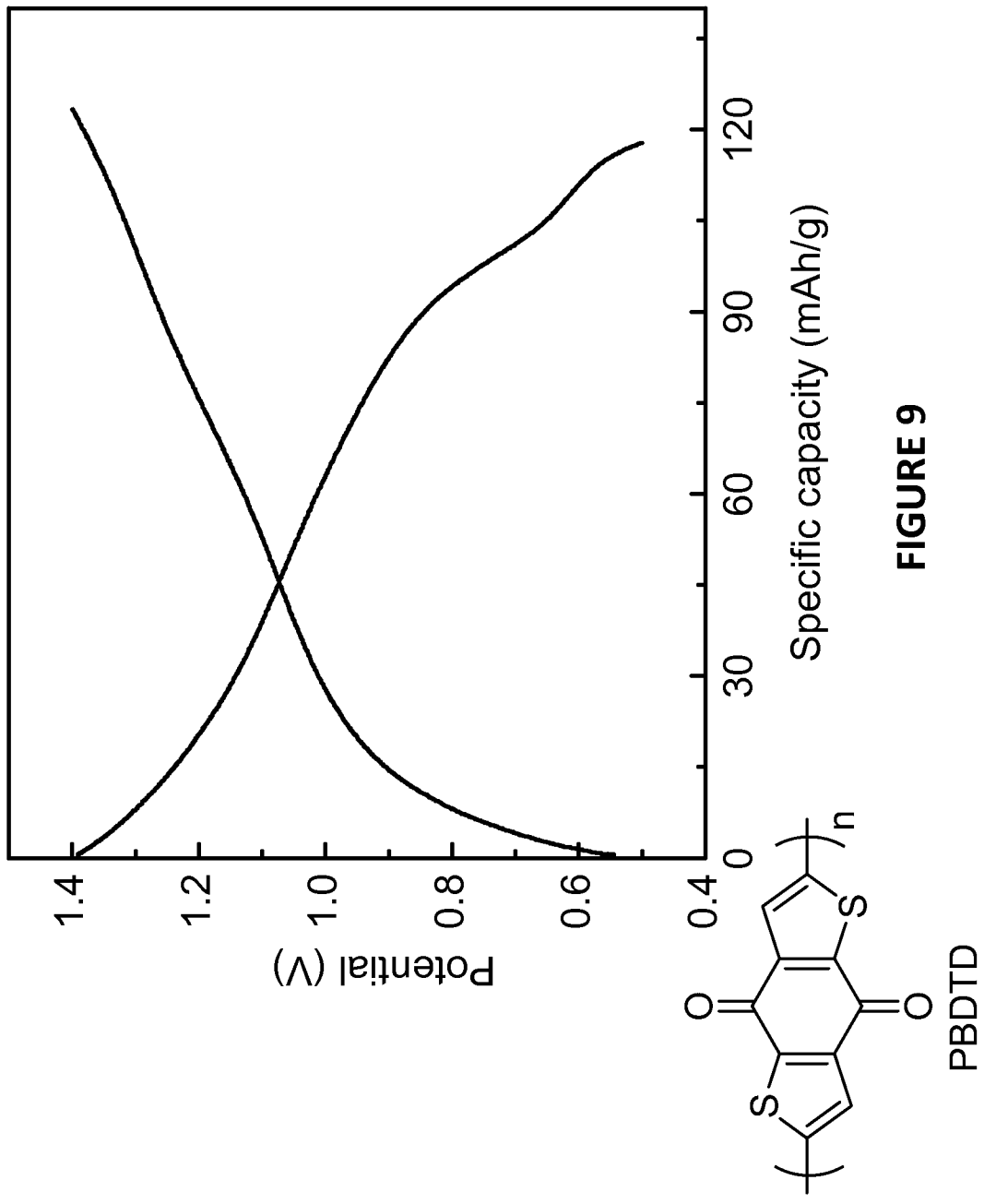

Potential (V)
1.4
1.2
1.0
0.8
0.6
0.4
0
30
60
90
120
Specific capacity (mAh/g)
O
O
S
S
n
PBDTD

FIGURE 9

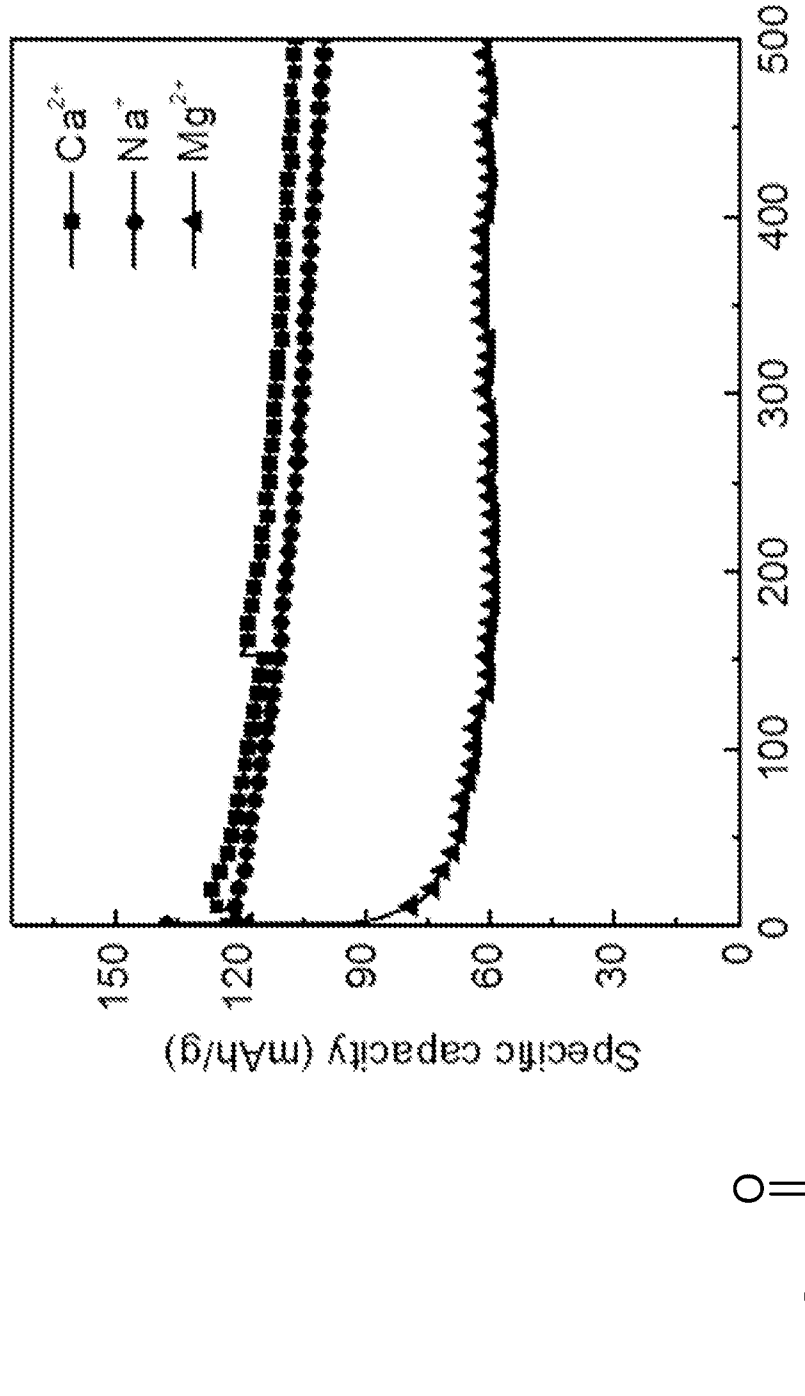

Ca2+
Na+
Mg2+
Specific capacity (mAh/g)
Cycle number
0
30
60
90
120
150
0
100
200
300
400
500
O
O
S
S
n
PBDTD

FIGURE 10

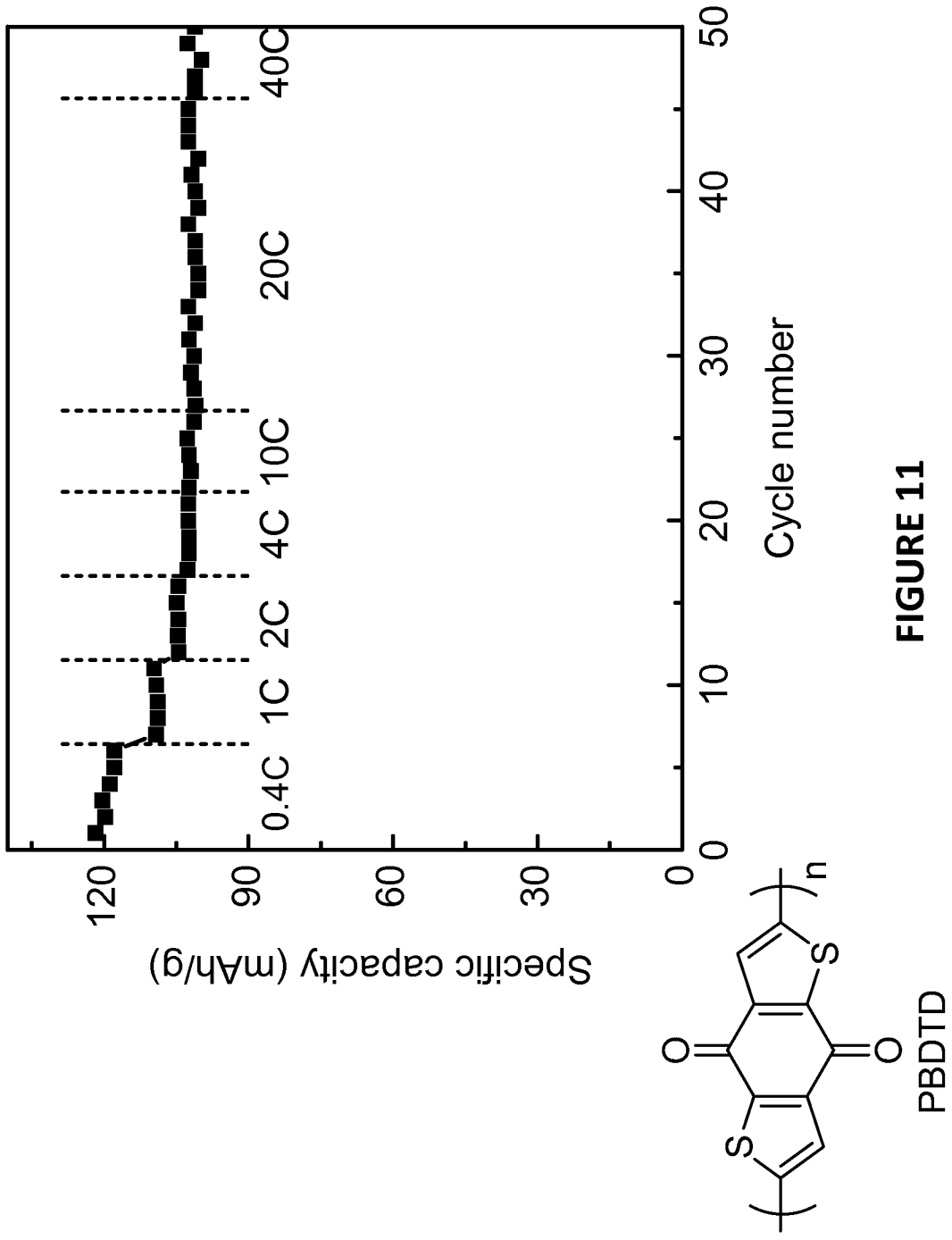

Specific capacity (mAh/g)
120
90
60
30
0
0
10
20
30
40
50
Cycle number
0.4C
1C
2C
4C
10C
20C
40C
O
O
S
S
n
PBDTD

FIGURE 11

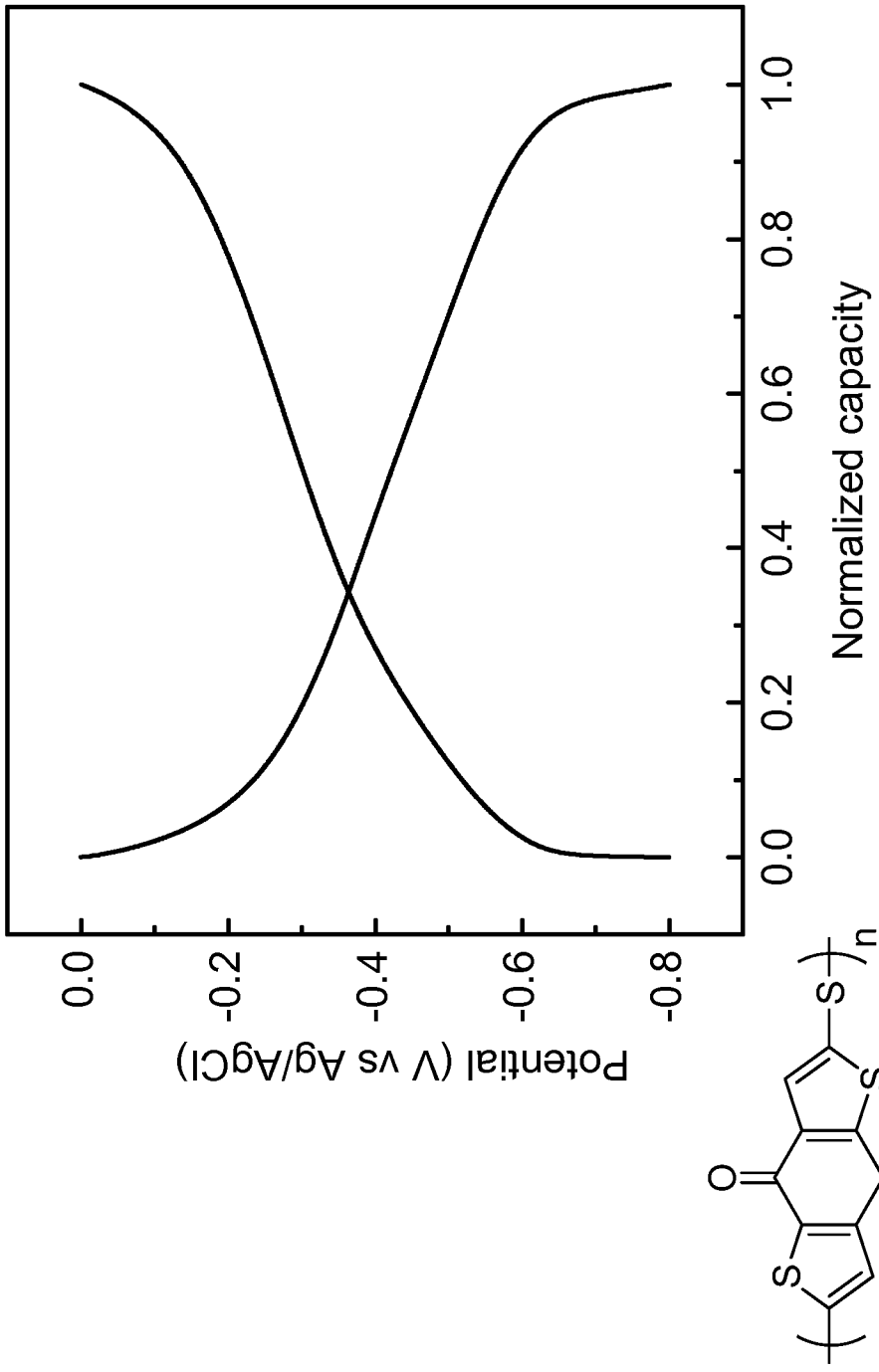

Potential (V vs Ag/AgCl)
0.0
-0.2
-0.4
-0.6
-0.8
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
S
S
n
PBDTDS

FIGURE 12

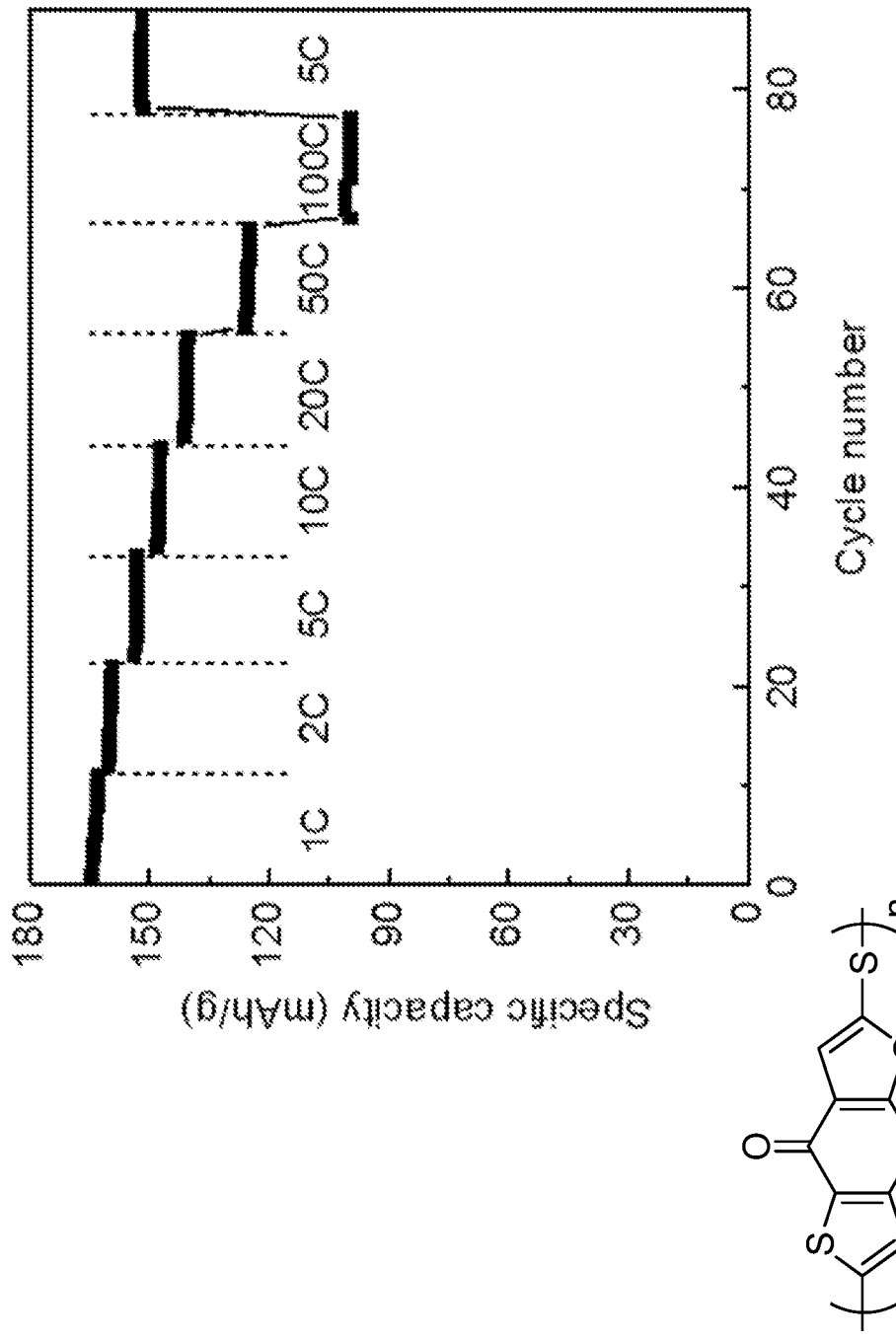

Specific capacity (mAh/g)
180
150
120
90
60
30
0
0
20
40
60
80
Cycle number
1C
2C
5C
10C
20C
50C
100C
5C
O
O
S
S
S
n
PBDTDS

FIGURE 13

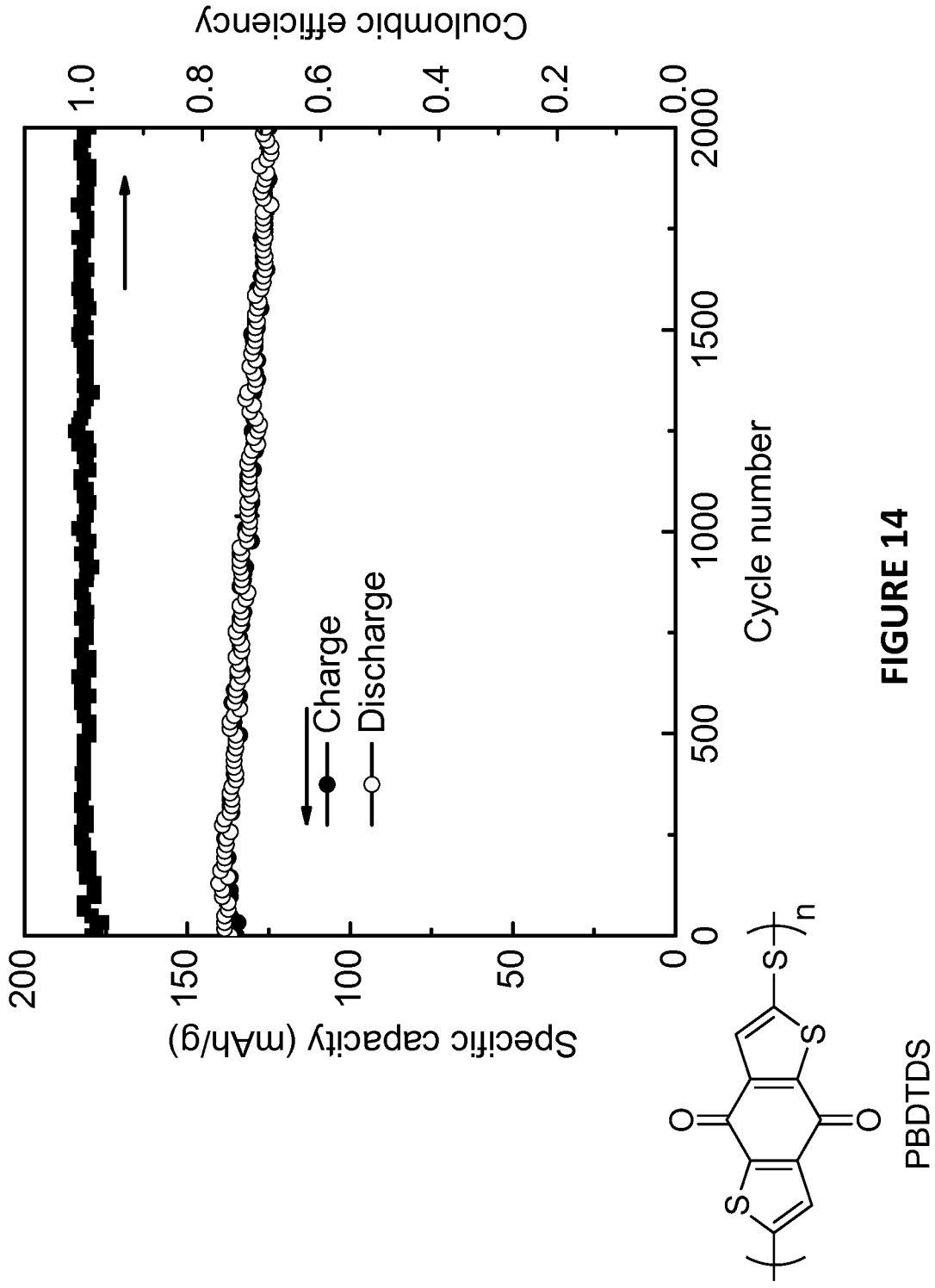

Coulombic efficiency
1.0
0.8
0.6
0.4
0.2
0.0
2000
1500
1000
500
0
Cycle number
Specific capacity (mAh/g)
200
150
100
50
0
Charge
Discharge
O
O
S
S
n
PBDTDS

FIGURE 14

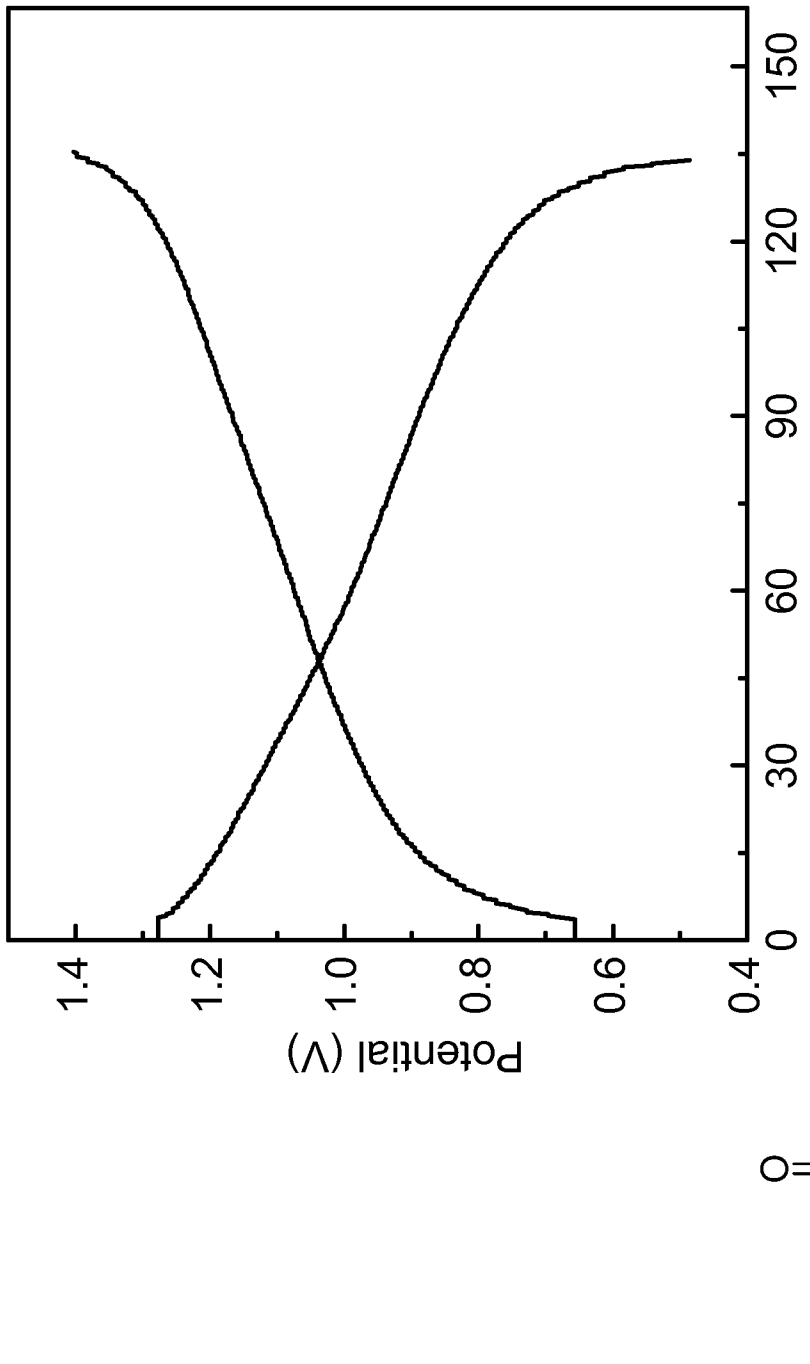

Potential (V)
1.4
1.2
1.0
0.8
0.6
0.4
0
30
60
90
120
150
Specific capacity (mAh/g)
O
O
S
S
S
n
PBDTDS

FIGURE 15

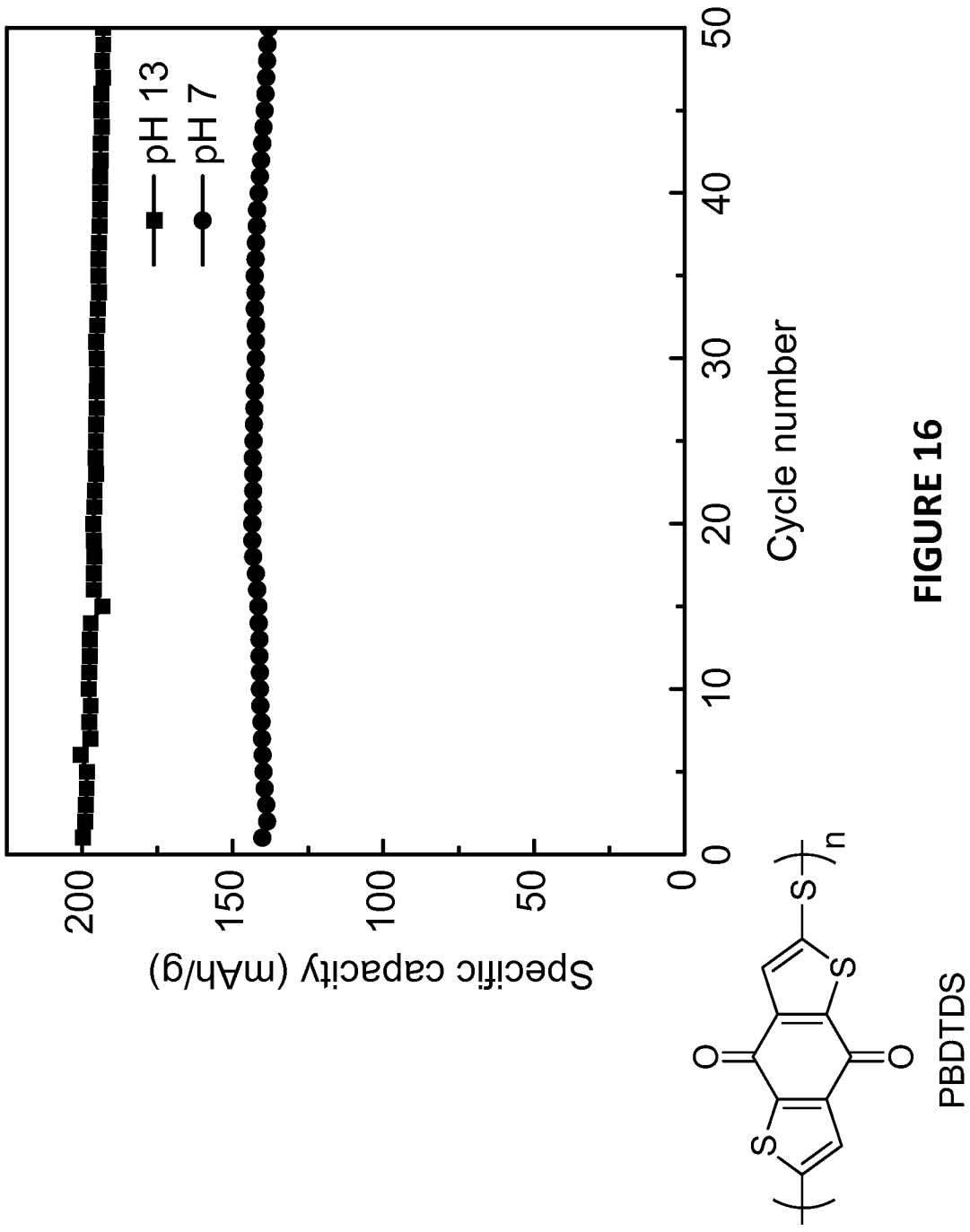

Specific capacity (mAh/g)
200
150
100
50
0
0
10
20
30
40
50
Cycle number
pH 13
pH 7
O
O
S
S
S
n
PBDTDS

FIGURE 16

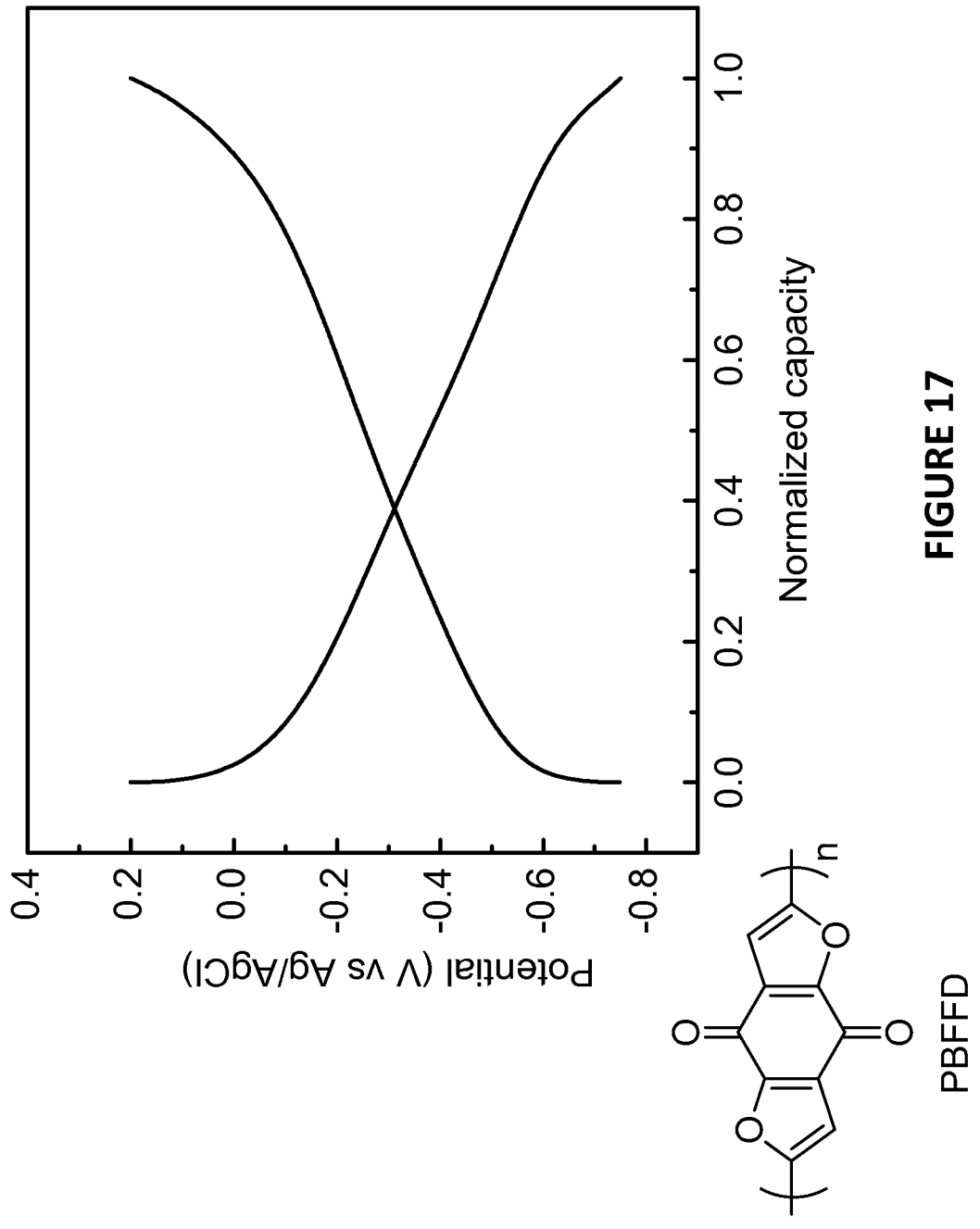

Potential (V vs Ag/AgCl)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
O
O
n
PBFFD

FIGURE 17

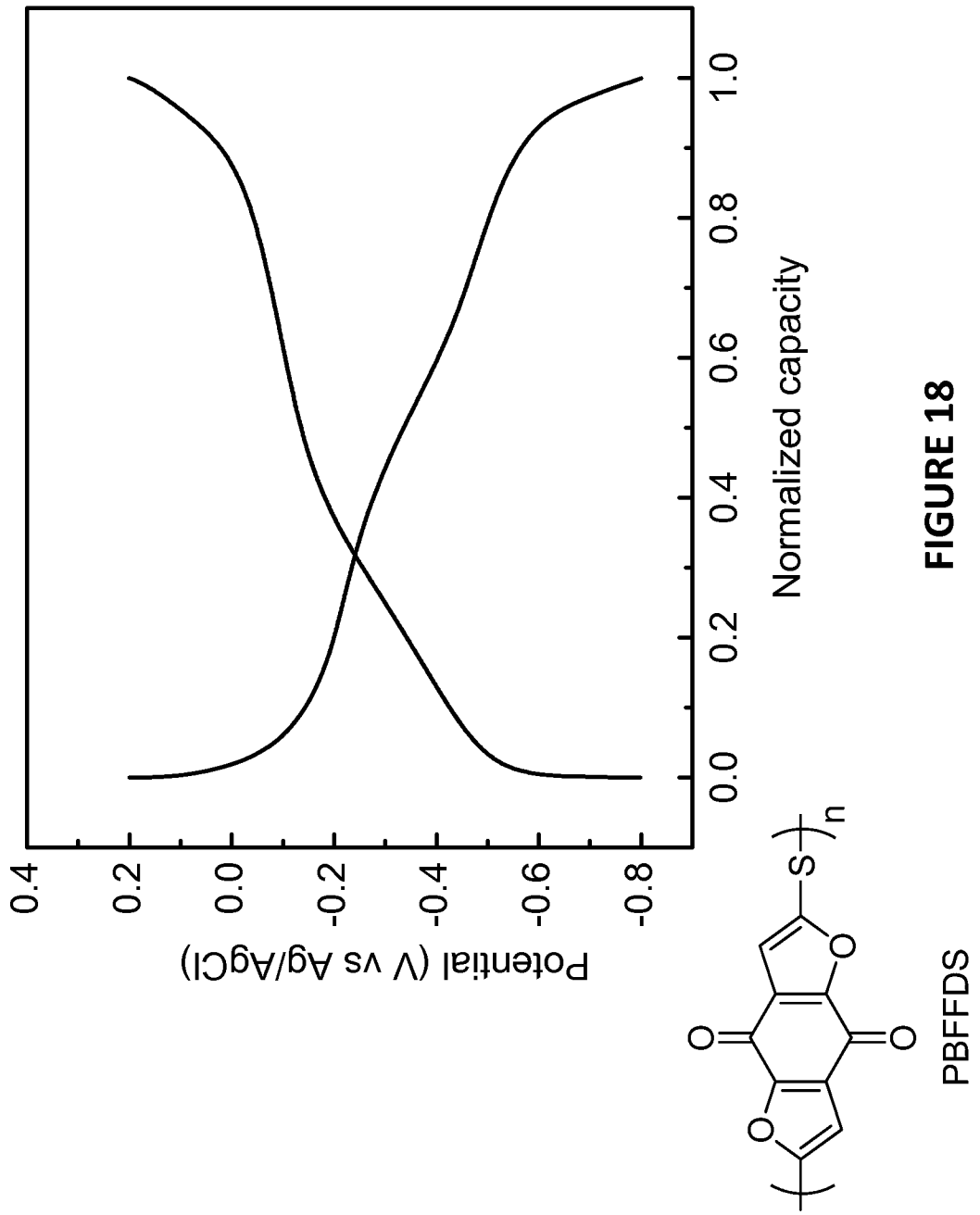

Potential (V vs Ag/AgCl)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
O
O
S
n
PBFFDS

FIGURE 18

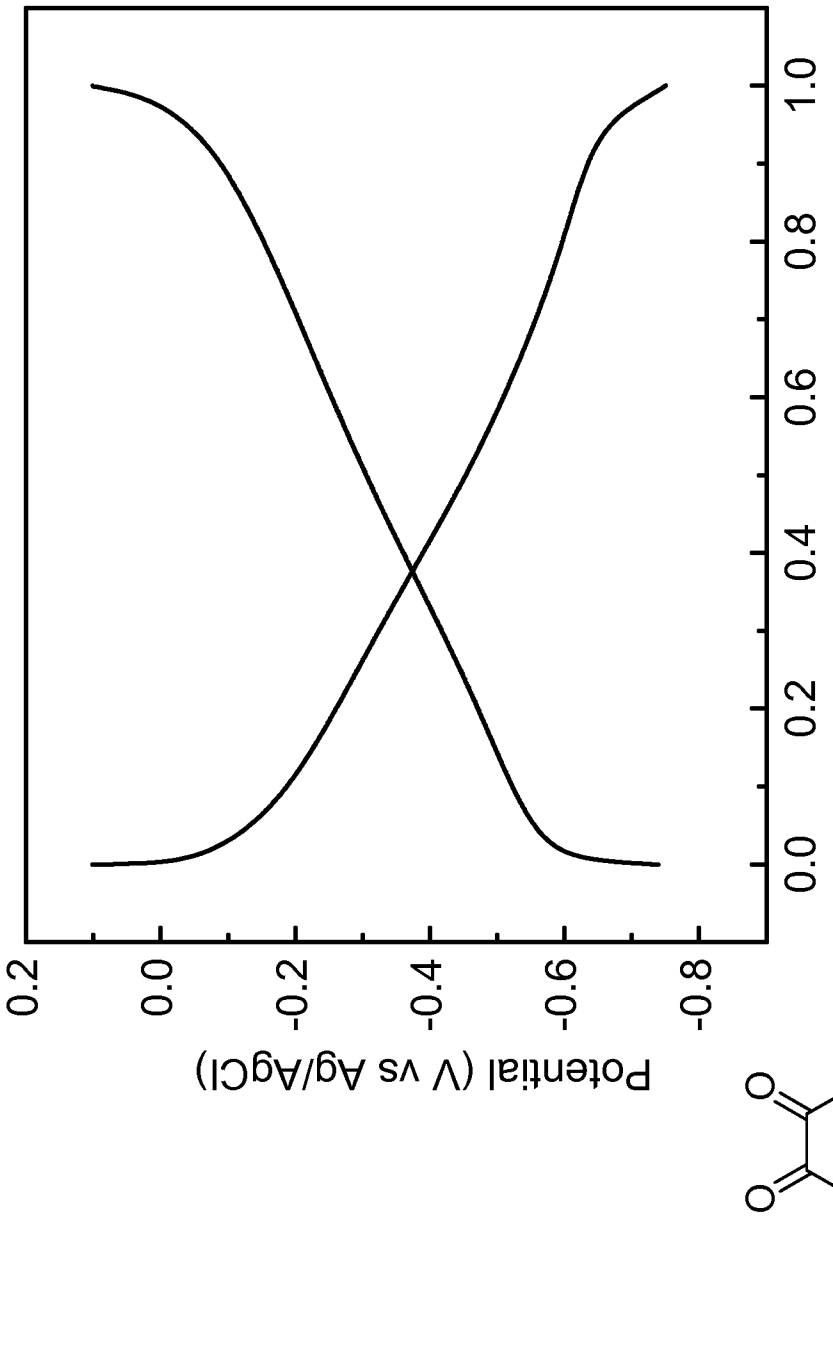

0.2
0.0
-0.2
-0.4
-0.6
-0.8
Potential (V vs Ag/AgCl)
0.0
0.2
0.4
0.6
0.8
1.0
Normalized capacity
O
O
n
PPQ

FIGURE 19

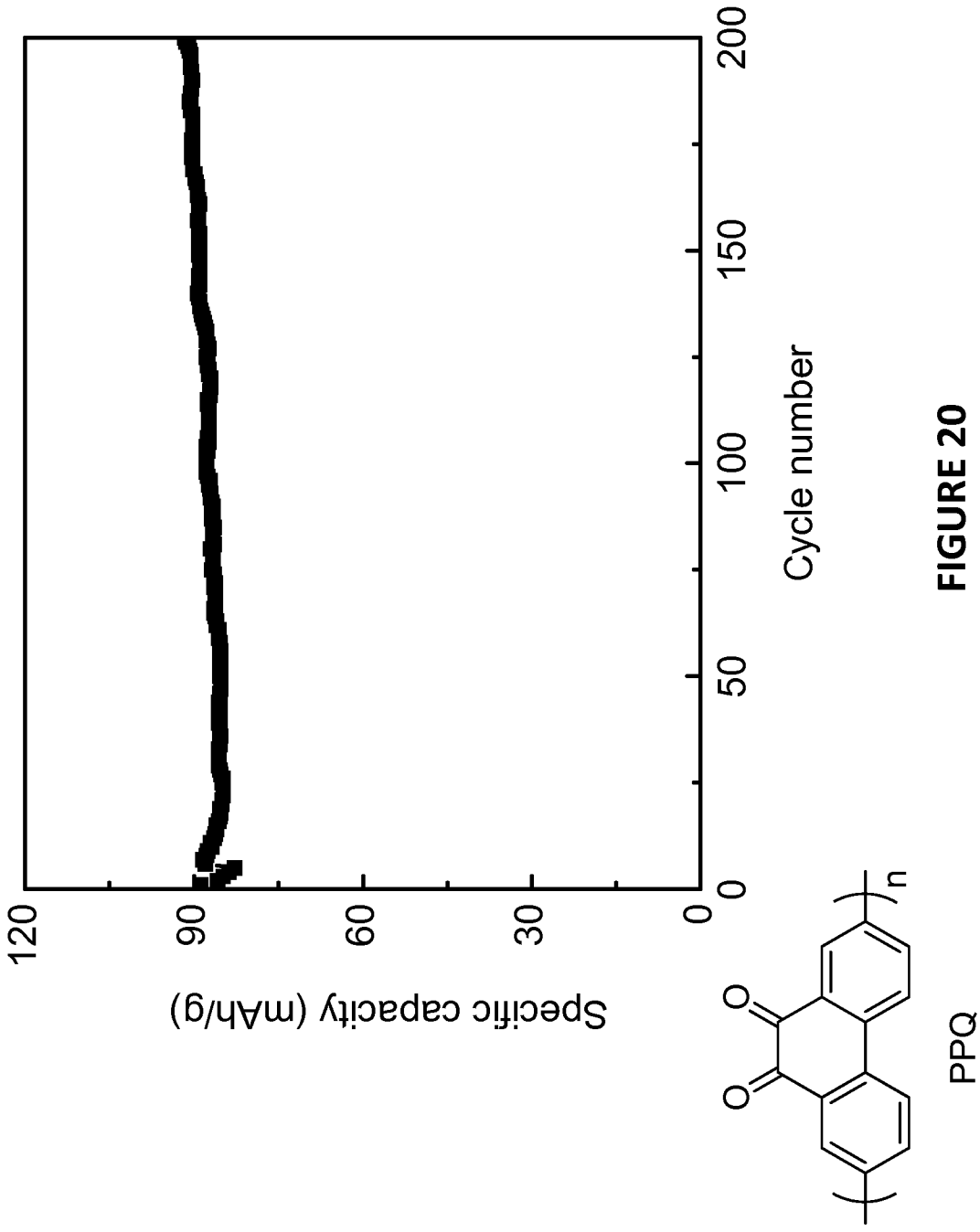

Specific capacity (mAh/g)
120
90
60
30
0
0
50
100
150
200
Cycle number
O
O
n
PPQ

FIGURE 20

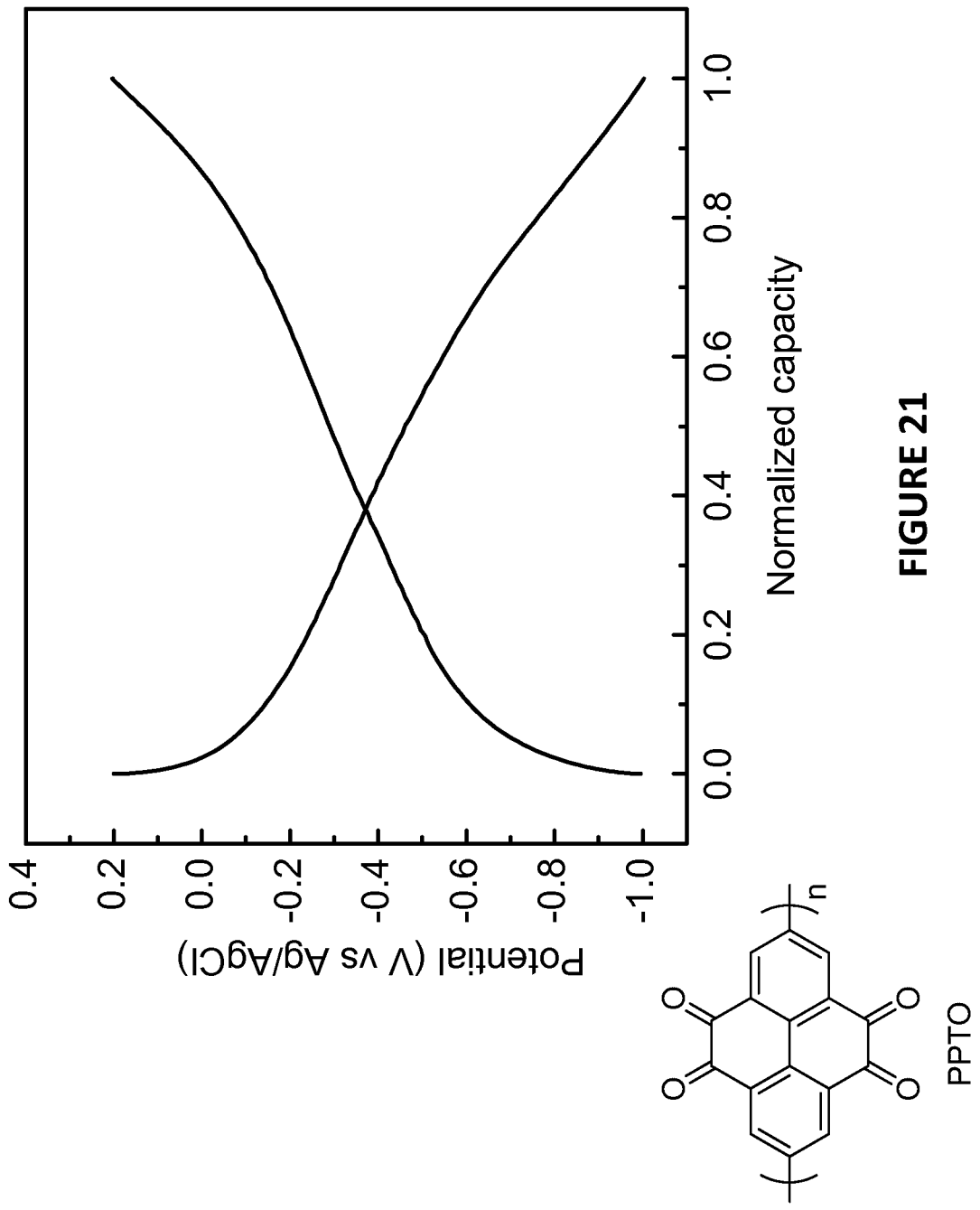
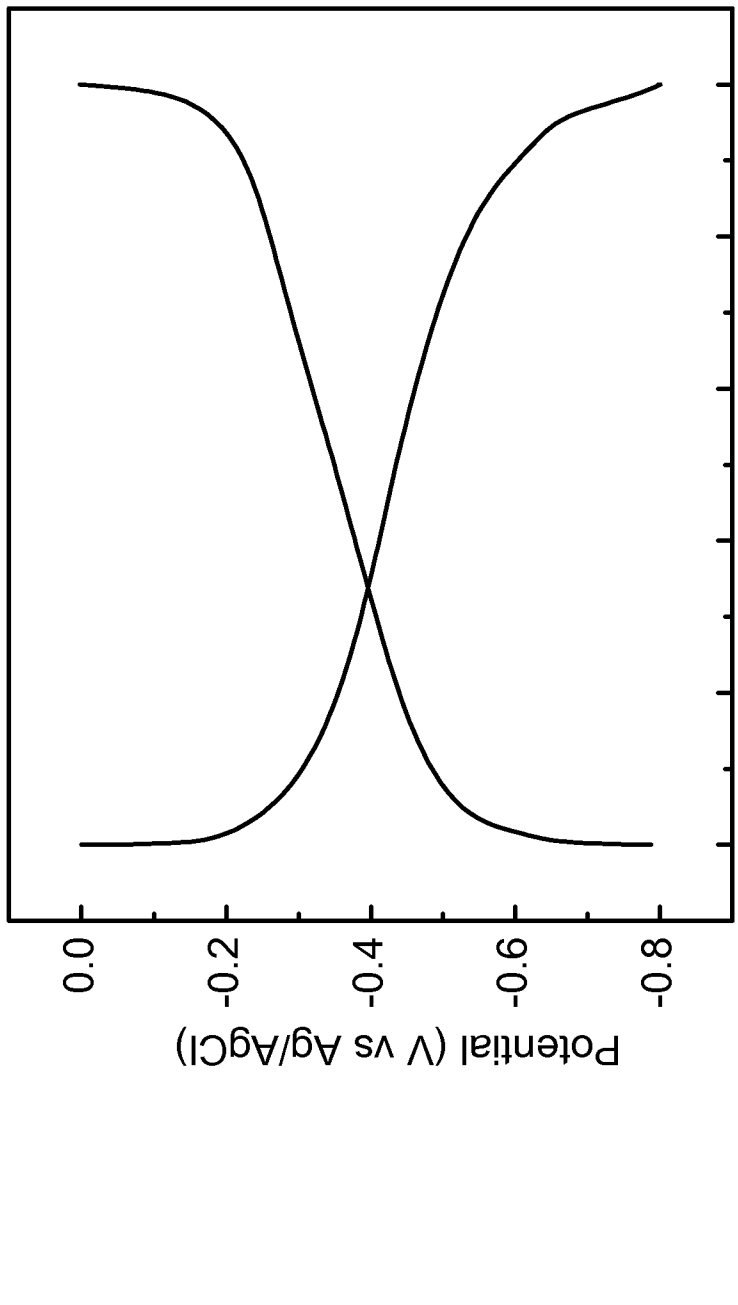

Potential (V vs Ag/AgCl)
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
O
O
O
O
n
PPTO

FIGURE 21


Potential (V vs Ag/AgCl)
0.0
-0.2
-0.4
-0.6
-0.8
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0

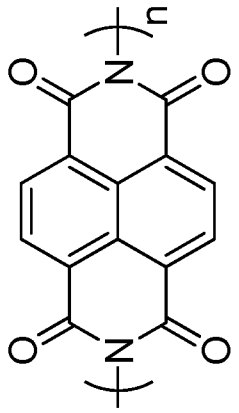
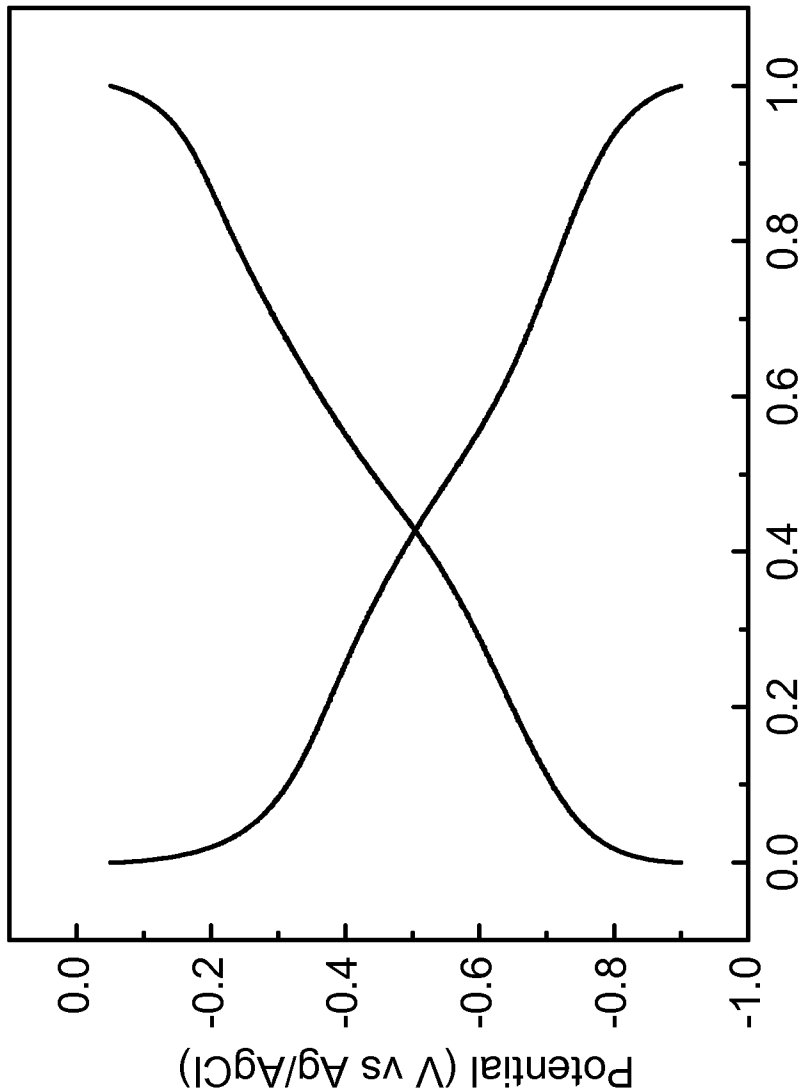
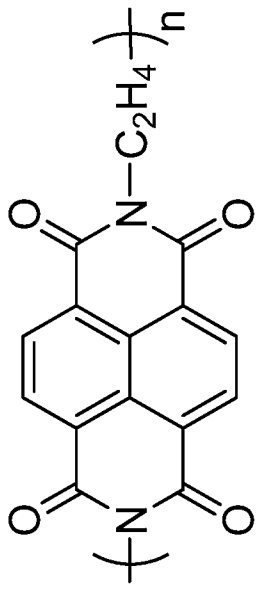

O
N
O
n
PNDI

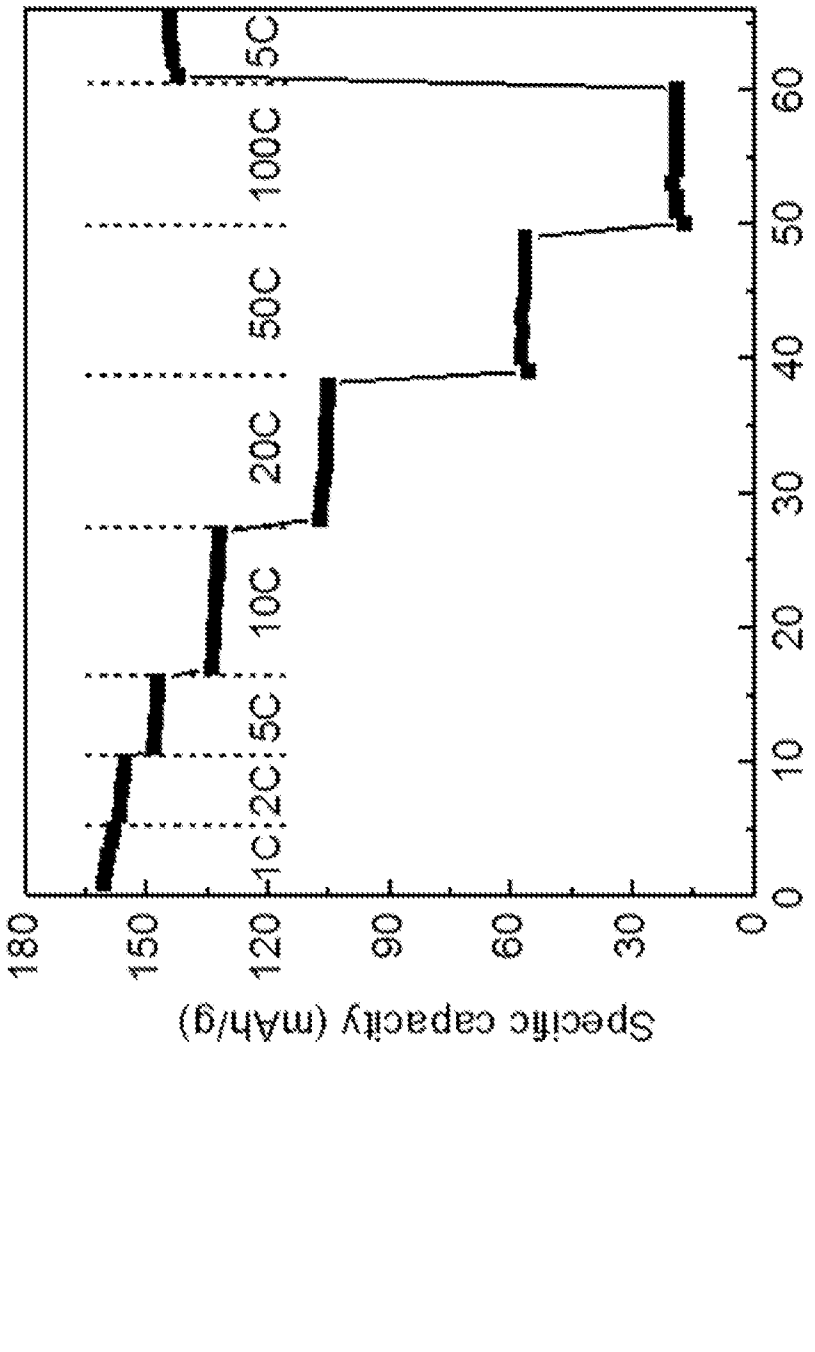
FIGURE 22

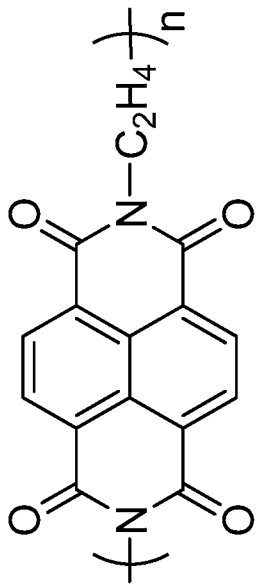




PNDIE

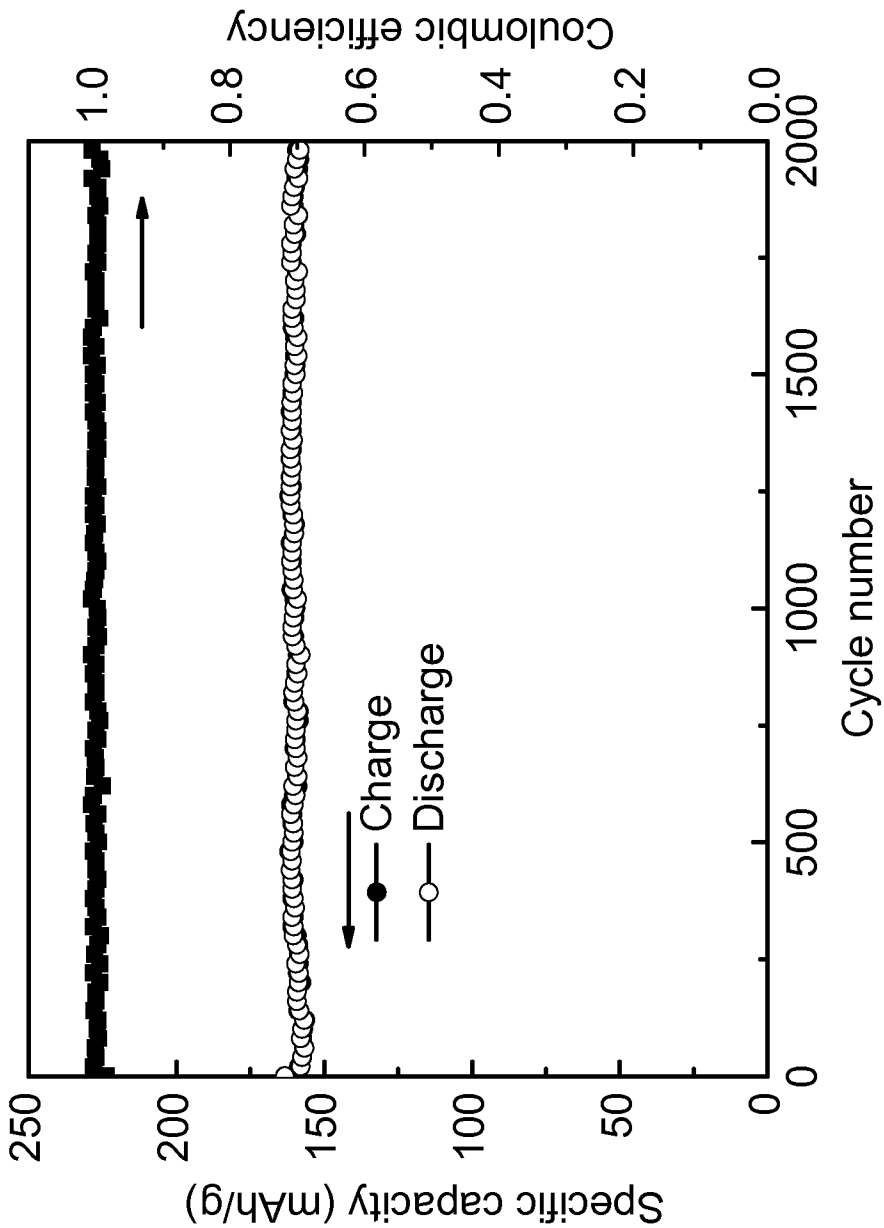
FIGURE 23

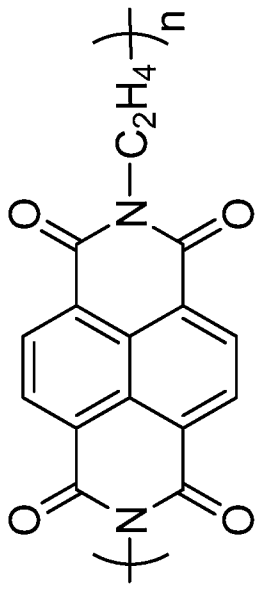




PNDIE

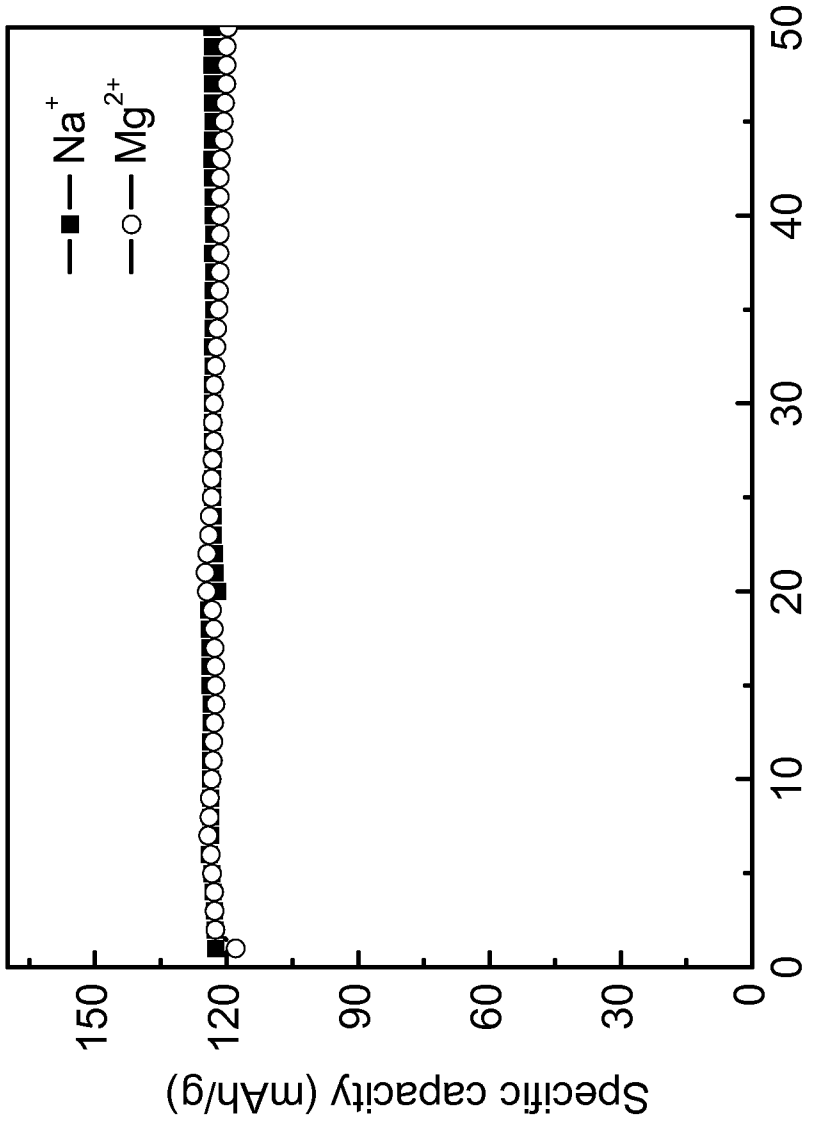
FIGURE 24

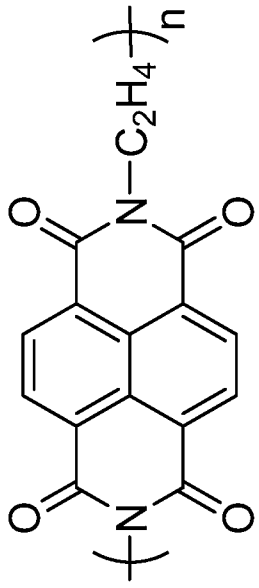




PNDIE

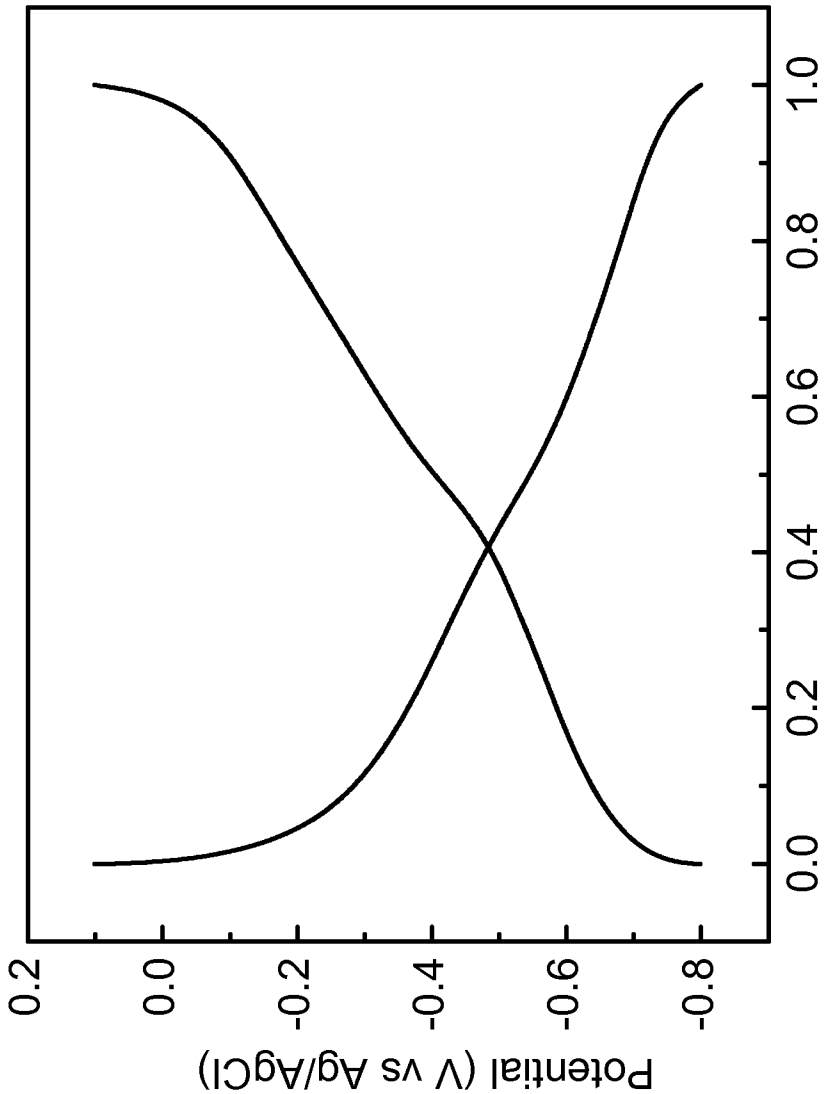
FIGURE 25

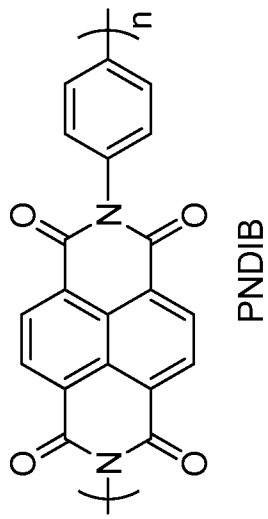




PNDIE

FIGURE 26





PNDIB

FIGURE 27

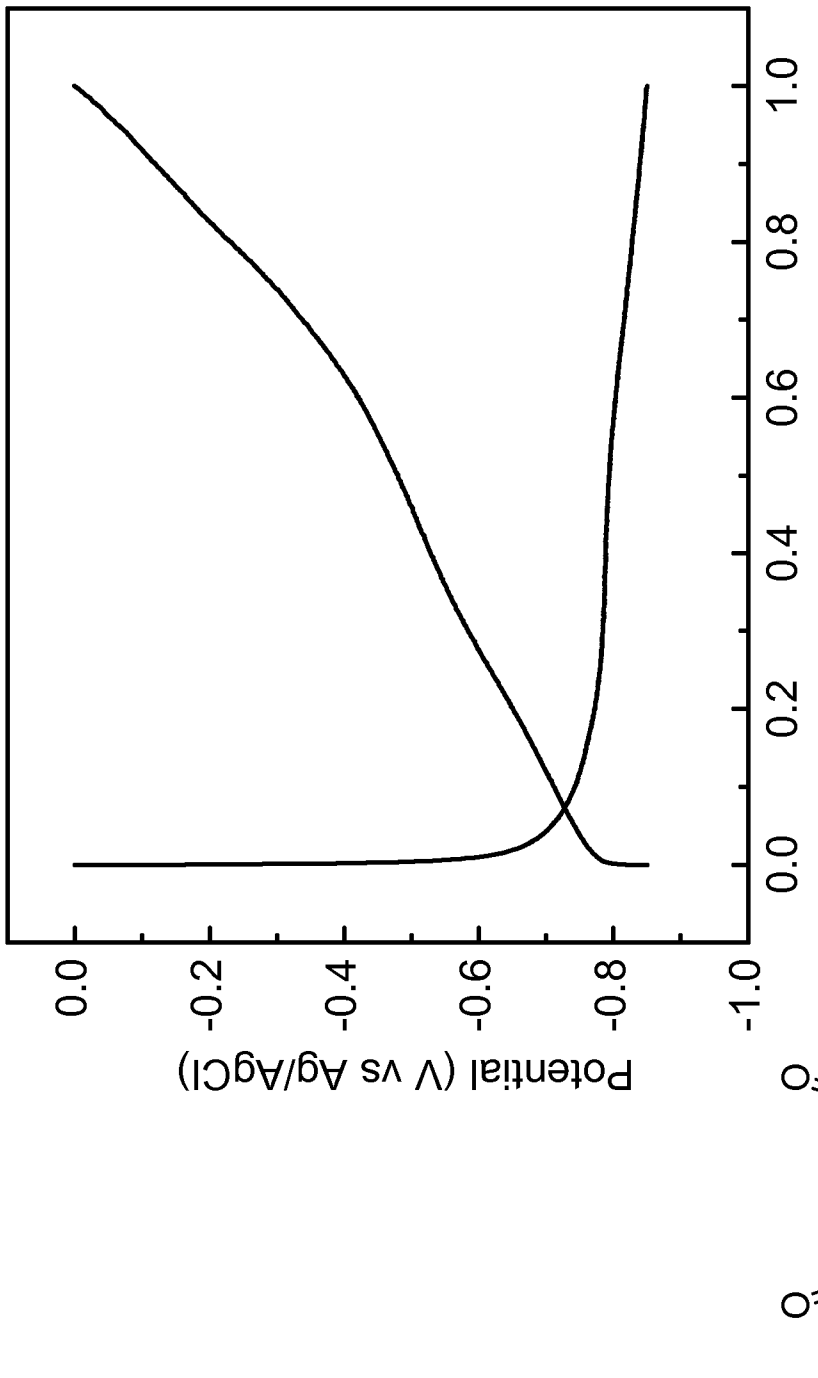

Potential (V vs Ag/AgCl)
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Normalized capacity
0.0
0.2
0.4
0.6
0.8
1.0
N–C2H4
n
O
O
O
O
N
N
PPDIE

FIGURE 28

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/033652

A. CLASSIFICATION OF SUBJECT MATTER

H01M 10/28(2006.01)i, H01M 4/60(2006.01)i, H01M 4/24(2006.01)i, H01M 10/36(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01M 10/28; H01M 4/60; H01M 4/24; H01M 8/00; H01M 6/04; C08G 73/04; H01M 10/36

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: aqueous, electrolyte, metal-ion, battery, carbonyl

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6248474 B1 (NISHIYAMA, TOSHIHIKO et al.) 19 June 2001 See abstract; column 2, line 65 - column 3, line 19, column 5, line 16 - column 7, line 10, column 9, line 25 - column 11, line 39; claims 1-2; and figures 2, 5-6.	11-19
Y		1-10,20-21
Y	US 2010-0248078 A1 (BEARD, KIRBY W.) 30 September 2010 See paragraphs [0008]-[0011], [0016]-[0026]; and claims 1-2, 5, 7, 16.	1-10,20-21
A	JP 06-056989 A (OSAKA GAS CO., LTD.) 1 March 1994 See abstract; paragraphs [0004]-[0028], [0040]-[0041]; and claims 1-7.	1-21
A	JP 10-294107 A (MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.) 4 November 1998 See abstract; paragraphs [0004]-[0018]; claims 1-3; and figures 1-3.	1-21
A	US 2003-0118877 A1 (ARMAND, MICHEL et al.) 26 June 2003 See abstract; paragraphs [0020]-[0039]; and claims 1-16.	1-21

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 September 2014 (29.09.2014)	**29 September 2014 (29.09.2014)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2014/033652

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		US 7879492 B2	01/02/2011
		WO 99-28984 A1	10/06/1999