

MODIFIED CURRENT COLLECTOR FOR SECONDARY BATTERY**FIELD OF THE INVENTION**

[001] The present invention relates to the field of batteries. In particular, this invention relates to a modified current collector in a battery electrode in a secondary battery.

BACKGROUND OF THE INVENTION

[002] Among various types of batteries, lithium-ion batteries (LIBs) in particular have become widely utilized for various applications over the past decades, especially in consumer electronics, because of their outstanding energy density, long cycle life and high discharging capability. Due to rapid market development of electric vehicles (EV) and grid energy storage, high-performance, low-cost LIBs are currently offering one of the most promising options for large-scale energy storage devices. However, many problems still exist in current lithium-ion battery technology, more specifically with respect to lithium-ion battery electrodes.

[003] Generally, lithium-ion battery electrodes are manufactured by casting an organic-based slurry onto a current collector. The slurry contains electrode active material, conductive carbon, and binder in an organic solvent. The binder provides a good electrochemical stability, holds together the electrode active materials and adheres them to the current collector in the fabrication of electrodes. Polyvinylidene fluoride (PVDF) is currently one of the most commonly used binders in the commercial lithium-ion battery industry. However, PVDF is insoluble in water and can only dissolve in some specific organic solvents such as N-methyl-2-pyrrolidone (NMP) which is flammable and toxic and hence requires specific handling.

[004] An NMP recovery system must be in place during the drying process to recover NMP vapors. This generates significant costs in the manufacturing process since it requires a large capital investment. Given the drawbacks of organic-based slurries, the use of water-based slurries which utilize less expensive and more environmentally-friendly solvents, such as aqueous solvents (most commonly water) are preferred in the present invention. These aqueous solvents are remarkably safer and easier to handle than NMP and do not require the implementation of a recovery system.

[005] However, there are problems associated with the use of water-based slurries in the manufacture of lithium-ion batteries. In particular, the electrode active material may react with water to create undesirable effects on the current collector. The complications are particularly noticeable when nickel-containing cathode active materials, such as lithium nickel-manganese-cobalt oxides (NMC), are used as they react strongly with water to form a basic

solution. Consequently, when the nickel-containing water-based slurry is coated onto a current collector to form a cathode, the basicity of the slurry would likely corrode the current collector. This problem strongly discourages the use of nickel-containing cathode active materials in water-based manufacturing of batteries, despite the high specific capacities of such active materials.

[006] In addition, several other issues affect the current collector in existing lithium-ion battery technology. A typical electrode comprises a current collector and an electrode layer located on one side or both sides of the current collector; an electrode layer-current collector interface exists where the electrode layer comes into contact with the current collector. This interface acts as a source of electrical resistance for electrons traveling between the electrode layer and the current collector. The interfacial resistance between the electrode layer and the current collector in battery electrodes greatly contributes to the overall internal resistance of the battery, which in turn leads to poor battery electrochemical performance.

[007] It is worth noting that the above problems are not particular to lithium-ion batteries. Other types of batteries, such as sodium-ion batteries, may also encounter similar problems.

[008] In view of the aforementioned problems, attempts have been made to mitigate the damage done to the current collector or to reduce the interfacial resistance between electrode layer and current collector in battery electrodes.

[009] US Patent Application Publication No. 20130295458 A1 discloses a current collector comprising a metal foil and a layer comprising electrically conductive particles, a binding agent and an organic acid; wherein the layer is provided on one or both surfaces of the metal foil. Polysaccharides and derivatives thereof are preferably used as the binding agent owing to their excellent adherence with a metal foil and high ionic permeability. The organic acid serves as a cross-linking agent for the binding agent, allowing the electrically conductive particles to be more firmly attached onto the metal foil. With such a configuration, it is believed that the internal resistance and impedance of an electrochemical element comprising said current collector could be reduced. However, the shortcoming of this system lies in the need for an additional cross-linking agent in facilitating the adherence of the electrically conductive particles onto the metal foil; the simple use of a binding agent is insufficient in performing this function. The involvement of an organic acid as a cross-linking agent within the layer, upon contact with the metal foil in forming the current collector, would likely to give rise to corrosion of the underlying metal foil over time.

[0010] Accordingly, it is an aim of the present invention to present a modified current collector to be used in battery electrodes, where the modified current collector is less susceptible

SUMMARY OF THE INVENTION

$$\begin{array}{c} \text{---} \text{---} \text{---} \\ | \quad | \\ \text{R}_1 \quad \text{R}_3 \\ | \quad | \\ \text{R}_2 \quad \text{R}_4 \\ | \quad | \\ \text{---} \text{---} \end{array}$$
$$\begin{array}{c} \text{---} \text{---} \text{---} \\ | \quad | \\ \text{R}_5 \quad \text{R}_7 \\ | \quad | \\ \text{R}_6 \quad \text{R}_8 \\ | \quad | \\ \text{---} \text{---} \end{array}$$

[0014] The invention as disclosed herein solves the above-mentioned problems that affect current collectors in battery electrodes. Firstly, the conductive layer of the modified current collector can act as a physical barrier between the substrate and the alkaline electrode active material in the electrode layer. This prevents the corrosion of the substrate without compromising the conductivity within the electrode.

[0015] Secondly, the conductive material in the conductive layer of the modified current collector reduces interfacial resistance between the electrode layer and the modified current collector itself, which improves the output performance of the electrode.

[0016] Furthermore, when a water-based electrode slurry is applied on the conductive layer of the modified current collector to form the electrode layer, there is a risk of the conductive layer reverting to a fluid by dissolving into the electrode slurry. This could lead to delamination of the conductive layer. The binder material in the conductive layer of the modified current collector disclosed herein has excellent adhesion to the substrate and thus improves the mechanical strength of the electrode to prevent such delamination of the conductive layer.

[0017] As a result of the above advantages, batteries comprising electrodes that are produced using a modified current collector of the present invention exhibit exceptional electrochemical performance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Figures 1a and 1b show the simplified views of two different embodiments of the modified current collector disclosed herein within an electrode.

DETAILED DESCRIPTION OF THE INVENTION

[0019] In one aspect, provided herein is a modified current collector in an electrode for a battery, wherein the modified current collector comprises a substrate and a conductive layer located on one side or both sides of the substrate. The conductive layer itself comprises a binder material and a conductive material, wherein the binder material comprises a suitable copolymer. The conductive layer can be produced by coating a conductive slurry on the substrate, wherein the conductive slurry comprises the conductive material, the binder material and an aqueous solvent. In another aspect, provided herein is an electrode, comprising the modified current collector and an electrode layer located on top of the modified current collector, wherein the electrode layer comprises an electrode active material and a binding agent, and may additionally comprise a conductive agent. The electrode layer can be produced by coating an electrode slurry onto the modified current collector of the present invention, wherein the electrode slurry comprises the electrode active material, the binding agent and an aqueous solvent (and optionally, the conductive agent).

[0020] The term “electrode” refers to a “cathode” or an “anode.”

[0021] The term “electrode component” refers to any substance that is present in an electrode layer of an electrode, including but not limited to electrode active materials, conductive agents, and binding agents.

[0022] The term “positive electrode” is used interchangeably with cathode. Likewise, the term “negative electrode” is used interchangeably with anode.

[0023] The term “binder”, “binder material” or “binding agent” refers to a chemical compound, a mixture of compounds or a polymer that is used to hold material(s) in place and adhere them onto a surface. In some embodiments, the binder material refers to a chemical compound, mixture of compounds, or polymer that is used to hold a conductive material in place and adhere it onto a substrate to form a modified current collector. In some embodiments, the binding agent refers to a chemical compound, mixture of compounds, or polymer that is used to hold an electrode material and/or a conductive agent in place and adhere them onto a modified current collector to form an electrode. In some embodiments, the electrode does not comprise any conductive material or conductive agent. In some embodiments, each of the binder material and the binding agent independently forms a colloid in an aqueous solvent such as water. In some embodiments, each of the binder material and the binding agent independently forms a solution or dispersion in an aqueous solvent such as water.

[0024] The term “conductive material” or “conductive agent” refers to a material that has good electrical conductivity. Therefore, a conductive material is often added in the making of a modified current collector to improve its electrical conductivity. In some embodiments, a conductive agent is mixed with an electrode active material at the time of forming an electrode to improve electrical conductivity of the electrode. In some embodiments, each of the conductive material and the conductive agent is independently chemically active. In some embodiments, each of the conductive material and the conductive agent is independently chemically inactive.

[0025] The term “polymer” refers to a compound prepared by polymerizing monomers, whether of the same type or of different types. The generic term “polymer” embraces the terms “homopolymer” and “copolymer”.

[0026] The term “homopolymer” refers to a polymer prepared by the polymerization of the same type of monomer.

[0027] The term “copolymer” refers to a polymer prepared by the polymerization of two or more different types of monomers.

[0028] The term “aqueous solvent” refers to a solution containing water as the major component and one or more minor components in addition to water, or a solution that consists solely of water.

[0029] With respect to a slurry, the term “water-based” means that the solvent of the slurry is an aqueous solvent. With respect to a mode of manufacturing electrodes or batteries, the term “water-based” means that at least one element of the electrode or battery is wholly or partially formed using an aqueous slurry.

[0030] The term “unsaturated” refers to a moiety having one or more units of unsaturation.

[0031] The term “alkyl” or “alkyl group” refers to a univalent group having the general formula C_nH_{2n+1} derived from removing a hydrogen atom from a saturated, unbranched or branched aliphatic hydrocarbon, where n is an integer.

[0032] The term “cycloalkyl” or “cycloalkyl group” refers to a saturated or unsaturated cyclic non-aromatic hydrocarbon radical having a single ring or multiple condensed rings. Examples of cycloalkyl groups include, but are not limited to, C₃-C₇ cycloalkyl groups, such as cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl, and cycloheptyl, and saturated cyclic and bicyclic terpenes and C₃-C₇ cycloalkenyl groups, such as cyclopropenyl, cyclobutenyl, cyclopentenyl, cyclohexenyl, and cycloheptenyl; and unsaturated cyclic and bicyclic terpenes. A cycloalkyl group can be unsubstituted or substituted by one or two suitable substituents. Furthermore, the cycloalkyl group can be monocyclic or polycyclic. In some embodiments, the cycloalkyl group contains at least 5, 6, 7, 8, 9, or 10 carbon atoms.

[0033] The term “alkenyl” refers to a univalent group derived from the removal of a hydrogen atom from any carbon atom of an unsaturated aliphatic hydrocarbon with at least one carbon-carbon double bond. Similarly, the term “alkynyl” refers to a univalent group derived from the removal of a hydrogen atom from any carbon atom of an unsaturated aliphatic hydrocarbon with at least one carbon-carbon triple bond. Furthermore, the term “enynyl” refers to a univalent group derived from the removal of a hydrogen atom from any carbon atom of an unsaturated aliphatic hydrocarbon with at least one carbon-carbon double bond and at least one carbon-carbon triple bond. The unsaturated aliphatic hydrocarbon of an alkenyl, alkynyl or enynyl may be branched or unbranched.

[0034] The term “alkoxy” refers to an alkyl group, as previously defined, attached to the principal carbon chain through an oxygen atom. Some non-limiting examples of the alkoxy group include methoxy, ethoxy, propoxy, butoxy, and the like. And the alkoxy defined above may be substituted or unsubstituted, wherein the substituent may be, but is not limited to, deuterium, hydroxy, amino, halo, cyano, alkoxy, alkyl, alkenyl, alkynyl, mercapto, nitro, and the like.

[0035] The term “alkylene” refers to a saturated divalent hydrocarbon group derived from the removal of two hydrogen atoms from a branched or unbranched saturated hydrocarbon. Examples of an alkylene group include methylene (-CH₂-), ethylene (-CH₂CH₂-), isopropylene (-CH(CH₃)CH₂-), and the like. The alkylene group is optionally substituted with one or more substituents described herein.

[0036] The term “aryl” or “aryl group” refers to an organic radical derived from a monocyclic or polycyclic aromatic hydrocarbon by removing a hydrogen atom. Non-limiting

examples of an aryl group include phenyl, naphthyl, benzyl, tolyl, sexiphenyl, phenanthrenyl, anthracenyl, coronenyl, and tolylphenyl. An aryl group can be unsubstituted or substituted with one or more suitable substituents. Furthermore, the aryl group can be monocyclic or polycyclic. In some embodiments, the aryl group contains at least 6, 7, 8, 9, or 10 carbon atoms.

[0037] The term “alkylamino” refers to a group derived from the removal of a hydrogen atom from a primary or secondary amine. Alkylamino embraces the terms “*N*-alkylamino” and “*N,N*-dialkylamino”, wherein the amino group is independently substituted with one or two alkyl groups, respectively. The alkylamino group is optionally substituted with one or more substituents described herein.

[0038] The term “alkylthio” refers to a group containing a branched or unbranched alkyl group attached to a divalent sulfur atom. Some non-limiting examples of the alkylthio group include methylthio (CH₃S-). The alkylthio group is optionally substituted with one or more substituents described herein.

[0039] The term “heteroatom” refers to one or more of oxygen (O), sulfur (S), nitrogen (N), phosphorus (P) or silicon (Si), including any oxidized form of nitrogen (N), sulfur (S) or phosphorus (P); the quaternized form of any basic nitrogen; or a substitutable nitrogen of a heterocyclic ring, for example N (as in 3,4-dihydro-2*H*-pyrrolyl), NH (as in pyrrolidinyl) or NR (as in *N*-substituted pyrrolidinyl).

[0040] The term “carbonyl” refers to -(C=O)-.

[0041] The term “acyl” refers to -(C=O)-Z, wherein Z is an alkyl.

[0042] The term “acyloxy” refers to -O-(C=O)-Z, wherein Z is an alkyl.

[0043] The term “acyloxyalkyl” refers to -Y-O-(C=O)-Z, wherein Z is an alkyl and Y is an alkylene.

[0044] The term “hydroxyalkyl” refers to -Y-O-H, wherein Y is alkylene. Therefore, hydroxyalkyl consists of hydroxyl bonded to alkylene.

[0045] The term “amido” refers to -NH(C=O)-R.

[0046] The term “aliphatic” refers to a non-aromatic hydrocarbon or groups derived therefrom. Some non-limiting examples of aliphatic compounds include alkanes, alkenes, alkynes, alkyl groups, alkenyl groups, alkynyl groups, alkylene groups, alkenylene groups, or alkynylene groups. In some embodiments, the term “aliphatic” refers to a C₁ to C₃₀ alkyl group, a C₂ to C₃₀ alkenyl group, a C₂ to C₃₀ alkynyl group, a C₁ to C₃₀ alkylene group, a C₂ to C₃₀ alkenylene group, or a C₂ to C₃₀ alkynylene group. In some embodiments, the alkyl group contains at least 2, 3, 4, 5, 6, 7, or 8 carbon atoms.

[0047] The term “aromatic” refers to groups comprising aromatic hydrocarbon rings,

optionally including heteroatoms or substituents. Examples of such groups include, but are not limited to, phenyl, tolyl, biphenyl, o-terphenyl, m-terphenyl, p-terphenyl, naphthyl, anthryl, phenanthryl, pyrenyl, triphenylenyl, and derivatives thereof.

[0048] The term “substituted” as used to describe a compound or chemical moiety wherein at least one hydrogen atom of that compound or chemical moiety is replaced with a second chemical moiety. Examples of substituents include, but are not limited to, halogen; alkyl; heteroalkyl; alkenyl; alkynyl; enynyl; aryl, heteroaryl, hydroxyl; alkoxy; amino; nitro; thiol; alkylthio; imine; cyano; amido; phosphonato; phosphinato; carboxyl; thiocarbonyl; sulfonyl; sulfonamide; acyl; formyl; acyloxy; alkoxycarbonyl; oxo; haloalkyl (*e.g.*, trifluoromethyl); carbocyclic cycloalkyl, which can be monocyclic or fused or non-fused polycyclic (*e.g.*, cyclopropyl, cyclobutyl, cyclopentyl or cyclohexyl) or a heterocycloalkyl, which can be monocyclic or fused or non-fused polycyclic (*e.g.*, pyrrolidiny, piperidiny, piperaziny, morpholiny or thiaziny); carbocyclic or heterocyclic aryl, which can be monocyclic or fused or non-fused polycyclic (*e.g.*, phenyl, naphthyl, pyrroly, indolyl, furanyl, thiophenyl, imidazolyl, oxazolyl, isoxazolyl, thiazolyl, triazolyl, tetrazolyl, pyrazolyl, pyridiny, quinoliny, isoquinoliny, acridiny, pyraziny, pyridaziny, pyrimidiny, benzimidazolyl, benzothiophenyl or benzofuranyl); amino, monoalkylamino and dialkylamino; o-lower alkyl; o-aryl, aryl; aryl-lower alkyl; -CO₂CH₃; -CONH₂; -OCH₂CONH₂; -NH₂; -SO₂NH₂; -OCHF₂; -CF₃; -OCF₃; -NH(alkyl); -N(alkyl)₂; -NH(aryl); -N(alkyl)(aryl); -N(aryl)₂; -CHO; -CO(alkyl); -CO(aryl); -CO₂(alkyl); and -CO₂(aryl); and such moieties can also be optionally substituted by a fused-ring structure or bridge, for example -OCH₂O-. These substituents can optionally be further substituted with a substituent selected from such groups. All chemical groups disclosed herein can be substituted, unless specified otherwise.

[0049] The term “straight-chain” refers to an organic compound or a moiety that does not comprise a side chain or a cyclic structure; *i.e.*, the carbon atoms of the organic compound or moiety all form a single linear arrangement. A straight-chain compound or moiety can be substituted or unsubstituted, as well as saturated or unsaturated.

[0050] The term “halogen” or “halo” refers to F, Cl, Br or I.

[0051] The term “monomeric unit” refers to the constitutional unit derived from a single monomer to the structure of a polymer.

[0052] The term “structural unit” refers to the total monomeric units derived from the same monomer type in a polymer.

[0053] The term “homogenizer” refers to an equipment that can be used to homogenize materials, *i.e.*, to distribute materials uniformly throughout a fluid. Where homogenization is disclosed herein, any conventional homogenizer can be used for the homogenization process. Some non-limiting examples of homogenizers include stirring mixers, planetary stirring mixers,

blenders and ultrasonicators.

[0054] The term “planetary mixer” refers to an equipment that can be used to mix or stir different materials for producing a homogeneous mixture, which comprises a vessel and blades conducting a planetary motion within the vessel. In some embodiments, the planetary mixer comprises at least one planetary blade and at least one high-speed dispersion blade. The planetary and the high-speed dispersion blades rotate on their own axes and also rotate continuously around the vessel. The rotation speed can be expressed in unit of rotations per minute (rpm), which refers to the number of rotations that a rotating body completes in one minute.

[0055] The term “ultrasonicator” refers to an equipment that can apply ultrasound energy to agitate particles in a sample. Some non-limiting examples of the ultrasonicator include an ultrasonic bath, a probe-type ultrasonicator and an ultrasonic flow cell.

[0056] The term “applying” refers to an act of laying or spreading a substance on a surface.

[0057] The term “current collector” refers to any conductive substrate, which is capable of conducting an electrical current flowing to electrodes during discharging or charging a secondary battery. Some non-limiting examples of a current collector include a single metal layer or single substrate, and a single metal layer or single substrate with an overlying conductive layer, such as a carbon black-based conductive layer. In some embodiments, the current collector may be in contact with an electrode layer.

[0058] The term “modified current collector” refers to a substrate with a conductive layer applied on one side or both sides of the substrate.

[0059] The term “electrode layer” refers to a layer that comprises an electrochemically active material. In some embodiments, the electrode layer is in contact with a current collector, a modified current collector or a substrate. In some embodiments, the electrode layer is made by applying a coating on to a current collector, a modified current collector or a substrate and drying the coating. In some embodiments, the electrode layer is located on the surface of the current collector or the modified current collector. In other embodiments, a three-dimensional porous current collector or modified current collector is coated conformally with an electrode layer.

[0060] The term “doctor blading” refers to a process for fabrication of large area films on rigid or flexible substrates. A coating thickness can be controlled by an adjustable gap width between a coating blade and a coating surface, which allows the deposition of variable wet layer thicknesses.

[0061] The term “room temperature” refers to indoor temperatures from about 18 °C to

about 30 °C, e.g., 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30 °C. In some embodiments, room temperature refers to a temperature of about 20 °C +/- 1 °C or +/- 2 °C or +/- 3 °C. In other embodiments, room temperature refers to a temperature of about 22 °C or about 25 °C.

[0062] The term “solid content” refers to the amount of non-volatile material remaining after evaporation.

[0063] The term “peeling strength” refers to the amount of force required to separate two materials that are adhered to each other, such as a current collector and an electrode layer. It is a measure of the binding strength between such two materials and is usually expressed in N/cm.

[0064] The term “adhesive strength” refers to the amount of force required to separate a substrate and a binder material adhered to the substrate. It is a measure of the adhesion strength between such two materials and is usually expressed in N/cm.

[0065] The term “C rate” refers to the charging or discharging rate of a cell or battery, expressed in terms of its total storage capacity in Ah or mAh. For example, a rate of 1 C means utilization of all of the stored energy in one hour; 0.1 C means utilization of 10% of the energy in one hour or full energy in 10 hours; and 5 C means utilization of full energy in 12 minutes.

[0066] The term “ampere-hour (Ah)” refers to a unit used in specifying the storage capacity of a battery. For example, a battery with 1 Ah capacity can supply a current of one ampere for one hour or 0.5 A for two hours, etc. Therefore, 1 ampere-hour (Ah) is the equivalent of 3,600 coulombs of electrical charge. Similarly, the term “milliampere-hour (mAh)” also refers to a unit of the storage capacity of a battery and is 1/1,000 of an ampere-hour.

[0067] The term “battery cycle life” refers to the number of complete charge/discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity.

[0068] The term “capacity” is a characteristic of an electrochemical cell that refers to the total amount of electrical charge an electrochemical cell, such as a battery, is able to hold. Capacity is typically expressed in units of ampere-hours. The term “specific capacity” refers to the capacity output of an electrochemical cell, such as a battery, per unit weight, usually expressed in Ah/kg or mAh/g.

[0069] In the following description, all numbers disclosed herein are approximate values, regardless of whether the word “about” or “approximate” is used in connection therewith. They may vary by 1 percent, 2 percent, 5 percent, or, sometimes, 10 to 20 percent. 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 0 percent to 100 percent. Moreover, any numerical range defined by two R numbers as defined above is also

specifically disclosed.

[0070] In the present description, all references to the singular include references to the plural and vice versa. In the present description, where the context allows, references to an “aqueous solvent” may also specifically refer to water.

[0071] Battery electrodes commonly comprise a current collector and an electrode layer located on one side or both sides of the current collector. Typically, the electrode is prepared by dispersing an electrode active material and a binding agent in a solvent to form an electrode slurry, then coating the electrode slurry onto a current collector and drying it to form the electrode layer. Said electrode slurry (and hence, the resultant electrode layer) may additionally comprise conductive carbon. Regardless of the components present in the electrode layer, the discontinuity between the electrode layer and the current collector of the electrode means that significant interfacial resistance exists between the electrode layer and the current collector. Batteries comprising such electrodes would then have suboptimal electrochemical performances as a result of such interfacial resistances.

[0072] Among batteries, lithium-ion batteries are some of the most widely researched and used. A common electrode slurry composition for lithium-ion batteries comprises PVDF as a binding agent and NMP as a solvent, but the use of NMP presents significant environmental, health and safety risks, in addition to incurring additional costs associated with a recovery system. Therefore, water-based electrode slurries comprising an aqueous solvent, such as water, have been proposed as an alternative. Lithium-ion batteries that comprise electrodes produced using such electrode slurries have excellent battery performance, and the electrode production process has reduced environmental, health and safety risks.

[0073] However, corrosion of current collectors is particularly pronounced in cathodes produced using a water-based slurry that comprises a nickel-containing cathode active material, such as NMC, since such a slurry would be quite basic.

[0074] To solve the aforementioned problems, inventors of the present invention have proposed the use of a novel modified current collector, comprising a substrate and a conductive layer located on one side or both sides of the substrate. In a battery electrode, the conductive layer of the modified current collector disclosed herein reduces interfacial resistance between the electrode layer and the modified current collector and acts as a physical barrier between the substrate and the electrode layer, which helps alleviate the corrosion tendency of the substrate. In addition, the conductive layer of the present invention has an edge on not reverting to a fluid when a water-based electrode slurry is applied on top of the conductive layer.

[0075] The modified current collector as described herein refers to a substrate with a conductive layer applied on one side or both sides of the substrate, wherein the conductive layer comprises a conductive material and a binder material. Figure 1a shows a simplified view of an

embodiment of the modified current collector of the present invention, represented by **10**, within an electrode **100**. The modified current collector **10** comprises a substrate **101** with a conductive layer **102** applied on one side of the substrate **101**. In battery electrode production, an electrode layer **20** may be located on the surface of the conductive layer **102**.

[0076] Figure 1b shows a simplified view of another embodiment of the modified current collector of the present invention, represented by **11**, within an electrode **110**. The modified current collector **11** comprises a substrate **111** with conductive layers **112a** and **112b** applied on both sides of the substrate **111**. In the process of manufacturing a battery electrode, electrode layers **21a** and **21b** could be applied on the surface of the conductive layers **112a** and **112b** respectively.

[0077] When applied in a battery system, the substrate within the modified current collector of the present invention specifically acts to collect electrons generated by electrochemical reactions of the cathode active material or to supply electrons required for the electrochemical reactions.

[0078] In some embodiments, the substrate may be in the form of a foil, sheet, film or porous body with a three-dimensional network structure. In some embodiments, the substrate may be made of a polymeric or metallic material or a metalized polymer. In some embodiments, the substrate is covered with a conformal carbon layer. In some embodiments, the substrate is made of a single material. In other embodiments, the substrate is made of more than one material.

[0079] In some embodiments, the substrate is a metal. In some embodiments, the substrate has a single-layer structure. In some embodiments, the substrate is selected from the group consisting of stainless steel, titanium, nickel, aluminum, copper, platinum, gold, silver, chromium, zirconium, tungsten, molybdenum, silicon, tin, vanadium, zinc, cadmium, alloys thereof, electrically-conductive resin and combinations thereof.

[0080] In certain embodiments, the substrate has a two-layered structure comprising an outer layer and an inner layer, wherein the outer layer comprises a conductive additive and the inner layer comprises an insulating material or another conductive additive; for example, aluminum mounted with a conductive resin layer or a polymeric insulating material coated with an aluminum layer. In some embodiments, the conductive additive is selected from the group consisting of stainless steel, titanium, nickel, aluminum, copper, platinum, gold, silver, chromium, zirconium, tungsten, molybdenum, silicon, tin, vanadium, zinc, cadmium, alloys thereof, electrically-conductive resin and combinations thereof.

[0081] In some embodiments, the substrate has a three-layered structure comprising an

outer layer, a middle layer, and an inner layer, wherein the outer and inner layers comprise a conductive additive, and the middle layer comprises an insulating material or another conductive additive; for example, plastic coated with a metal film on both sides. In certain embodiments, each of the outer layer, middle layer and inner layer is independently selected from the group consisting of stainless steel, titanium, nickel, aluminum, copper, platinum, gold, silver, chromium, zirconium, tungsten, molybdenum, silicon, tin, vanadium, zinc, cadmium, alloys thereof, electrically-conductive resin and combinations thereof.

[0082] In some embodiments, the insulating material is a polymeric material selected from the group consisting of polycarbonate, polyacrylate, polyacrylonitrile, polyester, polyamide, polystyrene, polyurethane, polyepoxy, poly(acrylonitrile butadiene styrene), polyimide, polyolefin, polyethylene, polypropylene, polyphenylene sulfide, poly(vinyl ester), polyvinyl chloride, polyether, polyphenylene oxide, cellulose polymer and combinations thereof. In certain embodiments, the substrate has more than three layers.

[0083] In some embodiments, the conductive layer comprises a conductive material and a binder material. In certain embodiments, the conductive layer further comprises a surfactant or dispersing agent.

[0084] In a battery electrode comprising the modified current collector of the present invention and an electrode layer, the conductive material in the conductive layer of the modified current collector provides conductive pathways for electrons in travelling in-between the electrode layer and the substrate of the modified current collector. This significantly reduces the interfacial resistance between the electrode layer and the modified current collector i.e., at the electrode layer-modified current collector interface.

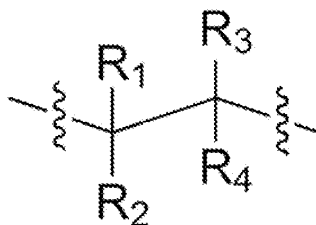
[0085] In some embodiments, the conductive material in the conductive layer is selected from the group consisting of natural graphite particulate, synthetic graphite particulate, hard carbon, soft carbon, mesocarbon microbeads (MCMB), carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibers, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, Super P, KS6, vapor grown carbon fibers (VGCF), mesoporous carbon and combinations thereof.

[0086] In a battery electrode comprising the modified current collector of the present invention and an electrode layer, the binder material in the conductive layer of the modified current collector provides adhesion of component(s) within the conductive layer to one another, as well as to the substrate.

[0087] In some embodiments, the binder material in the conductive layer comprises a copolymer. In some embodiments, the copolymer comprises a structural unit (a) and a structural unit (b). In some embodiments, structural unit (a) constitutes the hydrophilic portion of the

copolymer. In some embodiments, structural unit (b) constitutes the hydrophobic portion of the copolymer.

[0088] In some embodiments, the structural unit (a) in the copolymer of the binder material comprises one or more monomeric unit(s) with formula (1):



(1)

[0089] In some embodiments, each of R_1 , R_2 , R_3 and R_4 in formula (1) is independently H, hydroxyl, alkyl, hydroxyalkyl, halogen or alkyl halide. In certain embodiments, at least one of R_1 , R_2 , R_3 and R_4 is hydroxyl or hydroxyalkyl. In some embodiments, at least two of R_1 , R_2 , R_3 and R_4 are the same. In other embodiments, each of R_1 , R_2 , R_3 and R_4 differ from one another.

[0090] In some embodiments, an alkyl group has a general formula C_nH_{2n+1} , where n is an integer between 1 and 40, between 1 and 20 or between 1 and 8. In some embodiments, the alkyl group can be selected from the group consisting of C_1 - C_{40} alkyl group, C_1 - C_{30} alkyl group, C_1 - C_{20} alkyl group, C_1 - C_{10} alkyl group, C_5 - C_{40} alkyl group, C_5 - C_{30} alkyl group, C_5 - C_{20} alkyl group, C_5 - C_{10} alkyl group, C_{10} - C_{40} alkyl group, C_{10} - C_{30} alkyl group and C_{10} - C_{20} alkyl group.

[0091] Examples of alkyl groups include, but are not limited to, C_1 - C_8 alkyl groups, such as methyl, ethyl, propyl, isopropyl, 2-methyl-1-propyl, 2-methyl-2-propyl, 2-methyl-1-butyl, 3-methyl-1-butyl, 2-methyl-3-butyl, 2,2-dimethyl-1-propyl, 2-methyl-1-pentyl, 3-methyl-1-pentyl, 4-methyl-1-pentyl, 2-methyl-2-pentyl, 3-methyl-2-pentyl, 4-methyl-2-pentyl, 2,2-dimethyl-1-butyl, 3,3-dimethyl-1-butyl, 2-ethyl-1-butyl, butyl, isobutyl, *t*-butyl, pentyl, isopentyl, neopentyl, hexyl, heptyl and octyl. Longer alkyl groups include nonyl and decyl groups. An alkyl group can be unsubstituted or substituted with one or more suitable substituents. Furthermore, the alkyl group can be branched or unbranched. In some embodiments, the alkyl group contains at least 2, 3, 4, 5, 6, 7, or 8 carbon atoms.

[0092] In some embodiments, the hydroxyalkyl group can be selected from the group consisting of C_1 - C_{40} hydroxyalkyl group, C_1 - C_{30} hydroxyalkyl group, C_1 - C_{20} hydroxyalkyl group, C_1 - C_{10} hydroxyalkyl group, C_5 - C_{40} hydroxyalkyl group, C_5 - C_{30} hydroxyalkyl group, C_5 - C_{20} hydroxyalkyl group, C_5 - C_{10} hydroxyalkyl group, C_{10} - C_{40} hydroxyalkyl group, C_{10} - C_{30} hydroxyalkyl group and C_{10} - C_{20} hydroxyalkyl group.

[0093] Examples of hydroxyalkyl groups include, but are not limited to, hydroxymethyl, hydroxyethyl, hydroxypropyl, hydroxy methyl propyl, hydroxy butyl, and hydroxy methyl butyl,

hydroxy dimethyl propyl, hydroxy methyl pentyl, hydroxy dimethyl butyl, hydroxy ethyl butyl, hydroxy pentyl, hydroxy neopentyl, hydroxy neopentyl, hydroxy hexyl, hydroxy heptyl and hydroxy octyl. The alkyl group within hydroxyalkyl group can be branched or unbranched.

[0094] In some embodiments, the halogen can be selected from the group consisting of fluorine, chlorine, bromine, iodine, astatine and combinations thereof.

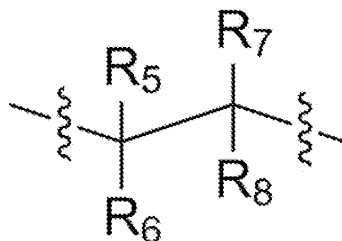
[0095] Some non-limiting examples of alkyl halide include methyl fluoride, methyl chloride, methyl bromide, methyl iodide, methyl astatide, ethyl fluoride, ethyl chloride, ethyl bromide, ethyl iodide, ethyl astatide, propyl fluoride, propyl chloride, propyl bromide, propyl iodide and propyl astatide.

[0096] In general, structural unit (a) is hydrophilic in nature. For this reason, it would be improbable for each of R₁, R₂, R₃ and R₄ in formula (1) in the monomeric unit(s) within structural unit (a) to independently comprise a long hydrocarbon chain. The presence of long hydrocarbon chain(s) within the monomeric unit(s) of structure unit (a) would render a loss in hydrophilicity of structural unit (a) in the copolymer. This might potentially affect the overall dispersion of the binder material during the making of the conductive layer, and thus its homogeneity. Not only this would create inconsistencies in adhesivity across the substrate-conductive layer interface, the conductivity network developed to facilitate electrons travelling between the electrode layer and the substrate could also be severely weakened, which would intensify the interfacial resistance between the electrode layer and the modified current collector. In some embodiments, the alkyl group and the hydroxyalkyl group are C₁–C₈ alkyl group and C₁–C₈ hydroxyalkyl group respectively.

[0097] Conversely, it is undesirable for each of R₁, R₂, R₃ and R₄ in formula (1) in the monomeric unit(s) within structural unit (a) to independently be a hydroxyl or hydroxyalkyl. Structural unit (a) comprising excessive amounts of hydroxyl or hydroxyalkyl groups might lead to an overabundance of hydrogen bonding interactions between the hydroxyl groups and/or the hydroxyalkyl groups, both within a copolymer chain and between different copolymer chains. As a result, this would induce agglomeration and poor dispersibility of the binder material produced therefrom and other material(s) (e.g., conductive material) within the conductive slurry in the production of the conductive layer. In some embodiments, no more than three of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl or hydroxyalkyl. In certain embodiments, no more than two of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl or hydroxyalkyl. In certain embodiments, only one of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl or hydroxyalkyl. In other embodiments, only one of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl. In certain embodiments, only one of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl and the remaining three of each of R₁, R₂, R₃ and R₄ in formula (1) is independently alkyl or H. In further embodiments, only one of R₁, R₂, R₃ and R₄ in formula (1) is hydroxyl and the remaining three of each of R₁, R₂, R₃ and R₄ in formula (1) is

independently H.

[0098] In some embodiments, the structural unit (b) in the copolymer of the binder material comprises one or more monomeric unit(s) with formula (2):



(2)

[0099] In some embodiments, each of R₅, R₆, R₇ and R₈ in formula (2) is independently H, alkyl, acyloxy, acyloxyalkyl, halogen or alkyl halide. In certain embodiments, at least one of R₅, R₆, R₇, and R₈ is acyloxy or acyloxyalkyl. In some embodiments, at least two of R₅, R₆, R₇ and R₈ are the same. In other embodiments, each of R₅, R₆, R₇ and R₈ differ from one another.

[00100] An acyloxy group has a structure of -O-(C=O)-Z, wherein Z refers to an alkyl group.

[00101] An acyloxyalkyl group has a structure of -Y-O-(C=O)-Z, wherein Y refers to an alkylene group and Z refers to an alkyl group.

[00102] In some embodiments, the alkyl group (Z) within each of an acyloxy group or an acyloxyalkyl group can independently be selected from the group consisting of a C₁-C₄₀ alkyl group, C₁-C₃₀ alkyl group, C₁-C₂₀ alkyl group, C₁-C₁₀ alkyl group, C₅-C₄₀ alkyl group, C₅-C₃₀ alkyl group, C₅-C₂₀ alkyl group, C₅-C₁₀ alkyl group, C₁₀-C₄₀ alkyl group, C₁₀-C₃₀ alkyl group and C₁₀-C₂₀ alkyl group.

[00103] Examples of an alkyl group within each of an acyloxy group or an acyloxyalkyl group include, but are not limited to, C₁-C₈ alkyl groups, such as methyl, ethyl, propyl, isopropyl, 2-methyl-1-propyl, 2-methyl-2-propyl, 2-methyl-1-butyl, 3-methyl-1-butyl, 2-methyl-3-butyl, 2,2-dimethyl-1-propyl, 2-methyl-1-pentyl, 3-methyl-1-pentyl, 4-methyl-1-pentyl, 2-methyl-2-pentyl, 3-methyl-2-pentyl, 4-methyl-2-pentyl, 2,2-dimethyl-1-butyl, 3,3-dimethyl-1-butyl, 2-ethyl-1-butyl, butyl, isobutyl, *t*-butyl, pentyl, isopentyl, neopentyl, hexyl, heptyl and octyl. Longer alkyl groups include nonyl and decyl groups. An alkyl group can be unsubstituted or substituted with one or more suitable substituents. Furthermore, the alkyl group can be branched or unbranched. In some embodiments, the alkyl group contains at least 2, 3, 4, 5, 6, 7, or 8 carbon atoms.

[00104] In some embodiments, the alkylene group (Y) within an acyloxyalkyl group can independently be selected from the group consisting of a C₁-C₄₀ alkylene group, C₁-C₃₀ alkylene group, C₁-C₂₀ alkylene group, C₁-C₁₀ alkylene group, C₅-C₄₀ alkylene group, C₅-C₃₀ alkylene

group, C₅-C₂₀ alkylene group, C₅-C₁₀ alkylene group, C₁₀-C₄₀ alkylene group, C₁₀-C₃₀ alkylene group and C₁₀-C₂₀ alkylene group. The alkylene group within the acyloxyalkyl group can be branched or unbranched. Examples of an alkylene group within an acyloxyalkyl group include, but are not limited to, methylene, ethylene, propylene, butylene, pentylene, hexylene, heptylene, octylene, nonylene, decylene, undecylene, dodecylene, tridecylene, tetradecylene, pentadecylene, hexadecylene, heptadecylene, octadecylene, nonadecylene, icosylene and a stereoisomer thereof. Some non-limiting examples of an acyloxyalkyl group include acyloxymethyl, acyloxyethyl, acyloxypropyl, acyloxy (methyl) propyl and acyloxy (methyl) butyl.

[00105] Despite the hydrophobic nature of structural unit (b), it is undesirable for each of R₅, R₆, R₇ and R₈ in formula (2) in the monomeric unit(s) within structural unit (b) to independently comprise a long hydrocarbon chain. Overabundance of long hydrocarbon chains in the monomer unit(s) within structural unit (b) brings about poor interaction of structure unit (b) with the aqueous solvent (e.g., water) in the conductive slurry and promotes aggregation of the entire copolymer chain. Winding motion between different copolymer chains might also occur, forming a compact globular structure. Consequently, the binder material produced therefrom as well as other materials within the conductive slurry are unable to be dispersed properly. In some embodiments, no more than three of R₅, R₆, R₇ and R₈ in formula (2) is alkyl, acyloxy or acyloxyalkyl. In certain embodiments, no more than two of R₅, R₆, R₇ and R₈ in formula (2) is alkyl, acyloxy or acyloxyalkyl. In certain embodiments, only one of R₅, R₆, R₇ and R₈ in formula (2) is acyloxy or acyloxyalkyl. In other embodiments, only one of R₅, R₆, R₇ and R₈ in formula (2) is acyloxy. In certain embodiments, only one of R₅, R₆, R₇ and R₈ in formula (2) is acetoxyl and the remaining three of each of R₅, R₆, R₇ and R₈ in formula (2) is independently alkyl or H. In further embodiments, only one of R₅, R₆, R₇ and R₈ in formula (2) is acetoxyl and the remaining three of each of R₅, R₆, R₇ and R₈ in formula (2) is independently H.

[00106] In some embodiments, the proportion of structural unit (a) in the copolymer of the binder material is from about 90% to about 100%, from about 91% to about 100%, from about 92% to about 100%, from about 93% to about 100%, from about 94% to about 100%, from about 95% to about 100%, from about 96% to about 100%, from about 90% to about 99.8%, from about 91% to about 99.8%, from about 92% to about 99.8%, from about 93% to about 99.8%, from about 94% to about 99.8%, from about 95% to about 99.8%, from about 96% to about 99.8%, from about 90% to about 99.5%, from about 91% to about 99.5%, from about 92% to about 99.5%, from about 93% to about 99.5%, from about 94% to about 99.5%, from about 95% to about 99.5%, from about 96% to about 99.5%, from about 90% to about 99%, from about 91% to about 99%, from about 92% to about 99%, from about 93% to about 99%, from about 94% to about 99%, from about 95% to about 99%, from about 90% to about 98.5%, from about 91% to about 98.5%, from about 92% to about 98.5%, from about 93% to about

98.5%, from about 94% to about 98.5%, from about 95% to about 98.5%, from about 90% to about 98%, from about 91% to about 98%, from about 92% to about 98%, from about 93% to about 98%, from about 94% to about 98% or from about 95% to about 98% by mole, based on the total number of moles of monomeric units in the copolymer.

[00107] In some embodiments, the proportion of structural unit (a) in the copolymer of the binder material is less than 100%, less than 99.9%, less than 99.8%, less than 99.7%, less than 99.6%, less than 99.5%, less than 99.4%, less than 99.3%, less than 99.2%, less than 99.1%, less than 99%, less than 98.8%, less than 98.5%, less than 98%, less than 97%, less than 96%, less than 95%, less than 94% less than 93% or less than 92% by mole, based on the total number of moles of monomeric units in the copolymer. In some embodiments, the proportion of structural unit (a) in the copolymer of the binder material is at least 90%, at least 91%, at least 92%, at least 93%, at least 93.5%, at least 94%, at least 94.5%, at least 95%, at least 95.5%, at least 96%, at least 96.5%, at least 97%, at least 97.5% or at least 98% by mole, based on the total number of moles of monomeric units in the copolymer.

[00108] In some embodiments, the proportion of structural unit (b) in the copolymer of the binder material is from about 0.1% to about 10%, from about 0.1% to about 9%, from about 0.1% to about 8%, from about 0.1% to about 7%, from about 0.1% to about 6%, from about 0.1% to about 5%, from about 0.1% to about 4%, from about 0.5% to about 10%, from about 0.5% to about 9%, from about 0.5% to about 8%, from about 0.5% to about 7%, from about 0.5% to about 6%, from about 0.5% to about 5%, from about 0.5% to about 4%, from about 1% to about 10%, from about 1% to about 9%, from about 1% to about 8%, from about 1% to about 7%, from about 1% to about 6%, from about 1% to about 5%, from about 1% to about 4%, from about 1.5% to about 10%, from about 1.5% to about 9%, from about 1.5% to about 8%, from about 1.5% to about 7%, from about 1.5% to about 6%, from about 1.5% to about 5%, from about 2% to about 10%, from about 2% to about 9%, from about 2% to about 8%, from about 2% to about 7%, from about 2% to about 6% or from about 2% to about 5% by mole, based on the total number of moles of monomeric units in the copolymer.

[00109] In some embodiments, the proportion of structural unit (b) in the copolymer of the binder material is less than 10%, less than 9%, less than 8%, less than 7%, less than 6%, less than 5%, less than 4.5%, less than 4%, less than 3.5%, less than 3%, less than 2.5% or less than 2% by mole, based on the total number of moles of monomeric units in the copolymer. In some embodiments, the proportion of structural unit (b) in the copolymer of the binder material is at least 0.1%, at least 0.2%, at least 0.4%, at least 0.6%, at least 0.8%, at least 1%, at least 1.2%, at least 1.4%, at least 1.6%, at least 1.8%, at least 2%, at least 3%, at least 4%, at least 5%, at least 6%, at least 7% or at least 8% by mole, based on the total number of moles of monomeric units in the copolymer.

[00110] The relative proportion of structural unit (a) to structural unit (b) in the copolymer within the binder material is crucial in governing the functionality (i.e., adhesive strength, dispersibility in an aqueous solvent and resistance against re-dissolution in an aqueous solvent) of the binder material. With the molar ratio of structural unit (a) to structural unit (b) in the copolymer of the binder material falling within the range as disclosed herein, the binder material is observed to exhibit exceptional adhesive strength. Furthermore, the binder material to be used in the present invention is capable of being homogeneously dispersed in an aqueous solvent, enabling excellent processibility of a conductive slurry formed therefrom in the making of the modified current collector. Most importantly, the binder material demonstrates a high level of resistance against re-dissolution in an aqueous solvent. This is particularly noticeable as an electrode layer slurry is applied on the surface of the binder material-containing conductive layer in forming an electrode. It is observed that the binder material disclosed herein is able to maintain its adhesive capability in binding the conductive layer onto the substrate without reverting to a fluid upon contact with an aqueous solvent. This keeps the conductive layer intact on the substrate which forms a physical barrier between the substrate and the electrode layer, and thus helps alleviate the likelihood of corrosion of substrate. The presence of this conductive layer drives the interfacial resistance between the electrode layer and the modified current collector down, which in turn improves the electrochemical performance of the battery.

[00111] In some embodiments, the molar ratio of structural unit (a) to structural unit (b) in the copolymer of the binder material is from about 9 to about 1000, from about 9 to about 900, from about 9 to about 800, from about 9 to about 700, from about 9 to about 600, from about 9 to about 500, from about 9 to about 400, from about 9 to about 300, from about 9 to about 200, from about 9 to about 150, from about 9 to about 100, from about 10 to about 1000, from about 10 to about 900, from about 10 to about 800, from about 10 to about 700, from about 10 to about 600, from about 10 to about 500, from about 10 to about 400, from about 10 to about 300, from about 10 to about 200, from about 10 to about 150, from about 10 to about 100, from about 12 to about 500, from about 12 to about 300, from about 12 to about 100, from about 14 to about 500, from about 14 to about 300, from about 14 to about 100, from about 16 to about 500, from about 16 to about 300, from about 16 to about 100, from about 18 to about 500, from about 18 to about 300 or from about 18 to about 100.

[00112] In some embodiments, the molar ratio of structural unit (a) to structural unit (b) in the copolymer of the binder material is less than 1000, less than 800, less than 600, less than 400, less than 200, less than 100, less than 80, less than 60, less than 40, less than 30, less than 20 or less than 15. In some embodiments, the molar ratio of structural unit (a) to structural unit (b) in the copolymer of the binder material is more than 9, more than 10, more than 12, more than 14, more than 16, more than 18, more than 20, more than 30, more than 40, more than 50, more than 100, more than 250, more than 500 or more than 700.

[00113] In some embodiments, the weight-average molecular weight (M_w) of the copolymer in the binder material is from about 10,000 g/mol to about 300,000 g/mol, from about 15,000 g/mol to about 300,000 g/mol, from about 20,000 g/mol to about 300,000 g/mol, from about 30,000 g/mol to about 300,000 g/mol, from about 40,000 g/mol to about 300,000 g/mol, from about 50,000 g/mol to about 300,000 g/mol, from about 75,000 g/mol to about 300,000 g/mol, from about 100,000 g/mol to about 300,000 g/mol, from about 125,000 g/mol to about 300,000 g/mol, from about 150,000 g/mol to about 300,000 g/mol, from about 200,000 g/mol to about 300,000 g/mol, from about 10,000 g/mol to about 200,000 g/mol, from about 15,000 g/mol to about 200,000 g/mol, from about 20,000 g/mol to about 200,000 g/mol, from about 30,000 g/mol to about 200,000 g/mol, from about 40,000 g/mol to about 200,000 g/mol, from about 50,000 g/mol to about 200,000 g/mol, from about 75,000 g/mol to about 200,000 g/mol, from about 100,000 g/mol to about 200,000 g/mol, from about 10,000 g/mol to about 150,000 g/mol, from about 15,000 g/mol to about 150,000 g/mol, from about 20,000 g/mol to about 150,000 g/mol, from about 30,000 g/mol to about 150,000 g/mol, from about 40,000 g/mol to about 150,000 g/mol, from about 50,000 g/mol to about 150,000 g/mol, from about 75,000 g/mol to about 150,000 g/mol or from about 100,000 g/mol to about 150,000 g/mol.

[00114] In some embodiments, the weight-average molecular weight of the copolymer in the binder material is less than 300,000 g/mol, less than 250,000 g/mol, less than 200,000 g/mol, less than 175,000 g/mol, less than 150,000 g/mol, less than 125,000 g/mol, less than 100,000 g/mol, less than 90,000 g/mol, less than 80,000 g/mol, less than 70,000 g/mol, less than 60,000 g/mol or less than 50,000 g/mol. In some embodiments, the weight-average molecular weight of the copolymer in the binder material is more than 10,000 g/mol, more than 15,000 g/mol, more than 20,000 g/mol, more than 25,000 g/mol, more than 30,000 g/mol, more than 35,000 g/mol, more than 40,000 g/mol, more than 50,000 g/mol, more than 60,000 g/mol, more than 70,000 g/mol, more than 80,000 g/mol, more than 100,000 g/mol or more than 150,000 g/mol.

[00115] In some embodiments, the viscosity of the binder material at 4% concentration in DI water at 20 °C is from about 5 mPa·s to about 80 mPa·s, from about 8 mPa·s to about 80 mPa·s, from about 10 mPa·s to about 80 mPa·s, from about 15 mPa·s to about 80 mPa·s, from about 20 mPa·s to about 80 mPa·s, from about 25 mPa·s to about 80 mPa·s, from about 30 mPa·s to about 80 mPa·s, from about 35 mPa·s to about 80 mPa·s, from about 40 mPa·s to about 80 mPa·s, from about 5 mPa·s to about 50 mPa·s, from about 8 mPa·s to about 50 mPa·s, from about 10 mPa·s to about 50 mPa·s, from about 15 mPa·s to about 50 mPa·s, from about 20 mPa·s to about 50 mPa·s, from about 25 mPa·s to about 50 mPa·s, from about 30 mPa·s to about 50 mPa·s, from about 5 mPa·s to about 30 mPa·s, from about 10 mPa·s to about 30 mPa·s, from about 15 mPa·s to about 30 mPa·s or from about 5 mPa·s to about 25 mPa·s.

[00116] In some embodiments, the viscosity of the binder material at 4% concentration in DI water at 20 °C is less than 80 mPa·s, less than 70 mPa·s, less than 60 mPa·s, less than 50

mPa·s, less than 45 mPa·s, less than 40 mPa·s, less than 35 mPa·s, less than 30 mPa·s, less than 25 mPa·s, less than 20 mPa·s, less than 15 mPa·s, less than 10 mPa·s or less than 8 mPa·s. In some embodiments, the viscosity of the binder material at 4% concentration in DI water at 20 °C is more than 5 mPa·s, more than 7 mPa·s, more than 10 mPa·s, more than 15 mPa·s, more than 20 mPa·s, more than 25 mPa·s, more than 30 mPa·s, more than 35 mPa·s, more than 40 mPa·s, more than 45 mPa·s, more than 50 mPa·s, more than 60 mPa·s or more than 70 mPa·s.

[00117] The binder material used in the present invention exhibits strong adhesive capability. In some embodiments, the adhesive strength between the binder material and the substrate is from about 2 N/cm to about 8 N/cm, from about 2 N/cm to about 7.5 N/cm, from about 2 N/cm to about 7 N/cm, from about 2 N/cm to about 6.5 N/cm, from about 2 N/cm to about 6 N/cm, from about 2 N/cm to about 6 N/cm, from about 2 N/cm to about 5.5 N/cm, from about 2 N/cm to about 5 N/cm, from about 2 N/cm to about 4.5 N/cm, from about 2 N/cm to about 4 N/cm, from about 2 N/cm to about 3.8 N/cm, from about 2 N/cm to about 3.6 N/cm, from about 2 N/cm to about 3.4 N/cm, from about 2 N/cm to about 3.2 N/cm, from about 2 N/cm to about 3 N/cm, from about 2.5 N/cm to about 8 N/cm, from about 3 N/cm to about 8 N/cm, from about 3.5 N/cm to about 8 N/cm, from about 4 N/cm to about 8 N/cm, from about 4.5 N/cm to about 8 N/cm, from about 5 N/cm to about 8 N/cm, from about 5.5 N/cm to about 8 N/cm, from about 6 N/cm to about 8 N/cm, from about 3 N/cm to about 7 N/cm, from about 3 N/cm to about 6 N/cm, from about 3 N/cm to about 5.5 N/cm or from about 4 N/cm to about 6 N/cm.

[00118] In some embodiments, the adhesive strength between the binder material and the substrate is less than 8 N/cm, less than 7.5 N/cm, less than 7 N/cm, less than 6.5 N/cm, less than 6 N/cm, less than 5.5 N/cm, less than 5 N/cm, less than 4.5 N/cm, less than 4 N/cm, less than 3.8 N/cm, less than 3.6 N/cm, less than 3.4 N/cm, less than 3.2 N/cm, less than 3 N/cm, less than 2.8 N/cm or less than 2.6 N/cm. In some embodiments, the adhesive strength between the binder material and the substrate is more than 2 N/cm, more than 2.2 N/cm, more than 2.4 N/cm, more than 2.6 N/cm, more than 2.8 N/cm, more than 3 N/cm, more than 3.2 N/cm, more than 3.4 N/cm, more than 3.6 N/cm, more than 3.8 N/cm, more than 4 N/cm, more than 4.5 N/cm, more than 5 N/cm, more than 5.5 N/cm, more than 6 N/cm, more than 6.5 N/cm, more than 7 N/cm or more than 7.5 N/cm.

[00119] The proportions of each of the binder material and the conductive material within the conductive layer of the modified current collector are of paramount importance in governing the effectiveness of the conductive layer in forming an unyielding conductive layer structure; reducing corrosion tendency of the substrate; and minimizing the interfacial resistance between the electrode layer and the modified current collector. An inadequate amount of conductive material within the conductive layer might lead to formation of a conductive network with insufficient coverage to facilitate an efficient and effective transfer of electrons between the electrode layer and the substrate, which is likely to drive up the interfacial resistance. On the

other hand, deficiency in the amount of binder material within the conductive layer might cause difficulty in holding the entire conductive layer in place. The conductive layer might easily be disintegrated, with components within falling apart when subjected to a slight change in external environment (e.g., scratching, pressure, etc.). Problems associated with corrosion of the substrate are likely to persist as a result.

[00120] In some embodiments, the proportion of each of the binder material and the conductive material within the conductive layer of the modified current collector is independently from about 20% to about 75%, from about 25% to about 75%, from about 30% to about 75%, from about 35% to about 75%, from about 40% to about 75%, from about 45% to about 75%, from about 50% to about 75%, from about 55% to about 75%, from about 60% to about 75%, from about 20% to about 70%, from about 25% to about 70%, from about 30% to about 70%, from about 35% to about 70%, from about 40% to about 70%, from about 45% to about 70%, from about 50% to about 70%, from about 55% to about 70%, from about 20% to about 65%, from about 25% to about 65%, from about 30% to about 65%, from about 35% to about 65%, from about 40% to about 65%, from about 45% to about 65%, from about 50% to about 65%, from about 20% to about 60%, from about 25% to about 60%, from about 30% to about 60%, from about 35% to about 60%, from about 40% to about 60%, from about 45% to about 60%, from about 20% to about 55%, from about 25% to about 55%, from about 30% to about 55%, from about 35% to about 55%, from about 40% to about 55%, from about 20% to about 50%, from about 25% to about 50%, from about 30% to about 50% or from about 35% to about 50% by weight, based on the total weight of the conductive layer.

[00121] In some embodiments, the proportion of each of the binder material and the conductive material within the conductive layer of the modified current collector is independently less than 75%, less than 70%, less than 65%, less than 60%, less than 55%, less than 50%, less than 45%, less than 40%, less than 35% less than 30% or less than 25% by weight, based on the total weight of the conductive layer. In some embodiments, the proportion of each of the binder material and the conductive material within the conductive layer of the modified current collector is independently more than 20%, more than 25%, more than 30%, more than 35%, more than 40%, more than 45%, more than 50%, more than 55%, more than 60%, more than 65% or more than 70% by weight, based on the total weight of the conductive layer.

[00122] In certain embodiments, the conductive layer additionally comprises a surfactant or a dispersing agent. These surface-active agents might be added during the production of the conductive slurry to enhance the dispersibility of conductive material in the slurry. There is no particular limitation with respect to the type of surfactant or dispersing agent used, except that it should be capable of dispersing the conductive material within the conductive slurry, while does not affect the overall performance of the resultant conductive layer produced therefrom. In other

embodiments, the conductive layer does not comprise a surfactant or a dispersing agent.

[00123] In some embodiments, the proportion of surfactant or dispersing agent in the conductive layer is from about 0% to about 5%, from about 0.5% to about 5%, from about 1% to about 5%, from about 1.5% to about 5%, from about 2% to about 5%, from about 2.5% to about 5%, from about 3% to about 5%, from about 0% to about 4%, from about 0.5% to about 4%, from about 1% to about 4%, from about 1.5% to about 4%, from about 2% to about 4%, from about 0% to about 3%, from about 0.5% to about 3%, from about 1% to about 3%, from about 0% to about 2.5%, from about 0.5% to about 2.5%, from about 1% to about 2.5%, from about 1.5% to about 2.5% or from about 2% to about 2.5% by weight, based on the total weight of the conductive layer.

[00124] In some embodiments, the proportion of surfactant or dispersing agent in the conductive layer is less than 5%, less than 4.5%, less than 4%, less than 3.5%, less than 3%, less than 2.5%, less than 2%, less than 1.5%, less than 1% or less than 0.5% by weight, based on the total weight of the conductive layer. In some embodiments, the proportion of surfactant or dispersing agent in the conductive layer is more than 0%, more than 0.5%, more than 1%, more than 1.5%, more than 2%, more than 2.5%, more than 3%, more than 3.5%, more than 4% or more than 4.5% by weight, based on the total weight of the conductive layer.

[00125] The thickness of the modified current collector in an electrode may affect the volume it occupies within the battery, the room available for electrode active material in the electrode layer, and hence the capacity of the battery. In certain embodiments, the modified current collector has a thickness of from about 5 μm to about 70 μm , from about 5 μm to about 60 μm , from about 5 μm to about 50 μm , from about 5 μm to about 40 μm , from about 5 μm to about 30 μm , from about 5 μm to about 20 μm , from about 10 μm to about 70 μm , from about 10 μm to about 60 μm , from about 10 μm to about 50 μm , from about 10 μm to about 40 μm , from about 10 μm to about 30 μm , from about 15 μm to about 70 μm , from about 15 μm to about 60 μm , from about 15 μm to about 50 μm , from about 15 μm to about 40 μm , from about 15 μm to about 30 μm , from about 20 μm to about 70 μm , from about 20 μm to about 60 μm , from about 20 μm to about 50 μm , from about 20 μm to about 40 μm , from about 25 μm to about 70 μm , from about 25 μm to about 60 μm , from about 25 μm to about 50 μm , from about 25 μm to about 40 μm , from about 25 μm to about 70 μm , from about 25 μm to about 60 μm , from about 25 μm to about 50 μm or from about 25 μm to about 40 μm .

[00126] In some embodiments, the modified current collector has a thickness of less than 70 μm , less than 60 μm , less than 50 μm , less than 40 μm , less than 30 μm , less than 25 μm , less than 20 μm , less than 15 μm or less than 10 μm . In some embodiments, the modified current collector has a thickness of more than 5 μm , more than 10 μm , more than 15 μm , more than 20 μm , more than 25 μm , more than 30 μm , more than 40 μm , more than 50 μm or more than 60 μm .

μm.

[00127] The thickness of the substrate in a modified current collector may affect the volume it occupies within the modified current collector and/or the electrode. This might influence the available space for conductive material and binder material in the conductive layer and/or electrode active material in the electrode layer. Thus, there are possibilities that the electrical conductivity of the battery system, the binding capability of the conductive layer to the substrate as well as the capacity of the battery may be impacted. In some embodiments, the substrate in the modified current collector has a thickness of from about 5 μm to about 50 μm, from about 5 μm to about 45 μm, from about 5 μm to about 40 μm, from about 5 μm to about 35 μm, from about 5 μm to about 30 μm, from about 5 μm to about 25 μm, from about 10 μm to about 50 μm, from about 10 μm to about 45 μm, from about 10 μm to about 40 μm, from about 10 μm to about 35 μm, from about 10 μm to about 30 μm, from about 15 μm to about 50 μm, from about 15 μm to about 45 μm, from about 15 μm to about 40 μm, from about 15 μm to about 35 μm, from about 20 μm to about 50 μm, from about 20 μm to about 45 μm or from about 20 μm to about 40 μm.

[00128] In some embodiments, the substrate in the modified current collector has a thickness of less than 50 μm, less than 45 μm, less than 40 μm, less than 35 μm, less than 30 μm, less than 25 μm, less than 20 μm, less than 15 μm or less than 10 μm. In some embodiments, the substrate in the modified current collector has a thickness of more than 5 μm, more than 10 μm, more than 15 μm, more than 20 μm, more than 25 μm, more than 30 μm, more than 35 μm, more than 40 μm or more than 45 μm.

[00129] In some embodiments, the conductive layer in the modified current collector has a thickness of from about 1 μm to about 20 μm, from about 1 μm to about 16 μm, from about 1 μm to about 12 μm, from about 1 μm to about 10 μm, from about 2 μm to about 20 μm, from about 2 μm to about 16 μm, from about 2 μm to about 12 μm, from about 2 μm to about 10 μm, from about 3 μm to about 20 μm, from about 3 μm to about 16 μm, from about 3 μm to about 12 μm, from about 3 μm to about 10 μm, from about 4 μm to about 20 μm, from about 4 μm to about 16 μm, from about 4 μm to about 12 μm or from about 4 μm to about 10 μm.

[00130] In some embodiments, the conductive layer in the modified current collector has a thickness of less than 20 μm, less than 18 μm, less than 16 μm, less than 14 μm, less than 12 μm, less than 10 μm, less than 8 μm, less than 6 μm or less than 4 μm. In some embodiments, the conductive layer in the modified current collector has a thickness of more than 1 μm, more than 2 μm, more than 4 μm, more than 6 μm, more than 8 μm, more than 10 μm, more than 12 μm, more than 14 μm, more than 16 μm or more than 18 μm.

[00131] As mentioned above, in some embodiments, the conductive layer in a modified current collector of the present invention is produced via a conductive slurry. In some

embodiments, the conductive slurry comprises a conductive material, a binder material and a solvent. In some embodiments, the binder material comprises a copolymer as discussed above. In some embodiments, the solvent in a conductive slurry is an aqueous solvent.

[00132] In certain embodiments, the aqueous solvent is water. In some embodiments, the aqueous solvent is selected from the group consisting of tap water, bottled water, purified water, pure water, distilled water, de-ionized water (DI water), D₂O, and combinations thereof.

[00133] In some embodiments, the aqueous solvent in the conductive slurry further comprises a minor component in addition to water. In some embodiments, the volume ratio of water to the minor component is from about 51:49 to about 99:1. Any water-miscible or volatile solvents can be used as the minor component of the aqueous solvent. Some non-limiting examples of the minor component include alcohols, lower aliphatic ketones, lower alkyl acetates, and combinations thereof. The addition of a minor component can improve the processibility of the conductive slurry.

[00134] Some non-limiting examples of the alcohol include C₁-C₄ alcohols, such as methanol, ethanol, isopropanol, n-propanol, tert-butanol, n-butanol, 1,2-butanediol, 1,3-butanediol, 1,4-butanediol, 2,3-butanediol, ethylene glycol, propylene glycol, glycerol, and combinations thereof. Some non-limiting examples of the lower aliphatic ketones include acetone, dimethyl ketone, methyl ethyl ketone (MEK), and combinations thereof. Some non-limiting examples of the lower alkyl acetates include ethyl acetate (EA), isopropyl acetate, propyl acetate, butyl acetate (BA), and combinations thereof. Some other non-limiting examples of the water-miscible solvents or volatile solvents include 1,4-dioxane, diethyl ether, methyl tert-butyl ether, cyclopentyl methyl ether, tetrahydrofuran (THF), 2-methyl tetrahydrofuran, acetonitrile, dimethyl sulfoxide (DMSO), sulfolane, nitromethane, propylene carbonate, ethylene carbonate, dimethyl carbonate, pyridine, acetaldehyde, formic acid, acetic acid, propanoic acid, butyric acid, γ -valerolactone (GVL), furfuryl alcohol, methyl lactate, ethyl lactate, diethanolamine, dimethylacetamide (DMAc), dimethylformamide (DMF), N-methylpyrrolidone (NMP), dihydrolevoglucosenone (Cyrene™), N,N'-dimethylpropyleneurea (DMPU), and dimethyl isosorbide (DMI). In some embodiments, no minor component is present in the aqueous solvent of the conductive slurry.

[00135] In some embodiments, the solid content of the conductive slurry is from about 5% to about 25%, from about 6% to about 25%, from about 7% to about 25%, from about 8% to about 25%, from about 9% to about 25%, from about 10% to about 25%, from about 11% to about 25%, from about 12% to about 25%, from about 13% to about 25%, from about 14% to about 25%, from about 15% to about 25%, from about 5% to about 20%, from about 6% to about 20%, from about 7% to about 20%, from about 8% to about 20%, from about 9% to about 20%, from about 10% to about 20%, from about 5% to about 17%, from about 6% to about 17%,

from about 7% to about 17%, from about 8% to about 17%, from about 9% to about 17%, from about 10% to about 17%, from about 5% to about 15%, from about 6% to about 15%, from about 7% to about 15%, from about 8% to about 15%, from about 9% to about 15% or from about 10% to about 15% by weight, based on the total weight of the conductive slurry.

[00136] In some embodiments, the solid content of the conductive slurry is less than 25%, less than 23%, less than 20%, less than 19%, less than 18%, less than 17%, less than 16%, less than 15%, less than 14%, less than 13%, less than 10%, less than 8% or less than 6% by weight, based on the total weight of the conductive slurry. In some embodiments, the solid content of the conductive slurry is more than 5%, more than 6%, more than 7%, more than 8%, more than 9%, more than 10%, more than 11%, more than 12%, more than 13%, more than 14%, more than 15%, more than 16%, more than 17%, more than 18%, more than 19%, more than 20% or more than 22% by weight, based on the total weight of the conductive slurry.

[00137] There are no particular limitations on the method used to produce a conductive slurry, except that all components of the slurry (e.g., conductive material, binder material, aqueous solvent) should be mixed evenly to form a homogeneous slurry, for example through the use of a homogenizer. In some embodiments, all the components of the conductive slurry are added into the homogenizer in a single batch. In other embodiments, each component of the conductive slurry can be added to the homogenizer in one or more batches, and each batch may comprise one or more components. However, when the conductive slurry comprises surfactant or dispersing agent, it is preferable for the surfactant or dispersing agent to be added into the homogenizer before the addition of conductive material, in order to ensure that the conductive material can be well dispersed in the slurry due to the action of the surfactant or dispersing agent.

[00138] Any homogenizer that can reduce or eliminate particle aggregation and/or promote homogeneous distribution of the various components of the conductive slurry can be used herein. In some embodiments, the homogenizer is a planetary stirring mixer, a stirring mixer, a blender, or an ultrasonicator. There are no particular limitations to the stirring speed and time taken, except that they should be sufficient to enable good dispersion of the conductive material and binder material in the aqueous solvent, in order to ensure that when the conductive slurry is coated onto a substrate, the coating can be homogeneous.

[00139] In addition, there are no particular limitations to the temperature at which the homogenization of the conductive slurry occurs, except that it should not be too high as to cause boiling of aqueous solvent, but at the same time be sufficiently high to ensure the slurry is not too viscous as to affect processability and that the binder material can be readily dissolved in the slurry. In some embodiments, homogenization of the conductive slurry occurs at a temperature

of from about 20 °C to about 95 °C, from about 25 °C to about 95 °C, from about 30 °C to about 95 °C, from about 20 °C to about 75 °C, from about 25 °C to about 75 °C, from about 30 °C to about 75 °C, from about 35 °C to about 75 °C, from about 40 °C to about 75 °C, from about 20 °C to about 60 °C, from about 25 °C to about 60 °C, from about 30 °C to about 60 °C, from about 35 °C to about 60 °C, from about 40 °C to about 60 °C, from about 25 °C to about 50 °C or from about 30 °C to about 50 °C.

[00140] In some embodiments, homogenization of the conductive slurry occurs at a temperature of less than 95 °C, less than 85 °C, less than 75 °C, less than 65 °C, less than 55 °C, less than 50 °C, less than 45 °C, less than 40 °C, less than 35 °C, less 30 °C or less than 25 °C. In some embodiments, homogenization of the conductive slurry occurs at a temperature of more than 20 °C, more than 25 °C, more than 30 °C, more than 35 °C, more than 40 °C, more than 45 °C, more than 50 °C, more than 55 °C, more than 60 °C, more than 65 °C, more than 70 °C or more than 75 °C.

[00141] In some embodiments, after homogenization of the conductive slurry, the slurry can be coated onto one side or both sides of a substrate to form a conductive layer film. There are no particular limitations to the equipment and the conditions used in coating the conductive slurry, except that a homogeneous, flat and smooth coated layer should be formed as a result. In certain embodiments, the coating process is performed using a doctor blade coater, a slot-die coater, a transfer coater, a spray coater, a roll coater, a gravure coater, a dip coater, or a curtain coater.

[00142] In some embodiments, following the coating of the conductive slurry onto a substrate, the coating is dried to form a modified current collector of the present invention. Any equipment that can dry the coating in order to affix the resultant conductive layer to the substrate can be used herein. Some non-limiting examples of such drying equipment include a batch drying oven, a conveyor drying oven, and a microwave drying oven.

[00143] There are no particular limitations to the conditions used for drying, except that the drying conditions should be sufficient to ensure that the conductive layer adheres strongly to the substrate. However, drying the conductive layer at temperatures above 100 °C may result in undesirable deformation of the resultant modified current collector, thus affecting the performance of any electrode prepared therefrom. The drying temperature should be optimized with respect to the other drying conditions, such as drying time, in order to ensure that the aqueous solvent is sufficiently removed from the conductive layer.

[00144] In some embodiments, the modified current collector is compressed mechanically following drying in order to increase the density of the conductive layer, and the final electrode can then be formed when an electrode layer is formed on the modified current collector. In other

embodiments, the modified current collector is not compressed.

[00145] In some embodiments, after coating and drying of a conductive slurry on a substrate, whether it is compressed or not compressed, the conductive layer in the resultant modified current collector has a thickness from about 0.1 μm to about 5.0 μm . The thickness of the conductive layer affects the total volume of the modified current collector, which in turn affects the total volume occupied by an electrode comprising the modified current collector and the corresponding amount of electrode active material needed in the electrode layer of the electrode. This would hence affect the capacity of a battery comprising the electrode.

[00146] In certain embodiments, the thickness of the conductive layer in a modified current collector of the present invention is from about 0.1 μm to about 5.0 μm , from about 0.1 μm to about 4.5 μm , from about 0.1 μm to about 4 μm , from about 0.1 μm to about 3.5 μm , from about 0.1 μm to about 3 μm , from about 0.1 μm to about 2.5 μm , from about 0.1 μm to about 2 μm , from about 0.5 μm to about 5.0 μm , from about 0.5 μm to about 4.5 μm , from about 1.0 μm to about 4.0 μm , from about 1.0 μm to about 3.5 μm , from about 1.0 μm to about 3.0 μm , from about 1.0 μm to about 2.5 μm , from about 1.0 μm to about 2.0 μm . In some embodiments, the thickness of the conductive layer is less than 5.0 μm , less than 4.5 μm , less than 4.0 μm , less than 3.5 μm , less than 3.0 μm , less than 2.5 μm , less than 2.0 μm , less than 1.5 μm , less than 1.0 μm , less than 0.5 μm or less than 0.3 μm . In some embodiments, the thickness of the conductive layer is more than 0.1 μm , more than 0.2 μm , more than 0.5 μm , more than 1.0 μm , more than 1.2 μm , more than 1.5 μm , more than 1.8 μm , more than 2.0 μm , more than 2.5 μm , more than 3.0 μm , more than 3.5 μm or more than 4.0 μm .

[00147] An electrode can subsequently be prepared using a modified current collector of the present invention by forming an electrode layer on the modified current collector. There are no particular limitations on the composition of the electrode layer, and any compositions known in the art are suitable for use in the present invention, as long as any battery comprising such electrodes can achieve good electrochemical performance. The composition of such electrode layers depends on the type of battery that is being produced, as well as whether the electrode layer is to be used in an anode or a cathode of a battery. In some embodiments, the type of battery may be a primary battery or a secondary battery. Some non-limiting examples of battery types include alkaline batteries, aluminum-air batteries, lithium batteries, lithium air batteries, magnesium batteries, silver-oxide batteries, zinc-air batteries, aluminum-ion batteries, lead-acid batteries, lithium-ion batteries, magnesium-ion batteries, potassium-ion batteries, sodium-ion batteries, sodium-air batteries, silicon-air batteries, zinc-ion batteries, and sodium-sulfur batteries. Furthermore, depending on the state of the electrolyte being used (i.e., liquid or solid

state), batteries can be classified as conventional batteries (when liquid electrolyte is used) or solid-state batteries (when solid electrolyte is used).

[00148] In some embodiments, the electrode layer comprises an electrode active material and a binding agent. In certain embodiments, the electrode layer additionally comprises a conductive agent. The electrode active material in the electrode layer can be a cathode active material or an anode active material. When an electrode layer comprises a cathode active material, the electrode layer is a cathode electrode layer. When an electrode layer comprises an anode active material, the electrode layer is an anode electrode layer.

[00149] In some embodiments, the electrode active material is a cathode active material. In some embodiments, the cathode active material is selected from the group consisting of LiCoO_2 , LiNiO_2 , $\text{LiNi}_{1-x}\text{M}_x\text{O}_2$, $\text{LiNi}_x\text{Mn}_y\text{O}_2$, $\text{LiCo}_x\text{Ni}_y\text{O}_2$, $\text{Li}_{1+z}\text{Ni}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$, $\text{LiNi}_x\text{Co}_y\text{Al}_z\text{O}_2$, LiV_2O_5 , LiTiS_2 , LiMoS_2 , LiMnO_2 , LiCrO_2 , LiMn_2O_4 , Li_2MnO_3 , LiFeO_2 , LiFePO_4 , and combinations thereof, wherein each x is independently from 0.1 to 0.9; each y is independently from 0 to 0.9; each z is independently from 0 to 0.4; and M is selected from the group consisting of Co, Mn, Al, Fe, Ti, Ga, Mg, and combinations thereof. In certain embodiments, each x in the above general formula is independently selected from 0.1, 0.125, 0.15, 0.175, 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, 0.475, 0.5, 0.525, 0.55, 0.575, 0.6, 0.625, 0.65, 0.675, 0.7, 0.725, 0.75, 0.775, 0.8, 0.825, 0.85, 0.875 and 0.9; each y in the above general formula is independently selected from 0, 0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375, 0.4, 0.425, 0.45, 0.475, 0.5, 0.525, 0.55, 0.575, 0.6, 0.625, 0.65, 0.675, 0.7, 0.725, 0.75, 0.775, 0.8, 0.825, 0.85, 0.875 and 0.9; each z in the above general formula is independently selected from 0, 0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2, 0.225, 0.25, 0.275, 0.3, 0.325, 0.35, 0.375 and 0.4. In some embodiments, each x , y and z in the above general formula independently has a 0.01 interval.

[00150] In certain embodiments, the cathode active material is selected from the group consisting of $\text{LiNi}_x\text{Mn}_y\text{O}_2$, $\text{Li}_{1+z}\text{Ni}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$ (NMC), $\text{LiNi}_x\text{Co}_y\text{Al}_z\text{O}_2$ (NCA), $\text{LiCo}_x\text{Ni}_y\text{O}_2$ and combinations thereof, wherein each x is independently from 0.4 to 0.6; each y is independently from 0.2 to 0.4; and each z is independently from 0 to 0.1. In other embodiments, the cathode active material is not LiCoO_2 , LiNiO_2 , LiV_2O_5 , LiTiS_2 , LiMoS_2 , LiMnO_2 , LiCrO_2 , LiMn_2O_4 , LiFeO_2 or LiFePO_4 . In further embodiments, the cathode active material is not $\text{LiNi}_x\text{Mn}_y\text{O}_2$, $\text{Li}_{1+z}\text{Ni}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$, $\text{LiNi}_x\text{Co}_y\text{Al}_z\text{O}_2$ or $\text{LiCo}_x\text{Ni}_y\text{O}_2$, wherein each x is independently from 0.1 to 0.9; each y is independently from 0 to 0.45; and each z is independently from 0 to 0.2. In certain embodiments, the cathode active material is $\text{Li}_{1+x}\text{Ni}_a\text{Mn}_b\text{Co}_c\text{Al}_{(1-a-b-c)}\text{O}_2$; wherein $-0.2 \leq x \leq 0.2$, $0 \leq a < 1$, $0 \leq b < 1$, $0 \leq c < 1$, and $a+b+c \leq 1$. In some embodiments, the cathode active material has the general formula $\text{Li}_{1+x}\text{Ni}_a\text{Mn}_b\text{Co}_c\text{Al}_{(1-a-b-c)}\text{O}_2$, with $0.33 \leq a \leq 0.92$, $0.33 \leq a \leq 0.9$, $0.33 \leq a \leq 0.8$, $0.4 \leq a \leq 0.92$, $0.4 \leq a \leq 0.9$, $0.4 \leq a \leq 0.8$, $0.5 \leq a \leq 0.92$,

$0.5 \leq a \leq 0.9$, $0.5 \leq a \leq 0.8$, $0.6 \leq a \leq 0.92$, or $0.6 \leq a \leq 0.9$; $0 \leq b \leq 0.5$, $0 \leq b \leq 0.4$, $0 \leq b \leq 0.3$, $0 \leq b \leq 0.2$, $0.1 \leq b \leq 0.5$, $0.1 \leq b \leq 0.4$, $0.1 \leq b \leq 0.3$, $0.1 \leq b \leq 0.2$, $0.2 \leq b \leq 0.5$, $0.2 \leq b \leq 0.4$, or $0.2 \leq b \leq 0.3$; $0 \leq c \leq 0.5$, $0 \leq c \leq 0.4$, $0 \leq c \leq 0.3$, $0.1 \leq c \leq 0.5$, $0.1 \leq c \leq 0.4$, $0.1 \leq c \leq 0.3$, $0.1 \leq c \leq 0.2$, $0.2 \leq c \leq 0.5$, $0.2 \leq c \leq 0.4$, or $0.2 \leq c \leq 0.3$. In some embodiments, the cathode active material has the general formula LiMPO_4 , wherein M is selected from the group consisting of Fe, Co, Ni, Mn, Al, Mg, Zn, Ti, La, Ce, Sn, Zr, Ru, Si, Ge, or combinations thereof.

[00151] In some embodiments, the cathode active material is selected from the group consisting of LiFePO_4 , LiCoPO_4 , LiNiPO_4 , LiMnPO_4 , LiMnFePO_4 , $\text{LiMn}_x\text{Fe}_{(1-x)}\text{PO}_4$, and combinations thereof; wherein $0 < x < 1$. In some embodiments, the cathode active material is $\text{LiNi}_x\text{Mn}_y\text{O}_4$; wherein $0.1 \leq x \leq 0.9$ and $0 \leq y \leq 2$. In certain embodiments, the cathode active material is $x\text{Li}_2\text{MnO}_3 \cdot (1-x)\text{LiMO}_2$, wherein M is selected from the group consisting of Ni, Co, Mn, and combinations thereof; and wherein $0 < x < 1$. In some embodiments, the cathode active material is $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, or LiVPO_4F . In certain embodiments, the cathode active material has the general formula Li_2MSiO_4 , wherein M is selected from the group consisting of Fe, Co, Mn, Ni, and combinations thereof.

[00152] In certain embodiments, the cathode active material is doped with a dopant selected from the group consisting of Co, Cr, V, Mo, Nb, Pd, F, Na, Fe, Ni, Mn, Al, Mg, Zn, Ti, La, Ce, Sn, Zr, Ru, Si, Ge, and combinations thereof. In some embodiments, the cathode active material is not doped with Co, Cr, V, Mo, Nb, Pd, F, Na, Fe, Ni, Mn, Mg, Zn, Ti, La, Ce, Ru, Si, or Ge. In certain embodiments, the cathode active material is not doped with Al, Sn or Zr.

[00153] In some embodiments, the cathode active material is $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$ (NMC333), $\text{LiNi}_{0.4}\text{Mn}_{0.4}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.5}\text{Mn}_{0.3}\text{Co}_{0.2}\text{O}_2$ (NMC532), $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$ (NMC622), $\text{LiNi}_{0.7}\text{Mn}_{0.15}\text{Co}_{0.15}\text{O}_2$, $\text{LiNi}_{0.7}\text{Mn}_{0.1}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$ (NMC811), $\text{LiNi}_{0.92}\text{Mn}_{0.04}\text{Co}_{0.04}\text{O}_2$, $\text{LiNi}_{0.85}\text{Mn}_{0.075}\text{Co}_{0.075}\text{O}_2$, $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$, $\text{LiNi}_{0.88}\text{Co}_{0.1}\text{Al}_{0.02}\text{O}_2$, LiNiO_2 (LNO) or combinations thereof.

[00154] In other embodiments, the cathode active material is not LiCoO_2 , LiNiO_2 , LiMnO_2 , LiMn_2O_4 or Li_2MnO_3 . In further embodiments, the cathode active material is not $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$, $\text{LiNi}_{0.4}\text{Mn}_{0.4}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.5}\text{Mn}_{0.3}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.7}\text{Mn}_{0.15}\text{Co}_{0.15}\text{O}_2$, $\text{LiNi}_{0.7}\text{Mn}_{0.1}\text{Co}_{0.2}\text{O}_2$, $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$, $\text{LiNi}_{0.92}\text{Mn}_{0.04}\text{Co}_{0.04}\text{O}_2$, $\text{LiNi}_{0.85}\text{Mn}_{0.075}\text{Co}_{0.075}\text{O}_2$, $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$, or $\text{LiNi}_{0.88}\text{Co}_{0.1}\text{Al}_{0.02}\text{O}_2$.

[00155] In certain embodiments, the cathode active material comprises or is a core-shell composite having a core and shell structure, wherein the core comprises a lithium transition metal oxide selected from the group consisting of $\text{Li}_{1+x}\text{Ni}_a\text{Mn}_b\text{Co}_c\text{Al}_{(1-a-b-c)}\text{O}_2$, LiCoO_2 , LiNiO_2 , LiMnO_2 , LiMn_2O_4 , Li_2MnO_3 , LiCrO_2 , $\text{Li}_4\text{Ti}_5\text{O}_{12}$, LiV_2O_5 , LiTiS_2 , LiMoS_2 , $\text{LiCo}_a\text{Ni}_b\text{O}_2$, $\text{LiMn}_a\text{Ni}_b\text{O}_2$, and combinations thereof; wherein $-0.2 \leq x \leq 0.2$, $0 \leq a < 1$, $0 \leq b < 1$, $0 \leq c < 1$, and $a+b+c \leq 1$. In some embodiments, the shell also comprises a lithium transition metal oxide. In

certain embodiments, the lithium transition metal oxide of the shell is selected from the above-mentioned group of lithium transitional metal oxides used for the core. In other embodiments, the shell comprises a transition metal oxide. In certain embodiments, the transition metal oxide of the shell is selected from the group consisting of Fe_2O_3 , MnO_2 , Al_2O_3 , MgO , ZnO , TiO_2 , La_2O_3 , CeO_2 , SnO_2 , ZrO_2 , RuO_2 and combinations thereof. In certain embodiments, the shell comprises a lithium transition metal oxide and a transition metal oxide.

[00156] In certain embodiments, the core and the shell each independently comprise two or more lithium transition metal oxides. In some embodiments, one of the core or shell comprises only one lithium transition metal oxide, while the other comprises two or more lithium transition metal oxides. The lithium transition metal oxide or oxides in the core and the shell may be the same, or they may be different or partially different. In some embodiments, the two or more lithium transition metal oxides are uniformly distributed over the core. In certain embodiments, the two or more lithium transition metal oxides are not uniformly distributed over the core.

[00157] In some embodiments, each of the metal oxides in the core and the shell is independently doped with a dopant selected from the group consisting of Co, Cr, V, Mo, Nb, Pd, F, Na, Fe, Ni, Mn, Al, Mg, Zn, Ti, La, Ce, Sn, Zr, Ru, Si, Ge and combinations thereof. In some embodiments, the cathode active material is not a core-shell composite.

[00158] In some embodiments, the electrode active material is a cathode active material for a sodium-ion battery. In some embodiments, the cathode active material for a sodium-ion battery is a Prussian blue-type sodium compound that satisfies the formula $\text{Na}_x\text{M}_y\text{A}_z$, wherein M is one or more metals and A is one or more anions that comprise one or more of O, P, N, C, H or a halogen. In certain embodiments, the cathode active material for a sodium-ion battery is the sodium analogue of the cathode active materials discussed above, with lithium replaced by sodium. In some embodiments, the cathode active material for a sodium-ion battery is selected from the group consisting of NaCoO_2 , NaFeO_2 , NaNiO_2 , NaCrO_2 , NaVO_2 , and NaTiO_2 , NaFePO_4 , $\text{Na}_3\text{V}_2(\text{PO}_4)_3$, $\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$, NMC-type mixed oxides, and combinations thereof. In some embodiments, the cathode active material for a sodium-ion battery is an organic material, such as disodium naphthalenediimide, doped quinone, pteridine derivatives, polyimides, polyamic acid, or combinations thereof.

[00159] In some embodiments, the cathode active material for a sodium-ion battery is comprises or is a core-shell composite having a core and shell structure. In some embodiments, the cathode active material for a sodium-ion battery is doped with a dopant. The same dopants listed above for the cathode active material for a lithium-ion battery can be used to dope the cathode active material for a sodium-ion battery.

[00160] In some embodiments, the average diameter of the cathode active material

particles is from about 0.1 μm to about 100 μm , from about 0.1 μm to about 50 μm , from about 0.5 μm to about 50 μm , from about 0.5 μm to about 30 μm , from about 0.5 μm to about 20 μm , from about 1 μm to about 20 μm , from about 2.5 μm to about 20 μm , from about 5 μm to about 20 μm , from about 7.5 μm to about 20 μm , from about 10 μm to about 20 μm , from about 15 μm to about 20 μm , from about 2.5 μm to about 50 μm , from about 5 μm to about 50 μm , from about 10 μm to about 50 μm , from about 15 μm to about 50 μm , from about 20 μm to about 50 μm or from about 50 μm to about 100 μm .

[00161] In some embodiments, the average diameter of the cathode active material particles is less than 100 μm , less than 80 μm , less than 60 μm , less than 50 μm , less than 40 μm , less than 30 μm , less than 20 μm , less than 15 μm , less than 10 μm , less than 7.5 μm , less than 5 μm , less than 2.5 μm , less than 1 μm , less than 0.75 μm or less than 0.5 μm . In some embodiments, the average diameter of the cathode active material particles is more than 0.1 μm , more than 0.25 μm , more than 0.5 μm , more than 0.75 μm , more than 1 μm , more than 2.5 μm , more than 5 μm , more than 7.5 μm , more than 10 μm , more than 15 μm , more than 20 μm , more than 30 μm , more than 40 μm or more than 50 μm .

[00162] In some embodiments, the electrode active material is an anode active material. In some embodiments, the anode active material is selected the group consisting of natural graphite particulate, synthetic graphite particulate, hard carbon, soft carbon, mesocarbon microbeads (MCMB), Sn particulate, SnO₂, SnO, Li₄Ti₅O₁₂ particulate, Si particulate, Si-C composite particulate and combinations thereof.

[00163] In certain embodiments, the anode active material is doped with a metallic element or a nonmetal element. In some embodiments, the metallic element is selected from the group consisting of Fe, Ni, Mn, Al, Mg, Zn, Ti, La, Ce, Sn, Zr, Ru and combinations thereof. In some embodiments, the nonmetal element is B, Si, Ge, N, P, F, S, Cl, I, Se or combinations thereof.

[00164] In some embodiments, the anode active material comprises or is a core-shell composite having a core and shell structure, wherein the core and the shell each is independently selected from the group consisting of natural graphite particulate, synthetic graphite particulate, hard carbon, soft carbon, mesocarbon microbeads (MCMB), Sn particulate, SnO₂, SnO, Li₄Ti₅O₁₂ particulate, Si particulate, Si-C composite particulate, and combinations thereof.

[00165] In certain embodiments, the anode active material in the form of a core-shell composite comprises a core comprising a carbonaceous material and a shell coated on the carbonaceous material core. In some embodiments, the carbonaceous material is selected from the group consisting of soft carbon, hard carbon, natural graphite particulate, synthetic graphite particulate, mesocarbon microbeads, Kish graphite, pyrolytic carbon, mesophase pitches, mesophase pitch-based carbon fiber and combinations thereof. In certain embodiments, the shell

is selected from the group consisting of natural graphite particulate, synthetic graphite particulate, hard carbon, soft carbon, mesocarbon microbeads (MCMB), Sn particulate, SnO₂, SnO, Li₄Ti₅O₁₂ particulate, Si particulate, Si-C composite particulate and combinations thereof.

[00166] In certain embodiments, the anode active material is not doped with a metallic element or a nonmetal element. In some embodiments, the anode active material is not doped with Fe, Ni, Mn, Al, Mg, Zn, Ti, La, Ce, Sn, Zr, Ru, B, Si, Ge, N, P, F, S, Cl, I, or Se.

[00167] In some embodiments, the electrode active material is an anode active material for a sodium-ion battery. Many embodiments of anode active materials used in lithium-ion batteries are also suitable for use as anode active material for a sodium-ion battery, although graphite is not preferable as the pores within the material are too small to hold sodium ions. Li₄Ti₅O₁₂ particulate is also not preferable as an anode active material for a sodium-ion battery as lithium is present, which would affect the reaction mechanism in a sodium-ion battery.

[00168] In some embodiments, the anode active material for a sodium-ion battery is selected from the group consisting of hard carbon, soft carbon, tin oxides such as SnO₂ and SnO, sodium titanates such as NaTi₂(PO₄)₃ and Na₂Ti₃O₇, SnS₂, NbS₂, SbO_x, wherein $0 < x \leq 2$, Sn-P compounds and composites, sodium alloys and combinations thereof. In some embodiments, the anode active material for a sodium-ion battery is a Prussian blue-type sodium compound that satisfies the formula Na_xM_yA_z, wherein M is one or more metals and A is one or more anions that comprise one or more of O, P, N, C, H or a halogen. In some embodiments, the cathode active material for a sodium-ion battery is an organic material, such as disodium naphthalenediimide, doped quinone, pteridine derivatives, polyimides, polyamic acid or combinations thereof.

[00169] In some embodiments, the anode active material for a sodium-ion battery comprises or is a core-shell composite having a core and shell structure. In some embodiments, the anode active material for a sodium-ion battery is doped with one or more elements selected from the group consisting of Sb, Sn, P, S, B, Al, Ga, In, Ge, Pb, As, Bi, Ti, Mo, Se, Te, Co and combinations thereof.

[00170] Modified current collectors of the present invention are particularly suitable for use in electrodes where the electrode layer is formed using a water-based slurry and comprises a nickel-containing cathode active material. Such a slurry would be quite basic in nature and would therefore corrode a conventional current collector (most commonly aluminum foil). However, when a basic water-based cathode slurry is coated onto a modified current collector of the present invention to form a cathode, the conductive layer in the modified current collector would form a physical barrier to prevent the conventional current collector (now the substrate of

the modified current collector) from coming into contact with the slurry. Corrosion of the substrate is hence prevented. Nonetheless, modified current collectors of the present invention are suitable for use in electrodes comprising any suitable electrode active materials (both cathode active materials and anode active materials), for any type of battery, and using any method of formation of the electrode layer on the modified current collectors.

[00171] There are no particular limitations to the binding agent used in the electrode layer, although the binding agent should have desirable properties as a binder. Furthermore, when the electrode layer is produced with a slurry, it is preferable that the binding agent can be dispersed well in the electrode slurry to ensure an even, smooth coating. The coating of electrode slurry comprising the binding agent used herein on the surface of the modified current collector should not be able to dissolve the underlying conductive layer within the modified current collector. In some embodiments, various types of binding agents could be used in the electrode layer, as long as they do not have a tendency giving rise to the dissolution of the conductive layer in the modified current collector. In some embodiments, the binding agent is aqueous in nature.

[00172] In some embodiments, the binding agent in the electrode layer comprises a polymer. In some embodiments, the binder polymer in the electrode layer is a copolymer. In other embodiments, the binder polymer in the electrode layer is a homopolymer.

[00173] In certain embodiments, the binding agent in the electrode layer comprises styrene-butadiene rubber (SBR), carboxymethyl cellulose (CMC), polyacrylic acid (PAA), polyacrylonitrile (PAN), polyacrylamide (PAM), acrylic acid-acrylonitrile-acrylamide copolymer, latex, a salt of alginic acid, polyvinylidene fluoride (PVDF), poly(vinylidene fluoride)-hexafluoropropene (PVDF-HFP), polytetrafluoroethylene (PTFE), polystyrene, poly(vinyl alcohol) (PVA), poly(vinyl acetate), polyisoprene, polyaniline, polyethylene, polyimide, polyurethane, polyvinyl butyral, polyvinyl pyrrolidone (PVP), gelatin, chitosan, starch, agar-agar, xanthan gum, gum arabic, gellan gum, guar gum, gum karaya, tara gum, gum tragacanth, casein, amylose, pectin, PEDOT:PSS, carrageenans, or combinations thereof. In certain embodiments, the salt of alginic acid comprises a cation selected from the group consisting of Na, Li, K, Ca, NH₄, Mg, Al, and combinations thereof. In certain embodiments, the binding agent in the electrode layer does not comprise styrene-butadiene rubber, carboxymethyl cellulose, polyacrylic acid, polyacrylonitrile, polyacrylamide, acrylic acid-acrylonitrile-acrylamide copolymer, latex, a salt of alginic acid, polyvinylidene fluoride, poly(vinylidene fluoride)-hexafluoropropene, polytetrafluoroethylene, polystyrene, poly(vinyl alcohol), poly(vinyl acetate), polyisoprene, polyaniline, polyethylene, polyimide, polyurethane, polyvinyl butyral, polyvinyl pyrrolidone, gelatin, chitosan, starch, agar-agar, xanthan gum, gum arabic, gellan gum, guar gum, gum karaya, tara gum, gum tragacanth, casein, amylose, pectin,

PEDOT:PSS, or carrageenans. In certain embodiments, the binding agent in the electrode layer does not comprise a fluorine-containing polymer such as PVDF, PVDF-HFP or PTFE.

[00174] In some embodiments, the binding agent in the electrode layer comprises one or more functional groups containing a halogen, O, N, S or a combination thereof. Some non-limiting examples of suitable functional groups include alkoxy, aryloxy, nitro, thiol, alkylthio, imine, cyano, amide, amino (primary, secondary or tertiary), carboxyl, epoxy, ketone, aldehyde, ester, hydroxyl, halo (fluoro, chloro, bromo, or iodo) and combinations thereof. In some embodiments, the functional group is or comprises carboxylic acid (*i.e.*, -COOH), carboxylic acid salt, sulfonic acid, sulfonic acid salt, sulfuric acid, sulfuric acid salt, phosphonic acid, phosphonic acid salt, phosphoric acid, phosphoric acid salt, nitric acid, nitric acid salt, amide, hydroxyl, nitrile, ester, epoxy, or -NH₂.

[00175] In certain embodiments, the binding agent in an electrode layer comprises a copolymer with a composition as described below. The presence of hydrophilic functional groups in the binding agent enables the copolymer to be well dispersed within aqueous solvents, as well as ensuring that the various electrode components can be bound together. On the other hand, the presence of hydrophobic functional groups in the binding agent ensures that the binding agent would not self-aggregate and impair dispersion, and that an electrode slurry comprising the copolymer would not be too viscous as to affect processability. Combining both hydrophilic and hydrophobic effects, this means that the various electrode components could be well bound together while still remaining dispersed in the solvent of a water-based electrode slurry with high processability. Electrode layers produced using such a slurry would then be smooth and homogeneous, and batteries comprising such electrodes would then have superb capacity and electrochemical performance.

[00176] In some embodiments, the binding agent in the electrode layer comprises a structural unit (i) that is derived from an acid group-containing monomer, wherein the acid group is selected from the group consisting of carboxylic acid, sulfonic acid, sulfuric acid, phosphonic acid, phosphoric acid, nitric acid, and combinations thereof. The acids listed above also include their salts and derivatives. In some embodiments, the salt of the acid comprises an alkali metal cation. Examples of an alkali metal forming the alkali metal cation include lithium, sodium, and potassium. In some embodiments, the salt of the acid comprises an ammonium cation.

[00177] In some embodiments, the carboxylic acid is acrylic acid, methacrylic acid, crotonic acid, 2-butyl crotonic acid, cinnamic acid, maleic acid, maleic anhydride, fumaric acid, itaconic acid, itaconic anhydride, tetraconic acid or a combination thereof. In certain embodiments, the carboxylic acid is 2-ethylacrylic acid, isocrotonic acid, cis-2-pentenoic acid, trans-2-pentenoic acid, angelic acid, tiglic acid, 3,3-dimethyl acrylic acid, 3-propyl acrylic acid,

trans-2-methyl-3-ethyl acrylic acid, cis-2-methyl-3-ethyl acrylic acid, 3-isopropyl acrylic acid, trans-3-methyl-3-ethyl acrylic acid, cis-3-methyl-3-ethyl acrylic acid, 2-isopropyl acrylic acid, trimethyl acrylic acid, 2-methyl-3,3-diethyl acrylic acid, 3-butyl acrylic acid, 2-butyl acrylic acid, 2-pentyl acrylic acid, 2-methyl-2-hexenoic acid, trans-3-methyl-2-hexenoic acid, 3-methyl-3-propyl acrylic acid, 2-ethyl-3-propyl acrylic acid, 2,3-diethyl acrylic acid, 3,3-diethyl acrylic acid, 3-methyl-3-hexyl acrylic acid, 3-methyl-3-tert-butyl acrylic acid, 2-methyl-3-pentyl acrylic acid, 3-methyl-3-pentyl acrylic acid, 4-methyl-2-hexenoic acid, 4-ethyl-2-hexenoic acid, 3-methyl-2-ethyl-2-hexenoic acid, 3-tert-butyl acrylic acid, 2,3-dimethyl-3-ethyl acrylic acid, 3,3-dimethyl-2-ethyl acrylic acid, 3-methyl-3-isopropyl acrylic acid, 2-methyl-3-isopropyl acrylic acid, trans-2-octenoic acid, cis-2-octenoic acid, trans-2-decenoic acid, α -acetoxycrylic acid, β -trans-aryloxyacrylic acid, α -chloro- β -E-methoxyacrylic acid, or combinations thereof.

[00178] In some embodiments, the sulfonic acid is vinylsulfonic acid, methylvinylsulfonic acid, allylvinylsulfonic acid, allylsulfonic acid, methallylsulfonic acid, styrenesulfonic acid, 2-sulfoethyl methacrylic acid, 2-methylprop-2-ene-1-sulfonic acid, 2-acrylamido-2-methyl-1-propane sulfonic acid, 3-allyloxy-2-hydroxy-1-propane sulfonic acid or combinations thereof.

[00179] In some embodiments, the sulfuric acid is allyl hydrogen sulfate, vinyl hydrogensulfate, 4-allyl phenol sulphate or combinations thereof.

[00180] In some embodiments, the phosphonic acid is phosphonoxyethyl acrylate, phosphonoxyethyl methacrylate, vinyl phosphonic acid, allyl phosphonic acid, 3-butenyl phosphonic acid, styrene phosphonic acid, vinyl benzyl phosphonic acid, (2-chloro-2-phenylvinyl)-phosphonic acid, acrylamide alkyl phosphonic acid, methacrylamide alkyl phosphonic acid, acrylamide alkyl diphosphonic acid, acryloylphosphonic acid, 2-methacryloyloxyethyl phosphonic acid, bis(2-methacryloyloxyethyl) phosphonic acid, ethylene 2-methacryloyloxyethyl phosphonic acid, ethyl-methacryloyloxyethyl phosphonic acid or combinations thereof.

[00181] In some embodiments, the phosphoric acid is mono (2-acryloyloxyethyl) phosphate, mono (2-methacryloyloxyethyl) phosphate, diphenyl (2-acryloyloxyethyl) phosphate, diphenyl (2-methacryloyloxyethyl) phosphate, phenyl (2-acryloyloxyethyl) phosphate, phosphoxyethyl methacrylate, 3-chloro-2-phosphoryloxy propyl methacrylate, phosphoryloxy poly(ethylene glycol) monomethacrylate, phosphoryloxy poly(propylene glycol) methacrylate, (meth)acryloyloxyethyl phosphate, (meth)acryloyloxypropyl phosphate, (meth)acryloyloxy-2-hydroxypropyl phosphate, (meth)acryloyloxy-3-hydroxypropyl phosphate, (meth)acryloyloxy-3-chloro-2 hydroxypropyl phosphate, allyl hydrogen phosphate, vinyl hydrogen phosphate, allyl hydrogen pyrophosphate, vinyl hydrogen pyrophosphate, allyl hydrogen triphosphosphate, vinyl hydrogen triphosphosphate, allyl hydrogen tetraphosphosphate, vinyl hydrogen tetraphosphosphate, allyl hydrogen trimetaphosphate, vinyl hydrogen trimetaphosphate,

isopentenyl phosphate, isopentenyl pyrophosphate or combinations thereof.

[00182] In some embodiments, the nitric acid is allyl hydrogen nitrate, ethenyl hydrogen nitrate or combinations thereof.

[00183] In some embodiments, the proportion of structural unit (i) within the binding agent is from about 15% to about 95%, from about 15% to about 85%, from about 15% to about 75%, from about 15% to about 65%, from about 15% to about 55%, from about 20% to about 95%, from about 20% to about 90%, from about 20% to about 80%, from about 20% to about 70%, from about 20% to about 60%, from about 20% to about 50%, from about 25% to about 95%, from about 25% to about 85%, from about 25% to about 75%, from about 25% to about 65%, from about 25% to about 55%, from about 30% to about 95%, from about 30% to about 85%, from about 30% to about 75%, from about 30% to about 65%, from about 35% to about 95%, from about 35% to about 85%, from about 35% to about 75%, from about 35% to about 65%, from about 40% to about 95%, from about 40% to about 85%, from about 40% to about 75%, from about 40% to about 65%, from about 45% to about 95%, from about 45% to about 85%, from about 45% to about 75%, from about 50% to about 95%, from about 50% to about 85%, from about 50% to about 75%, from about 55% to about 95%, from about 55% to about 85%, from about 55% to about 75%, from about 60% to about 95% or from about 60% to about 85% by mole, based on the total number of moles of monomeric units in the copolymer.

[00184] In some embodiments, the proportion of structural unit (i) within the binding agent is less than 95%, less than 85%, less than 75%, less than 65%, less than 55%, less than 45%, less than 35% or less than 25% by mole, based on the total number of moles of monomeric units in the copolymer. In some embodiments, the proportion of structural unit (i) within the binding agent is more than 15%, more than 25%, more than 35%, more than 45%, more than 55%, more than 65%, more than 75% or more than 85% by mole, based on the total number of moles of monomeric units in the copolymer.

[00185] In some embodiments, the binding agent in the electrode layer further comprises a structural unit (ii) that is derived from a monomer selected from the group consisting of an amide group-containing monomer, a hydroxyl group-containing monomer and combinations thereof.

[00186] In some embodiments, the amide group-containing monomer is acrylamide, methacrylamide, N-methyl methacrylamide, N-ethyl methacrylamide, N-n-propyl methacrylamide, N-isopropyl methacrylamide, isopropyl acrylamide, N-n-butyl methacrylamide, N-isobutyl methacrylamide, N,N-dimethyl acrylamide, N,N-dimethyl methacrylamide, N,N-diethyl acrylamide, N,N-diethyl methacrylamide, N-methylol methacrylamide, N-(methoxymethyl)methacrylamide, N-(ethoxymethyl)methacrylamide, N-(propoxymethyl)methacrylamide, N-(butoxymethyl)methacrylamide, N,N-dimethyl

methacrylamide, N,N-dimethylaminopropyl methacrylamide, N,N-dimethylaminoethyl methacrylamide, N,N-dimethylol methacrylamide, diacetone methacrylamide, diacetone acrylamide, methacryloyl morpholine, N-hydroxyl methacrylamide, N-methoxymethyl acrylamide, N-methoxymethyl methacrylamide, N,N'-methylene-bis-acrylamide (MBA), N-hydroxymethyl acrylamide, or a combination thereof.

[00187] In some embodiments, the hydroxyl group-containing monomer is an acrylate or methacrylate containing a C₁-C₂₀ alkyl or C₅-C₂₀ cycloalkyl with a hydroxyl group. In some embodiments, the hydroxyl group-containing monomer is 2-hydroxyethylacrylate, 2-hydroxyethyl methacrylate, 2-hydroxypropyl acrylate, 2-hydroxypropyl methacrylate, 2-hydroxybutyl methacrylate, 3-hydroxypropylacrylate, 3-hydroxypropylmethacrylate, 4-hydroxybutyl methacrylate, 5-hydroxypentylacrylate, 6-hydroxyhexyl methacrylate, 1,4-cyclohexanedimethanol monoacrylate, 1,4-cyclohexanedimethanol monomethacrylate, 3-chloro-2-hydroxypropyl methacrylate, diethylene glycol monoacrylate, diethylene glycol monomethacrylate, allyl alcohol, or a combination thereof.

[00188] In some embodiments, the proportion of structural unit (ii) within the binding agent is from about 5% to about 50%, from about 5% to about 45%, from about 5% to about 40%, from about 5% to about 35%, from about 5% to about 30%, from about 5% to about 25%, from about 10% to about 50%, from about 10% to about 45%, from about 10% to about 40%, from about 10% to about 35%, from about 10% to about 30%, from about 15% to about 50%, from about 15% to about 45%, from about 15% to about 40%, from about 20% to about 50%, from about 20% to about 45%, from about 20% to about 40%, or from about 25% to about 50% by mole, based on the total number of moles of monomeric units in the copolymer.

[00189] In some embodiments, the proportion of structural unit (ii) within the binding agent is less than 50%, less than 45%, less than 40%, less than 35%, less than 30%, less than 25%, less than 20%, or less than 15% by mole, based on the total number of moles of monomeric units in the copolymer. In some embodiments, the proportion of structural unit (ii) within the binding agent is more than 5%, more than 10%, more than 15%, more than 20%, more than 25%, more than 30%, more than 35%, or more than 40% by mole, based on the total number of moles of monomeric units in the copolymer.

[00190] In some embodiments, the binding agent in the electrode layer further comprises a structural unit (iii) that is derived from a monomer selected from the group consisting of a nitrile group-containing monomer, an ester group-containing monomer, an epoxy group-containing monomer and combinations thereof.

[00191] In some embodiments, the nitrile group-containing monomer is or comprises an α,β -ethylenically unsaturated nitrile monomer. In some embodiments, the nitrile group-containing monomer is acrylonitrile, α -halogenoacrylonitrile, α -alkylacrylonitrile, or a

combination thereof. In some embodiments, the nitrile group-containing monomer is α -chloroacrylonitrile, α -bromoacrylonitrile, α -fluoroacrylonitrile, methacrylonitrile, α -ethylacrylonitrile, α -isopropylacrylonitrile, α -n-hexylacrylonitrile, α -methoxyacrylonitrile, 3-methoxyacrylonitrile, 3-ethoxyacrylonitrile, α -acetoxyacrylonitrile, α -phenylacrylonitrile, α -tolylacrylonitrile, α -(methoxyphenyl)acrylonitrile, α -(chlorophenyl)acrylonitrile, α -(cyanophenyl)acrylonitrile, vinylidene cyanide, or a combination thereof.

[00192] In some embodiments, the ester group-containing monomer is C₁-C₂₀ alkyl acrylate, C₁-C₂₀ alkyl methacrylate, cycloalkyl acrylate or a combination thereof. In some embodiments, the ester group-containing monomer is methyl acrylate, ethyl acrylate, n-propyl acrylate, isopropyl acrylate, n-butyl acrylate, sec-butyl acrylate, tert-butyl acrylate, pentyl acrylate, hexyl acrylate, heptyl acrylate, octyl acrylate, 3,3,5-trimethylhexyl acrylate, 2-ethylhexyl acrylate, nonyl acrylate, decyl acrylate, lauryl acrylate, n-tetradecyl acrylate, octadecyl acrylate, cyclohexyl acrylate, phenyl acrylate, methoxymethyl acrylate, methoxyethyl acrylate, ethoxymethyl acrylate, ethoxyethyl acrylate, perfluorooctyl acrylate, stearyl acrylate or a combination thereof.

[00193] In some embodiments, the epoxy group-containing monomer is vinyl glycidyl ether, allyl glycidyl ether, allyl 2,3-epoxypropyl ether, butenyl glycidyl ether, butadiene monoepoxide, chloroprene monoepoxide, 3,4-epoxy-1-butene, 4,5-epoxy-2-pentene, 3,4-epoxy-1-vinylcyclohexane, 1,2-epoxy-4-vinylcyclohexane, 3,4-epoxy cyclohexylethylene, epoxy-4-vinylcyclohexene, 1,2-epoxy-5,9-cyclododecadiene, or a combination thereof.

[00194] In some embodiments, the proportion of structural unit (iii) within the binding agent is from about 5% to about 80%, from about 5% to about 70%, from about 5% to about 60%, from about 5% to about 50%, from about 5% to about 40%, from about 5% to about 30%, from about 10% to about 80%, from about 10% to about 70%, from about 10% to about 60%, from about 10% to about 50%, from about 10% to about 40%, from about 15% to about 80%, from about 15% to about 70%, from about 15% to about 60%, from about 15% to about 50%, from about 15% to about 40%, from about 20% to about 80%, from about 20% to about 70%, from about 20% to about 60%, from about 20% to about 50%, from about 25% to about 80%, from about 25% to about 70%, from about 25% to about 60%, from about 25% to about 50%, from about 30% to about 80%, from about 30% to about 70%, from about 30% to about 60%, from about 35% to about 80%, from about 35% to about 70%, from about 35% to about 60%, from about 40% to about 80%, from about 40% to about 70%, from about 45% to about 80%, from about 45% to about 70%, from about 50% to about 80% or from about 50% to about 70% by mole, based on the total number of moles of monomeric units in the copolymer.

[00195] In some embodiments, the proportion of structural unit (iii) within the binding agent is less than 80%, less than 70%, less than 60%, less than 50%, less than 40%, less than

30%, less than 20% or less than 15% by mole, based on the total number of moles of monomeric units in the copolymer. In some embodiments, the proportion of structural unit (iii) within the binding agent is more than 5%, more than 15%, more than 25%, more than 35%, more than 45%, more than 55% or more than 60% by mole, based on the total number of moles of monomeric units in the copolymer.

[00196] In some embodiments, the electrode layer additionally comprises a conductive agent. The presence of a conductive agent enhances the electrically-conducting properties of the electrode layer in an electrode. Therefore, it may be advantageous for the electrode layer to comprise a conductive agent. Any suitable material can act as a conductive agent. Any embodiments of conductive material suitable for use in the conductive layer of a modified current collector of the present invention are also suitable for use as conductive agent in the electrode layer. In other embodiments, the conductive agent is not a conductive material used in the conductive layer of a modified current collector. The conductive agent used in the electrode layer and the conductive material used in the conductive layer of a modified current collector may be the same, different, or partially different.

[00197] In some embodiments, the conductive agent comprises a conductive polymer selected from the group consisting of polypyrrole, polyaniline, polyacetylene, polyphenylene sulfide (PPS), polyphenylene vinylene (PPV), poly(3,4-ethylenedioxythiophene) (PEDOT), polythiophene, and combinations thereof. In some embodiments, the conductive polymer plays two roles simultaneously, not only as a conductive agent but also as a binder. In other embodiments, the conductive agent does not comprise a conductive polymer.

[00198] In some embodiments, the proportion of electrode active material in the electrode layer is from about 60% to about 99%, from about 70% to about 99%, from about 75% to about 99%, from about 80% to about 99%, from about 85% to about 99%, from about 90% to about 99%, from about 60% to about 95%, from about 65% to about 95%, from about 70% to about 95%, from about 75% to about 95%, from about 80% to about 95%, from about 85% to about 95%, from about 60% to about 90%, from about 65% to about 90%, from about 70% to about 90%, from about 75% to about 90%, from about 80% to about 90%, from about 60% to about 85%, from about 65% to about 85%, from about 70% to about 85%, from about 75% to about 85%, from about 60% to about 80%, from about 65% to about 80%, or from about 70% to about 80% by weight, based on the total weight of the electrode layer.

[00199] In some embodiments, the proportion of electrode active material in the electrode layer is less than 99%, less than 95%, less than 90%, less than 85%, less than 80%, less than 75%, less than 70%, or less than 65% by weight, based on the total weight of the electrode layer. In some embodiments, the proportion of electrode active material in the electrode layer is more than 60%, more than 65%, more than 70%, more than 75%, more than 80%, more than 85%,

more than 90%, or more than 95% by weight, based on the total weight of the electrode layer.

[00200] In some embodiments, the proportion of binding agent and conductive material in the electrode layer is each independently from about 1% to about 20%, from about 2% to about 20%, from about 3% to about 20%, from about 4% to about 20%, from about 5% to about 20%, from about 6% to about 20%, from about 7% to about 20%, from about 8% to about 20%, from about 9% to about 20%, from about 10% to about 20%, from about 11% to about 20%, from about 12% to about 20%, from about 13% to about 20%, from about 14% to about 20%, from about 15% to about 20%, from about 1% to about 15%, from about 2% to about 15%, from about 3% to about 15%, from about 4% to about 15%, from about 5% to about 15%, from about 6% to about 15%, from about 7% to about 15%, from about 8% to about 15%, from about 9% to about 15%, from about 10% to about 15%, from about 1% to about 10%, from about 2% to about 10%, from about 3% to about 10%, from about 4% to about 10%, from about 5% to about 10%, from about 1% to about 5%, from about 2% to about 5%, or from about 3% to about 5% by weight, based on the total weight of the electrode layer.

[00201] In some embodiments, the proportion of binding agent and conductive agent in the electrode layer is each independently less than 20%, less than 19%, less than 18%, less than 17%, less than 16%, less than 15%, less than 14%, less than 13%, less than 12%, less than 11%, less than 10%, less than 9%, less than 8%, less than 7%, or less than 6% by weight, based on the total weight of the electrode layer. In some embodiments, the proportion of binding agent and conductive agent in the electrode layer is each independently more than 1%, more than 2%, more than 3%, more than 4%, more than 5%, more than 6%, more than 7%, more than 8%, more than 9%, more than 10%, more than 11%, more than 12%, more than 13%, more than 14%, or more than 15% by weight, based on the total weight of the electrode layer.

[00202] In some embodiments, the electrode layer of an electrode may additionally comprise other additives for enhancing electrode properties. In some embodiments, the additives may include surfactants, dispersants and flexibility-enhancing additives, salts, ion conductive polymers, and inorganic solid-state electrolytes.

[00203] In certain embodiments, an electrode slurry is used to form the electrode layer of an electrode; the electrode slurry is coated onto a modified current collector of the present invention and subsequently dried. In some embodiments, the electrode slurry comprises a solvent in addition to the various electrode components that are to form the electrode layer, such as electrode active materials, binding agents and conductive agents. In some embodiments, the solvent of the electrode slurry is an aqueous solvent. Any aqueous solvent suitable for use as the solvent of a conductive slurry is also suitable for use as the solvent of an electrode slurry. In certain embodiments, when both the conductive slurry and the electrode slurry use aqueous solvents, the composition of the aqueous solvents of the two slurries may be the same, different,

or partially different.

[00204] In some embodiments, the solid content of the electrode slurry is from about 40% to about 80%, from about 40% to about 75%, from about 40% to about 70%, from about 40% to about 65%, from about 40% to about 60%, from about 40% to about 55%, from about 45% to about 80%, from about 45% to about 75%, from about 45% to about 70%, from about 45% to about 65%, from about 45% to about 60%, from about 50% to about 80%, from about 50% to about 75%, from about 50% to about 70%, from about 50% to about 65%, from about 55% to about 80%, from about 55% to about 75%, from about 55% to about 70%, from about 60% to about 80%, from about 60% to about 75%, from about 65% to about 80%, from about 65% to about 75%, or from about 70% to about 80% by weight, based on the total weight of the electrode slurry.

[00205] In some embodiments, the solid content of the electrode slurry is less than 80%, less than 75%, less than 70%, less than 65%, less than 60%, less than 55%, or less than 50% by weight, based on the total weight of the electrode slurry. In some embodiments, the solid content of the electrode slurry is more than 40%, more than 45%, more than 50%, more than 55%, more than 60%, more than 65%, or more than 70% by weight, based on the total weight of the electrode slurry.

[00206] There are no particular limitations on the method used to produce an electrode slurry from the various electrode components, except that all electrode components should be mixed to form a homogeneous electrode slurry, for example through mixing in a homogenizer. In some embodiments, all the materials used to produce the electrode slurry are added into the homogenizer in a single batch. In other embodiments, each electrode component of the electrode slurry can be added to the homogenizer in one or more batches, and each batch may comprise more than one electrode component. Any homogenizer that can reduce or eliminate particle aggregation and/or promote homogeneous distribution of electrode components in the electrode slurry can be used herein. Homogeneous distribution plays an important role in fabricating batteries with good battery performance. In some embodiments, the homogenizer is a planetary stirring mixer, a stirring mixer, a blender, or an ultrasonicator.

[00207] There are no particular limitations to the conditions used to form the electrode slurry, except such conditions should be sufficient to produce a homogenous slurry with good dispersion of the electrode components within the slurry. There are no particular limitations on the time taken or the temperature or stirring speed used to homogenize the electrode slurry, except that the time period, temperature and stirring speed should be sufficient to ensure homogeneous distribution of the various electrode components in the electrode slurry and the electrode slurry to be processed easily.

[00208] In some embodiments, after homogenization of an electrode slurry, the electrode slurry can be coated onto one side or both sides of a modified current collector of the present invention to form an electrode layer. There are no particular limitations to the equipment and the conditions used in coating the slurry, except that a homogeneous, flat and smooth electrode layer film should be formed. In certain embodiments, the coating process is performed using a doctor blade coater, a slot-die coater, a transfer coater, a spray coater, a roll coater, a gravure coater, a dip coater, or a curtain coater. In some embodiments, the electrode slurry is applied directly onto a modified current collector. In other embodiments, the electrode slurry is first applied onto a release film to form a free-standing electrode layer. The free-standing electrode layer is then combined with a modified current collector and pressed to form an electrode layer.

[00209] In some embodiments, following the coating of the electrode slurry onto a modified current collector of the present invention, the coating is dried. Any equipment that can dry the coating in order to affix the electrode layer onto the modified current collector can be used herein.

[00210] There are no particular limitations to the conditions used for drying, except that the drying conditions should be sufficient to ensure that the electrode layer adheres strongly to the modified current collector. However, drying the electrode slurry at temperatures above 100 °C may result in undesirable deformation of the electrode, thus affecting the performance of the resultant electrode. In some embodiments, the resultant electrode is compressed mechanically following drying of the film in order to increase the density of the electrode.

[00211] In certain embodiments, the thickness of the electrode layer is from about 5 μm to about 90 μm, from about 5 μm to about 50 μm, from about 5 μm to about 25 μm, from about 10 μm to about 90 μm, from about 10 μm to about 50 μm, from about 10 μm to about 30 μm, from about 15 μm to about 90 μm, from about 20 μm to about 90 μm, from about 25 μm to about 90 μm, from about 25 μm to about 80 μm, from about 25 μm to about 70 μm, from about 25 μm to about 50 μm, from about 30 μm to about 90 μm, or from about 30 μm to about 80 μm. In some embodiments, the thickness of the electrode layer is more than 5 μm, more than 10 μm, more than 15 μm, more than 20 μm, more than 25 μm, more than 30 μm, more than 40 μm, more than 50 μm, more than 60 μm, more than 70 μm, or more than 80 μm. In some embodiments, the thickness of the electrode layer is less than 90 μm, less than 80 μm, less than 70 μm, less than 60 μm, less than 50 μm, less than 40 μm, less than 30 μm, less than 25 μm, less than 20 μm, less than 15 μm, or less than 10 μm.

[00212] In some embodiments, the surface density of the electrode layer is from about 1 mg/cm² to about 50 mg/cm², from about 2.5 mg/cm² to about 50 mg/cm², from about 5 mg/cm²

to about 50 mg/cm², from about 10 mg/cm² to about 50 mg/cm², from about 15 mg/cm² to about 50 mg/cm², from about 20 mg/cm² to about 50 mg/cm², from about 30 mg/cm² to about 50 mg/cm², from about 1 mg/cm² to about 30 mg/cm², from about 2.5 mg/cm² to about 30 mg/cm², from about 5 mg/cm² to about 30 mg/cm², from about 10 mg/cm² to about 30 mg/cm², from about 15 mg/cm² to about 30 mg/cm², from about 20 mg/cm² to about 30 mg/cm², from about 1 mg/cm² to about 20 mg/cm², from about 2.5 mg/cm² to about 20 mg/cm², from about 5 mg/cm² to about 20 mg/cm², from about 10 mg/cm² to about 20 mg/cm², from about 1 mg/cm² to about 15 mg/cm², from about 2.5 mg/cm² to about 15 mg/cm², from about 5 mg/cm² to about 15 mg/cm², or from about 10 mg/cm² to about 15 mg/cm².

[00213] In some embodiments, the surface density of the electrode layer is less than 50 mg/cm², less than 40 mg/cm², less than 30 mg/cm², less than 20 mg/cm², less than 15 mg/cm², less than 10 mg/cm², less than 5 mg/cm², or less than 2.5 mg/cm². In some embodiments, the surface density of the electrode layer is more than 1 mg/cm², more than 2.5 mg/cm², more than 5 mg/cm², more than 10 mg/cm², more than 15 mg/cm², more than 20 mg/cm², more than 30 mg/cm², or more than 40 mg/cm².

[00214] In an electrode comprising a modified current collector of the present invention, the electrode layer exhibits strong adhesion to the modified current collector. It is important for the electrode layer to have a high peeling strength with respect to the modified current collector, as this prevents delamination or separation of the electrode, which would greatly impact the mechanical stability of the electrode and the cyclability of a battery comprising the electrode. Therefore, the electrodes should have sufficient peeling strength to withstand the rigors of battery manufacture.

[00215] In some embodiments, the peeling strength between the electrode layer and the modified current collector is in the range of from about 1.0 N/cm to about 8.0 N/cm, from about 1.0 N/cm to about 6.0 N/cm, from about 1.0 N/cm to about 5.0 N/cm, from about 1.0 N/cm to about 4.0 N/cm, from about 1.0 N/cm to about 3.0 N/cm, from about 1.0 N/cm to about 2.5 N/cm, from about 1.0 N/cm to about 2.0 N/cm, from about 1.2 N/cm to about 3.0 N/cm, from about 1.2 N/cm to about 2.5 N/cm, from about 1.2 N/cm to about 2.0 N/cm, from about 1.5 N/cm to about 3.0 N/cm, from about 1.5 N/cm to about 2.5 N/cm, from about 1.5 N/cm to about 2.0 N/cm, from about 1.8 N/cm to about 3.0 N/cm, from about 1.8 N/cm to about 2.5 N/cm, from about 2.0 N/cm to about 6.0 N/cm, from about 2.0 N/cm to about 5.0 N/cm, from about 2.0 N/cm to about 3.0 N/cm, from about 2.0 N/cm to about 2.5 N/cm, from about 2.2 N/cm to about 3.0 N/cm, from about 2.5 N/cm to about 3.0 N/cm, from about 3.0 N/cm to about 8.0 N/cm, from about 3.0 N/cm to about 6.0 N/cm, or from about 4.0 N/cm to about 6.0 N/cm.

[00216] In some embodiments, the peeling strength between the electrode layer and the modified current collector is more than 1.0 N/cm, more than 1.2 N/cm, more than 1.5 N/cm, more than 2.0 N/cm, more than 2.2 N/cm, more than 2.5 N/cm, more than 3.0 N/cm, more than 3.5 N/cm, more than 4.0 N/cm, more than 4.5 N/cm, more than 5.0 N/cm, more than 5.5 N/cm, more than 6.0 N/cm, more than 6.5 N/cm, or more than 7.0 N/cm. In some embodiments, the peeling strength between the electrode layer and the modified current collector is less than 8.0 N/cm, less than 7.5 N/cm, less than 7.0 N/cm, less than 6.5 N/cm, less than 6.0 N/cm, less than 5.5 N/cm, less than 5.0 N/cm, less than 4.5 N/cm, less than 4.0 N/cm, less than 3.5 N/cm, less than 3.0 N/cm, less than 2.8 N/cm, less than 2.5 N/cm, less than 2.2 N/cm, less than 2.0 N/cm, less than 1.8 N/cm, or less than 1.5 N/cm.

[00217] In some embodiments, once an electrode comprising a modified current collector is formed, the electrode can be assembled with a counter-electrode and an electrolyte to form a battery. When the electrode is a cathode, the counter-electrode is an anode; when the electrode is an anode, the counter-electrode is an anode.

[00218] In some embodiments, the electrolyte is a liquid electrolyte. Such a liquid electrolyte comprises an electrolyte solvent and a salt. In some embodiments, the electrolyte solvent is water; the liquid electrolyte is then an aqueous electrolyte. In other embodiments, the electrolyte solvent is a liquid composed of one or more organic solvents; the liquid electrolyte is then a non-aqueous electrolyte. In some embodiments, each organic solvent is selected from a carbonate-based, ester-based, ether-based or other aprotic solvent. Some non-limiting examples of the carbonate-based solvent include dimethyl carbonate, diethyl carbonate, dipropyl carbonate, methylpropyl carbonate, ethylpropyl carbonate, ethyl methyl carbonate, ethylene carbonate, propylene carbonate, butylene carbonate, and combinations thereof. Some non-limiting examples of the ester-based solvent include methyl acetate, methyl propanoate, ethyl acetate, n-propyl acetate, dimethyl acetate, methyl propionate, ethyl propionate, and combinations thereof. Some non-limiting examples of the ether-based solvent include dibutyl ether, tetraglyme, diglyme, dimethoxyethane, 2-methyltetrahydrofuran, tetrahydrofuran, and combinations thereof. Some non-limiting examples of the other aprotic solvent include methyl bromide, ethyl bromide, methyl formate, acetonitrile, dimethyl sulfoxide, dimethylformamide, N-methyl-2-pyrrolidone, and combinations thereof.

[00219] In some embodiments, the liquid electrolyte is for a conventional lithium-ion battery. The salt in the liquid electrolyte is then a lithium salt. In some embodiments, the lithium salt present in the liquid electrolyte for a conventional lithium-ion battery is selected from the group consisting of LiPF_6 , LiBO_2 , LiBF_4 , LiSbF_6 , LiAsF_6 , LiAlCl_4 , LiClO_4 , LiCl , LiI , LiNO_3 ,

LiB(C₂O₄)₂, LiSO₃CF₃, LiN(SO₂F)₂, LiN(SO₂CF₃)₂, LiN(SO₂CF₂CF₃)₂, LiC₂H₃O₂, and combinations thereof.

[00220] In some embodiments, the liquid electrolyte is for a conventional sodium-ion battery. The salt in the liquid electrolyte is then a sodium salt. In some embodiments, the sodium salt present in the liquid electrolyte for a conventional sodium-ion battery is the sodium analogue of the lithium salts discussed above, with the lithium replaced by sodium. Such sodium salts include NaPF₆, NaBF₄, NaN(SO₂CF₃)₂, NaN(SO₂F)₂, NaClO₄, NaSO₃CF₃ and combinations thereof. In some embodiments, the salt present in the liquid electrolyte for a conventional sodium-ion battery is one or more of NaMF_x; wherein each x=4 or 6; and wherein each M is selected from the group consisting of Al³⁺, B³⁺, Ga³⁺, In³⁺, Sc³⁺, Y³⁺, La³⁺, P⁵⁺, As⁵⁺, and combinations thereof.

[00221] In some embodiments, the electrolyte is a solid-state electrolyte. In some embodiments, the solid-state electrolyte is a polymer electrolyte. Such a polymer electrolyte comprises an ion-conductive polymer as well as a salt. In some embodiments, the ion-conductive polymer is selected from the group consisting of polyether, polycarbonate, polyacrylate, polysiloxane, polyphosphazene, polyethylene derivative, alkylene oxide derivative, phosphate polymer, poly-lysine, polyester sulfide, polyvinyl alcohol, polyvinylidene fluoride, polymer containing one or more ionically dissociable groups, copolymer thereof and combinations thereof. In some embodiments, the ion-conductive polymer is selected from the group consisting of polyacrylonitrile (PAN), polyethylene carbonate (PEC), polyacrylamide (PAM), polyethylene glycol (PEG), polyethylene oxide (PEO), polyhydroxyethylmethacrylate (P(HEMA)), polyphosphonate (PPh), polysiloxane, polyamide (PA), polydilactone, polydiester, polyphosphazene (PPHOS), polyurethane (PU) copolymer thereof and combinations thereof.

[00222] In some embodiments, the polymer electrolyte is for a solid-state lithium-ion battery. In certain embodiments, the salt present in the polymer electrolyte for a solid-state lithium-ion battery is one or more of the lithium salts discussed above. Similarly, in some embodiments, the polymer electrolyte is for a solid-state sodium-ion battery. In certain embodiments, the salt present in the polymer electrolyte for a solid-state sodium-ion battery is one or more of the sodium salts discussed above.

[00223] In some embodiments, the solid-state electrolyte is an inorganic solid-state electrolyte. In certain embodiments, the inorganic solid-state electrolyte is for a solid-state lithium-ion battery. In some embodiments, the inorganic solid-state electrolyte for a solid-state lithium-ion battery is selected from the group consisting of sulfides, for example, Li₂S - P₂S₅; Li_{14-x}Ge_{1-x}P_xS₄ (LGPS, x is 0.1 to 2); Li_{10±1}MP₂X₁₂ (M = Ge, Si, Sn, Al; X = S, Se); Li_{3.833}

$\text{Sn}_{0.833}\text{As}_{0.166}\text{S}_4$; Li_4SnS_4 ; $\text{B}_2\text{S}_3 - \text{Li}_2\text{S}$; $x \text{Li}_2\text{S} - (100-x) \text{P}_2\text{S}_5$ (x is 70 to 80); $\text{Li}_2\text{S} - \text{SiS}_2 - \text{Li}_3\text{N}$; $\text{Li}_2\text{S} - \text{P}_2\text{S}_5 - \text{LiI}$; $\text{Li}_2\text{S} - \text{SiS}_2 - \text{LiI}$; $\text{Li}_2\text{S} - \text{B}_2\text{S}_3 - \text{LiI}$; $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$; $\text{Li}_6\text{PS}_5\text{X}$ Argyrodite (where X is a halogen); thio-LISICON compounds such as $\text{Li}_{3.25}\text{Ge}_{0.25}\text{P}_{0.75}\text{S}_4$; anti-perovskites such as Li_3SX (X is Cl or Br); lithium-phosphorus-iodine-oxygen sulfides; lithium-phosphorus-oxygen sulfides; lithium-zinc-germanium sulfides; lithium-germanium-sulfides; LLTO-based compounds such as $(\text{La}, \text{Li}) \text{TiO}_3$; $\text{Li}_6\text{La}_2\text{CaTa}_6\text{O}_{12}$; $\text{Li}_6\text{La}_2\text{ANb}_2\text{O}_{12}$ (A is Ca and / or Sr); $\text{Li}_2\text{Nd}_3\text{TeSbO}_{12}$; $\text{Li}_3\text{BO}_{2.5}\text{N}_{0.5}$; $\text{Li}_9\text{SiAlO}_8$; LAGP compounds $(\text{Li}_{1+x}\text{Al}_x\text{Ge}_{2-x}(\text{PO}_4)_3$, where $0 \leq x \leq 1$, $0 \leq y \leq 1$); $\text{Li}_2\text{O} - \text{LATP}$ compounds such as $\text{Al}_2\text{O}_3 - \text{TiO}_2 - \text{P}_2\text{O}_5$; $\text{Li}_{1+x}\text{Al}_x\text{Ti}_{2-x}(\text{PO}_4)_3$ (where $0 \leq x \leq 1$, $0 \leq y \leq 1$); $\text{Li}_{1+x}\text{Ti}_{2-x}\text{Al}_x\text{Si}_y(\text{PO}_4)_{3-y}$ (where $0 \leq x \leq 1$, $0 \leq y \leq 1$); $\text{LiAl}_x\text{Zr}_{2-x}(\text{PO}_4)_3$ (where $0 \leq x \leq 1$, $0 \leq y \leq 1$); $\text{LiTi}_x\text{Zr}_{2-x}(\text{PO}_4)_3$ (where $0 \leq x \leq 1$, $0 \leq y \leq 1$); LISICON type solid-state electrolytes; LIPON compounds $(\text{Li}_{3+y}\text{PO}_{4-x}\text{N}_x$, where $0 \leq x \leq 1$, $0 \leq y \leq 1$); Perovskite compounds $((\text{La}, \text{Li}) \text{TiO}_3)$; NASICON compounds such as $\text{LiTi}_2(\text{PO}_4)_3$; anti-perovskites such as Li_3OX (X is Cl or Br); lithium-aluminum-titanium-silicon phosphates (LATSP); lithium-aluminum oxides; lithium-vanadium-germanium oxides; lithium-zinc-germanium oxides; lithium-stuffed garnets such as lithium-lanthanum-zirconium oxides; lithium-lanthanum-zirconium-aluminum oxides; lithium-lanthanum-zirconium-tantalum oxides; Li_3N ; lithium-aluminum chlorides; and combinations thereof.

[00224] In certain embodiments, the inorganic solid-state electrolyte is for a solid-state sodium-ion battery. In some embodiments, the inorganic solid-state electrolyte for a solid-state sodium-ion battery is the sodium analogue of the inorganic solid-state electrolytes suitable for use in a solid-state lithium-ion battery discussed above, with the lithium replaced by sodium. In some embodiments, inorganic solid-state electrolyte for a solid-state sodium-ion battery is a NASICON-type inorganic solid-state electrolyte, a NaPS sulfide containing sulfur and phosphorus such as $75\text{Na}_2\text{S}-25\text{P}_2\text{S}_5$, sodium polyaluminate and combinations thereof.

[00225] In some embodiments, the solid-state electrolyte is a gel electrolyte. Such a gel electrolyte comprises a polymer electrolyte and an electrolyte solvent.

[00226] Due to the presence of a conductive layer in a modified current collector of the present invention, batteries comprising electrodes that use the modified current collector exhibit exceptional electrochemical performance. Compared to a conventional current collector, a modified current collector of the present invention brings about considerable improvement to the electrode, such improvement being made possible by the contribution of each individual component present in the conductive layer of the modified current collector. More specifically, the conductive material decreases the interfacial resistance between the modified current collector and the electrode layer, thereby reducing inherent capacity losses that arise from the

internal resistance of the electrodes in a battery. The conductive layer also acts as a physical barrier to prevent corrosion of the substrate. The binder material not only provides more effective binding capability between the conductive material particles and between the conductive material particles and the substrate, but also improves the mechanical strength of the electrode as a whole. Furthermore, when a water-based slurry is used to produce the conductive layer, the binder material within the conductive layer still maintains excellent binding properties even if an aqueous electrode slurry is subsequently applied on the conductive layer. The conductive layer would not disintegrate or delaminate from the substrate.

[00227] The following examples are presented to exemplify embodiments of the invention but are not intended to limit the invention to the specific embodiments set forth. Unless indicated to the contrary, all parts and percentages are by weight. All numerical values are approximate. When numerical ranges are given, it should be understood that embodiments outside the stated ranges may still fall within the scope of the invention. Specific details described in each example should not be construed as necessary features of the invention.

[00228] While the invention has been described with respect to a limited number of embodiments, the specific features of one embodiment should not be attributed to other embodiments of the invention. In some embodiments, the methods may include numerous steps not mentioned herein. In other embodiments, the methods do not include, or are substantially free of, any steps not enumerated herein. Variations and modifications from the described embodiments exist. The appended claims intend to cover all those modifications and variations as falling within the scope of the invention.

EXAMPLES

[00229] The composite volume resistivity of the cathode and the interface resistance between the cathode layer and the modified current collector were measured using an electrode resistance measurement system (RM2610, HIOKI).

[00230] The viscosity of the binder material used in the conductive layer were measured using a rotational viscosity meter (NDJ-5S, Shanghai JT Electronic Technology Co. Ltd., China) at 4% concentration in DI water and 20 °C.

Example 1

A) Preparation of Conductive Material Mixture

[00231] 150 g of graphite powder (obtained from Timcal Ltd, Bodio, Switzerland) was added into 500 g of DI water. After the addition, the mixture was stirred for about 75 mins at 25 °C at a speed of 1000 rpm to form a conductive material mixture.

B) Preparation of Binder Material Solution

[00232] A binder material was prepared by a method known in the art. In the structural unit (a) of the copolymer, any three of R₁, R₂, R₃ and R₄ are H; and any one of R₁, R₂, R₃ and R₄ is hydroxyl. In the structural unit (b) of the copolymer, any three of R₅, R₆, R₇ and R₈ are H; and any one of R₅, R₆, R₇ and R₈ is acetoxy. The proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 99% and 1% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The components of the binder material of Example 1 and their respective proportions are shown in Table 1 below.

[00233] 75 g of binder material was then added into 750 g of DI water and heated to 70 °C. The mixture was stirred at 600 rpm for 30 mins using a magnetic stirrer to form a binder material solution. The solid content of the binder material solution is 9.1% by weight. The weight-average molecular weight of the copolymer is 130,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 30 mPa·s.

C) Preparation of Conductive Slurry

[00234] 150 g of the binder material solution was added into 50 g of the conductive material mixture. After the addition, the mixture was stirred for about 15 mins at 25 °C at a speed of 1000 rpm to form a conductive slurry. The solid content of the conductive slurry is 12.6% by weight.

D) Preparation of Modified Current Collector

[00235] An aluminum foil having a thickness of 16 μm was used as a substrate. The conductive slurry was coated onto both sides of the substrate using a doctor blade coater with a gap width of 8 μm. The coated slurry of 4.5 μm on the aluminum foil was dried to form a conductive layer using an electrically heated oven at 85 °C. The drying time was about 30 mins.

E) Preparation of Binding Agent Solution

[00236] 16 g of sodium hydroxide (NaOH) was added into a round-bottom flask containing 380 g of distilled water. The sodium hydroxide solution was stirred at 80 rpm for 30 mins to obtain a first suspension.

[00237] 36.04 g of acrylic acid was added into the first suspension. The mixture was further stirred at 80 rpm for 30 mins to obtain a second suspension.

[00238] 19.04 g of acrylamide (AM) was dissolved in 10 g of DI water to form an AM solution. Thereafter, 29.04 g of AM solution was added into the second suspension. The mixture was further heated to 55 °C and stirred at 80 rpm for 45 mins to obtain a third suspension.

[00239] 12.92 g of acrylonitrile (AN) was added into the third suspension. The mixture was further stirred at 80 rpm for 10 mins to obtain a fourth suspension.

[00240] Furthermore, 0.015 g of water-soluble free radical initiator (ammonium

persulfate, APS; obtained from Aladdin Industries Corporation, China) was dissolved in 3 g of DI water and 0.0075 g of reducing agent (sodium bisulfite; obtained from Tianjin Damao Chemical Reagent Factory, China) was dissolved in 1.5 g of DI water. 3.015 g of APS solution and 1.5075 g of sodium bisulfite solution were added into the fourth suspension. The mixture was stirred at 200 rpm for 24 h at 55 °C to obtain a fifth suspension.

[00241] After the complete reaction, the temperature of the fifth suspension was lowered to 25 °C. 3.72 g of NaOH was dissolved in 400 g of DI water. Thereafter, 403.72 g of sodium hydroxide solution was added dropwise into the fifth suspension to adjust pH to 7.31 to form the sixth suspension. The binding agent was filtered using 200 µm nylon mesh. The solid content of the binding agent solution is 9.00 wt.%.

F) Preparation of Positive Electrode

[00242] A first mixture was prepared by dispersing 12 g of conductive agent (SuperP; obtained from Timcal Ltd, Bodio, Switzerland) and 100 g of the binding agent solution (9.00 wt.% solid content) in 74 g of deionized water while stirring with an overhead stirrer (R20, IKA). After the addition, the first mixture was further stirred for about 30 mins at 25 °C at a speed of 1,200 rpm.

[00243] Thereafter, a second mixture was prepared by adding 276 g of NMC811 (obtained from Shandong Tianjiao New Energy Co., Ltd, China) to the first mixture at 25 °C while stirring with an overhead stirrer. Then, the second mixture was degassed under a pressure of about 10 kPa for 1 hour. The second mixture was further stirred for about 60 mins at 25 °C at a speed of 1,200 rpm to form a homogenized cathode slurry.

[00244] The homogenized cathode slurry was coated onto both sides of the surface of the modified current collector prepared above using a doctor blade coater with a gap width of 120 µm. The coated slurry of 80 µm on the modified current collector was dried to form a cathode layer using an electrically heated oven at 70 °C. The drying time was about 10 mins. The electrode was then pressed to decrease the thickness of the cathode layer to 23 µm. The surface density of the cathode layer on the modified current collector is 7.00 mg/cm². The volume resistivity of the cathode is 2.120 Ω·cm. The interfacial resistance between the electrode layer and the modified current collector of Example 1 was measured and is shown in Table 1 below.

G) Assembly of Coin Cell

[00245] The electrochemical performance of the cathode prepared above was tested in CR2032 coin-type Li cells assembled in an argon-filled glove box. The cathode was cut into disc-form shapes for coin-type cell assembly. A lithium metal foil having a thickness of 500 µm was used as a counter-electrode. The cathode and counter-electrode were kept apart by a separator. The separator was a ceramic coated microporous membrane made of nonwoven fabric

(MPM, Japan), which had a thickness of about 25 μm . The electrode assembly was then dried in a box-type resistance oven under vacuum (DZF-6020, obtained from Shenzhen Kejing Star Technology Co. Ltd., China) at 105 °C for about 16 hours.

[00246] An electrolyte was then injected into the case holding the packed electrodes under a high-purity argon atmosphere with a moisture and oxygen content of less than 3 ppm respectively. The electrolyte was a solution of LiPF_6 (1 M) in a mixture of ethylene carbonate (EC), ethyl methyl carbonate (EMC) and dimethyl carbonate (DMC) at a volume ratio of 1:1:1. After electrolyte filling, the coin cell was mechanically pressed using a punch tooling with a standard circular shape.

H) Electrochemical Measurements

[00247] The coin cells were analyzed in a constant current mode using a multi-channel battery tester (BTS-4008-5V10mA, obtained from Neware Electronics Co. Ltd, China). After 1 cycle at C/20 was completed, they were charged and discharged at a rate of C/2. The charging/discharging cycling tests of the cells were performed between 3.0 and 4.3 V at a current density of C/2 at 25 °C to obtain the discharge capacity. The electrochemical performance of the coin cell of Example 1 was measured and is shown in Table 1 below.

Preparation of Conductive Material Mixture of Examples 2-5, 7-9, 14-18 and Comparative Examples 1-2, 4-5

[00248] The conductive material mixtures of Examples 2-5, 7-9, 14-18 and Comparative Example 1-2, 4-5 were prepared in the same manner as in Example 1.

Preparation of Conductive Material Mixture of Example 6

[00249] The conductive material mixture was prepared in the same manner as in Example 1, except that 200 g of graphite powder was added into 500 g of DI water.

Preparation of Conductive Material Mixture of Example 10

[00250] The conductive material mixture was prepared in the same manner as in Example 1, except that 150 g of carbon black (obtained from Timcal Ltd, Bodio, Switzerland) was used instead of graphite powder.

Preparation of Conductive Material Mixture of Example 11

[00251] The conductive material mixture was prepared in the same manner as in Example 1, except that 25 g of carbon black was first added into 500 g of DI water, which was stirred for 15 mins at 25 °C at a speed of 1000 rpm to form a mixture; 125 g of graphite powder was then added into the mixture and was further stirred for 60 mins at 25 °C at a speed of 1000 rpm to form a conductive material mixture.

Preparation of Conductive Material Mixture of Example 12

[00252] The conductive material mixture was prepared in the same manner as in Example 1, except that 25 g of vapor grown carbon nanofibers (VGCFs; obtained from Showa Denko K.K., Japan) was first added into 500 g of DI water, which was stirred for 15 mins at 25 °C at a speed of 1000 rpm to form a mixture; 125 g of graphite powder was then added into the mixture and was further stirred for 60 mins at 25 °C at a speed of 1000 rpm to form a conductive material mixture.

Preparation of Conductive Material Mixture of Example 13

[00253] The conductive material mixture was prepared in the same manner as in Example 1, except that 25 g of carbon nanotubes (CNTs; obtained from Jiangsu Cnano Technology Co. Ltd., China) was first added into 500 g of DI water, which was stirred for 15 mins at 25 °C at a speed of 1000 rpm to form a mixture; 125 g of graphite powder was then added into the mixture and was further stirred for 60 mins at 25 °C at a speed of 1000 rpm to form a conductive material mixture.

Preparation of Conductive Material Mixture of Comparative Example 3

[00254] The conductive material mixture was not prepared for Comparative Example 3.

Preparation of Binder Material Solution of Example 2

[00255] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 98% and 2% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 110,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 20 mPa·s.

Preparation of Binder Material Solution of Example 3

[00256] The binder material solution was prepared in the same manner as in Example 1, except that the binder material solution was prepared such that the weight-average molecular weight of the copolymer is 20,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 6 mPa·s.

Preparation of Binder Material Solution of Example 4

[00257] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 98% and 2% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 16,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 5

mPa·s.

Preparation of Binder Material Solution of Example 5

[00258] The binder material solution was prepared in the same manner as in Example 1, except that the binder material solution was prepared such that the weight-average molecular weight of the copolymer is 200,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 66 mPa·s.

Preparation of Binder Material Solution of Example 6

[00259] The binder material solution was prepared in the same manner as in Example 1, except that the binder material solution was prepared such that the weight-average molecular weight of the copolymer is 120,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 32 mPa·s.

Preparation of Binder Material Solution of Example 7

[00260] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 96% and 4% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 78,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 17 mPa·s.

Preparation of Binder Material Solution of Example 8

[00261] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 94% and 6% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 80,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 17 mPa·s.

Preparation of Binder Material Solution of Example 9

[00262] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 92% and 8% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 82,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 17 mPa·s.

Preparation of Binder Material Solution of Examples 10-18 and Comparative Examples 4-5

[00263] The binder material solutions of Examples 10-18 and Comparative Examples 4-5 were prepared in the same manner as in Example 1.

Preparation of Binder Material Solution of Comparative Example 1

[00264] The binder material solution was prepared in the same manner as in Example 1, except that the proportions of structural unit (a) and structural unit (b) in the copolymer of the binder material are 89% and 11% by mole respectively, based on the total number of moles of monomeric units in the copolymer. The weight-average molecular weight of the copolymer is 75,000 g/mol. The viscosity of the binder material at 4% concentration in DI water at 20 °C is 13 mPa·s.

Preparation of Binder Material Solution of Comparative Example 2

[00265] 750 g of polyacrylic acid (PAA) solution at 9.1wt.% solid content was used as the binder material solution.

Preparation of Binder Material Solution of Comparative Example 3

[00266] The binder material solution was not prepared for Comparative Example 3.

Preparation of Conductive Slurry of Examples 2-5, 7-18 and Comparative Examples 1-2

[00267] The conductive slurries of Examples 2-5, 7-18 and Comparative Examples 1-2 were prepared in the same manner as in Example 1.

Preparation of Conductive Slurry of Example 6

[00268] The conductive slurry was prepared in the same manner as in Example 1. The solid content of the conductive slurry is 14.0% by weight.

Preparation of Conductive Slurry of Comparative Example 3

[00269] The conductive slurry was not prepared for Comparative Example 3.

Preparation of Conductive Slurry of Comparative Example 4

[00270] The conductive slurry was prepared in the same manner as in Example 1, except that 150 g of the binder material solution was added into 250 g of the conductive material mixture. The solid content of the conductive slurry is 17.8% by weight.

Preparation of Conductive Slurry of Comparative Example 5

[00271] The conductive slurry was prepared in the same manner as in Example 1, except that 680 g of the binder material solution was added into 50 g of the conductive material mixture. The solid content of the conductive slurry is 10.0% by weight.

Preparation of Modified Current Collector of Examples 2-18 and Comparative Examples 1-2, 4-5

[00272] The modified current collectors of Examples 2-18 and Comparative Examples 1-2, 4-5 were prepared in the same manner as in Example 1.

Preparation of Modified Current Collector of Comparative Example 3

[00273] The modified current collector was not prepared for Comparative Example 3.

Preparation of Binding Agent Solution of Examples 2-18 and Comparative Examples 1-5

[00274] The binding agent solutions of Examples 2-18 and Comparative Examples 1-5 were prepared in the same manner as in Example 1.

Preparation of Positive Electrode of Examples 2-13 and Comparative Examples 1-2, 4-5

[00275] The positive electrodes of Examples 2-13 and Comparative Examples 1-2, 4-5 were prepared in the same manner as in Example 1.

Preparation of Positive Electrode of Example 14

[00276] The positive electrode was prepared in the same manner as in Example 1, except that 276 g of NMC811 was replaced with NMC622 of the same weight in the preparation of positive electrode.

Preparation of Positive Electrode of Example 15

[00277] The positive electrode was prepared in the same manner as in Example 1, except that 276 g of NMC811 was replaced with NMC532 of the same weight in the preparation of positive electrode.

Preparation of Positive Electrode of Example 16

[00278] The positive electrode was prepared in the same manner as in Example 1, except that 276 g of NMC811 was replaced with NCA of the same weight in the preparation of positive electrode.

Preparation of Positive Electrode of Example 17

[00279] The positive electrode was prepared in the same manner as in Example 1, except that 276 g of NMC811 was replaced with a core-shell cathode active material (C-S) comprising NMC532 as the core and $\text{Li}_{0.95}\text{Ni}_{0.53}\text{Mn}_{0.29}\text{Co}_{0.15}\text{Al}_{0.03}\text{O}_2$ as the shell of the same weight in the preparation of positive electrode.

Preparation of Positive Electrode of Example 18

[00280] The positive electrode was prepared in the same manner as in Example 1, except that 276 g of NMC811 was replaced with LFP of the same weight in the preparation of positive electrode.

Preparation of Positive Electrode of Comparative Example 3

[00281] The positive electrode was prepared in the same manner as in Example 1, except that the homogenized cathode slurry was coated onto both sides of a substrate. The substrate used is an aluminum foil having a thickness of 16 μm . The volume resistivity of the cathode is 11.414 $\Omega\cdot\text{cm}$.

Assembly of Coin Cell of Examples 2-18 and Comparative Examples 1-5

[00282] The coin cells of Examples 2-18 and Comparative Examples 1-5 were assembled in the same manner as in Example 1.

Electrochemical Measurements of Examples 2-17 and Comparative Examples 1-3

[00283] The electrochemical performance of the coin cells of Examples 2-17 and Comparative Examples 1-3 were measured in the same manner as in Example 1 and the test results are shown in Table 1 below.

Electrochemical Measurements of Example 18

[00284] The electrochemical performance of the coin cells of Example 18 were measured in the same manner as in Example 1, except that the charging/discharging cycling tests of the cells were performed between 2.00 and 3.65 V at a current density of C/2 at 25 °C to obtain the discharge capacity.

Electrochemical Measurements of Comparative Example 4

[00285] The electrochemical performance of the coin cells of Comparative Example 4 was measured in the same manner as in Example 1. The interfacial resistance between the electrode layer and the modified current collector is 8.437 $\Omega\cdot\text{cm}^2$. The initial discharging capacity at 0.5 C is 164 mAh/g and the capacity retention after 50 cycles is 78.03%.

Electrochemical Measurements of Comparative Example 5

[00286] The electrochemical performance of the coin cells of Comparative Example 5 was measured in the same manner as in Example 1. The interfacial resistance between the electrode layer and the modified current collector is 18.385 $\Omega\cdot\text{cm}^2$. The initial discharging capacity at 0.5 C is 161 mAh/g and the capacity retention after 50 cycles is 78.71%.

Table 1

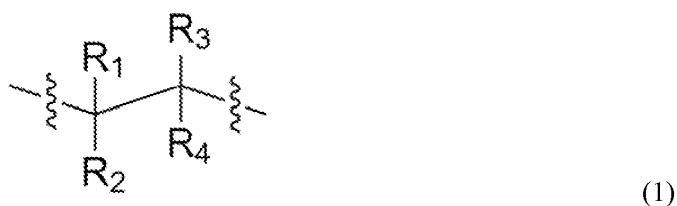
	Conductive material		Conductive layer		Cathode active material	Interfacial resistance (Ωcm^2)	0.5C Initial discharging capacity (mAh/g)	Capacity retention after 50 cycles (%)
	Material 1	Material 2	Proportion of structural unit (a)	Proportion of structural unit (b)				
Example 1	Graphite	-	99	1	NMC811	4.578	189	90.24
Example 2	Graphite	-	98	2	NMC811	4.252	187	91.40
Example 3	Graphite	-	99	1	NMC811	5.043	187	89.82
Example 4	Graphite	-	98	2	NMC811	3.971	188	90.06
Example 5	Graphite	-	99	1	NMC811	3.898	189	87.72
Example 6	Graphite	-	99	1	NMC811	4.025	190	89.47
Example 7	Graphite	-	96	4	NMC811	4.115	187	90.55
Example 8	Graphite	-	94	6	NMC811	4.326	187	88.62
Example 9	Graphite	-	92	8	NMC811	4.638	188	87.29
Example 10	Carbon black	-	99	1	NMC811	4.922	185	85.97
Example 11	Graphite	Carbon black	99	1	NMC811	4.177	195	92.88
Example 12	Graphite	VGCFs	99	1	NMC811	4.363	193	93.57
Example 13	Graphite	CNTs	99	1	NMC811	4.819	194	92.81
Example 14	Graphite	-	99	1	NMC622	4.233	153	90.58
Example 15	Graphite	-	99	1	NMC532	5.006	146	89.72
Example 16	Graphite	-	99	1	NCA	4.527	182	92.66
Example 17	Graphite	-	99	1	C-S	5.263	145	89.83
Example 18	Graphite	-	99	1	LFP	4.847	148	91.52
Comparative Example 1	Graphite	-	89	11	NMC811	-*	-*	-*
Comparative Example 2	Graphite	-	PAA		NMC811	-*	-*	-*
Comparative Example 3	-	-	-	-	NMC811	29.610	142	64.25

* A viable coin cell could not be produced.

CLAIMS

What is claimed is:

1. A modified current collector for a secondary battery, comprising a substrate and a conductive layer applied on one side or both sides of the substrate, wherein the conductive layer comprises a conductive material and a binder material, wherein the binder material comprises a copolymer comprising a structural unit (a), wherein the structural unit (a) comprises one or more monomeric unit(s) with formula (1):



and wherein each of R₁, R₂, R₃ and R₄ in formula (1) is independently H, hydroxyl, alkyl, hydroxyalkyl, halogen or alkyl halide.

2. The modified current collector of claim 1, wherein the copolymer further comprises a structural unit (b), wherein the structural unit (b) comprises one or more monomeric unit(s) with formula (2):



and wherein each of R₅, R₆, R₇ and R₈ in formula (2) is independently H, alkyl, acyloxy, acyloxyalkyl, halogen or alkyl halide.

3. The modified current collector of claim 1, wherein the proportion of the structural unit (a) in the copolymer is at least 90% by mole, based on the total number of moles of monomeric units in the copolymer.

4. The modified current collector of claim 1, wherein the proportion of the structural unit (a) in the copolymer is from about 90% to about 99.8% by mole, based on the total number of moles of monomeric units in the copolymer.

5. The modified current collector of claim 2, wherein the proportion of the structural

unit (b) in the copolymer is from about 0.1% to about 10% by mole, based on the total number of moles of monomeric units in the copolymer.

6. The modified current collector of claim 2, wherein the molar ratio of structural unit (a) to structural unit (b) in the copolymer is from about 9 to about 1000.

7. The modified current collector of claim 1, wherein the modified collector has a thickness of from about 5 μm to about 70 μm .

8. The modified current collector of claim 1, wherein the substrate is selected from the group consisting of stainless steel, titanium, nickel, aluminum, copper, platinum, gold, silver, chromium, zirconium, tungsten, molybdenum, silicon, tin, vanadium, zinc, cadmium, or alloys thereof, electrically-conductive resin or combinations thereof.

9. The modified current collector of claim 1, wherein the conductive material is selected from the group consisting of carbon, carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibers, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, Super P, KS6, vapor grown carbon fibers (VGCF), mesoporous carbon and combinations thereof.

10. The modified current collector of claim 2, wherein the weight-average molecular weight of the copolymer is from about 10,000 g/mol to about 300,000 g/mol.

11. The modified current collector of claim 1, wherein the proportion of the conductive material in the conductive layer is from about 25% to about 75% by weight, based on the total weight of the conductive layer.

12. The modified current collector of claim 1, wherein the proportion of the copolymer in the conductive layer is from about 25% to about 75% by weight, based on the total weight of the conductive layer.

13. The modified current collector of claim 1, wherein the hydroxyalkyl is selected from the group consisting of hydroxymethyl, hydroxyethyl, hydroxypropyl, hydroxy (methyl) propyl, hydroxy (methyl) butyl and combinations thereof.

14. The modified current collector of claim 2, wherein the acyloxyalkyl is selected from the group consisting of acyloxymethyl, acyloxyethyl, acyloxypropyl, acyloxy (methyl) propyl, acyloxy (methyl) butyl and combinations thereof.

15. An electrode, comprising the modified current collector of claim 1 and an electrode layer, wherein the electrode layer is located on the surface of the conductive layer, and wherein the electrode layer comprises an electrode active material and a binding agent.

16. The electrode of claim 15, wherein the electrode active material is a cathode active material selected from the group consisting of LiCoO_2 , LiNiO_2 , $\text{LiNi}_{1-x}\text{M}_x\text{O}_2$, $\text{LiNi}_x\text{Mn}_y\text{O}_2$, $\text{LiCo}_x\text{Ni}_y\text{O}_2$, $\text{Li}_{1+z}\text{Ni}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$, $\text{LiNi}_x\text{Co}_y\text{Al}_z\text{O}_2$, LiV_2O_5 , LiTiS_2 , LiMoS_2 , LiMnO_2 , LiCrO_2 , LiMn_2O_4 , Li_2MnO_3 , LiFeO_2 , LiFePO_4 , and combinations thereof; wherein each x is independently from 0.1 to 0.9; each y is independently from 0 to 0.9; each z is independently from 0 to 0.4; and wherein M is selected from the group consisting of Co, Mn, Al, Fe, Ti, Ga, Mg and combinations thereof.

17. The electrode of claim 15, wherein the electrode active material is a cathode active material selected from the group consisting of NaCoO_2 , NaFeO_2 , NaNiO_2 , NaCrO_2 , NaVO_2 , NaTiO_2 , NaFePO_4 , $\text{Na}_3\text{V}_2(\text{PO}_4)_3$, $\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$, NMC-type mixed oxides, Prussian blue-type sodium compounds and combinations thereof.

18. The electrode of claim 15, wherein the electrode active material is an anode active material selected the group consisting of natural graphite particulate, synthetic graphite particulate, hard carbon, soft carbon, mesocarbon microbeads (MCMB), Sn particulate, SnO_2 , SnO, $\text{Li}_4\text{Ti}_5\text{O}_{12}$ particulate, Si particulate, Si-C composite particulate and combinations thereof.

19. The electrode of claim 15, wherein the binding agent comprises a polymer comprising one or more functional group(s) containing a halogen, O, N, S or a combination thereof.

20. The electrode of claim 19, wherein each functional group is independently selected from the group consisting of carboxylic acid, carboxylic acid salt, sulfonic acid, sulfonic acid salt, sulfuric acid, sulfuric acid salt, phosphonic acid, phosphonic acid salt, phosphoric acid, phosphoric acid salt, nitric acid, nitric acid salt, amide, hydroxyl, nitrile, ester, epoxy, $-\text{NH}_2$ and combinations thereof.