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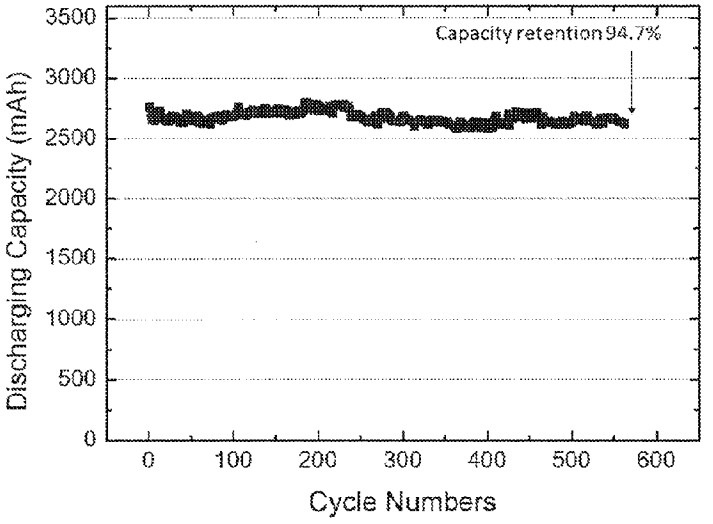

(57) Abrégé/Abstract:
Provided herein is electrode assembly for a nonaqueous electrolyte secondary battery, comprising at least one anode, at least one cathode and at least one separator interposed between the at least one anode and at least one cathode, wherein the at least one anode comprises an anode current collector and an anode electrode layer, and the at least one cathode comprises a cathode current collector and a cathode electrode layer, wherein each of the cathode and anode electrode layers independently has a void volume of less than 35%, and wherein each of the at least one cathode and anode independently has a peeling strength of 0.15 N/cm or more.

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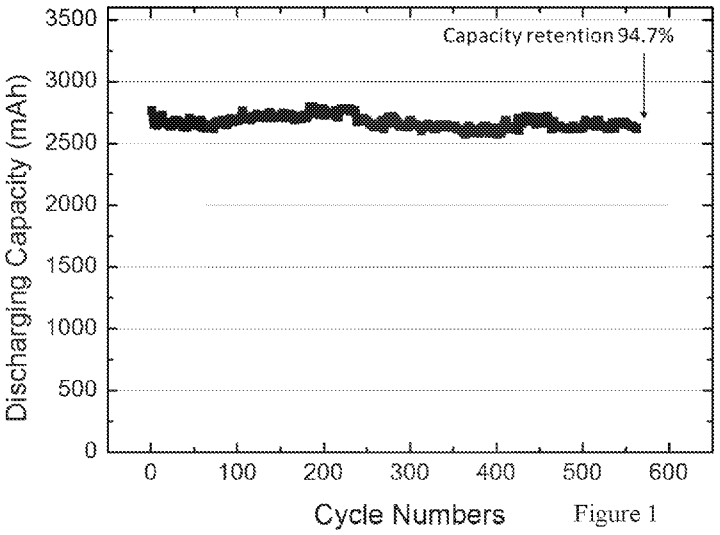

Figure 1

(57) Abstract: Provided herein is electrode assembly for a nonaqueous electrolyte secondary battery, comprising at least one anode, at least one cathode and at least one separator interposed between the at least one anode and at least one cathode, wherein the at least one anode comprises an anode current collector and an anode electrode layer, and the at least one cathode comprises a cathode current collector and a cathode electrode layer, wherein each of the cathode and anode electrode layers independently has a void volume of less than 35%, and wherein each of the at least one cathode and anode independently has a peeling strength of 0.15 N/cm or more.

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ELECTRODE ASSEMBLIES

FIELD OF THE INVENTION

[001] The present invention relates to the field of batteries. In particular, this invention relates to methods for drying electrode assemblies of lithium-ion batteries and electrode assemblies made by the methods disclosed herein.

BACKGROUND OF THE INVENTION

[002] Lithium-ion batteries (LIBs) have attracted extensive attention in the past two decades for a wide range of applications in portable electronic devices such as cellular phones and laptop computers. 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.

[003] Currently, electrodes are prepared by dispersing fine powders of an active battery electrode material, a conductive agent, and a binder material in an appropriate solvent. The dispersion can be coated onto a current collector such as a copper or aluminum metal foil, and then dried at an elevated temperature to remove the solvent. Sheets of the cathode and anode are subsequently stacked or rolled with the separator separating the cathode and anode to form a battery.

[004] The lithium-ion battery manufacturing process is sensitive to moisture. A battery with high water content leads to serious attenuation of electrochemical performance and affects stability of battery. Therefore, environmental humidity must be controlled strictly for the production process of LIBs. Most of the LIBs are produced in an environment with less than 1 percent humidity. However, significant cost is incurred because of the stringent moisture-free process. To address the moisture sensitive issue of electrode assembly, it is important to dry the electrode assembly prior to electrolyte filing so as to reduce the water content in the battery.

[005] Chinese Patent No. 104142045 B describes a method of drying an electrode assembly of LIBs. The method comprises heating an electrode assembly under vacuum at a temperature of 30-100 ^{o}C; filling the oven with dry air or inert gas; repeating these two steps for

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1-10 times. This method provides the electrode assembly with a water content between 430.5 ppm and 488.1 ppm.

[006] Chinese Patent Application No. 105115250 A describes a method of drying an electrode assembly of LIBs. The method comprises heating an electrode assembly under vacuum at a temperature of 85±5 °C; filling the oven with hot, dry nitrogen gas; repeating these two steps for 10-20 times. This method provides the electrode assembly with a water content of less than 200 ppm.

[007] None of the above patent references discloses any binder composition in the electrodes for evaluating the relationship between the drying profile and binder composition. In addition, the water contents of the electrode assemblies as dried by the existing methods range from a hundred ppm to several hundreds ppm, which may affect the cycling stability and rate capability of LIBs. Even if a battery is manufactured using the electrode obtained by the above method, exfoliation of an electrode layer may occur and sufficient durability of the electrode layer cannot be obtained.

[008] JP Patent No. 5523678 B2 describes a positive electrode for a nonaqueous electrolyte secondary battery, having a current collector and an electrode layer containing an active material, a conductive agent and a binder, wherein the electrode layer has a percentage of void of 33.0% or more to retain sufficient amount of electrolyte. However, it does not contain any data for evaluating the electrochemical performance of the electrodes prepared by this method.

[009] In view of the above, there is always a need to provide a nonaqueous electrolyte rechargeable battery using electrodes having high durability by inhibiting exfoliation of an electrode layer and good electrochemical performance.

SUMMARY OF THE INVENTION

[0010] The aforementioned needs are met by various aspects and embodiments disclosed herein.

[0011] In one aspect, provided herein is an electrode assembly for a nonaqueous electrolyte secondary battery, comprising at least one anode, at least one cathode and at least one

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separator interposed between the at least one anode and at least one cathode, wherein the at least one anode comprises an anode current collector and an anode electrode layer, and the at least one cathode comprises a cathode current collector and a cathode electrode layer, wherein each of the cathode and anode electrode layers independently has a void volume of less than 35%, and wherein each of the at least one cathode and anode independently has a peeling strength of 0.15 N/cm or more.

[0012] In some embodiments, the surface roughness R_a of each of the cathode and anode current collectors is independently 2 μm or less, or 1 μm or less.

[0013] In certain embodiments, the density of each of the cathode and anode electrode layers is independently from about 1.0 g/cm^3 to about 6.5 g/cm^3 or from about 1.0 g/cm^3 to about 3.0 g/cm^3.

[0014] In some embodiments, the thickness of each of the cathode and anode electrode layers is independently from about 1.0 μm to about 40 μm or from about 1.0 μm to about 25 μm.

[0015] In certain embodiments, the cathode electrode layer comprises a cathode material, a binder material and a conductive agent, and the anode electrode layer comprises an anode material, a binder material and a conductive agent, and wherein each of the binder materials in the cathode and anode electrode layers is independently selected from the group consisting of styrene-butadiene rubber, acrylated styrene-butadiene rubber, acrylonitrile copolymer, acrylonitrile-butadiene rubber, nitrile butadiene rubber, acrylonitrile-styrene-butadiene copolymer, acryl rubber, butyl rubber, fluorine rubber, polytetrafluoroethylene, polyethylene, polypropylene, ethylene/propylene copolymers, polybutadiene, polyethylene oxide, chlorosulfonated polyethylene, polyvinylpyrrolidone, polyvinylpyridine, polyvinyl alcohol, polyvinyl acetate, polyepichlorohydrin, polyphosphazene, polyacrylonitrile, polystyrene, latex, acrylic resins, phenolic resins, epoxy resins, carboxymethyl cellulose, hydroxypropyl cellulose, cellulose acetate, cellulose acetate butyrate, cellulose acetate propionate, cyanoethylcellulose, cyanoethylsucrose, polyester, polyamide, polyether, polyimide, polycarboxylate, polycarboxylic acid, polyacrylic acid, polyacrylate, polymethacrylic acid, polymethacrylate, polyacrylamide, polyurethane, fluorinated polymer, chlorinated polymer, a salt of alginic acid, polyvinylidene fluoride, poly(vinylidene fluoride)-hexafluoropropene, and combinations thereof.

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[0016] In some embodiments, each of the binder materials in the cathode and anode electrode layers is independently present in an amount from 2% to 10% by weight, based on the total weight of the cathode or anode electrode layer.

[0017] In certain embodiments, the cathode electrode layer comprises a cathode material selected from the group consisting of $LiCoO_2$, $LiNiO_2$, $LiNi_xMn_yO_2$, $Li_{1+z}Ni_xMn_yCo_{1-x-y}O_2$, $LiNi_xCo_yAl_zO_2$, LiV_2O_5, $LiTiS_2$, $LiMoS_2$, $LiMnO_2$, $LiCrO_2$, $LiMn_2O_4$, $LiFeO_2$, $LiFePO_4$, $LiNi_{0.5}Mn_{1.5}O_4$, $LiNi_{0.4}Mn_{1.6}O_4$, and combinations thereof, wherein each x is independently from 0.3 to 0.8; each y is independently from 0.1 to 0.45; and each z is independently from 0 to 0.2.

[0018] In some embodiments, the cathode material is present in an amount from 60% to 99% by weight, based on the total weight of the cathode electrode layer.

[0019] In certain embodiments, the cathode electrode layer comprises a cathode material, a binder material and a conductive agent, and the anode electrode layer comprises an anode material, a binder material and a conductive agent, and wherein each of the conductive agents in the cathode and anode electrode layers is independently selected from the group consisting of carbon, carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibres, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, mesoporous carbon, and combinations thereof.

[0020] In some embodiments, each of the conductive agents in the cathode and anode electrode layers is independently present in an amount from 2% to 10% by weight, based on the total weight of the cathode or anode electrode layer.

[0021] In certain embodiments, the anode electrode layer comprises an anode material selected from the group consisting of natural graphite particulate, synthetic graphite particulate, Sn particulate, $Li_4Ti_5O_{12}$ particulate, Si particulate, Si-C composite particulate, and combinations thereof.

[0022] In some embodiments, the anode material is present in an amount from 50% to 99% by weight, based on the total weight of the anode electrode layer.

[0023] In certain embodiments, each of the cathode and anode current collectors is independently stainless steel, titanium, nickel, aluminum, copper, or electrically-conductive

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resin. In some embodiments, the cathode current collector is an aluminum thin film, and the anode current collector is a copper thin film.

[0024] In some embodiments, the water content of the electrode assembly is less than 20 ppm, less than 10 ppm, or less than 5 ppm by weight, based on the total weight of the electrode assembly.

[0025] In certain embodiments, the at least one anode and at least one cathode have a water content of less than 20 ppm, less than 10 ppm, or less than 5 ppm by weight, based on the total weight of the at least one anode and at least one cathode.

[0026] In some embodiments, the at least one separator has a water content of less than 20 ppm, less than 10 ppm, or less than 5 ppm by weight, based on the total weight of the at least one separator.

[0027] Also provided herein is a lithium-ion battery comprising the electrode assembly prepared by the method disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] Figure 1 depicts cycling performance of an electrochemical cell containing an electrode assembly prepared by the method described in Example 2.

[0029] Figure 2 depicts cycling performance of an electrochemical cell containing an electrode assembly prepared by the method described in Example 4.

[0030] Figure 3 depicts cycling performance of an electrochemical cell containing an electrode assembly prepared by the method described in Example 6.

[0031] Figure 4 depicts cycling performance of an electrochemical cell containing an electrode assembly prepared by the method described in Example 8.

DETAILED DESCRIPTION OF THE INVENTION

[0032] Provided herein is an electrode assembly for a nonaqueous electrolyte secondary battery, comprising at least one anode, at least one cathode and at least one separator interposed between the at least one anode and at least one cathode, wherein the at least one anode comprises

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an anode current collector and an anode electrode layer, and the at least one cathode comprises a cathode current collector and a cathode electrode layer, wherein each of the cathode and anode electrode layers independently has a void volume of less than 35%, and wherein each of the at least one cathode and anode independently has a peeling strength of 0.15 N/cm or more.

[0033] The term "electrode" refers to a "cathode" or an "anode."

[0034] The term "positive electrode" is used interchangeably with cathode. Likewise, the term "negative electrode" is used interchangeably with anode.

[0035] The term "binder material" refers to a chemical or a substance that can be used to hold the active battery electrode material and conductive agent in place.

[0036] The term "water-based binder material" refers to a water-soluble or water-dispersible binder polymer. Some non-limiting examples of the water-based binder material include styrene-butadiene rubber, acrylated styrene-butadiene rubber, acrylonitrile-butadiene rubber, acryl rubber, butyl rubber, fluorine rubber, polytetrafluoroethylene, polyethylene, polypropylene, ethylene/propylene copolymers, polybutadiene, polyethylene oxide, polyvinylpyrrolidone, polyepichlorohydrin, polyphosphazene, polyacrylonitrile, polystyrene, ethylene/propylene/diene copolymers, polyvinylpyridine, chlorosulfonated polyethylene, latex, polyester resins, acrylic resins, phenolic resins, epoxy resins, polyvinyl alcohol, carboxymethyl cellulose, hydroxypropyl cellulose, and combinations thereof.

[0037] The term "organic-based binder material" refers to a binder dissolved or dispersed in an organic solvent, in particular, N-methyl-2-pyrrolidone (NMP). Some non-limiting examples of the organic-based binder material include polytetrafluoroethylene (PTFE), perfluoroalkoxy polymer (PFA), polyvinylidene fluoride (PVDF), copolymer of tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), fluorinated ethylene-propylene (FEP) copolymer, terpolymer of tetrafluoroethylene, hexafluoropropylene and vinylidene fluoride, and combinations thereof.

[0038] The term "current collector" refers to a support for coating the active battery electrode material and a chemically inactive high electron conductor for keeping an electric current flowing to electrodes during discharging or charging a secondary battery.

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[0039] The term "conductive agent" refers to a material which is chemically inactive and has good electrical conductivity. Therefore, the conductive agent is often mixed with an electrode active material at the time of forming an electrode to improve electrical conductivity of the electrode. In some embodiments, the conductive agent is a carbonaceous material.

[0040] The term "electrode assembly" refers to a structure comprising at least one positive electrode, at least one negative electrode, and at least one separator interposed between the positive electrode and the negative electrode.

[0041] The term "peeling strength" refers to the force required to separate a coating layer from a substrate to which it has been laminated.

[0042] The term "surface roughness" refers to the irregularities of shape present on the surface of a material.

[0043] The term "surface roughness (R_a)" refers to the arithmetical mean surface roughness measured by the method described in JIS B 0601-1994.

[0044] The term "surface roughness (R_z)" refers to the ten point mean roughness defined in JIS B 0601-1994.

[0045] 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.

[0046] 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; a 0.1 C means utilization of 10% of the energy in one hour or full energy in 10 hours; and a 5 C means utilization of full energy in 12 minutes.

[0047] 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 3600 coulombs of electrical charge. Similarly, the term "miniampere-hour (mAh)" also refers to a unit of the storage capacity of a battery and is 1/1,000 of an ampere-hour.

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[0048] 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.

[0049] In the following description, all numbers disclosed herein are approximate values, regardless 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 1 percent to 100 percent with a 1 percent increment, *i.e.*, k is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent,..., 50 percent, 51 percent, 52 percent,..., 95 percent, 96 percent, 97 percent, 98 percent, 99 percent, or 100 percent. Moreover, any numerical range defined by two R numbers as defined in the above is also specifically disclosed.

[0050] Generally, lithium-ion battery manufacturing processes are carried out in dry rooms where the environment must be carefully controlled to preserve optimum production conditions. The dew point of the air is an indicator of the quality of the dry room. Typical dew point values for battery production range from -40 °C to -65 °C. Efficiency and service life of a battery are determined in the cell production stage.

[0051] An electrode assembly can be constructed by sequentially stacking at least one negative electrode, at least one separator, and at least one positive electrode. The number and arrangement of the at least one positive electrode, the at least one negative electrode, and the at least one separator, for configuring the electrode assembly are not particularly limited. In some embodiments, the electrode assembly has a stacked structure in which two outermost electrodes comprise an opposing polarities (i.e., a positive electrode and a negative electrode), such as a positive electrode/separator/negative electrode structure or a positive electrode/separator/negative electrode/separator/positive electrode/separator/negative electrode structure.

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[0052] In some embodiments, disclosed is an electrode assembly for use in a non-aqueous electrolyte secondary battery. In certain embodiments, disclosed is an electrode assembly for use in a lithium-ion battery.

[0053] In certain embodiments, the electrode assembly has a stacked structure in which two outermost electrodes comprise the same polarity (i.e., positive electrodes or negative electrodes), such as a positive electrode/separator/negative electrode/separator/positive electrode structure or a negative electrode/separator/positive electrode/separator/negative electrode structure.

[0054] In some embodiments, the electrode assembly has a structure in which a separator is disposed on one of the outermost sides, such as a separator/positive electrode/separator/negative electrode structure or a positive electrode/separator/negative electrode/separator structure. In other embodiments, the electrode assembly has a structure in which separators are disposed on both the outermost sides, such as a separator/positive electrode/separator/negative electrode/separator structure.

[0055] In certain embodiments, the electrode assembly is assembled under strict humidity control in which the air has a dew point of -65 °C. In some embodiments, the electrode assembly is assembled under dry conditions in which the air has a dew point of -50 °C, -40 °C, -30 °C, -20 °C, -10 °C, 0 °C, 5 °C, or 10 °C. In certain embodiments, the electrode assembly is assembled in the open air with no control of humidity.

[0056] The separator disposed between the opposing active anode and cathode surfaces can prevent contact between the anode and cathode and a short circuit of the lithium ion battery. In some embodiments, the separator may comprise woven or nonwoven polymeric fibers, natural fibers, carbon fibers, glass fibers or ceramic fibers. In certain embodiments, the separator comprises woven or nonwoven polymeric fibers.

[0057] In certain embodiments, the fibers of the nonwoven or woven are made of organic polymers, such as polyolefin, polyethylene, high-density polyethylene, linear low-density polyethylene, low-density polyethylene, ultrahigh-molecular-weight polyethylene, polypropylene, polypropylene/polyethylene co-polymer, polybutylene, polypentene, polyacetal, polyamide, polycarbonate, polyimide, polyetherether ketone, polysulfones, polyphenylene oxide,

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polyphenylene sulfide, polyacrylonitrile, polyvinylidene fluoride, polyoxymethylene, polyvinyl pyrrolidone, polyester, polyethylene terephthalate, polybutylene terephthalate, polyethylene naphthalene, polybutylene naphthalate, derivatives thereof, or a combination thereof. In certain embodiments, the separator is made of polyolefinic fibers selected from the group consisting of polyethylene, high-density polyethylene, linear low-density polyethylene, low-density polyethylene, ultrahigh-molecular-weight polyethylene, polypropylene, polypropylene/polyethylene co-polymer, and combinations thereof. In some embodiments, the separator is made of polymeric fibers selected from the group consisting of polyester, polyacetal, polyamide, polycarbonate, polyimide, polyetherether ketone, polyether sulfone, polyphenylene oxide, polyphenylene sulfide, polyethylene naphthalene, and combinations thereof. In other embodiments, the polymeric fiber is not polyethylene, high-density polyethylene, linear low-density polyethylene, low-density polyethylene, ultrahigh-molecular-weight polyethylene, polypropylene, or polypropylene/polyethylene co-polymer. In further embodiments, the polymeric fiber is not polyacetal, polyether sulfone, polyphenylene oxide, polyphenylene sulfide, or polycarbonate. In still further embodiments, polymeric fiber is not polyamide, polyimide, or polyetherether ketone. But all other known polymeric fibers or many natural fibers can be used as well.

[0058] In some embodiments, the separator disclosed herein has a melting point of 100 °C or higher, 110 °C or higher, 120 °C or higher, 130 °C or higher, 140 °C or higher, 150 °C or higher, 160 °C or higher, 170 °C or higher, 180 °C or higher, 190 °C or higher, 200 °C or higher, 210 °C or higher, 220 °C or higher, 230 °C or higher, 240 °C or higher, or 250 °C or higher. In certain embodiments, the separator has a melting point from about 100 °C to about 300 °C, from about 120 °C to about 300 °C, from about 100 °C to about 250 °C, from about 120 °C to about 250 °C, from about 140 °C to about 250 °C, from about 160 °C to about 250 °C, from about 180 °C to about 250 °C, or from about 200 °C to about 250 °C. Separator having high melting point shows high thermal stability and therefore can be dried at high temperature without thermally shrinking. This also allows the drying to be more efficiently performed. Therefore, the electrode assembly can be dried in a relatively short time, resulting in a short production time.

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[0059] The separator can be in a coated or uncoated form. In some embodiments, the separator has a thickness from about 10 μm to about 200 μm, from about 30 μm to about 100 μm, from about 10 μm to about 75 μm, from about 10 μm to about 50 μm, from about 10 μm to about 20 μm, from about 15 μm to about 40 μm, from about 15 μm to about 35 μm, from about 20 μm to about 40 μm, from about 20 μm to about 35 μm, from about 20 μm to about 30 μm, from about 30 μm to about 60 μm, from about 30 μm to about 50 μm, or from about 30 μm to about 40 μm.

[0060] In certain embodiments, the separator has a thickness of about 15 μm, about 20 μm, or about 25 μm. In some embodiments, the separator of the present invention has a thickness of less than 40 μm, less than 35 μm, less than 30 μm, less than 25 μm, or less than 20 μm. If the separator is sufficiently thin, the moisture may be evaporated at high drying rates.

[0061] In some embodiments, the separator is uncoated and does not comprise a protective porous layer. In certain embodiments, the separator is coated and comprises a porous base material and a protective porous layer coated on one or both surfaces of the porous base material, wherein the protective porous layer comprises a binder material and an inorganic filler. In certain embodiments, the inorganic filler is selected from the group consisting of Al_2O_3, SiO_2, TiO_2, ZrO_2, BaO_x, ZnO, $CaCO_3$, TiN, AlN, and combinations thereof, wherein x is 1 or 2.

[0062] In some embodiments, the electrode assembly is loosely stacked. In the loosely stacked electrode assembly, there is a void space between the electrode layer and separator layer, allowing moisture to escape. Therefore, the loosely stacked electrode assembly can be effectively dried in a short period of time. On the other hand, when the electrode assembly is pressed under pressure before drying, the tightly packed electrode assembly has little or no void space between the electrode layer and separator layer, thus reducing airflow and drying efficiency.

[0063] In certain embodiments, the positive electrode, separator and negative electrode are stacked and spirally wound into a jelly-roll configuration before drying. Since a roll electrode assembly is tightly packed, there is also little or no void space between the electrode layer and separator layer, thus reducing airflow and drying efficiency. In some embodiments, the electrode assembly is not in a jelly-roll configuration.

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[0064] A positive electrode includes a cathode electrode layer supported on a cathode current collector. The cathode electrode layer comprises at least a cathode material and a binder material. The cathode electrode layer may further comprise a conductive agent for enhancing electron conductivity of the cathode electrode layer. A negative electrode includes an anode electrode layer supported on an anode current collector. The anode electrode layer comprises at least an anode material and a binder material. The anode electrode layer may further comprise a conductive agent for enhancing electron conductivity of the anode electrode layer.

[0065] In some embodiments, the at least one cathode comprises a cathode current collector and a cathode electrode layer comprising a cathode material, a binder material and a conductive agent, and the at least one anode comprises an anode current collector and an anode electrode layer comprising an anode material, a binder material and a conductive agent, wherein each of the cathode and anode electrode layers independently has a void volume of less than 40%, less than 39 %, less than 38 %, less than 37%, less than 36 %, less than 35%, less than 34 %, less than 33%, less than 32 %, less than 31 %, less than 30%, less than 29 %, less than 28 %, less than 27 %, less than 26 %, less than 25%, less than 24 %, less than 23 %, less than 22 %, less than 21 %, 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 %, less than 6 %, or less than 5 %, based on the total volume of the cathode or anode electrode layer. In certain embodiments, the void volume of the cathode or anode electrode layer is at least 5 %, at least 6 %, at least 7 %, at least 8 %, at least 9 %, at least 10 %, at least 11 %, at least 12 %, at least 13 %, at least 14 %, at least 15 %, at least 16 %, at least 17 %, at least 18 %, at least 19 %, at least 20 %, at least 21 %, at least 22 %, at least 23 %, at least 24 %, at least 25 %, at least 26 %, at least 27 %, at least 28 %, at least 29 %, at least 30 %, at least 31 %, at least 32 %, at least 33 %, at least 34 %, at least 35 %, at least 36 %, at least 37 %, at least 38 %, at least 39 %, or at least 40 %, based on the total volume of the cathode or anode electrode layer. In certain embodiments, the void volume of the cathode or anode electrode layer is between 8% and 40%, between 8% and 35%, between 8% and 30%, between 10% and 30%, between 13% and 30%, between 13% and 33%, between 15% and 30%, between 18% and 30%, between 20% and 30%, between 25% and 30%, between 5% and 30%, between 5% and 25%, between 5 % and 20 %, between 5 % and 15 %, between 5 % and 10 %, between

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10 % and 20 %, between 10 % and 15 %, between 20% and 25 %, between 15 % and 25 %, between 15 % and 20 %, between 12 % and 20 %, between 13% and 18%, between 15 % and 19 %, between 11% and 19 %, between 18 % and 25 %, between 22% and 26 %, or between 21 % and 28 %, based on the total volume of the cathode or anode electrode layer.

[0066] If the void volume of the electrode layer is 35% or more, both the energy density and power output of the battery are low. When the void volume of the electrode layer is between 10% and 35% or between 5% and 35%, the battery exhibits good diffusibility of lithium ions and high-output performance.

[0067] In some embodiments, the void volume of the cathode electrode layer is larger than the void volume of the anode electrode layer, or vice versa. In some embodiments, the void volume of the cathode electrode layer is equal to the void volume of the anode electrode layer. In certain embodiments, the difference between the void volume of the cathode electrode layer and the anode electrode layer is from about 1 % to about 30 %, from about 1% to about 25 %, from about 1 % to about 20 %, from about 1% to about 15 %, from about 1 % to about 10 %, from about 1 % to about 5 %, from about 5 % to about 20 %, from about 5 % to about 15 %, from about 10 % to about 20 %, or from about 10 % to about 15 %. In some embodiments, the difference between the void volume of the cathode electrode layer and the anode electrode layer is less than 30 %, less than 25 %, less than 20 %, less than 20 %, less than 15 %, less than 10 %, less than 5 %, or less than 1 %. In certain embodiments, the difference between the void volume of the cathode electrode layer and the anode electrode layer is at least 1 %, at least 5 %, at least 10 %, at least 15 %, at least 20 %, at least 25 %, or at least 30 %.

[0068] In some embodiments, the ratio of the void volume of the cathode electrode layer to the void volume of the anode electrode layer is from about 5:1 to about 1:5, from about 5:1 to about 1:4, from about 5:1 to about 1:3, from about 5:1 to about 1:2, from about 5:1 to about 1:1, from about 5:1 to about 2:1, from about 5:1 to about 3:1, from about 5:1 to about 4:1, from about 3:1 to about 1:3, from about 3:1 to about 1:1, from about 1:1 to about 1:3, from about 2:1 to about 1:2, from about 2:1 to about 1:1, or from about 1:1 to about 1:2. In certain embodiments, the ratio of the void volume of the cathode electrode layer to the void volume of the anode electrode layer is less than 5:1, less than 4:1, less than 3:1, less than 2:1, less than 1:1, less than

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1:2, less than 1:3, less than 1:4, or less than 1:5. In some embodiments, the ratio of the void volume of the cathode electrode layer to the void volume of the anode electrode layer is greater than 5:1, greater than 4:1, greater than 3:1, greater than 2:1, greater than 1:1, greater than 1:2, greater than 1:3, greater than 1:4, or greater than 1:5.

[0069] The current collector acts to collect electrons generated by electrochemical reactions of the active battery electrode material or to supply electrons required for the electrochemical reactions. In some embodiments, each of the current collectors of the positive and negative electrodes, which can be in the form of a foil, sheet or film, is independently stainless steel, titanium, nickel, aluminum, copper or electrically-conductive resin. In certain embodiments, the cathode current collector is an aluminum thin film. In some embodiments, the anode current collector is a copper thin film. In some embodiments, the current collector is not subjected surface treatment. In certain embodiments, the surface of the current collector does not comprise a coating.

[0070] In some embodiments, the current collector has a thickness from about 6 μm to about 100 μm. Thickness of the current collector will affect the volume occupied by the current collector within a battery and the amount of the electrode material and hence the capacity in the battery.

[0071] In certain embodiments, each of the cathode and anode current collectors independently has a surface roughness R_a from about 0.1 μm to about 5 μm, from about 0.1 μm to about 2.5 μm, from about 0.1 μm to about 2 μm, from about 0.1 μm to about 1.5 μm, from about 1 μm to about 3 μm, from about 0.1 μm to about 1 μm, from about 0.1 μm to about 0.5 μm, from about 1 μm to about 4 μm, from about 1 μm to about 2 μm, or from about 2.5 μm to about 5 μm. In some embodiments, each of the cathode and anode current collectors independently has a surface roughness R_a less than 5 μm, less than 4 μm, less than 3 μm, less than 2.5 μm, less than 2 μm, less than 1.5 μm, less than 1 μm, less than 0.5 μm, or less than 0.1 μm. In certain embodiments, each of the cathode and anode current collectors independently has a surface roughness R_a higher than 0.1 μm, higher than 0.2 μm, higher than 0.3 μm, higher than 0.4 μm, higher than 0.5 μm, higher than 1 μm, higher than 1.5 μm, higher than 2 μm, higher than 3 μm, higher than 4 μm, or higher than 5 μm.

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[0072] In some embodiments, each of the cathode and anode current collectors independently has a surface roughness R_z from about 0.1 μm to about 50 μm, from about 0.1 μm to about 40 μm, from about 0.1 μm to about 30 μm, from about 0.1 μm to about 25 μm, from about 0.1 μm to about 20 μm, from about 0.1 μm to about 15 μm, from about 0.1 μm to about 10 μm, from about 0.1 μm to about 9 μm, from about 0.1 μm to about 8 μm, from about 0.1 μm to about 7 μm, from about 0.1 μm to about 6 μm, from about 0.1 μm to about 5 μm, from about 0.1 μm to about 4 μm, from about 0.1 μm to about 3 μm, from about 0.1 μm to about 2 μm, from about 0.1 μm to about 1 μm, or from about 0.1 μm to about 0.5 μm. In certain embodiments, each of the cathode and anode current collectors independently has a surface roughness R_z less than 50 μm, less than 40 μm, less than 30 μm, less than 25 μm, less than 20 μm, less than 15 μm, less than 10 μm, less than 9 μm, less than 8 μm, less than 7 μm, less than 6 μm, less than 5 μm, less than 4 μm, less than 3 μm, less than 2 μm, less than 1 μm, less than 0.5 μm, or less than 0.1 μm. In some embodiments, each of the cathode and anode current collectors independently has a surface roughness R_z of at least 0.1 μm, at least 0.5 μm, at least 1 μm, at least 2 μm, at least 3 μm, at least 4 μm, at least 5 μm, at least 6 μm, at least 7 μm, at least 8 μm, at least 9 μm, at least 10 μm, at least 15 μm, at least 20 μm, at least 25 μm, or at least 30 μm.

[0073] In some embodiments, the surface roughness of the cathode current collector is larger than the surface roughness of the anode current collector, or vice versa. In some embodiments, the surface roughness of the cathode current collector is equal to the surface roughness of the anode current collector. In certain embodiments, the difference between the surface roughness R_a or R_z of the cathode current collector and the anode current collector is from about 0.01 μm to about 5 μm, from about 0.01 μm to about 4 μm, from about 0.01 μm to about 3 μm, from about 0.01 μm to about 2 μm, from about 0.01 μm to about 1 μm, from about 0.01 μm to about 0.5 μm, from about 0.01 μm to about 0.1 μm, from about 0.1 μm to about 2 μm, or from about 0.1 μm to about 1 μm. In some embodiments, the difference between the surface roughness R_a or R_z of the cathode current collector and the anode current collector is less than 5 μm, less than 4 μm, less than 3 μm, less than 2 μm, less than 1.5 μm, less than 1 μm, less than 0.5 μm, less than 0.4 μm, less than 0.3 μm, less than 0.2 μm, or less than 0.1 μm. In certain embodiments, the difference between the surface roughness R_a or R_z of the cathode current

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collector and the anode current collector is more than 0.1 μm, more than 0.5 μm, more than 1 μm, more than 2 μm, more than 3 μm, more than 4 μm, or more than 5 μm.

[0074] The thickness of the cathode and anode electrode layer on the current collector is less than 150 μm and less than 120 μm respectively. When this layer thickness is too thin (i.e., less than 30 μm), the amount of the electrode active material is insufficient, so that an intended battery performance is hardly obtained. On the other hand, when this layer thickness is too thick, the electrode layer is also easily peeled off. In certain embodiments, the thickness of each of the cathode and anode electrode layers on the current collector is independently from about 1 μm to about 200 μm, from about 10 μm to about 200 μm, from about 10 μm to about 150 μm, from about 10 μm to about 120 μm, from about 20 μm to about 100 μm, from about 30 μm to about 150 μm, from about 30 μm to about 120 μm, from about 1 μm to about 150 μm, from about 1 μm to about 120 μm, from about 1 μm to about 100 μm, from about 1 μm to about 50 μm, from about 1 μm to about 40 μm, from about 10 μm to about 40 μm, from about 10 μm to about 30 μm, from about 10 μm to about 25 μm, from about 20 μm to about 80 μm, from about 20 μm to about 60 μm, from about 50 μm about 100 μm, from about 50 μm to about 80 μm, or from about 25 μm to about 50 μm. In some embodiments, the thickness of the electrode layer on the current collector is less than 300 μm, less than 200 μm, less than 100 μm, less than 90 μm, less than 80 μm, less than 70 μm, less than 60 μm, less than 50 μm, less than 40 μm, or less than 30 μm. In certain embodiments, the thickness of the electrode layer on the current collector is at least 10 μm, at least 20 μm, at least 30 μm, at least 40 μm, at least 50 μm, at least 60 μm, at least 70 μm, at least 80 μm, at least 90 μm, at least 100 μm, at least 110 μm, at least 120 μm, at least 130 μm, at least 140 μm, or at least 150 μm. In certain embodiments, the thickness of the electrode layer on the current collector is about 10 μm, about 15 μm, about 20 μm, about 25 μm, about 30 μm, about 35 μm, or about 40 μm.

[0075] In some embodiments, the thickness of the cathode electrode layer is larger than the thickness of the anode electrode layer, or vice versa. In some embodiments, the thickness of the cathode electrode layer is equal to the thickness of the anode electrode layer. In some embodiments, the difference in thickness between the cathode electrode layer and the anode electrode layer is from about 1 μm to about 100 μm, from about 1 μm to about 50 μm, from

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about 1 μm to about 40 μm, from about 1 μm to about 30 μm, from about 1 μm to about 20 μm, from about 1 μm to about 10 μm, from about 1 μm to about 5 μm, from about 5 μm to about 30 μm, from about 5 μm to about 25 μm, from about 5 μm to about 20 μm, from about 5 μm to about 15 μm, from about 5 μm to about 10 μm, from about 10 μm to about 20 μm, or from about 10 μm to about 15 μm. In certain embodiments, the difference in thickness between the cathode electrode layer and the anode electrode layer is less than 50 μm, less than 40 μm, less than 30 μm, less than 25 μm, less than 20 μm, less than 15 μm, less than 10 μm, less than 5 μm, or less than 1 μm. In some embodiments, the difference in thickness between the cathode electrode layer and the anode electrode layer is at least 1 μm, at least 5 μm, at least 10 μm, at least 15 μm, at least 20 μm, at least 25 μm, or at least 30 μm.

[0076] In certain embodiments, the density of each of the cathode and anode electrode layers on the current collector is independently from about 1.0 g/cm^3 to about 6.5 g/cm^3, from about 1.0 g/cm^3 to about 5.0 g/cm^3, from about 1.0 g/cm^3 to about 4.0 g/cm^3, from about 1.0 g/cm^3 to about 3.5 g/cm^3, from about 1.0 g/cm^3 to about 3.0 g/cm^3, from about 1.0 g/cm^3 to about 2.0 g/cm^3, from about 2.0 g/cm^3 to about 5.0 g/cm^3, from about 2.0 g/cm^3 to about 4.0 g/cm^3, from about 3.0 g/cm^3 to about 5.0 g/cm^3, or from about 3.0 g/cm^3 to about 6.0 g/cm^3. In some embodiments, the density of each of the cathode and anode electrode layers on the current collector is independently less than 6.5 g/cm^3, less than 6 g/cm^3, less than 5 g/cm^3, less than 4 g/cm^3, less than 3 g/cm^3, less than 2 g/cm^3, or less than 1 g/cm^3. In certain embodiments, the density of each of the cathode and anode electrode layers on the current collector is independently at least 1 g/cm^3, at least 2 g/cm^3, at least 3 g/cm^3, at least 4 g/cm^3, at least 5 g/cm^3, at least 6 g/cm^3, or at least 6.5 g/cm^3. Similarly, an increase in the density of the electrode layer will result in a reduction of void volume in the final electrode coating and a denser electrode, thereby achieving desired battery capacity.

[0077] In some embodiments, the density of the cathode electrode layer is larger than the density of the anode electrode layer, or vice versa. In some embodiments, the density of the cathode electrode layer is equal to the density of the anode electrode layer. In certain embodiments, the difference in density between the cathode electrode layer and the anode electrode layer is from about 0.1 g/cm^3 to about 5 g/cm^3, from about 0.1 g/cm^3 to about 4 g/cm^3,

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from about 0.1 g/cm^3 to about 3 g/cm^3, from about 0.1 g/cm^3 to about 2 g/cm^3, from about 0.1 g/cm^3 to about 1 g/cm^3, from about 0.1 g/cm^3 to about 0.5 g/cm^3, from about 1 g/cm^3 to about 5 g/cm^3, from about 1 g/cm^3 to about 4 g/cm^3, from about 1 g/cm^3 to about 3 g/cm^3, from about 1 g/cm^3 to about 2 g/cm^3, or from about 2 g/cm^3 to about 4 g/cm^3. In some embodiments, the difference in density between the cathode electrode layer and the anode electrode layer is less than 5 g/cm^3, less than 4 g/cm^3, less than 3 g/cm^3, less than 2 g/cm^3, less than 1 g/cm^3, less than 0.5 g/cm^3, or less than 0.1 g/cm^3. In certain embodiments, the difference in density between the cathode electrode layer and the anode electrode layer is at least 0.1 g/cm^3, at least 0.5 g/cm^3, at least 1 g/cm^3, at least 2 g/cm^3, at least 3 g/cm^3, at least 4 g/cm^3, or at least 5 g/cm^3.

[0078] In some embodiments, the cathode material is selected from the group consisting of $LiCoO_2$ (LCO), $LiNiO_2$ (LNO), $LiNi_xMn_yO_2$, $Li_{1+z}Ni_xMn_yCo_{1-x-y}O_2$, $LiNi_xCo_yAl_zO_2$, LiV_2O_5, $LiTiS_2$, $LiMoS_2$, $LiMnO_2$, $LiCrO_2$, $LiMn_2O_4$ (LMO), $LiFeO_2$, $LiFePO_4$ (LFP), $LiNi_{0.5}Mn_{1.5}O_4$, $LiNi_{0.4}Mn_{1.6}O_4$, and combinations thereof, wherein each x is independently from 0.3 to 0.8; each y is independently from 0.1 to 0.45; and each z is independently from 0 to 0.2. In certain embodiments, the cathode material is selected from the group consisting of $LiCoO_2$, $LiNiO_2$, $LiNi_xMn_yO_2$, $Li_{1+z}Ni_xMn_yCo_{1-x-y}O_2$, $LiNi_xCo_yAl_zO_2$, LiV_2O_5, $LiTiS_2$, $LiMoS_2$, $LiMnO_2$, $LiCrO_2$, $LiMn_2O_4$, $LiFeO_2$, $LiFePO_4$, $LiNi_{0.5}Mn_{1.5}O_4$, $LiNi_{0.4}Mn_{1.6}O_4$, 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 material is not $LiCoO_2$, $LiNiO_2$, LiV_2O_5, $LiTiS_2$, $LiMoS_2$, $LiMnO_2$, $LiCrO_2$, $LiMn_2O_4$, $LiFeO_2$, $LiFePO_4$, $LiNi_{0.5}Mn_{1.5}O_4$, or $LiNi_{0.4}Mn_{1.6}O_4$. In further embodiments, the cathode material is not $LiNi_xMn_yO_2$, $Li_{1+z}Ni_xMn_yCo_{1-x-y}O_2$, or $LiNi_xCo_yAl_zO_2$, wherein each x is independently from 0.3 to 0.8; each y is independently from 0.1 to 0.45; and each z is independently from 0 to 0.2.

[0079] In certain embodiments, the anode material is selected from the group consisting of natural graphite particulate, synthetic graphite particulate, Sn (tin) particulate, $Li_4Ti_5O_{12}$ particulate, Si (silicon) particulate, Si-C composite particulate, and combinations thereof. In other embodiments, the anode material is not natural graphite particulate, synthetic graphite particulate, Sn (tin) particulate, $Li_4Ti_5O_{12}$ particulate, Si (silicon) particulate, or Si-C composite particulate.

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[0080] In some embodiments, the amount of each of the cathode and anode materials is independently at least 50%, at least 55%, at least 60%, at least 65%, at least 70%, at least 75%, at least 80%, at least 81%, at least 82%, at least 83%, at least 84%, at least 85%, at least 86%, at least 87%, at least 88%, at least 89%, at least 90%, at least 91%, at least 92%, at least 93%, at least 94%, or at least 95% by weight, based on the total weight of the cathode or anode electrode layer. In certain embodiments, the amount of each of the cathode and anode materials is independently at most 50%, at most 55%, at most 60%, at most 65%, at most 70%, at most 75%, at most 80%, at most 81%, at most 82%, at most 83%, at most 84%, at most 85%, at most 86%, at most 87%, at most 88%, at most 89%, at most 90%, at most 91%, at most 92%, at most 93%, at most 94%, or at most 95% by weight, based on the total weight of the cathode or anode electrode layer.

[0081] In certain embodiments, the conductive agent is selected from the group consisting of carbon, carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibres, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, mesoporous carbon, and combinations thereof. In some embodiments, the conductive agent is not carbon, carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibres, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, or mesoporous carbon. In certain embodiments, the conductive agent is not subjected to a pre-treatment. In some embodiments, the conductive agent is not pretreated by an acid or a base.

[0082] In some embodiments, the amount of the conductive agent in each of the cathode and anode electrode layers is independently at least 1%, at least 2%, at least 3%, at least 4%, at least 5%, at least 6%, at least 7%, at least 8%, at least 9%, at least 10%, at least 15%, at least 20%, at least 25%, at least 30%, at least 35%, at least 40%, at least 45%, or at least 50% by weight, based on the total weight of the cathode or anode electrode layer. In certain embodiments, the amount of the conductive agent in each of the cathode and anode electrode layers is independently at most 1%, at most 2%, at most 3%, at most 4%, at most 5%, at most 6%, at most 7%, at most 8%, at most 9%, at most 10%, at most 15%, at most 20%, at most 25%,

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at most 30%, at most 35%, at most 40%, at most 45%, or at most 50% by weight, based on the total weight of the cathode or anode electrode layer.

[0083] In certain embodiments, the amount of the conductive agent in each of the cathode and anode electrode layers is independently from about 0.05 wt.% to about 0.5 wt.%, from about 0.1 wt.% to about 1 wt.%, from about 0.25 wt.% to about 2.5 wt.%, from about 0.5 wt.% to about 5 wt.%, from about 2 wt.% to about 5 wt.%, from about 3 wt.% to about 7 wt.%, or from about 5 wt.% to about 10 wt.%, based on the total weight of the cathode or anode electrode layer.

[0084] After assembling the electrode assembly, the electrode assembly is placed into a drying chamber. In some embodiments, the drying chamber is connected to a vacuum pump, so that the pressure in the chamber can be reduced. The pressure is reduced sufficiently so as to lower the boiling point of water. The drying time can therefore be considerably reduced. In certain embodiments, the drying chamber is connected to a central vacuum supply, thereby allowing several vacuum drying ovens to be operated simultaneously. In some embodiments, the number of vacuum drying ovens connected to a central vacuum supply ranges from 1 to 20 depending on the number of pumps operated. In certain embodiments, a vacuum pump or central vacuum supply is connected to the drying chamber by a suction line equipped with a gas outlet valve. In some embodiments, the drying chamber is also connected to a gas reservoir containing dry air or inert gas by a duct equipped with a gas inlet valve. When the gas outlet valve is closed and the gas inlet valve is opened, vacuum is lost in the drying chamber. The valve might be of a solenoid or needle type or a mass flow controller. Any devices allowing an appropriate flow adjustment might be used.

[0085] To reduce the power required for the pumps, a condenser can be provided between the drying chamber and the pump. The condenser condenses out water vapor, which is then separated.

[0086] The present invention comprises drying the electrode assembly with at least two drying stages, namely, the first stage and the second stage. The electrode assembly disclosed herein is progressively dried in at least two successive stages, in which the temperature of the first stage being lower than the temperature in any of the subsequent stages.

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[0087] The temperature in the first stage can be within the range of 50 °C to 90 °C. A partially-dried electrode assembly is obtained from the first stage. In certain embodiments, the electrode assembly can be dried under vacuum in the first stage at a temperature from about 50 °C to about 90 °C, from about 50 °C to about 85 °C, from about 50 °C to about 80 °C, from about 60 °C to about 90 °C, from about 60 °C to about 85 °C, from about 60 °C to about 80 °C, or from about 70 °C to about 90 °C. In some embodiments, the electrode assembly can be dried under vacuum in the first stage at a temperature of about 50 °C or higher, about 60 °C or higher, about 70 °C or higher, or about 80 °C or higher. In certain embodiments, the electrode assembly can be dried under vacuum in the first stage at a temperature of less than 90 °C, less than 85 °C, less than 80 °C, less than 75 °C, less than 70 °C, less than 65 °C, less than 60 °C, less than 55 °C, or less than 50 °C.

[0088] A lower temperature in the first stage is beneficial to slow drying to avoid crack or embrittlement of the electrode layer. Surface of the electrode layer should dry out slowly to reduce possibility of surface cracking since the interior of the electrode layer dries slower than the surface of the electrode layer.

[0089] The drying time for the first stage can be in the range of about 5 minutes to about 4 hours. In some embodiments, the time period for drying the electrode assembly under vacuum in the first stage is from about 5 minutes to about 4 hours, from about 5 minutes to about 3 hours, from about 5 minutes to about 2 hours, from about 5 minutes to about 1 hour, from about 10 minutes to about 2 hours, from about 15 minutes to about 2 hours, from about 15 minutes to about 1 hour, from about 30 minutes to about 4 hours, from about 30 minutes to about 3 hours, from about 30 minutes to about 2 hours, from about 30 minutes to about 1 hour, from about 1 hour to about 4 hours, from about 1 hour to about 3 hours, or from about 1 hour to about 2 hours. In some embodiments, the time period for drying the electrode assembly under vacuum in the first stage is from about 5 minutes to about 2 hours, or from about 15 minutes to about 30 minutes.

[0090] The temperature in the second stage can be within the range of 80 °C to 155 °C. In certain embodiments, the electrode assembly can be dried under vacuum in the second stage at a temperature from about 70 °C to about 155 °C, from about 80 °C to about 155 °C, from

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about 90 °C to about 155 °C, from about 100 °C to about 155 °C, from about 100 °C to about 140 °C, from about 100 °C to about 130 °C, from about 100 °C to about 120 °C, from about 100 °C to about 110 °C, or from about 110 °C to about 130 °C. In certain embodiments, the electrode assembly can be dried under vacuum in the second stage at a temperature from about 80 °C to about 155 °C. In some embodiments, the electrode assembly can be dried under vacuum in the second stage at a temperature of about 80 °C or higher, about 90 °C or higher, about 100 °C or higher, about 110 °C or higher, about 120 °C or higher, about 130 °C or higher, about 140 °C or higher, or about 150 °C or higher. In certain embodiments, the electrode assembly can be dried under vacuum in the second stage at a temperature of less than 155 °C, less than 150 °C, less than 145 °C, less than 140 °C, less than 135 °C, less than 130 °C, less than 125 °C, less than 120 °C, less than 115 °C, less than 110 °C, less than 105 °C, less than 100 °C, or less than 90 °C.

[0091] The drying time of the second stage can be in the range of about 15 minutes to about 4 hours. In some embodiments, the time period for drying the electrode assembly under vacuum in the second stage is from about 15 minutes to about 3 hours, from about 15 minutes to about 2 hours, from about 15 minutes to about 1 hour, from about 15 minutes to about 30 minutes, from about 30 minutes to about 4 hours, from about 30 minutes to about 3 hours, from about 30 minutes to about 2 hours, from about 30 minutes to about 1 hour, from about 1 hour to about 4 hours, from about 1 hour to about 3 hours, from about 1 hour to about 2 hours, from about 2 hours to about 4 hours, or from about 2 hours to about 3 hours. In some embodiments, the time period for drying the electrode assembly under vacuum in the second stage is from about 5 minutes to about 2 hours, or from about 15 minutes to about 30 minutes.

[0092] Any vacuum pumps that can reduce the pressure of the drying chamber can be used herein. Some non-limiting examples of the vacuum pumps include dry vacuum pumps, turbo pumps, rotary vane vacuum pumps, cryogenic pumps, and sorption pumps.

[0093] In some embodiments, the vacuum pump is an oil free pump. The oil free pump operates without the need for oil in the pump parts which are exposed to gases being pumped, or partial vacuum. Thus, any gases backstreaming through the pump are free from oil vapour. Progressive oil vapour deposited on surfaces of the electrode assembly may reduce the

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electrochemical performance of a battery. An example of such pump is a diaphragm vacuum pump.

[0094] In certain embodiments, high vacuum can be achieved by using a two-stage pumping system to evacuate the drying chamber. The pumping system comprises a primary vacuum pump such as a rotary pump or diaphragm pump arranged in series with a high vacuum pump such as a turbo-molecular pump.

[0095] In some embodiments, the electrode assembly is dried under atmospheric pressure. In certain embodiments, the drying is performed in a vacuum state. In further embodiments, the vacuum state is maintained at a pressure within the range from about 1×10^{-1} Pa to about 1×10^{-4} Pa, from about 10 Pa to about 1×10^{-1} Pa, from about 1×10^{3} Pa to about 10 Pa, or from about 2.5×10^{4} Pa to about 1×10^{3} Pa. In still further embodiments, the vacuum state is at a pressure of about 1×10^{3} Pa, about 2×10^{3} Pa, about 5×10^{3} Pa, about 1×10^{4} Pa, or about 2×10^{4} Pa.

[0096] After a predetermined drying time period, the drying chamber vents directly to a gas reservoir containing dry air or inert gas via a gas inlet valve. In some embodiments, the gas reservoir is a nitrogen gas cylinder. In certain embodiments, the inert gas is selected from the group consisting of helium, argon, neon, krypton, xenon, nitrogen, carbon dioxide, and combinations thereof. In some embodiments, the water content of the dry air or inert gas is maintained less than or equal to 10 ppm, less than or equal to 8 ppm, less than or equal to 5 ppm, less than or equal to 4 ppm, less than or equal to 3 ppm, less than or equal to 2 ppm, or less than or equal to 1 ppm.

[0097] In certain embodiments, the gas filling step is performed after the second drying stage by filling the drying chamber with dry air or inert gas. In other embodiments, the gas filling step is performed after the first and second drying stages by filling the drying chamber with dry air or inert gas.

[0098] In some embodiments, the dry air or inert gas is preheated before entering the drying chamber. In certain embodiments, the temperature of the dry air or inert gas is from about 70 °C to about 130 °C, from about 70 °C to about 110 °C, from about 70 °C to about 100 °C, from about 70 °C to about 90 °C, from about 70 °C to about 80 °C, from about 80 °C to about

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155 °C, from about 80 °C to about 120 °C, from about 80 °C to about 100 °C, from about 90 °C to about 155 °C, from about 90 °C to about 130 °C, from about 90 °C to about 100 °C, from about 70 °C to about 155 °C, from about 100 °C to about 130 °C, or from about 100 °C to about 120 °C. In some embodiments, the dry air or inert gas is preheated to a temperature from about 70 °C to about 155 °C before entering the drying chamber.

[0099] In certain embodiments, the dry air or inert gas stays in the drying chamber for a time period from about 30 seconds to about 2 hours, from about 1 minute to about 1 hour, from about 5 minutes to about 30 minutes, from about 5 minutes to about 15 minutes, from about 5 minutes to about 10 minutes, from about 10 minutes to about 30 minutes, from about 10 minutes to about 20 minutes, from about 10 minutes to about 15 minutes, from about 15 minutes to about 1 hour, from about 15 minutes to about 30 minutes, from about 15 minutes to about 20 minutes, or from about 30 minutes to about 1 hour. In some embodiments, the dry air or inert gas stays in the drying chamber for a time period from about 30 seconds to about 2 hours, from about 5 minutes to about 2 hours, or from about 15 minutes to about 30 minutes.

[00100] In some embodiments, the electrode assembly can be further dried under vacuum after incubating the electrode assembly with the dry gas for a predetermined time. This procedure can be repeated as many times as required to reduce the moisture content of the electrode assembly to an appropriate level. In certain embodiments, this procedure can be repeated around 2 to 50 times until the moisture content in the electrode assembly is less than 40 ppm, less than 30 ppm, less than 20 ppm, less than 15 ppm, less than 10 ppm, or less than 5 ppm by weight, based on the total weight of the dried electrode assembly.

[00101] In certain embodiments, the steps of vacuum drying and gas filling can be repeated at least 2 times, at least 3 times, at least 4 times, at least 5 times, at least 6 times, at least 7 times, at least 8 times, at least 9 times, at least 10 times, at least 12 times, at least 14 times, at least 16 times, at least 18 times, at least 20 times, at least 22 times, at least 24 times, at least 26 times, at least 28 times, or at least 30 times. In some embodiments, the steps of vacuum drying and gas filling can be repeated between 2 and 50 times, between 2 and 30 times, between 2 and 20 times, between 2 and 10 times, between 5 and 30 times, between 5 and 20 times, or between

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5 and 10 times. In certain embodiments, the steps of vacuum drying and gas filling can be repeated between 2 or more times.

[00102] In some embodiments, the process for drying the electrode assembly comprises vacuum drying, followed by hot air drying. In some embodiments, the drying chamber blows hot air toward the electrode assembly from above and/or underneath. In certain embodiments, the hot air drying is performed at an air velocity from about 1 meter/second to about 50 meters/second, from about 1 meter/second to about 40 meters/second, from about 1 meter/second to about 30 meters/second, from about 1 meter/second to about 20 meters/second, from about 1 meter/second to about 10 meters/second, from about 10 meters/second to about 50 meters/second, from about 10 meters/second to about 40 meters/second, from about 10 meters/second to about 30 meters/second, from about 10 meters/second to about 20 meters/second, from about 20 meters/second to about 30 meters/second, from about 30 meters/second to about 40 meters/second, or from about 40 meters/second to about 50 meters/second. In other embodiments, a heated inert gas (i.e., helium, argon) is used instead of heated air.

[00103] The drying gas might be preheated through heat exchange surfaces. In some embodiments, the temperature of the hot air ranges from about 50 °C to about 155 °C, from about 60 °C to about 150 °C, from about 80 °C to about 150 °C, from about 100 °C to about 150 °C, from about 70 °C to about 150 °C, from about 70 °C to about 130 °C, from about 70 °C to about 100 °C, from about 80 °C to about 150 °C, from about 80 °C to about 130 °C, from about 80 °C to about 110 °C, from about 100 °C to about 140 °C, or from about 100 °C to about 120 °C.

[00104] In certain embodiments, the time period for hot air drying is from about 1 minute to about 2 hours, from about 1 minute to about 1 hour, from about 1 minute to about 30 minutes, from about 1 minute to about 15 minutes, from about 5 minutes to about 30 minutes, from about 5 minutes to about 20 minutes, from about 5 minute to about 15 minutes, from about 5 minutes to about 10 minutes, from about 10 minutes to about 1 hour, from about 10 minutes to about 30 minutes, from about 10 minutes to about 20 minutes, from about 15 minutes to about 1 hour, or from about 15 minutes to about 30 minutes.

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[00105] In some embodiments, the electrode assembly can be further dried under vacuum after blowing hot air for a predetermined time. This procedure can be repeated as many times as required to reduce the moisture content of the electrode assembly to an appropriate level, such as 40 ppm, 30 ppm, 20 ppm, 19 ppm, 18 ppm, 17 ppm, 16 ppm, 15 ppm, 14 ppm, 13 ppm, 12 ppm, 11 ppm, 10 ppm, 9 ppm, 8 ppm, 7 ppm, 6 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, or 1 ppm by weight, based on the total weight of the electrode assembly.

[00106] Currently, water is the key factor needed to be strictly controlled in the organic-based production process of lithium-ion batteries. The advantages of the present invention is that most of the fabrication can take place outside a dry room. In some embodiments, the assembling process can take place outside a dry room or a glove box. In certain embodiments, only the step for filling electrolyte or both the steps for drying the electrode assembly and filing electrolyte are carried out in a dry room or a glove box. Thus, humidity control in the factory can be avoided, significantly lowering the investment cost.

[00107] The presence of moisture is detrimental to the operation of a battery. Generally, water content in the electrode assembly prepared by conventional methods contains an amount of water greater than 100 ppm by weight, based on the total weight of the electrode assembly. Even if the initial battery performance is acceptable, the rate of deterioration of the battery performance may be unacceptable. To be able to achieve sufficiently high battery performance, it would therefore be advantageous to have a low water content in the battery.

[00108] In some embodiments, the water content of the undried electrode assembly is greater than 100 ppm, greater than 200 ppm, greater than 300 ppm, greater than 400 ppm, greater than 500 ppm, greater than 1,000 ppm, greater than 2,000 ppm, greater than 3,000 ppm, greater than 4,000 ppm, greater than 5,000 ppm, or greater than 10,000 ppm by weight, based on the total weight of the undried electrode assembly.

[00109] The electrode assembly prepared by the method disclosed herein has a particularly low water content, contributing to reliable performance of the lithium-ion batteries. In some embodiments, the water content in the dried electrode assembly is from about 5 ppm to about 50 ppm, from about 5 ppm to about 40 ppm, from about 5 ppm to about 30 ppm, from about 5 ppm to about 20 ppm, from about 5 ppm to about 10 ppm, from about 3 ppm to about 30

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ppm, from about 3 ppm to about 20 ppm, or from about 3 ppm to about 10 ppm by weight, based on the total weight of the dried electrode assembly.

[00110] In certain embodiments, the water content in the dried electrode assembly is less than 50 ppm, less than 40 ppm, less than 30 ppm, less than 20 ppm, less than 19 ppm, less than 18 ppm, less than 17 ppm, less than 16 ppm, less than 15 ppm, less than 14 ppm, less than 13 ppm, less than 12 ppm, less than 11 ppm, less than 10 ppm, less than 9 ppm, less than 8 ppm, less than 7 ppm, less than 6 ppm, less than 5 ppm, less than 4 ppm, less than 3 ppm, less than 2 ppm, or less than 1 ppm by weight, based on the total weight of the dried electrode assembly. In some embodiments, the dried electrode assembly disclosed herein has a water concentration therein no greater than about 5 ppm by weight, based on the total weight of the dried electrode assembly.

[00111] In some embodiments, the dried electrode assembly comprises at least one dried anode and at least one dried cathode, wherein the at least one dried anode and at least one dried cathode have a water content of less than 50 ppm, less than 40 ppm, less than 30 ppm, less than 20 ppm, less than 19 ppm, less than 18 ppm, less than 17 ppm, less than 16 ppm, less than 15 ppm, less than 14 ppm, less than 13 ppm, less than 12 ppm, less than 11 ppm, less than 10 ppm, less than 9 ppm, less than 8 ppm, less than 7 ppm, less than 6 ppm, less than 5 ppm, less than 4 ppm, less than 3 ppm, less than 2 ppm, or less than 1 ppm by weight, based on the total weight of the at least one dried anode and at least one dried cathode.

[00112] In certain embodiments, each of the at least one dried cathode and at least one dried anode independently has a water content less than 50 ppm, less than 40 ppm, less than 30 ppm, less than 20 ppm, less than 19 ppm, less than 18 ppm, less than 17 ppm, less than 16 ppm, less than 15 ppm, less than 14 ppm, less than 13 ppm, less than 12 ppm, less than 11 ppm, less than 10 ppm, less than 9 ppm, less than 8 ppm, less than 7 ppm, less than 6 ppm, or less than 5 ppm by weight, based on the total weight of the at least one dried cathode or at least one dried anode.

[00113] In certain embodiments, the dried electrode assembly comprises at least one dried separator, wherein the at least one dried separator has a water content of less than 50 ppm, less than 40 ppm, less than 30 ppm, less than 20 ppm, less than 19 ppm, less than 18 ppm, less than

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17 ppm, less than 16 ppm, less than 15 ppm, less than 14 ppm, less than 13 ppm, less than 12 ppm, less than 11 ppm, less than 10 ppm, less than 9 ppm, less than 8 ppm, less than 7 ppm, less than 6 ppm, or less than 5 ppm by weight, based on the total weight of the at least one dried separator.

[00114] The peeling strength of the electrode coating layer has been conventionally increased by increasing the amount of binder in the coating layer. However, increase in the amount of binder naturally leads to decrease in the amount of the electrode active material in the electrode coating layer, thereby decreasing the battery capacity per unit weight. By performing a two-stage drying process, a practically sufficient peeling strength is obtained.

[00115] The present invention comprises drying the electrode assembly with two drying stages, the first stage and the second stage, in which the temperature of the first stage is lower than the temperature of the second stage. A lower temperature in the first stage prevents rapid loss of surface moisture and increases product quality by virtually eliminating non-uniformity in drying. If drying is too rapid or the temperature is too high, this can cause uneven drying and may make the electrode layer to shrink unevenly, thereby causing a reduction in electrode peeling strength.

[00116] No prior art document discloses a drying method that describes the relation between a binder composition and an electrode peeling strength. The two-stage drying process is particularly suitable for electrodes comprising aqueous binders. Binders make up only a small part of the electrode composition, but in some cases, they play an important role in affecting the battery performance such as cycling stability and rate capability of lithium-ion batteries. Aqueous binders are greener and easier to be used for electrode fabrication. However, water-based binder such as carboxymethyl cellulose (CMC) is considered a brittle binder, which breaks after little deformation. If drying is too rapid or the temperature is too high, the aqueous binder is likely to become brittle, resulting in a brittle electrode. If the binding strength between electrode layers and current collector is insufficient, the electrode in a rolled electrode assembly will easily detach from the current collector, affecting the performance of a battery.

[00117] High electrode peeling strength requires large amount of binder. However, this may reduce the amount of electrode material in the electrode layer. Therefore, the drying process

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has a strong effect on the peeling strength of the electrode. In some embodiments, the at least one dried cathode comprises a cathode current collector and a dried cathode electrode layer and the at least one dried anode comprises an anode current collector and a dried anode electrode layer, wherein each of the peeling strength of the dried cathode electrode layer from the cathode current collector and dried anode electrode layer from the anode current collector is independently 0.05 N/cm or more, 0.1 N/cm or more, 0.15 N/cm or more, 0.2 N/cm or more, 0.25 N/cm or more, 0.3 N/cm or more, 0.35 N/cm or more, 0.4 N/cm or more, 0.5 N/cm or more, 0.6 N/cm or more, 0.7 N/cm or more, or 0.75 N/cm or more. In certain embodiments, the peeling strength of the dried cathode electrode layer from the cathode current collector and dried anode electrode layer from the anode current collector is independently less than 0.75 N/cm, less than 0.7 N/cm, less than 0.6 N/cm, less than 0.5 N/cm, less than 0.4 N/cm, less than 0.35 N/cm, less than 0.3 N/cm, less than 0.25 N/cm, less than 0.2 N/cm, or less than 0.15 N/cm. In certain embodiments, the peeling strength of the dried cathode electrode layer from the cathode current collector and dried anode electrode layer from the anode current collector is independently between 0.05 N/cm and 0.75 N/cm, between 0.05 N/cm and 0.6 N/cm, between 0.05 N/cm and 0.5 N/cm, between 0.1 N/cm and 0.5 N/cm, between 0.1 N/cm and 0.45 N/cm, between 0.1 N/cm and 0.4 N/cm, between 0.1 N/cm and 0.35 N/cm, between 0.1 N/cm and 0.3 N/cm, between 0.1 N/cm and 0.25 N/cm, between 0.1 N/cm and 0.2 N/cm, between 0.1 N/cm and 0.15 N/cm, between 0.15 N/cm and 0.5 N/cm, between 0.15 N/cm and 0.45 N/cm, between 0.15 N/cm and 0.4 N/cm, between 0.15 N/cm and 0.35 N/cm, between 0.15 N/cm and 0.3 N/cm, between 0.15 N/cm and 0.25 N/cm, between 0.15 N/cm and 0.2 N/cm, between 0.2 N/cm and 0.6 N/cm, between 0.2 N/cm and 0.5 N/cm, between 0.2 N/cm and 0.4 N/cm, or between 0.2 N/cm and 0.3 N/cm.

[00118] In certain embodiments, the peeling strength of the dried cathode is larger than the peeling strength of the dried anode, or vice versa. In certain embodiments, the peeling strength of the dried cathode is equal to the peeling strength of dried anode. In some embodiments, the difference between the peeling strength of the dried cathode and the dried anode is from about 0.01 N/cm to about 1 N/cm, from about 0.01 N/cm to about 0.8 N/cm, from about 0.01 N/cm to about 0.6 N/cm, from about 0.01 N/cm to about 0.5 N/cm, from about 0.01 N/cm to about 0.4 N/cm, from about 0.01 N/cm to about 0.3 N/cm, from about 0.01 N/cm to

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about 0.2 N/cm, from about 0.01 N/cm to about 0.1 N/cm, from about 0.01 N/cm to about 0.05 N/cm, from about 0.1 N/cm to about 0.5 N/cm, from about 0.1 N/cm to about 0.4 N/cm, from about 0.1 N/cm to about 0.3 N/cm, from about 0.1 N/cm to about 0.2 N/cm, from about 0.2 N/cm to about 0.6 N/cm, from about 0.2 N/cm to about 0.5 N/cm, from about 0.2 N/cm to about 0.4 N/cm, from about 0.2 N/cm to about 0.3 N/cm, or from about 0.3 N/cm to about 0.6 N/cm. In certain embodiments, the difference between the peeling strength of the dried cathode and the dried anode is less than 1 N/cm, less than 0.9 N/cm, less than 0.8 N/cm, less than 0.7 N/cm, less than 0.6 N/cm, less than 0.5 N/cm, less than 0.4 N/cm, less than 0.3 N/cm, less than 0.2 N/cm, less than 0.1 N/cm, less than 0.05 N/cm, or less than 0.01 N/cm. In some embodiments, the difference in peeling strength of the dried cathode and the dried anode is more than 0.01 N/cm, more than 0.05 N/cm, more than 0.1 N/cm, more than 0.2 N/cm, more than 0.3 N/cm, more than 0.4 N/cm, more than 0.5 N/cm, more than 0.6 N/cm, more than 0.7 N/cm, more than 0.8 N/cm, more than 0.9 N/cm, or more than 1 N/cm.

[00119] In certain embodiments, the ratio of the peeling strength of the dried cathode to the peeling strength of the dried anode is from about 10:1 to about 1:10, from about 10:1 to about 1:5, from about 10:1 to about 1:1, from about 10:1 to about 1:2, from about 10:1 to about 1:4, from about 10:1 to about 1:6, from about 10:1 to about 1:8, from about 5:1 to about 1:5, from about 5:1 to about 1:3, from about 5:1 to about 1:1, from about 5:1 to about 1:3, from about 2:1 to about 1:2, or from about 2:1 to about 1:1. In some embodiments, the ratio of the peeling strength of the dried cathode to the peeling strength of the dried anode is less than 10:1, less than 8:1, less than 6:1, less than 4:1, less than 2:1, less than 1:1, less than 1:2, less than 1:4, less than 1:6, less than 1:8, or less than 1:10. In certain embodiments, the ratio of the peeling strength of the dried cathode to the peeling strength of the dried anode is greater than 10:1, greater than 8:1, greater than 6:1, greater than 4:1, greater than 2:1, greater than 1:1, greater than 1:2, greater than 1:4, greater than 1:6, greater than 1:8, or greater than 1:10.

[00120] In some embodiments, the cathode and/or anode electrode peeling strength remains more or less unchanged after drying. Values of peeling strength of cathode and anode are measured before and after drying. In certain embodiments, the difference in peeling strength between the undried and dried cathodes is from about 0.001 N/cm to about 0.1 N/cm, from about

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0.001 N/cm to about 0.8 N/cm, from about 0.001 N/cm to about 0.6 N/cm, from about 0.001 N/cm to about 0.4 N/cm, from about 0.001 N/cm to about 0.2 N/cm, from about 0.001 N/cm to about 0.1 N/cm, from about 0.001 N/cm to about 0.05 N/cm, from 0.001 N/cm to about 0.04 N/cm, from about 0.001 N/cm to about 0.03 N/cm, from about 0.001 N/cm to about 0.02 N/cm, or from about 0.001 N/cm to about 0.01 N/cm. In some embodiments, the difference in peeling strength between the undried and dried cathodes is less than 0.1 N/cm, less than 0.08 N/cm, less than 0.06 N/cm, less than 0.04 N/cm, less than 0.02 N/cm, or less than 0.01 N/cm. In certain embodiments, the difference in peeling strength between the undried and dried cathodes is at least 0.001 N/cm, at least 0.005 N/cm, at least 0.01 N/cm, at least 0.02 N/cm, at least 0.03 N/cm, at least 0.04 N/cm, at least 0.05 N/cm, or at least 0.1 N/cm.

[00121] In certain embodiments, the difference in peeling strength between the undried and dried anodes is from about 0.001 N/cm to about 0.1 N/cm, from about 0.001 N/cm to about 0.8 N/cm, from about 0.001 N/cm to about 0.6 N/cm, from about 0.001 N/cm to about 0.4 N/cm, from about 0.001 N/cm to about 0.2 N/cm, from about 0.001 N/cm to about 0.1 N/cm, from about 0.001 N/cm to about 0.05 N/cm, from 0.001 N/cm to about 0.04 N/cm, from about 0.001 N/cm to about 0.03 N/cm, from about 0.001 N/cm to about 0.02 N/cm, or from about 0.001 N/cm to about 0.01 N/cm. In some embodiments, the difference in peeling strength between the undried and dried anodes is less than 0.1 N/cm, less than 0.08 N/cm, less than 0.06 N/cm, less than 0.04 N/cm, less than 0.02 N/cm, or less than 0.01 N/cm. In certain embodiments, the difference in peeling strength between the undried and dried anodes is at least 0.001 N/cm, at least 0.005 N/cm, at least 0.01 N/cm, at least 0.02 N/cm, at least 0.03 N/cm, at least 0.04 N/cm, at least 0.05 N/cm, or at least 0.1 N/cm.

[00122] In some embodiments, the ratio of the peeling strength of the undried cathode to the peeling strength of the dried cathode is independently from about 0.7 to about 1.3, from about 0.8 to about 1.2, from about 0.8 to about 1.05, from about 0.8 to about 1, from about 0.8 to about 0.95, from about 0.8 to about 0.9, from about 0.9 to about 1.1, from about 0.9 to about 1.05, from about 0.9 to about 1, from about 1 to about 1.2, from about 1 to about 1.15, from about 1 to about 1.1, from about 1 to about 1.05, or from about 1.1 to about 1.2. In certain embodiments, the ratio of the peeling strength of the undried cathode to the peeling strength of

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the dried cathode is independently less than 1.2, less than 1.15, less than 1.05, less than 1, less than 0.95, less than 0.95, or less than 0.9. In some embodiments, the ratio of the peeling strength of the undried cathode to the peeling strength of the dried cathode of each of the cathode and anode is independently at least 0.8, at least 0.85, at least 0.9, at least 0.95, at least 1, at least 1.05, or at least 1.1.

[00123] In some embodiments, the ratio of the peeling strength of the undried anode electrode layer to the peeling strength of the dried anode electrode layer is from about 0.7 to about 1.3, from about 0.8 to about 1.2, from about 0.8 to about 1.05, from about 0.8 to about 1, from about 0.8 to about 0.95, from about 0.8 to about 0.9, from about 0.9 to about 1.1, from about 0.9 to about 1.05, from about 0.9 to about 1, from about 1 to about 1.2, from about 1 to about 1.15, from about 1 to about 1.1, from about 1 to about 1.05, or from about 1.1 to about 1.2. In certain embodiments, the ratio of the peeling strength of the undried anode electrode layer to the peeling strength of the dried anode electrode layer is less than 1.2, less than 1.15, less than 1.05, less than 1, less than 0.95, or less than 0.9. In some embodiments, the ratio of the peeling strength of the undried anode electrode layer to the peeling strength of the dried anode electrode layer is at least 0.8, at least 0.85, at least 0.9, at least 0.95, at least 1, at least 1.05, or at least 1.1.

[00124] Detachment of the active material is less likely to occur during repetitive charging and discharging when the peeling strength between the current collector and the electrode layer is high. In the case where the electrode peeling strength is 0.15 N/cm or more, the electrode has sufficient peeling strength after lamination of the active electrode material onto a surface of the current collector and the electrode layer does not separate during volume change due to shrinkage and expansion of the electrode active material during charging and discharging of a rechargeable lithium battery.

[00125] After the drying step, the electrode assembly can then be naturally cooled to 50 °C or less before being removed from the drying chamber. In some embodiments, the electrode assembly is cooled to 45 °C or less, 40 °C or less, 35 °C or less, 30 °C or less, or 25 °C or less before being removed from the drying chamber. In certain embodiments, the electrode assembly is cooled to room temperature. In some embodiments, the electrode assembly is cooled down by blowing a dry gas or inert gas in order to reach the target temperature more quickly.

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[00126] The binder material in the electrode layer performs a role of binding the electrode material and conductive agent together on the current collector. In certain embodiments, each of the at least one anode and at least one cathode independently comprises a binder material selected from the group consisting of an organic-based binder material, a water-based binder material, or a mixture of water-based and organic-based binder materials.

[00127] In some embodiments, each of the binder materials in the cathode and anode electrode layers is independently selected from the group consisting of styrene-butadiene rubber, acrylated styrene-butadiene rubber, acrylonitrile copolymer, acrylonitrile-butadiene rubber, nitrile butadiene rubber, acrylonitrile-styrene-butadiene copolymer, acryl rubber, butyl rubber, fluorine rubber, polytetrafluoroethylene, polyethylene, polypropylene, ethylene/propylene copolymers, polybutadiene, polyethylene oxide, chlorosulfonated polyethylene, polyvinylpyrrolidone, polyvinylpyridine, polyvinyl alcohol, polyvinyl acetate, polyepichlorohydrin, polyphosphazene, polyacrylonitrile, polystyrene, latex, acrylic resins, phenolic resins, epoxy resins, carboxymethyl cellulose, hydroxypropyl cellulose, cellulose acetate, cellulose acetate butyrate, cellulose acetate propionate, cyanoethylcellulose, cyanoethylsucrose, polyester, polyamide, polyether, polyimide, polycarboxylate, polycarboxylic acid, polyacrylic acid, polyacrylate, polymethacrylic acid, polymethacrylate, polyacrylamide, polyurethane, fluorinated polymer, chlorinated polymer, a salt of alginic acid, polyvinylidene fluoride, poly(vinylidene fluoride)-hexafluoropropene, and combinations thereof. In further embodiments, the salt of alginic acid comprises a cation selected from Na, Li, K, Ca, NH_4, Mg, Al, or a combination thereof.

[00128] In certain embodiments, each of the binder materials in the cathode and anode electrode layers is independently selected from the group consisting of styrene-butadiene rubber, carboxymethyl cellulose, polyvinylidene fluoride, acrylonitrile copolymer, polyacrylic acid, polyacrylonitrile, poly(vinylidene fluoride)-hexafluoropropene, latex, a salt of alginic acid, and combinations thereof.

[00129] In some embodiments, each of the binder materials in the cathode and anode electrode layers is independently selected from SBR, CMC, PAA, a salt of alginic acid, or a combination thereof. In certain embodiments, each of the binder materials in the cathode and

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anode electrode layers is independently acrylonitrile copolymer. In some embodiments, each of the binder materials in the cathode and anode electrode layers is independently polyacrylonitrile. In certain embodiments, each of the binder materials in the cathode and anode electrode layers independently is free of styrene-butadiene rubber, carboxymethyl cellulose, polyvinylidene fluoride, acrylonitrile copolymer, polyacrylic acid, polyacrylonitrile, poly(vinylidene fluoride)-hexafluoropropene, latex, or a salt of alginic acid.

[00130] In some embodiments, the binder materials in the cathode and/or anode is not styrene-butadiene rubber, acrylated styrene-butadiene rubber, acrylonitrile copolymer, acrylonitrile-butadiene rubber, nitrile butadiene rubber, acrylonitrile-styrene-butadiene copolymer, acryl rubber, butyl rubber, fluorine rubber, polytetrafluoroethylene, polyethylene, polypropylene, ethylene/propylene copolymers, polybutadiene, polyethylene oxide, chlorosulfonated polyethylene, polyvinylpyrrolidone, polyvinylpyridine, polyvinyl alcohol, polyvinyl acetate, polyepichlorohydrin, polyphosphazene, polyacrylonitrile, polystyrene, latex, acrylic resins, phenolic resins, epoxy resins, carboxymethyl cellulose, hydroxypropyl cellulose, cellulose acetate, cellulose acetate butyrate, cellulose acetate propionate, cyanoethylcellulose, cyanoethylsucrose, polyester, polyamide, polyether, polyimide, polycarboxylate, polycarboxylic acid, polyacrylic acid, polyacrylate, polymethacrylic acid, polymethacrylate, polyacrylamide, polyurethane, fluorinated polymer, chlorinated polymer, a salt of alginic acid, polyvinylidene fluoride, poly(vinylidene fluoride)-hexafluoropropene, and combinations thereof.

[00131] In some embodiments, the binder materials in the cathode and/or anode electrode layers is free of additive material. In some embodiments, the additive material comprises α-methylstyrene or amine. In certain embodiments, the amine comprises hydroxylamine sulfate, dimethylhydroxylamine, diethylhydroxylamine, or N-isopropylhydroxylamine. The electrodes may be poisoned by undesirable reactions on the electrode in the presence of amine in the binder material, thereby affecting the electrochemical performance of battery such as life cycle of battery.

[00132] In certain embodiments, the binder material comprises a core-shell structure. In some embodiments, the binder material does not comprise a core-shell structure. In certain embodiments, the core of the core-shell structure is not a partially coated.

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[00133] In order to ensure strong adhesion between electrode layer and current collector, the amount of the binder material in each of the cathode and anode electrode layers is independently at least 0.5 wt.%, based on the total weight of the cathode or anode layer. In certain embodiments, the amount of the binder material in each of the cathode and anode electrode layers is independently at least 0.5%, at least 0.6%, at least 0.7%, at least 0.8%, at least 0.9%, at least 1%, at least 2%, at least 3%, at least 4%, at least 5%, at least 6 %, at least 7 %, at least 8 %, at least 9 %, at least 10%, at least 15%, at least 20%, at least 25%, at least 30%, at least 35%, at least 40%, at least 45%, or at least 50% by weight, based on the total weight of the cathode or anode electrode layer. In some embodiments, the amount of the binder material in each of the cathode and anode electrode layers is independently at most 1%, at most 2%, at most 3%, at most 4%, at most 5%, at most 6 %, at most 7 %, at most 8 %, at most 9 %, at most 10%, at most 15%, at most 20%, at most 25%, at most 30%, at most 35%, at most 40%, at most 45%, or at most 50% by weight, based on the total weight of the cathode or anode electrode layer.

[00134] In some embodiments, the amount of the binder material in each of the cathode and anode electrode layers is independently is from about 1 wt.% to about 10 wt.%, from about 1 wt.% to about 8 wt.%, from about 1 wt.% to about 6 wt.%, from about 1 wt.% to about 4 wt.%, from about 1 wt.% to about 2 wt.%, from about 2 wt.% to about 10 wt.%, from about 2 wt.% to about 8 wt.%, from about 2 wt.% to about 6 wt.%, from about 2 wt.% to about 4 wt.%, from about 3 wt.% to about 6 wt.%, from about 5 wt.% to about 10 wt.%, from about 7.5 wt.% to about 15 wt.%, from about 10 wt.% to about 20 wt.%, from about 15 wt.% to about 25 wt.%, from about 20 wt.% to about 40 wt.%, or from about 35 wt.% to about 50 wt.%, based on the total weight of the cathode or anode electrode layer.

[00135] In order to prevent moisture from being present within the sealed container, the step of filling electrolyte is carried out in a dry room. After drying, the electrode assembly is placed inside a container and then an electrolyte is added to fill the pores of all of the layers of separator and electrodes, and each of the gaps between the positive and negative electrodes and the separator in the electrode assembly under an inert atmosphere before sealing.

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[00136] The method disclosed herein reduces the production costs of lithium-ion batteries by consuming less energy and shortens manufacturing times needed for drying. Therefore, this method is especially suited for industrial processes because of its low cost and ease of handling.

[00137] Also provided herein is a lithium battery comprising the electrode assembly prepared by the method disclosed herein.

[00138] In some embodiments, the lithium battery is able to retain at least about 80%, at least about 85 %, or at least 90 % of its initial storage capacity after 1,000 cycles at a rate of 1C at room temperature in a full cell. In certain embodiments, the lithium battery is able to retain at least about 80 %, or at least 85 % of its initial storage capacity after 1,500 cycles at a rate of 1C at room temperature in a full cell.

[00139] The following examples are presented to exemplify embodiments of the invention. All numerical values are approximate. Specific details described in each example should not be construed as necessary features of the invention.

EXAMPLES

[00140] The water content in the electrode assembly was measured by Karl-fisher titration. The electrode assembly was cut into small pieces of 1 cm x 1 cm in a glove box filled with argon gas. The cut electrode assembly having a size of 1 cm x 1 cm was weighed in a sample vial. The weighed electrode assembly was then added into a titration vessel for Karl Fischer titration using Karl Fischer coulometry moisture analyzer (831 KF Coulometer, Metrohm, Switzerland). Measurements were repeated three times to find the average value.

[00141] The water content in the electrodes or separator was measured by Karl-fisher titration. The electrode assembly was cut into small pieces of 1 cm x 1 cm in a glove box filled with argon gas. The electrode assembly was separated into the anode, cathode and separator layers. The water contents of the separated electrode layers and separator layers were analysed separately by Karl Fischer titration. Measurements were repeated three times to find the average value.

[00142] The peeling strengths of the electrodes were measured by a peeling tester (obtained from Instron, US; model no. MTS 5581). The dried electrode assembly was separated

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into the anode, cathode and separator layers. Each of the cathode and anode layers was cut into a rectangular shape having a size of 25 mm×100 mm. Then, a strip of mending tape (3M; US; model no. 810) was attached onto the electrode surface having the electrode coating layer, and then pressed by a reciprocating movement of a 2 kg roller thereon to prepare samples for peeling strength test. Each of the samples was mounted on the peeling tester, followed by measurement of the peeling strength by peeling off the mending tape at 180° at room temperature. The mending tape was peeled off at a rate of 50 mm/minute. Measurements were taken at a predetermined interval of 10 mm to 70 mm and were repeated 3 times.

Example 1

A) Preparation of positive electrode slurry

[00143] A positive electrode slurry was prepared by mixing 94 wt.% cathode material (LNMC TLM 310, obtained from Xinxiang Tianli Energy Co. Ltd., China), 3 wt.% carbon black (SuperP; obtained from Timcal Ltd, Bodio, Switzerland) as a conductive agent, and 0.8 wt.% polyacrylic acid (PAA, #181285, obtained from Sigma-Aldrich, US), 1.5 wt.% styrene butadiene rubber (SBR, AL-2001, obtained from NIPPON A&L INC., Japan) and 0.7 wt.% polyvinylidene fluoride (PVDF; Solef® 5130, obtained from Solvay S.A., Belgium) as a binder, which were dispersed in deionized water to form a slurry with a solid content of 50 wt.%. The slurry was homogenized by a planetary stirring mixer.

B) Preparation of positive electrode

[00144] The homogenized slurry was coated onto both sides of an aluminum foil having a thickness of 20 μm and a surface roughness R_a of 0.7 μm using a transfer coater (ZY-TSF6-6518, obtained from Jin Fan Zhanyu New Energy Technology Co. Ltd., China) with an area density of about 26 mg/cm^2. The coated film on the aluminum foil were dried for 3 minutes by a 24-meter-long conveyor hot air drying oven as a sub-module of the transfer coater operated at a conveyor speed of about 8 meters/minute to obtain a positive electrode. The temperature-programmed oven allowed a controllable temperature gradient in which the temperature gradually rose from the inlet temperature of 60 °C to the outlet temperature of 75 °C. The electrode was then pressed to increase the density of the coating and the density was 2.74 g/cm^3. The thickness of the coating was 23 μm. The void volume of the electrode layer is 31%.

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C) Preparation of negative electrode

[00145] A negative electrode slurry was prepared by mixing 90 wt.% hard carbon (HC; 99.5% purity, Ruifute Technology Ltd., Shenzhen, Guangdong, China), 5 wt.% carbon black and 5 wt.% polyacrylonitrile in deionized water to form a slurry having a solid content of 50 wt.%. The slurry was coated onto both sides of a copper foil having a thickness of 9 μm and a surface roughness R_a of 1.2 μm using a transfer coater with an area density of about 15 mg/cm^2. The coated film on the copper foil were dried at about 50 °C for 2.4 minutes by a 24-meter-long conveyor hot air dryer operated at a conveyor speed of about 10 meters/minute to obtain a negative electrode. The electrode was then pressed to increase the density of the coating and the density was 1.8 g/cm^3. The thickness of the coating was 10 μm. The void volume of the electrode layer is 19%.

Example 2

Assembling of electrode assembly

[00146] After drying, the resulting cathode film and anode film of Example 1 were used to prepare the cathode and anode respectively by cutting into individual electrode plates. An electrode assembly was prepared by stacking anodes, cathodes and separators interposed between the positive electrode and the negative electrode in the open air with no control of humidity. The separator was a microporous membrane made of nonwoven PET fabric (obtained from MITSUBISHI PAPER MILLS LTD, Japan), which had a thickness of 30 μm. The electrode assembly was dried in a vacuum oven inside a glove box under a pressure of 5x10^3 Pa at 70 °C for 2.5 hours during the first stage of drying. The electrode assembly was further dried under vacuum at 5x10^3 Pa at 120 °C for 1.5 hours during the second stage of drying. The drying chamber was then filled with hot, dry air having a water content of 5 ppm and a temperature of 90 °C. The hot, dry air was retained in the drying chamber for 15 minutes before evacuating the drying chamber. The cycle involving the steps of vacuum drying in the second stage and gas filling performed after the second stage was repeated 10 times.

Moisture contents of electrode assembly, electrodes and separator

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[00147] The average values of moisture contents of the electrode assembly, electrodes and separator were 5 ppm, 9 ppm and 13 ppm respectively.

Assembling of pouch-type battery

[00148] A pouch cell was assembled by packaging the dried electrode assembly in a case made of an aluminum-plastic laminated film. The cathode and anode electrode plates were kept apart by separators and the case was pre-formed. An electrolyte was then filled into the case holding the packed electrodes in high-purity argon atmosphere with moisture and oxygen content < 1 ppm. 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) in a volume ratio of 1:1:1. After electrolyte filling, the pouch cells were vacuum sealed and then mechanically pressed using a punch tooling with standard square shape.

Electrochemical measurements of Example 2

I) Nominal capacity

[00149] The cell was tested galvanostatically at a current density of C/2 at 25 °C on a battery tester (BTS-5V20A, obtained from Neware Electronics Co. Ltd, China) between 3.0 V and 4.2 V. The nominal capacity was about 2.8 Ah.

II) Cyclability performance

[00150] The cyclability performance of the pouch cell was tested by charging and discharging at a constant current rate of 1C between 3.0 V and 4.2 V. Test result of cyclability performance is shown in Figure 1. The capacity retention after 562 cycles was about 94.7% of the initial value.

Example 3

A) Preparation of positive electrode slurry

[00151] A positive electrode slurry was prepared by mixing 92 wt.% cathode material ($LiMn_2O_4$ obtained from HuaGuan HengYuan LiTech Co. Ltd., Qingdao, China), 4 wt.% carbon black (SuperP; obtained from Timcal Ltd, Bodio, Switzerland) as a conductive agent, and 4 wt.% polyvinylidene fluoride (PVDF; Solef® 5130, obtained from Solvay S.A., Belgium) as a binder,

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which were dispersed in N-methyl-2-pyrrolidone (NMP; purity of ≥99%, Sigma-Aldrich, USA) to form a slurry with a solid content of 50 wt.%. The slurry was homogenized by a planetary stirring mixer.

B) Preparation of positive electrode

[00152] The homogenized slurry was coated onto both sides of an aluminum foil having a thickness of 20 μm and a surface roughness R_a of 0.7 μm using a transfer coater with an area density of about 2.4 mg/cm^2. The coated film on the aluminum foil were dried for 6 minutes by a 24-meter-long conveyor hot air drying oven as a sub-module of the transfer coater operated at a conveyor speed of about 4 meters/minute to obtain a positive electrode. The temperature-programmed oven allowed a controllable temperature gradient in which the temperature gradually rose from the inlet temperature of 65 °C to the outlet temperature of 80 °C. The electrode was then pressed to increase the density of the coating and the density was 2.83 g/cm^3.

C) Preparation of negative electrode

[00153] A negative electrode slurry was prepared by mixing 90 wt.% of hard carbon (HC; purity of 99.5%, obtained from Ruifute Technology Ltd., Shenzhen, Guangdong, China) with 1.5 wt.% carboxymethyl cellulose (CMC, BSH-12, DKS Co. Ltd., Japan) and 3.5 wt.% SBR (AL-2001, NIPPON A&L INC., Japan) as a binder, and 5 wt.% carbon black as a conductive agent, which were dispersed in deionized water to form another slurry with a solid content of 50 wt.%. The slurry was coated onto both sides of a copper foil having a thickness of 9 μm and a surface roughness R_a of 0.55 μm using a transfer coater with an area density of about 15 mg/cm^2. The coated film on the copper foil were dried at about 50 °C for 2.4 minutes by a 24-meter-long conveyor hot air dryer operated at a conveyor speed of about 10 meters/minute to obtain a negative electrode. The electrode was then pressed to increase the density of the coating and the density was 1.8 g/cm^3.

Example 4

Assembling of electrode assembly

[00154] After drying, the resulting cathode film and anode film of Example 3 were used to prepare the cathode and anode respectively by cutting into individual electrode plates. An

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electrode assembly was prepared by stacking anodes, cathodes and separators interposed between the positive electrode and the negative electrode in the open air with no control of humidity. The separator was a ceramic coated microporous membrane made of nonwoven fabric (SEPARION, Evonik Industries, Germany) having a thickness of 35 µm. The electrode assembly was dried in a vacuum oven inside a glove box under a pressure of $1x10^4$ Pa at 85 °C for 1.5 hours during the first stage of drying. The electrode assembly was further dried under vacuum at $5x10^3$ Pa at 105 °C for 2.5 hours during the second stage of drying. The drying chamber was then filled with hot, dry air having a water content of 5 ppm and a temperature of 90 °C. The hot, dry air was retained in the drying chamber for 15 minutes before evacuating the drying chamber. The cycle involving the steps of vacuum drying in the second stage and gas filling performed after the second stage was repeated 5 times.

Moisture contents of electrode assembly, electrodes and separator

[00155] The average values of moisture contents of the electrode assembly, electrodes and separator were 13 ppm, 9 ppm and 15 ppm respectively.

Electrochemical measurements of Example 4

I) Nominal capacity

[00156] A pouch cell containing the dried electrode assembly prepared by method described in Example 4 was assembled according to the method described in Example 2. The cell was tested galvanostatically at a current density of C/2 at 25 °C on a battery tester between 3.0 V and 4.2 V. The nominal capacity was about 2.9 Ah.

II) Cyclability performance

[00157] The cyclability performance of the pouch cell was tested by charging and discharging at a constant current rate of 1C between 3.0 V and 4.2 V. Test result of cyclability performance is shown in Figure 2.

Example 5

A) Preparation of positive electrode slurry

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[00158] A positive electrode slurry was prepared by mixing 94 wt.% cathode material $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (obtained from Shenzhen Tianjiao Technology Co. Ltd., China), 3 wt.% carbon black (SuperP; obtained from Timcal Ltd, Bodio, Switzerland) as a conductive agent, and 1.5 wt.% polyacrylic acid (PAA, #181285, obtained from Sigma-Aldrich, US) and 1.5 wt.% polyacrylonitrile (LA 132, Chengdu Indigo Power Sources Co., Ltd., China) as a binder, which were dispersed in deionized water to form a slurry with a solid content of 50 wt.%. The slurry was homogenized by a planetary stirring mixer.

B) Preparation of positive electrode

[00159] The homogenized slurry was coated onto both sides of an aluminum foil having a thickness of 20 μm and a surface roughness R_a of 0.7 μm using a transfer coater with an area density of about 32 mg/cm^2. The coated film on the aluminum foil were dried for 4 minutes by a 24-meter-long conveyor hot air drying oven as a sub-module of the transfer coater operated at a conveyor speed of about 6 meters/minute to obtain a positive electrode. The temperature-programmed oven allowed a controllable temperature gradient in which the temperature gradually rose from the inlet temperature of 60 °C to the outlet temperature of 75 °C. The electrode was then pressed to increase the density of the coating and the density was 3.47 g/cm^3.

C) Preparation of negative electrode

[00160] A negative electrode slurry was prepared by mixing 90 wt.% hard carbon, 5 wt.% carbon black and 5 wt.% polyacrylonitrile in deionized water to form a slurry having a solid content of 50 wt.%. The slurry was coated onto both sides of a copper foil having a thickness of 9 μm and a surface roughness R_a of 0.55 μm using a transfer coater with an area density of about 15 mg/cm^2. The coated film on the copper foil were dried at about 50 °C for 2.4 minutes by a 24-meter-long conveyor hot air dryer operated at a conveyor speed of about 10 meters/minute to obtain a negative electrode. The electrode was then pressed to increase the density of the coating and the density was 2.4 g/cm^3.

Example 6

Assembling of electrode assembly

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[00161] After drying, the resulting cathode film and anode film of Example 5 were used to prepare the cathode and anode respectively by cutting into individual electrode plates. An electrode assembly was prepared by stacking anodes, cathodes and separators interposed between the positive electrode and the negative electrode in the open air with no control of humidity. The separator was a microporous membrane made of polyimide (Jiangxi Advanced Nanofiber Technology Co., Ltd., China) having a thickness of 20 μm. The electrode assembly was dried in a vacuum oven inside a glove box under a pressure of $1.5x10^4$ Pa at 95 °C for 3.5 hours during the first stage of drying. The electrode assembly was further dried under vacuum at $5x10^3$ Pa at 115 °C for 2 hours during the second stage of drying. The drying chamber was then filled with hot, dry air having a water content of 5 ppm and a temperature of 85 °C. The hot, dry air was retained in the drying chamber for 15 minutes before evacuating the drying chamber. The cycle involving the steps of vacuum drying in the second stage and gas filling performed after the second stage was repeated 11 times.

Moisture content of electrode assembly

[00162] The average value of moisture content of the electrode assembly was 6 ppm.

Electrochemical measurements of Example 6

I) Nominal capacity

[00163] A pouch cell containing the dried electrode assembly prepared by method described in Example 6 was assembled according to the method described in Example 2. The cell was tested galvanostatically at a current density of C/2 at 25 °C on a battery tester between 3.0 V and 4.2 V. The nominal capacity was about 10 Ah.

II) Cyclability performance

[00164] The cyclability performance of the pouch cell was tested by charging and discharging at a constant current rate of 1C between 3.0 V and 4.2 V. Test result of cyclability performance is shown in Figure 3.

Example 7

A) Preparation of positive electrode slurry

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[00165] A positive electrode slurry was prepared by mixing 91 wt.% cathode material $LiFePO_4$ (obtained from Xiamen Tungsten Co. Ltd., China), 5 wt.% carbon black (SuperP; obtained from Timcal Ltd, Bodio, Switzerland) as a conductive agent, and 4 wt.% polyacrylonitrile (LA 132, Chengdu Indigo Power Sources Co., Ltd., China) as a binder, which were dispersed in deionized water to form a slurry with a solid content of 50 wt.%. The slurry was homogenized by a planetary stirring mixer.

B) Preparation of positive electrode

[00166] The homogenized slurry was coated onto both sides of an aluminum foil having a thickness of 30 μm and a surface roughness R_a of 0.7 μm using a transfer coater with an area density of about 56 mg/cm^2. The coated film on the aluminum foil were then dried for 6 minutes by a 24-meter-long conveyor hot air drying oven as a sub-module of the transfer coater operated at a conveyor speed of about 4 meters/minute to obtain a positive electrode. The temperature-programmed oven allowed a controllable temperature gradient in which the temperature gradually rose from the inlet temperature of 75 °C to the outlet temperature of 90 °C. The electrode was then pressed to increase the density of the coating and the density was 2.98 g/cm^3.

C) Preparation of negative electrode

[00167] A negative electrodes were prepared by mixing 90 wt.% of hard carbon (HC; purity of 99.5%, obtained from Ruifute Technology Ltd., China) with 1.5 wt.% CMC (BSH-12, DKS Co. Ltd., Japan) and 3.5 wt.% SBR (AL-2001, NIPPON A&L INC., Japan) as a binder, and 5 wt.% carbon black as a conductive agent, which were dispersed in deionized water to form another slurry with a solid content of 50 wt.%. The slurry was coated onto both sides of a copper foil having a thickness of 9 μm and a surface roughness R_a of 0.55 μm using a transfer coater with an area density of about 15 mg/cm^2. The coated film on the copper foil were then dried at about 50 °C for 2.4 minutes by a 24-meter-long conveyor hot air dryer operated at a conveyor speed of about 10 meters/minute to obtain a negative electrode. The electrode was then pressed to increase the density of the coating and the density was 1.6 g/cm^3.

Example 8

Assembling of electrode assembly

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[00168] After drying, the resulting cathode film and anode film of Example 7 were used to prepare the cathode and anode respectively by cutting into individual electrode plates. An electrode assembly was prepared by stacking anodes, cathodes and separators interposed between the positive electrode and the negative electrode in the open air with no control of humidity. The separator was a ceramic coated microporous membrane made of nonwoven fabric (SEPARION, Evonik Industries, Germany), which had a thickness of about 35 μm. The electrode assembly was dried in a vacuum oven inside a glove box under a pressure of $7x10^3$ Pa at 65 °C for 4 hours. The electrode assembly was further dried under vacuum at $1x10^4$ Pa at 115 °C for 1.2 hours. The drying chamber was then filled with hot, dry air having a water content of 5 ppm and a temperature of 100 °C. The hot, dry air was retained in the drying chamber for 5 minutes before evacuating the drying chamber. The cycle involving the steps of vacuum drying in the second stage and gas filling performed after the second stage was repeated 8 times.

Moisture content of electrode assembly

[00169] The average value of moisture content of the electrode assembly was 7 ppm.

Electrochemical measurements of Example 8

I) Nominal capacity

[00170] A pouch cell containing the dried electrode assembly prepared by method described in Example 8 was assembled according to the method described in Example 2. The cell was tested galvanostatically at a current density of C/2 at 25 °C on a battery tester between 3.0 V and 4.2 V. The nominal capacity was about 9 Ah.

II) Cyclability performance

[00171] The cyclability performance of the pouch cell was tested by charging and discharging at a constant current rate of 1C between 3.0 V and 4.2 V. Test result of cyclability performance is shown in Figure 4.

Example 9-12 and Comparative Example 1-9

[00172] The pouch cells of Example 9-10 and Comparative Example 1-13 were prepared by the method described in Example 1 or 2 except different parameters described in Table 1

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below are used. The electrode assemblies of Example 9-10 and Comparative Example 1-13 were dried by the method described in Example 2 except different drying conditions described in Table 2 below are used.

[00173] The formulations of the pouch cell of each of these Examples and Comparative Examples are summarized in Table 1 below. The drying conditions of the electrode assembly of each of these Examples and Comparative Examples are shown in Table 2 below. Various physical parameters of undried and dried electrodes of each of these Examples and Comparative Examples are shown in Table 3 below. The test results of the cyclability performance of the pouch cell of each of these Examples and Comparative Examples are shown in Table 4 below. The electrochemical tests of these Examples show the good electrochemical stability of the battery in a wide range of potential, as well as outstanding cycle performance.

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Table 1

	Cathode material	Cathode binder material	Solvent		Separator	Surface roughness of current collector (μm)[1]	
			Cathode	Anode		Cathode	Anode
Example 1	NMC333	PAA+SBR+PVDF	H_2O	H_2O	PET	0.7	1.2
Example 3	LMO	PVDF	NMP	H_2O	Ceramic coated PET	0.7	0.55
Example 5	NMC333	PAA+LA132	H_2O	H_2O	PI	0.7	0.55
Example 7	LFP	LA132	H_2O	H_2O	Ceramic coated PET	0.7	0.55
Example 9	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Example 10	NMC333	PAA+LA132	H_2O	H_2O	PET	2.1	1.54
Example 11	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.88
Example 12	NMC333	PAA+LA132	H_2O	H_2O	PET	0.67	0.55
Comparative Example 1	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 2	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.2
Comparative Example 3[2]	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 4	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 5	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 6	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 7	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 8	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55
Comparative Example 9	NMC333	PAA+LA132	H_2O	H_2O	PET	0.7	0.55

Note: [1]The surface roughness R_a was used in all Examples and Comparative Examples except Example 10 that R_z was used instead.

[2]The amount of anode binder material of Comparative Example 3 is 10 wt.%, based on the total weight of the anode.

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Table 2

	1st stage drying (A)			2nd stage drying (B)			Gas filling (C)		No. of cycle (B+C)	Total time (hrs) (A+B+C)
	Pressure (Pa)	Temp (°C)	Time (hrs)	Pressure (Pa)	Temp (°C)	Time (hrs)	Temp (°C)	Time (mins)		
Example 1	5,000	70	2.5	5,000	120	1.5	90	15	10	20
Example 3	10,000	85	1.5	5,000	105	2.5	90	15	5	15.3
Example 5	15,000	95	3.5	5,000	115	2	85	15	11	28.3
Example 7	7,000	65	4	10,000	115	1.2	100	5	8	14.3
Example 9	3,900	70	1	1,000	85	1	90	20	8	11.7
Example 10	1,000	85	3.5	1,200	110	1.5	100	15	6	14.0
Example 11	6,300	80	3.5	2,500	110	1.5	100	5	8	16.2
Example 12	3,900	95	1.5	1,900	105	3	85	10	5	17.3
Comparative Example 1	6,300	155	4.5	3,100	160	1	100	20	9	16.5
Comparative Example 2	10,000	85	4.5	3,100	95	1	90	10	6	11.5
Comparative Example 3	1,500	70	3.5	3,100	90	3	100	10	4	16.2
Comparative Example 4	3,900	75	1	5,000	100	2	100	20	7	17.3
Comparative Example 5	5,000	90	1.5	10,000	105	2.5	85	20	8	24.2
Comparative Example 6	6,300	95	2	2,500	110	2	100	20	10	25.3
Comparative Example 7	1,900	80	1	1,900	90	2.5	85	15	5	14.8
Comparative Example 8	7,900	65	4.5	2,500	100	2	85	20	6	18.5
Comparative Example 9	3,100	75	2.5	10,000	85	2	95	10	8	19.8

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Table 3

	Electrode layer									
	Peeling strength (N/cm)				Void volume (%)		Density (g/cm^3)		Thickness (μm)	
	Cathode		Anode							
	Undried	Dried	Undried	Dried	Cathode	Anode	Cathode	Anode	Cathode	Anode
Example 1	0.44	0.45	0.21	0.23	31	19	2.74	1.8	23	10
Example 3	0.32	0.31	0.17	0.18	29	19	2.83	1.8	20	7.5
Example 5	0.49	0.51	0.25	0.28	13	20	3.47	2.4	24	13
Example 7	0.37	0.38	0.22	0.24	26	21	2.98	1.6	19	9
Example 9	0.38	0.35	0.25	0.23	24	24	/	/	38	15
Example 10	0.36	0.35	0.23	0.21	7	22	/	/	22	14
Example 11	0.36	0.34	0.22	0.21	18	10	/	/	26	10
Example 12	0.37	0.36	0.24	0.22	22	25	/	/	33	15
Comparative Example 1	0.37	0.12	0.22	0.12	31	17	/	/	37	11
Comparative Example 2	0.38	0.35	0.23	0.12	28	12	/	/	35	9
Comparative Example 3	0.39	0.36	0.35	0.33	9	21	/	/	21	13
Comparative Example 4	0.38	0.37	0.23	0.21	37	18	/	/	35	12
Comparative Example 5	0.37	0.35	0.23	0.22	17	40	/	/	24	16
Comparative Example 6	0.37	0.36	0.24	0.23	4	19	/	/	20	11
Comparative Example 7	0.36	0.35	0.24	0.23	20	4	/	/	28	8
Comparative Example 8	0.38	0.13	0.24	0.22	26	12	/	/	65	19
Comparative Example 9	0.37	0.35	0.24	0.11	11	28	/	/	33	49

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Table 4

	No. of cycle	Capacity retention (%)
Example 1	562	94.7
Example 3	1,050	94.2
Example 5	601	94.3
Example 7	452	94.2
Example 9	579	94.5
Example 10	501	94.4
Example 11	599	94.9
Example 12	547	94.3
Comparative Example 1	140	94.7
Comparative Example 2	234	94.9
Comparative Example 3	236	94.9
Comparative Example 4	249	94.7
Comparative Example 5	206	94.7
Comparative Example 6	243	94.8
Comparative Example 7	172	94.3
Comparative Example 8	260	94.2
Comparative Example 9	231	95

[00174] 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. 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.

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What is claimed is:

1. An electrode for a lithium-ion battery, comprising a current collector and an electrode layer, wherein the current collector is in the form of a foil, sheet, or film, wherein the electrode layer has a void volume between 10% and 35%, wherein the electrode has a peeling strength between 0.15 N/cm and 0.31 N/cm, and wherein the electrode layer comprises a cathode material or an anode material, a binder material and a conductive agent, and wherein the binder material in the electrode layer is styrene-butadiene rubber, acrylated styrene-butadiene rubber, acrylonitrile copolymer, acrylonitrile-butadiene rubber, nitrile butadiene rubber, acrylonitrile-styrene-butadiene copolymer, acryl rubber, butyl rubber, polytetrafluoroethylene, polyethylene, polypropylene, ethylene/propylene copolymers, polybutadiene, polyethylene oxide, chlorosulfonated polyethylene, polyvinylpyrrolidone, polyvinylpyridine, polyvinyl alcohol, polyvinyl acetate, polyepichlorohydrin, polyphosphazene, polyacrylonitrile, polystyrene, latex, acrylic resins, phenolic resins, carboxymethyl cellulose, hydroxypropyl cellulose, cellulose acetate, cellulose acetate butyrate, cellulose acetate propionate, cyanoethylcellulose, cyanoethylsucrose, polyester, polyamide, polyether, polyimide, polycarboxylate, polycarboxylic acid, polyacrylic acid, polyacrylate, polymethacrylic acid, polymethacrylate, polyacrylamide, polyurethane, chlorinated polymer, a salt of alginic acid, or a combination thereof.

2. The electrode of claim 1, wherein the surface roughness of the current collector is 4 μm or less.

3. The electrode of claim 1 or 2, wherein the density of the electrode layer is from about 1.0 g/cm^3 to about 6.5 g/cm^3.

4. The electrode of claim 1 or 2, wherein the density of the electrode layer is from about 1.0 g/cm^3 to about 3.0 g/cm^3.

5. The electrode of any one of claims 1 to 4, wherein the thickness of the electrode layer is from about 1.0 μm to about 40 μm.

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6. The electrode of any one of claims 1 to 4, wherein the thickness of the electrode layer is from about 1.0 µm to about 25 µm.

7. The electrode of claim 1, wherein the cathode material is $LiCoO_2$, $LiNiO_2$, $LiNi_xMn_yO_2$, $Li_{1+z}Ni_xMn_yCo_{1-x-y}O_2$, $LiNi_xCo_yAl_zO_2$, LiV_2O_5, $LiTiS_2$, $LiMoS_2$, $LiMnO_2$, $LiCrO_2$, $LiMn_2O_4$, $LiFeO_2$, $LiFePO_4$, or a combination thereof, wherein each x is independently selected from 0.3 to 0.8; each y is independently selected from 0.1 to 0.45; and each z is independently selected from 0 to 0.2.

8. The electrode of claim 1 or 7, wherein the binder material in the electrode layer is present in an amount from 1% to 10% by weight, based on the total weight of the electrode layer.

9. The electrode of claim 1 or 7, wherein the cathode material is present in an amount from 60% to 99% by weight, based on the total weight of the electrode layer.

10. The electrode of any one of claims 1 and 7 to 9, wherein the conductive agent in the electrode layer is carbon, carbon black, graphite, expanded graphite, graphene, graphene nanoplatelets, carbon fibres, carbon nano-fibers, graphitized carbon flake, carbon tubes, carbon nanotubes, activated carbon, mesoporous carbon, or a combination thereof.

11. The electrode of any one of claims 1 and 7 to 10, wherein the anode material is natural graphite particulate, synthetic graphite particulate, Sn particulate, $Li_4Ti_5O_{12}$ particulate, Si particulate, Si-C composite particulate, or a combination thereof.

12. The electrode of claim 11, wherein the conductive agent in the electrode layer is present in an amount from 1% to 10% by weight, based on the total weight of the electrode layer.

13. The electrode of claim 11, wherein the anode material is present in an amount from 50% to 99% by weight, based on the total weight of the electrode layer.

14. The electrode of any one of claims 1 to 13, wherein the current collector is stainless steel, titanium, nickel, aluminum, copper, or electrically-conductive resin.

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15. The electrode of any one of claims 1 to 14, wherein the electrode is a cathode and the current collector is an aluminum thin film.

16. The electrode of any one of claims 1 to 14, wherein the electrode is an anode and the current collector is a copper thin film.

17. The electrode of any one of claims 1 to 16, wherein the electrode has a water content of less than 20ppm, based on the total weight of the electrode.

18. The electrode of any one of claims 1 to 16, wherein the electrode has a water content of less than 10ppm, based on the total weight of the electrode.

19. A lithium battery comprising the electrode of any one of claims 1 to 18.

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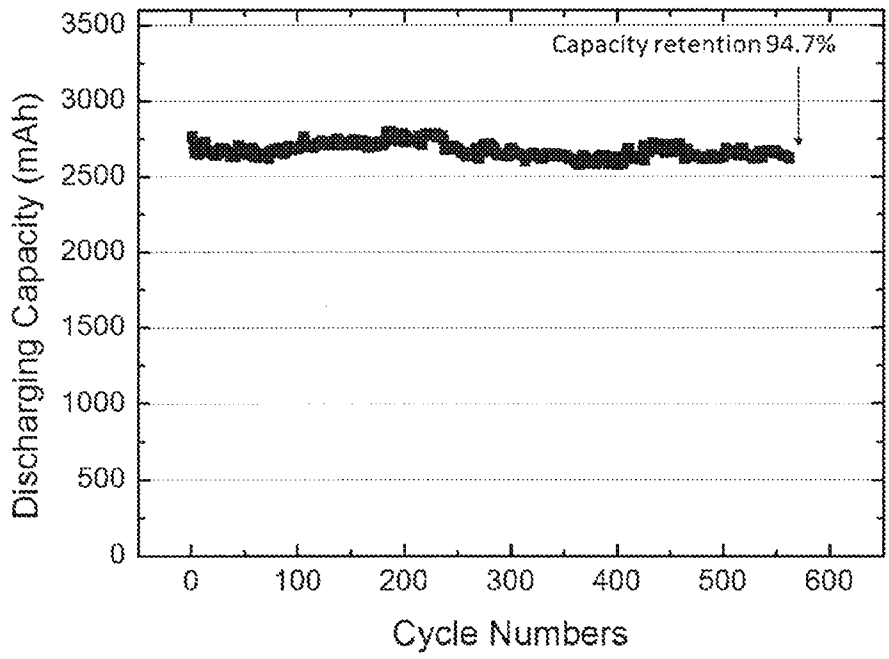


Figure 1

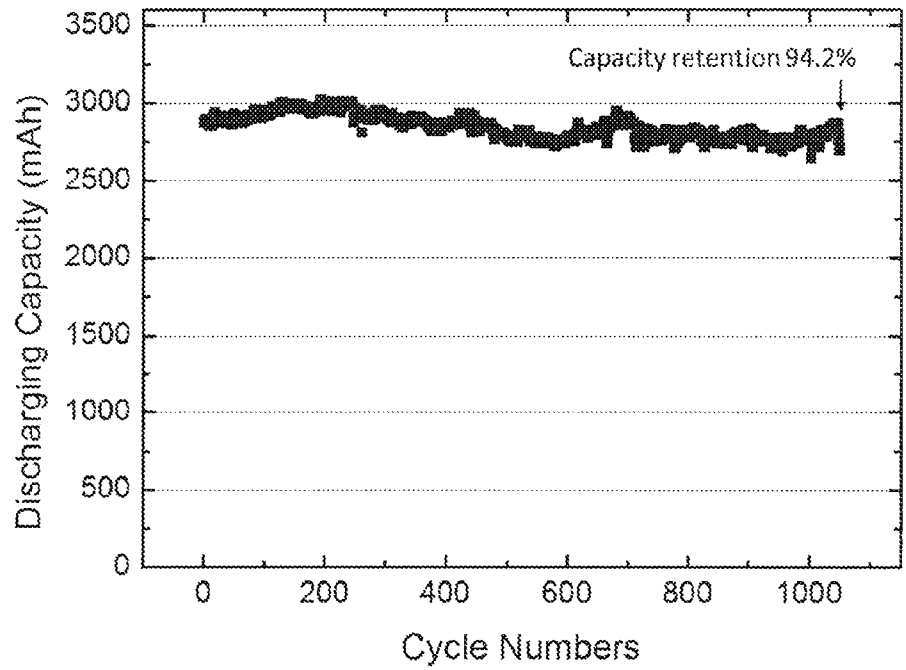


Figure 2

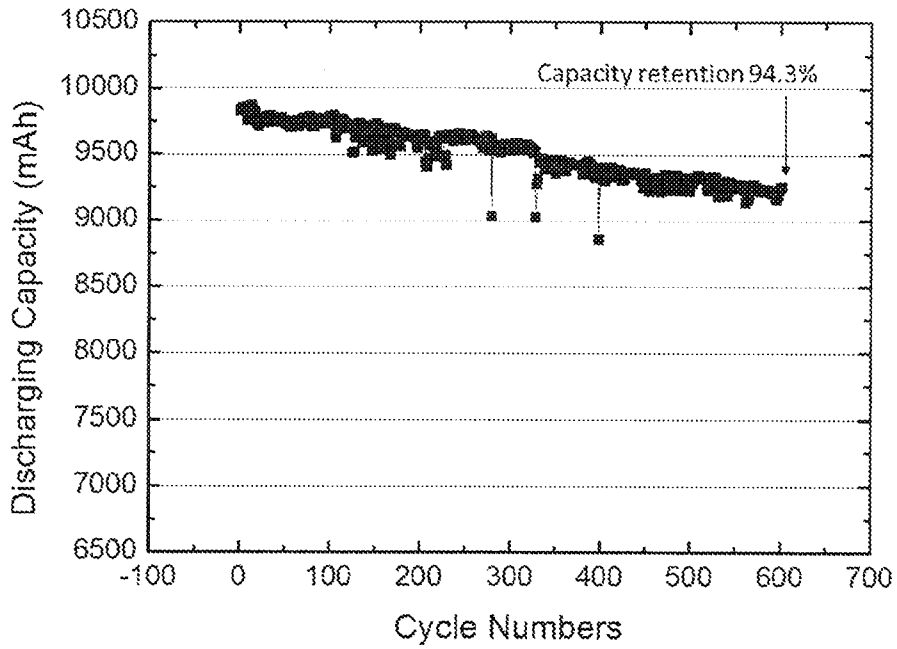


Figure 3

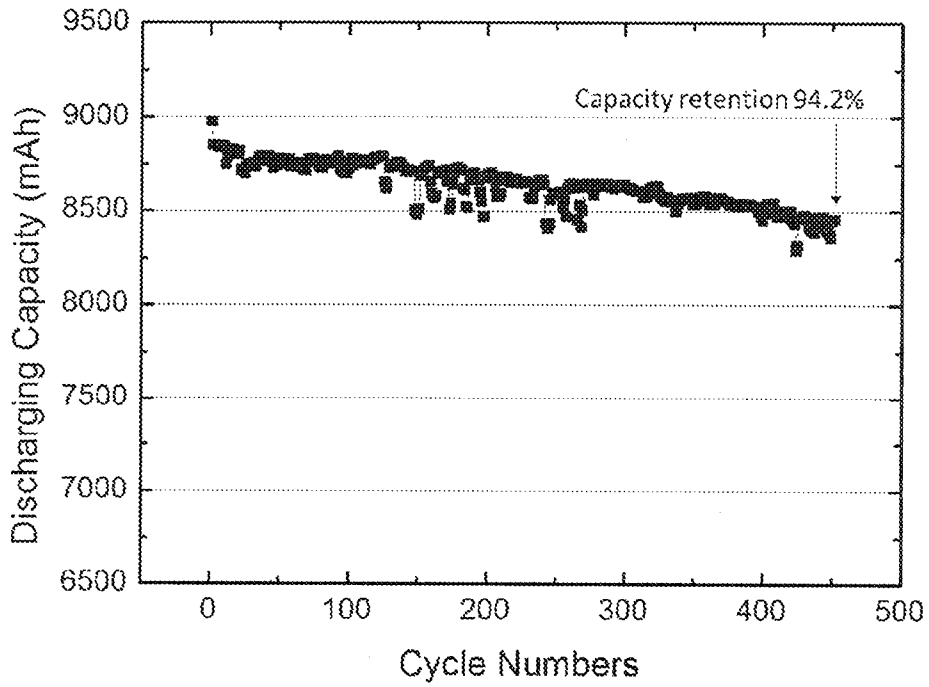
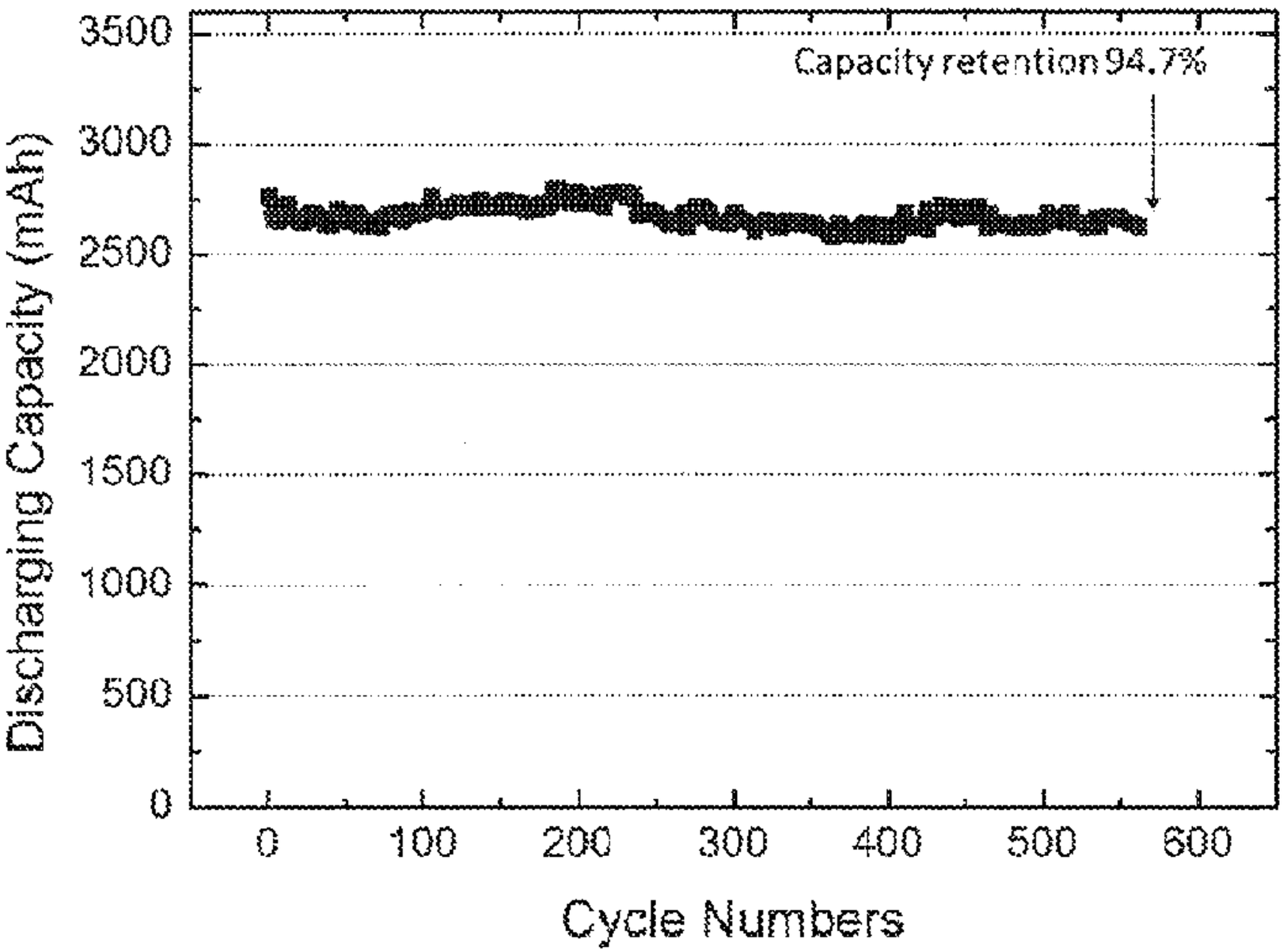


Figure 4


Capacity retention 94.7%
Discharging Capacity (mAh)
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
Cycle Numbers