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(54) **COATED POROUS SEPARATORS AND COATED ELECTRODES FOR LITHIUM BATTERIES**

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(71) Applicant: **GM Global Technology Operations LLC, Detroit, MI (US)**

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(72) Inventors: **Gayatri Vyas Dadheech**, Bloomfield Hills, MI (US); **Li Yang**, Troy, MI (US); **Mei Cai**, Bloomfield Hills, MI (US)

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(73) Assignee: **GM Global Technology Operations LLC, Detroit, MI (US)**

(57) **ABSTRACT**

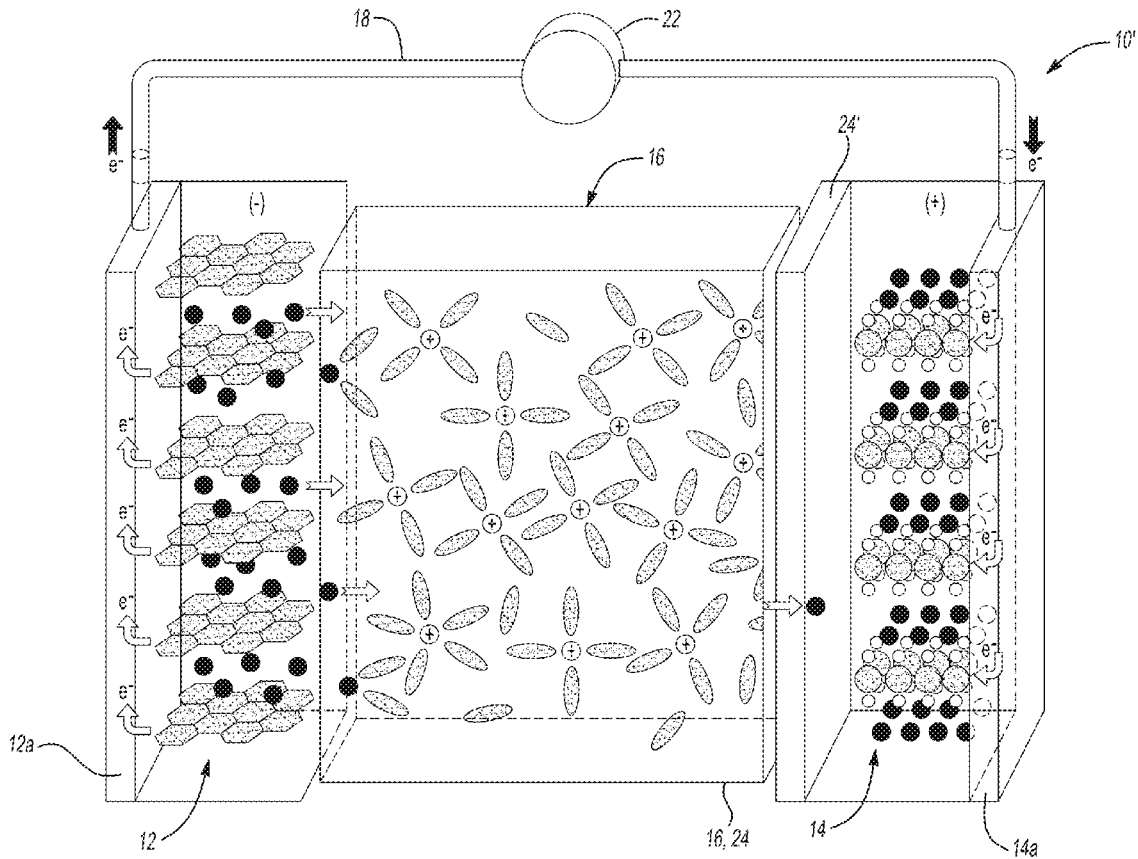
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(60) Provisional application No. 61/868,346, filed on Aug. 21, 2013.

An example of a porous separator includes an untreated porous polymer membrane, and a nanocomposite structure i) formed on a surface of the porous polymer membrane, or ii) dispersed in pores of the porous polymer membrane, or iii) combinations of i and ii. The nanocomposite structure is selected from the group consisting of a carbon nanocomposite structure, a metal oxide nanocomposite structure, and a mixed carbon and metal oxide nanocomposite structure.



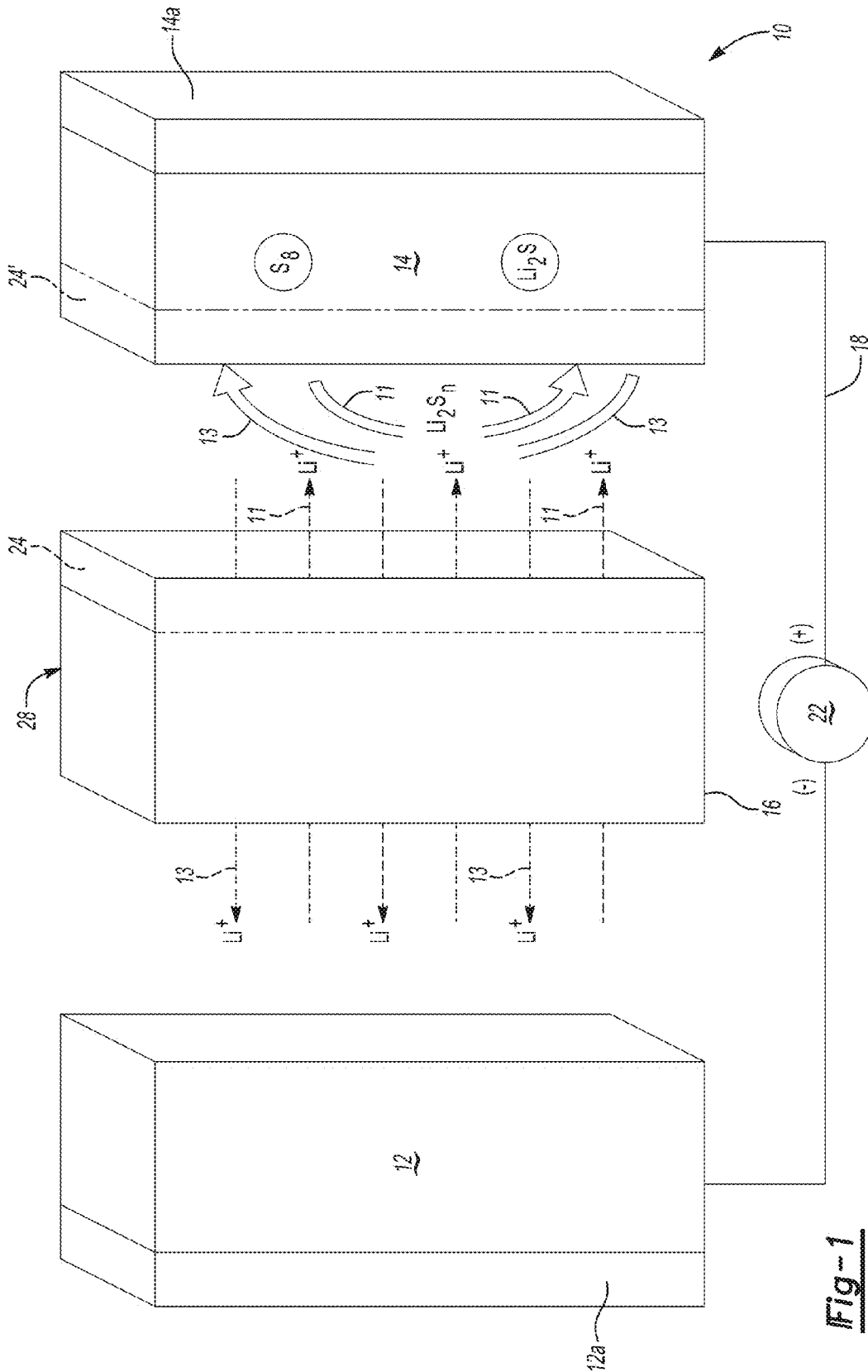


Fig-1

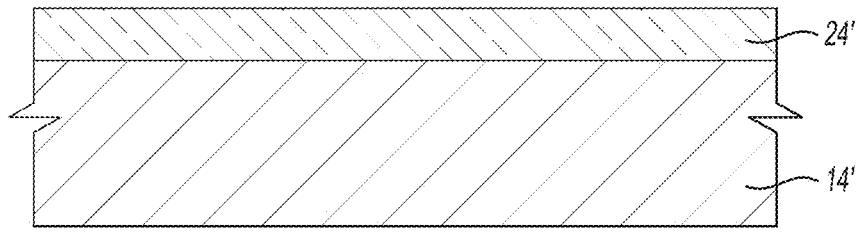


Fig-2

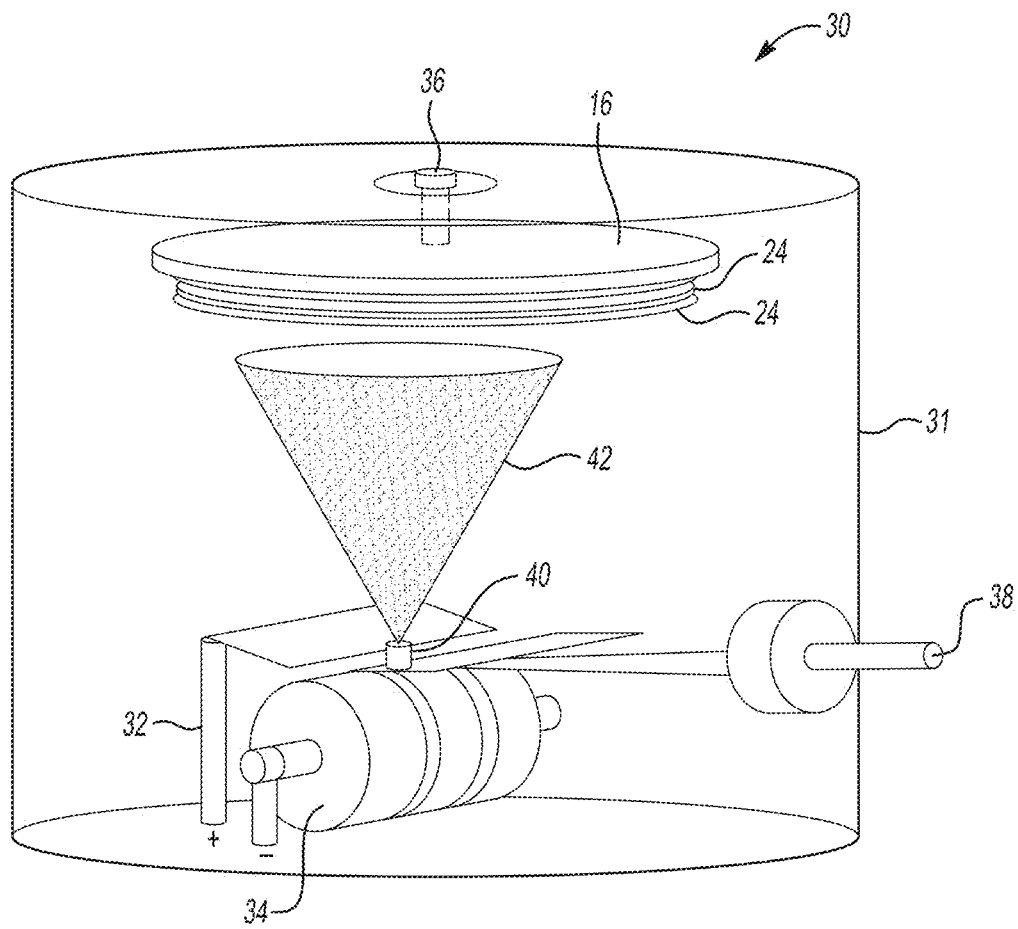


Fig-4

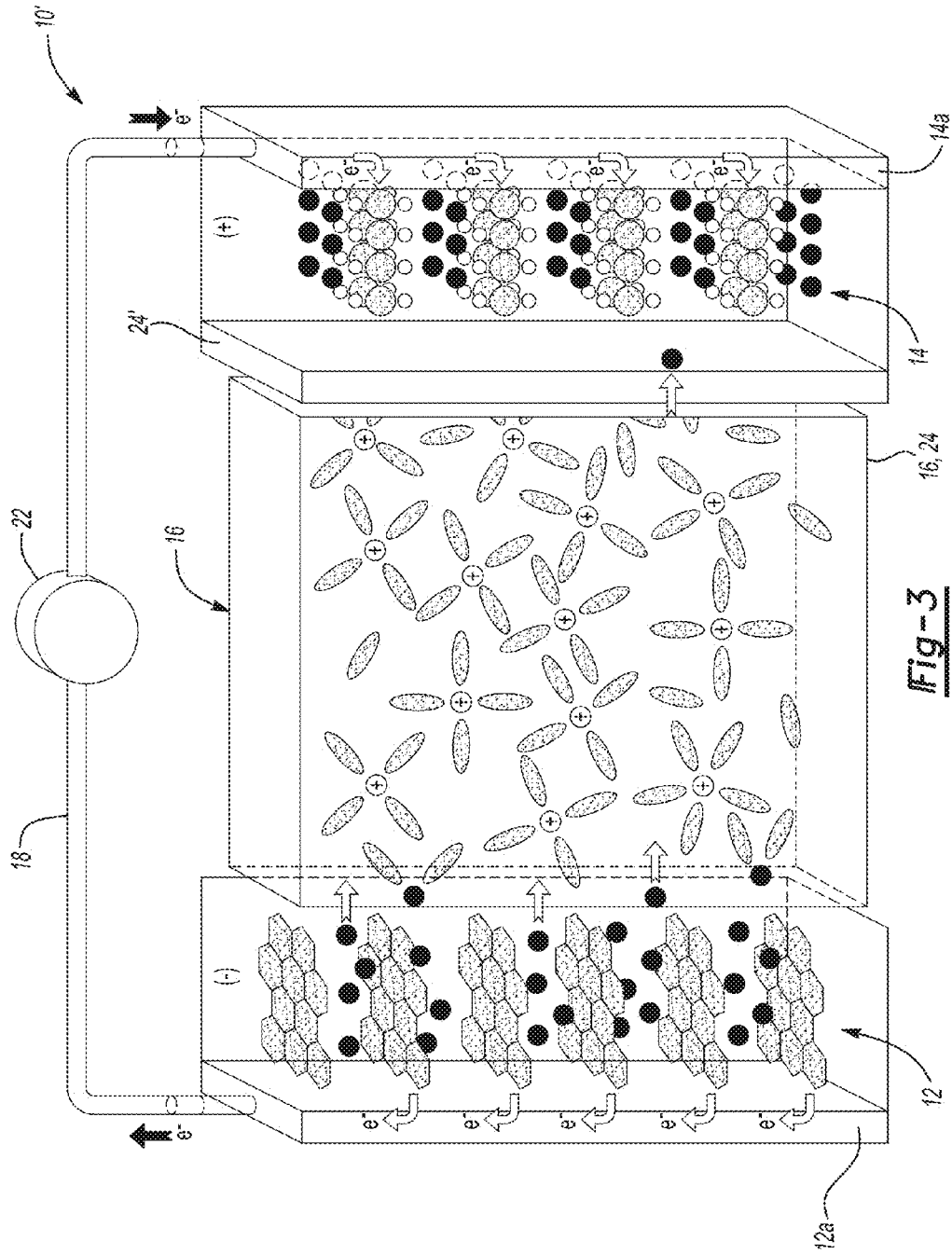


Fig-3

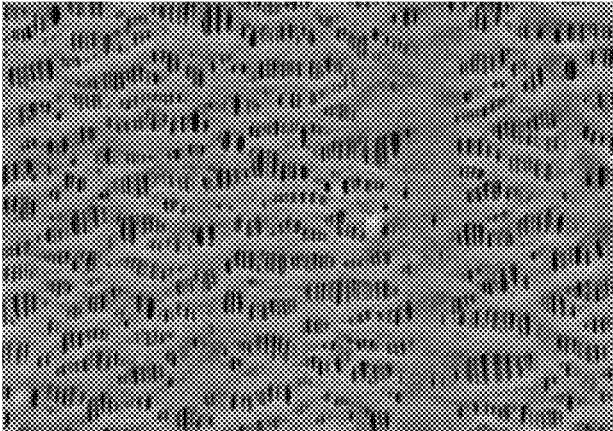


Fig-5A

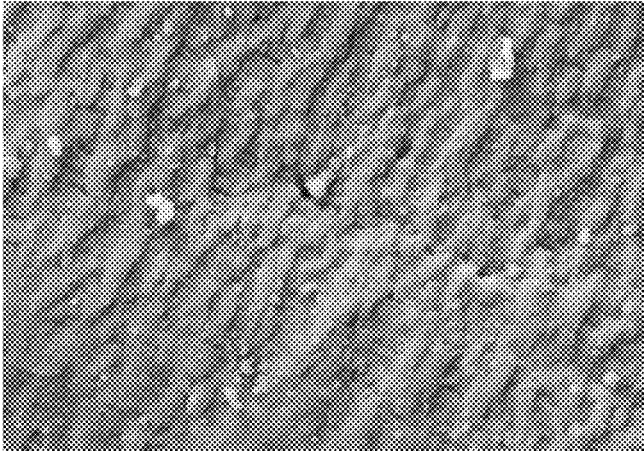


Fig-5B

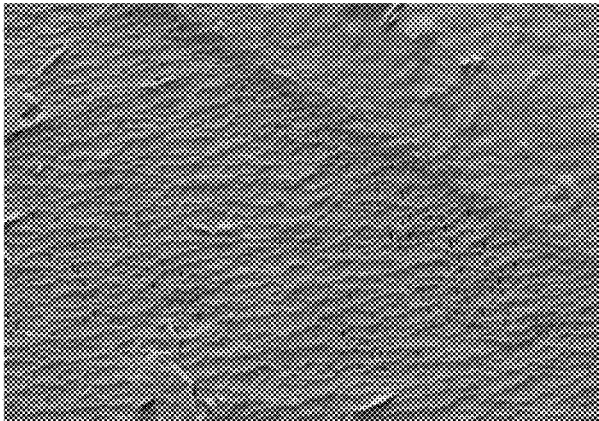


Fig-5C

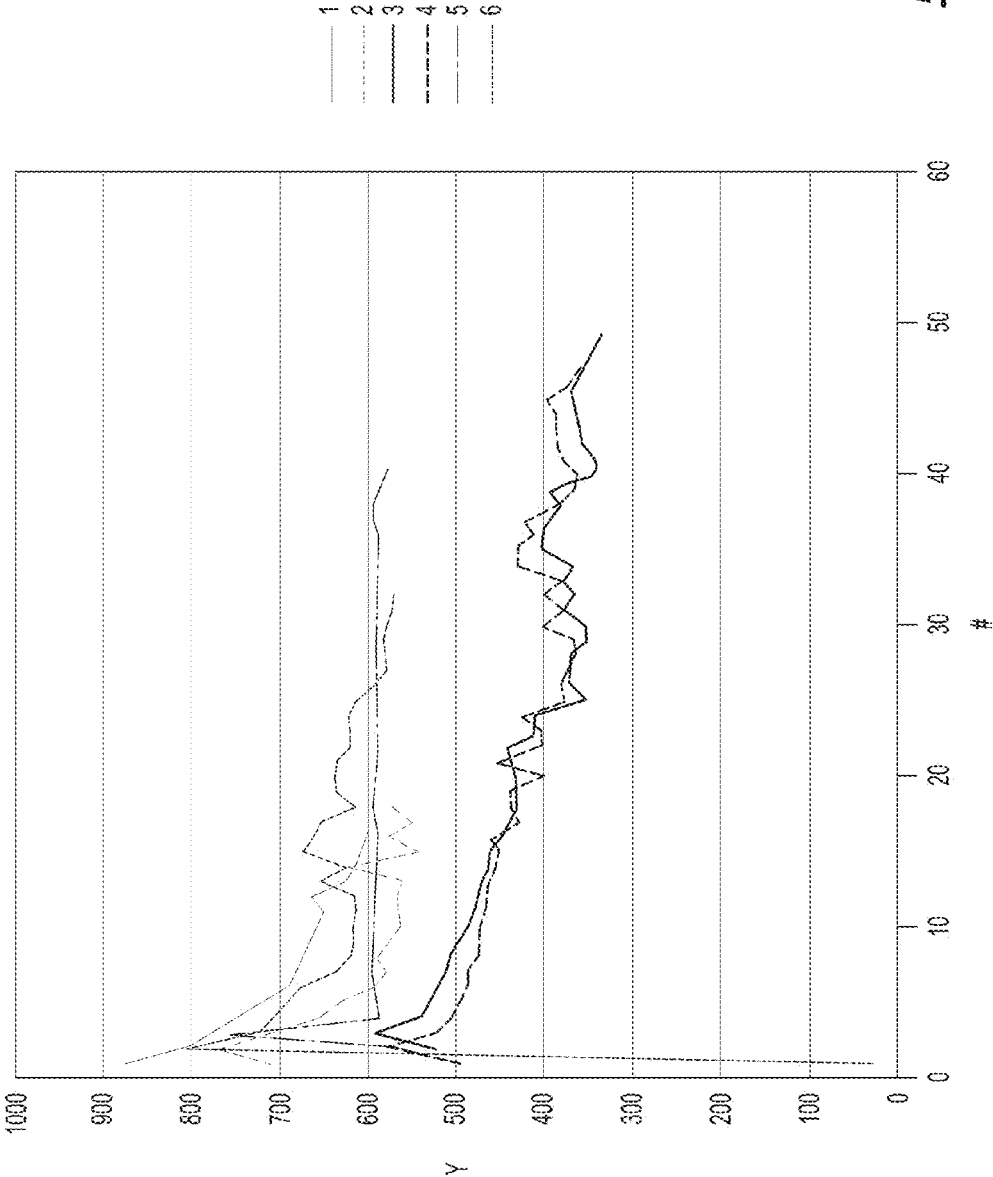


Fig-6

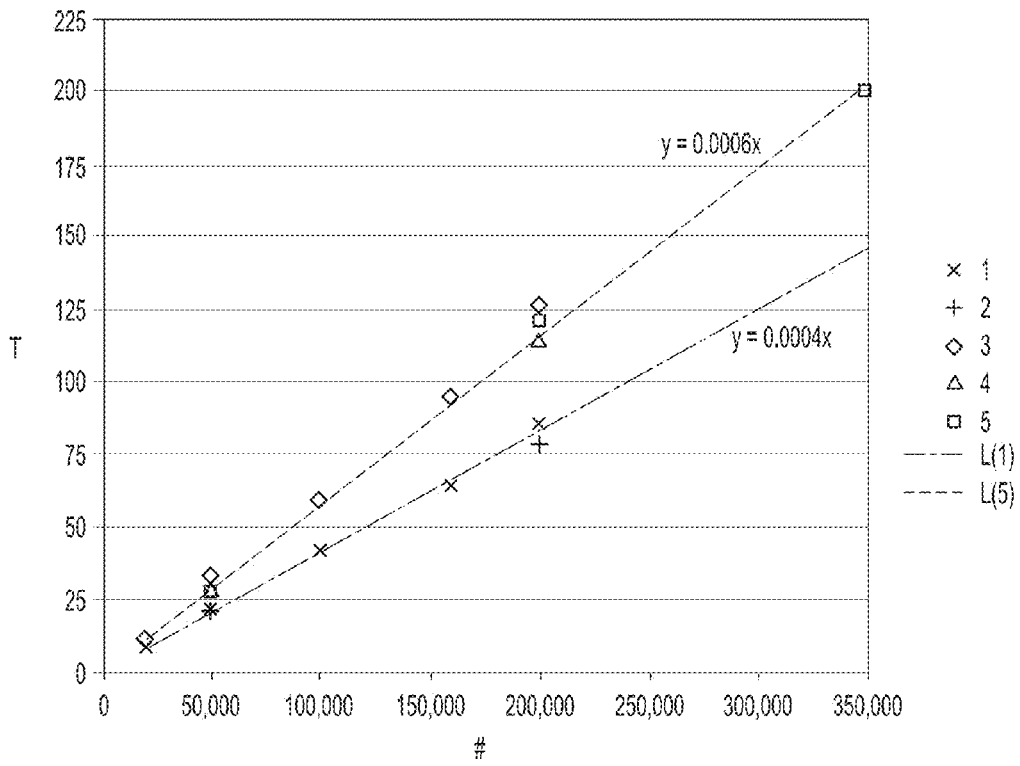


Fig-7

COATED POROUS SEPARATORS AND COATED ELECTRODES FOR LITHIUM BATTERIES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Patent Provisional Application Ser. No. 61/868,346, filed Aug. 21, 2013.

BACKGROUND

[0002] Secondary, or rechargeable, lithium-sulfur batteries or lithium ion batteries are often used in many stationary and portable devices, such as those encountered in the consumer electronic, automobile, and aerospace industries. The lithium class of batteries has gained popularity for various reasons including a relatively high energy density, a general nonappearance of any memory effect when compared to other kinds of rechargeable batteries, a relatively low internal resistance, and a low self-discharge rate when not in use. The ability of lithium batteries to undergo repeated power cycling over their useful lifetimes makes them an attractive and dependable power source.

SUMMARY

[0003] An example of a porous separator includes an untreated porous polymer membrane, and a nanocomposite structure i) formed on a surface of the porous polymer membrane, or ii) dispersed in pores of the porous polymer membrane, or iii) combinations of i and ii. The nanocomposite structure is selected from the group consisting of a carbon nanocomposite structure, a metal oxide nanocomposite structure, and a mixed carbon and metal oxide nanocomposite structure.

[0004] A coated electrode and a lithium battery are also disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Features and advantages of examples of the present disclosure will become apparent by reference to the following detailed description and drawings, in which like reference numerals correspond to similar, though perhaps not identical, components. For the sake of brevity, reference numerals or features having a previously described function may or may not be described in connection with other drawings in which they appear.

[0006] FIG. 1 is a schematic, perspective view of an example of a lithium-sulfur battery showing a charging and discharging state, the battery including an example of the porous separator according to the present disclosure;

[0007] FIG. 2 is a cross-sectional view of an example of a coated electrode according to the present disclosure;

[0008] FIG. 3 is a schematic, perspective view of an example of a lithium ion battery during a discharging state, the battery including an example of the coated electrode according to the present disclosure;

[0009] FIG. 4 is a schematic view of an example of a system for coating the porous separator or electrode;

[0010] FIGS. 5A through 5C are scanning electron microscope (SEM) images of an uncoated porous polymer membrane (FIG. 5A), a carbon nanocomposite structure coated porous polymer membrane (FIG. 5B), and a SnO₂ nanocomposite structure coated porous polymer membrane (FIG. 5C);

[0011] FIG. 6 is a graph illustrating the discharge capacity (mAh/g) for examples of the porous separator disclosed herein and for comparative examples; and

[0012] FIG. 7 is a graph illustrating the effect of laser discharges and laser frequency on the thickness of the nanocomposite structure that is formed.

DETAILED DESCRIPTION

[0013] Lithium-sulfur batteries and other lithium ion batteries generally operate by reversibly passing lithium ions between a negative electrode (sometimes called an anode) and a positive electrode (sometimes called a cathode). The negative and positive electrodes are situated on opposite sides of a porous polymer separator soaked with an electrolyte solution that is suitable for conducting the lithium ions. Each of the electrodes is also associated with respective current collectors, which are connected by an interruptible external circuit that allows an electric current to pass between the negative and positive electrodes.

[0014] It has been found that the lithium-sulfur battery life cycle may be limited by the migration, diffusion, or shuttling of polysulfides from the sulfur cathode during the battery discharge process, through the porous polymer separator, to the anode. The S_x polysulfides generated at the cathode are soluble in the electrolyte, and can migrate to the anode (e.g., a lithium electrode) where they react with the anode in a parasitic fashion to generate lower-order polysulfides. These polysulfides diffuse back to the cathode and regenerate the higher forms of polysulfide. As a result, a shuttle effect takes place. This effect leads to decreased sulfur utilization, self-discharge, poor cycleability, and reduced Coulombic efficiency of the battery. It is believed that even a small amount of polysulfide at the anode can lead to parasitic loss of active lithium at the anode, which prevents reversible electrode operation and reduces the useful life of the lithium-sulfur battery.

[0015] Similarly, it has been found that the lithium ion battery containing a lithium transition metal oxide-based cathode may suffer from manganese dissolution. For instance, a graphite anode may be poisoned by Mn⁺² cations that dissolve from spinel LiMn₂O₄ of the cathode. For instance, the Mn⁺² cations may migrate through the battery electrolyte and porous polymer separator, and deposit onto the graphite electrode. When deposited onto the graphite, the Mn⁺² cations become Mn atoms. It is believed that a small amount (e.g., 1 ppm) of Mn atoms can poison the graphite electrode, and prevent reversible electrode operation and thus reduce the useful life of the battery.

[0016] In some of the examples disclosed herein, the diffusive polysulfide of the lithium-sulfur battery or the diffusive Mn⁺² cations of the lithium ion battery may be reduced or prevented by incorporating a nanocomposite structure coating on a surface of and/or in pores of a porous polymer membrane, and/or on a surface of the cathode. In any of the examples disclosed herein, the nanocomposite structure coating may be formed of carbon, a metal oxide, or a mixture of carbon and metal oxide. The nanocomposite structure coating may be a single layer, a bilayer, or a multi-layered structure with three or more layers. The nanocomposite structure coating is lithium conducting and includes pores sized to i) allow lithium ions to pass through and ii) block/trap polysulfide ions or manganese cations from passing through. As such, the

nanocomposite structure coating disclosed herein acts as a barrier that may improve the capacity and useful life of the battery.

[0017] An example of a secondary lithium-sulfur battery **10** is schematically shown in FIG. 1. The battery **10** generally includes an anode **12**, a cathode **14**, and a porous polymer separator **28**. The porous polymer separator **28** includes a porous polymer membrane **16** having the nanocomposite structure **24** formed on its surface and/or in its pores (not shown). The lithium-sulfur battery **10** also includes an interruptible external circuit **18** that connects the anode **12** and the cathode **14**. Each of the anode **12**, the cathode **14**, and the porous polymer separator **16** are soaked in an electrolyte solution that is capable of conducting lithium ions. The presence of the electrolyte solution may provide a larger contact surface for lithium ion transport and may enhance the conductivity of the cathode **14**.

[0018] The porous polymer separator **28**, which operates as both an electrical insulator and a mechanical support, is sandwiched between the anode **12** and the cathode **14** to prevent physical contact between the two electrodes **12**, **14** and to prevent the occurrence of a short circuit. The nanocomposite structure **24** that is formed on the surface of the membrane **16** may be positioned to face the cathode **14**. The porous polymer separator **28** (i.e., the membrane **16** and the nanocomposite structure **24**), in addition to providing a physical barrier between the two electrodes **12**, **14**, ensures passage of lithium ions (identified by the Li^+) and some related anions through the electrolyte solution filling its pores. However, as discussed above, the microporous polymer separator **28** also blocks the passage of polysulfide ions due to the presence of the nanocomposite structure **24**.

[0019] A negative-side current collector **12a** and a positive-side current collector **14a** may be positioned in contact with the anode **12** and the cathode **14**, respectively, to collect and move free electrons to and from the external circuit **18**.

[0020] The lithium-sulfur battery **10** may support a load device **22** that can be operatively connected to the external circuit **18**. The load device **22** may be powered fully or partially by the electric current passing through the external circuit **18** when the lithium-sulfur battery **10** is discharging. While the load device **22** may be any number of known electrically-powered devices, a few specific examples of a power-consuming load device include an electric motor for a hybrid vehicle or an all-electrical vehicle, a laptop computer, a cellular phone, and a cordless power tool. The load device **22** may also, however, be a power-generating apparatus that charges the lithium-sulfur battery **10** for purposes of storing energy. For instance, the tendency of windmills and solar panels to variably and/or intermittently generate electricity often results in a need to store surplus energy for later use.

[0021] The lithium-sulfur battery **10** can include a wide range of other components that, while not depicted here, are nonetheless known to skilled artisans. For instance, the lithium-sulfur battery **10** may include a casing, gaskets, terminals, tabs, and any other desirable components or materials that may be situated between or around the anode **12** and the cathode **14** for performance-related or other practical purposes. Moreover, the size and shape of the lithium-sulfur battery **10**, as well as the design and chemical make-up of its main components, may vary depending on the particular application for which it is designed. Battery-powered automobiles and hand-held consumer electronic devices, for example, are two instances where the lithium-sulfur battery

10 would most likely be designed to different size, capacity, and power-output specifications. The lithium-sulfur battery **10** may also be connected in series and/or in parallel with other similar lithium-sulfur batteries **10** to produce a greater voltage output and current (if arranged in parallel) or voltage (if arranged in series) if the load device **22** so requires.

[0022] The lithium-sulfur battery **10** can generate a beneficial electric current during battery discharge (shown by reference numeral **11** in FIG. 1). During discharge, the chemical processes in the battery **10** include delithiation from the surface of the anode **12** and incorporation of the lithium cations into alkali metal polysulfide salts (i.e., Li_2S_x). As such, lithium polysulfides are formed (sulfur is reduced) on the surface of the cathode **14** in sequence while the battery **10** is discharging. The chemical potential difference between the cathode **14** and the anode **12** (ranging from approximately 1.5 to 3.0 volts, depending on the exact chemical make-up of the electrodes **12**, **14**) drives electrons produced by the delithiation at the anode **12** through the external circuit **18** towards the cathode **14**. The resulting electric current passing through the external circuit **18** can be harnessed and directed through the load device **22** until the lithium in the anode is depleted and the energy of the lithium-sulfur battery **10** is diminished.

[0023] The lithium-sulfur battery **10** can be charged or re-powered at any time by applying an external power source to the lithium-sulfur battery **10** to reverse the electrochemical reactions that occur during battery discharge. During charging (shown at reference numeral **13** in FIG. 1), lithium plating to the anode **12** takes place and sulfur formation at the cathode **14** takes place. The connection of an external power source to the lithium-sulfur battery **10** compels the otherwise non-spontaneous oxidation of lithium sulfides at the cathode **14** to produce electrons and free lithium cations. The electrons, which flow back towards the anode **12** through the external circuit **18**, and the lithium ions (Li^+), which are carried by the electrolyte across the porous polymer separator **28** back towards the anode **12**, reunite at the anode **12** and replenish the anode **12** with lithium for consumption during the next battery discharge cycle. The external power source that may be used to charge the lithium-sulfur battery **10** may vary depending on the size, construction, and particular end-use of the lithium-sulfur battery **10**. Some suitable external power sources include a battery charger plugged into an AC wall outlet and a motor vehicle alternator.

[0024] The anode **12** may include any lithium host material that can sufficiently undergo lithium plating and stripping while functioning as the negative terminal of the lithium-sulfur battery **10**. The negative electrode **12** may also be a silicon-based material that is prelithiated. For lithium ion cells, the negative electrode **12** may also include a polymer binder material to structurally hold the lithium host material together. For example, the negative electrode **12** may be formed of an active material, made from graphite or a low surface area amorphous carbon, intermingled with a binder, made from polyvinylidene fluoride (PVdF), an ethylene propylene diene monomer (EPDM) rubber, sodium alginate, or carboxymethyl cellulose (CMC). These materials may be mixed with a high surface area carbon, such as acetylene black, to ensure electron conduction between the current collector **12a** and the active material particles of the anode **12**. Graphite is widely utilized to form the negative electrode because it exhibits reversible lithium intercalation and deintercalation characteristics, is relatively non-reactive, and can store lithium in quantities that produce a relatively high

energy density. Commercial forms of graphite that may be used to fabricate the anode **12** are available from, for example, Timcal Graphite & Carbon (Bodio, Switzerland), Lonza Group (Basel, Switzerland), or Superior Graphite (Chicago, Ill.). Other materials can also be used to form the negative electrode including, for example, lithium titanate. The negative-side current collector **12a** may be formed from copper or any other appropriate electrically conductive material known to skilled artisans.

[0025] The cathode **14** of the lithium-sulfur battery **10** may be formed from any sulfur-based active material that can sufficiently undergo lithiation and delithiation while functioning as the positive terminal of the lithium-sulfur battery **10**. Examples of sulfur-based active materials include S_8 , Li_2S_8 , Li_2S_6 , Li_2S_4 , Li_2S_2 , and Li_2S . As will be discussed below, the cathode **14** may be coated (e.g., on a single surface) or encapsulated with an example of the carbon and/or mixed metal oxide nanostructure **24'** disclosed herein. In addition, the cathode **14** may also include a polymer binder material to structurally hold the sulfur-based active material together. The polymeric binder may be made of at least one of polyvinylidene fluoride (PVdF), polyethylene oxide (PEO), an ethylene propylene diene monomer (EPDM) rubber, or carboxymethyl cellulose (CMC). The positive-side current collector **14a** may be formed from aluminum or any other appropriate electrically conductive material known to skilled artisans.

[0026] Any appropriate electrolyte solution that can conduct lithium ions between the anode **12** and the cathode **14** may be used in the lithium-sulfur battery **10**. In one example, the non-aqueous electrolyte solution may be an ether based electrolyte that is stabilized with lithium nitrite. Other non-aqueous liquid electrolyte solutions may include a lithium salt dissolved in an organic solvent or a mixture of organic solvents. Examples of lithium salts that may be dissolved in the ether to form the non-aqueous liquid electrolyte solution include $LiClO_4$, $LiAlCl_4$, LiI , $LiBr$, $LiSCN$, $LiBF_4$, $LiB(C_6H_5)_4$, $LiAsF_6$, $LiCF_3SO_3$, $LiN(FSO_2)_2$, $LiN(CF_3SO_2)_2$, $LiAsF_6$, $LiPF_6$, and mixtures thereof. The ether based solvents may be composed of cyclic ethers, such as 1,3-dioxolane, tetrahydrofuran, 2-methyltetrahydrofuran, and chain structure ethers, such as 1,2-dimethoxyethane, 1-2-diethoxyethane, ethoxymethoxyethane, tetraethylene glycol dimethyl ether (TEGDME), polyethylene glycol dimethyl ether (PEGDME), and mixtures thereof.

[0027] The porous polymer membrane **16** of the porous polymer separator **28** may be formed, e.g., from a polyolefin. The polyolefin may be a homopolymer (derived from a single monomer constituent) or a heteropolymer (derived from more than one monomer constituent), and may be either linear or branched. If a heteropolymer derived from two monomer constituents is employed, the polyolefin may assume any copolymer chain arrangement including those of a block copolymer or a random copolymer. The same holds true if the polyolefin is a heteropolymer derived from more than two monomer constituents. As examples, the polyolefin may be polyethylene (PE), polypropylene (PP), a blend of PE and PP, or multi-layered structured porous films of PE and/or PP. Commercially available porous polymer membranes include single layer polypropylene membranes, such as CELGARD 2400 and CELGARD 2500 from Celgard, LLC (Charlotte, N.C.). It is to be understood that the porous polymer membrane **16** is uncoated or untreated. For example, the porous polymer membrane does not include any surfactant treatment

thereon. It is believed that the uncoated/untreated membrane adheres better to the nanocomposite structure **24**.

[0028] In another example, the membrane **16** of the porous polymer separator **28** may be formed from another polymer chosen from polyethylene terephthalate (PET), polyvinylidene fluoride (PVdF), polyamides (Nylons), polyurethanes, polycarbonates, polyesters, polyetheretherketones (PEEK), polyethersulfones (PES), polyimides (PI), polyamide-imides, polyethers, polyoxymethylene (e.g., acetal), polybutylene terephthalate, polyethylenenaphthenate, polybutene, polyolefin copolymers, acrylonitrile-butadiene styrene copolymers (ABS), polystyrene copolymers, polymethylmethacrylate (PMMA), polyvinyl chloride (PVC), polysiloxane polymers (such as polydimethylsiloxane (PDMS)), polybenzimidazole (PBI), polybenzoxazole (PBO), polyphenylenes (e.g., PARMAX™ (Mississippi Polymer Technologies, Inc., Bay Saint Louis, Mississippi)), polyarylene ether ketones, polyperfluorocyclobutanes, polytetrafluoroethylene (PTFE), polyvinylidene fluoride copolymers and terpolymers, polyvinylidene chloride, polyvinyl fluoride, liquid crystalline polymers (e.g., VECTRAN™ (Hoechst AG, Germany) and ZENITE® (DuPont, Wilmington, Del.)), polyaramides, polyphenylene oxide, and/or combinations thereof. It is believed that another example of a liquid crystalline polymer that may be used for the membrane **16** of the separator **28** is poly(p-hydroxybenzoic acid). In yet another example, the membrane **16** of the porous polymer separator **18** may be chosen from a combination of the polyolefin (such as PE and/or PP) and one or more of the polymers for the membrane **16** listed above.

[0029] The porous polymer membrane **16** may be a single layer or may be a multi-layer (e.g., bilayer, trilayer, etc.) laminate fabricated from either a dry or wet process. In some instances, the membrane **16** may include fibrous layer(s) to impart appropriate structural and porosity characteristics.

[0030] As mentioned above, the nanocomposite structure **24** is a carbon nanocomposite structure, a metal oxide nanocomposite structure, or a mixed carbon and metal oxide nanocomposite structure. In some instances, the mixed carbon and metal oxide nanocomposite structure may be desirable due to the increased conductivity that carbon, and in some instances the selected metal, provide. It is to be understood that in the examples disclosed herein, the nanocomposite structure **24** is not required to be conductive in order to serve as the barrier; however, the conductivity may be desirable for reduced cell level resistance. In some examples, any group 2 (beryllium group), 4 (titanium group), 5 (vanadium group), 6 (chromium group), 7 (manganese group), 13 (boron group) and/or 14 (carbon group) metal oxide may be used. As examples, the metal oxide may be a titanium oxide (e.g., TiO_2 or Ti_4O_7), a zirconium oxide, a hafnium oxide, a vanadium oxide, a niobium oxide, a tantalum oxide, a boron oxide, an aluminum oxide, a gallium oxide, an indium oxide, a thalium oxide, a silicon oxide, a germanium oxide, a tin oxide, a lead oxide, and mixtures thereof (e.g., an indium tin oxide). Other examples of suitable metal oxides, that may be used alone or in combination with any of the previously listed metal oxides, include a calcium oxide, an antimony oxide, a magnesium oxide, and a tungsten oxide (e.g., WO_3).

[0031] When the nanocomposite structure **24** is a mixed carbon and metal oxide nanocomposite structure, the ratio of carbon to metal oxide may range from about 20:80 to about 80:20. In other words, the amount of carbon in the mixed carbon and metal oxide nanocomposite structure may range

from about 20 wt. % to about 80 wt. %, and the amount of metal oxide in the mixed carbon and metal oxide nanocomposite structure may range from about 80 wt. % to about 20 wt. %. In another example, the ratio of carbon to metal oxide may range from about 50:80 to about 80:20.

[0032] When the carbon nanocomposite structure is formed, the ratio of sp² orbitals to sp³ orbitals ranges from about 0.9 to about 4. Furthermore, the carbon nanocomposite structure may consist of amorphous carbon or it may consist of crystalline carbon. In an example, the amorphous nanocomposite structure 24 (or 24') has a very small crystalline nature. By "very small", it is meant that less than 10% of the amorphous nanocomposite structure 24 (or 24') is crystalline and the crystallite would be nanocrystallites. The crystallinity of the final nanocomposite structure 24 (or 24') may be controlled during the processes disclosed herein, for example, by altering the arc intensity.

[0033] In any of the examples of the nanocomposite structure 24 (or 24' discussed below), the surface roughness may range from about 200 nm to about 1000 nm.

[0034] The nanocomposite structure 24 may be formed on the surface of the fibers (not shown) of the porous polymer membrane 16 and/or may penetrate (e.g., disperse within) the pores (not shown) of the porous polymer membrane 16. While the nanocomposite structure 24 may fill the pores of the membrane 16, the nanocomposite structure 24 itself is lithium conducting and includes pores which are small enough to block polysulfide ions from moving therethrough, and are large enough to allow lithium cations to move therethrough. In an example, the porosity of the nanocomposite structure 24 (and thus of the porous polymer separator 28) is greater than 0% and is equal to or less than 50%. In another example, the porosity of the nanocomposite structure 24 (and thus of the porous polymer separator 28) ranges from about 10% to about 40%. The porosity of the porous polymer separator 28 may depend, at least in part, on the thickness of the nanocomposite structure 24. In general, it is believed that the thicker the structure 24, the less porous the structure 24. This is due, at least in part, to subsequently deposited material(s) that add to the thickness of the structure 24 filling pores that had been formed.

[0035] The nanocomposite structure 24 has a thickness of 2 μm or less (e.g., down to about 1 nm). In other examples, the thickness is 1 μm or less, 100 nm or less, or 50 nm or less. It is to be understood that the nanocomposite structure 24 may be a single layer, a bilayer, or some other multi-layered structure (i.e., 3 or more layers). In these instances, the total thickness is still 2 μm or less.

[0036] FIG. 1 illustrates a lithium-sulfur battery 10 with an example of the porous polymer separator 28 disclosed herein. In this example, the polysulfides may dissolve in the electrolyte, but are prevented from pass through the separator 28 due to the nanocomposite structure 24.

[0037] In another example of the lithium-sulfur battery 10, the porous polymer separator 28 is utilized, and the cathode 14 is also coated with the nanocomposite structure 24' (shown in phantom in FIG. 1). The nanocomposite structure 24' in this example may be deposited on the surface of the positive electrode 14 that faces the separator 28 (as shown in FIG. 1), or may completely encapsulate the electrode 14 (not shown). It is to be understood that the materials and thickness of the nanocomposite structure 24' is similar to those and that of the nanocomposite structure 24, and thus the nanocomposite structure 24' is lithium conducting but polysulfide blocking.

In still another example of the lithium-sulfur battery 10 (not shown), the porous polymer membrane 16 is used without the nanocomposite structure 24 therein and thereon, and the cathode 14 is coated with nanocomposite structure 24'. When the nanocomposite structure 24' is utilized (either in conjunction with the separator 28 or with the membrane 16 without nanocomposite structure 24), it is to be understood that the polysulfides would be blocked from even dissolving in the electrolyte.

[0038] Examples of how the nanocomposite structures 24 and 24' are formed will be discussed further in reference to FIG. 4.

[0039] As noted above, a lithium ion battery (see FIG. 3) including a positive electrode (14' in FIG. 2) based on a lithium transition metal oxide-based active material may also benefit from the nanocomposite structure 24' disclosed herein being deposited on the positive electrode 14'. An example of the nanocomposite structure 24' coated on a positive electrode 14' is shown in FIG. 2. The nanocomposite structure 24' in this example may be deposited on the surface of the positive electrode 14' in accordance with the method(s) disclosed herein. It is to be understood that the materials and thickness of the nanocomposite structure 24' are similar to those and that of the nanocomposite structure 24.

[0040] In the example shown in FIG. 2, the positive electrode 14' may include a lithium transition metal oxide-based active material intermingled with a polymeric binder and mixed with a high surface area carbon, such as acetylene black. The active material in the positive electrode 14' may be any lithium host material that can sufficiently undergo lithium intercalation and deintercalation while functioning as the positive terminal of a lithium ion battery. As examples, the active material in this positive electrode 14' may be made of at least one of spinel lithium manganese oxide (LiMn₂O₄), a nickel-manganese oxide spinel [Li(Ni_{0.5}Mn_{1.5})O₂], a layered nickel-manganese-cobalt oxide [Li(Ni_xMn_yCo_z)O₂], LiCoO₂, LiNiO₂, LiFePO₄, Li₂MSiO₄ (M=Co, Fe, Mn), a lithium rich layer-structure cathode, such as xLi₂MnO₃-(1-x)LiMO₂ (M is composed of any ratio of Ni, Mn and Co), or HE-NMC (high efficiency Nickel-Manganese-Cobalt) cathodes.

[0041] An example of the lithium ion battery 10' including the cathode 14' and the nanocomposite structure 24' is shown in FIG. 3. The battery 10' generally includes an anode 12, the cathode 14' having the nanocomposite structure 24' formed on surface(s) thereof, and the porous polymer membrane 16. The lithium ion battery 10' also includes an interruptible external circuit 18 that connects the anode 12 and the cathode 14'. Each of the anode 12, the cathode 14', and the porous polymer membrane 16 may be soaked in an electrolyte solution that is capable of conducting lithium ions. The presence of the electrolyte solution may provide a larger contact surface for lithium ion transport and may enhance the conductivity of the cathode 14'.

[0042] Any example of the anode 12, the negative-side current collector 12a, the cathode 14' and the nanocomposite structure 24', and the positive-side current collector 14a described herein may be used in the lithium ion battery 10'. The negative-side current collector 12a and the positive-side current collector 14a may be positioned in contact with the anode 12 and the cathode 14', respectively, to collect and move free electrons to and from the external circuit 18.

[0043] Furthermore, any of the examples of the porous polymer membrane 16 may be used in the battery 10' shown

in FIG. 3. The porous polymer membrane 16 operates as both an electrical insulator and a mechanical support, and is sandwiched between the anode 12 and the cathode 14' to prevent physical contact between the two electrodes 12, 14' and the occurrence of a short circuit. The porous polymer membrane 16, in addition to providing a physical barrier between the two electrodes 12, 14', ensures passage of lithium ions (identified by the black dots and by the open circles having a (+) charge in FIG. 3) through the liquid electrolyte filling the pores (not shown) of the membrane 16.

[0044] Any appropriate electrolyte solution that can enhance the conductivity and wet the cathode 14' may be used in the lithium ion battery 10'. In one example, the electrolyte solution may be a non-aqueous liquid electrolyte solution that includes a lithium salt dissolved in an organic solvent or a mixture of organic solvents. Skilled artisans are aware of the many non-aqueous liquid electrolyte solutions that may be employed in the lithium ion battery 10 as well as how to manufacture or commercially acquire them. Examples of lithium salts that may be dissolved in an organic solvent to form the non-aqueous liquid electrolyte solution for the battery 10' include LiClO₄, LiAlCl₄, LiI, LiBr, LiSCN, LiBF₄, LiB(C₆H₅)₄, LiAsF₆, LiCF₃SO₃, LiN(FSO₂)₂, LiN(CF₃SO₂)₂, LiAsF₆, LiPF₆, and mixtures thereof. These and other similar lithium salts may be dissolved in a variety of organic solvents such as cyclic carbonates (ethylene carbonate, propylene carbonate, butylene carbonate), linear carbonates (dimethyl carbonate, diethyl carbonate, ethylmethyl carbonate), aliphatic carboxylic esters (methyl formate, methyl acetate, methyl propionate), γ -lactones (γ -butyrolactone, γ -valerolactone), chain structure ethers (1,2-dimethoxyethane, 1-2-diethoxyethane, ethoxymethoxyethane, tetraglyme), cyclic ethers (tetrahydrofuran, 2-methyltetrahydrofuran, 1,3-dioxolane), and mixtures thereof.

[0045] The lithium ion battery 10' may support a load device 22 that can be operatively connected to the external circuit 18. The load device 22 may be powered fully or partially by the electric current passing through the external circuit 18 when the lithium ion battery 10' is discharging. While the load device 22 may be any number of known electrically-powered devices, a few specific examples of a power-consuming load device include an electric motor for a hybrid vehicle or an all-electrical vehicle, a laptop computer, a cellular phone, and a cordless power tool. The load device 22 may also, however, be a power-generating apparatus that charges the lithium ion battery 10' for purposes of storing energy. For instance, the tendency of windmills and solar panels to variably and/or intermittently generate electricity often results in a need to store surplus energy for later use.

[0046] The lithium ion battery 10' can also include a wide range of other components that, while not depicted here, are nonetheless known to skilled artisans. For instance, the lithium ion battery 10' may include a casing, gaskets, terminals, tabs, and any other desirable components or materials that may be situated between or around the anode 12 and the cathode 14 for performance-related or other practical purposes. Moreover, the size and shape of the lithium ion battery 10', as well as the design and chemical make-up of its main components, may vary depending on the particular application for which it is designed. Battery-powered automobiles and hand-held consumer electronic devices, for example, are two instances where the lithium-sulfur battery 10' would most likely be designed to different size, capacity, and power-output specifications. The lithium ion battery 10' may also be

connected in series and/or in parallel with other similar lithium ion battery 10' to produce a greater voltage output and current (if arranged in parallel) or voltage (if arranged in series) if the load device 22 so requires.

[0047] The lithium ion battery 10' can generate a useful electric current during battery discharge by way of reversible electrochemical reactions that occur when the external circuit 18 is closed to connect the anode 12 and the cathode 14' at a time when the anode 12 contains a sufficiently higher relative quantity of intercalated lithium. The chemical potential difference between the cathode 14' and the anode 12 (ranging from approximately 1.5 volts to 5.0 volts, depending on the exact chemical make-up of the electrodes 12, 14') drives electrons produced by the oxidation of intercalated lithium at the anode 12 through the external circuit 18 towards the cathode 14'. Lithium ions, which are also produced at the anode 12, are concurrently carried by the anions through the porous polymer membrane 16 and towards the cathode 14'. The electrons flowing through the external circuit 18 and the lithium ions migrating across the porous polymer membrane 16 in the liquid electrolyte eventually reconcile and form intercalated lithium at the cathode 14'. The electric current passing through the external circuit 18 can be harnessed and directed through the load device 22 until the intercalated lithium in the anode is depleted and the capacity of the lithium ion battery 10' is diminished.

[0048] The lithium ion battery 10' can be charged or re-powered at any time by applying an external power source to the lithium ion battery 10' to reverse the electrochemical reactions that occur during battery discharge. The connection of an external power source to the lithium ion battery 10' compels the otherwise non-spontaneous oxidation of lithium transition metal oxide or phosphate at the cathode 14' to produce electrons and release lithium ions. The electrons, which flow back towards the anode 12 through the external circuit 18, and the lithium ions, which are carried by the liquid electrolyte across the porous polymer membrane 16 back towards the anode 12, reunite at the anode 12 and replenish the anode 12 with intercalated lithium for consumption during the next battery discharge cycle. In this example, while the nanocomposite structure 24' carries the lithium ions through its pores, it also blocks the passage of manganese cations from the cathode 14' to the anode 12. The external power source that may be used to charge the lithium ion battery 10' may vary depending on the size, construction, and particular end-use of the lithium ion battery 10'. Some suitable external power sources include a battery charger plugged into an AC wall outlet and a motor vehicle alternator.

[0049] The nanocomposite structure 24 or 24' may be formed using a laser arc plasma deposition process, a cathodic arc deposition process, an electron beam evaporation process, or a pulsed laser deposition process. These processes can be tuned to utilize relatively low temperatures (ranging from about 30° C. to about 70° C.), and thus do not deleteriously affect the membrane 16 or the electrode 14 or 14'. It is believed that better adhesion between the membrane 16 or electrode 14' and the nanocomposite structure 24, 24' may also be obtained using these processes.

[0050] FIG. 4 schematically illustrates an example of the system 30 used in laser arc plasma deposition. A substrate holder 36 holds the membrane 16 or electrode 14 or 14' (not shown in FIG. 4) in place within a vacuum chamber 31 (having a pressure of about 10⁻⁴ Pa). In general, an electric arc is used to vaporize material 42 from a cathode target 34

(which is operatively connected to an anode 32). The vaporized material 42 (e.g., carbon and/or metal oxide) then condenses on the membrane 16 or electrode 14 or 14'. In the example shown in FIG. 4, a pulsing and oscillating laser beam 38 strikes the surface of the cathode target 34 with a high current, forming a cathode spot. At the cathode spot, plasma is ignited (reference numeral 40), which generates a jet of vaporized material 42 which forms the nanocomposite structure 24, 24' on the membrane 16 or electrode 14 or 14'. The cathode spot is active for a short period of time, and then it self-extinguishes and re-ignites in a new area close to the previous spot. This causes the apparent motion of the arc.

[0051] In an example system 30, the chamber 31 is a Laser-Arc Module (LAM) vacuum chamber, and the laser beam 38 is produced using a pulsed solid-state Nd:YAG laser (wavelength 1.06 μm , pulse length 150 ns, 10 kHz repetition rate, average pulse power density 15 mJ cm^{-2}). The system 30 may also include a pulsed power supply (peak current 2 kA, pulse length 100 μs , repetition rate 1.8 kHz, average current 260 A) and a software/hardware controller. In an example, the chamber 31 houses a cylindrical (e.g., 160 mm diameter, up to 500 mm length) graphite (which functions as the cathode 34) and metal oxide target and a rod-shaped anode 32 for the arc discharge. The cathode 34 and anode 32 may be externally connected to a charged capacitor bank in the pulse power supply.

[0052] In an example, the laser pulses aim through a window into the LAM chamber 31 and focus onto the surface of the graphite cylinder target 34. The 150 ns laser pulse generates a rapidly expanding carbon plasma plume, which in turn ignites a 150 μs vacuum arc discharge pulse between the graphite target (cathode 34) and an anode 32. The vacuum arc discharge is the main energy source to evaporate the graphite. The pulse forming components of the power supply are designed to adjust the maximal arc current, timing and pulse shape. It is to be understood that a combination of a rotating target 34 with a linear scan of the laser pulse (arc location) along the length of the target 34 ensures very uniform target erosion and film deposition. A single laser can be used to ignite several arc sources for boosting deposition rates for coating deposition.

[0053] The carbon and/or metal oxide thin films may be reproducibly deposited over a wide thickness range from a few nanometers to a few micrometers. As such, these deposition techniques also enable control over the thickness of the nanocomposite structure 24, 24'. In an example, the thickness is less than 2 μm . Film thickness control may be accomplished by adjusting the number of ignited arc discharges (i.e., discharge pulses). In an example, the thickness may be decreased by lowering the plasma laser arc discharge pulses. Film thickness control may also be accomplished by adjusting the processing time. Generally, longer processing times results in thicker films.

[0054] To further illustrate the present disclosure, examples are given herein. It is to be understood that these examples are provided for illustrative purposes and are not to be construed as limiting the scope of the disclosed example(s).

Example 1

[0055] Porous separators were formed according to an example of the method disclosed herein. Using laser arc plasma deposition (i.e., a plasma deposition process involving a laser arc), a carbon nanocomposite structure was formed on a CELGARD 2400 separator (Example 5), and a SnO_2

nanocomposite structure was formed on a CELGARD 2400 separator (Example 6). The CELGARD 2400 separator is an untreated single layer polypropylene separator. Each of the nanocomposite structures in Examples 5 and 6 had a thickness of about 50 nm.

[0056] Comparative porous separators were also used. The CELGARD 2400 separator without any coating was used as Example 1. A surfactant treated separator (i.e., CELGARD 3501) was also used in some of the comparative examples. Example 2 included a V_2O_5 coating on the CELGARD 3501 separator, where the V_2O_5 coating had a thickness of about 5 μm . The V_2O_5 coating was prepared via a sol-gel method. An attempt was made to coat the CELGARD 2400 separator with a sol-gel prepared V_2O_5 coating, but the V_2O_5 coating did not adhere. Other comparative examples included a SnO_2 nanocomposite structure formed on the CELGARD 3501 separator using laser arc plasma deposition (Example 3) and a carbon nanocomposite structure formed on the CELGARD 3501 separator using laser arc plasma deposition (Example 4), each of which had a thickness of about 50 nm.

[0057] FIG. 5A is a scanning electron micrograph (SEM) image of Example 1 (i.e., the comparative example of the bare CELGARD 2400 separator), FIG. 5B is a SEM image of Example 5 (i.e., the carbon nanocomposite structure formed on the CELGARD 2400 separator), and FIG. 5C is a SEM image of Example 6 (i.e., the SnO_2 nanocomposite structure formed on the CELGARD 2400 separator). As illustrated, the carbon and metal oxide adhere to the bare membrane and form a thin nanocomposite structure thereon.

[0058] The separators (Examples 5 and 6) and the comparative separators (Examples 1-4) were assembled into respective coin cells (i.e., half cells). The coin cells were composed of a lithium metal anode, one of the examples as the porous separator, and a sulfur cathode. The coin cells were assembled in an argon-filled glove box. The electrolyte was LiTFSI salt in dioxolane/1,2-dimethoxyethane (DIOX:DME) plus 2 wt. % LiNO_3 . Galvanostatic charge and discharge cycle tests were carried out at 25° C. between 2.75 V and 1.5 V.

[0059] FIG. 6 illustrates the discharge curves for each of the examples. As illustrated, the carbon and metal oxide nanocomposite structures coated on the bare polypropylene membranes illustrated the best discharge capacity (Y in FIG. 6, mAh/g) with the longest cycle time (# in FIG. 6). It is believed that the cycle time and capacity may be increased even further if a mixed carbon and metal oxide nanocomposite structure were used. While Examples 3 and 4 exhibited desirably long cycle times, the discharge capacity was the worst of all of the Examples.

Example 2

[0060] Experiments were performed to determine the deposited film thickness and film thickness uniformity as a function of the number of laser pulses/arc discharges in the range from 20,000 to 200,000 pulses as well as the repetition rate (500 Hz, 1 kHz, and 1500 Hz) of these discharges. Silicon wafers were rotated in front of a graphite cylinder during the deposition runs so that both sample sides were coated with a carbon nanocomposite structure coating. It is desirable for the thickness values to be obtained from both the front and back-sides of the samples.

[0061] During these experiments, the arc discharge power supply had to be repaired. Samples 1 and 2 were prepared with the original discharge power supply, and Samples 3-5 were prepared after a new controller component was

installed. After the installation of the new controller component, the thickness data per number of arc discharges remained within 10%.

[0062] The laser frequency used to create Sample 1 was 500 Hz, the laser frequency used to create Sample 2 was 1 kHz, the laser frequency used to create Sample 3 was 500 Hz, the laser frequency used to create Sample 4 was 1 kHz, and the laser frequency used to create Sample 5 was 1500 Hz.

[0063] The thicknesses were determined using contact profilometry as a direct measurement on coated silicon wafers, as well as a spectroscopic method that measures material removal per area and requires mass density values to calculate thickness for a material.

[0064] The results of the film thickness measurements are shown in FIG. 7. The Y axis is the thickness (T) in nanometers, and the X-axis is the number of vacuum arc discharges. The linear extrapolations of Samples 1 and 5 are also shown. At a pulse frequency of 500 Hz, the double-sided deposition rate of 4 nm per 10,000 pulses translates to a deposition rate of 12 nm/min. This corresponds to a direct deposition rate of at least 24 nm/min at 500 Hz and 48 nm/min at 1 kHz operation. These results indicate that laser-arc technology is capable of reproducibly depositing the targeted thickness range, which in some instances ranges from about 30 nm to about 50 nm. Reproducible results were seen for thicknesses of less than 10 nm.

[0065] As illustrated in FIG. 7, the thickness of the nanocomposite structure coating may be controlled by adjusting the laser pulses/arc discharges. Also as illustrated, the thickness may increase linearly with increasing laser pulses/arc discharges.

[0066] It is to be understood that the ranges provided herein include the stated range and any value or sub-range within the stated range. For example, a range of 50 nm or less should be interpreted to include not only the explicitly recited limits of 50 nm or less, but also to include individual values, such as 25 nm, 38 nm, 10.5 nm, etc., and sub-ranges, such as from about 1 nm to about 49 nm; from about 5 nm to about 40 nm, etc. Furthermore, when "about" is utilized to describe a value, this is meant to encompass minor variations (up to +/-5%) from the stated value.

[0067] Reference throughout the specification to "one example", "another example", "an example", and so forth, means that a particular element (e.g., feature, structure, and/or characteristic) described in connection with the example is included in at least one example described herein, and may or may not be present in other examples. In addition, it is to be understood that the described elements for any example may be combined in any suitable manner in the various examples unless the context clearly dictates otherwise.

[0068] In describing and claiming the examples disclosed herein, the singular forms "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

[0069] While several examples have been described in detail, it will be apparent to those skilled in the art that the disclosed examples may be modified. Therefore, the foregoing description is to be considered non-limiting.

What is claimed is:

1. A porous separator, comprising:

an untreated porous polymer membrane; and

a nanocomposite structure i) formed on a surface of the porous polymer membrane, or ii) dispersed in pores of the porous polymer membrane, or iii) combinations of i and ii, the nanocomposite structure selected from the

group consisting of a carbon nanocomposite structure, a metal oxide nanocomposite structure, and a mixed carbon and metal oxide nanocomposite structure.

2. The porous separator as defined in claim 1 wherein the metal oxide nanocomposite structure or a metal oxide of the mixed carbon and metal oxide nanocomposite structure is a group 2 metal oxide, a group 4 metal oxide, a group 5 metal oxide, a group 6 metal oxide, a group 7 metal oxide, a group 13 metal oxide, a group 14 metal oxide, or combinations thereof.

3. The porous separator as defined in claim 1 wherein the metal oxide nanocomposite structure or the metal oxide of the mixed carbon and metal oxide nanocomposite structure is selected from the group consisting of an aluminum oxide, an antimony oxide, a calcium oxide, a magnesium oxide, a tin oxide, a titanium oxide, a tungsten oxide, a silicon oxide, a vanadium oxide, a zirconium oxide, and mixtures thereof.

4. The porous separator as defined in claim 1 wherein the nanocomposite structure has a porosity of 50% or less.

5. The porous separator as defined in claim 1 wherein the untreated porous polymer membrane is an uncoated, untreated porous polypropylene membrane.

6. The porous separator as defined in claim 1 wherein a thickness of the nanocomposite structure ranges from about 1 nm to about 2 μ m.

7. The porous separator as defined in claim 1 wherein the nanocomposite structure is: lithium conducting and includes pores having a size to transport lithium ions and to block transport of polysulfide ions or manganese ions.

8. The porous separator as defined in claim 1 wherein the nanocomposite structure has a surface roughness ranging from about 200 nm to about 1000 nm.

9. The porous separator as defined in claim 1 wherein the nanocomposite structure includes at least two layers, and wherein a total thickness of the nanocomposite structure is 2 μ m or less.

10. The porous separator as defined in claim 1 wherein a ratio of carbon to metal oxide in the mixed carbon and metal oxide nanocomposite structure ranges from about 20:80 to about 80:20.

11. The porous separator as defined in claim 1 wherein the nanocomposite structure is the carbon nanocomposite structure, and wherein:

the carbon nanocomposite structure consists of amorphous carbon; or

the carbon nanocomposite structure consists of crystalline carbon.

12. The porous separator as defined in claim 1 wherein the nanocomposite structure is the carbon nanocomposite structure having an sp³ orbital to an sp² orbital ratio ranging from 0.9 to 4.

13. An electrode, comprising:

a positive electrode including an active material selected from a sulfur-based active material for a lithium-sulfur battery and a lithium transition metal oxide-based active material for a lithium ion battery; and

a nanocomposite structure formed on a surface of the positive electrode, the nanocomposite structure being selected from the group consisting of a carbon nanocomposite structure, a metal oxide nanocomposite structure, and a mixed carbon and metal oxide nanocomposite structure, and the nanocomposite structure having a thickness of 2 μ m or less.

14. The electrode as defined in claim **13** wherein the nanocomposite structure is formed from a laser arc plasma deposition process, a cathodic arc deposition process, or a pulsed laser deposition process.

15. The electrode as defined in claim **13** wherein a ratio of carbon to metal oxide in the mixed carbon and metal oxide nanocomposite structure ranges from about 20:80 to about 80:20.

16. The electrode as defined in claim **13** wherein the metal oxide nanocomposite structure or a metal oxide of the mixed carbon and metal oxide nanocomposite structure is a group 2 metal oxide, a group 4 metal oxide, a group 5 metal oxide, a group 6 metal oxide, a group 7 metal oxide, a group 6 metal oxide, a group 7 metal oxide, a group 6 metal oxide, a group 7 metal oxide, a group 13 metal oxide, a group 14 metal oxide, or combinations thereof.

17. A lithium sulfur battery, comprising:

a sulfur-based positive electrode;

a negative electrode; and

a porous polymer separator, including:

a porous polymer membrane; and

a nanocomposite structure i) formed on a surface of the porous polymer membrane, or ii) dispersed in pores of the porous polymer membrane, or iii) combinations of i and ii, the nanocomposite structure selected from the group consisting of a carbon nanocomposite struc-

ture, a metal oxide nanocomposite structure, and a mixed carbon and metal oxide nanocomposite structure;

the porous polymer separator being disposed between the sulfur-based positive electrode and the negative electrode such that the nanocomposite structure is positioned between the porous polymer membrane and the sulfur-based positive electrode.

18. The lithium sulfur battery as defined in claim **17** wherein a thickness of the nanocomposite structure ranges from about 1 nm to about 2 μm .

19. The lithium sulfur battery as defined in claim **17** wherein the metal oxide nanocomposite structure or a metal oxide of the mixed carbon and metal oxide nanocomposite structure is a group 2 metal oxide, a group 4 metal oxide, a group 5 metal oxide, a group 6 metal oxide, a group 7 metal oxide, a group 13 metal oxide, a group 14 metal oxide, or a combination thereof.

20. The lithium sulfur battery as defined in claim **17**, further comprising an other nanocomposite structure formed on a surface of the positive electrode, the other nanocomposite structure selected from the group consisting of an other carbon nanocomposite structure, an other metal oxide nanocomposite structure, and an other mixed carbon and metal oxide nanocomposite structure.

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