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SOLID STATE BATTERY APPARATUS

Abstract

Solid state battery apparatus. The solid state battery comprises a cell. The cell comprises a cathode, an anode electrode, and a solid electrolyte layer. The cathode electrode comprises cathode active material particles, solid electrolyte particles and carbon particles. The cathode active material particles comprise a cathode active material configured to bind with lithium ions. The cathode active material particles comprise single crystalline particles, each of which does not include polycrystalline grains therein, such that inside of the single crystalline particles is substantially free of the first and second solid electrolyte material while the first solid electrolyte material contacts surfaces of the single crystalline particles. The cathode electrode has lithium ion diffusibility ranging from about 1×10^{-14} cm²/s to about 1×10^{-7} cm²/s.

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Background/Summary

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application are hereby incorporated by reference under 37 CFR 1.57.

BACKGROUND

Field

[0002] The present disclosure relates to solid state battery apparatus.

Secondary Batteries

[0003] Secondary batteries have become increasingly desirable power sources for a wide range of various electronic devices, such as cars, computers, cell phones, tools, scooter, bikes, electronic automobiles, power storage systems, drones, and other devices. Among secondary batteries, lithium-based batteries have gained particular prominence due to their ability to provide a desirable balance of voltage and energy density. In addition to their performance advantages, lithium ion secondary batteries contribute to addressing climate change by enabling the electrification of transportation and facilitating the integration of renewable energy sources. These batteries help reduce greenhouse gas emissions by powering electric vehicles and storing energy from intermittent renewable sources like solar and wind. Furthermore, the long cycle life and high energy density of lithium ion batteries may support the development of smart grids and decentralized energy systems, potentially improving overall energy efficiency and reducing reliance on fossil fuels. Traditionally, lithium secondary batteries include a liquid electrolyte, typically comprising a lithium salt dissolved in an organic solvent. However, there has been growing interest in developing an all solid-state lithium secondary battery as an alternative to conventional liquid electrolyte-based systems. Solid-state batteries offer potential advantages in terms of safety, stability, and energy density. Despite these potential benefits, the development of practical all solid-state lithium secondary batteries faces several significant challenges.

Challenges of all Solid-State Secondary Batteries

[0004] One challenge in solid-state battery design is achieving and maintaining sufficient lithium ion diffusivity within the solid electrolyte material. Further, volume changes (e.g. swelling and shrinking) of certain components of the battery—such as the electrode—may occur during discharging and charging of the battery. These volume changes may lead to mechanical stress or result in a loss of contact between various components within the battery structure. The loss of contact between battery components can cause degradation of charging and discharging characteristics, as well as deterioration of overall battery capacity. Researchers and engineers in the field of energy storage are actively working to address these challenges. Efforts are focused on developing new materials and battery designs that can achieve desirable lithium ion diffusivity while also accommodating the mechanical stresses associated with battery cycling. Improving the stability of interfaces within solid-state batteries remains an area of investigation. Overcoming the current limitations of solid-state battery systems could potentially lead to significant advancements in energy storage capabilities for a wide range of applications.

No Admission of Prior Art

[0005] The discussion in this section is intended to provide background information related to the present disclosure and does not constitute an admission of prior art.

SUMMARY

Various Aspects of Present Disclosure

[0006] One aspect of the present disclosure provides a solid state battery comprising a cell. The cell comprises a cathode, an anode electrode, and a solid electrolyte layer. The cathode electrode comprises cathode active material particles, solid electrolyte particles and carbon particles. The cathode active material particles comprise a cathode active material configured to bind with lithium ions. The solid electrolyte particles comprise a first solid electrolyte material configured to enable transport of lithium ions within the cathode electrode. The carbon particles are configured to enable transport of electrons within the cathode electrode. The solid electrolyte layer is positioned between the cathode electrode and the anode layer. The solid electrolyte is configured to enable transport of lithium ions between the cathode layer and the anode layer. The solid electrolyte layer comprises a second solid electrolyte material that is the same as or different from the first solid electrolyte material. The cathode active material particles, the solid electrolyte particles and the carbon particles are mixed and distributed in the cathode electrode. The cathode active material particles comprise single crystalline particles, each of which does not include polycrystalline grains therein, such that inside of the single crystalline particles is substantially free of the first and second solid electrolyte material while the first solid electrolyte material contacts surfaces of the single crystalline particles. The cathode electrode has lithium ion diffusibility ranging from about 1×10^{-14} cm²/s to about 1×10^{-7} cm²/s.

[0007] In one general aspect, the solid state battery is under a pressure in a range of about 1 MPa to about 10 MPa.

[0008] In one general aspect, the single crystalline particles have a particle size in a range of about 1 nm to about 1,000 nm.

[0009] In one general aspect, the single crystalline particles have an particle size in a range of about 1 nm to about 100 nm.

[0010] In one general aspect, the cathode electrode has a thickness in a range of about 10 μ m to about 100 μ m.

[0011] In one general aspect, the cathode active material includes lithium nickel manganese oxide.

[0012] In one general aspect, the cathode electrode includes at least about 60% by weight of the cathode active material based on a total weight of the cathode electrode.

[0013] In one general aspect, the cathode electrode includes at least about 75% by weight of cathode active material based on a total weight of the cathode electrode.

[0014] In one general aspect, the cathode electrode further includes a binder.

[0015] In one general aspect, the solid state battery is under a pressure in a range of about 1 MPa to about 5 MPa.

[0016] In one general aspect, the solid state battery includes a specific capacity of greater than about 100 mAh/g.

[0017] In one general aspect, the solid state battery has a c-rate of at least about 0.33.

[0018] In one general aspect, a thickness of the cell is about 1 mm or less.

[0019] In one general aspect, the cathode active material particles further include polycrystalline particles, each of which includes polycrystalline grains.

Summary Not Limiting

[0020] It is understood that this disclosure is not limited to the examples summarized in this Summary. Various other aspects are described and exemplified herein.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. 1 is an example of a solid state battery according to the present disclosure;

[0022] FIG. 2 is graphs of examples of solid state battery apparatus according to the present disclosure; and

[0023] FIG. 3 is a graph of examples of solid state battery apparatus according to the present disclosure; and

[0024] FIG. 4 is a graph of examples of solid state battery apparatus according to the present disclosure.

EXEMPLIFICATIONS NOT LIMITING

[0025] The exemplifications set out herein illustrate certain non-limiting embodiments, in one form, and such exemplifications are not to be construed as limiting the scope of the appended claims in any manner.

DETAILED DESCRIPTION

Examples and Embodiments

[0026] The presently disclosed subject matter now will be described and discussed in more detail in terms of some specific embodiments and examples with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Like numbers refer to like elements or parts throughout unless otherwise referenced. The presently disclosed subject matter may be embodied in many different forms and should not be construed as limited to the specific embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Indeed, many modifications and other embodiments of the presently disclosed subject matter will come to the mind of one skilled in the art to which the presently disclosed subject matter pertains. Therefore, it is to be understood that the presently disclosed subject matter is not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims.

“A,” “An” And “The”

[0027] As used herein, the singular form of a word includes the plural, unless the context clearly dictates otherwise. The plural encompasses the singular and vice versa. Thus, the references “a,” “an” and “the” are generally inclusive of the plurals of the respective terms. For example, while the present disclosure has been described in terms of “a” layer, “a” substrate, “a” cell, and the like, more than one of these and other components, including combinations, can be used.

“About”

[0028] The term “about” indicates and encompasses an indicated value and a range above and below that value.

“Comprise,” “Consisting Essentially Of”, And “Consisting Of”

[0029] The words “comprise,” “comprises,” and “comprising” are to be interpreted inclusively rather than exclusively. Likewise, the terms “include,” “including” and “or” should all be construed to be inclusive, unless such a construction is clearly prohibited from the context. A disclosure of an embodiment defined using the term “comprising” is also a disclosure of embodiments “consisting essentially of” and “consisting of” the disclosed components. The phrase “consisting of” excludes any element, step, or ingredient not specified.

“And/Or”

[0030] The term “and/or” used in the context of “X and/or Y” should be interpreted as “X,” “Y,” or “X and Y.”

“On” And “Over”

[0031] As used herein, the terms “on,” “applied on,” “formed on,” “deposited on,” “provided on,” and the like mean applied, formed, overlaid, deposited, or provided on in contact with an underlying or overlying surface. On the other hand, the terms “over” “applied over,” “formed

over,” “deposited over,” “overlay,” “provided over,” and the like, mean applied, formed, overlaid, deposited, or provided on or over but not necessarily in contact with the surface. For example, a formed layer “applied over” a substrate layer may contact the substrate without an intervening material; however, the same phrase does not preclude the presence of one or more other layers of the same or different composition located between the formed layer and the substrate layer.

Markush Group

[0032] As used herein, the term “combination thereof” included in any Markush-type expression means a combination or mixture of one or more elements selected from the group of elements disclosed in the Markush-type expression, and refers to the presence of one or more elements selected from the group. The term “combinations thereof” includes every possible combination of elements to which the term refers.

“Between”

[0033] As used herein, the expression “between” is inclusive of end points.

Numerical Ranges

[0034] Furthermore, all numerical ranges herein should be understood to include all integers, whole or fractions, within the range. Moreover, any numerical range recited herein is intended to include all sub-ranges subsumed therein, and these numerical ranges should be construed as providing support for a claim directed to any number or subset of numbers in that range. For example, a disclosure of from 1 to 10 should be construed as supporting a range of from 1 to 8, from 3 to 7, from 1 to 9, from 3.6 to 4.6, from 3.5 to 9.9, and so forth. When ranges are given, any endpoints of those ranges and/or numbers within those ranges can be combined with the scope of the present disclosure.

“Including,” “Such As” and “For Example”

[0035] As used herein, “including,” “such as,” “for example,” and like terms mean “including/such as/for example but not limited to.”

Combination of Embodiments

[0036] As used herein, the term “example,” particularly when followed by a listing of terms, is merely illustrative, and should not be deemed to be exclusive or comprehensive. Any embodiment disclosed herein can be combined with any other embodiment disclosed herein unless explicitly indicated otherwise.

Particle Size

[0037] As used herein, particle size refers to the mean particle diameter (D.sub.50) as measured using microscopy (e.g., optical microscopy, electron microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), confocal microscopy, X-ray microscopy, cryo-electron microscopy, Raman microscopy, or fluorescence microscopy). The size can be the diameter of spherical particles or the length along the largest dimension of ellipsoidal or otherwise irregularly shaped particles. As used herein, “D.sub.50” of particles refers to the diameter at which 50% of the particles have a smaller diameter.

Solid State Lithium Ion Batteries

[0038] A solid state battery can receive a charge and discharge an electrical load various times. A solid state battery includes electrodes, a cathode electrode and an anode electrode, and an electrolyte to allow lithium ions to travel between the electrodes. In contrast to conventional liquid electrolyte batteries, the solid state battery does not include any flowable liquids. Forming a circuit between the electrodes causes electricity to flow between the electrodes. During charging of the lithium ion rechargeable battery, lithium ions are emitted from the cathode electrode and are intercalated into an active material of the anode electrode. During discharging of the lithium ion rechargeable battery, lithium ions are emitted from the anode electrode and are intercalated into an active material of the cathode electrode. As lithium ions reciprocate between the electrodes, they transfer energy.

Solid State Battery Configuration

[0039] The present disclosure provides a solid state battery **100** comprising a cathode electrode **102**, an anode electrode **104**, and a solid electrolyte layer **106** intermediate the cathode electrode **102** and the anode electrode **104**. While listed as exemplary, the solid state battery **100** does not require all of these components. For example, in some configurations, such as in anodeless system, the anode electrode **104** may be omitted.

Optional Additional Layers

[0040] The solid state battery **100** can optionally comprise an additional layer or layers, such as, for example, a separator layer, a protective layer, an inhibitor layer, a solid electrolyte interface layer, or a combination thereof.

Protective Layer

[0041] For example, a protective layer may be incorporated between the electrodes **102** and **104** and the solid electrolyte layer **106** and/or a protective layer may be between the electrode **102** and current collector **110** in an anodeless system. The protective layer may also serve to mitigate dendrite formation, particularly on the anode side, thereby improving the overall cycle life and safety of the battery. In some cases, the protective layer may help improve interfacial stability between the electrodes and electrolyte, potentially reducing unwanted side reactions. Additionally, the protective layer may enhance the mechanical properties of the electrode-electrolyte interface, which could be beneficial for maintaining good contact during cycling.

Protective Layer Materials

[0042] This protective layer may comprise materials such as lithium phosphate, lithium titanate, or lithium lanthanum zirconium oxide (LLZO), which can help prevent undesirable side reactions at the electrode-electrolyte interface. Other options for the protective layer material may include, but are not limited to, lithium niobium oxide (LiNbO₃), lithium tantalum oxide (LiTaO₃), lithium aluminum titanium phosphate (LATP), lithium aluminum germanium phosphate (LAGP), lithium silicate, and lithium boron oxide.

Separator Layer

[0043] A separator layer may also be included in some configurations of the solid state battery **100**. These separator layers can provide additional mechanical support to the battery structure while still allowing for efficient ion transport. The separator layer may also be designed to have a gradient structure, with properties optimized for contact with both the cathode and anode materials. This gradient structure could involve, for example, varying the porosity, composition, or surface properties across the thickness of the separator. In some aspects, the separator surface may be functionalized with ion-conductive groups or coatings to enhance lithium ion transport at the electrode-separator interfaces. The separator layer may further be designed with multiple layers, by incorporating different materials optimized for specific functions, such as a mechanically strong core layer sandwiched between ion-conductive outer layers. The separator layer may additionally be designed to be self-healing e.g., by reforming bonds after mechanical stress to help prevent short circuits caused by dendrite growth.

Separator Layer Materials

[0044] While traditional liquid electrolyte batteries often use porous polymer separators, solid state batteries may employ thin ceramic or glass-ceramic layers as separators. Materials such as LLZO, LATP (lithium aluminum titanium phosphate), or LAGP (lithium aluminum germanium phosphate) may be used for this purpose. Other separator layer materials that may be suitable for solid state batteries include lithium phosphate oxynitride (LiPON), lithium lanthanum titanate (LLTO), lithium garnet-type materials like Li_{0.6}Ba_{0.2}Ta_{0.2}O₁₂, sulfide-based materials like Li₁₀GeP₂S₁₂, and polymer-ceramic composites combining materials like polyethylene oxide (PEO) with ceramic fillers.

Solid State Battery Cell

[0045] FIG. **1** illustrates a cell **101** of a solid state battery **100** according to an embodiment. The cell **101** includes a cathode electrode **102**, an anode electrode **104**, and a solid electrolyte layer **106**

intermediate the cathode electrode **102** and the anode electrode **104**. The cell **101** can optionally include an additional layer or layers, such as, for example, a separator layer, a protective layer, an inhibitor layer, a solid electrolyte interface layer, or a combination thereof.

Cell Configuration

[0046] As illustrated in FIG. **1**, the solid state battery **100** may include a single cell **101**. In other examples, the solid state battery **100** can include multiple cells, such as, at least two cells, at least three cells, or at least four cells. Connecting the cells in series increases a voltage of the solid state battery **100** and connecting the cells in parallel increases an amp-hour capacity of the solid state battery **100**.

Dimensions of Cell

[0047] The cell **101** may have a width, $w_{\text{sub.1}}$, a length, $l_{\text{sub.1}}$, and a thickness, $t_{\text{sub.1}}$.

Thickness of Cell

[0048] A thickness, $t_{\text{sub.1}}$, of the cell **101** can be at or about any number in a range of from about 100 μm to about 5000 μm , such as about 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 810, 820, 830, 840, 850, 860, 870, 880, 890, 900, 910, 920, 930, 940, 950, 960, 970, 980, 990, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 3000, 4000, or 5000 μm . In some embodiments, the thickness, $t_{\text{sub.1}}$, of the cell **101** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range of from about 100 μm to about 5000 μm , e.g., between about 100 μm and about 5,000 μm or about 100 μm and about 1,000 μm .

Aspect Ratio of Width

[0049] The width, $w_{\text{sub.1}}$, of the cell **101** may be substantially greater than the thickness, $t_{\text{sub.1}}$, of the cell **101**. In some embodiments, an aspect ratio of the width, $w_{\text{sub.1}}$, to the thickness, $t_{\text{sub.1}}$, may be at least 10, at least 20, at least 30, at least 40, at least 50, at least 60, at least 70, at least 80, at least 90, at least 100, at least 110, at least 120, at least 130, at least 140, at least 150, at least 160, at least 170, at least 180, at least 190, at least 200, at least 210, at least 220, at least 230, at least 240, at least 250, at least 260, at least 270, at least 280, at least 290, at least 300, at least 350, at least 400, at least 450, at least 500, at least 550, at least 600, at least 650, at least 700, at least 750, at least 800, at least 850, at least 900, at least 950, at least 1000, at least 2000, at least 3000, at least 4000, at least 5000, at least 6000, at least 7000, at least 8000, at least 9000, or at least 10000.

Aspect Ratio of Length

[0050] The length, $l_{\text{sub.1}}$, of the cell **101** may be substantially greater than the thickness, $t_{\text{sub.1}}$, of the cell **101**. In some embodiments, an aspect ratio of the length, $l_{\text{sub.1}}$, to the thickness, $t_{\text{sub.1}}$, may be at least 10, at least 20, at least 30, at least 40, at least 50, at least 60, at least 70, at least 80, at least 90, at least 100, at least 110, at least 120, at least 130, at least 140, at least 150, at least 160, at least 170, at least 180, at least 190, at least 200, at least 210, at least 220, at least 230, at least 240, at least 250, at least 260, at least 270, at least 280, at least 290, at least 300, at least 350, at least 400, at least 450, at least 500, at least 550, at least 600, at least 650, at least 700, at least 750, at least 800, at least 850, at least 900, at least 950, at least 1000, at least 2000, at least 3000, at least 4000, at least 5000, at least 6000, at least 7000, at least 8000, at least 9000, or at least 10000.

Cathode Electrode

[0051] The cathode electrode **102** is associated with one polarity (e.g., positive) of the solid state battery **100**. The cathode electrode **102** is configured as a positive electrode during discharge of the solid state battery **100**. The cathode electrode **102** is suitable for lithium ion diffusion between a current collector **108** and the solid electrolyte layer **106**. The cathode electrode **102** is in electrical

communication with the current collector **108**.

Cathode Electrode Positioning

[0052] In embodiments, the cathode electrode **102** is formed over and in direct contact with the current collector **108**. In other embodiments, another functional layer may be interposed between the cathode electrode **102** and the current collector **108**.

Materials for Cathode Electrode

[0053] The cathode electrode **102** may be capable of reversible intercalation and deintercalation of lithium ions. For example, the cathode electrode **102** can comprise a cathode active material alone. In other examples, the cathode electrode **102** may optionally include one or more of a conductive carbon, a solid electrolyte material, and a binder. Optionally, the cathode electrode **102** may further comprise an additive, such as, for example, an oxidation stabilizing agent, a reduction stabilizing agent, a flame retardant, a heat stabilizer, an antifogging agent, a thickener, a plasticizer, an ion conductivity enhancer, a binder (described in detail further below), a dispersant, a wetting agent, an adhesion promoter, a crosslinking agent, a colorant, the like, or a combination thereof.

Examples of Additives

[0054] Examples of these additives may include butylated hydroxyanisole (BHA) or butylated hydroxytoluene (BHT) as oxidation stabilizing agents, ascorbic acid or sodium sulfite as reduction stabilizing agents, aluminum hydroxide or magnesium hydroxide as flame retardants, phenolic compounds or phosphites as heat stabilizers, polyethylene glycol or silica nanoparticles as antifogging agents, carboxymethyl cellulose (CMC) or xanthan gum as thickeners, dibutyl phthalate or triethyl citrate as plasticizers, ceramic fillers or ionic liquids as ion conductivity enhancers, polyvinylpyrrolidone or sodium dodecyl sulfate as dispersants, polysorbates or poloxamers as wetting agents, silanes or titanates as adhesion promoters, peroxides or aziridines as crosslinking agents, and carbon black or metal oxides as colorants.

Cathode Active Material

[0055] The cathode active material can include lithium cobalt oxide ($\text{LiCoO}_{0.2}$), lithium nickel oxide ($\text{LiNiO}_{0.2}$), $\text{Li}[\text{Ni}_{0.2}\text{Co}_{0.2}\text{Mn}_{0.2}\text{M}_{0.4}]\text{O}_{0.2}$ (wherein $\text{M}_{0.4}$ is any one element elected from the group consisting of Al, Ga, In, or a combination thereof, $0.33 \leq a < 1.0$, $0 \leq b \leq 0.5$, $0 \leq c \leq 0.5$, $0 \leq d \leq 0.1$, and $a+b+c+d=1$), $\text{Li}(\text{Li}_{0.2}\text{M}_{0.2}\text{M}_{0.2}\text{M}_{0.2}\text{M}_{0.2})\text{O}_{0.2}$ (wherein $0 \leq e \leq 0.2$, $0.6 \leq f \leq 1$, $0 \leq f' \leq 0.2$, $0 \leq g \leq 0.2$, $\text{M}_{0.2}$ includes Mn and at least one element selected from the group consisting of Ni, Co, Fe, Cr, V, Cu, Zn and Ti, $\text{M}_{0.2}$ is at least one element selected from the group consisting of Al, Mg and B, and A is at least one element selected from the group consisting of P, F, S and N), or those compounds substituted with one or more transition metals; lithium manganese oxides such as those represented by the chemical formula of $\text{Li}_{1+h}\text{Mn}_{0.2}\text{O}_{0.4}$ (wherein $0 \leq h \leq 0.33$), $\text{LiMnO}_{0.3}$, $\text{LiMn}_{0.2}\text{O}_{0.3}$, $\text{LiMnO}_{0.2}$, or the like; lithium copper oxide ($\text{Li}_{0.2}\text{CuO}_{0.2}$); vanadium oxides such as $\text{LiV}_{0.3}\text{O}_{0.8}$, $\text{V}_{0.2}\text{O}_{0.5}$ or $\text{Cu}_{0.2}\text{V}_{0.2}\text{O}_{0.7}$; Ni-site type lithium nickel oxides represented by the chemical formula of $\text{LiNi}_{0.1}\text{M}_{0.4}\text{O}_{0.2}$ (wherein $\text{M}_4=\text{Co}$, Mn, Al, Cu, Fe, Mg, B or Ga, and $0.01 \leq y \leq 0.3$); lithium manganese composite oxides represented by the chemical formula of $\text{LiMn}_{0.2}\text{M}_{0.5}\text{O}_{0.2}$ (wherein $\text{M}_5=\text{Co}$, Ni, Fe, Cr, Zn, or Ta, and $0.01 \leq y \leq 0.1$) or $\text{Li}_{0.2}\text{Mn}_{0.3}\text{M}_{0.6}\text{O}_{0.8}$ (wherein $\text{M}_6=\text{Fe}$, Co, Ni, Cu, or Zn); $\text{LiMn}_{0.2}\text{O}_{0.4}$ in which Li is partially substituted with an alkaline earth metal ion; disulfide compounds; $\text{LiFe}_{0.3}\text{O}_{0.4}$, $\text{Fe}_{0.2}(\text{MoO}_{0.4})_{0.3}$; the like; or combinations thereof.

Phosphate-Based Materials

[0056] In addition to the cathode active materials previously mentioned, the cathode electrode may include other types of materials. For example, lithium iron phosphate (LiFePO_4) may be used as a cathode active material due to its excellent thermal stability and long cycle life. Other phosphate-based materials such as lithium manganese iron phosphate ($\text{LiMn}_x\text{Fe}_{1-x}\text{PO}_4$), lithium vanadium phosphate (LiVOPO_4), lithium titanium phosphate ($\text{LiTi}_2(\text{PO}_4)_3$), lithium nickel phosphate (LiNiPO_4), fluorophosphates such as LiVPO_4F or LiFeSO_4F , or lithium cobalt phosphate

(LiCoPO₄) may also be suitable.

Layered Oxide Materials

[0057] The cathode active material may also include layered oxide materials with various compositions, such as Li(Ni_{1-x-y}Co_xMn_y)O₂ (NCM) or Li(Ni_{1-x-y}Co_xAl_y)O₂ (NCA), where the ratios of Ni, Co, Mn, and Al can be adjusted to optimize performance characteristics. For instance, NCM materials with high nickel content, such as NCM811 (LiNi_{0.8}Co_{0.1}Mn_{0.1}O₂), may be used to achieve higher energy density. In some cases, the cathode active material may comprise spinel structures like LiNi_{0.5}Mn_{1.5}O₄, which can offer high voltage operation. Alternatively, materials with tavorite structures, such as LiFeSO₄F or LiVPO₄F, may be employed for their potential for high energy density and good thermal stability.

Composite or Blended Cathode Materials

[0058] Composite or blended cathode materials, combining two or more active materials, may also be used. For example, a blend of layered oxides and spinel materials might be employed to balance energy density and power capability. As another example, lithium iron phosphate may be blended with one or more of the cathode active materials described above. In some embodiments, the cathode active material may include surface-modified versions of the aforementioned compounds, where the surface modification aims to improve stability, conductivity, or other performance metrics.

Emerging Classes of Materials

[0059] The cathode active material may also include emerging classes of materials such as disordered rock salt structures (e.g., Li₃NbO₄-based materials), lithium-rich anti-perovskites (e.g., Li₃OCl), cation-disordered oxides (e.g., Li—Mn—V—O systems), or high-entropy oxides, which may offer desirable combinations of high capacity and structural stability. In some cases, the cathode active material may incorporate dopants or substitutional elements to further tune its electrochemical properties.

Particulate Nature of Cathode Active Material

[0060] The cathode active material can be particle shaped. The cathode active material can have a particle size in a range of from about 1 nm to about 1000 μ m, such as about any of 10 nm, 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, 100 nm, 110 nm, 120 nm, 130 nm, 140 nm, 150 nm, 160 nm, 170 nm, 180 nm, 190 nm, 200 nm, 210 nm, 220 nm, 230 nm, 240 nm, 250 nm, 260 nm, 270 nm, 280 nm, 290 nm, 300 nm, 310 nm, 320 nm, 330 nm, 340 nm, 350 nm, 360 nm, 370 nm, 380 nm, 390 nm, 400 nm, 410 nm, 420 nm, 430 nm, 440 nm, 450 nm, 460 nm, 470 nm, 480 nm, 490 nm, 500 nm, 550 nm, 600 nm, 650 nm, 700 nm, 750 nm, 800 nm, 850 nm, 900 nm, 950 nm, 1000 nm, 5 μ m, 10 μ m, 15 μ m, 20 μ m, 25 μ m, 30 μ m, 35 μ m, 40 μ m, 45 μ m, 50 μ m, 55 μ m, 60 μ m, 65 μ m, 70 μ m, 75 μ m, 80 μ m, 85 μ m, 90 μ m, 95 μ m, 100 μ m, 110 μ m, 120 μ m, 130 μ m, 140 μ m, 150 μ m, 160 μ m, 170 μ m, 180 μ m, 190 μ m, 200 μ m, 210 μ m, 220 μ m, 230 μ m, 240 μ m, 250 μ m, 260 μ m, 270 μ m, 280 μ m, 290 μ m, 300 μ m, 310 μ m, 320 μ m, 330 μ m, 340 μ m, 350 μ m, 360 μ m, 370 μ m, 380 μ m, 390 μ m, 400 μ m, 410 μ m, 420 μ m, 430 μ m, 440 μ m, 450 μ m, 460 μ m, 470 μ m, 480 μ m, 490 μ m, 500 μ m, 550 μ m, 600 μ m, 650 μ m, 700 μ m, 750 μ m, 800 μ m, 850 μ m, 900 μ m, 950 μ m, or 1,000 μ m. In embodiments, particle size of the cathode active material may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of from about 1 nm to about 1000 μ m, e.g., between about 10 nm and about 1,000 μ m. Gaps between cathode active material particles in the cathode electrode **102** can be filled with the solid electrolyte material.

Amount of Cathode Active Material in Cathode Electrode

[0061] The amount of the cathode active material in the solid state battery **100** affects the charge and discharge capacity of the solid state battery **100**. In order to manufacture a high-capacity cathode electrode **102**, a high level of cathode active material can be included in the cathode electrode **102**. For example, the cathode electrode **102** includes at, about, or greater than 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 98, or 99 wt % based on the total

weight of the cathode electrode **102**. In embodiments, cathode active material in the cathode electrode **102** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range from greater than 0 to about 100 wt %, e.g., between about 40 wt % and about 98 wt %.

Conductive Material in Cathode Electrode

[0062] The conductive material in the cathode electrode **102** is not particularly limited, as long as it has conductivity while not causing any chemical change in the corresponding solid state battery **100**. For example, the conductive material can comprise graphite, such as natural graphite or artificial graphite; carbon black, such as acetylene black, ketjen black, channel black, furnace black, lamp black or thermal black; conductive fibers, such as carbon fibers or metal fibers; carbon nanotubes (CNT), including both singled-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT); metal powder, such as fluorocarbon, aluminum or nickel powder; conductive whiskers, such as zinc oxide or potassium titanate; conductive metal oxides, such as titanium oxide; conductive polymers, such as polyphenylene derivatives; graphene, metallic nanowires (e.g. silver nanowires), indium tin oxide (ITO), antimony-doped tin oxide (ATO), fluorine-doped tin oxide (FTO), aluminum-doped zinc oxide (AZO), gallium-doped zinc oxide (GZO), conductive ceramics like titanium nitride or titanium carbide, the like, or combinations thereof.

Amount of Conductive Material in Cathode Electrode

[0063] The cathode electrode **102** includes at or about 1, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30 wt % of conductive material based on the total weight of the cathode electrode **102**. In embodiments, conductive material in the cathode electrode **102** may be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 1 wt % and about 30 wt %.

Materials for Binder

[0064] The binder can comprise various types of binder polymers, such as, for example, polyvinylidene fluoride-co-hexafluoropropylene (PVdF-co-HFP), polyvinylidene fluoride, polyacrylonitrile, polymethyl methacrylate, polyvinyl alcohol, carboxymethyl cellulose (CMC), starch, hydroxypropyl cellulose, regenerated cellulose, polyvinyl pyrrolidone, tetrafluoroethylene, polyethylene, polypropylene, polyacrylate, ethylene-propylene-diene monomer (EPDM), sulfonated EPDM, styrene butadiene rubber (SBR), fluororubber, polyacrylic acid, polyimide, polyamide-imide, polyurethane, polyethylene oxide (PEO), poly(ethylene-co-vinyl acetate) (PEVA), poly(vinyl acetate) (PVA), chitosan, guar gum (GG), xanthan gum, carrageenan, pectin, water-soluble polymers, lignin, polymers thereof whose hydrogen atoms are substituted with Li, Na or Ca, various copolymers thereof, the like, or combinations thereof.

Other Binder Materials

[0065] In addition to the binder materials previously mentioned, other types of binder materials may be used in the cathode electrode to enhance its performance and stability. For instance, water-soluble binders such as sodium alginate, gelatin, or polyacrylamide may be employed to improve the environmental friendliness of the electrode manufacturing process. These binders may also offer advantages in terms of electrode flexibility and adhesion strength. In some cases, conductive binders like poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) or polyaniline (PANI) may be used to simultaneously improve both the mechanical integrity and electrical conductivity of the electrode.

Novel Binder Systems

[0066] Novel binder systems, such as self-healing polymers or supramolecular assemblies, may be incorporated to enhance the long-term stability and cycle life of the battery. Additionally, composite binders combining multiple polymers or incorporating inorganic nanoparticles may be utilized to tailor the mechanical, thermal, and electrochemical properties of the electrode. In some embodiments, bio-derived or biodegradable binders, such as cellulose derivatives or chitosan, may

be employed to reduce the environmental impact of battery production and disposal.

Amount of Binder in the Cathode Electrode

[0067] The cathode electrode **102** may include at or about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30 wt % of binder based on the total weight of the cathode electrode **102**. In embodiments, binder in the cathode electrode **102** may be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 1 wt % and about 30 wt %.

Solid Electrolyte Material

[0068] The solid electrolyte material in the cathode electrode **102** can be configured the same as the material for the solid electrolyte layer **106** discussed below. The solid electrolyte material in the cathode electrode **102** can be the same as or different than the material for the solid electrolyte layer **106**.

Amount of Solid Electrolyte Material in Cathode Electrode

[0069] The cathode electrode **102** may include about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30 wt % of solid electrolyte material based on the total weight of the cathode electrode **102**. In embodiments, the amount of solid electrolyte material in the cathode electrode **102** may be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 1 wt % and about 30 wt %.

Thickness of Cathode Electrode

[0070] A thickness, $t_{\text{sub.2}}$, of the cathode electrode **102** can be at or about any number in a range of from greater than 0 to 1000 μm , such as 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 810, 820, 830, 840, 850, 860, 870, 880, 890, 900, 910, 920, 930, 940, 950, 960, 970, 980, 990, 1,000 μm . In embodiments, the thickness, $t_{\text{sub.2}}$, of the cathode electrode **102** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range of from greater than 0 to about 1000 μm , e.g., between about 10 μm and about 1,000 μm or between about 10 μm and about 100 μm .

Porosity of Cathode Electrode

[0071] A porosity of the cathode electrode **102** can be at or about any number in a range of from 0 to 20 vol %, such as 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, or 18 vol % or any other vol % within the range of 0 to 20 vol %, based on the total volume of the cathode electrode **102**. In embodiments, the porosity of the cathode electrode **102** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range of 0 to 20 vol %, e.g., between 0 vol % and about 18 vol %.

Lithium Ion Diffusivity of Cathode Electrode

[0072] The cathode electrode **102** can include a lithium ion diffusivity at or about any number in a range of from greater than 0 to $1 \times 10^{\text{sup.}-7} \text{ cm}^{\text{sup.2}}/\text{s}$, such as $1 \times 10^{\text{sup.}-14} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-13} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-12} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-11} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-10} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-9} \text{ cm}^{\text{sup.2}}/\text{s}$, $1 \times 10^{\text{sup.}-8} \text{ cm}^{\text{sup.2}}/\text{s}$, or $1 \times 10^{\text{sup.}-7} \text{ cm}^{\text{sup.2}}/\text{s}$. In embodiments, the lithium ion diffusivity of the cathode electrode **102** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range of from greater than 0 to $1 \times 10^{\text{sup.}-7} \text{ cm}^{\text{sup.2}}/\text{s}$, e.g., between $1 \times 10^{\text{sup.}-14} \text{ cm}^{\text{sup.2}}/\text{s}$ and about $1 \times 10^{\text{sup.}-7} \text{ cm}^{\text{sup.2}}/\text{s}$.

Current Collector at Cathode Electrode

[0073] The current collector **108** collects electrical energy generated at the cathode electrode **102** and supports the cathode electrode **102**.

Materials for Current Collector at Cathode Electrode

[0074] The material of the current collector **108** is not particularly limited as long as it allows

adhesion of the cathode electrode **102**, has a suitable electrical conductivity, and does not cause significant chemical changes in the corresponding solid state battery **100** in the voltage range of the solid state battery **100**. For example, the current collector **108** is made of or includes various materials, such as, a metal, a conductive carbon, or a conductive ceramic, although not limited thereto. The metal of the current collector **108** may include one or more selected from the group consisting aluminum, an aluminum alloy, copper, a copper alloy, nickel, a nickel alloy, titanium, a titanium alloy, iron, an iron alloy (e.g., steel, stainless steel), silver, a silver alloy, gold, platinum, palladium, chromium, molybdenum, tungsten, tantalum, niobium, zirconium, vanadium, manganese, cobalt, indium, tin, lead, bismuth, or a combination thereof, although not limited thereto.

Current Collector Geometry

[0075] The current collector **108** may also be configured in various other geometries to optimize its performance and integration with the cathode electrode **102**, and may be sized for specific form factors, such as pouch, cylindrical, and/or prismatic form factors.

Shape of Current Collector at Cathode Electrode

[0076] It is possible to increase the adhesion of the cathode electrode **102** to the current collector **108** by forming fine surface irregularities on the surface of the current collector **108**. The current collector **108** may have various shapes, such as, for example, a film, a sheet, a foil, a net, a porous body, a foam, a non-woven web, the like, or combinations thereof.

Examples of Shape and Size of Current Collector

[0077] For instance, the current collector **108** may be structured as a mesh or grid, which can provide enhanced mechanical support while maintaining high surface area for electrode adhesion. In some embodiments, the current collector **108** may be designed with a corrugated or wavy pattern, potentially increasing the contact area with the cathode material and improving overall conductivity. The current collector **108** may also be fabricated as a perforated sheet, allowing for better electrolyte penetration and ion transport. In certain cases, the current collector **108** may be formed as a three-dimensional structure, such as an interconnected network of fibers or a honeycomb-like configuration, which could enhance the structural integrity of the electrode assembly while facilitating efficient current collection.

Thickness of Current Collector at Cathode Electrode

[0078] A thickness, $t_{sub.3}$, of the current collector **108** can be at or about any number in a range of from greater than 0 to 500 μm , such as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, or 500 μm . In embodiments, the thickness, $t_{sub.3}$, of the current collector **108** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers within the range of from greater than 0 to 500 μm , e.g., between about 5 μm and about 500 μm .

Manufacturing Methods for Cathode Electrode

[0079] The cathode electrode **102** may be obtained by various methods.

Dry Powder Coating Process

[0080] For instance, a dry powder coating process may be employed, where the cathode active material, conductive additives, and binder are mixed in a dry state and then directly applied to the current collector **108** using electrostatic deposition or mechanical compression. This method may reduce environmental impact by reducing use of solvents.

3D Printing

[0081] In some cases, the cathode electrode **102** may be fabricated using additive manufacturing techniques such as 3D printing. This approach allows for precise control over the electrode structure and porosity, potentially enhancing the electrode's performance and energy density. Various 3D printing methods, including fused deposition modeling (FDM), selective laser sintering (SLS), or direct ink writing (DIW), may be utilized depending on the specific materials and desired

electrode properties.

Electrospinning

[0082] Another method for manufacturing the cathode electrode **102** may involve electrospinning. In this process, a solution containing the cathode active material, conductive additives, and a polymer binder is extruded through a nozzle under an electric field, resulting in the formation of nanofibers. These fibers can be collected directly on the current collector **108** to form a highly porous electrode structure with increased surface area.

Tape Casting

[0083] In some embodiments, the cathode electrode **102** may be prepared using a tape casting method. This technique involves spreading a slurry of electrode materials onto a moving carrier film using a doctor blade, followed by drying and calendaring. The resulting electrode tape can then be laminated onto the current collector **108**.

Spray Coating

[0084] Alternatively, the cathode electrode **102** may be fabricated using a spray coating technique. In this method, a fine mist of the electrode slurry is sprayed onto the current collector **108** using compressed air or ultrasonic atomization. This approach may allow for the creation of thin, uniform electrode layers and can be particularly useful for large-scale production.

Freeze-Casting

[0085] In certain cases, the cathode electrode **102** may be manufactured using a freeze-casting method. This process involves freezing a slurry of electrode materials, followed by sublimation of the ice to create a porous structure. The resulting porous electrode can then be sintered and attached to the current collector **108**.

Sol-Gel Process

[0086] For some applications, the cathode electrode **102** may be prepared using a sol-gel process. This method involves the formation of a colloidal suspension (sol) that is then converted into a gel-like network containing the cathode active material and other components. The gel can be applied to the current collector **108** and subsequently heat-treated to form the final electrode structure.

Slurry-Based Process

[0087] For example, the cathode active material can be mixed and agitated with a solvent, and optionally a binder, conductive material, and a dispersing agent to form slurry. Then, the slurry can be applied (e.g., coated) onto the current collector **108**, followed by pressing and drying, to obtain the cathode electrode **102**.

Application Methods for Slurry for Cathode Electrode

[0088] The application of the slurry to the cathode electrode **102** may include using a technique selected from the group consisting of slot die coating, gravure coating, spin coating, spray coating, roll coating, curtain coating, extrusion, casting, screen printing, inkjet printing, spray printing, gravure printing, heat transfer printing, a Toppan printing method, intaglio printing, offset printing, the like, and combinations thereof.

Double Layer Slot Die Coating

[0089] In some embodiments, the cathode electrode **102** may be fabricated using a double layer slot die coating (DLD) technique. This method involves the simultaneous application of two distinct layers of electrode materials onto the current collector **108** in a single pass. The DLD process may allow for the creation of gradient structures within the electrode, potentially optimizing both the electrochemical performance and mechanical properties of the cathode. Additionally, this technique may enable the incorporation of functional interlayers or protective coatings as part of the electrode manufacturing process, potentially enhancing the overall battery performance and longevity.

Solvent for Slurry for Cathode Electrode

[0090] The solvent for forming the cathode electrode **102** may include water and/or an organic solvents, such as, for example, N-methyl pyrrolidone (NMP), dimethyl formamide (DMF), acetone, dimethyl acetamide, dimethyl sulfoxide (DMSO), isopropyl alcohol, the like, or combinations

thereof. The solvent may be used in an amount sufficient to dissolve and disperse the electrode ingredients, such as the cathode active material, binder, and conductive material, considering the slurry coating thickness, production yield, the like, or combinations thereof. Additional solvents that may be used include ethanol, methanol, propanol, butanol, ethyl acetate, methyl ethyl ketone, tetrahydrofuran, diethyl ether, and toluene.

Solvent-Free Methods

[0091] In some aspects of the disclosure, the cathode electrode **102** may be prepared using a solvent-free method, such as dry powder processing or melt extrusion, which reduce the use of liquid solvents and may offer environmental and cost benefits.

Dispersing Agent for Slurry for Cathode Electrode

[0092] The dispersing agent forming the cathode electrode **102** may include an aqueous dispersing agent and/or an organic dispersing agent, such as, for example, N-methyl-2-pyrrolidone. Other possible dispersing agents may include polyvinylpyrrolidone (PVP), carboxymethyl cellulose (CMC), sodium dodecyl sulfate (SDS), Triton X-100, polyethylene glycol (PEG), polyacrylic acid (PAA), and various surfactants such as polysorbates or poloxamers.

Drying Technique for Slurry for Cathode Electrode

[0093] The slurry for the cathode electrode **102** may be dried by irradiating heat, electron beams (E-beams), gamma rays, or UV (G, H, I-line), the like, or combinations thereof, to vaporize the solvent. For example, the slurry may be vacuum dried at room temperature. Although the solvent is removed through evaporation by the drying step, the other ingredients do not evaporate and remain as they are to form the cathode electrode **102**.

Additional Drying Techniques

[0094] In addition to the drying techniques mentioned, the cathode electrode **102** may be dried using other methods such as infrared (IR) drying, microwave drying, or freeze-drying.

Combination of Drying Techniques

[0095] In some embodiments, a combination of drying techniques may be employed, such as using convection heating followed by vacuum drying, to optimize the drying process and ensure complete solvent removal while maintaining the integrity of the electrode structure.

Anode Electrode Generally

[0096] The anode electrode **104** is associated with one polarity (e.g., negative) of the solid state battery **100**, which is different than the polarity of the cathode electrode **102**. The anode electrode **104** is configured as a negative electrode during discharge of the solid state battery **100**. The anode electrode **104** is suitable for lithium ion diffusion between a current collector **110** and the solid electrolyte layer **106**.

Anode Electrode Positioning

[0097] The anode electrode **104** is in electrical communication with the current collector **110**. In embodiments, the anode electrode **104** is formed over and in direct contact with the current collector **110**. In other embodiments, another functional layer may be interposed between the anode electrode **104** and the current collector **110**.

Anodeless Electrode System

[0098] In some embodiments, as explained above, the solid state battery **100** may utilize an anodeless electrode system. In such configurations, the anode electrode **104** may be omitted, and lithium metal may be deposited directly onto the current collector **110** during charging. This approach may potentially increase the energy density of the battery and eliminate a separate anode material, while also potentially reducing the overall thickness of the battery structure.

Materials for Anode Electrode

[0099] The anode electrode **104** may be capable of reversible intercalation and deintercalation of lithium ions. For example, the anode electrode **104** can comprise an anode active material alone. In other examples, the anode electrode **104** may include conductive particles, a binder, the like, or combinations thereof.

Additives for Anode Electrode

[0100] Optionally, the anode electrode **104** may further comprise an additive, such as, for example, an oxidation stabilizing agent (e.g., butylated hydroxyanisole, butylated hydroxytoluene, propyl gallate, tert-butylhydroquinone), a reduction stabilizing agent (e.g., ascorbic acid, sodium sulfite, erythorbic acid, sodium metabisulfite), a flame retardant (e.g., aluminum hydroxide, magnesium hydroxide, ammonium polyphosphate, melamine cyanurate), a heat or light stabilizer (e.g., phenolic compounds, phosphites, hindered amine light stabilizers, UV absorbers like benzophenones or benzotriazoles), an antifogging agent (e.g., polyethylene glycol, silica nanoparticles, glycerol, sorbitol), a thickener (e.g., carboxymethyl cellulose, xanthan gum), the like, or a combination thereof.

Other Additives for Anode Electrode

[0101] Additionally, conductive additives such as carbon black, graphene, or carbon nanotubes may be incorporated to enhance electrical conductivity, while binder modifiers like styrene-butadiene rubber or polyacrylic acid may improve adhesion and mechanical stability. Functional additives such as fluoroethylene carbonate or vinylene carbonate may also be included to promote the formation of a stable solid electrolyte interphase layer on the anode surface.

Materials for Anode Active Material

[0102] The anode active material is made of or includes various materials, such as, for example, an alkali earth metal, an alkaline earth metal, a group 3B metal, a transition metal, a metalloid, an alloy thereof, a conductive carbon, the like, or a combination thereof, although not limited thereof. In embodiments, the anode active material can comprise silicon, a silicon alloy, lithium, a lithium alloy, a conductive carbon, or a combination thereof, although not limited thereto. In embodiments, the lithium alloy is made of or includes a lithium alloy comprising silicon, chlorine, or a combination thereof. A lithium metal thin film may be used as the anode active material.

Other Materials Anode Active Materials

[0103] The anode active material can include carbon-based material such as artificial graphite, natural graphite, graphitized carbon fiber, amorphous carbon or the like; a metallic compound capable of alloying with lithium such as Si, Al, Sn, Pb, Zn, Bi, In, Mg, Ga, Cd, a Si alloy, a Sn alloy, an Al alloy, or the like; a metal oxide capable of doping and dedoping lithium ions such as SiO_x ($0 < x < 2$), SnO_2 , vanadium oxide or lithium vanadium oxide; and a composite including the metallic compound and the carbon-based material such as a Si—C composite or a Sn—C composite.

Carbon-Based Materials

[0104] The carbon-based material can include low-crystallinity carbon, high-crystallinity carbon, the like, or combinations thereof. A representative example of low-crystallinity carbon is soft carbon or hard carbon, and a representative example of the high-crystallinity carbon is high-temperature calcined carbon such as amorphous, platy, flaky, spherical or fibrous natural graphite or artificial graphite, kish graphite, pyrolytic carbon, mesophase pitch-based carbon fiber, meso-carbon microbeads, mesophase pitches, petroleum or coal tar pitch-derived coke, the like, or combinations thereof.

Metal Carbon Composite Materials

[0105] Alternatively, according to aspects of the disclosure, the anode electrode **104** may comprise an anode material with a metal carbon composite, such as a silver-carbon blend or composite, where silver particles are complexed between amorphous and/or crystalline carbon particles. Here silver is used as an example, and other metals may be used, including for example, tin and/or zinc. Silicon can be used in place of the silver.

Further Materials for Anode Active Material

[0106] In addition to the materials mentioned, the anode active material may also include titanium-based compounds such as lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) or titanium dioxide (TiO_2), which can offer excellent cycling stability and high-rate capability. Other potential materials may include transition

metal oxides like molybdenum oxides (MoO_x), iron oxides (FeO_x), or nickel oxides (NiO_x), which can provide high theoretical capacities. In some cases, composite materials combining different active materials, such as silicon-graphite composites or tin-carbon composites, may be used to leverage the advantages of multiple materials while mitigating their individual limitations.

Dendrite Formation

[0107] When the anode electrode **104** is made of or includes lithium or a lithium alloy, dendrites may form on the anode electrode **104**. The dendrites are a metallic lithium structure formed when extra lithium ions accumulate on a surface of the anode electrode **104**. The formed dendrites may damage the solid electrolyte layer **106**, reduce battery capacity of the solid state battery **100**, and/or otherwise lead to undesired performance of the solid state battery **100**. Dendrite formation is a significant challenge in lithium-based batteries, as these structures can grow through the electrolyte, potentially causing short circuits and safety hazards. The growth rate and morphology of dendrites may be influenced by factors such as current density, temperature, and the nature of the electrolyte-electrode interface.

Advantages of Solid Electrolytes in Mitigating Dendrite Formation

[0108] Solid electrolytes offer several advantages over liquid electrolytes when it comes to mitigating dendrite formation. The mechanical strength of solid electrolytes may help suppress dendrite growth by providing a physical barrier to lithium metal penetration. Additionally, the uniform ion distribution in solid electrolytes may promote more even lithium deposition, reducing the likelihood of localized dendrite nucleation. Some solid electrolytes may also form a stable interface with the lithium metal anode, further inhibiting dendrite formation. However, while solid electrolytes can significantly reduce the risk of dendrite growth, they may not completely eliminate it, and ongoing research aims to develop advanced solid electrolyte materials with enhanced dendrite suppression capabilities.

Shape of Anode Active Material

[0109] The anode active material can be particle shaped or it may be a continuous, unitary form (e.g., a thin film or sheet).

Particle Size

[0110] In embodiments where the anode active material is particle shaped, the anode active material can comprise a particle size of any number in a range from at or about 10 nm to at or about 1000 μ m, such as at or about 10 nm, 15 nm, 20 nm, 25 nm, 30 nm, 35 nm, 40 nm, 45 nm, 50 nm, 55 nm, 60 nm, 65 nm, 70 nm, 75 nm, 80 nm, 85 nm, 90 nm, 95 nm, 100 nm, 110 nm, 120 nm, 130 nm, 140 nm, 150 nm, 160 nm, 170 nm, 180 nm, 190 nm, 200 nm, 210 nm, 220 nm, 230 nm, 240 nm, 250 nm, 260 nm, 270 nm, 280 nm, 290 nm, 300 nm, 310 nm, 320 nm, 330 nm, 340 nm, 350 nm, 360 nm, 370 nm, 380 nm, 390 nm, 400 nm, 410 nm, 420 nm, 430 nm, 440 nm, 450 nm, 460 nm, 470 nm, 480 nm, 490 nm, 500 nm, 510 nm, 520 nm, 530 nm, 540 nm, 550 nm, 560 nm, 570 nm, 580 nm, 590 nm, 600 nm, 610 nm, 620 nm, 630 nm, 640 nm, 650 nm, 660 nm, 670 nm, 680 nm, 690 nm, 700 nm, 710 nm, 720 nm, 730 nm, 740 nm, 750 nm, 760 nm, 770 nm, 780 nm, 790 nm, 800 nm, 810 nm, 820 nm, 830 nm, 840 nm, 850 nm, 860 nm, 870 nm, 880 nm, 890 nm, 900 nm, 910 nm, 920 nm, 930 nm, 940 nm, 950 nm, 960 nm, 970 nm, 980 nm, 990 nm, 1000 nm, 2 μ m, 3 μ m, 4 μ m, 5 μ m, 6 μ m, 7 μ m, 8 μ m, 9 μ m, 10 μ m, 15 μ m, 20 μ m, 25 μ m, 30 μ m, 35 μ m, 40 μ m, 45 μ m, 50 μ m, 55 μ m, 60 μ m, 65 μ m, 70 μ m, 75 μ m, 80 μ m, 85 μ m, 90 μ m, 95 μ m, 100 μ m, 110 μ m, 120 μ m, 130 μ m, 140 μ m, 150 μ m, 160 μ m, 170 μ m, 180 μ m, 190 μ m, 200 μ m, 210 μ m, 220 μ m, 230 μ m, 240 μ m, 250 μ m, 260 μ m, 270 μ m, 280 μ m, 290 μ m, 300 μ m, 310 μ m, 320 μ m, 330 μ m, 340 μ m, 350 μ m, 360 μ m, 370 μ m, 380 μ m, 390 μ m, 400 μ m, 410 μ m, 420 μ m, 430 μ m, 440 μ m, 450 μ m, 460 μ m, 470 μ m, 480 μ m, 490 μ m, 500 μ m, 510 μ m, 520 μ m, 530 μ m, 540 μ m, 550 μ m, 560 μ m, 570 μ m, 580 μ m, 590 μ m, 600 μ m, 610 μ m, 620 μ m, 630 μ m, 640 μ m, 650 μ m, 660 μ m, 670 μ m, 680 μ m, 690 μ m, 700 μ m, 710 μ m, 720 μ m, 730 μ m, 740 μ m, 750 μ m, 760 μ m, 770 μ m, 780 μ m, 790 μ m, 800 μ m, 810 μ m, 820 μ m, 830 μ m, 840 μ m, 850 μ m, 860 μ m, 870 μ m, 880 μ m, 890 μ m, 900 μ m, 910 μ m, 920 μ m, 930 μ m, 940 μ m, 950 μ m, 960 μ m, 970 μ m, 980 μ m, 990

μm, or 1,000 μm. In embodiments, particle size of the anode active material may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of from at or about 10 nm to at or about 1000 μm, e.g., between about 10 nm and about 1,000 μm.

Amount of Anode Active Material in Anode Electrode

[0111] The amount of the anode active material in the solid state battery **100** affects the charge and discharge capacity of the solid state battery **100**. In order to manufacture a high-capacity anode electrode **104**, a high level of anode active material can be included in the anode electrode **104**. For example, the anode electrode **104** includes at, about, or greater than 70, 80, 90, 95, 98, 99, or 100 wt % of anode active material based on the total weight of the anode electrode **104**. In embodiments, anode active material in the anode electrode **104** may be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 70 wt % and about 100 wt %.

Materials for Binder in Anode Electrode

[0112] The binder can comprise various types of binder polymers, such as, for example, polyvinylidene fluoride-co-hexafluoropropylene (PVdF-co-HFP), polyvinylidene fluoride, polyacrylonitrile, polymethyl methacrylate, polyvinyl alcohol, carboxymethyl cellulose (CMC), starch, hydroxypropyl cellulose, regenerated cellulose, polyvinyl pyrrolidone, tetrafluoroethylene, polyethylene, polypropylene, polyacrylate, ethylene-propylene-diene monomer (EPDM), sulfonated EPDM, styrene butadiene rubber (SBR), fluororubber, polyacrylic acid, polymers thereof whose hydrogen atoms are substituted with Li, Na or Ca, various copolymers thereof, the like, or combinations thereof.

Examples of Materials for Binder in Anode Electrode

[0113] In addition to the binders mentioned, other suitable binders for use in the anode electrode may include polyimide, polyamide-imide, polyurethane, polyethylene oxide (PEO), poly(ethylene-co-vinyl acetate) (PEVA), poly(vinyl acetate) (PVA), alginate, chitosan, guar gum, xanthan gum, carrageenan, pectin, gelatin, lignin, and various water-soluble polymers or their derivatives. In some cases, conductive polymers such as polypyrrole, polyaniline, or poly(3,4-ethylenedioxythiophene) (PEDOT) may also be used as binders to simultaneously improve adhesion and electrical conductivity within the anode electrode.

Amount of Binder in Anode Electrode

[0114] The anode electrode **104** may include at or about 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, or 30 wt %, or any other wt % in the range between 0 and 30 wt % of binder based on the total weight of the anode electrode **104**. In embodiments, binder in the anode electrode **104** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range between 0 and 30 wt %, e.g., between about 0 wt % and about 30 wt %.

Thickness of Anode Electrode

[0115] The anode electrode **104** can have a thickness of at or about 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, or 100 μm. In embodiments, the thickness, $t_{sub.4}$, of the anode electrode **104** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of from 10 μm to about 100 μm, e.g., between about 10 μm and about 100 μm or about 10 μm and about 20 μm.

Porosity of Anode Electrode

[0116] A porosity of the anode electrode **104** can be about 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, or 18 vol %, or any other vol % in the range from 0 to 18 vol %, based on the total volume of the anode electrode **104**. In embodiments, the porosity of the anode electrode **104** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range from between 0 vol % to about 18 vol %.

Lithium Ion Diffusivity of Anode Electrode.

[0117] The anode electrode **104** may include a lithium ion diffusivity of at or about $1 \times 10^{sup.-14}$

cm.sup.2/s, $1 \times 10^{\text{sup.}-13}$ cm.sup.2/s, $1 \times 10^{\text{sup.}-12}$ cm.sup.2/s, $1 \times 10^{\text{sup.}-11}$ cm.sup.2/s, $1 \times 10^{\text{sup.}-10}$ cm.sup.2/s, $1 \times 10^{\text{sup.}-9}$ cm.sup.2/s, $1 \times 10^{\text{sup.}-8}$ cm.sup.2/s, or $1 \times 10^{\text{sup.}-7}$ cm.sup.2/s. In embodiments, the lithium ion diffusivity of the anode electrode **104** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range from at or about $1 \times 10^{\text{sup.}-14}$ cm.sup.2/s to at or about $1 \times 10^{\text{sup.}-7}$ cm.sup.2/s.

Current Collector at Anode Electrode

[0118] The current collector **110** collects electrical energy generated at the anode electrode **104** and supports the anode electrode **104**.

Materials for Current Collector at Anode Electrode

[0119] The material of the current collector **110** is not particularly limited as long as it allows adhesion of the anode electrode **104**, has a suitable electrical conductivity, and does not cause significant chemical changes in the corresponding solid state battery **100** in the voltage range of the solid state battery **100**. For example, the current collector **110** is made of or includes a metal or a conductive carbon, although not limited thereto.

Metal for Current Collector

[0120] The metal of the current collector **110** may include one or more selected from the group consisting aluminum, an aluminum alloy, copper, a copper alloy, nickel, a nickel alloy, titanium, a titanium alloy, iron, an iron alloy (e.g., steel, stainless steel), silver, a silver alloy, or a combination thereof, although not limited thereto.

Shape of Current Collector at Anode Electrode

[0121] It is possible to increase the adhesion of the anode electrode **104** to the current collector **110** by forming fine surface irregularities on the surface of the current collector **110**. The current collector **110** may have various shapes, such as, for example, a film, a sheet, a foil, a net, a porous body, a foam, a non-woven web body, the like, or combinations thereof. In addition to the shapes mentioned, the current collector **110** may also be configured as a honeycomb structure, a perforated sheet, a woven or non-woven mesh, a sintered porous body, or a three-dimensional interconnected network. These various shapes can be tailored to optimize the surface area, mechanical strength, and current collection efficiency of the current collector **110**.

Design of Current Collector at Anode Electrode

[0122] Furthermore, the current collector **110** may be designed to accommodate different form factors of solid state batteries, such as pouch cells, cylindrical cells, or prismatic cells, each may offer advantages in terms of packaging efficiency, thermal management, and overall battery performance.

Thickness of Current Collector at Anode Electrode

[0123] A thickness, $t_{\text{sub.5}}$, of the current collector **110** can be at or about 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, or 500 μm . In embodiments, the thickness, $t_{\text{sub.5}}$, of the current collector **110** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of from at or about 1 μm to at or about 500 μm , e.g., between about 5 μm and about 500 μm .

Manufacturing Methods for Anode Electrode

[0124] The anode electrode **104** may be obtained by various methods, such as, for example, atomic deposition, extrusion, rolling, a slurry method, or a combination thereof. In addition to the methods mentioned, the anode electrode **104** may be manufactured using various other techniques, including dry electrode processes. These alternative methods may offer advantages in terms of environmental impact, cost-effectiveness, and scalability.

Dry Powder Coating

[0125] Dry powder coating may be employed as an alternative to the slurry method. In this process,

the anode active material, conductive additives, and binder are mixed in a dry state and then directly applied to the current collector **110** using electrostatic deposition or mechanical compression. This method may reduce the use of solvents, potentially reducing environmental impact and processing time.

3D Printing

[0126] Additive manufacturing techniques, such as 3D printing, may be used to fabricate the anode electrode **104**. Various 3D printing methods, including fused deposition modeling (FDM), selective laser sintering (SLS), or direct ink writing (DIW), can be utilized depending on the specific materials and desired electrode properties. This approach allows for precise control over the electrode structure and porosity.

Electrospinning

[0127] Electrospinning is another potential method for manufacturing the anode electrode **104**. In this process, a solution containing the anode active material, conductive additives, and a polymer binder is extruded through a nozzle under an electric field, resulting in the formation of nanofibers. These fibers can be collected directly on the current collector **110** to form a highly porous electrode structure with increased surface area.

Tape Casting

[0128] Tape casting may be employed to prepare the anode electrode **104**. This technique involves spreading a slurry of electrode materials onto a moving carrier film using a doctor blade, followed by drying and calendaring. The resulting electrode tape can then be laminated onto the current collector **110**.

Spray Coating

[0129] Spray coating techniques may be used to fabricate the anode electrode **104**. A fine mist of the electrode slurry is sprayed onto the current collector **110** using compressed air or ultrasonic atomization. This approach may allow for the creation of thin, uniform electrode layers and can be particularly useful for large-scale production.

Freeze-Casting

[0130] Freeze-casting is another potential method for manufacturing the anode electrode **104**. This process involves freezing a slurry of electrode materials, followed by sublimation of the ice to create a porous structure. The resulting porous electrode can then be sintered and attached to the current collector **110**.

Sol-Gel Process

[0131] In some cases, a sol-gel process may be used to prepare the anode electrode **104**. This method involves the formation of a colloidal suspension (sol) that is then converted into a gel-like network containing the anode active material and other components. The gel can be applied to the current collector **110** and subsequently heat-treated to form the final electrode structure.

Vapor Deposition

[0132] For certain applications, physical vapor deposition (PVD) or chemical vapor deposition (CVD) techniques may be employed to create thin film anodes directly on the current collector **110**. These methods can produce highly uniform and dense electrode layers, which may be particularly beneficial for certain types of solid-state batteries.

Alloying and Ball Milling

[0133] Mechanical alloying and high-energy ball milling may be used to prepare composite anode materials, which can then be pressed into electrodes or applied to the current collector **110** using one of the aforementioned methods. This technique can be particularly useful for creating nanostructured or amorphous anode materials with enhanced electrochemical properties.

Slurry Method

[0134] For example, the anode active material can be mixed and agitated with a solvent, and optionally a binder, and a dispersing agent to form slurry. Then, the slurry can be applied (e.g., coated) onto the current collector **110**, followed by pressing and drying, to obtain the anode

electrode **104**.

Application Methods for Slurry for Anode Electrode

[0135] The application of the slurry for the anode electrode **104** may include using a technique selected from the group consisting of slot die coating, gravure coating, spin coating, spray coating, roll coating, curtain coating, extrusion, casting, screen printing, inkjet printing, spray printing, gravure printing, heat transfer printing, a Toppan printing method, intaglio printing, offset printing, the like, and combinations thereof. In addition to the aforementioned techniques, other methods for applying the anode slurry to the current collector may include doctor blade coating, dip coating, and meniscus coating.

Double Slot Die Layer Coating

[0136] Double slot die layer coating may also be employed, which allows for the simultaneous application of two distinct layers of electrode materials onto the current collector in a single pass. This method can potentially enable the creation of gradient structures within the electrode, optimizing both electrochemical performance and mechanical properties.

Solvent for Slurry for Anode Electrode

[0137] The solvent for forming the anode electrode **104** may include water and/or an organic solvents, such as, for example, N-methyl pyrrolidone (NMP), dimethyl formamide (DMF), acetone, dimethyl acetamide, dimethyl sulfoxide (DMSO), isopropyl alcohol, the like, or combinations thereof. The solvent may be used in an amount sufficient to dissolve and disperse the electrode ingredients, such as the anode active material and binder, considering the slurry coating thickness, production yield, the like, or combinations thereof. Additional organic solvents that may be used include ethanol, methanol, propanol, butanol, ethyl acetate, methyl ethyl ketone, tetrahydrofuran, diethyl ether, and toluene.

Solvent-Free Methods

[0138] In some embodiments, the anode electrode **104** may be prepared using a solvent-free method, such as dry powder processing or melt extrusion, which eliminates the need for liquid solvents and may offer environmental and cost benefits.

Dispersing Agent for Slurry for Anode Electrode

[0139] The dispersing agent forming the anode electrode **104** may include an aqueous dispersing agent and/or an organic dispersing agent, such as, for example, N-methyl-2-pyrrolidone. Other examples of aqueous dispersing agents may include sodium dodecyl sulfate (SDS), polyvinylpyrrolidone (PVP), and carboxymethyl cellulose (CMC), while additional organic dispersing agents may include Triton X-100, polyethylene glycol (PEG), and various surfactants such as polysorbates or poloxamers.

Methods without a Dispersing Agent

[0140] In some embodiments, the anode electrode **104** may be prepared using methods that do not require a dispersing agent, such as dry powder processing or certain additive manufacturing techniques.

Drying Technique for Slurry for Anode Electrode

[0141] The slurry for the anode electrode **104** may be dried by irradiating heat, electron beams (E-beams), gamma rays, or UV (G, H, I-line), the like, or combinations thereof, to vaporize the solvent. For example, the slurry may be vacuum dried at room temperature. Although the solvent is removed through evaporation by the drying step, the other ingredients do not evaporate and remain as they are to form the anode electrode **104**.

Other Drying Techniques

[0142] In addition to the drying techniques mentioned, several other methods may be employed to dry the anode electrode slurry. These additional techniques can offer various advantages depending on the specific materials, production requirements, and desired electrode properties.

Infrared (IR) Drying

[0143] Infrared (IR) drying may be used to rapidly heat the electrode surface, promoting efficient

solvent evaporation. This method can be particularly effective for thin electrode coatings and may allow for precise control of the drying process.

Microwave Drying

[0144] Microwave drying is another option that can provide volumetric heating of the electrode material, potentially leading to more uniform drying throughout the electrode thickness. In some cases, a combination of convection and microwave drying may be employed to optimize both drying speed and uniformity.

Freeze-Drying

[0145] Freeze-drying, also known as lyophilization, may be utilized for certain electrode formulations. This process involves freezing the slurry and then sublimating the solvent under vacuum conditions. Freeze-drying can help maintain the porous structure of the electrode, which may be beneficial for electrolyte penetration and ion transport.

Supercritical CO₂ Drying

[0146] Supercritical CO₂ drying is an advanced technique that may be employed for specialized electrode materials. This method involves replacing the solvent with liquid CO₂, which is then brought to its supercritical state and vented. This approach can help preserve delicate nanostructures within the electrode and may be particularly useful for aerogel-based electrodes.

Two-Step Drying

[0147] In some cases, a two-step drying process may be employed. For example, initial drying may be performed at a lower temperature to remove bulk solvent, followed by a higher temperature step to remove residual solvent and potentially initiate any desired chemical reactions within the electrode material.

Ultrasonic Drying

[0148] Ultrasonic drying may also be considered for certain electrode formulations. This technique uses high-frequency sound waves to agitate the solvent molecules, potentially accelerating the drying process and improving solvent removal from porous structures within the electrode.

Solid Electrolyte Layer Generally

[0149] The solid electrolyte layer **106** is suitable for lithium ion diffusion between the cathode electrode **102** and the anode electrode **104**. The solid electrolyte layer **106** provides an electrically conductive pathway for the movement of charge carriers between the cathode electrode **102** and the anode electrode **104**. The solid electrolyte layer **106** is in electrical communication with the cathode electrode **102** and the anode electrode **104**.

Solid Electrolyte Positioning

[0150] In embodiments, the solid electrolyte layer **106** is formed over and in direct contact with the cathode electrode **102** or the anode electrode **104**. In embodiments, the solid electrolyte layer **106** is in direct contact with the cathode electrode **102** and the anode electrode **104**. In other embodiments, another functional layer may be interposed between the solid electrolyte layer **106** and the cathode electrode **102** and/or the anode electrode **104**.

Materials for Solid Electrolyte Layer

[0151] The solid electrolyte layer **106** may be capable of transport of lithium ions. The material of the solid electrolyte layer **106** is not particularly limited as long as it allows adhesion with adjacent layers, has a suitable electrical conductivity, and does not cause significant chemical changes in the corresponding solid state battery **100** in the voltage range of the solid state battery **100**. For example, the solid electrolyte layer **106** may include various inorganic solid electrolytes, polymer solid electrolytes, and/or polymer gel electrolytes, although not limited thereto. Additionally or alternatively, the solid electrolyte layer **106** may include ceramic electrolytes, glass electrolytes, hybrid organic-inorganic electrolytes, and nanostructured electrolytes, although not limited to these categories.

Inorganic Solid Electrolyte

[0152] The inorganic solid electrolyte may include a crystalline solid electrolyte, a non-crystalline

solid electrolyte, a glass ceramic solid electrolyte, the like, or a combination thereof, although not limited thereto. The inorganic solid electrolyte may be sulfide-based, oxide-based, the like, or a combination thereof. In addition to sulfide-based and oxide-based inorganic solid electrolytes, other types of inorganic solid electrolytes may include halide-based electrolytes, nitride-based electrolytes, and borate-based electrolytes. For example, lithium-rich anti-perovskites (LiRAP) such as Li_3OCl and Li_3OBr , lithium nitride (Li_3N), and lithium borohydride (LiBH_4) have been investigated as potential solid electrolyte materials for lithium-ion batteries.

Sulfide Based Solid Electrolyte

[0153] The sulfide-based solid electrolyte includes sulfur(S) and has ionic conductivity of metal belonging to Group I or Group II of the periodic table, and may include Li-P-S -based glass or Li-P-S -based glass ceramics.

Examples of Sulfide-Based Solid Electrolyte

[0154] For example, the sulfide-based solid electrolyte may include lithium sulfide, silicon sulfide, germanium sulfide and boron sulfide. Particular examples of the inorganic solid electrolyte may include $\text{Li}_{0.3833}\text{Sn}_{0.8333}\text{As}_{0.166}\text{S}_4$, $\text{Li}_{0.4}\text{SnS}_4$, $\text{Li}_{0.325}\text{Ge}_{0.25}\text{P}_{0.75}\text{S}_4$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}$, $\text{B}_{0.2}\text{S}_{0.3}\text{-Li}_{0.2}\text{S}$, $\text{XLi}_{0.2}\text{S-(100-x)P}_{0.2}\text{S}_{0.5}$ ($x=70-80$), $\text{Li}_{0.2}\text{S-SiS}_2\text{-Li}_{0.3}\text{N}$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}\text{-LiI}$, $\text{Li}_{0.2}\text{S-SiS}_2\text{-LiI}$, $\text{Li}_{0.2}\text{S-B}_{0.2}\text{S}_{0.3}\text{-LiI}$, $\text{Li}_{0.3}\text{N}$, LISICON, LIPON ($\text{Li}_{0.3+y}\text{PO}_{0.4-x}\text{N}_x$), thio-LISICON ($\text{Li}_{0.325}\text{Ge}_{0.25}\text{P}_{0.75}\text{S}_4$), $\text{Li}_{0.2}\text{O-Al}_{0.2}\text{O}_{0.3}\text{-TiO}_{0.2}\text{-P}_{0.2}\text{O}_{0.5}$ (LATP), $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-LiI-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-LiI-Li}_{0.2}\text{O-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-LiBr-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-Li}_{0.2}\text{O-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-Li}_{0.3}\text{PO}_{0.4}\text{-P}_{0.2}\text{S}_{0.5}$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}\text{-P}_{0.2}\text{O}_{0.5}$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}\text{-SiS}_2$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}\text{-SnS}$, $\text{Li}_{0.2}\text{S-P}_{0.2}\text{S}_{0.5}\text{-Al}_{0.2}\text{S}_{0.3}$, $\text{Li}_{0.2}\text{S-GeS}_2$, $\text{Li}_{0.2}\text{S-GeS}_2\text{-ZnS}$, $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ (LGPS), $\text{Li}_7\text{P}_3\text{S}_{11}$, $\text{Li}_6\text{PS}_5\text{Cl}$, $\text{Li}_6\text{PS}_5\text{Br}$, $\text{Li}_6\text{PS}_5\text{I}$, $\text{Li}_{9.54}\text{Si}_{1.74}\text{P}_{1.44}\text{S}_{11.7}\text{Cl}_{0.3}$, $\text{Li}_{11}\text{Si}_2\text{PS}_{12}$, the like, or combinations thereof.

Doped Variants

[0155] In some cases, doped variants of these materials, such as Al-doped $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ or Sb-doped $\text{Li}_6\text{PS}_5\text{Cl}$, may also be employed to further enhance ionic conductivity or stability.

Oxide Based Solid Electrolyte

[0156] The oxide-based solid electrolyte material contains oxygen (O) and has ionic conductivity of metal belonging to Group I or II of the periodic table.

Examples of Oxide-Based Solid Electrolyte Material

[0157] The oxide-based solid electrolyte material may include at least one selected from the group consisting of LLTO-based compounds, $\text{Li}_{0.6}\text{La}_{0.2}\text{CaTa}_{0.2}\text{O}_{12}$, $\text{Li}_{0.6}\text{La}_{0.2}\text{ANb}_{0.2}\text{O}_{12}$ (A is Ca or Sr), $\text{Li}_{0.2}\text{Nd}_{0.3}\text{TeSbO}_{12}$, $\text{Li}_{0.3}\text{BO}_{0.25}\text{N}_{0.5}$, Li_2SiO_8 , LAGP-based compounds, LATP-based compounds, $\text{Li}_{1+x}\text{Ti}_{0.2-x}\text{Al}_x\text{Si}_y(\text{PO}_4)_{0.3-y}$ ($0 \leq x \leq 1$, $0 \leq y \leq 1$), $\text{LiAl}_x\text{Zr}_{0.2-x}(\text{PO}_4)_3$ ($0 \leq x \leq 1$, $0 \leq y \leq 1$), LISICON-based compounds, LIPON-based compounds, perovskite-based compounds, NASICON-based compounds and LLZO-based or derived compounds (such as Al-doped $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ and Ta-doped $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$). Lithium-rich anti-perovskites like Li_3OCl and Li_3OBr have also been investigated as potential oxide-based solid electrolytes.

Composite Oxide Electrolyte

[0158] In some cases, composite oxide electrolytes combining multiple oxide materials, such as LLZO-LATP composites, may be employed to leverage the advantages of different oxide systems.

Polymer Solid Electrolyte

[0159] The polymer solid electrolyte is a composite of electrolyte salt with polymer resin and has lithium ion conductivity. The polymer solid electrolyte may include a polyether polymer, a

polycarbonate polymer, an acrylate polymer, a polysiloxane polymer, a phosphazene polymer, a polyethylene derivative, an alkylene oxide derivative, a phosphate polymer, a polyagitation lysine, a polyester sulfide, a polyvinyl alcohol, a polyvinylidene fluoride, a polymer containing an ionically dissociable group, poly(ethylene imine) (PEI), poly(methyl methacrylate) (PMMA), poly(acrylonitrile) (PAN), poly(ethylene succinate) (PES), biopolymers such as chitosan and cellulose derivatives, the like, or combinations thereof.

Polymer Resin for the Solid Polymer Electrolyte

[0160] The solid polymer electrolyte may include a polymer resin, such as a branched copolymer including polyethylene oxide (PEO) backbone copolymerized with a comonomer including an amorphous polymer, such as, for example, PMMA, polycarbonate, polydioxane (pdms) and/or phosphazene, comb-like polymer, crosslinked polymer resin, polyethylene glycol (PEG), polypropylene oxide (PPO), polyacrylonitrile (PAN), poly(methyl methacrylate) (PMMA), poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP), poly(ethylene oxide-co-propylene oxide) (PEO-PPO), poly(ethylene imine) (PEI), poly(vinyl pyrrolidone) (PVP), poly(vinyl alcohol) (PVA), various block copolymers or graft copolymers incorporating these materials, the like, or combinations thereof.

Polymer Gel Electrolyte

[0161] The polymer gel electrolyte can be formed by incorporating an organic electrolyte containing an organic solvent and an electrolyte salt, an ionic liquid, monomer, or oligomer to a polymer resin, the like, or combinations thereof. The polymer resin for the polymer gel can include polyether polymers, PVC polymers, PMMA polymers, polyacrylonitrile (PAN), polyvinylidene fluoride (PVDF), poly(vinylidene fluoride-co-hexafluoropropylene: PVDF-co-HFP), the like, or combinations thereof.

Examples of Polymer Gel Electrolyte

[0162] Examples of polymer gel electrolytes that may be suitable for solid state batteries include poly(ethylene oxide) (PEO), poly(methyl methacrylate-co-ethyl acrylate) (PMMA-EA), poly(acrylonitrile-co-methyl methacrylate) (PAN-MMA), poly(vinyl acetate) (PVAc), poly(ethylene glycol diacrylate) (PEGDA), poly(vinyl pyrrolidone) (PVP), poly(ethylene glycol methyl ether acrylate) (PEGMEA), poly(ethylene glycol methyl ether methacrylate) (PEGMEMA), poly(ionic liquid) (PIL), poly(ethylene glycol-co-propylene glycol) (PEG-PPG), poly(vinyl alcohol-co-ethylene) (PVA-PE), poly(acrylamide) (PAM), poly(2-hydroxyethyl methacrylate) (PHEMA), poly(ethylene glycol-co-polyethylene oxide) (PEG-PEO), and poly(methacrylic acid) (PMAA) based gel electrolytes to optimize the electrochemical and physical properties of the solid electrolyte.

Electrolyte Salt

[0163] The electrolyte salt is an ionizable lithium salt and may be represented by $\text{Li}^{\text{sup.}}+\text{X}^{\text{sup.-}}$. $\text{X}^{\text{sup.-}}$ may include an anion selected from the group consisting of $\text{F}^{\text{sup.-}}$, $\text{Cl}^{\text{sup.-}}$, $\text{Br}^{\text{sup.-}}$, $\text{NO}^{\text{sub.3.sup.-}}$, $\text{N}(\text{CN})^{\text{sub.2.sup.-}}$, $\text{BF}^{\text{sub.4.sup.-}}$, $\text{ClO}^{\text{sub.4.sup.-}}$, $\text{AlO}^{\text{sub.4.sup.-}}$, $\text{AlCl}^{\text{sub.4.sup.-}}$, $\text{PF}^{\text{sub.6.sup.-}}$, $\text{SbF}^{\text{sub.6.sup.-}}$, $\text{AsF}^{\text{sub.6.sup.-}}$, $\text{BF}^{\text{sub.2C.sub.2O.sub.4.sup.-}}$, $\text{BC}^{\text{sub.4O.sub.8.sup.-}}$, $(\text{CF}^{\text{sub.3}})^{\text{sub.2PF.sub.4.sup.-}}$, $(\text{CF}^{\text{sub.3}})^{\text{sub.3PF.sub.3.sup.-}}$, $(\text{CF}^{\text{sub.3}})^{\text{sub.4PF.sub.2.sup.-}}$, $(\text{CF}^{\text{sub.3}})^{\text{sub.5PF.sub.3.sup.-}}$, $(\text{CF}^{\text{sub.3}})^{\text{sub.6PF.sub.3.sup.-}}$, $\text{CF}^{\text{sub.3SO.sub.3.sup.-}}$, $\text{C}^{\text{sub.4F.sub.9SO.sub.3.sup.-}}$, $\text{CF}^{\text{sub.3CF.sub.2SO.sub.3.sup.-}}$, $(\text{CF}^{\text{sub.3SO.sub.2}})^{\text{sub.2N.sup.-}}$, $(\text{F}^{\text{sub.2SO.sub.2}})^{\text{sub.2N.sup.-}}$, $\text{CF}^{\text{sub.3CF.sub.2}}(\text{CF}^{\text{sub.3}})^{\text{sub.2CO.sup.-}}$, $(\text{CF}^{\text{sub.3SO.sub.2}})^{\text{sub.2CH.sup.-}}$, $\text{CF}^{\text{sub.3}}(\text{CF}^{\text{sub.2}})^{\text{sub.7SO.sub.3.sup.-}}$, $\text{CF}^{\text{sub.3CO.sub.2.sup.-}}$, $\text{CH}^{\text{sub.3CO.sub.2.sup.-}}$, SCN , $(\text{CF}^{\text{sub.3CF.sub.2SO.sub.2}})^{\text{sub.2N.sup.-}}$, and the like.

Examples of Lithium Salt

[0164] For example, the lithium salt may be any one selected from the group consisting of LiTFSI , LiCl , LiBr , LiI , $\text{LiClO}^{\text{sub.4}}$, lithium tetrafluoroborate ($\text{LiBF}^{\text{sub.4}}$), $\text{LiB}^{\text{sub.10Cl.sub.10}}$, lithium hexafluorophosphate ($\text{LiPF}^{\text{sub.6}}$), $\text{LiAsF}^{\text{sub.6}}$, $\text{LiSbF}^{\text{sub.6}}$, $\text{LiAlCl}^{\text{sub.4}}$, LiSCN ,

LiCF.sub.3CO.sub.2, LiCH.sub.3SO.sub.3, LiCF.sub.3SO.sub.3, LIN (SO.sub.2CF.sub.3).sub.2, LIN (SO.sub.2C.sub.2F.sub.5).sub.2, LiC.sub.4F.sub.9SO.sub.3, LiC(CF.sub.3SO.sub.2).sub.3, (CF.sub.3SO.sub.2).sub.2NLi, lithium chloroborate, lithium lower aliphatic carboxylate, lithium imide 4-phenylborate, lithium bis(oxalato) borate (LiBOB), lithium difluoro (oxalato) borate (LiDFOB), lithium bis(fluorosulfonyl)imide (LiFSI), lithium 4,5-dicyano-2-(trifluoromethyl)imidazolidine (LiTDI), lithium bis(trifluoromethanesulfonyl)imide (LiTFSI), and lithium bis(fluorosulfonyl)imide (LiFSI), the like, and combinations thereof. The electrolyte salt can include any combination of the salts described herein.

Amount of Electrolyte Salt

[0165] The solid electrolyte layer **106** can include at or about 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, or 400 parts, all based on the total weight of the solid electrolyte layer **106**. In embodiments, electrolyte salt in the solid electrolyte layer **106** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers between about 0 parts and about 400 parts, or about 60 parts and 400 parts, based on the total weight of the solid electrolyte layer **106**.

Ion Conductivity of Solid Electrolyte Layer

[0166] The solid electrolyte layer **106** may have a suitable reduction stability and/or ion conductivity. Since the solid electrolyte layer **106** mainly functions to transport lithium ions between electrodes, the solid electrolyte layer **106** can include a desirable ion conductivity of at, about, or greater than, for example, 10.sup.-7 S/cm, 10.sup.-6 S/cm, 10.sup.-5 S/cm, or 10.sup.-4 S/cm.

Thickness of Solid Electrolyte Layer

[0167] A thickness, to, of the solid electrolyte layer **106** can be at or about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 810, 820, 830, 840, 850, 860, 870, 880, 890, 900, 910, 920, 930, 940, 950, 960, 970, 980, 990, or 1,000 μm . In embodiments, the thickness, t.sub.6, of the solid electrolyte layer **106** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of between 0 and at or about 1,000 μm , e.g., between about 5 μm and about 1,000 μm , about 30 μm and about 100 μm , or about 30 μm and about 50 μm .

Unfinished Product

[0168] The cell **101** as shown in FIG. 1 can be provided as an unfinished product. In embodiments, the cell **101** is stored, transported, and/or delivered to a reseller, customer, or the like that finishes manufacture of a battery assembly or product comprising the cell **101**. In other embodiments, the cell **101** is a finished battery assembly or product.

Sealing Battery

[0169] An enclosure **112** of the solid state battery can be sealed to finish making the solid state battery **100** such that it will work as a battery. The sealing process may involve various techniques to ensure the internal components are protected from external environmental factors and to maintain the integrity of the battery structure. For example, the enclosure **112** may be hermetically sealed using methods such as laser welding, ultrasonic welding, or adhesive bonding. In some cases, the sealing process may also include the introduction of a protective atmosphere or the removal of air to create a vacuum within the enclosure. This sealing step may be helpful for preventing moisture ingress, which could potentially degrade the performance of the sulfide-based solid electrolyte. Additionally, the sealing process may incorporate safety features such as pressure relief mechanisms to manage any potential gas build-up during battery operation.

After Sealing Battery

[0170] Once properly sealed, the solid state battery **100** is ready for final quality control checks, which may include electrical testing, leak detection, and visual inspections. After passing these checks, the solid state battery **100** could be packaged and sold as a finished product, ready for integration into various electronic devices, electric vehicles, energy storage systems (e.g., an energy storage system for storing power generated by a wind generator and/or a solar power generator), and so forth.

Battery Configuration

[0171] The solid state battery **100** is provided in various configurations to suit different applications and device requirements. In some aspects, the battery may be manufactured in a cylindrical form, which can be advantageous for certain types of portable electronics or automotive applications. Alternatively, the solid state battery **100** may be produced in a prismatic form, which can allow for more efficient space utilization in devices with rectangular form factors. In other cases, a pouch form may be employed, offering flexibility in shape and potentially reducing overall battery weight. The pouch form may further be especially suitable for solid state batteries due to easier application and control of uniform pressures within the battery.

Choice of Configuration

[0172] The choice of configuration may depend on factors such as the intended use, space constraints, thermal management requirements, and manufacturing considerations. In some embodiments, hybrid or custom configurations combining elements of different forms may be utilized as desired. The versatility in battery form factors can enable the integration of solid state batteries into a wide range of products, from small wearable devices to large-scale energy storage systems.

Voltage

[0173] The solid state battery **100** is configured to output a voltage of at or about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 48, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 96, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, or 500 V. In embodiments, the output voltage of the solid state battery **100** may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of between 0 and at or about 500 V, e.g., between about 1 V DC and about 500 V DC.

Capacity

[0174] The solid state battery **100** may be configured to have a capacity of at, about, or greater than 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, or 300 mAh/g. In embodiments, the output voltage of the solid state battery **100** may have a capacity formed by selecting any two numbers listed above or by selecting any two numbers in the range of between 0 and 300 mAh/g or between 0 and about 300 mAh/g, e.g., between about 100 mAh/g and about 300 mAh/g.

Volume Expansion Calculation

[0175] The solid state battery **100** may be configured to have a desirable volume expansion rate. The volume expansion rate may be calculated from a change in thickness after the first cycle of charging and discharging compared to the initial thickness. The volume expansion rate may be a ratio of the thickness change to the initial thickness. A first cycle of charging and discharging is performed by CC-CV charging a battery at 0.1 C and cutting off at 4.25 to 4.4 V and 0.02 C, and CC discharging the battery at 0.1 C and cutting off at 3 V. The volume expansion rate is calculated by Equation 1 below in which A may represent a thickness before charging and discharging and B may represent a thickness after charging and discharging. The thickness may be measured using a Mauser micrometer or a scanning electron microscope (SEM).

[00001] $\text{Volumeexpansionrate} = [(B - A) / A] \times 100$ Equation1

C-Rate

[0176] C-rate as used herein refers to the rate at which the battery is discharged relative to its maximum capacity. For example, a 1 C rate means the discharge current will discharge the entire battery within one hour. That is, for a battery with a capacity of 20 Amp-hrs, a discharge current at a 1 C would be 20 Amps.

C-Rate of the Battery

[0177] The solid state battery **100** can comprise a C-rate of at, about, or greater than 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, 3, 4, or 5. In embodiments, the C-rate of the solid state battery **100** can be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 0.33 and about 5.

Other Examples for Volumetric Expansion

[0178] Other ways to measure and calculate the volume expansion rate for a solid state battery may include using volumetric expansion measurement (e.g., gas pycnometry), in-situ dilatometry, X-ray tomography, strain gauge measurements, optical methods (e.g., digital image correlation or laser interferometry), pressure-based methods, and electrochemical strain microscopy.

Conflicts

[0179] The additional features, embodiments and examples discussed below will be applicable to various aspects of the invention discussed above. In case there is a conflict between information in the foregoing discussions and information in the following discussions, however, the information in the foregoing section should apply.

Configuration of Cathode Electrode

[0180] Referring to the detail view in FIG. **1**, the cathode active material particles **114**, the solid electrolyte particles **116**, and the carbon particles **118** are mixed and distributed in the cathode electrode. The solid electrolyte particles **116** contact surfaces of the single crystalline particles. Gaps between cathode active material particles **114** in the cathode electrode **102** can be filled with the solid electrolyte particles **116** and/or carbon particles **118**.

Single Crystalline Particles

[0181] The cathode active material particles **114** comprise single crystalline particles (e.g., a particle consisting of a single grain), each of which does not include polycrystalline grains therein. The inside of the single crystalline particles is substantially free of the solid electrolyte particles **116** and solid electrolyte from the solid electrolyte layer **106**.

Advantages of Single Crystalline Particles

[0182] The cathode electrode **102** is in direct contact with the solid electrolyte layer **106** and side reactions in the cathode electrode **102** are substantially inhibited after the charging and discharging by reducing particle interfaces with the single crystalline particles.

Optional Polycrystalline Particles

[0183] Optionally, the cathode active material particles **114** can additionally include polycrystalline particles, each of which comprises polycrystalline grains. In embodiments, the cathode active material particles **114** do not comprise any polycrystalline particles or are substantially free of polycrystalline particles.

Particulate Nature of Cathode Active Material

[0184] The single crystalline particles can have a particle size in a range of from about 1 nm to about 1000 μm , such as about any of 10 nm, 20 nm, 30 nm, 40 nm, 50 nm, 60 nm, 70 nm, 80 nm, 90 nm, 100 nm, 110 nm, 120 nm, 130 nm, 140 nm, 150 nm, 160 nm, 170 nm, 180 nm, 190 nm, 200 nm, 210 nm, 220 nm, 230 nm, 240 nm, 250 nm, 260 nm, 270 nm, 280 nm, 290 nm, 300 nm, 310 nm, 320 nm, 330 nm, 340 nm, 350 nm, 360 nm, 370 nm, 380 nm, 390 nm, 400 nm, 410 nm, 420 nm, 430 nm, 440 nm, 450 nm, 460 nm, 470 nm, 480 nm, 490 nm, 500 nm, 550 nm, 600 nm, 650 nm, 700 nm, 750 nm, 800 nm, 850 nm, 900 nm, 950 nm, 1000 nm, 5 μm , 10 μm , 15 μm , 20 μm , 25 μm , 30 μm , 35 μm , 40 μm , 45 μm , 50 μm , 55 μm , 60 μm , 65 μm , 70 μm , 75 μm , 80 μm , 85 μm , 90 μm , 95 μm , 100 μm , 110 μm , 120 μm , 130 μm , 140 μm , 150 μm , 160 μm , 170 μm , 180 μm , 190

μm, 200 μm, 210 μm, 220 μm, 230 μm, 240 μm, 250 μm, 260 μm, 270 μm, 280 μm, 290 μm, 300 μm, 310 μm, 320 μm, 330 μm, 340 μm, 350 μm, 360 μm, 370 μm, 380 μm, 390 μm, 400 μm, 410 μm, 420 μm, 430 μm, 440 μm, 450 μm, 460 μm, 470 μm, 480 μm, 490 μm, 500 μm, 550 μm, 600 μm, 650 μm, 700 μm, 750 μm, 800 μm, 850 μm, 900 μm, 950 μm, or 1,000 μm. In embodiments, particle size of the cathode active material may be within a range formed by selecting any two numbers listed above or by selecting any two numbers in the range of from about 1 nm to about 1000 μm, e.g., between about 10 nm and about 1,000 μm or between about 1 nm and about 100 μm. Gaps between cathode active material particles in the cathode electrode **102** can be filled with the solid electrolyte material.

Material for the Cathode Active Material

[0185] The cathode active material particles **114** can comprise a cathode active material configured to bind with lithium ions. The cathode active material can include lithium cobalt oxide

(LiCoO₂), lithium nickel oxide (LiNiO₂),

Li[Ni_aCo_bMn_cM¹]₂O (wherein M¹ is any one element elected from the group consisting of Al, Ga, In, or a combination thereof, 0.33 ≤ a < 1.0, 0 ≤ b ≤ 0.5, 0 ≤ c ≤ 0.5, 0 ≤ d ≤ 0.1, and a + b + c + d = 1), Li(Li_eM²₂(f-e)fM³₃)O₂-gA_g (wherein 0 ≤ e ≤ 0.2, 0.6 ≤ f ≤ 1, 0 ≤ f' ≤ 0.2, 0 ≤ g ≤ 0.2, M² includes Mn and at least one element selected from the group consisting of Ni, Co, Fe, Cr, V, Cu, Zn and Ti, M³ is at least one element selected from the group consisting of Al, Mg and B, and A is at least one element selected from the group consisting of P, F, S and N), or those compounds substituted with one or more transition metals;

lithium manganese oxides such as those represented by the chemical formula of

Li_{1+h}Mn₂O₄ (wherein 0 ≤ h ≤ 0.33), LiMnO₃, LiMn₂O₃, LiMnO₂, or the like; lithium copper oxide (Li₂CuO₂); vanadium oxides such as LiV₃O₈,

V₂O₅ or Cu₂V₂O₇; Ni-site type lithium nickel oxides represented by the chemical formula of LiNi_{1-i}M⁴₄O₂ (wherein M⁴ = Co, Mn, Al, Cu, Fe, Mg,

B or Ga, and 0.01 ≤ y ≤ 0.3); lithium manganese composite oxides represented by the chemical

formula of LiMn₂-jM⁵₅O₂ (wherein M⁵ = Co, Ni, Fe, Cr, Zn, or Ta, and 0.01 ≤ y ≤ 0.1) or Li₂Mn₃M⁶₆O₈ (wherein M⁶ = Fe, Co, Ni, Cu, or Zn);

LiMn₂O₄ in which Li is partially substituted with an alkaline earth metal ion; disulfide compounds; LiFe₃O₄, Fe₂(MoO₄)₃; the like; or combinations thereof. In embodiments, the cathode active material comprises lithium nickel manganese oxide.

Material for the Carbon Particles in the Cathode Electrode

[0186] The carbon particles **118** are configured to enable transport of electrons within the cathode electrode **102**. The carbon particles **118** in the cathode electrode **102** is not particularly limited, as long as it has conductivity while not causing any chemical change in the corresponding solid state battery **100**. For example, the carbon particles **118** can comprise graphite, such as natural graphite or artificial graphite; carbon black, such as acetylene black, ketjen black, channel black, furnace black, lamp black or thermal black; carbon fibers; the like; or combinations thereof.

Amount of Carbon Particles in the Cathode Electrode

[0187] The cathode electrode **102** includes at or about 1, 2, 5, 10, 15, 20, 25, or 30 wt % of carbon particles based on the total weight of the cathode electrode **102**. In embodiments, carbon particles in the cathode electrode **102** may be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 1 wt % and about 30 wt %.

Enhance Thickness Stability of the Anode Electrode

[0188] In embodiments, the thickness, t₄, of the anode electrode **104** can change less than 10%, 5%, 2%, 1%, or 0% during the charging and discharging cycles at a given pressure (e.g., 10 MPa or less, 8 MPa or less, 5 MPa or less) applied to the solid state battery. In embodiments, the thickness, t₂, of the cathode electrode **102** may change within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 0% and about 10%.

Pressure Applied to the Battery

[0189] The layers of the solid state battery **100** can be under a pressure of at or about 1 MPa, 2 MPa, 3 MPa, 4 MPa, 5 MPa, 6 MPa, 7 MPa, 8 MPa, 9 MPa, or 10 MPa. In embodiments, the layers of the solid state battery **100** can be within a range formed by selecting any two numbers listed in the immediately previous sentence, e.g., between about 1 MPa and about 10 MPa or 1 MPa and 5 MPa. For example, the anode can be under a pressure in a range of about 1 MPa and about 10 MPa or 1 MPa and 5 MPa.

Method for Use of the Solid State Battery

[0190] A method of using the solid state battery is provided. The method comprises repeatedly charging and discharging the solid state battery. The cathode is in direct contact with the solid electrolyte and side reactions in the cathode are substantially inhibited after the charging and discharging by reducing particle interfaces with the single crystalline particles.

Method of Manufacture of the Solid State Battery

[0191] A method of manufacturing a cell of a solid state battery is provided. The method comprises depositing a cathode layer, depositing a solid electrolyte layer, and an anode layer. The method comprises configuring the solid state battery such that the solid electrolyte layer is positioned intermediate the cathode layer and the anode layer in order to enable transport of lithium ions between the cathode layer and the anode layer.

EXAMPLES

[0192] Examples will be described more fully hereinafter so that the present disclosure can be understood with ease. However, the following examples are for illustrative purposes only and the scope of the present disclosure is not limited thereto.

Manufacturing Procedure for Examples

[0193] A cathode active material, a solid-state electrolyte, and an electron conducting agent were shear-mixed by mortar and pestle to prepare a cathode composite. In a 10 mm die, solid-state electrolyte powders were spread and pressed at 300 MPa to form a separator layer. Afterward, the cathode composite power was spread on a first side of the separator layer, and the anode electrode was placed on a second side of the separator layer. The three layers (cathode-separator-anode) were then pressed at 500 MPa to assemble a cell.

First Example

[0194] A first example of a solid state battery comprising a cathode electrode having 66% by weight cathode active material, where the cathode active material is polycrystalline and does not comprise single crystalline particles was manufactured.

Second Example

[0195] A second example of a solid state battery comprising a cathode electrode having 66% by weight cathode active material, where the cathode active material is single crystalline was manufactured.

Third Example

[0196] A third example of a solid state battery comprising a cathode electrode having 80% by weight cathode active material, where the cathode active material is polycrystalline and does not comprise single crystalline particles was manufactured.

Fourth Example

[0197] A fourth example of a solid state battery comprising a cathode electrode having 80% by weight cathode active material, where the cathode active material is single crystalline was manufactured.

Example Results

[0198] The Examples were tested and the results of the Examples are shown in FIGS. 2-4.

Combinations and Characteristics Included

[0199] Various features and characteristics are described in this specification to provide an understanding of the composition, structure, production, function, and/or operation of the present disclosure, which includes the disclosed compositions, coatings, and methods. It is understood that

the various features and characteristics of the present disclosure described in this specification can be combined in any suitable manner, regardless of whether such features and characteristics are expressly described in combination in this specification. The Inventors and the Applicant expressly intend such combinations of features and characteristics to be included within the scope of the present disclosure described in this specification. As such, the claims can be amended to recite, in any combination, any features and characteristics expressly or inherently described in, or otherwise expressly or inherently supported by, this specification. Furthermore, the Applicant reserves the right to amend the claims to affirmatively disclaim features and characteristics that may be present in the prior art, even if those features and characteristics are not expressly described in this specification. Therefore, any such amendments will not add new matter to the specification or claims and will comply with the written description, sufficiency of description, and added matter requirements.

INCORPORATED BY REFERENCE

[0200] Any patent, publication, or other document identified in this specification is incorporated by reference into this specification in its entirety unless otherwise indicated but only to the extent that the incorporated material does not conflict with existing descriptions, definitions, statements, illustrations, or other disclosure material expressly set forth in this specification. As such, and to the extent necessary, the express disclosure as set forth in this specification supersedes any conflicting material incorporated by reference. Any material, or portion thereof, that is incorporated by reference into this specification but that conflicts with existing definitions, statements, or other disclosure material set forth herein, is only incorporated to the extent that no conflict arises between that incorporated material and the existing disclosure material. Applicant reserves the right to amend this specification to expressly recite any subject matter, or portion thereof, incorporated by reference. The amendment of this specification to add such incorporated subject matter will comply with the written description, sufficiency of description, and added matter requirements.

ILLUSTRATION OF VARIOUS ASPECTS

[0201] While the present disclosure provides descriptions of various specific aspects for the purpose of illustrating various aspects of the present disclosure and/or its potential applications, it is understood that variations and modifications will occur to those skilled in the art. Accordingly, the present disclosure herein should be understood to be at least as broad as claimed and not as more narrowly defined by particular illustrative aspects provided herein.

Claims

1. A solid state battery comprising a cell which comprises: a cathode electrode comprising cathode active material particles, solid electrolyte particles, and carbon particles, the cathode active material particles comprising a cathode active material configured to bind with lithium ions, the solid electrolyte particles comprising a first solid electrolyte material configured to enable transport of lithium ions within the cathode electrode, carbon particles configured to enable transport of electrons within the cathode electrode; an anode electrode; and a solid electrolyte layer positioned between the cathode electrode and the anode layer, and configured to enable transport of lithium ions between the cathode layer and the anode layer, wherein the solid electrolyte layer comprises a second solid electrolyte material that is the same as or different from the first solid electrolyte material, wherein the cathode active material particles, the solid electrolyte particles and the carbon particles are mixed and distributed in the cathode electrode, wherein the cathode active material particles comprise single crystalline particles, such that inside of the single crystalline particles is substantially free of the first and second solid electrolyte material while the first solid electrolyte material contacts surfaces of the single crystalline particles, wherein the cathode electrode has lithium ion diffusibility ranging from about 1×10^{-14} cm²/s to about 1×10^{-7} cm²/s.

2. The solid state battery of claim 1, wherein each of the single crystalline particles do not include polycrystalline grains therein.
3. The solid state battery of claim 1, wherein the single crystalline particles have a particle size in a range of about 1 nm to about 1,000 nm.
4. The solid state battery of claim 1, wherein the single crystalline particles have an particle size in a range of about 1 nm to about 100 nm.
5. The solid state battery of claim 1, wherein the cathode electrode has a thickness in a range of about 10 μm to about 100 μm .
6. The solid state battery of claim 1, wherein the cathode active material comprises lithium nickel manganese oxide.
7. The solid state battery of claim 1, wherein the cathode electrode comprises at least about 60% by weight of the cathode active material based on a total weight of the cathode electrode.
8. The solid state battery of claim 1, wherein the cathode electrode comprises at least about 75% by weight of cathode active material based on a total weight of the cathode electrode.
9. The solid state battery of claim 1, wherein the cathode electrode further comprises a binder.
10. The solid state battery of claim 1, wherein the solid state battery is under a pressure in a range of about 1 MPa to about 5 MPa.
11. The solid state battery of claim 1, wherein the solid state battery comprises a specific capacity of greater than about 100 mAh/g.
12. The solid state battery of claim 1, wherein solid state battery has a c-rate of at least about 0.33.
13. The solid state battery of claim 1, wherein a thickness of the cell is about 1 mm or less.
14. The solid state battery of claim 1, wherein the cathode active material particles further comprise polycrystalline particles, each of which comprises polycrystalline grains.
15. An electric vehicle comprising the solid state battery of claim 1.
16. An energy storage system for storing power generated by a wind generator and/or a solar power generator, comprising the solid state battery of claim 1.
17. A solid state battery comprising at least two cells, each cell comprises: a cathode electrode comprising cathode active material particles, solid electrolyte particles, and carbon particles, the cathode active material particles comprising a cathode active material configured to bind with lithium ions, the solid electrolyte particles comprising a first solid electrolyte material configured to enable transport of lithium ions within the cathode electrode, carbon particles configured to enable transport of electrons within the cathode electrode; an anode electrode; and a solid electrolyte layer positioned between the cathode electrode and the anode layer, and configured to enable transport of lithium ions between the cathode layer and the anode layer, wherein the solid electrolyte layer comprises a second solid electrolyte material that is the same as or different from the first solid electrolyte material, wherein the cathode active material particles, the solid electrolyte particles and the carbon particles are mixed and distributed in the cathode electrode, wherein the cathode active material particles comprise single crystalline particles, such that inside of the single crystalline particles is substantially free of the first and second solid electrolyte material while the first solid electrolyte material contacts surfaces of the single crystalline particles, wherein the cathode electrode has lithium ion diffusibility ranging from about $1 \times 10^{-14} \text{ cm}^2/\text{s}$ to about $1 \times 10^{-7} \text{ cm}^2/\text{s}$.
18. The solid state battery of claim 17, wherein each of the single crystalline particles do not include polycrystalline grains therein.
19. The solid state battery of claim 17, wherein the single crystalline particles have an particle size in a range of about 1 nm to about 100 nm and the cathode electrode has a thickness in a range of about 10 μm to about 100 μm .
20. A method of using a solid state battery, the method comprising: repeatedly charging and discharging the solid state battery, the solid state battery comprising a cell which comprises: a cathode electrode comprising cathode active material particles, solid electrolyte particles, and

carbon particles, the cathode active material particles comprising a cathode active material configured to bind with lithium ions, the solid electrolyte particles comprising a first solid electrolyte material configured to enable transport of lithium ions within the cathode electrode, carbon particles configured to enable transport of electrons within the cathode electrode; an anode electrode; and a solid electrolyte layer positioned between the cathode electrode and the anode layer, and configured to enable transport of lithium ions between the cathode layer and the anode layer, wherein the solid electrolyte layer comprises a second solid electrolyte material that is the same as or different from the first solid electrolyte material, wherein the cathode active material particles, the solid electrolyte particles and the carbon particles are mixed and distributed in the cathode electrode, wherein the cathode active material particles comprise single crystalline particles, such that inside of the single crystalline particles is substantially free of the first and second solid electrolyte material while the first solid electrolyte material contacts surfaces of the single crystalline particles, wherein the cathode electrode has lithium ion diffusibility ranging from about 1×10^{-14} cm²/s to about 1×10^{-7} cm²/s, wherein the cathode electrode is in direct contact with the solid electrolyte layer and side reactions in the cathode are substantially inhibited after the charging and discharging by reducing particle interfaces with the single crystalline particles.
