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(54) Title: SOLID-STATE BATTERIES INCLUDING AN ION-CONDUCTING MATERIAL BETWEEN AN ANODE AND A SOLID-STATE ELECTROLYTE

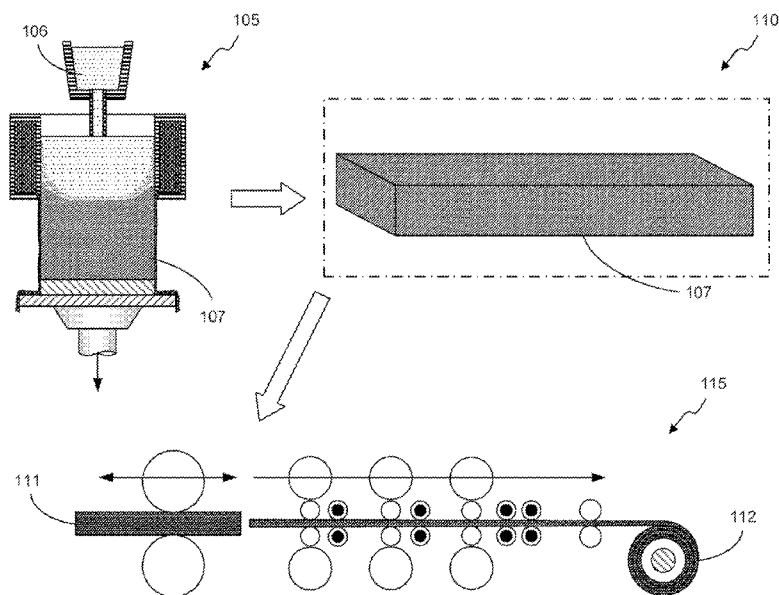


FIG. 1

(57) Abstract: Lithium-ion batteries containing aluminum-based foil anode may have an ion-conducting material thereon to maintain ionic conduction between the anode and a solid-state electrolyte during charge-discharge cycling. During charge-discharge cycling, the anode changes volume, which can cause the anode to separate from the solid-state electrolyte. Said ion-conducting material is preferably deformable and maintains contact with the anode and the solid-state electrolyte through the volume changes, which may stabilize the cycling capacity and increase the useful life of the battery.



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- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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SOLID-STATE BATTERIES INCLUDING AN ION-CONDUCTING MATERIAL BETWEEN AN ANODE AND A SOLID-STATE ELECTROLYTE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application No. 63/507,587, filed on June 12, 2023, the content of which is hereby incorporated by reference in its entirety.

FIELD

[0002] The present disclosure relates to solid-state batteries, and more particularly, to solid-state batteries including an ion-conducting material to conduct ions between the anode and a solid-state electrolyte during charge-discharge cycling.

BACKGROUND

[0003] Solid-state batteries are an emerging technology that could replace conventional lithium-ion batteries due to their improved safety and potential for higher energy density. Solid-state batteries generally include a cathode, an anode, and a solid electrolyte. The cathode and anode store ions that travel back and forth between the anode and the cathode during charge-discharge cycling.

[0004] Solid-state batteries can have a higher energy density than lithium-ion batteries. Lithium-ion batteries use a liquid electrolyte solution to carry ions between the anode and cathode. Solid-state batteries include a solid electrolyte, which could enable the use of high-capacity electrode materials to increase overall energy density and specific energy. However, the use of solid-state batteries is limited due to their drawbacks. For example, if solid-state batteries include anodes that constantly expand and contract in volume during charge-discharge cycling, this can cause loss of contact. Accordingly, brittle electrode materials may crack or break during charge-discharge cycling. Additionally, because the solid-state electrolyte maintains its structure and the electrodes change in volume, the electrodes may separate from the electrolyte, which reduces the charge and discharge capacities of the solid-state battery. Therefore, solid-state batteries have reliability issues that have limited their widespread use despite having higher energy density than conventional electrochemical batteries.

SUMMARY

[0005] The term embodiment and like terms are intended to refer broadly to all of the subject matter of this disclosure and the claims below. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope of the claims below. Embodiments of the present disclosure covered herein are defined by the claims below, not this summary. This summary is a high-level overview of various aspects of the disclosure and introduces some of the concepts that are further described in the Detailed Description section below. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings and each claim.

[0006] In an aspect, described herein are batteries or electrochemical cells. In some examples, a battery comprises an anode; a cathode; a solid-state electrolyte between the anode and the cathode; an ion-conducting material between and contacting the anode and the solid-state electrolyte; and a battery casing. In some examples, the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery. In some embodiments, the ion-conducting material has a yield strength from about 100 MPa or less, such as from 0.1 MPa to 100 MPa, from 0.1 MPa to 5 MPa, from 1 MPa to 10 MPa, from 5 MPa to 15 MPa, from 10 MPa to 25 MPa, from 20 MPa to 35 MPa, from 30 MPa to 45 MPa, from 40 MPa to 55 MPa, from 50 MPa to 65 MPa, from 60 MPa to 75 MPa, from 70 MPa to 85 MPa, from 80 MPa to 95 MPa, or from 90 MPa to 100 MPa. Yield strength can be measured according to ASTM D638-14 at 25 °C. In some embodiments, the ion-conducting material has a Shore A from about 10 to about 100, such as from 10 to 20, from 15 to 25, from 20 to 30, from 25 to 35, from 30 to 40, from 35 to 45, from 40 to 50, from 45 to 55, from 50 to 60, from 55 to 65, from 60 to 70, from 65 to 75, from 70 to 80, from 75 to 85, from 80 to 90, from 85 to 95, or from 90 to 100. In some embodiments, the ion-conducting material has a Mohs hardness of about 2.0 or less, such as from 0.2 to 2.0, from 0.5 to 1.5, from 1.0 to 1.8, from 0.2 to 0.7, from 0.3 to 0.8, from 0.4 to 0.9, from 0.5 to 1.0, from 0.6 to 1.1, from 0.7 to 1.2, from 0.8 to 1.3, from 0.9 to 1.4, from 1.0 to 1.5, from 1.1 to 1.6, from 1.2 to 1.7, from 1.3 to 1.8, from 1.4 to 1.9, or from 1.5 to 2.0.

[0007] In some examples, the ion-conducting material comprises a metal, a metal alloy, a metal compound, a polymer (e.g., an elastomer, a thermoplastic, or a thermoplastic elastomer), or any other deformable material that conducts ions. In some examples, the ion-

conducting material comprises one or more of indium, indium alloys, lithium alloys, lithium compounds, or sodium alloys. In some examples, the ion-conducting material comprises one or more of polyethylene oxide, polypropylene oxide, polyethylene-polystyrene copolymer, poly(acrylonitrile), poly(methyl methacrylate), polyamide, polyaniline, poly(vinylidene fluoride), poly bis-methoxy ethoxyethoxide-phosphazene, polyvinyl chloride, polydimethylsiloxane, poly(vinylidene fluoride)-hexafluoropropylene copolymer, polypyrrole, sulfonated polypyrrole, polythiophene, poly(p-phenylene), poly(p-phenylene vinylene), or phenol formaldehyde resins.

[0008] In some examples, the ion-conducting material exhibits an ionic conductivity for alkali metal ions of about 10^{-2} S/cm or less, such as 10^{-3} S/cm or less. In some examples, the ion-conducting material exhibits an ionic conductivity for alkali metal ions of about 10^{-8} S/cm or greater, such as 10^{-7} S/cm or greater. In some examples, the ion-conducting material exhibits an ionic conductivity for alkali metal ions from about 10^{-8} S/cm to about 10^{-2} S/cm, such as from 10^{-7} S/cm to 10^{-2} S/cm, from 10^{-6} S/cm to 10^{-2} S/cm, from 10^{-8} S/cm to 10^{-3} S/cm, or from 10^{-7} S/cm to 10^{-3} S/cm.

[0009] In some examples, the ion-conducting material has a thickness of from about 0.001 μm to about 500 μm , such as from 0.001 μm to 3 μm , from 0.001 μm to 0.05 μm , from 0.001 μm to 0.25 μm , from 0.05 μm to 0.5 μm , from 0.25 μm to 3 μm , from 1 μm to 10 μm , from 5 μm to 50 μm , from 50 μm to 200 μm , from 100 μm to 300 μm , from 200 μm to 400 μm , or from 300 μm to 500 μm .

[0010] In some examples, the battery casing is configured to apply a stack pressure between the anode and the cathode of from about 0.1 MPa to about 20 MPa, such as from 0.1 MPa to 10 MPa, from 0.1 MPa to 5 MPa, from 0.1 MPa to 1 MPa, from 0.5 MPa to 10 MPa, from 0.5 MPa to 5 MPa, from 0.1 MPa to 0.5 MPa, from 0.5 MPa to 1 MPa, from 1 MPa to 2 MPa, from 2 MPa to 3 MPa, from 3 MPa to 4 MPa, from 4 MPa to 5 MPa, from 5 MPa to 6 MPa, from 6 MPa to 7 MPa, from 7 MPa to 8 MPa, from 8 MPa to 9 MPa, from 9 MPa to 10 MPa, from 5 MPa to 15 MPa, or from 10 MPa to 20 MPa.

[0011] In some examples, the charge-discharge cycling of the batteries may exhibit an average Coulombic efficiency over at least 50 charge-discharge cycles, such as over 5 to 10 charge/discharge cycles, over 10 to 20 charge/discharge cycles, over 20 to 30 charge/discharge cycles, over 30 to 40 charge/discharge cycles, or over 40 to 50 charge/discharge cycles, of from about 95% to 100%, such as from 95% to 96%, from 96% to 97%, from 97% to 98%, from 98% to 99%, or from 99% to 100%.

[0012] In some examples, the anode may comprise an aluminum-based foil. For example, the aluminum-based foil may comprise at least 50 wt.% aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, and/or silver. It will be appreciated that these non-aluminum elements may enhance the ability of aluminum to be used as an alloying anode, such as by providing structural integrity, improved reversibility, and/or lowering yield strength for the alloying anode. In some examples, the anode may comprise an aluminum-based lithium alloying anode.

[0013] Any suitable aluminum alloy may be used in the batteries described herein, such as for the aluminum-based foil of the anode material. In various examples, the aluminum alloy may comprise a 1xxx series aluminum alloy, a 2xxx series aluminum alloy, a 3xxx series aluminum alloy, a 4xxx series aluminum alloy, a 5xxx series aluminum alloy, a 6xxx series aluminum alloy, a 7xxx series aluminum alloy, an 8xxx series aluminum alloy, and/or a recycled content aluminum alloy.

[0014] In various examples, any suitable solid-state electrolyte may be used with the batteries described herein. In some examples, the solid-state electrolyte may comprise an inorganic solid electrolyte. For example, the solid-state electrolyte may comprise a lithium argyrodite material, such as $\text{Li}_6\text{PS}_5\text{Cl}$, a lithium super ionic conductor (LISICON), a doped garnet material, such as $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO), $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$, $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$, lithium phosphorus sulfide (Li_3PS_4), halide materials, such as Li_3YCl_6 , or lithium phosphorus oxynitride (LIPON). In some examples, the solid-state electrolyte has a thickness of from 10 μm to 300 μm . In some examples, the solid-state electrolyte may comprise a polymer electrolyte or a gel electrolyte.

[0015] Any suitable cathode may be used with the batteries described herein. For example, the cathode may comprise a lithium host material, a lithium transition metal oxide cathode, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, lithium manganese oxide, lithium iron phosphate, lithium cobalt oxide, a conversion cathode, lithiated FeS_2 , lithiated FeF_3 , a sulfur-based cathode, or sulfur.

[0016] In some examples, the solid-state batteries described herein may further comprise one or more of: a cathode current collector in contact with the cathode; or an anode current collector in contact with the anode. Optionally, the anode current collector comprises a protected aluminum alloy foil. Optionally, however, the batteries may not include or comprise an anode current collector. For example, in some cases the aluminum-based foil may function as an anode current collector without a separate anode current collector.

[0017] In some examples, the battery casing may be or comprise a rigid structure encasing the anode, the cathode, and the solid-state electrolyte to apply a stack pressure to at least the anode. The battery casing can advantageously provide structural support and prevent physical damage to the battery while enclosing the battery with the rigid structure such that the stack pressure is applied to the battery.

[0018] In another aspect, methods of making batteries are described. In some examples, a method of this aspect comprises: providing an anode having an ion-conducting material disposed on a surface of the anode; providing a cathode; and positioning the anode and the cathode in a battery casing with a solid-state electrolyte added between the ion-conducting material and the cathode such that the ion-conducting material is between and contacting the anode and the solid-state electrolyte. Optionally, methods of this aspect may further comprise one or more of: contacting the anode with an anode current collector; or contacting the cathode with a cathode current collector. Methods of this aspect may be used to prepare any of the batteries described herein.

[0019] In some examples, the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery. In some embodiments, the ion-conducting material has a yield strength from about 100 MPa or less, such as from 0.1 MPa to 100 MPa, from 0.1 MPa to 5 MPa, from 1 MPa to 10 MPa, from 5 MPa to 15 MPa, from 10 MPa to 25 MPa, from 20 MPa to 35 MPa, from 30 MPa to 45 MPa, from 40 MPa to 55 MPa, from 50 MPa to 65 MPa, from 60 MPa to 75 MPa, from 70 MPa to 85 MPa, from 80 MPa to 95 MPa, or from 90 MPa to 100 MPa. Yield strength can be measured according to ASTM D638-14 at 25 °C. In some embodiments, the ion-conducting material has a Shore A from about 10 to about 100, such as from 10 to 20, from 15 to 25, from 20 to 30, from 25 to 35, from 30 to 40, from 35 to 45, from 40 to 50, from 45 to 55, from 50 to 60, from 55 to 65, from 60 to 70, from 65 to 75, from 70 to 80, from 75 to 85, from 80 to 90, from 85 to 95, or from 90 to 100. In some embodiments, the ion-conducting material has a Mohs hardness of about 2.0 or less, such as from 0.2 to 2.0, from 0.5 to 1.5, from 1.0 to 1.8, from 0.2 to 0.7, from 0.3 to 0.8, from 0.4 to 0.9, from 0.5 to 1.0, from 0.6 to 1.1, from 0.7 to 1.2, from 0.8 to 1.3, from 0.9 to 1.4, from 1.0 to 1.5, from 1.1 to 1.6, from 1.2 to 1.7, from 1.3 to 1.8, from 1.4 to 1.9, or from 1.5 to 2.0.

[0020] In some embodiments, the anode comprises aluminum, aluminum alloys, or multiphase aluminum-based composites. For example, the anode may comprise an aluminum-based foil including an aluminum alloy.

[0021] In some examples, providing the anode comprises applying the ion-conducting material to a surface of the anode, where applying includes one or more of electrodeposition, electroless deposition, sputter coating, evaporative deposition, spray coating, slurry casting, spin coating, roll-to-roll coating, or dip coating.

[0022] In examples when the anode comprises an aluminum-based foil that includes an aluminum alloy, providing the anode may optionally comprise preparing the aluminum-based foil that comprises at least 50 wt.% aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, and/or silver. Various methods can be used for preparing the aluminum-based foil. In some examples, providing the anode comprises: casting a molten metal mixture comprising the aluminum alloy to create a cast aluminum-based product; and processing the cast aluminum-based product to generate the aluminum-based foil.

[0023] In yet another aspect, methods of using batteries are described herein. An example method can comprise: providing a battery; and subjecting the battery to one or more charge-discharge cycles. In some examples, the battery comprises: an anode; a cathode; a solid-state electrolyte between the anode and the cathode; an ion-conducting material between and contacting the anode and the solid-state electrolyte; and a battery casing.

[0024] In some examples, the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery. In some embodiments, the ion-conducting material has a yield strength from about 100 MPa or less, such as from 0.1 MPa to 100 MPa, from 0.1 MPa to 5 MPa, from 1 MPa to 10 MPa, from 5 MPa to 15 MPa, from 10 MPa to 25 MPa, from 20 MPa to 35 MPa, from 30 MPa to 45 MPa, from 40 MPa to 55 MPa, from 50 MPa to 65 MPa, from 60 MPa to 75 MPa, from 70 MPa to 85 MPa, from 80 MPa to 95 MPa, or from 90 MPa to 100 MPa. Yield strength can be measured according to ASTM D638-14 at 25 °C. In some embodiments, the ion-conducting material has a Shore A from about 10 to about 100, such as from 10 to 20, from 15 to 25, from 20 to 30, from 25 to 35, from 30 to 40, from 35 to 45, from 40 to 50, from 45 to 55, from 50 to 60, from 55 to 65, from 60 to 70, from 65 to 75, from 70 to 80, from 75 to 85, from 80 to 90, from 85 to 95, or from 90 to 100. In some embodiments, the ion-conducting material has a Mohs hardness of about 2.0 or less, such as from 0.2 to 2.0, from 0.5 to 1.5, from 1.0 to 1.8, from 0.2 to 0.7, from 0.3 to 0.8, from 0.4 to 0.9, from 0.5 to 1.0, from 0.6 to 1.1, from 0.7 to 1.2, from 0.8 to 1.3, from 0.9 to 1.4, from 1.0 to 1.5, from 1.1 to 1.6, from 1.2 to 1.7, from 1.3 to 1.8, from 1.4 to 1.9, or from 1.5 to 2.0.

[0025] In some embodiments, the anode comprises aluminum, aluminum alloys, or multiphase aluminum-based composites. For example, the anode may comprise an aluminum-based foil including an aluminum alloy.

[0026] Other objects and advantages will be apparent from the following detailed description of non-limiting examples.

BRIEF DESCRIPTION OF THE FIGURES

[0027] The specification makes reference to the following appended figures, in which use of like reference numerals in different figures is intended to illustrate like or analogous components.

[0028] FIG. 1 provides a schematic overview of an example method for making a rolled aluminum alloy product.

[0029] FIG. 2 provides a schematic illustration of an example electrochemical cell including an anode comprising an aluminum alloy as an anode active material.

[0030] FIG. 3 provides a cross-sectional electron micrograph image with a scale of 5 μm showing an example aluminum-based anode foil having an ion-conducting material comprising indium disposed on a surface of the aluminum-based anode foil.

[0031] FIG. 4 provides the galvanostatic voltage curves for the first, tenth, and one-hundredth cycles of the example electrochemical cell that includes indium as an ion-conductive material between an anode and a solid-state electrolyte.

[0032] FIG. 5 provides the galvanostatic cycling data over 100 cycles of the example electrochemical cell that includes indium as an ion-conductive material between an anode and a solid-state electrolyte.

[0033] FIG. 6 provides the galvanostatic voltage curves on the first, tenth, and one-hundredth cycles of the control electrochemical cell that does not include an ion-conductive material between an anode and a solid-state electrolyte.

[0034] FIG. 7 provides the galvanostatic cycling data over the 100 cycles for the control electrochemical cell that does not include an ion-conductive material between an anode and a solid-state electrolyte.

[0035] FIG. 8 provides the galvanostatic voltage curves for the first, tenth, and one-hundredth cycles of the example electrochemical cell that includes indium as an ion-conductive material between an anode and a solid-state electrolyte.

[0036] FIG. 9 provides the galvanostatic cycling data over 100 cycles for the example electrochemical cell that includes indium as an ion-conductive material between an anode and a solid-state electrolyte.

DETAILED DESCRIPTION

[0037] The present disclosure provides solid-state batteries and methods of producing solid-state batteries including an ion-conducting material between and contacting both an anode and a solid-state electrolyte to maintain ionic conduction between the anode and the solid-state electrolyte during charge-discharge cycling.

[0038] As discussed above, in operation, a solid-state battery may undergo a plurality of charge-discharge cycles. During charge-discharge cycling, ions move reversibly from the anode to the cathode through the solid-state electrolyte. In particular, the anode receives ions (e.g., lithium ions) from the cathode through the solid-state electrolyte during charging and the anode releases ions to the cathode through the solid-state electrolyte during discharging. The anode may undergo a volume increase when receiving ions during charging and then undergo a volume decrease when releasing ions during discharge. The change in volume of the anode during charge-discharge cycling can cause the anode to separate from the solid-state electrolyte.

[0039] One conventional approach to mitigate separation of the anode and the solid-state electrolyte is to use a high stack pressure that physically compresses the components of the solid-state battery together. However, at high stack pressures, the volume changes of the anode during charge-discharge cycling further increase the pressure exerted on the components of the solid-state battery, which could physically damage said components. Further, commercial batteries prefer lower stack pressures (e.g., about 10 MPa or less, and preferably about 5 MPa or less) due to limitations in the available designs to produce high stack pressures.

[0040] In contrast to conventional approaches, the solid-state batteries of the present disclosure include an ion-conducting material between and contacting each of an anode and a solid-state electrolyte. The ion-conducting material is deformable, which facilitates maintaining contact with the anode and the solid-state electrolyte during charge-discharge cycling. Specifically, the ion-conducting material maintains ionic conduction between the anode and a solid-state electrolyte despite the volume changes of the anode during charge-discharge cycling. Maintaining ionic conduction between the anode and the solid-state electrolyte stabilizes the cycling capacity and increases the useful life of the battery.

[0041] Advantageously, the deformability of the ion-conducting material enables the construction of solid-state batteries with a low stack pressure.

Definitions and Descriptions:

[0042] As used herein, the terms “invention,” “the invention,” “this invention” and “the present invention” are intended to refer broadly to all of the subject matter of this patent application and the claims below. Statements containing these terms should be understood not to limit the subject matter described herein or to limit the meaning or scope of the patent claims below.

[0043] In this description, reference is made to alloys identified by AA numbers and other related designations, such as “series” or “7xxx.” For an understanding of the number designation system most commonly used in naming and identifying aluminum and its alloys, see “International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys” or “Registration Record of Aluminum Association Alloy Designations and Chemical Compositions Limits for Aluminum Alloys in the Form of Castings and Ingot,” both published by The Aluminum Association.

[0044] As used herein, a plate generally has a thickness of greater than about 15 mm. For example, a plate may refer to an aluminum product having a thickness of greater than about 15 mm, greater than about 20 mm, greater than about 25 mm, greater than about 30 mm, greater than about 35 mm, greater than about 40 mm, greater than about 45 mm, greater than about 50 mm, or greater than about 100 mm.

[0045] As used herein, a shate (also referred to as a sheet plate) generally has a thickness of from about 4 mm to about 15 mm. For example, a shate may have a thickness of about 4 mm, about 5 mm, about 6 mm, about 7 mm, about 8 mm, about 9 mm, about 10 mm, about 11 mm, about 12 mm, about 13 mm, about 14 mm, or about 15 mm.

[0046] As used herein, a sheet generally refers to an aluminum product having a thickness of less than about 4 mm. For example, a sheet may have a thickness of less than about 4 mm, less than about 3 mm, less than about 2 mm, less than about 1 mm, less than about 0.5 mm, or less than about 0.3 mm (e.g., about 0.2 mm). It will be appreciated that the term foil, as used herein, may refer to a thin subset of sheets, such as referring to aluminum products having a thickness less than or about 0.5 mm, less than or about 0.45 mm, less than or about 0.4 mm, less than or about 0.35 mm, less than or about 0.3 mm, less than or about 0.25 mm, less than or about 0.2 mm, less than or about 0.15 mm, less than or about 0.1 mm, or less than or about 0.05 mm.

[0047] Reference may be made in this application to alloy temper or condition. For an understanding of the alloy temper descriptions most commonly used, see “American National Standards (ANSI) H35 on Alloy and Temper Designation Systems.” An F condition or temper refers to an aluminum alloy as fabricated. An O condition or temper refers to an aluminum alloy after annealing. An Hxx condition or temper, also referred to herein as an H temper, refers to a non-heat treatable aluminum alloy after cold rolling with or without thermal treatment (e.g., annealing). Suitable H tempers include HX1, HX2, HX3 HX4, HX5, HX6, HX7, HX8, or HX9 tempers. A T1 condition or temper refers to an aluminum alloy cooled from hot working and naturally aged (e.g., at room temperature). A T2 condition or temper refers to an aluminum alloy cooled from hot working, cold worked and naturally aged. A T3 condition or temper refers to an aluminum alloy solution heat treated, cold worked, and naturally aged. A T4 condition or temper refers to an aluminum alloy solution heat treated and naturally aged. A T5 condition or temper refers to an aluminum alloy cooled from hot working and artificially aged (at elevated temperatures). A T6 condition or temper refers to an aluminum alloy solution heat treated and artificially aged. A T7 condition or temper refers to an aluminum alloy solution heat treated and artificially overaged. A T8x condition or temper refers to an aluminum alloy solution heat treated, cold worked, and artificially aged. A T9 condition or temper refers to an aluminum alloy solution heat treated, artificially aged, and cold worked. A W condition or temper refers to an aluminum alloy after solution heat treatment.

[0048] As used herein, terms such as “cast metal product,” “cast product,” “cast aluminum alloy product,” and the like are interchangeable and refer to a product produced by direct chill casting (including direct chill co-casting) or semi-continuous casting, continuous casting (including, for example, by use of a twin belt caster, a twin roll caster, a block caster, or any other continuous caster), electromagnetic casting, hot top casting, or any other casting method.

[0049] As used herein, the meaning of “room temperature” can include a temperature of from about 15 °C to about 30 °C, for example about 15 °C, about 16 °C, about 17 °C, about 18 °C, about 19 °C, about 20 °C, about 21 °C, about 22 °C, about 23 °C, about 24 °C, about 25 °C, about 26 °C, about 27 °C, about 28 °C, about 29 °C, or about 30 °C. As used herein, the meaning of “ambient conditions” can include temperatures of about room temperature, relative humidity of from about 20% to about 100%, and barometric pressure of from about 975 millibar (mbar) to about 1050 mbar. For example, relative humidity can be about 20%, about 21%, about 22%, about 23%, about 24%, about 25%, about 26%, about 27%, about

28%, about 29%, about 30%, about 31%, about 32%, about 33%, about 34%, about 35%, about 36%, about 37%, about 38%, about 39%, about 40%, about 41%, about 42%, about 43%, about 44%, about 45%, about 46%, about 47%, about 48%, about 49%, about 50%, about 51%, about 52%, about 53%, about 54%, about 55%, about 56%, about 57%, about 58%, about 59%, about 60%, about 61%, about 62%, about 63%, about 64%, about 65%, about 66%, about 67%, about 68%, about 69%, about 70%, about 71%, about 72%, about 73%, about 74%, about 75%, about 76%, about 77%, about 78%, about 79%, about 80%, about 81%, about 82%, about 83%, about 84%, about 85%, about 86%, about 87%, about 88%, about 89%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99%, about 100%, or anywhere in between. For example, barometric pressure can be about 975 mbar, about 980 mbar, about 985 mbar, about 990 mbar, about 995 mbar, about 1000 mbar, about 1005 mbar, about 1010 mbar, about 1015 mbar, about 1020 mbar, about 1025 mbar, about 1030 mbar, about 1035 mbar, about 1040 mbar, about 1045 mbar, about 1050 mbar, or anywhere in between.

[0050] All ranges disclosed herein are to be understood to encompass any and all subranges subsumed therein. For example, a stated range of “1 to 10” should be considered to include any and all subranges between (and inclusive of) the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more, e.g., 1 to 6.1, and ending with a maximum value of 10 or less, e.g., 5.5 to 10. Unless stated otherwise, the expression “up to” when referring to the compositional amount of an element means that element is optional and includes a zero percent composition of that particular element. Unless stated otherwise, all compositional percentages are in weight percent (wt.%).

[0051] As used herein, the meaning of “a,” “an,” and “the” includes singular and plural references unless the context clearly dictates otherwise.

[0052] In the following examples, aluminum alloy products and their components may be described in terms of their elemental composition in weight percent (wt.%). In each alloy, the remainder is aluminum, with a maximum of 0.25 wt. % for the sum of all impurities.

[0053] Incidental elements, such as grain refiners and deoxidizers, or other additives may be present in the invention and may add other characteristics on their own without departing from or significantly altering the alloy described herein or the characteristics of the alloy described herein.

[0054] Unavoidable impurities, including materials or elements may be present in an alloy in minor amounts due to inherent properties of aluminum or leaching from contact with processing equipment. Some alloys, as described, may contain no more than about 0.25 wt.%

of any element besides the alloying elements, incidental elements, and unavoidable impurities.

Methods of Producing the Alloys and Aluminum Alloy Products

[0055] As discussed herein, parts of the solid-state batteries described herein can be produced from aluminum alloy products. For example, portions of the anode can be produced from a foil comprising an aluminum alloy. Further, the anode current collector may comprise an aluminum alloy. The aluminum alloy products described herein (e.g., foils) can be prepared using suitable methods. For example, aluminum alloys may be cast, homogenized, hot-rolled, cold-rolled, heat treated, formed, or the like to produce aluminum alloy products.

[0056] FIG. 1 provides an overview of an example method of making an aluminum alloy product. The method of FIG. 1 begins at 105, where an aluminum alloy 106 is cast to form a cast aluminum alloy product 107, such as an ingot or other cast product. At 110, the cast aluminum alloy product 107 is homogenized to form a homogenized aluminum alloy product 111. At 115, the homogenized aluminum alloy product 111 is subjected to one or more hot rolling passes and/or one or more cold rolling passes to form a rolled aluminum alloy product 112, which may correspond to an aluminum alloy article, such as an aluminum alloy plate, an aluminum alloy shate, or an aluminum alloy sheet. Optionally, the rolled aluminum alloy product 112 is subjected to additional processing steps, as described below, to form an aluminum alloy article.

[0057] Non-limiting examples of casting processes include a direct chill (DC) casting process or a continuous casting (CC) process. For example, FIG. 1 depicts a schematic illustration of a DC casting process at 105, but other casting processes can be used. A continuous casting system can include a pair of moving opposed casting surfaces (e.g., moving opposed belts, rolls or blocks), a casting cavity between the pair of moving opposed casting surfaces, and a molten metal injector. The molten metal injector can have an end opening from which molten metal can exit the molten metal injector and be injected into the casting cavity.

[0058] A cast aluminum alloy product, such as a cast ingot, cast slab, or other cast product, can be processed by any desirable techniques. Optionally, the processing steps can be used to prepare rolled aluminum alloy products, such as aluminum alloy sheets. Example optional processing steps include, but are not limited to, homogenization, hot rolling, cold rolling, annealing, solution heat treatment, and pre-aging.

[0059] In a homogenization step, a cast product may be heated to a temperature ranging from about 400 °C to about 600 °C. For example, the cast product can be heated to a temperature of 400 °C, 410 °C, 420 °C, 430 °C, 440 °C, 450 °C, 460 °C, 470 °C, 480 °C, 490 °C, 500 °C, 510 °C, 520 °C, 530 °C, 540 °C, 550 °C, 560 °C, 570 °C, 580 °C, 590 °C, or 600 °C. The product may then be allowed to soak (e.g., held at the indicated temperature) for a period of time to form a homogenized product. In some examples, the total time for the homogenization step, including the heating and soaking phases, can be up to 24 hours. For example, the product can be heated up to 500 °C to 600 °C, and soaked, for a total time of up to 18 hours for the homogenization step. Optionally, the product can be heated to below 490 °C and soaked, for a total time of greater than 18 hours for the homogenization step. In some cases, the homogenization step comprises multiple processes. In some non-limiting examples, the homogenization step includes heating a cast product to a first temperature for a first period of time followed by heating to a second temperature for a second period of time. For example, a cast product can be heated to about 465 °C for about 3.5 hours and then heated to about 480 °C for about 6 hours.

[0060] Following a homogenization step, a hot rolling step can be optionally performed. Prior to the start of hot rolling, the homogenized product can be allowed to cool to a temperature between about 300 °C to about 450 °C. For example, the homogenized product can be allowed to cool to a temperature of between 325 °C to 425 °C or from 350 °C to 400 °C. The homogenized product can then be hot rolled at a temperature between 300 °C to 450 °C to form a hot rolled plate, a hot rolled shate or a hot rolled sheet having a gauge between about 3 mm and about 200 mm (e.g., 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm, 55 mm, 60 mm, 65 mm, 70 mm, 75 mm, 80 mm, 85 mm, 90 mm, 95 mm, 100 mm, 110 mm, 120 mm, 130 mm, 140 mm, 150 mm, 160 mm, 170 mm, 180 mm, 190 mm, 200 mm, or anywhere in between).

[0061] Optionally, the cast product can be a continuously cast product that can be allowed to cool to a temperature between about 300 °C to about 450 °C. For example, the continuously cast product can be allowed to cool to a temperature of between 325 °C to 425 °C or from 350 °C to 400 °C. The continuously cast products can then be hot rolled at a temperature between 300 °C to 450 °C to form a hot rolled plate, a hot rolled shate or a hot rolled sheet having a gauge between about 3 mm and about 200 mm (e.g., 3 mm, 4 mm, 5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 50 mm, 55 mm, 60 mm, 65 mm, 70 mm, 75 mm, 80 mm, 85 mm, 90 mm, 95 mm, 100 mm, 110 mm, 120 mm, 130 mm, 140 mm, 150 mm, 160 mm, 170 mm, 180 mm, 190 mm,

200 mm, or anywhere in between). During hot rolling, temperatures and other operating parameters can be controlled so that the temperature of the hot rolled intermediate product upon exit from the hot rolling mill is no more than 470 °C, no more than 450 °C, no more than 440 °C, or no more than 430 °C.

[0062] Cast, homogenized, or hot-rolled products can be optionally cold rolled using cold rolling mills into thinner products, such as a cold rolled sheet. The cold rolled product can have a gauge between about 0.5 to about 10 mm (e.g., between about 0.7 to about 6.5 mm). Optionally, the cold rolled product can have a gauge of 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm, 6.5 mm, 7.0 mm, 7.5 mm, 8.0 mm, 8.5 mm, 9.0 mm, 9.5 mm, or 10.0 mm. The cold rolling can be performed to result in a final gauge thickness that represents a gauge reduction of up to about 85% (e.g., up to 10%, up to 20%, up to 30%, up to 40%, up to 50%, up to 60%, up to 70%, up to 80%, or up to 85% reduction) as compared to a gauge prior to the start of cold rolling. Optionally, an interannealing step can be performed during the cold rolling step, such as where a first cold rolling process is applied, followed by an annealing process (interannealing), followed by a second cold rolling process. The interannealing step can be performed at a temperature of from about 300 °C to about 450 °C (e.g., 310 °C, 320 °C, 330 °C, 340 °C, 350 °C, 360 °C, 370 °C, 380 °C, 390 °C, 400 °C, 410 °C, 420 °C, 430 °C, 440 °C, or 450 °C). In some cases, the interannealing step comprises multiple processes. In some non-limiting examples, the interannealing step includes heating the partially cold rolled product to a first temperature for a first period of time followed by heating to a second temperature for a second period of time. For example, the partially cold rolled product can be heated to about 410 °C for about 1 hour and then heated to about 330 °C for about 2 hours.

[0063] Subsequently, a cast, homogenized, or rolled product can optionally undergo a solution heat treatment step. The solution heat treatment step can be any suitable treatment for the product that results in solutionizing of soluble particles. The cast, homogenized, or rolled product can be heated to a peak metal temperature (PMT) of up to about 590 °C (e.g., from 400 °C to 590 °C) and soaked for a period of time at the PMT to form a hot product. For example, the cast, homogenized, or rolled product can be soaked at 480 °C for a soak time of up to 30 minutes (e.g., 0 seconds, 60 seconds, 75 seconds, 90 seconds, 5 minutes, 10 minutes, 20 minutes, 25 minutes, or 30 minutes). After heating and soaking, the hot product is rapidly cooled at rates greater than 200 °C/s to a temperature between about 500 °C and about 200 °C to form a heat-treated product. In one example, the hot product is cooled at a quench rate of above 200 °C/second at temperatures between 450 °C and 200 °C. Optionally, the cooling

rates can be faster in other cases. Optionally, the temperature can be lower in other cases. In one example, the hot product is cooled at a quench rate of above 200 °C/second at temperatures between 450 °C and 200 °C.

[0064] After quenching, the heat-treated product can optionally undergo a pre-aging treatment by reheating before coiling. The pre-aging treatment can be performed at a temperature of from about 70 °C to about 125 °C for a period of time of up to 6 hours. For example, the pre-aging treatment can be performed at a temperature of 70 °C, 75 °C, 80 °C, 85 °C, 90 °C, 95 °C, 100 °C, 105 °C, 110 °C, 115 °C, 120 °C, or 125 °C. Optionally, the pre-aging treatment can be performed for about 30 minutes to about 6 hours, such as 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, or 6 hours. The pre-aging treatment can be carried out by passing the heat-treated product through a heating device, such as a device that emits radiant heat, convective heat, induction heat, infrared heat, or the like.

[0065] The cast products described herein can be used to make products in the form of sheets, plates, or other suitable products. For example, plates including the products as described herein can be prepared by processing an ingot in a homogenization step or casting a product in a continuous caster followed by a hot rolling step. In the hot rolling step, the cast product can be hot rolled to a 200 mm thick gauge or less (e.g., from about 10 mm to about 200 mm). For example, the cast product can be hot rolled to a plate having a final gauge thickness of 10 mm to 175 mm, 15 mm to 150 mm, 20 mm to 125 mm, 25 mm to 100 mm, 30 mm to 75 mm, or 35 mm to 50 mm. In some cases, plates may be rolled into thinner metal products, such as sheets.

Example Metals and Metal Alloys

[0066] Described herein are methods of preparing, and using, metals and metal alloys, including aluminum, aluminum alloys, or multiphase aluminum-based composites, others, and the resultant treated metals and metal alloys. Said metals and metal alloys may be used in solid-state batteries, especially the anode (e.g., as a foil) and the anode current collector.

[0067] In some examples, the metals for use in the methods described herein include aluminum alloys, for example, 1xxx series aluminum alloys, 2xxx series aluminum alloys, 3xxx series aluminum alloys, 4xxx series aluminum alloys, 5xxx series aluminum alloys, 6xxx series aluminum alloys, 7xxx series aluminum alloys, or 8xxx series aluminum alloys. In some examples, the materials for use in the methods described herein include non-ferrous materials, including aluminum, aluminum alloys, magnesium, magnesium-based materials, magnesium alloys, magnesium composites, titanium, titanium-based materials, titanium

alloys, copper, copper-based materials, composites, sheets used in composites, or any other suitable metal, non-metal or combination of materials.

[0068] Monolithic as well as non-monolithic, such as roll-bonded materials, clad alloys, clad layers, composite materials, such as but not limited to carbon fiber-containing materials, or various other materials may also be useful with the methods described herein. In some examples, aluminum alloys containing iron are useful with the methods described herein.

[0069] In some examples, the metals and metal alloys comprise aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, and/or silver. In some examples, an aluminum alloy may comprise a conductive element having a lithium alloying potential higher than, similar to, or about equal to that of aluminum.

[0070] For example, the metals and metal alloys may comprise aluminum in amounts from about 50 wt.% to about 100 wt.% aluminum, such as from 50 wt.% to 55 wt.%, from 55 wt.% to 60 wt.%, from 60 wt.% to 65 wt.%, from 65 wt.% to 70 wt.%, from 70 wt.% to 75 wt.%, from 75 wt.% to 80 wt.%, from 80 wt.% to 85 wt.%, from 85 wt.% to 90 wt.%, from 90 wt.% to 95 wt.%, from 95 wt.% to 99 wt.%, from 99 wt.% to 99.9 wt.%, or 99.9 wt.% to 99.99 wt.%. In some embodiments, the metals and metal alloys may comprise one or more other elements like silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, silver, or the like, in amounts from about 0.1 wt.% to about 60 wt.%, or less than or about 1 wt.%, such as from 0.1 wt.% to 0.5 wt.%, from 0.5 wt.% to 1 wt.% to 2 wt.%, from 2 wt.% to 5 wt.%, from 5 wt.% to 10 wt.%, from 10 wt.% to 15 wt.%, from 15 wt.% to 20 wt.%, from 20 wt.% to 25 wt.%, from 25 wt.% to 30 wt.%, from 30 wt.% to 35 wt.%, from 35 wt.% to 40 wt.%, from 40 wt.% to 45 wt.%, or from 45 wt.% to 50 wt.%.

[0071] By way of non-limiting example, exemplary 1xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA1100, AA1100A, AA1200, AA1200A, AA1300, AA1110, AA1120, AA1230, AA1230A, AA1235, AA1435, AA1145, AA1345, AA1445, AA1150, AA1350, AA1350A, AA1450, AA1370, AA1275, AA1185, AA1285, AA1385, AA1188, AA1190, AA1290, AA1193, AA1198, or AA1199.

[0072] Non-limiting exemplary 2xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA2001, AA2002, AA2004, AA2005, AA2006, AA2007, AA2007A, AA2007B, AA2008, AA2009, AA2010, AA2011, AA2011A, AA2111, AA2111A, AA2111B, AA2012, AA2013, AA2014, AA2014A, AA2214, AA2015,

AA2016, AA2017, AA2017A, AA2117, AA2018, AA2218, AA2618, AA2618A, AA2219, AA2319, AA2419, AA2519, AA2021, AA2022, AA2023, AA2024, AA2024A, AA2124, AA2224, AA2224A, AA2324, AA2424, AA2524, AA2624, AA2724, AA2824, AA2025, AA2026, AA2027, AA2028, AA2028A, AA2028B, AA2028C, AA2029, AA2030, AA2031, AA2032, AA2034, AA2036, AA2037, AA2038, AA2039, AA2139, AA2040, AA2041, AA2044, AA2045, AA2050, AA2055, AA2056, AA2060, AA2065, AA2070, AA2076, AA2090, AA2091, AA2094, AA2095, AA2195, AA2295, AA2196, AA2296, AA2097, AA2197, AA2297, AA2397, AA2098, AA2198, AA2099, or AA2199.

[0073] Non-limiting exemplary 3xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA3002, AA3102, AA3003, AA3103, AA3103A, AA3103B, AA3203, AA3403, AA3004, AA3004A, AA3104, AA3204, AA3304, AA3005, AA3005A, AA3105, AA3105A, AA3105B, AA3007, AA3107, AA3207, AA3207A, AA3307, AA3009, AA3010, AA3110, AA3011, AA3012, AA3012A, AA3013, AA3014, AA3015, AA3016, AA3017, AA3019, AA3020, AA3021, AA3025, AA3026, AA3030, AA3130, or AA3065.

[0074] Non-limiting exemplary 4xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA4004, AA4104, AA4006, AA4007, AA4008, AA4009, AA4010, AA4013, AA4014, AA4015, AA4015A, AA4115, AA4016, AA4017, AA4018, AA4019, AA4020, AA4021, AA4026, AA4032, AA4043, AA4043A, AA4143, AA4343, AA4643, AA4943, AA4044, AA4045, AA4145, AA4145A, AA4046, AA4047, AA4047A, or AA4147.

[0075] Non-limiting exemplary 5xxx series aluminum alloys for use in the methods and solid-state batteries described herein product can include AA5182, AA5183, AA5005, AA5005A, AA5205, AA5305, AA5505, AA5605, AA5006, AA5106, AA5010, AA5110, AA5110A, AA5210, AA5310, AA5016, AA5017, AA5018, AA5018A, AA5019, AA5019A, AA5119, AA5119A, AA5021, AA5022, AA5023, AA5024, AA5026, AA5027, AA5028, AA5040, AA5140, AA5041, AA5042, AA5043, AA5049, AA5149, AA5249, AA5349, AA5449, AA5449A, AA5050, AA5050A, AA5050C, AA5150, AA5051, AA5051A, AA5151, AA5251, AA5251A, AA5351, AA5451, AA5052, AA5252, AA5352, AA5154, AA5154A, AA5154B, AA5154C, AA5254, AA5354, AA5454, AA5554, AA5654, AA5654A, AA5754, AA5854, AA5954, AA5056, AA5356, AA5356A, AA5456, AA5456A, AA5456B, AA5556, AA5556A, AA5556B, AA5556C, AA5257, AA5457, AA5557, AA5657, AA5058, AA5059, AA5070, AA5180, AA5180A, AA5082, AA5182, AA5083,

AA5183, AA5183A, AA5283, AA5283A, AA5283B, AA5383, AA5483, AA5086, AA5186, AA5087, AA5187, or AA5088.

[0076] Non-limiting exemplary 6xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA6101, AA6101A, AA6101B, AA6201, AA6201A, AA6401, AA6501, AA6002, AA6003, AA6103, AA6005, AA6005A, AA6005B, AA6005C, AA6105, AA6205, AA6305, AA6006, AA6106, AA6206, AA6306, AA6008, AA6009, AA6010, AA6110, AA6110A, AA6011, AA6111, AA6012, AA6012A, AA6013, AA6113, AA6014, AA6015, AA6016, AA6016A, AA6116, AA6018, AA6019, AA6020, AA6021, AA6022, AA6023, AA6024, AA6025, AA6026, AA6027, AA6028, AA6031, AA6032, AA6033, AA6040, AA6041, AA6042, AA6043, AA6151, AA6351, AA6351A, AA6451, AA6951, AA6053, AA6055, AA6056, AA6156, AA6060, AA6160, AA6260, AA6360, AA6460, AA6460B, AA6560, AA6660, AA6061, AA6061A, AA6261, AA6361, AA6162, AA6262, AA6262A, AA6063, AA6063A, AA6463, AA6463A, AA6763, AA6963, AA6064, AA6064A, AA6065, AA6066, AA6068, AA6069, AA6070, AA6081, AA6181, AA6181A, AA6082, AA6082A, AA6182, AA6091, or AA6092.

[0077] Non-limiting exemplary 7xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA7011, AA7019, AA7020, AA7021, AA7039, AA7072, AA7075, AA7085, AA7108, AA7108A, AA7015, AA7017, AA7018, AA7019A, AA7024, AA7025, AA7028, AA7030, AA7031, AA7033, AA7035, AA7035A, AA7046, AA7046A, AA7003, AA7004, AA7005, AA7009, AA7010, AA7011, AA7012, AA7014, AA7016, AA7116, AA7122, AA7023, AA7026, AA7029, AA7129, AA7229, AA7032, AA7033, AA7034, AA7036, AA7136, AA7037, AA7040, AA7140, AA7041, AA7049, AA7049A, AA7149, AA7204, AA7249, AA7349, AA7449, AA7050, AA7050A, AA7150, AA7250, AA7055, AA7155, AA7255, AA7056, AA7060, AA7064, AA7065, AA7068, AA7168, AA7175, AA7475, AA7076, AA7178, AA7278, AA7278A, AA7081, AA7181, AA7185, AA7090, AA7093, AA7095, or AA7099.

[0078] Non-limiting exemplary 8xxx series aluminum alloys for use in the methods and solid-state batteries described herein can include AA8005, AA8006, AA8007, AA8008, AA8010, AA8011, AA8011A, AA8111, AA8211, AA8112, AA8014, AA8015, AA8016, AA8017, AA8018, AA8019, AA8021, AA8021A, AA8021B, AA8022, AA8023, AA8024, AA8025, AA8026, AA8030, AA8130, AA8040, AA8050, AA8150, AA8076, AA8076A, AA8176, AA8077, AA8177, AA8079, AA8090, AA8091, or AA8093.

[0079] The aluminum alloys and related products (e.g., sheets and foils) described herein can be used in battery applications. For example, the disclosed aluminum alloys and related

products can be used as current collectors and/or electrode materials (e.g., electrode active materials) for batteries or electrochemical cells.

Solid-State Batteries including an Ion-Conducting Material Between and Contacting the Anode and the Solid-State Electrolyte

[0080] The solid-state batteries described herein may include electrodes (e.g., an anode and a cathode) and a solid-state electrolyte where an ion-conducting material is between and contacting the anode and the solid-state electrolyte. FIG. 2 provides a schematic illustration of an example electrochemical cell 200 of a solid-state battery. The electrochemical cell 200 includes an anode active material 205, a cathode active material 210, a solid-state electrolyte 215, and an ion-conducting material 220. The ion-conducting material 220 is disposed on a surface of the anode active material 205. The ion-conducting material 220 can be an interfacial layer between the anode active material 205 and the solid-state electrolyte 215. That is, the ion-conducting material 220 is located between the anode active material 205 and the solid-state electrolyte 215 and is in contact with the anode active material 205 and the solid-state electrolyte 215.

[0081] The ion-conducting material 220 is preferably a deformable material that exhibits good ionic conductivity. The ion-conducting material 220 may comprise a metal, a metal alloy, a metal compound, a polymer (e.g., elastomers, thermoplastics, or thermoplastic elastomers), or any other deformable material that has ionic conductivity. The ion-conducting material 220 may be selected to exhibit elastic deformation at the stack pressure of the solid-state battery. For example, after a stack pressure is applied and released using a Shore A indenter, the indentation recovers at least 80% of the original shape, measured at room temperature.

[0082] Suitable materials for the ion-conducting material 220 may exhibit a yield strength from about 100 MPa or less, such as from 0.1 MPa to 100 MPa, from 0.1 MPa to 5 MPa, from 1 MPa to 10 MPa, from 5 MPa to 15 MPa, from 10 MPa to 25 MPa, from 20 MPa to 35 MPa, from 30 MPa to 45 MPa, from 40 MPa to 55 MPa, from 50 MPa to 65 MPa, from 60 MPa to 75 MPa, from 70 MPa to 85 MPa, from 80 MPa to 95 MPa, or from 90 MPa to 100 MPa. Yield strength can be measured according to ASTM D638-14 at 25 °C. Elastomeric materials do not exhibit a yield strength. As such, suitable materials comprising polymers for the ion-conducting material 220 may not exhibit a yield strength.

[0083] Suitable materials for the ion-conducting material 220 may exhibit a Shore A from about 10 to about 100, such as from 10 to 20, from 15 to 25, from 20 to 30, from 25 to 35, from 30 to 40, from 35 to 45, from 40 to 50, from 45 to 55, from 50 to 60, from 55 to 65, from 60 to 70, from 65 to 75, from 70 to 80, from 75 to 85, from 80 to 90, from 85 to 95, or from 90 to 100. Shore A can be measured according to ASTM D2240-15(2021) at 25 °C.

[0084] Suitable materials for the ion-conducting material 220 may exhibit a Mohs hardness of about 2.0 or less, such as from 0.2 to 2.0, from 0.5 to 1.5, from 1.0 to 1.8, from 0.2 to 0.7, from 0.3 to 0.8, from 0.4 to 0.9, from 0.5 to 1.0, from 0.6 to 1.1, from 0.7 to 1.2, from 0.8 to 1.3, from 0.9 to 1.4, from 1.0 to 1.5, from 1.1 to 1.6, from 1.2 to 1.7, from 1.3 to 1.8, from 1.4 to 1.9, or from 1.5 to 2.0.

[0085] Suitable materials for the ion-conducting material 220 may exhibit an ionic conductivity for alkali metal ions of about 10^{-2} S/cm or less, such as 10^{-3} S/cm or less. Suitable materials for the ion-conducting material 220 may exhibit an ionic conductivity for alkali metal ions of about 10^{-8} S/cm or greater, such as 10^{-7} S/cm or greater. Suitable materials for the ion-conducting material 220 may exhibit an ionic conductivity for alkali metal ions from about 10^{-8} S/cm to about 10^{-2} S/cm, such as from 10^{-7} S/cm to 10^{-2} S/cm, from 10^{-6} S/cm to 10^{-2} S/cm, from 10^{-8} S/cm to 10^{-3} S/cm, or from 10^{-7} S/cm to 10^{-3} S/cm. Ionic conductivity can be measured with electrochemical impedance spectroscopy (EIS) at 25 °C.

[0086] Example polymeric materials for the ion-conducting material 220 include, but are not limited to, those comprising one or more of polyethylene oxide, polypropylene oxide, polyethylene-polystyrene copolymer, poly(acrylonitrile), poly(methyl methacrylate), polyamide, polyaniline, poly(vinylidene fluoride), poly bis-methoxy ethoxyethoxide-phosphazene, polyvinyl chloride, polydimethylsiloxane, poly(vinylidene fluoride)-hexafluoropropylene copolymer, polypyrrole, sulfonated polypyrrole, polythiophene, poly(p-phenylene), poly(p-phenylene vinylene), or phenol formaldehyde resins. Example metal and metal-containing materials for the ion-conducting material 220 include, but are not limited to, those comprising one or more of indium, indium alloys, lithium alloys, lithium compounds, or sodium alloys.

[0087] The ion-conducting material 220 may have a thickness of from about 0.001 μm to about 500 μm , such as from 0.001 μm to 3 μm , from 0.001 μm to 0.05 μm , from 0.001 μm to 0.25 μm , from 0.05 μm to 0.5 μm , from 0.25 μm to 3 μm , from 1 μm to 10 μm , from 5 μm to 50 μm , from 50 μm to 200 μm , from 100 μm to 300 μm , from 200 μm to 400 μm , or from 300 μm to 500 μm .

[0088] As described above, solid-state batteries of the present disclosure can advantageously incorporate an aluminum alloy (e.g., an aluminum-based foil that includes an aluminum alloy). The anode active material 205 may comprise an aluminum-based foil. For example, the anode comprising an aluminum alloy (e.g., the anode active material 205 comprising an aluminum alloy) can exhibit higher energy storage densities than commonly used anode materials for solid-state batteries, such as graphite, due to the higher storage potential of lithium ions in aluminum alloys. Although the storage capability of aluminum alloys may not be as high as metallic lithium, anodes comprising aluminum alloys do not suffer from dendrite formation. Thus, anodes produced from aluminum alloys provide safer operation of solid-state batteries (rechargeable or secondary) as compared to batteries including an anode comprising lithium metal.

[0089] Incorporation of aluminum-based materials as the anode active material 205 in a solid-state electrochemical cell can also allow for incorporation of recycled content material directly in the anode of an electrochemical cell. For example, the anode active material 205 of the solid-state electrochemical cells described herein can comprise aluminum alloys incorporating high amounts of recycled content, such as up to 10%, up to 20%, up to 30%, up to 40%, or more.

[0090] The anode active material 205 may comprise an aluminum alloy comprising lithium. Lithium can alloy with aluminum at potentials encountered at the anode, where lithium ions can be reduced and incorporated into the bulk of the aluminum material as an alloy during charging. During discharging, lithium can be oxidized and released from an alkali metal alloying anode as lithium ions. Lithium can also alloy with other metals or conductive elements at potentials encountered at the anode; when such other metals or conductive elements are also present with aluminum, it may be desirable that other metals or conductive elements alloy with lithium before aluminum alloys with lithium. The aluminum used for the anode active material 205 can be a foil, such as a foil that comprises aluminum or an aluminum alloy. In some embodiments, the anode active material 205 comprises an aluminum-based foil including from about 50 wt.% to about 100 wt.% aluminum, such as from 50 wt.% to 55 wt.%, from 55 wt.% to 60 wt.%, from 60 wt.% to 65 wt.%, from 65 wt.% to 70 wt.%, from 70 wt.% to 75 wt.%, from 75 wt.% to 80 wt.%, from 80 wt.% to 85 wt.%, from 85 wt.% to 90 wt.%, from 90 wt.% to 95 wt.%, from 95 wt.% to 99 wt.%, from 99 wt.% to 99.9 wt.%, or 99.9 wt.% to 99.99 wt.%. In some embodiments, the anode active material 205 comprises an aluminum-based foil including at least 50 wt.% aluminum and one or more other elements like silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc,

titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, silver, or the like, in amounts from about 0.1 wt.% to about 60 wt.%, or less than or about 1 wt.%, such as from 0.1 wt.% to 0.5 wt.%, from 0.5 wt.% to 1 wt.% to 2 wt.%, from 2 wt.% to 5 wt.%, from 5 wt.% to 10 wt.%, from 10 wt.% to 15 wt.%, from 15 wt.% to 20 wt.%, from 20 wt.% to 25 wt.%, from 25 wt.% to 30 wt.%, from 30 wt.% to 35 wt.%, from 35 wt.% to 40 wt.%, from 40 wt.% to 45 wt.%, or from 45 wt.% to 50 wt.%. In some examples, anode active material 205 may comprise a composite including a first plurality of aluminum or aluminum alloy particles and a second plurality of particles selected from at least one of metal particles or non-metal particles. Additional details on composite anodes may be found in PCT International Patent Application Publication No. WO 2023/044264, filed on September 9, 2022, hereby incorporated by reference.

[0091] As described herein, foils used as anode active materials or current collectors can be processed using metal casting and rolling processes, but other techniques can be used to prepare foils including powder-based sintering or laser melting processes, such as laser powder bed fusion techniques.

[0092] In some embodiments, the anode active material 205 may comprise aluminum, aluminum alloys, or multiphase aluminum-based composites, such as eutectic alloys, solid solution alloys, mixed metal systems, multiphase metal systems, or composite particle systems. In some examples, anode active material 205 may comprise a multi-component foil comprising aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, or silver. Additional details on aluminum-based multi-component foils may be found in PCT International Application No.

PCT/US2023/017867, filed on April 7, 2023, hereby incorporated by reference. In some examples, anode active material 205 may comprise a composite including a first plurality of aluminum or aluminum alloy particles and a second plurality of particles selected from at least one of metal particles or non-metal particles. Additional details on composite anodes may be found in U.S. Application No. 63/261,216, filed on September 15, 2021, and PCT International Application No. PCT/US2022/076169, filed on September 9, 2022, hereby incorporated by reference.

[0093] In examples, the anode active material 205 may have a thickness of from about 5 μm to about 60 μm , such as from 5 μm to 10 μm , from 10 μm to 15 μm , from 15 μm to 20 μm , from 20 μm to 25 μm , from 25 μm to 30 μm , from 30 μm to 35 μm , from 35 μm to 40 μm , from 40 μm to 45 μm , from 45 μm to 50 μm , from 50 μm to 55 μm , or from 55 μm to 60

μm. In some examples, the anode active material 205 may exhibit a change in thickness or volume upon charging or discharging, due to the uptake or release of lithium ions. In some examples, a thickness increase in the anode active material 205 upon charging or during lithium-ion uptake may be offset by a thickness decrease in the anode active material 205 upon discharge or during lithium-ion release. In examples, the anode active material 205 may have a yield strength of from about 0.1 MPa to about 300 MPa, such as from 0.1 MPa to 1 MPa, from 1 MPa to 10 MPa, from 10 MPa to 20 MPa, from 20 MPa to 30 MPa, from 30 MPa to 40 MPa, from 40 MPa to 50 MPa, from 50 MPa to 60 MPa, from 60 MPa to 70 MPa, from 70 MPa to 80 MPa, from 80 MPa to 90 MPa, from 90 MPa to 100 MPa, from 100 MPa to 110 MPa, from 110 MPa to 120 MPa, from 120 MPa to 130 MPa, from 130 MPa to 140 MPa, from 140 MPa to 150 MPa, from 150 MPa to 160 MPa, from 160 MPa to 170 MPa, from 170 MPa to 180 MPa, from 180 MPa to 190 MPa, from 190 MPa to 200 MPa, from 200 MPa to 210 MPa, from 210 MPa to 225 MPa, from 225 MPa to 235 MPa, from 235 MPa to 240 MPa, from 240 MPa to 250 MPa, from 250 MPa to 260 MPa, from 260 MPa to 270 MPa, from 270 MPa to 280 MPa, from 280 MPa to 290 MPa, or from 290 MPa to 300 MPa.

[0094] In some examples, charge-discharge cycling of the electrochemical cell 200 including the anode active material 205 may exhibit an average Coulombic efficiency over at least 50 charge-discharge cycles of from about 95% to 100%. For example, the electrochemical cell 200 can exhibit an average Coulombic efficiency from 95% to 96%, from 96% to 97%, from 97% to 98%, from 98% to 99%, or from 99% to 100%, over 1 to 5 charge/discharge cycles, over 5 to 10 charge/discharge cycles, over 10 to 20 charge/discharge cycles, over 20 to 30 charge/discharge cycles, over 30 to 40 charge/discharge cycles, or over 40 to 50 charge/discharge cycles.

[0095] The anode active material 205 may exhibit a specific capacity of from about 300 mAh/g to about 1000 mAh/g or more, such as from 300 mAh/g to 400 mAh/g, from 400 mAh/g to 500 mAh/g, from 500 mAh/g to 600 mAh/g, from 600 mAh/g to 700 mAh/g, from 700 mAh/g to 800 mAh/g, from 800 mAh/g to 900 mAh/g, or from 900 mAh/g to 1000 mAh/g. In some examples, the specific capacity may be higher still, such as if other components with higher specific capacities are included in the anode active material.

[0096] Any suitable solid-state electrolyte 215 may be used in the electrochemical cell 200. The solid-state electrolyte 215 may comprise an ion-conducting and electrically insulating material, such as an inorganic solid electrolyte. In some cases, the solid-state electrolyte 215 may comprise a polymer solid electrolyte, a composite polymer electrolyte, a gel-polymer electrolyte, or a gel electrolyte. In some embodiments, the solid-state electrolyte

215 comprises an inorganic solid electrolyte and does not include a solid polymer electrolyte, composite polymer electrolyte, or gel electrolyte. Inorganic solid electrolytes include, but are not limited to, crystalline, glassy, or ceramic ion conducting materials (e.g., alkali metal ion conducting materials). Example solid-state electrolytes include, but are not limited to, those comprising one or more of lithium super ionic conductors (LISICON), lithium argyrodite materials, (e.g., $\text{Li}_6\text{PS}_5\text{Cl}$), doped garnet materials, (e.g., $\text{Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$, LLZO), $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ and related materials, such as $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$, lithium phosphorus sulfide (e.g., Li_3PS_4), halide materials (e.g., Li_3YCl_6), or lithium phosphorus oxynitride (LIPON). Suitable materials for the solid-state electrolyte may exhibit an ionic conductivity for alkali metal ions of about 10^{-4} S/cm or more (e.g., from 10^{-4} S/cm to 0.01 S/cm). In examples, the solid-state electrolyte 215 may have a thickness of from about 10 μm to about 300 μm , such as from 10 μm to 50 μm , from 50 μm to 100 μm , from 100 μm to 200 μm , or from 200 μm to 300 μm .

[0097] In some embodiments, the electrochemical cell 200 may include an anode current collector 225 and a cathode current collector 230. In such embodiments, the anode comprises the anode current collector 225 and the anode active material 205, and the cathode comprises the cathode current collector 230 and the cathode active material 210. In some examples, the anode current collector 225 is optional and is not present in some implementations.

[0098] The anode current collector 225 may comprise any suitable material, such as copper or other conductive materials, like aluminum. Copper can be beneficial for use as anode current collector 225, as copper is non-reactive at the potentials involved in solid-state battery systems and exhibits high electrical conductivity. Aluminum can alloy with lithium at the potentials involved, making it useful as the anode active material 205, but such characteristics may not be desirable for use of aluminum as anode current collector 225. In some examples, however, aluminum may be used as anode current collector 225, as aluminum is also a highly conductive material and can be constructed as a foil. Optionally, when anode active material 205 comprises a metal foil, anode current collector 225 may not be used, as electrical connections can instead be established directly with anode active material 205 to provide conduction of electrons to/from external circuits (e.g., a load or a power supply). In some cases, aluminum may be used as anode current collector 225 in the form of a protected aluminum or aluminum alloy foil.

[0099] Anode current collector 225 may also be made to have an engineered structure. By engineering the structure, the structure may include additional space and/or micro-porosity. Without being bound by theory, such additional space and/or micro-porosity may compensate for volume changes within the anode current collector 225. Various methods may be used to

form this engineered structure, including powder metallurgy, forming a micro-porous or nano-porous structure by additive manufacturing, using metallic foams, forming perforations by laser or deep etching, de-alloying (e.g., chemical de-alloying), or other methods. In some examples, an engineered structure may be processed by rolling, such as to at least partially consolidate or otherwise make a foil from the engineered structure. In some examples, an engineered structure may comprise or be coupled to, joined to, or bonded to a solid aluminum-based or aluminum alloy-based structure (e.g., a foil) as a solid base layer. In some examples, an engineered structure may be coupled to, joined to, or bonded to a current collector, for example a foil-based current collector, such as a copper current collector or a protected or coated aluminum or aluminum alloy current collector (e.g., an aluminum or aluminum foil coated with Fe, TiN, Ni, or the like). Examples of aluminum-based current collectors, including protected or coated aluminum current collectors, are described in PCT International Application No. PCT/US2021/070250, which is hereby incorporated by reference.

[0100] In some embodiments, the cathode current collector 230 comprises a high-purity aluminum foil, the cathode active material 210 comprises a lithium metal oxide, the anode active material 205 comprises an aluminum alloy, and the anode current collector 225 comprises copper foil. An interface material is not explicitly shown between the electrolyte 215 and the cathode active material 210 in FIG. 2 but may be present.

[0101] For example, the cathode active material 210 and cathode current collector 230 may incorporate materials used in conventional battery systems. Optionally, the cathode current collector 230 may comprise aluminum, such as in the form of an aluminum alloy foil. In some cases, cathode current collector 230 may comprise a high purity aluminum alloy, such as comprising 99.00 wt.% Al or more. Use of high-purity aluminum alloys is useful for maintaining the electrical conductivity of the cathode current collector 230 at as high a level as possible. In some examples, cathode current collector 230 may comprise recycled content, such as at least 1% recycled content, at least 10% recycled content, at least 20% recycled content, at least 30% recycled content, or at least 40% recycled content. The cathode active material 210 may comprise any suitable cathode active material including but not limited to, alkali metal host materials (e.g., a lithium host material) or alkali metal-transition metal oxide cathode active materials, such as lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, lithium manganese oxide, lithium iron phosphate, or lithium metal cobalt oxide. Additional examples of the suitable cathode active material can include a conversion cathode, lithiated FeS₂, lithiated FeF₃, or sulfur.

[0102] In some embodiments, a stack pressure can be applied to ensure that good electrical and ionic communication is maintained during charging or discharging to account for volumetric contraction or expansion by release or uptake of lithium ions. The stack pressure can be applied through a casing or other components.

[0103] FIG. 2 also schematically illustrates a case 235 surrounding the electrochemical cell 200. Case 235 can be any suitable casing to provide the application of a stack pressure to components of the solid-state battery. For example, the case 235 can apply a stack pressure between the ion-conducting material 220 and the adjacent components (i.e., the anode active material 205 and the solid-state electrolyte 215) by applying a force (or compressive force) between anode and cathode. Depending on the components present in the solid-state battery, the force applied to the anode may be applied to the anode active material 205 or the anode current collector 225, if present, or another component of the anode. Further, the force applied to the cathode may be applied to the cathode active material 210 or the cathode current collector 230, if present, or another component of the cathode.

[0104] Example stack pressures may range from about 0.1 MPa to about 20 MPa, such as from 0.1 MPa to 10 MPa, from 0.1 MPa to 5 MPa, from 0.1 MPa to 1 MPa, from 0.5 MPa to 10 MPa, from 0.5 MPa to 5 MPa, from 0.1 MPa to 0.5 MPa, from 0.5 MPa to 1 MPa, from 1 MPa to 2 MPa, from 2 MPa to 3 MPa, from 3 MPa to 4 MPa, from 4 MPa to 5 MPa, from 5 MPa to 6 MPa, from 6 MPa to 7 MPa, from 7 MPa to 8 MPa, from 8 MPa to 9 MPa, from 9 MPa to 10 MPa, from 5 MPa to 15 MPa, or from 10 MPa to 20 MPa. Advantageously, the ion-conducting material 220 is deformable and facilitates lower stack pressures including about 10 MPa or less or more preferably about 5 MPa or less, such as from 0.1 MPa to 10 MPa, from 0.1 MPa to 5 MPa, from 0.1 MPa to 1 MPa, from 0.5 MPa to 10 MPa, from 0.5 MPa to 5 MPa, from 0.1 MPa to 0.5 MPa, from 0.5 MPa to 1 MPa, from 1 MPa to 2 MPa, from 2 MPa to 3 MPa, from 3 MPa to 4 MPa, from 4 MPa to 5 MPa, from 5 MPa to 6 MPa, from 6 MPa to 7 MPa, from 7 MPa to 8 MPa, from 8 MPa to 9 MPa, or from 9 MPa to 10 MPa.

[0105] Case 235 can comprise any suitable material (e.g., an aluminum alloy, steel, plastic, etc.) and exhibit any desirable thickness or geometry for protecting electrochemical cell 200 and/or for applying a stack pressure to at least anode active material 205.

[0106] The electrochemical cell 200 may be constructed in any suitable configuration, such as a cylindrical or spiral wound configuration, a prismatic or pouch configuration, a coin-cell configuration, etc. The components of the electrochemical cell 200 can have any suitable dimensions, depending on the application. The electrochemical cell 200 may be

subjected to repeated charging and discharging (e.g., cycling), for any desirable or possible number of cycles.

[0107] The composition of each of the components of the solid-state batteries may be chosen to provide desired properties (e.g., electrical conductivity, ion conductivity, yield strength, tensile strength, deformability, and the like) at a variety of operating temperatures. Said operating temperatures may be from about -30 °C to about 150 °C, such as -30 °C to 30 °C, -10 °C to 50 °C, 10 °C to 70 °C, 30 °C to 90 °C, 50 °C to 110 °C, 70 °C to 130 °C, or 90 °C to 150 °C.

[0108] The solid-state batteries described herein can further enhance safety, manufacturability, and other characteristics of a battery system, for example, as compared to lithium-ion batteries. Lithium-ion batteries generally incorporate liquid organic solvents in the electrolytes, such as carbonate solvents. Such solvents are generally flammable and undergo undesirable side reactions at surfaces of the anode active materials at the potentials involved. These side reactions can form a solid electrolyte interphase (SEI) layer that degrades performance and reduces capacity of the battery.

[0109] The use of liquid electrolytes together with aluminum-based materials can exacerbate the formation of SEI layers, as aluminum-based active materials undergo volumetric changes when they uptake or release lithium ions. As the active materials uptake lithium, the active material expands, disturbing any SEI material on the surface of the active material and exposing fresh active material to the liquid electrolyte, which can undergo further reaction at the exposed active material and form additional SEI material. In this way, liquid electrolytes used with aluminum-based active materials are susceptible to buildup of SEI material above the active material.

[0110] However, when a solid-state electrolyte is used, such buildup of SEI material can be avoided. For example, solid-state electrolytes may comprise solid materials, such as ceramic type sulfate materials like lithium argyrodite materials (e.g., $\text{Li}_6\text{PS}_5\text{Cl}$), which do not flow like liquid electrolytes. When such solid-state electrolytes encounter volumetric expansion of the anode active material through uptake of lithium, the solid-state electrolyte cannot flow to enter cracks and interfaces of exposed fresh active material, limiting the formation of SEI materials.

Methods of Making Solid-State Batteries

[0111] Methods are also provided for making solid-state batteries. An example method of making a battery can comprise providing an anode having an ion-conducting material

disposed on a surface of the anode; providing a cathode; and positioning the anode and the cathode in a battery casing with a solid-state electrolyte added between the ion-conducting material and the cathode such that the ion-conducting material is between and contacting the anode and the solid-state electrolyte. The methods may include applying the ion-conducting material to a surface of the anode (e.g., to the anode active material 205 of FIG. 2).

Application methods may include, but are not limited to, one or more of electrodeposition, electroless deposition, sputter coating, evaporative deposition, spray coating, slurry casting, spin coating, roll-to-roll coating, or dip coating. For ion-conducting materials comprising a metal or a metal alloy, preferred application methods may be electrodeposition, electroless deposition, sputter coating, or evaporative deposition. For ion-conducting materials comprising a polymer, preferred application methods may be spray coating, slurry casting, spin coating, roll-to-roll coating, or dip coating. The methods of applying the ion-conducting material to a surface of the anode may include using a mask to control the location of the application. For example, in electroless deposition, an aluminum-based foil may have deposited thereon an ion-conducting material comprising indium. If desired, the ion-conducting material can be deposited on both sides of the aluminum-based foil. Alternatively, a mask can be applied to one side of the aluminum-based foil before the electroless deposition. Then, after application of the ion-conducting material to the non-masked side of the aluminum-based foil, the mask can be removed and the aluminum-based foil having the ion-conducting material deposited on one side thereof may be used as or as a part of the anode.

[0112] Examples of useful anodes, anode active materials, cathodes, liquid electrolytes, and solid electrolytes are described herein. In one example, an anode or anode active material may comprise an aluminum-based anode foil as described herein.

[0113] In additional or alternative examples, the methods can comprise, providing a battery comprising an anode; a cathode; a solid-state electrolyte between the anode and the cathode; an ion-conducting material between and contacting the anode and the solid-state electrolyte; and a battery casing; and subjecting the battery to one or more charge-discharge cycles.

[0114] The examples disclosed herein will serve to further illustrate aspects of the invention without, at the same time, however, constituting any limitation thereof. On the contrary, it is to be clearly understood that resort may be had to various embodiments, modifications and equivalents thereof which, after reading the description herein, may suggest themselves to those skilled in the art without departing from the spirit of the

invention. The examples and embodiments described herein may also make use of conventional procedures, unless otherwise stated. Some of the procedures are described herein for illustrative purposes.

EXAMPLE 1

[0115] This Example describes details of preparing an anode with an ion-conducting material disposed thereon.

[0116] Indium was deposited on an aluminum-based foil including an aluminum alloy using electroless deposition. The aluminum-based foil served as the anode. Indium was deposited on aluminum through the use of an electroless chemical deposition method, in which the aluminum-based foil was immersed into an indium salt solution (1 M indium chloride aqueous solution) for about 10-20 seconds. Indium can be deposited on both sides of the aluminum-based foil, or only on one side, by using an adhesive mask.

[0117] FIG. 3 is a cross-sectional scanning electron microscopy (SEM) image of the aluminum-based foil anode after having indium deposited thereon via electroless deposition. The indium has a thickness of about 0.8 μm .

EXAMPLE 2

[0118] Sample solid-state batteries were tested to determine the properties of solid-state batteries incorporating an ion-conductive layer at low stack pressures. This example describes details of comparative testing of electrochemical cells of solid-state batteries with or without the inclusion of an ion-conducting material between and contacting the anode and a solid-state electrolyte. Sample 1 and Comparative Sample 1 each included a cathode, a solid-state electrolyte, and an anode. The cathode comprised $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$, the solid-state electrolyte comprised $\text{Li}_6\text{PS}_5\text{Cl}$, and the anode comprised an aluminum alloy foil. Sample 1 included an ion-conductive layer having thickness of 1 μm . The ion-conductive layer comprised indium that was deposited on the surface of the anode. The anode including the ion-conductive layer of Sample 1 was prepared by a similar method to that of EXAMPLE 1. Sample 1 and Comparative Sample 1 were encased with a stack pressure of 5 MPa.

[0119] FIG. 4 provides the galvanostatic voltage curves for the first, tenth, and one-hundredth cycles of the example electrochemical cell using Sample 1 and including an ion-conductive material between an anode and a solid-state electrolyte. FIG. 5 provides the galvanostatic cycling data over 100 cycles for the example electrochemical cell using Sample 1 and including an ion-conductive material between an anode and a solid-state electrolyte.

FIG. 6 provides the galvanostatic voltage curves on the first, tenth, and one-hundredth cycles of the example electrochemical cell using Comparative Sample 1 and not including an ion-conductive material between an anode and a solid-state electrolyte. FIG. 7 provides the galvanostatic cycling data over the 100 cycles for the example electrochemical cell using Comparative Sample 1 and not including an ion-conductive material between an anode and a solid-state electrolyte.

[0120] For each of Sample 1 and Comparative Sample 1, the first two charge-discharge cycles were conducted at a current density of 0.2 mA/cm^2 . The remaining charge-discharge cycles were conducted at a current density of 1 mA/cm^2 . As shown in FIG. 4, the theoretical areal capacity of 5 mAh/cm^2 is achieved on the first charge of Sample 1. After an initial drop, Sample 1 has relatively stable cycling at an areal capacity of approximately 3 mAh/cm^2 for 100 cycles (FIG. 5). In contrast, while Comparative Sample 1 achieved a high initial discharging capacity of about 2.5 mAh/cm^2 (FIG. 6), the capacity rapidly decreases to less than 1 mAh/cm^2 over a few cycles (FIG. 7). Without being limited by theory, the rapid decrease in capacity when cycling the control electrochemical cell is believed to be due to a disconnection and contact loss between the anode and the solid-state electrolyte. Beneficially, indium reacts with lithium to form the ion-conductive phase LiIn . The ion-conductive layer can deform and maintain contact between the sulfide solid-state electrolyte used here ($\text{Li}_6\text{PS}_5\text{Cl}$) and the aluminum alloy foil during charge/discharge to avoid the setbacks of Comparative Sample 1.

EXAMPLE 3

[0121] Sample solid-state batteries were tested to determine the properties of solid-state batteries incorporating an ion-conductive layer at low stack pressures. Sample 2 included a cathode, a solid-state electrolyte, and an anode. The cathode comprised $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$, the solid-state electrolyte comprised $\text{Li}_6\text{PS}_5\text{Cl}$, and the anode comprised an aluminum alloy foil. Sample 2 included an ion-conductive layer having thickness of $1 \text{ }\mu\text{m}$. The ion-conductive layer comprised indium that was deposited on the surface of the anode. The anode including the ion-conductive layer of Sample 2 were prepared by a similar method to that of EXAMPLE 1. Sample 2 was encased with a stack pressure of 2 MPa .

[0122] FIG. 8 provides the galvanostatic voltage curves for the first, tenth, and one-hundredth cycles of the example electrochemical cell using Sample 2 and including an ion-conductive material between an anode and a solid-state electrolyte. FIG. 9 provides the

galvanostatic cycling data over 100 cycles for the example electrochemical cell using Sample 2 and including an ion-conductive material between an anode and a solid-state electrolyte.

[0123] For Sample 2, the cathode loading was 5 mAh/cm², the first two charge-discharge cycles were conducted at a current density of 0.2 mA/cm², and the remaining charge-discharge cycles were conducted at a current density of 1 mA/cm² for charging and 0.2 mA/cm² for discharging.

[0124] As shown in FIG. 8, the theoretical areal capacity of 5 mAh/cm² is achieved on the first charge of Sample 2. Sample 2 also has relatively stable cycling at an areal capacity of approximately 2 mAh/cm² for 100 cycles (FIG. 9).

[0125] In this example, without being limited by theory, the rapid decrease in capacity when cycling the control electrochemical cell is also believed to be due to a disconnection and contact loss between the anode and the solid-state electrolyte. Beneficially, indium reacts with lithium to form the ion-conductive phase LiIn. The ion-conductive layer can deform and maintain contact between the sulfide solid-state electrolyte used here (Li₆PS₅Cl) and the aluminum alloy foil during charge/discharge to avoid the setbacks of commensurate electrochemical cell but devoid of an ion-conductive material like indium between an anode and a solid-state electrolyte.

ILLUSTRATIVE ASPECTS

[0126] As used below, any reference to a series of aspects (e.g., “Aspects 1-4”) or non-enumerated group of aspects (e.g., “any previous or subsequent aspect”) is to be understood as a reference to each of those aspects disjunctively (e.g., “Aspects 1-4” is to be understood as “Aspects 1, 2, 3, or 4”).

[0127] Aspect 1 is a battery, comprising: an anode; a cathode; a solid-state electrolyte between the anode and the cathode; an ion-conducting material between and contacting the anode and the solid-state electrolyte, wherein the ion-conducting material has an ionic conductivity of 10⁻² S/cm or less and exhibits elastic deformation at a stack pressure of the battery; and a battery casing.

[0128] Aspect 2 is the battery of any previous or subsequent aspect, wherein the ionic conductivity of the ion-conducting material is 10⁻⁸ S/cm to 10⁻² S/cm.

[0129] Aspect 3 is the battery of any previous or subsequent aspect, wherein a yield strength of the ion-conducting material is 0.1 MPa to 100 MPa.

[0130] Aspect 4 is the battery of any previous or subsequent aspect, wherein a Shore A of the ion-conducting material is 10 to 100.

[0131] Aspect 5 is the battery of any previous or subsequent aspect, wherein a Mohs hardness of the ion-conducting material is 2.0 or less.

[0132] Aspect 6 is the battery of any previous or subsequent aspect, wherein the ion-conducting material comprises one or more of a metal, a metal alloy, a metal compound, a polymer.

[0133] Aspect 7 is the battery of any previous or subsequent aspect, wherein the ion-conducting material comprises one or more of indium, an indium alloy, a lithium alloy, a lithium compound, or a sodium alloy.

[0134] Aspect 8 is the battery of any previous or subsequent aspect, wherein the ion-conducting material comprises one or more of polyethylene oxide, polypropylene oxide, polyethylene-polystyrene copolymer, poly(acrylonitrile), poly(methyl methacrylate), polyamide, polyaniline, poly(vinylidene fluoride), poly bis-methoxy ethoxyethoxide-phosphazene, polyvinyl chloride, polydimethylsiloxane, poly(vinylidene fluoride)-hexafluoropropylene copolymer, polypyrrole, sulfonated polypyrrole, polythiophene, poly(p-phenylene), poly(p-phenylene vinylene), or a phenol formaldehyde resin.

[0135] Aspect 9 is the battery of any previous or subsequent aspect, wherein the ion-conducting material has a thickness of 0.001 μm to 500 μm .

[0136] Aspect 10 is the battery of any previous or subsequent aspect, wherein the battery casing is configured to apply a stack pressure between the anode and the cathode, wherein the stack pressure is 0.1 MPa to 20 MPa.

[0137] Aspect 11 is the battery of any previous or subsequent aspect, wherein the anode comprises an aluminum-based foil that includes an aluminum alloy.

[0138] Aspect 12 is the battery of aspect 11, wherein the aluminum alloy comprises a 1xxx series aluminum alloy, a 2xxx series aluminum alloy, a 3xxx series aluminum alloy, a 4xxx series aluminum alloy, a 5xxx series aluminum alloy, a 6xxx series aluminum alloy, a 7xxx series aluminum alloy, an 8xxx series aluminum alloy, or a recycled content aluminum alloy.

[0139] Aspect 13 is the battery of any previous or subsequent aspect, wherein a charge-discharge cycling of the battery exhibits an average Coulombic efficiency over at least 50 charge-discharge cycles of from about 95% to 100%.

[0140] Aspect 14 is the battery of any previous or subsequent aspect, wherein the solid-state electrolyte comprises a lithium argyrodite material, a lithium super ionic conductor, a doped garnet material, $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$, $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$, lithium phosphorus sulfide, halide materials, or lithium phosphorus oxynitride.

[0141] Aspect 15 is the battery of any previous or subsequent aspect, wherein the solid-state electrolyte comprises a polymer electrolyte or a gel electrolyte.

[0142] Aspect 16 is the battery of any previous or subsequent aspect, wherein the cathode comprises a lithium host material, a lithium transition metal oxide cathode, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, lithium manganese oxide, lithium iron phosphate, lithium cobalt oxide, a conversion cathode, FeS_2 , FeF_3 , a sulfur-based cathode, or sulfur.

[0143] Aspect 17 is the battery of any previous or subsequent aspect, further comprising one or more of: a cathode current collector in contact with the cathode; or an anode current collector in contact with the anode.

[0144] Aspect 18 is the battery of any previous or subsequent aspect, wherein the battery does not include or comprise an anode current collector, or wherein the anode functions as an anode current collector without a separate anode current collector.

[0145] Aspect 19 is a method comprising: providing an anode having an ion-conducting material disposed on a surface of the anode, wherein the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery; providing a cathode; and positioning the anode and the cathode in a battery casing with a solid-state electrolyte added between the ion-conducting material and the cathode such that the ion-conducting material is between and contacting the anode and the solid-state electrolyte.

[0146] Aspect 20 is the method of any previous or subsequent aspect, wherein providing the anode comprises: applying the ion-conducting material to a surface of the anode, wherein applying comprises one or more of electrodeposition, electroless deposition, sputter coating, evaporative deposition, spray coating, slurry casting, spin coating, roll-to-roll coating, or dip coating.

[0147] Aspect 21 is the method of any previous or subsequent aspect, wherein the anode comprises an aluminum-based foil that includes an aluminum alloy, and wherein providing the anode comprises: preparing the aluminum-based foil, the aluminum-based foil comprising at least 50 wt.% aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, or silver.

[0148] Aspect 22 is the method of any previous or subsequent aspect, wherein the anode comprises an aluminum-based foil that includes an aluminum alloy, and wherein providing the anode comprises: casting a molten metal mixture comprising the aluminum alloy to create

a cast aluminum-based product; and processing the cast aluminum-based product to generate the aluminum-based foil.

[0149] Aspect 23 is the method of any previous or subsequent aspect, wherein at least the anode, the cathode, the ion-conducting material, the solid-state electrolyte, and the battery casing together correspond to or comprise the battery of any previous or subsequent aspect.

[0150] Aspect 24 is a method comprising: providing a battery, the battery comprising: an anode; a cathode; a solid-state electrolyte between the anode and the cathode; an ion-conducting material between and contacting the anode and the solid-state electrolyte, wherein the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery; and a battery casing; and subjecting the battery to one or more charge-discharge cycles.

[0151] Aspect 25 is the method of any previous or subsequent aspect, wherein at least the anode, the cathode, the ion conducting material, the solid-state electrolyte, and the battery casing together correspond to or comprise the battery of any previous or subsequent aspect.

[0152] All patents and publications cited herein are incorporated by reference in their entirety. The foregoing description of the embodiments, including illustrated embodiments, has been presented only for the purpose of illustration and description and is not intended to be exhaustive or limiting to the precise forms disclosed. Numerous modifications, adaptations, and uses thereof will be apparent to those skilled in the art.

WHAT IS CLAIMED IS:

1. A battery, comprising:
an anode;
a cathode;
a solid-state electrolyte between the anode and the cathode;
an ion-conducting material between and contacting the anode and the solid-state electrolyte, wherein the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery; and
a battery casing.
2. The battery of claim 1, wherein the ionic conductivity of the ion-conducting material is 10^{-8} S/cm to 10^{-2} S/cm.
3. The battery of claim 1, wherein a yield strength of the ion-conducting material is 0.1 MPa to 100 MPa.
4. The battery of claim 1, wherein a Shore A of the ion-conducting material is 10 to 100.
5. The battery of claim 1, wherein a Mohs hardness of the ion-conducting material is 2.0 or less.
6. The battery of claim 1, wherein the ion-conducting material comprises one or more of a metal, a metal alloy, a metal compound, a polymer.
7. The battery of claim 1, wherein the ion-conducting material comprises one or more of indium, an indium alloy, a lithium alloy, a lithium compound, or a sodium alloy.
8. The battery of claim 1, wherein the ion-conducting material comprises one or more of polyethylene oxide, polypropylene oxide, polyethylene-polystyrene copolymer, poly(acrylonitrile), poly(methyl methacrylate), polyamide, polyaniline, poly(vinylidene fluoride), poly bis-methoxy ethoxyethoxide-phosphazene, polyvinyl chloride, polydimethylsiloxane, poly(vinylidene fluoride)-hexafluoropropylene copolymer,

polypyrrole, sulfonated polypyrrole, polythiophene, poly(p-phenylene), poly(p-phenylene vinylene), or a phenol formaldehyde resin.

9. The battery of claim 1, wherein the ion-conducting material has a thickness of 0.001 μm to 500 μm .

10. The battery of claim 1, wherein the battery casing is configured to apply a stack pressure between the anode and the cathode, wherein the stack pressure is 0.1 MPa to 20 MPa.

11. The battery of claim 1, wherein the anode comprises an aluminum-based foil that includes an aluminum alloy.

12. The battery of claim 11, wherein the aluminum alloy comprises a 1xxx series aluminum alloy, a 2xxx series aluminum alloy, a 3xxx series aluminum alloy, a 4xxx series aluminum alloy, a 5xxx series aluminum alloy, a 6xxx series aluminum alloy, a 7xxx series aluminum alloy, an 8xxx series aluminum alloy, or a recycled content aluminum alloy.

13. The battery of claim 1, wherein a charge-discharge cycling of the battery exhibits an average Coulombic efficiency over at least 50 charge-discharge cycles of from about 95% to 100%.

14. The battery of claim 1, wherein the solid-state electrolyte comprises a lithium argyrodite material, a lithium super ionic conductor, a doped garnet material, $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$, $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$, lithium phosphorus sulfide, halide materials, or lithium phosphorus oxynitride.

15. The battery of claim 1, wherein the solid-state electrolyte comprises a polymer electrolyte or a gel electrolyte.

16. The battery of claim 1, wherein the cathode comprises a lithium host material, a lithium transition metal oxide cathode, lithium nickel manganese cobalt oxide, lithium nickel cobalt aluminum oxide, lithium manganese oxide, lithium iron phosphate, lithium cobalt oxide, a conversion cathode, FeS_2 , FeF_3 , a sulfur-based cathode, or sulfur.

17. A method comprising:

providing an anode having an ion-conducting material disposed on a surface of the anode, wherein the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery;

providing a cathode; and

positioning the anode and the cathode in a battery casing with a solid-state electrolyte added between the ion-conducting material and the cathode such that the ion-conducting material is between and contacting the anode and the solid-state electrolyte.

18. The method of claim 17, wherein providing the anode comprises:

applying the ion-conducting material to a surface of the anode, wherein applying comprises one or more of electrodeposition, electroless deposition, sputter coating, evaporative deposition, spray coating, slurry casting, spin coating, roll-to-roll coating, or dip coating.

19. The method of claim 17, wherein the anode comprises an aluminum-based foil that includes an aluminum alloy, and wherein providing the anode comprises:

preparing the aluminum-based foil, the aluminum-based foil comprising at least 50 wt.% aluminum and one or more of silicon, iron, copper, manganese, magnesium, chromium, nickel, zinc, titanium, lead, vanadium, zirconium, gallium, indium, tin, indium, carbon, antimony, germanium, bismuth, or silver.

20. A method comprising:

providing a battery, the battery comprising:

an anode;

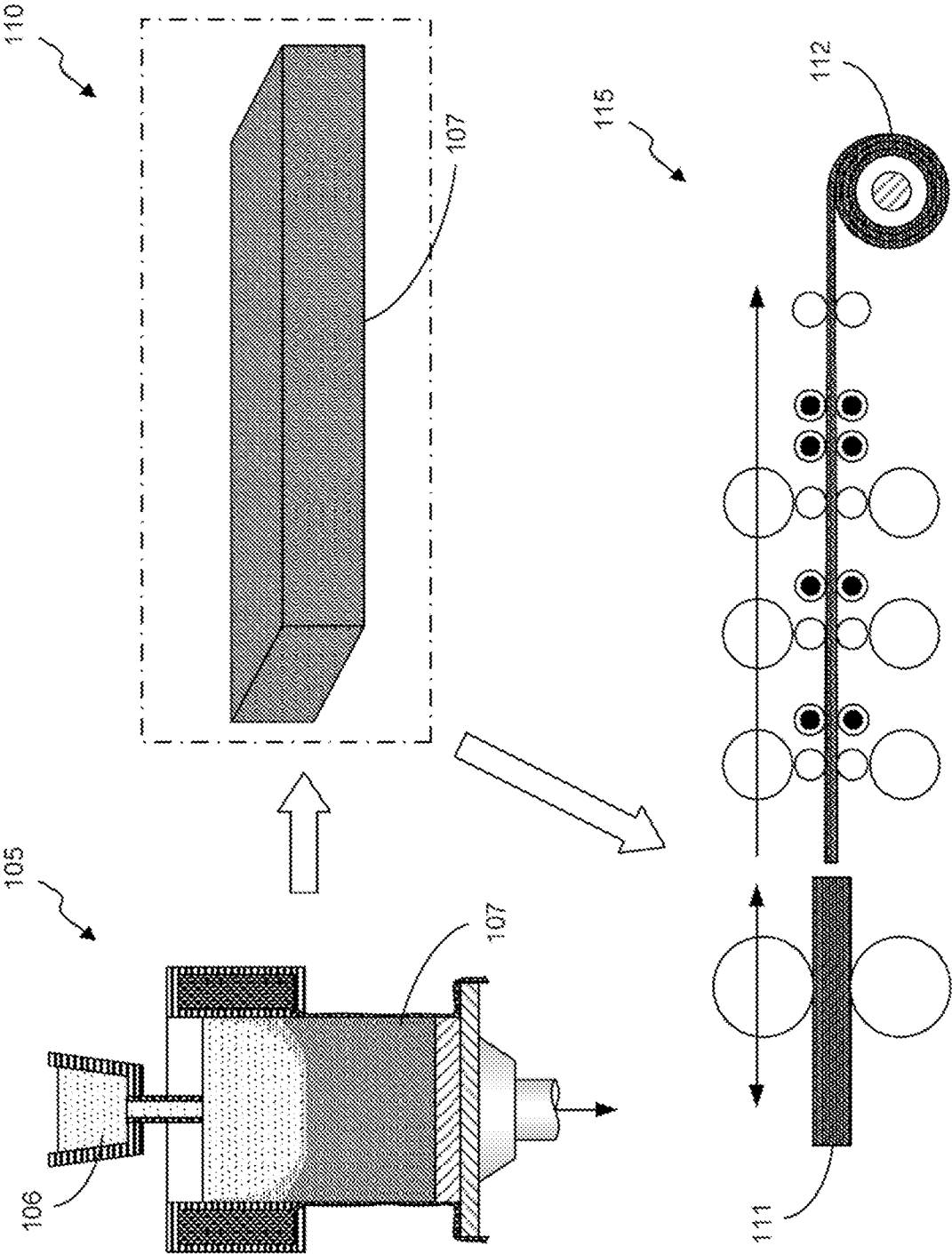
a cathode;

a solid-state electrolyte between the anode and the cathode;

an ion-conducting material between and contacting the anode and the solid-state electrolyte, wherein the ion-conducting material has an ionic conductivity of 10^{-2} S/cm or less and exhibits elastic deformation at a stack pressure of the battery; and

a battery casing; and

subjecting the battery to one or more charge-discharge cycles.



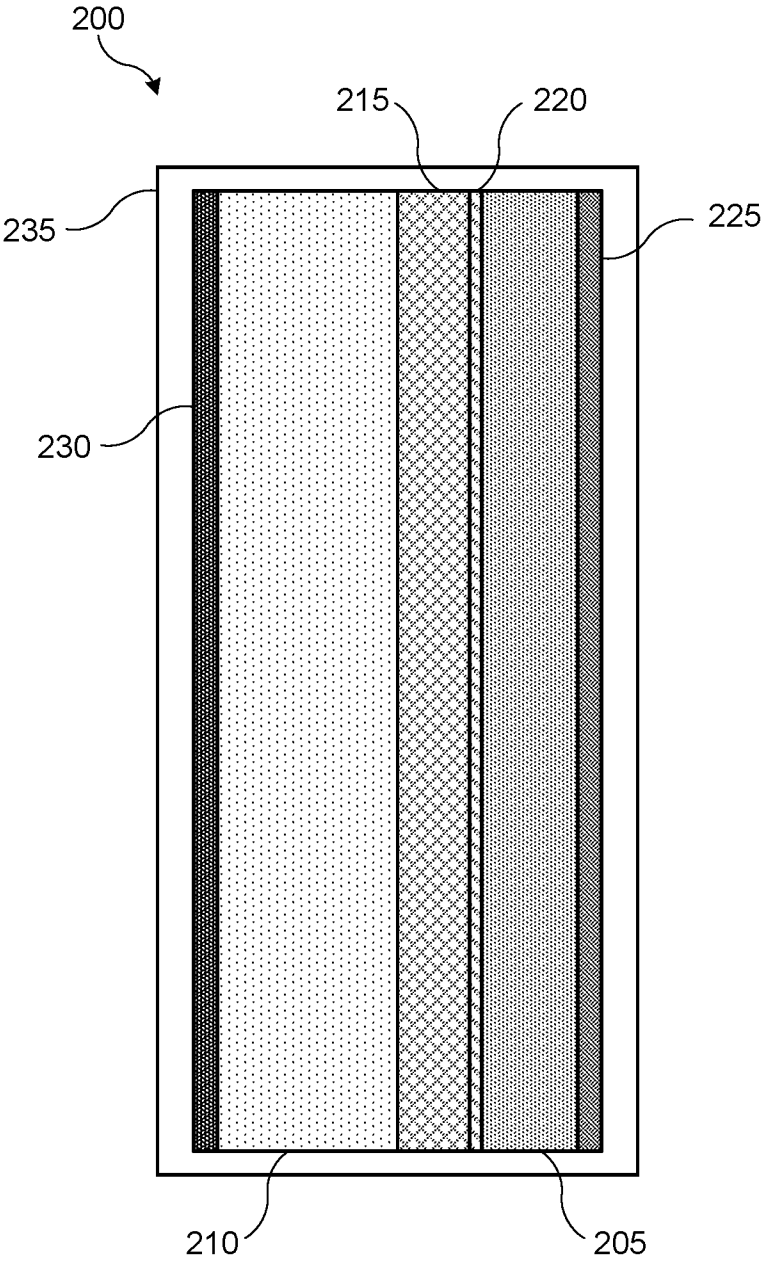


FIG. 2

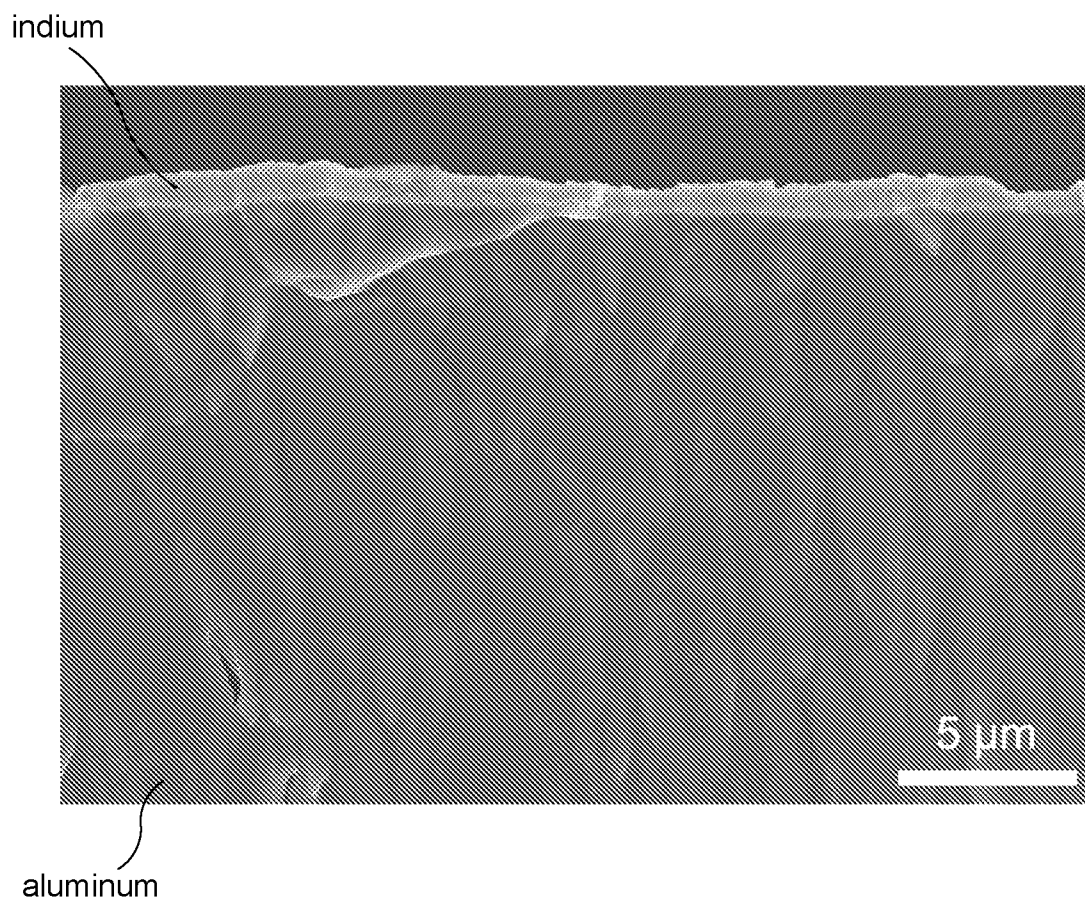
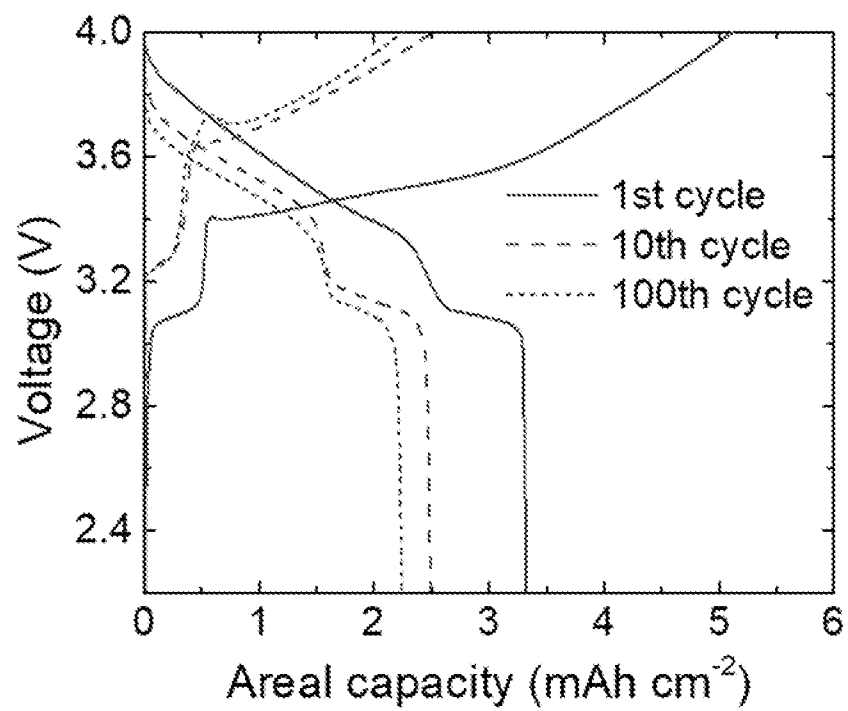
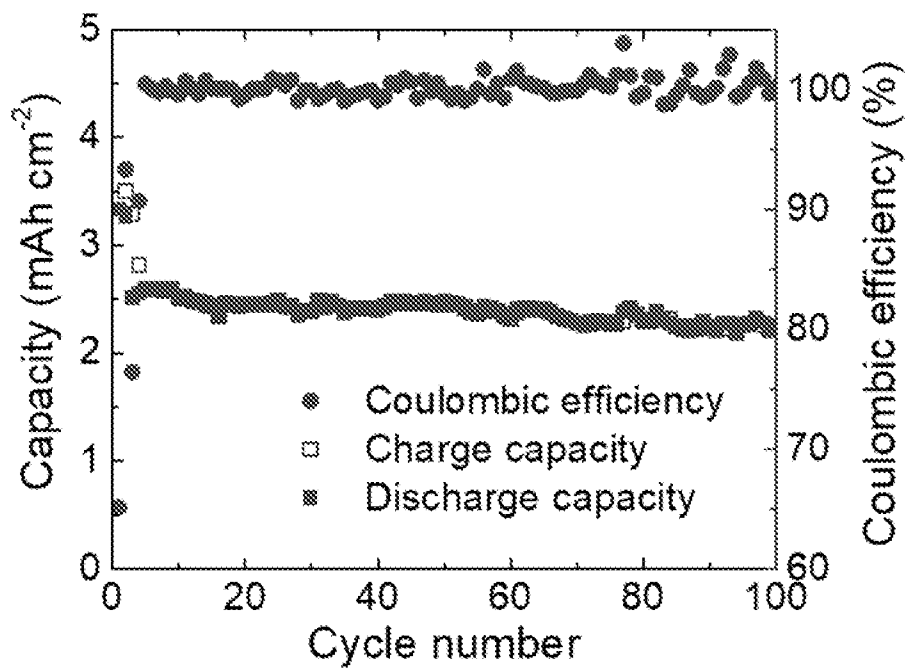
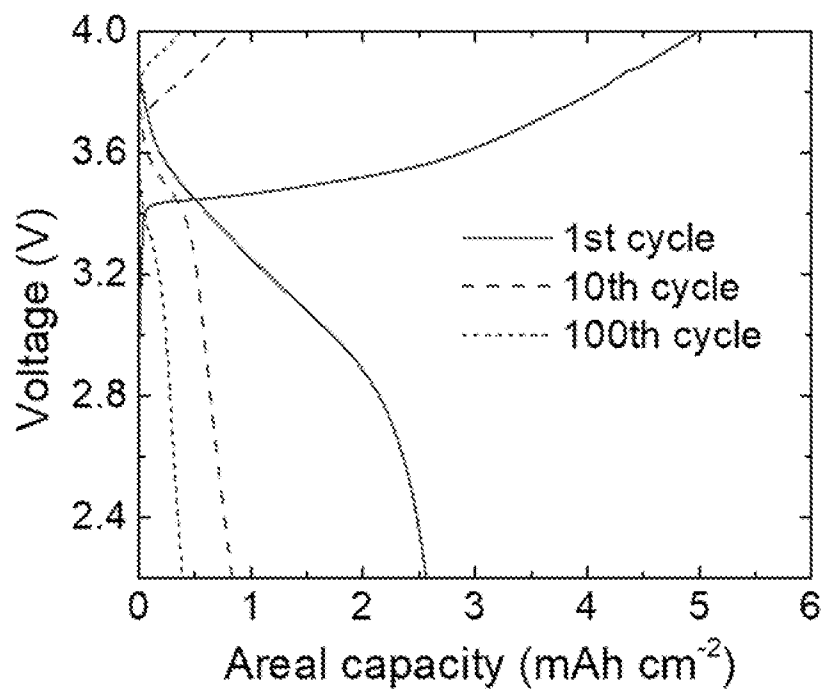
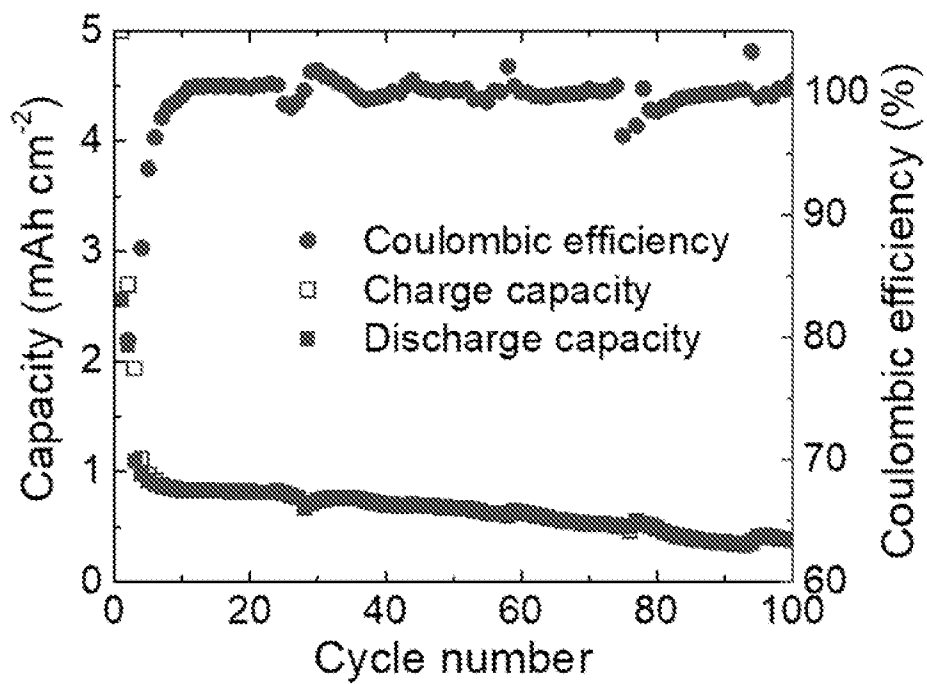
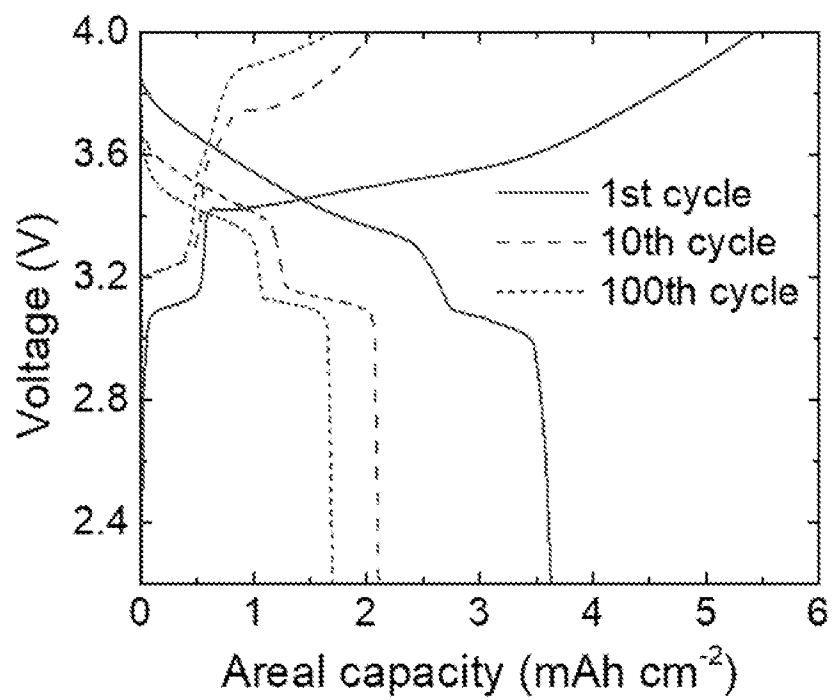
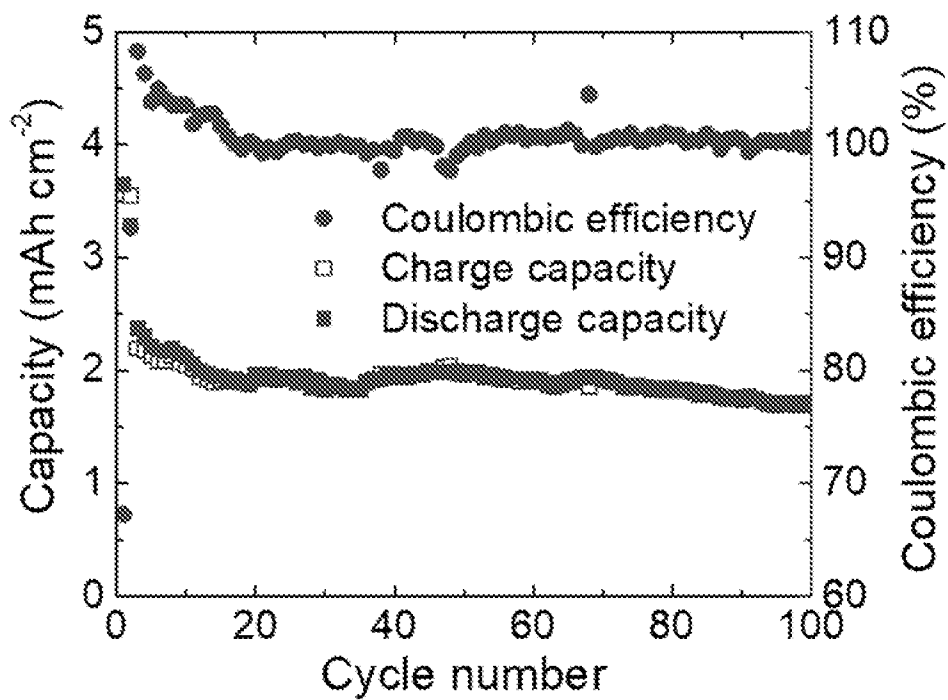


FIG. 3

**FIG. 4****FIG. 5**

**FIG. 6****FIG. 7**

**FIG. 8****FIG. 9**

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/029056

A. CLASSIFICATION OF SUBJECT MATTER					
INV.	H01M4/36	H01M4/38	H01M4/40	H01M4/46	H01M10/0525
	H01M10/0562	H01M10/0565	H01M50/46		
ADD.					
According to International Patent Classification (IPC) or to both national classification and IPC					
B. FIELDS SEARCHED					
Minimum documentation searched (classification system followed by classification symbols) H01M					
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched					
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal					
C. DOCUMENTS CONSIDERED TO BE RELEVANT					
Category*	Citation of document, with indication, where appropriate, of the relevant passages				Relevant to claim No.
X	US 2022/181637 A1 (JANG BOR Z [US]) 9 June 2022 (2022-06-09) paragraphs [0123] - [0140]; figure 2; examples 11,12; table 1 -----				1,2,4,6, 8,9, 11-20
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X	EP 3 813 161 A1 (SAMSUNG ELECTRONICS CO LTD [KR]) 28 April 2021 (2021-04-28) paragraphs [0123] - [0138], [0179]; examples 1-4 ----- -/-				1-3,5-7, 9,11-14, 16-20
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.					
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family					
Date of the actual completion of the international search 15 August 2024			Date of mailing of the international search report 16/09/2024		
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016			Authorized officer Rausch, Elisabeth		

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/029056

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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