(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 April 2014 (24.04.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/062898 A1

(51) International Patent Classification:
H01M 10/0566 (2010.01) *H01M 10/05* (2010.01)
H01M 10/0565 (2010.01)

(21) International Application Number:
PCT/US2013/065396

(22) International Filing Date:
17 October 2013 (17.10.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/716,253 19 October 2012 (19.10.2012) US
61/812,510 16 April 2013 (16.04.2013) US

(71) Applicant: **THE UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL** [US/US]; 308 Bynum Hall, Campus Box 4105, Chapel Hill, North Carolina 27599 (US).

(72) Inventors: **DESIMONE, Joseph M.**; 7315 Crescent Ridge, Chapel Hill, North Carolina 27516 (US). **PANDYA, Ashish**; 104 Drakeshire Court, Morrisville, North Carolina 27560 (US). **WONG, Dominica**; 605 Jones Ferry Road #VV08, Carrboro, North Carolina 27510 (US). **VITALE, Alessandra**; Via Della Rocca 33, I-10123 Torino (IT).

(74) Agent: **SIBLEY, Kenneth D.**; Myers Bigel Sibley & Sajovec, P.A., P.O. Box 37428, Raleigh, North Carolina 27627 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

WO 2014/062898 A1

(54) Title: ION CONDUCTING POLYMERS AND POLYMER BLENDS FOR ALKALI METAL ION BATTERIES

(57) Abstract: Electrolyte compositions for batteries such as lithium ion and lithium air batteries are described. In some embodiments the compositions are liquid compositions comprising (a) a homogeneous solvent system, said solvent system comprising a perfluropolyether (PFPE) and polyethylene oxide (PEO); and (b) an alkali metal salt dissolved in said solvent system. In other embodiments the compositions are solid electrolyte compositions comprising: (a) a solid polymer, said polymer comprising a crosslinked product of a crosslinkable perfluropolyether (PFPE) and a crosslinkable polyethylene oxide (PEO); and (b) an alkali metal ion salt dissolved in said polymer. Batteries containing such compositions as electrolytes are also described.

ION CONDUCTING POLYMERS AND POLYMER BLENDS FOR ALKALI METAL ION BATTERIES

Joseph M. DeSimone, Ashish Pandya, Dominica Wong and Alessandra Vitale

Government Support

This invention was made with government support under Grant No. DE-SC0001011 from the Department of Energy. The US Government has certain rights to this invention.

Related Applications

This application claims the benefit of United States Provisional Patent Applications Number 61/812,510, filed April 16, 2013, and United States Provisional Patent Application No. 61/716,253, filed October 19, 2012, the disclosures of which are incorporated by reference herein in their entirety.

Field of the Invention

The present invention concerns liquid and solid polymer electrolyte compositions for use in batteries such as lithium-ion batteries, lithium air batteries, sodium-ion, and sodium-air batteries.

Background of the Invention

One of the biggest challenges faced by modern society is to secure sustainable resources that meet burgeoning energy demands (R. Marom et al., *Journal of Materials Chemistry* **21**, 9938 (2011)). One area of great interest is developing lithium (Li) batteries suitable for large-scale applications, such as transportation and energy storage (J. Tarascon and M. Armand, *Nature* **414**, 359 (Nov, 2001)). Currently, Li-ion batteries are used in electric vehicles (EVs), but factors including cost and longevity limit their prevalence (O. Egbue and S. Long, *Energy Policy* **48**, 717 (2012)). Safety is also a primary concern; most commercial Li-ion batteries consist of a flammable mixture of alkyl carbonates that serves as the electrolyte solvent.

In the last decade, there has been extensive efforts to introduce alternative solvents, salts, and additives that can improve the quality and performance of electrolytes (D. Aurbach *et al.*, *Electrochimica Acta* **50**, 247 (2004)). The preparation of polyelectrolytes is an emerging area of interest due to their potential lower costs, easy handling, and better safety.

Poly(ethylene oxide) (PEO) is the most prominently featured homopolymer in this field due its unique ability to solvate Li-based salts. The crystallinity of PEO, however, hinders ionic conductivity, rendering PEO-LiX electrolytes useful at temperatures between 60° to 80°C (F. Croce et al., *Nature* **394**, 456 (1998)). Dendrite formation at the anode electrode remains a persistant issue, causing shortcircuits and overcharging, which can lead to cell ignition or explosion (S. Tobishima et al., *Journal of Power Sources* **90**, 188 (2000); H. Ghassemi et al., *Applied Physics Letters* **99**, 123113 (2011)). Accordingly, there is a need for new electrolyte compositions for lithium ion batteries, and other types of alkali metal ion batteries.

Summary of the Invention

Liquid and solid polymer electrolyte compositions useful in alkali metal batteries are described herein, along with alkali metal ion batteries (including lithium and sodium ion and air batteries) containing the same. In some embodiments, the compositions are advantageously characterized by, one, some or all of: low flammability/high flame resistance; low glass transition temperature, flexibility, high ionic conductivity, and/or a broad electrochemical stability window.

In some embodiments, the composition is a liquid electrolyte composition, comprising, consisting of, or consisting essentially of: (a) a homogeneous solvent system, said solvent system comprising, consisting of, or consisting essentially of a perfluropolyether (PFPE) and polyethylene oxide (PEO); and (b) an alkali metal salt dissolved in the solvent system. In other embodiments, the composition is a solid electrolyte composition comprising, consisting of, or consisting essentially of: (a) a solid polymer, said polymer comprising, consisting of or consisting of a crosslinked or the crosslinking product of a crosslinkable perfluropolyether (PFPE) and a crosslinkable polyethylene oxide (PEO); and (b) an alkali metal ion salt dissolved in said polymer.

In some embodiments the alkali metal salt is a lithium salt; in other embodiments the alkali metal salt is a sodium or potassium salt.

Other ingredients, such as standard contaminants found in battery-grade reagents, initiators, and/or electrode stabilizing agents, may optionally be included.

In some embodiments, the composition is free or substantially free of organic carbonate solvent such as loweralkyl carbonate solvents (*e.g.*, contains not more than 5, 4, 3, 2, or 1 percent by weight of organic carbonate solvent).

In some embodiments, the composition has a T_g between -120 or -115 °C and -40 or -20 °C.

In some embodiments, the electrolyte compositions do not ignite when heated to a temperature of 235 °C and then contacted to a flame for 15 seconds in a Kohler open cup rapid flash test apparatus.

In some embodiments, the electrolyte compositions have an ionic conductivity of from 10^{-4} or 10^{-3} to 10^{1} or 10^{2} siemens per centimeter at 25 ° C.

In some embodiments, the electrolyte compositions have an electrochemical stability window of from 1 or to 6 volts against Li/Li^{+}.

Methods of making the same, along with alkali metal ion batteries containing the same, are also described.

Small amounts of perfluoropolyether polymers as an additive in lithium ion batteries are described in G. Marchionni et al., US Patent Application Publication No. US2002/0127475 (Sep. 12, 2002), and in E. Eweka, J. R. Owen and A. Ritchie, *Journal of Power Sources* **1997**, *65*, 247-251. In both of these systems, PFPE is only used in small amounts and not as a solvent. In addition, both of these references describe the PFPE as an additive in a carbonate solvent, and not in combination with PEO.

PEO networks are described for lithium ion batteries in J. R. Nair et al., *Reactive and Functional Polymers* **2011**, *71*, 409-416. This reference, however, does not suggest the use of PFPE in combination therewith.

PFPE additives for electrolyte compositions are described in G. Marchionni et al., European Patent Application No. 1221733. At page 3 paragraph 17 matrixes having the function of separating the anode from the cathode in a battery containing the same to avoid short circuits are described, and it is said that the matrix material can be a solid polymer such as PEO. A homogeneous electrolyte composition comprising both PFPE and PEO is neither suggested nor described, and a copolymer of PFPE and PEO is neither suggested nor described.

The present invention is explained in greater detail in the specification set forth below. The disclosure of all United States patent references cited herein are to be incorporated herein by reference in their entirety.

Detailed Description of Illustrative Embodiments

Perfluoropolyethers (PFPEs) useful for carrying out the present invention are known. In some embodiments, the PFPE has a weight average molecular weight of from 0.4 or 0.8 Kg/mol, up to 15 or 20 Kg/mol, or more. Examples of perfluoropolyethers include but are not limited to those described in US Patent Nos. 8,084,405; 7,294,731; 6,608,138; 5,612,043; 4,745,009; 4,178,465; etc.

Polyethylene oxides (PEOs) useful for carrying out the present invention are also known. In some embodiments, the PEO has a weight average molecular weight of from 0.2 or 0.3 Kg/mol, up to 3 or 4 Kg/mol, or more. Numerous examples are known and include but are not limited to those described in US Patent Nos. 8,080,615; 7,897,080; 6,515,075; 5,618,316; etc.

Crosslinkable PFPEs and PEOs useful for carrying out some embodiments are also known. Such compounds generally include a PFPE or PEO main chain, with a cross-linkable group substituted on or covalently coupled to either or both end terminus thereof. In some embodiments, the cross-linkable group may also, or in the alternative, be coupled to one or more side-chains of the main chain. Suitable cross-linkable groups include, but are not limited to, ester groups such as methacrylate, vinyl groups such as styrene, carboxylic acid groups, amide or amidic groups, epoxy groups, etc. Examples include but are not limited to those described in US Patent Nos. 8,080,615 and 4,745,009, and in F. Pilati et al., *Macromolecules* **32**, 6969-6976 (1999); R. Bongiovanni et al., *J. Appl Polym Sci* **75**, 651-659 (2000); J. Rolland et al., *J. Am. Chem. Soc* **126**, 2322-2323 (2004); Z. Hu et al., *Macromolecules* **42**, 6999-7007 (2009); and R. Bongiovanni et al., *Polym Int.* **61**, 65-73 (2012).

Alkali metal ion salts that can be used to carry out the present invention are also known or will be apparent to those skilled in the art. Any suitable salt can be used, including both lithium salts and sodium salts, and potassium salts: That is, salts containing lithium or sodium or potassium as a cation, and an anion. Any suitable anion may be used, examples of which include, but are not limited to, boron tetrafluoride, aluminate, (oxalate)borate, difluoro(oxalate)borate, phosphorus hexafluoride, alkylsulfonate, fluoroalkylsulfonate, arylsulfonate, bis(alkylsulfonyl)amide, perchlorate, bis(fluoroalkylsulfonyl)amide, bis(arylsulfonyl)amide, alkyl fluorophosphate, (fluoroalkylsulfonyl)(fluoroalkylcarbonyl)amide, halide, nitrate, nitrite, sulfate, hydrogen sulfate, alkyl sulfate, aryl sulfate, carbonate, bicarbonate, carboxylate, phosphate, hydrogen phosphate, dihydrogen phosphate, hypochlorite, an anionic site of a cation-exchange resin,

and a mixture of any two or more thereof. *See, e.g.,* Zhang et al., US Patent Application Publication No. 2012/0082903.

Methods of making.

In the present invention, electrolyte compositions for an alkali metal ion battery, can be made without the use of flammable or otherwise undesirable organic solvents such as carbonate solvents.

In general, the compositions are made by combining perfluropolyether (PFPE), polyethylene oxide (PEO), alkali metal salt, and optionally a photoinitiator, in the absence of additional solvent. Any suitable conditions for combining can be used, including stirring, agitation, heat and/or pressure, for any suitable time, as required to obtain a single phase solution comprising, consisting of, or consisting essentially of a solvent system of the PFPE and PEO, and the alkali metal salt dissolved in the solvent system. Conditions and amounts may be adjusted as needed depending upon the particular choice of ingredients to achieve a solution with the salt dissolved therein. The composition can be used as an electrolyte in liquid form, or if desired crosslinked to provide a solid polymer or film electrolyte, as discussed further below.

The alkali metal salt may be included in the liquid or solid compositions in any suitable amount, typically from about 5 or 10 percent by weight, up to 20 or 30 percent by weight. Likewise, the solvent system or crosslinked polymer may be included in the composition in any suitable amount, typically from 70 or 75 percent by weight up to 85, 90 or 95 percent by weight.

The PFPE and PEO may be included in the solvent system in any suitable amount, such in a weight ratio (PFPE:PEO) range of between (on one end of the range) 40:60, 50:50, or 60:40, up to (on the other end of the range) 80:20, 90:10 or 95:5.

In some embodiments, the PFPE and PEO in the solvent system/composition are crosslinked to form a solid polymer having the alkali metal salt dissolved therein and formed into a suitable shape such as a film for use as an electrolyte by any suitable technique (*e.g.,* casting, spraying, coating, dipping, etc.). The crosslinking step may be carried out by any suitable technique, such as by adding an initiator and, if necessary, heating or irradiating (*e.g.,* with light or actinic radiation) the composition in a manner appropriate for the particular initiator. Any suitable initiator can beused, , including but not limited to photoinitiators such as Norrish Type I photoinitiators, thermal initiators, free radical

generators, photoacid generators, etc. Examples include but are not limited to those set forth in US Patents Nos. 8,197,943; 8,133,580; 7,429,409; 6,958,256; 5,506,279, etc.

If desired, an electrode stabilizing agent can be added to or included in the electrolyte compositions (in some embodiments before cross-linking thereof), in accordance with known techniques. *See, e.g.,* Zhang et al., US Pat. App. Pub No. 2012/0082903. For example, the electrolytes can include an electrode stabilizing additive that can be reduced or polymerized on the surface of a negative electrode to form a passivation film on the surface of the negative electrode. Likewise, the electrolytes can include an electrode stabilizing additive that can be oxidized or polymerized on the surface of the positive electrode to form a passivation film on the surface of the positive electrode. In some embodiments, electrolytes can include mixtures of the two types of electrode stabilizing additives. The additives are typically present at a concentration of about 0.001 to 8 wt %. For example, an electrode stabilizing additive can be a substituted or unsubstituted linear, branched or cyclic hydrocarbon comprising at least one oxygen atom and at least one aryl, alkenyl or alkynyl group. The passivating film formed from such electrode stabilizing additives may also be formed from a substituted aryl compound or a substituted or unsubstituted heteroaryl compound where the additive comprises at least one oxygen atom. Numerous particular examples are described in Zhang et al. at paragraphs 173-174 therein.

If desired, fillers or conductivity enhances may optionally be included in the electrolyte compositions. Examples include but are not limited to include but are not limited to Al_2O_3, AlOOH, $BaTiO_3$, BN, LiN_3 $LiAlO_2$, lithium fluorohectorite, and/or fluoromica clay. Finally, additives such as hexamethyldisilazane (HMDS) may also be included to improve interfacial resistance in a lithium cell and trap (react) with any available water and that may be present and detrimental to cell performance. *See,* US Patent App. Pub. No. 2011/0311881 at paragraphs 87-88.

Alkali metal batteries.

An alkali metal battery (sometimes also referred to as alkali metal ion batteries, and including alkali metal-air batteries) of the present invention generally includes (a) an anode; (b) a cathode; (c) a liquid or solid electrolyte composition as described above operatively associated with the anode and cathode, and (d) optionally a separator for physically separating the anode and cathode (*See, e.g.,* M. Armand and J.-M. Tarascon, Building Bettery Batteries, *Nature* 451, 652-657 (2008)). Examples of suitable battery components include but are not limited to those described in US Patent Nos. 5,721,070; 6,413,676; 7,729,949; and

7,732,100, and in US Patent Application Publication Nos. 2009/0023038; 2011/0311881; and 2012/0082930; and S.-W. Kim et al., *Adv. Energy Mater.* 2, 710-721 (2012).

Examples of suitable anodes include but are not limited to anodes formed of lithium metal, lithium alloys, sodium metal, sodium alloys, carbonaceous materials such as graphite, and combinations thereof. Examples of suitable cathodes include, but are not limited to cathodes formed of transition metal oxides, doped transition metal oxides, metal phosphates, metal sulfides, lithium iron phosphate, and combinations thereof. See, e.g., US Patent No. 7,722,994. Additional examples include but are not limited to those described in Zhang et al., US Pat. App. Pub No. 2012/0082903, at paragraphs 178 to 179. In some embodiments, an electrode such as a cathode can be a liquid electrode, such as described in Y. Lu et al., *J. Am. Chem. Soc.* **133,** 5756-5759 (2011). Numerous carbon electrode materials, including but not limited to carbon foams, fibers, flakes, nanotubes and other nanomaterials, etc., alone or as composites with each other or other materials, are known and described in, for example, US Patents Nos. 4,791,037; 5,698,341; 5,723,232; 5,776,610; 5,879,836; 6,066,413; 6,146,791; 6,503,660; 6,605,390; 7,071,406; 7,172,837; 7,465,519; 7,993,780; 8,236,446, and 8,404,384. In an alkali metal-air battery such as a lithium-air battery, sodium-air battery, or potassium-air battery, the cathode is preferably permeable to oxygen (*e.g.,* mesoporous carbon, porous aluminum, etc.), and the cathode may optionally contain a metal catalyst (*e.g.,* manganese, cobalt, ruthenium, platinum, or silver catalysts, or combinations thereof) incorporated therein to enhance the reduction reactions occurring with lithium ion and oxygen at the cathode. *See, e.g.,* US Patent No. 8,012,633 and US Patent Application Publication Nos. 2013/0029234; 2012/0295169; 2009/0239113; *see also* P. Hartmann et al., A rechargeable room-temperature sodium superoxide (NaO_2) battery. *Nature Materials* **12**, 228–232 (2013).

Where the electrolyte composition is a liquid composition, a separator formed from any suitable material permeable to ionic flow can also be included to keep the anode and cathode from directly electrically contacting one another. Examples of suitable separators include, but are not limited to, porous membranes or films formed from organic polymers such as polypropylene, polyethylene, etc., including composites thereof. *See generally* P. Arora and Z. Zhang, Battery Separators, *Chem. Rev.* **104**, 4419-4462 (2004). When the electrolyte composition is a solid composition, particularly in the form of a film, it can serve as its own separator. Such solid film electrolyte compositions of the present invention may be of any suitable thickness depending upon the particular battery design, such as from 0.01, 0.02, 0.1 or 0.2 microns thick, up to 25, 30, or 50 microns thick, or more.

All components of the battery can be included in or packaged in a suitable rigid or flexible container with external leads or contacts for establishing an electrical connection to the anode and cathode, in accordance with known techniques.

The present invention is explained in greater detail in the following non-limiting Examples.

EXAMPLE 1

Characterization

Thermogravimetric analysis for Liquid Blends. Thermogravimetric analysis (TGA) was performed using a Perkin Elmer, Pyris 1 TGA apparatus. Scan was made under nitrogen atmosphere from 20°C to 600°C with a heating rate of 10°C/minute.

Differential Scanning Calorimetry for Liquid Blends. Glass transition state (T_g), crystallization (T_c) and melting temperatures (T_m) were measured using a differential scanning calorimeter (DSC) (TA Instruments, DSC Q 200) in air using the method of heat/cool/heat at a heating and cooling rate of 10°C and 5°C/minute respectively, over a temperature range of -130°C to 100°C. The T_g was determined using the midpoint method on the second heating cycle thermogram. The T_c and T_m were determined as the peak maximum and minimum of the cooling and heating cycle respectively.

Differential Scanning Calorimetry for Solid State Elastomers. Differential scanning calorimetric measurements (DSC) (TA Instruments, DSC Q 200) were used to measure solid polyelectrolyte glass transition temperature (T_g), and crystallization (T_c) and melting (T_m) temperatures. DSC analysis were performed in air, using the method of heat/cool/heat at a heating and cooling rate of 10°C and 5°C/minute respectively over a temperature range of -130°C to 100°C. The T_g was determined using the midpoint method on the second heating cycle thermogram. The T_c and T_m were determined as the peak maximum and minimum of the cooling and heating cycle respectively.

Ionic Conductivity for Liquid Blends. Electrochemical measurements were obtained in a procedure similar to that previously reported by Teran et. al. (*Solid State Ionics* **203**, 18-21 (2011). In brief, the polyelectrolyte blends were placed in conductivity cells that were built to enable examination of samples with a wide range of viscosities. Sample thicknesses were determined by subtracting the thickness of the lower and upper electrodes from the overall assembled cell thickness. The thicknesses ranged from 1 to 2.5 mm.

A home-made temperature controlled box was used to house the cells during the electrochemical experiments. The AC impedance spectroscopy measurements, performed using a 16-channel Bio-Logic VMP3 potentiostat, were made across the frequency range 1MHz to 10Hz at a peak-to-peak amplitude voltage of 20mV. The electrolyte resistance, R, was determined by the low-frequency minimum on a Nyquist impedance plot. Measurements were made at a series of temperatures with a minimum of 2h calibration at each temperature. All data presented in this work are from heating runs. Calculating the sample conductivity from the measured resistance R requires knowledge of both the electrode separation, *L*, and the effective cross-sectional area A_{eff}. To find the effective area of a conductivity cell with two unequally sized electrodes, the experimental set-up was modeled in COMSOL Multiphysics. Solving Laplace's equation for the primary current distribution in the polymer electrolyte yielded the steady state current, I, through the electrodes as a function of applied voltage, V and assumed value of electrolyte conductivity, σmodel. These were used to calculate the effective cross-sectional area by Aeff = LI/(Vσmodel). The linearity of Laplace's equation means that Aeff depends only on geometry and is independent of V and σ model. The numerical data were found to obey the empirical equation,

$$A_{eff} = 0.0023^{\square}L^3 - 0.0291^{\square}L^2 + 0.135^{\square}L + 0.498$$

Sample conductivity, σ, was calculated using σ=L/(AeffR). Three samples from each electrolyte were tested, with error bars of data points representing the standard deviation. The exception was PEO (5000)/LiTFSI, for which only one sample was run. The accuracy of our procedure was verified using an aqueous KCl conductivity standard. Conductivity measurements were made between 330 and 368 K. The PEO/LiTFSI mixtures are in the amorphous state in this temperature

$$\sigma = \frac{L}{A_{eff}R}$$

$$A_{eff} = 0.0023L^3 - 0.0291L^2 + 0.135L + 0.498 \quad (3)$$

Ionic Conductivity of Solid State Elastomers. Crosslinked films were cut into 1 cm diameter disks and blocked between stainless steel electrodes. The AC impedance spectroscopy measurements were made using a homemade test cell on thermostated pressed samples in the glovebox.

Ionic conductivity was calculated from the complex impedance data ($Z^*=Z'-iZ''$) collected at temperatures between 40°C and 120°C. All of the samples were annealed at 120°C for 1h prior to commencement of the conductivity measurements.

The bulk resistance of the electrolyte, R, is based on the diameters of Z' vs Z'' Nyquist plot semicircles. The ionic conductivity is given by: $\sigma=R/LA$; where L is the electrolyte thickness and A is the area in contact with the current collectors. Three samples from each electrolyte were tested, with error bars of data points representing the standard deviation.

Cyclic Voltammetry. Electrochemical measurements were performed in a one-compartment cell using a glassy carbon working electrode (0.07 cm^2 surface area). A platinum wire was used as a counter electrode. Potentials were referenced to Ag/AgCl (aqueous, 3M NaCl) without regard for the liquid junction. The working electrode was polished (1-micron alumina dispersed in water) prior to use, followed by washing with water and acetone.

Electrochemical experiments were performed using a CH Instruments Electrochemical Workstation 660D potentiostat. In a typical experiment, a neat solution of the ionic liquid was degassed with argon for at least five minutes (typically fifteen minutes) prior to electrochemical cycling. The working, reference, and counter electrodes were placed in the degassed ionic liquid, and cycling was performed over a wide electrochemical window (typically -5 V to 5 V).

Flammability. Sustained burning of polymeric liquids was measured by a modified ASTM D-4206 procedure. In brief, a Koehler Rapid Flash Tester apparatus was used ad the temperature of the control unit was set to 235 degrees Celsius. Two mL of each sample was deposited into the depression of the aluminum testing block. During the 60 second warming period, the gas jet assembly is set in the "off" position (gas jet is positioned so that the flame is away from the depression), and the flame is ignited. Using the machinist scale, the flame is adjusted so that it is 2.2 mm above the lip of the depression and 4 mm in diameter. After 60 seconds (determined to be length of time to allow sample to equilibrate with block), the flame is positioned over the center of the depression (the "on" position). The flame is left there for 15 seconds. After 15 seconds passes, the flame is placed in the "off' position. The sustained combustion properties of the material is observed and recorded per the following criteria: The material under test is considered to sustain burning if the material: a) ignites when the flame

is over the well and burning is sustained for more than 15 seconds, or b) flashes and burns when the test flame is in the "off" position prior to swinging it over the well.

EXAMPLE 2

Preparation of PFPE/PEO Liquid Blend

10 wt% of lithium salt was added directly to PFPE, PFPE:PEO, and PEO blends and stirred at room temperature for about 12 h. The concentration of salt in the electrolytes is specified by *r* defined as the ratio of lithium salt (LiTFSI: 287.09 g/mol, LiNFBS: 306.03 g/mol) and polymer repeating units (the average molecular weights of the repeating unit in PEO and PFPE are 44.05 g/mol and 100.22 g/mol respectively). Thus, *r* is the molar ratio of Li^+ ions to ethylene oxide and perfluoroether moieties, $r = [Li^+]/([EO]+[PFE])$, without accounting for the –OH end groups of each of the polymer chains.

EXAMPLE 3

Preparation of PFPE/PEO Solid State Elastomer

Perfluoropolyether dimethacrylate (PFPE-DMA) was synthesized as previously reported (*see, e.g.*, J. Rolland et al., *J. Am. Chem. Soc* **126,** 2322-2323 (2004); Z. Hu et al., *Macromolecules* **42**, 6999-7007 (2009)). Briefly, commercially available hydroxy-terminated PFPEs (Fluorolink D10, average M_w=1000 g mol^{-1}, and Fluorolink D, average M_w=2000 g mol^{-1}, both from Solvay Solexis) were treated with isocyanato ethyl methacrylate (Aldrich) to obtain a clear, colorless, pourable and viscous oil.

Poly(ethylene glycol) dimethacrylate (PEO-DMA) with an average M_n of 550 g mol^{-1} was obtained from Sigma Aldrich. The commercial PEO-DMA, before use, was first passed through a chromatographic column (with neutral alumina) to remove any inhibitor.

Lithium bistrifluoromethylsulfonyl imide (LiTFSI) and lithium nonofluorobutane sulfonate (LiNFBS) were obtained from Acros Organics and TCI America respectively.

Argon glove-boxes (MBraun and Vacuum Atmospheres Company) with oxygen and water at sub-ppm levels were used for all sample preparations and testing steps. All polymers were dried at 40°C under vacuum in a glovebox antechamber for at least 24h. LiTFSI and LiNFBS were dried at 120°C under vacuum in a glovebox antechamber for three days.

6 or 10 wt% of lithium salt was added directly to PFPE-DMA, PFPE-DMA:PEO-DMA (composition weight ratio of 80:20), and PEO-DMA blends; moreover 0.5 wt% of the photoinitiator 1-hydroxycyclohexyl phenyl ketone (HCPK, Aldrich) was dissolved into the

solutions to make photocurable liquid resins. The mixtures were stirred at room temperature for about 12 h and colorless, clear and homogeneous liquid blends were obtained.

Polymer solutions were cast on a Si wafer by means of a Doctor Blade (standard aluminum single blade) to obtain films with a thickness of around 100 μm. Subsequent photocuring of the material was accomplished through UV irradiation, with a Light Exposure System ELC-500 (ElecroLite Corporation, λ=365 nm) for 4 min. This resulted in a completely clear, elastomeric material.

The foregoing is illustrative of the present invention, and is not to be construed as limiting thereof. The invention is defined by the following claims, with equivalents of the claims to be included therein.

THAT WHICH IS CLAIMED IS:

1. A liquid electrolyte composition, comprising:

(a) a homogeneous solvent system, said solvent system comprising a perfluropolyether (PFPE) and polyethylene oxide (PEO); and

(b) an alkali metal salt dissolved in said solvent system.

2. The composition of claim 1, wherein said alkali metal salt is a lithium salt.

3. The composition of claim 1, wherein said alkali metal salt is a sodium salt.

4. The composition of claim 1 to 3, wherein

said solvent system is included in said composition in an amount of from 70 to 95 percent by weight;

said salt is included in said composition in an amount of from 5 to 30 percent by weight; and

said PFPE and said PEO are included in said solvent system in a weight ratio (PFPE:PEO) of from 40:60 to 95:5.

5. The composition of claim 1 to 4, wherein:

said PEO has a weight average molecular weight of from 0.2 to 4 Kg/mol, and

said PFPE has a weight average molecular weight of from 0.4 to 20 Kg/mol.

6. The composition of claim 1 to 5, wherein said PEO and said PFPE are crosslinkable.

7. The composition of claim 1 to 6, further comprising an initiator and/or an electrode stabilizing agent.

8. The composition of claim 1 to 7, wherein said composition is substantially free of carbonate solvent.

9. The composition of claim 1 to 8, wherein said composition has a T_g between -120 °C and -20 °C.

10. The composition of claim 1 to 9, wherein said composition does not ignite when heated to a temperature of 235 °C and then contacted to a flame for 15 seconds in a Kohler open cup rapid flash test apparatus.

11. The composition of claim 1 to 10, wherein said composition has an ionic conductivity of from 10^{-4} to 10^{2} siemens per centimeter at 25 ° C.

12. The composition of claim 1 to 11, wherein said composition has an electrochemical stability window of from 3 to 6 volts against Li/Li^{+}.

13. A solid electrolyte composition for a battery, comprising:

(a) a solid polymer, said polymer comprising a crosslinked product of a crosslinkable perfluropolyether (PFPE) and a crosslinkable polyethylene oxide (PEO); and

(b) an alkali metal ion salt dissolved in said polymer.

14. The composition of claim 13, wherein said alkali metal salt is a lithium salt.

15. The composition of claim 13, wherein said alkali metal salt is a sodium salt.

16. The composition of claim 13 to 15, wherein said composition is in the form of a film.

17. The composition of claim 13 to 16, wherein said polymer is amorphous.

18. The composition of claim 13 to 17, wherein

said solid polymer is included in said composition in an amount of from 70 to 95 percent by weight;

said salt is included in said composition in an amount of from 5 to 30 percent by weight; and

said PFPE and said PEO are included in said solid polymer in a weight ratio (PFPE:PEO) of from 40:60 to 95:5.

19. The composition of claim 13 to 18, wherein:
said PEO has a weight average molecular weight of from 0.2 to 4 Kg/mol, and
said PFPE has a weight average molecular weight of from 0.4 to 20 Kg/mol.

20. The composition of claim 13 to 19, further comprising an initiator and/or an electrode stabilizing agent.

21. The composition of claim 13 to 20, wherein said composition is substantially free of carbonate solvent.

22. The composition of claim 13 to 21, wherein said composition has a T_g between -120 °C and -20 °C.

23. The composition of claim 13 to 22, wherein said composition does not ignite when heated to a temperature of 235 °C and then contacted to a flame for 15 seconds in a Kohler open cup rapid flash test apparatus.

24. The composition of claim 13 to 23, wherein said composition has an ionic conductivity of from 10^{-4} to 10^{2} siemens per centimeter at 25 ° C.

25. The composition of claim 13 to 24, wherein said composition has an electrochemical stability window of from 3 to 6 volts against Li/Li^{+}.

26. A battery, comprising:
(a) an anode;
(b) a cathode; and
(c) a liquid or solid electrolyte composition operatively associated with said anode and cathode, wherein said electrolyte composition is a composition of claim 1 to 25.

27. A method of making an electrolyte composition for a battery, comprising:
(a) combining perfluropolyether (PFPE), polyethylene oxide (PEO), alkali metal salt, and optionally a photoinitiator, in the absence of additional solvent under conditions in which a single phase solution solvent system is formed; and then optionally

(b) crosslinking said PFPE and said PEO to form a solid polymer having said alkali metal salt dissolved therein.

28. The method of claim 27, wherein

said solvent system is included in said composition in an amount of from 70 to 95 percent by weight;

said salt is included in an amount of from 5 to 30 percent by weight; and

said PFPE and said PEO are included in said solvent system in a weight ratio (PFPE:PEO) of from 40:60 to 95:5.

29. The method of claim 27 or 28, wherein said alkali metal ion salt is a lithium salt or sodium salt.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/065396

A. CLASSIFICATION OF SUBJECT MATTER

H01M 10/0566(2010.01)i, H01M 10/0565(2010.01)i, H01M 10/05(2010.01)i

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 10/0566; H01M 10/40; H01M 2/16; C07C 69/96; H01M 4/38; H01M 6/18; H01M 4/02; C08J 5/22; H01M 10/0565

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: liquid electrolyte,solvent,perfluropolyether,polyethylene oxide,alkali metal salt,solid,photoinitiator

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KWEON, JUNG-OHK, et al. 'Perfluoropolyether addition Effect on the Properties of Poly(Ethylene Oxide)-Based Solid Polymer Electrolytes', Korean Chem. Eng. Res., December 2004, Vol.42, No. 6, pp. 741-747. See abstract; and pages 741, 742, 744.	1,2,13,14,27-29
Y		3,15
Y	WO 95-15588 A (VALENCE TECHNOLOGY, INC.) 08 June 1995 See abstract; page 3, lines 10 - 16; page 5, lines 4 - 9; and claims 1, 2.	3,15
A		1,2,13,14,27-29
A	US 2012-0214043 A1 (OLSCHIMKE, J. et al.) 23 August 2012 See abstract; paragraphs [0005], [0012], [0024] - [0026], [0050], [0088]; and claims 1, 2, 4, 12, 14.	1-3,13-15,27-29
A	US 2003-0215719 A1 (NAVARRINI, W. et al.) 20 November 2003 See abstract; and paragraphs [0001], [0010], [0013], [0015], [0031].	1-3,13-15,27-29
A	US 2009-0111019 A1 (HIROSE, T. et al.) 30 April 2009 See abstract; paragraphs [0089], [0143], [0179], [0180]; and claim 46.	1-3,13-15,27-29

☐ 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	Date of mailing of the international search report
06 January 2014 (06.01.2014)	**06 January 2014 (06.01.2014)**

Name and mailing address of the ISA/KR
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
Facsimile No. +82-42-472-7140

Authorized officer
LEE, Dong Wook
Telephone No. +82-42-481-8163

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/065396

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-12,16-26
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2013/065396

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 95-15588 A1	08/06/1995	WO 95-15588 A1	08/06/1995
US 2012-0214043 A1	23/08/2012	CN 102668232 A	12/09/2012
		EP 2494648 A1	05/09/2012
		JP 2013-508927 A	07/03/2013
		KR 10-2012-0101414 A	13/09/2012
		TW 201140902 A	16/11/2011
		WO 2011-051275 A1	05/05/2011
US 2003-0215719 A1	20/11/2003	DE 60320728 D1	19/06/2008
		EP 1403958 A1	31/03/2004
		EP 1403958 B1	07/05/2008
		IT MI20020902 A1	27/10/2003
		IT MI20020902 DO	26/04/2002
		JP 04430324 B2	10/03/2010
		JP 2004-002841 A	08/01/2004
		US 7704639 B2	27/04/2010
US 2009-0111019 A1	30/04/2009	CN 101425575 A	06/05/2009
		CN 101425575 B	03/10/2012
		JP 2009-110845 A	21/05/2009
		KR 10-2009-0045113 A	07/05/2009