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(54) Title: POLYMER ELECTROLYTE COMPOSITION BASED UPON THIOL-ENE CHEMISTRY

(57) Abstract

Electrolyte compositions in which a salt is disposed in a thiol-ene matrix. The compositions retain their shape under operating conditions and exhibit an ionic conductivity of at least $1x10^{-6}$ S/cm when measured in the absence of solvent at 25 °C.

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POLYMER ELECTROLYTE COMPOSITION BASED UPON THIOL-ENE CHEMISTRY

Background of the Invention

This invention relates to electrolyte compositions.

Polyethylene oxide (PEO) polymers have been proposed for use as electrolyte compositions for batteries and other applications. Advantages of such polymers include the ability to form lightweight solid (or gelled) films. One problem with such materials, however, is the relatively high degree of crystallinity associated with the PEO polymer which inhibits ion transport (and thus ionic conductivity). It would be desirable to provide an electrolyte composition having the advantages of PEO polymers, but having higher conductivity under ambient conditions.

Summary of the Invention

In one aspect, the invention features an electrolyte composition that includes a salt disposed in a matrix. The matrix in turn, includes the reaction product of (a) a diene-functional alkylene oxide, (b) a di-functional thiol, and (c) a multi-functional reactant having a functionality greater than two comprising a multi-ene-functional reactant, a multi-functional thiol, or combination thereof; in which the relative amounts of alkylene oxide, thiol, and multi-functional reactant having a functionality greater than two are selected such that (a) the composition, when formed into a shape, has sufficient mechanical integrity to retain that shape under operating conditions and (b) the composition exhibits an ionic conductivity of at least 1×10^{-6} S/cm ,when measured in the absence of solvent at 25°C.

In preferred embodiments, the electrolyte composition has an ionic conductivity of at least 5×10^{-6} S/cm, and more preferably at least 1×10^{-5} S/cm, when measured in the absence of solvent at 25°C.

Preferred di-functional thiols include 1,8-dimercapto-3,6-dioxooctane. Also preferred are mercapto-siloxanes having a functionality equal to two (e.g., tetramethylbis(3-mercaptopropyl)disiloxane).

Preferred diene-functional alkylene oxides include polyalkylene oxide divinyl or diallyl ethers such as triethylene glycol divinyl ether, triethylene glycol diallyl ether, tetraethylene glycol diallyl ether, polyethylene glycol diallyl ether, and combinations thereof. Also preferred are polyalkylene oxide di(meth)acrylates such as tetraethylene glycol di(meth)acrylate.

The amount of multi-functional reactant having a functionality greater than two preferably ranges from about 0.1 to about 20 equivalent percent, more preferably from about 0.1 to about 10 equivalent percent, and even more preferably from about 0.1 to about 5 equivalent percent.

An example of a preferred multi-ene-functional reactant having a functionality greater than two is triallyl cyanurate. Examples of preferred multi-functional thiol reactants having a functionality greater than two include reactants having the formula $Z[OCO(CH_2)_nSH]_m$ where Z is a polyvalent organic moiety which is a CH_{0-3} group-containing nucleus of a tri- or tetravalent alcohol of the type of glycerol or pentaerythritol, m is 3 or 4, and n is an integer between 1 and 5, inclusive. Thiol reactants having this formula include trimethylolpropane tris(3-mercaptopropionate), pentaerythritol tetra(3-mercaptopropionate), and combinations thereof. Also preferred are reactants that are mercapto-siloxanes having a functionality greater than two (e.g., poly(3-mercaptopropylmethylsiloxane)).

The composition may further include an electrolyte solvent.

In a second aspect, the invention features an electrolyte composition that includes a salt disposed in a matrix comprising the crosslinked reaction product of a multi-ene-functional alkylene oxide and a multi-functional thiol. The relative amounts of the alkylene oxide and the thiol are selected such that (a) the composition, when formed into a shape, has sufficient mechanical integrity to retain that shape under operating conditions and (b) the composition exhibits an ionic conductivity of at least 1×10^{-6} S/cm when measured in the absence of solvent at 25°C.

In a third aspect, the invention features a method of preparing the above-described electrolyte compositions in the form of a film. The method includes

the steps of: (a) providing a solvent-free polymerizable monomeric or prepolymeric syrup that includes a multi-ene-functional alkylene oxide, a multi-functional thiol, and an electrolyte salt; (b) coating a substrate with the syrup; and (c) exposing the syrup to radiation to polymerize the syrup to yield the electrolyte composition. A preferred reaction mixture includes (a) a diene-functional alkylene oxide, (b) a di-functional thiol, and (c) a multi-functional reactant, having a functionality greater than two comprising a multi-ene-functional reactant, a multi-functional thiol, or combination thereof.

Preferably, the syrup is exposed to ultraviolet, thermal, or electron beam radiation to polymerize the syrup. Moreover, the syrup is preferably coated onto an electrode.

The invention further features an electrochemical cell having an anode, a cathode, and the above-described electrolyte compositions.

As used throughout this application:

A "polyalkylene oxide" is a polymer or oligomer containing two or more alkylene oxide units.

An "ene" is a reactant having a polymerizable carbon-carbon double bond. A "multi-ene-functional reactant" is a reactant having two or more polymerizable carbon-carbon double bonds.

A "multi-ene-functional alkylene oxide" is an alkylene oxide reactant provided with two or more ene-functional groups. A diene-functional alkylene oxide contains two ene-functional groups. The ene-functional groups may be in the form of end-terminal groups, pendant groups, or a combination thereof so long as the groups are available to participate in the polymerization reaction.

A "multi-functional thiol" is a reactant provided with two or more thiol-functional groups. A di-functional thiol has two thiol-functional groups. As in the case of the alkylene oxide reactants, the thiol-functional groups may be in the form of end-terminal groups, pendant groups, or a combination thereof so long as the groups are available to participate in the polymerization reaction.

"Matrix" refers to a solid or gel medium in which one or more electrolyte salts may be dissolved or dispersed to form an ionically conductive electrolyte composition.

"Equivalent percent" in the case of multi-ene-functional reactants having a functionality greater than two is equal to the number of equivalents of said ene reactants divided by the total number of equivalents of thiol reactants. In the case of multi-functional thiol reactants having a functionality greater than two, "equivalent percent" is equal to the number of equivalents of said thiol reactants divided by the total number of equivalents of ene reactants. Where a combination of multi-functional thiol reactants having a functionality greater than two and multi-ene-functional reactants having a functionality greater than two is used, "equivalent percent" refers to the sum of said ene and thiol reactants divided by the total equivalents of all ene and thiol reactants in the reaction mixture.

The invention provides a lightweight electrolyte composition having sufficient mechanical integrity to allow the composition to retain its shape when applied to a substrate, coupled with relatively high ionic conductivity (even in the absence of solvent). The composition thus provides the benefits of PEO-based electrolyte compositions, but with the advantage of higher conductivity owing to the reduced crystallinity of the thiol-ene polymer relative to PEO. The thiol-ene matrix polymers are also relatively insensitive to the particular type of electrolyte salt incorporated therein, thus expanding the class of suitable electrolyte salts that can be used.

A further advantage is that the electrolyte compositions are readily prepared using a solvent-free polymerization process that may be conducted either in air or in an inert atmosphere. Because the process is solvent-free, the invention offers advantages from an environmental standpoint. Moreover, polymerization and electrolyte salt incorporation are accomplished in a single step.

Other features and advantages of the invention will be apparent from the following description of the preferred embodiments thereof, and from the claims.

Brief Description of the Drawings

Fig. 1 is an Arrhenius plot showing conductivity of various electrolyte compositions as a function of lithium to (oxygen plus sulfur) ratio.

Fig. 2 is an Arrhenius plot showing conductivity of various electrolyte compositions as a function of type of lithium salt.

Fig. 3 is an Arrhenius plot showing conductivity of various electrolyte compositions as a function of crosslinking level.

Fig. 4 is a charge/discharge curve for the first and fifth cycles of a lithium-polypyrrole battery according to the invention.

Description of the Preferred Embodiments

Electrolyte compositions according to the invention include a polymer matrix in which is disposed one or more electrolyte salts. The polymer matrix is preferably the reaction product of one or more di-functional thiols, one or more diene-functional alkylene oxides, and one or more multi-ene-functional reactants, multi-functional thiols, or combination thereof, each having a functionality greater than two. However, the polymer matrix may also be the reaction product of (a) a multi-functional thiol having a functionality greater than two and a diene-functional alkylene oxide, (b) a di-functional thiol and a multi-ene-functional alkylene oxide having a functionality greater than two, or (c) a multi-functional thiol having a functionality greater than two and a multi-ene-functional alkylene oxide having a functionality greater than two if the multi-functional reactants have a relatively high molecular weight between functional groups.

The reactants are chosen such that the electrolyte composition has sufficient mechanical integrity to retain its shape (e.g., when prepared in the form of a film), but does not substantially impede ion transport through the electrolyte (as measured by the ionic conductivity of the electrolyte composition). In general, the ionic conductivity of the electrolyte composition (measured as described below in the absence of solvent at 25°C) is at least 1×10^{-6} S/cm, more preferably at least 5×10^{-6} S/cm, and most preferably at least 1×10^{-5} S/cm. In addition, the reactants may be adjusted to achieve a particular tack level to provide sufficient adhesion between

the electrolyte and a substrate such as an electrode to which the electrolyte is applied.

Examples of suitable di-functional thiols include 1,8-dimercapto-3,6-dioxoocane, bis-(2-mercaptoethyl) ether, bis-(2-mercaptoethyl) sulfide, ethane dithiol, and di-thiols having the formula

$$HS\text{-}(CH)_n\text{-}C(O)\text{-}O\text{-}CH_2\text{-}CH_2\text{-}O\text{-}(O)C\text{-}(CH)_n\text{-}SH$$

such as ethylene glycol bis(mercapto acetate) (n=1) and ethylene glycol bis(mercapto propionate) (n=2). Also preferred are mercapto-siloxanes having a functionality equal to two (e.g., tetramethylbis(3-mercaptopropyl)disiloxane and higher analogs thereof). The thiol may also be provided with a variety of functional groups, including

$$\text{-S-, -S(O)-; -S(O)}_2\text{-, -C(O)-, -C-(O)O-,-}\underset{|}{\text{N}}\text{-, -NH-C-(O)O-, -}\underset{|}{\text{As}}\text{-,-Si(R)(R)-,}$$

$$\underset{|}{\text{-P(O)-}}\text{, or -}\underset{|}{\text{P}}\text{-, or combination thereof.}$$

Examples of suitable diene-functional alkylene oxides include alkylene oxides having the formula $[(CHR^1)_n(CHR^2O)_m]_x$, (where R^1 and R^2, independently, are H or a C_1-C_3 alkyl group, and m and n , independently, are 1-4) provided with two ene-functional groups, or copolymers thereof. Examples of suitable ene-functional groups include allyls, (meth)acrylates, (meth)acrylamides, vinyl silanes, vinyl ethers, fumarates, maleates, styryls, norbornenyls, and combinations thereof. Particularly preferred are polyethylene glycol-based divinyl ethers having the general formula:

$$CH_2\text{=}CH\text{-}O\text{-}(CH_2\text{-}CH_2\text{-}O)_n\text{-}CH_2\text{=}CH_2;$$

polyethylene glycol-based diallyl ethers having the general formula:

$$CH_2\text{=}CH\text{-}CH_2\text{-}O\text{-}(CH_2\text{-}CH_2\text{-}O)_n\text{-}CH_2\text{-}CH\text{=}CH_2;$$

and polyethylene glycol-based di(meth)acrylates. Specific examples include triethylene glycol divinyl ether, tetraethylene glycol di(meth)acrylate, triethylene glycol diallyl ether, tetraethylene glycol diallyl ether, polyethylene glycol diallyl ether, and allyl-functional oligomers such as 9460 commercially available from Monomer-Polymer & Dajac Laboratories, Feastville, PA. The alkylene oxide may further be provided with a variety of functional groups, including

-S-, -S(O)-; -S(O)$_2$-, -C(O)-, -C-(O)O-, -N-, -NH-C-(O)O-, -As-,-Si(R)(R)-, -P(O)-, or -P-, or combination thereof.

In general, the amount of multi-functional reactant having a functionality greater than two ranges from about 0.1 to about 20 equivalent percent, preferably from about 0.1 to about 10 equivalent percent, and more preferably from about 0.1 to about 5 equivalent percent, with reactants having higher functionalities falling at the lower end of the range.

Examples of suitable multi-functional thiols having a functionality greater than two include those having the general formula $Z[OCO(CH_2)_n,SH]_m$ where Z is a polyvalent organic moiety which is a CH_{0-3} group-containing nucleus of a tri- or tetravalent alcohol of the type of glycerol or pentaerythritol, m is 3 or 4, and n is an integer between 1 and 5, inclusive. Specific examples include trimethylolpropane tris(3-mercaptopropionate), pentaerythritol tetra(3-mercaptopropionate), and combinations thereof. Also useful are mercapto-functional siloxanes (e.g., poly(3-mercaptopropylmethylsiloxane), or oligomers or copolymers thereof, siloxanes such as those commercially available from United Chemical Technologies, Inc. under the trade designation "PS405"; and combinations thereof. In addition, tri-functional thiols such as those commercially available from Henkel Corp. under the designation "Copure™ 3-800" and from Morton International as the "Liquid Polysulfide Polymer Series" can be used.

Examples of suitable enes having functionalities greater than two include allyl ethers, vinyl ethers, and (meth)acrylates. Specific examples of allyls include triallyl isocyanurate, allyl-functional urethane oligomers, and allyl-functional siloxanes. Examples of acrylates and methacrylates include trimethylpropane triacrylate and pentaerythritol tetraacrylate. Examples of vinyl ethers include trimethanolpropane trivinyl ether.

As a consequence of the thiol-ene matrix materials described above, a wide variety of electrolyte salts can be used in electrolyte compositions according to the invention. Such salts are well-known and include alkali metal, alkaline earth metal,, and Group IIIB metal (e.g., aluminum) salts of anions such as BF_4^-; PF_6^-;

AsF_6^-; ClO_4^-; SbF_6^-; $R_fSO_3^-$ (in which R_f is a perfluoroalkyl group having between 1 and 12 carbon atoms, inclusive); a bis-sulfonamide anion (R_f-SO_2-N^--SO_2-R_f';) in which R_f and R_f', independently, are perfluoroalkyl groups having between 1 and 12 carbon atoms, inclusive; a bis-sulfonamide anion (R_f-SO_2-C^-(R)-SO_2-R_f';) in which R_f and R_f', independently, are perfluoroalkyl groups having between 1 and 12 carbon atoms, inclusive, and R is H, Br, Cl, I, an alkyl group having between 1 and 20 carbon atoms, inclusive, aryl, or alkylaryl; and a tris-sulfonylmethide anion ($-C(SO_2R_f)SO_2R_f')(SO_2R_f"$)) in which R_f, R_f', and $R_f"$, independently, are perfluoroalkyl groups having between 1 and 12 carbon atoms, inclusive. Such salts also include cyclic perfluoroaliphatic disulfonimide salts, such as those described in U.S. Pat. No. 4,387,222 (Koshar), and metal salts of acids, such as those described by DesMarteau et al. in J. Fluor. Chem. 45, 24 (1989).

Representative examples of suitable salts include $LiBF_4$, $LiAsF_6$, $LiClO_4$, $LiPF_6$, CF_3SO_3Li, $C_2F_5SO_3Li$, $C_{10}F_{21}SO_3Li$, $(CF_3SO_2)_2NLi$, $(CF_3SO_2)_2NNa$, $[(CF_3SO_2)_2N]_3Al$, $(CF_3SO_2)_2C(H)Li$, cyclo-$(CF_2SO_2)_2NLi$, cyclo-$(CF_2SO_2)_2C(H)Li$, $(CF_3SO_2)_3CLi$, and mixtures thereof.

Preferably, the ratio of the total number of oxygen and sulfur atoms in the thiol-ene polymer to the number of salt cations ranges from about 5 to about 40, with ratios of between 10 and 20 being most preferred.

The electrolyte compositions according to the invention are preferably prepared by photoinitiated bulk polymerization according to the technique described in Martens et al., U.S. Patent No. 4,181,752. The reactants, electrolyte salt, and a photoinitiator are mixed together in the absence of solvent and preferably partially polymerized to a viscosity in the range of from about 10 cps to about 50,000 cps to achieve a coatable syrup.

The resulting composition is coated onto a substrate such as an electrode, e.g., according to the technique described in WO95/29811. Low intensity ultraviolet lamps with different spectral outputs are commercially available and preferably used, although high intensity lamps may be used as well. The lamp should be selected such that the maximum output of the lamp is near the maximum absorption of the initiator. Fluorescent lamps (e.g., F40TI2-350BL lamps

commercially available from Osram Sylvania, Danvers, MA) in which the intensity of each lamp bank is in the range of about 0.25 to 10 mW/cm^2 (more preferably in the range of about 0.5 to 5 mW/cm^2) are suitable for this application. The total radiation to which the reactants are exposed preferably is in the range of about 100 to 1500 mJ/ cm^2. The particular radiation intensity and total energy exposure requirements will vary depending on the initiator and reactants.

The amount of photoinitiator generally ranges from about 0.01 to about 10 parts per 100 parts of reactants. Examples of suitable polymerization initiators include benzoin ethers, substituted benzoin ethers such as benzoin methyl ether or benzoin isopropyl ether, substituted acetophenones such as 2,2-diethoxy-acetophenone, and 2,2-dimethoxy-2-phenyl-acetophenone, substituted alpha-ketols such as 2-methyl-2-hydroxypropiophenone, aromatic sulphonyl chlorides such as 2-naphthalene sulphonyl chloride, and photoactive oximes such as 1-phenyl-1,1-propanedione-2-(O-ethoxycarbonyl) oximes. Other suitable initiators include 2,4-bistrichloro-methyl-6-substituted-s-triazines, and benzophenone with an amine (for example, benzophenone and p-N,N-diethylamino) ethyl benzoate). Sensitizers such as phenanthrene may be used in conjunction with the photoinitiators as well.

Polymerization may also be carried out by exposure to thermal radiation (in which case a thermal initiator is included) or electron beam radiation (which does not require the use of an initiator). Electron beam radiation has the advantage that it can be used in conjunction with non-ultraviolet/visible transparent substrates such as filled electrodes. Thus, the same material can be used for both the electrolyte composition and one (or both) of the electrodes, thereby eliminating interfaces between electrolyte and electrode that can impede ion transport.

Following polymerization, the electrolyte compositions may be swollen (if desired) with solvent. Aprotic liquids are preferred. Such liquids are generally dry (e.g., have a water content less than about 100 ppm, preferably less than about 50 ppm). Examples of suitable aprotic liquids include linear ethers such as diethyl ether and 1,2-dimethoxyethane; cyclic ethers such as tetrahydrofuran, 2-methyltetrahydrofuran, dioxane, dioxolane, and 4-methyldioxolane; esters such as methyl formate, ethyl formate, methyl acetate, diethyl carbonate, propylene

carbonate, ethylene carbonate, and butyrolactones; nitrites such as acetonitrile and benzonitrile; nitro compounds such as nitromethane or nitrobenzene; amides such as N,N-dimethylformamide, N,N-diethylformamide, and N-methylpyrrolidone; sulfoxides such as dimethyl sulfoxide; sulfones such as dimethylsulfone, tetramethylene sulfone, and other sulfolanes; oxazolidones such as N-methyl-2-oxazolidone; and mixtures thereof.

As stated above, the electrolyte compositions according to the invention generally have conductivities of at least about 1×10^{-6} S/cm at 25°C (measured in the absence of solvent). The compositions thus find application in a wide variety of areas, including primary and secondary batteries (e.g., lithium batteries), sensor, capacitors, and electrochromic devices (e.g., for use as optical shutters or displays).

The invention will now be described further by way of the following examples.

EXAMPLES

EXAMPLE 1

A mixture of triethylene glycol divinyl ether (6.068 gm, 30 mmol, available from Aldrich Chemicals, Milwaukee, WI), tetramethylbis(3-mercaptopropyl)disiloxane (7.198 gm, 27 mmol, available from United Chemicals Technologies, Inc. Bristol, PA), trimethylopropane tri(2-mercaptoacetate) (0.797 gm, 2 mmol, available from Aldrich Chemicals, Milwaukee, WI), benzophenone (120 mg, available from Aldrich Chemicals, Milwaukee, WI), and lithium trifluoromethanesulfonyl imide (1.435 gm, 5 mmol, available from 3M, St. Paul, MN) was shaken in a sealed glass bottle under ambient conditions until all solids had dissolved (approximately 2 hours). The resulting solution was irradiated with a black light (λ_{max} nm) for ~20 sec. to obtain a coatable prepolymer syrup. A 0.0127 mm thick coating of the resulting syrup was applied to a silicone-treated polyester release liner using a knife coater, a second silicone-treated release liner placed over

the syrup, and the syrup polymerized by passing the laminate between two banks of fluorescent lamps (F40TI2-350BL lamps commercially available from Osram Sylvania, Danvers, MA) for a total residence time of about 3.5 minutes. The UV light profile was 330 mJ, 1.5 mW and 300 mJ, 1.3 mW for the top and bottom lights, respectively, as measured with a UVIMAP Model #UMD365H-S photometer (available from EIT Electronic Instrumentation Technology, Inc., Sterling, VA). The resulting polymer electrolyte film was a clear, slightly tacky film which was readily removed from the release liners. The conductivity of the electrolyte film, which was measured by laminating a sample of the film between two pieces of zinc foil (approximately 22 cm x 25 cm) and measuring its ac impedance using a Schlumberger FRA 1260 Impedance/Gain Phase Analyzer linked to a computer-controlled PARC 273A potentiostat, was $3.3x10^{-5}$ S/cm.

EXAMPLE 2

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of triethylene glycol divinyl ether (4.045 gm, 20 mmol), tetramethylbis(3-mercaptopropyl)disiloxane (5.066 gm, 19 mmol), poly(3-mercaptopropyl)methyldisiloxane (0.320 gm, 2 mmol, available from United Chemicals Technologies, Inc.), dimethoxybenzil (KB-1, 20 mg, available from Sartomer Chemical, Exton, PA), and lithium trifluoromethanesulfonyl imide (1.435 gm, 5 mmol). (The molar equivalent weight of poly(3-mercaptopropyl)methyldisiloxane was based on a repeat unit of $OSi(Me)CH_2CH_2CH_2SH$). The resulting polymer electrolyte film had a conductivity of $2.0x10^{-5}$ S/cm.

EXAMPLE 3

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of triethylene glycol divinyl ether (2.022 gm, 10 mmol), 1,8-dimercapto-4,6-dioxooctane (1.732 gm, 9.5 mmol, available from Nisso Maruzen Chemical, Tokyo, Japan), poly(3-mercaptopropyl)methyldisiloxane (0.090 gm, 0.56 mmol), dimethoxybenzil (KB-1,

12 mg), and lithium trifluoromethanesulfonyl imide (2.296 gm, 8 mmol). The resulting polymer electrolyte film had a conductivity of $1.7x10^{-5}$ S/cm.

EXAMPLE 4

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of triethylene glycol divinyl ether (2.188 gm, 9.5 mmol), 1,8-dimercapto-4,6-dioxooctane (1.732 gm, 9.5 mmol), triallyl cyanurate (0.025 gm, 0.1 mmol, available from Aldrich Chemicals, Milwaukee, WI), benzophenone (BP, 20 mg), and lithium trifluoromethanesulfonyl imide (2.296 gm, 8 mmol). The resulting polymer electrolyte film had a conductivity of $2.1x10^{-5}$ S/cm

EXAMPLE 5

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of triethylene glycol diallyl ether (2.188 gm, 9.5 mmol, prepared as described below), 1,8-dimercapto-4,6-dioxooctane (1.823 gm, 10 mmol), pentaerythritol tetra-allyl ether (0.148 gm, 0.5 mmol, available from Monomer-Polymer & Dajac Labs, Feasterville, PA), dimethoxybenzil (KB-1, 8 mg), and lithium trifluoromethanesulfonyl imide (2.296 gm, 8 mmol). The triethylene glycol diallyl ether was prepared by adding allyl bromide (48.0 gm, 0.4 mol) dropwise, to a mixture of triethylene glycol (30.34 gm, 0.2 mol) and sodium hydroxide (10.0 gm, 0.25 mol) and refluxing the resulting mixture for 4 hours. The reaction mixture was cooled to room temperature, diluted with ether (100mL), and the precipitate removed by filtration. The filtrate was washed with 5% HCI (100 mL), saturated sodium bicarbonate (100 mL), and dried over anhydrous sodium sulfate. The sodium sulfate was removed by filtration, the ether stripped on a rotary evaporator, and the crude product distilled under vacuum. The structure of the distilled product was confirmed by NMR analysis. The resulting polymer electrolyte film had a conductivity of $2.9 x10^{-5}$ S/cm.

EXAMPLE 6

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of tetraethylene glycol diallyether (2.605 gm, 4 9.5 mmol, (prepared according to the procedure used to prepare triethylene glycol diallyl ether described in Example 5, but substituting the appropriate molar quantity of tetraethylene glycol for the triethylene glycol)), 1,8-dimercapto-4,6-dioxooctane (1.823 gm, 10 mmol), pentaerythritol tetra-allyl ether (0.148 gm, 0.5 mmol), dimethoxybenzil (KB-1, 8 mg), and lithium trifluoromethanesulfonyl imide (2.583 gm 9 mmol). The resulting polymer electrolyte film had a conductivity of 5.1×10^{-5} S/cm.

EXAMPLE 7

A polymer electrolyte. film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of polyethylene glycol 400 diallyether (4.598 gm, 9.5 mmol (prepared by substituting the appropriate molar quantity of polyethylene glycol 400 for the triethylene glycol)), 1,8-mercapto-4,6-dioxooctane (1.823 gm, 10 mmol), pentaerythritol tetra-allyl ether (0.148 gm, 0.5 mmol), dimethoxybenzil (KB-1, 8 mg), and lithium trifluoromethanesulfonyl imide (4.020 gm, 14 mmol). The resulting polymer electrolyte film had a conductivity of 3.9×10^{-5} S/cm.

EXAMPLE 8

A polymer electrolyte film was prepared according to the procedure of Example 1 except that the reaction mixture consisted of tetraethylene glycol diacrylate (3.023 gm, 10 mmol, available from Aldrich Chemicals, Milwaukee, WI), 1,8-dimercapto-3,6-dioxooctane (1.732 gm, 9.5 mmol, available from Nisso Maruzen Chemical), poly(3-mercaptopropyl)methyldisiloxane (0.067 gm, 0.50 mmol), dimethoxybenzil (KB-1, 15 mg), and lithium trifluoromethanesulfonyl imide (2.583 gm, 9 mmol). The resulting polymer electrolyte film had a conductivity of 2.8×10^{-5} S/cm.

EXAMPLE 9

A series of four polymer electrolyte films were prepared according to the procedure of Example 1 except that the polymer matrix for all four samples was based on a reaction mixture consisting of triethylene glycol divinyl ether (DVE-3, 1.980 gm, 9.85 mmol), 1,8-dimercapto-3,6-dioxooctane (1.823 gm, 10.0 mmol), triallyl cyanuarate (0.025 gm, 0.1 mmol), and dimethoxybenzil (KB-1, 4 mg). The concentration of lithium trifluoromethanesulfonate (available from 3M, St. Paul, MN) was systematically increased over the range indicated in Table 1 to provide a range of Li/(O+S) ratios, also indicated in Table 1. Cells were constructed with each polymer electrolyte film by laminating the film between two circular polished stainless steel electrodes, mounting the thus-formed cells in aluminum cans with springs, and hermetically sealing the can.

Table 1

Conductivity as a Fraction of Li/(O+S) Ratio

Sample	Gm $LiN(SO_2CF_3)_2$	Mmol $LiN(SO_2CF_3)_2$	Li/(O+S) Ratio
9a	2.870	10	1/8
9b	2.296	8	1/10
9c	1.148	4	1/20
9d	0.574	2	1/40

(The process of preparing the cells, mounting the cells in the can and sealing the can was carried out in an inerted dry box.) The cans were placed in a temperature-controlled oven and the conductivity of each film determined over a temperature range of 23-80°C. Arrhenius plots of the data obtained from these studies, which are presented in Figure 1, where curve A corresponds to sample 9a, curve B corresponds to sample 9b, curve C corresponds to sample 9c, and curve D corresponds to sample 9d, demonstrate that the polymer electrolyte films of the present invention have good conductivity over a wide range of Li/(O+S) ratios.

EXAMPLE 10

A series of polymer electrolyte films were prepared according to the procedure of Example 9 except that the Li/(O+S) ratio was held constant at 1/20 and four different Li salts were incorporated into the polymer electrolyte formulations as indicated in Table 2.

Table. 2

Conductivity as a Function of Type of Li Salt

Sample	Li Salt	Gm Salt	Mmol Salt
10a	$LiN(SO_2CF_3)_2$[1]	1.148	4
10b	LiO_3SCF_3[1]	0.624	4
10c	$LiO_3SC_4F_9$[1]	1.224	4
10d	$LiClO_4$[2]	0.425	4

1. Available from 3M.
2. Available from Aldrich Chemical.

Arrhenius plots of the data obtained from these studies, which are presented in Figure 2, where curve E corresponds to sample 10a, curve F corresponds to sample 10b, curve G corresponds to sample 10c, and curve H corresponds to sample 10d, demonstrate that the polymer electrolyte films of the present invention have good conductivity with a range of salts, several of which do not exhibit a plasticizing effect on the polymer electrolyte.

EXAMPLE 11

A series of polymer electrolyte films were prepared according to the procedure of Example 9 except that the Li/(O+S) ratio was held constant at 1/20 and the crosslinker level was systematically varied from 0.6% to 6.0%, where the crosslinker level was defined as (meq triallyl cyanuarate/meq dithiol) X 100%. These preparations were carried out at an X level of the preparations described in Example 9. Actual weights and molar equivalents of the triallyl cyanuarate used in the various samples are indicated in Table 3.

Table 3

Conductivity as a function of Crosslink Density

Sample	Gm DVE-3	meq DVE-3	Gm Triallyl Cyanurate	Mmol Triallyl Cyanurate	X-Linker Level (%)
11a	16.128	79.76	19.942	0.06	0.6
11b	16.080	79.52	39.8844	0.12	1.2
11c	16.032	79.28	59.824	0.18	1.8
11d	15.984	79.04	79.768	0.24	2.4
11e	15.936	78.80	99.708	0.30	3.0
11f	15.816	79.24	149.564	0.45	4.5
11g	15.696	77.60	199.416	0.60	6.0

Arrhenius plots of the data obtained from these studies, which are shown in Figure 3, where curve I corresponds to sample 11a, curve J corresponds to sample 11b, curve K corresponds to sample 11c, curve L corresponds to sample 11d, curve M corresponds to sample 11e, curve N corresponds to sample 11f and curve O corresponds to sample 11g, demonstrate that within the crosslinker range studied, lower crosslinker levels produced higher conductivities in the polymer electrolytes of the present invention.

EXAMPLE 12

A 5.9 cm^2 Li/polypyrrole battery cell was assembled by laminating a 127 μm thick film of sample 10d between a lithium foil (152 μm thick) and a polypyrrole film deposited on a platinum foil, which was prepared according to the procedure described by Osaka et. al. in J. Electrochem. Soc., 141, (1994), pp 1994 -1998. The polypyrrole film was formed on the platinum foil by an electro-oxidative polymerization at 42 volts vs. Li/Li^+ in propylene carbonate containing 0.2 M $LiClO_4$and 0.2 M pyrrole. Polymerization was terminated after passing a charge of 0.5 C/cm^2. The polypyrrole film was washed twice with 0.2 M $LiClO_4$and dried overnight under vacuum at 80°C. The cell was placed in an aluminum can as described in Example 9 and subjected to charge-discharge cycling at 78°C on a

Maccor 2000 battery test system (available from Maccor, Inc., Tulsa, OK). The charge-discharge curve for the first and fifth cycles of this cell, which were obtained at a current density of 0.017 that/cm^2, are shown in Figure 4.

What is claimed is:

1. An electrolyte composition comprising a salt disposed in a matrix comprising the reaction product of (a) a diene-functional alkylene oxide, b) a di-functional thiol and (c) a multi-functional reactant having a functionality greater than two comprising a multi-ene-functional reactant multi-functional thiol, or combination thereof,

the relative amounts of said alkylene oxide, said thiol, and said multi-functional reactant having a functionality greater than two being selected such that (a) said composition, when formed into a shape, has sufficient mechanical integrity to retain said shape under operating conditions and (b) said composition exhibits an ionic conductivity of at least 1×10^{-6} S/cm when measured in the absence of solvent at 25°C.

2. The electrolyte composition of claim 1 having an ionic conductivity of at least 1×10^{-5} S/cm when measured in the absence of solvent at 25°C.

3. The electrolyte composition of claim 1 wherein said di-functional thiol comprises 1,8-dimercapto-3,6-dioxooctane.

4. The electrolyte composition of claim 1 wherein said di-functional thiol comprises a mercapto-siloxane having a functionality equal to two.

5. The electrolyte composition of claim 1 wherein said diene-functional alkylene oxide comprises a polyalkylene oxide divinyl or diallyl ether.

6. The electrolyte composition of claim 1 wherein said diene-functional alkylene oxide comprises a polyalkylene oxide di(meth)acrylate.

7. The electrolyte composition of claim 1 wherein said diene-functional alkylene oxide comprises tetraethylene glycol di(meth)acrylate.

8. The electrolyte composition of claim 1 wherein said multi-functional reactant having a functionality greater than two comprises a reactant having the formula $Z[OCO(CH_2)_nSH]_m$ where Z is a polyvalent organic moiety which is a CH_{0-3} group-containing nucleus of a tri- or tetravalent alcohol of the type of glycerol or pentaerythritol, m is 3 or 4, and n is an integer between 1 and 5, inclusive.

9. The electrolyte composition of claim 1 wherein said multi-functional reactant having a functionality greater than two comprises a mercapto-siloxane having a functionality greater than two.

10. The electrolyte composition of claim 1 comprising from about 0.1 to about 20 equivalent percent of said multi-functional reactant having a functionality greater than two.

11. An electrolyte composition comprising a salt disposed in a matrix comprising the crosslinked reaction product of a multi-ene-functional alkylene oxide and a multi-functional thiol,

the relative amounts of said alkylene oxide and said thiol being selected such that (a) said composition, when formed into a shape, has sufficient mechanical integrity to retain said shape under operating conditions and (b) said composition exhibits an ionic conductivity of at least 1×10^{-1} S/cm when measured in the absence of solvent at 25°C.

12. A method of preparing an electrolyte composition in the form of a film comprising the steps of:

(a) providing a solvent-free polymerizable monomeric or prepolymeric syrup comprising a multi-ene-functional alkylene oxide, a multi-functional thiol, and an electrolyte salt;

(b) coating a substrate with said syrup; and

(c) exposing said syrup to radiation to polymerize said syrup to yield an electrolyte composition comprising an electrolyte salt disposed in a matrix,

the relative amounts of said alkylene oxide and said thiol being selected such that (a) said matrix when formed into a shape, has sufficient mechanical integrity to retain said shape under ambient conditions and (b) said composition exhibits an ionic conductivity of at least 1×10^{-1} S/cm when measured in the absence of solvent at 25°C.

13. An electrochemical cell comprising

an anode;

a cathode; and

an electrolyte composition comprising a salt disposed in a matrix comprising the crosslinked reaction product of a multi-ene-functional akylene oxide and a multi-functional thiol,

the relative amounts of said alkylene oxide and said thiol being selected such that (a) said composition when formed into a shape, has sufficient mechanical integrity to retain said shape under operating conditions and (b) said composition exhibits an ionic conductivity of at least 1×10^{-6} S/cm when measured in the absence of solvent at 25°C.

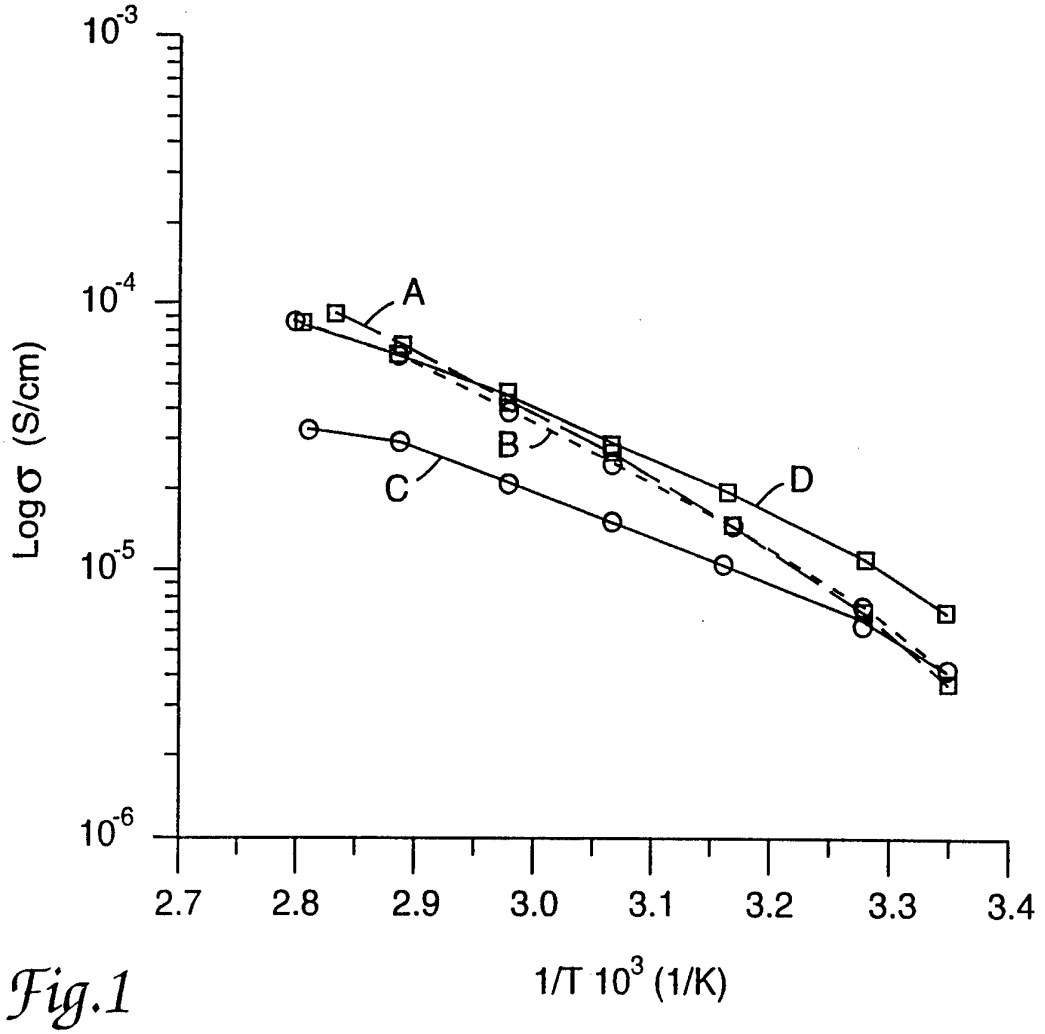


Fig.1

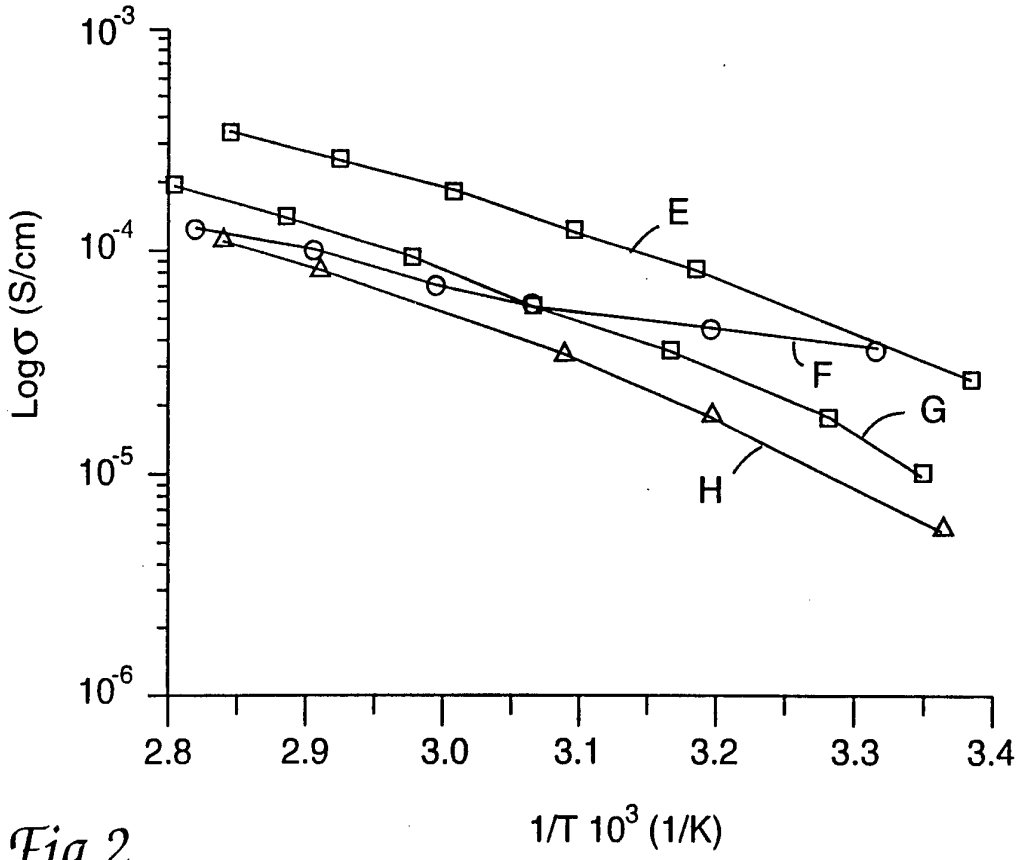


Fig.2

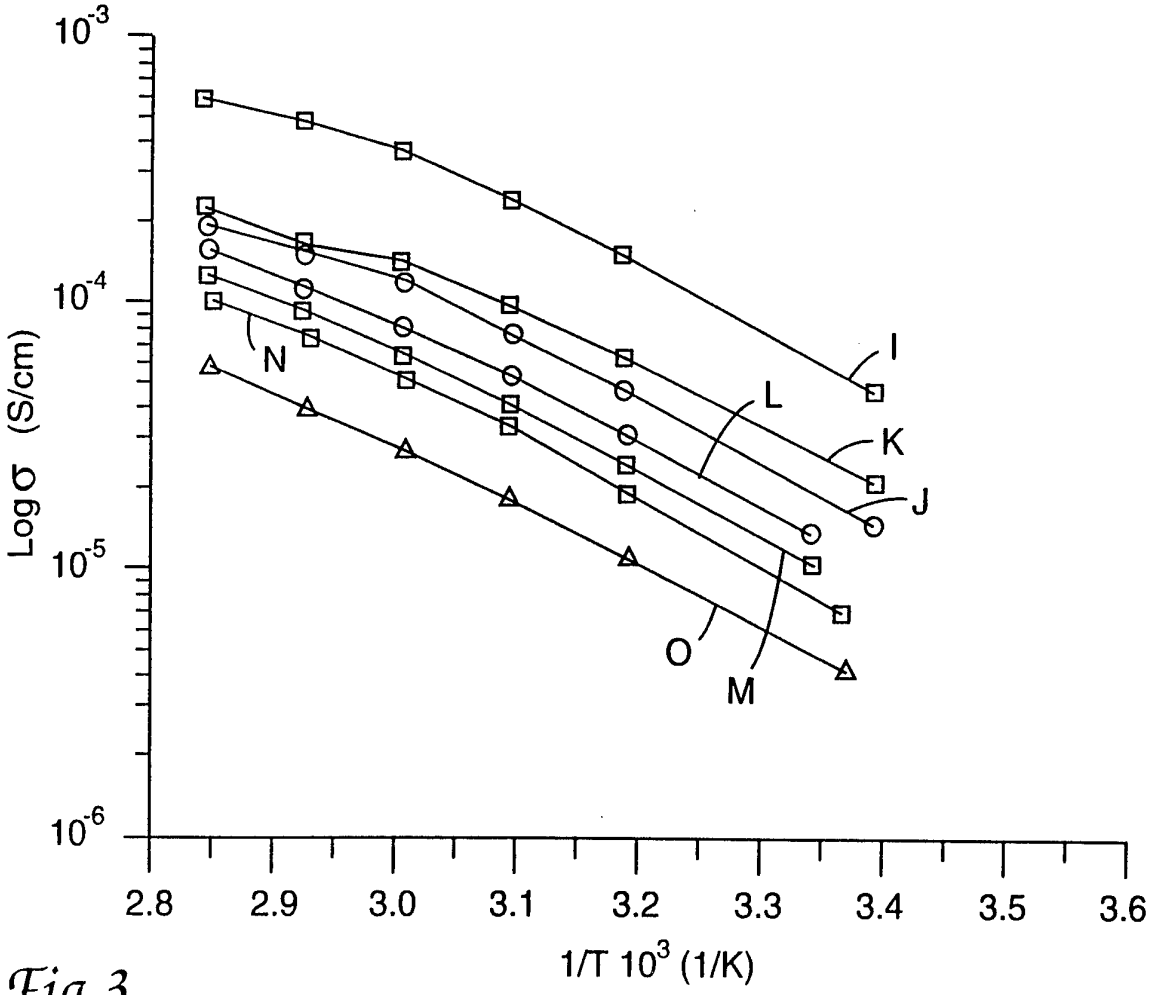

10^{-3}
10^{-4}
10^{-5}
10^{-6}
Log σ (S/cm)
2.8
2.9
3.0
3.1
3.2
3.3
3.4
3.5
3.6
1/T 10^3 (1/K)
I
K
J
L
N
O
M

Fig.3

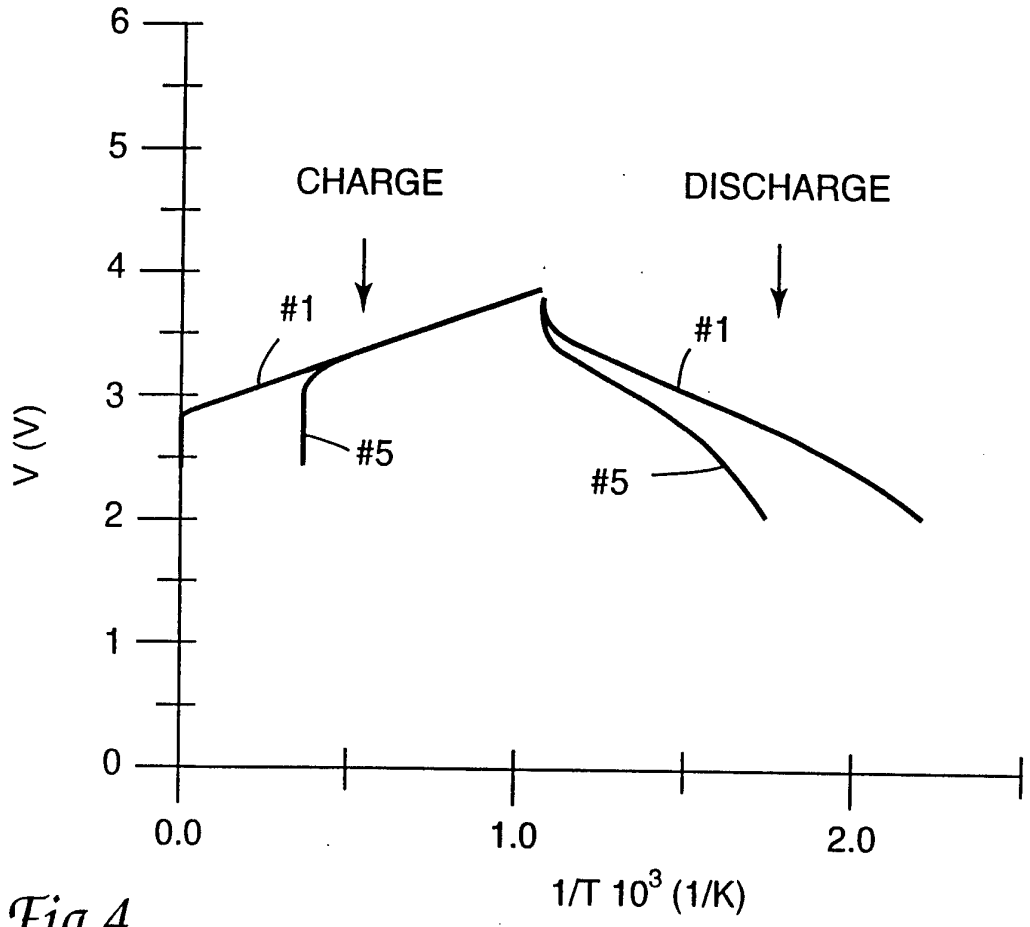


Fig.4

INTERNATIONAL SEARCH REPORT

Int. .onal Application No
PCT/US 96/05723

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01M6/18 C08G65/329 C08G65/334 H01B1/12

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)
IPC 6 H01M C08G H01B

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 practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO,A,86 01521 (DOW CHEMICAL CO) 13 March 1986 see page 10, line 1 - line 4 see page 10, line 19 - line 20 see page 12, line 13 - line 28 ---	1
A	US,A,5 223 353 (OHSAWA TOSHIYUKI ET AL) 29 June 1993 see column 3, line 64 - column 4, line 55 see column 9, line 11 - column 10, line 55; claims 5,10 -----	11,13

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 August 1996	13.09.96

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte onal Application No
PCT/US 96/05723

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
WO-A-8601521	13-03-86	US-A-	4618630	21-10-86
		AU-B-	564708	20-08-87
		AU-B-	4778485	24-03-86
		CA-A-	1284243	14-05-91
		EP-A-	0191845	27-08-86
		SG-A-	116993	15-04-94
		US-A-	4617325	14-10-86
US-A-5223353	29-06-93	JP-A-	5012913	22-01-93
		DE-T-	4190481	23-04-92
		JP-A-	5205515	13-08-93
		WO-A-	9114294	19-09-91