taken in conjunction with the accompanying figures and this background of the disclosure.

Summary

According to the present disclosure, there is provided a composite material comprising:

an ionic liquid A; and

a polymer matrix comprising a network of crosslinked poly(ionic liquid B).

According to a first aspect of the present disclosure, there is provided a composite material comprising:

an ionic liquid A, wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI); and

a polymer matrix comprising a network of crosslinked poly(ionic liquid B), wherein the polymer matrix is formed by reaction of an ionic liquid B with a crosslinking agent, wherein the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).

Advantageously, the composite materials are in a solid state or immobilized, and are thus non-volatile (i.e., do not evaporate) and do not leak and/or seep. Furthermore, the composite materials are flexible and/or deformable with low glass transition temperature (T_g) and modulus. The composite materials are advantageously stable with long lifetime, durable and do not pose any safety concerns.

Also advantageously, the composite materials are highly transparent in visible and part of near-infrared region (i.e., 380 nm to 1250 nm). This allows the composite material to be used for various applications such as electrochromic devices.

Advantageously, the polymer matrix may comprise chemicals with similar structures as well as compatibilized polarity and solubility. This advantageously results in a homogenized polymer matrix where the chemicals in the polymer matrix are miscible with one another and form a single phase. Furthermore, the chemicals in the polymer matrix may advantageously remain miscible with one another during temperature changes such that there is no phase separation occurring in the polymer matrix when temperature changes. This temperature independence means that the composite materials of the present invention do not undergo phase changes with temperature variations. The composite materials may remain stable and do not experience phase separation or aggregation. This advantage can be attributed to the presence of electrostatic interactions between the ionic liquid and the polymer matrix. These interactions

stabilize the composite material and prevent phase separation or aggregation at different temperatures which make them excellent materials for electrochromic devices. The advantage of having a homogenized polymer matrix is that it improves the structural integrity of the composite material by having a consistent distribution of components within the polymer matrix which helps distribute stress and load evenly across the polymer matrix. This reduces the likelihood of localized weak points or areas prone to failure. Furthermore, a homogenized polymer matrix ensures a uniform performance across the composite material.

Further advantageously, the composite materials comprise ionic liquids, which possess remarkable thermal/chemical stability, non-volatility, and good conductivity

in solid state. As a result, the composite materials possess excellent physicochemical stability, including thermal stability (from -20 °C to 100 °C), electrochemical stability, and air stability, allowing them to perform in various conditions and applications.

Even more advantageously, the composite materials exhibit high ionic conductivity in the region of mS/cm, allowing good electrochemical and electrochromic performance (in terms of optical modulation, response time, stability) with either organic or inorganic electrochromic materials. Hence, the composite materials may be utilized as solid-state composite materials for electrochromic applications due to its high ionic conductivity with promising thermal and electrochemical stability.

According to the present disclosure, there is provided a method of preparing a composite material as disclosed herein, comprising the steps of:

(i) preparing a mixture of ionic liquid A, ionic liquid B, crosslinking agent, and a photoinitiator;

(ii) curing the mixture with light irradiation,

wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B).

According to another aspect of the present disclosure, there is provided a method of preparing a composite material as disclosed herein, comprising the steps of:

(i) preparing a mixture of ionic liquid A, ionic liquid B, crosslinking agent, and a photoinitiator; and

(ii) curing the mixture with light irradiation,

wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B); and

wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI), the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).

Advantageously, the disclosed method enables the preparing of composite materials in less than a minute under ambient conditions. The disclosed method is fast, simple and easy to perform. Furthermore, the materials required for the method are inexpensive and easy to obtain.

According to yet another aspect of the present disclosure, there is provided an electrochromic device comprising an electrolyte sandwiched between two electrodes, wherein the electrolyte comprises the composite material as disclosed herein.

Advantageously, benefitting from the properties of the composite material, the assembled electrochromic device may display high colour contrast and fast response time with good endurance over thousands of switching cycles and exhibit great performance as an electrochromic device. The composite materials of the present invention may display colour-switching properties in response to changes in temperature or changes in applied current/potential while still retaining its state and form. Further advantageously, distorting or twisting the composite material does not have an effect on its ability to colour-switch. The composite materials may turn from a transparent state to a transmissive coloured state which still allows for partial visualization. This advantageously allows the composite materials of the present disclosure to be used in applications where changing coloured states and partial visualization are important, such as in optical applications (e.g. sunglasses, protective eye wears and lenses and window films. For instance, having partial visualization in architectural windows in buildings can balance natural light, allowing occupants to enjoy the view outside while maintaining a level of shielding from excessive sunlight. In addition, complete blockage of light or

visibility may not be suitable for specific industries, such as aircraft windows, due to safety reasons.

Also advantageously, the composite materials show good compatibility when coupled with deformable substrates (like ultra-thin indium doped tin oxide (ITO) glass, conductive textile, and indium-doped tin oxide polyethylene terephthalate (ITO-PET) substrate) to form and realize electrochromic devices such as flexible electrochromic eye protector and display applications.

According to the present disclosure, there is provided a method of forming an electrochromic device comprising:

(i) applying a mixture of ionic liquid A, ionic liquid B, crosslinking agent, a photoinitiator, and optionally a metal borate complex between two electrodes; and

(ii) curing the mixture with light irradiation,

wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B).

According to a further aspect of the present disclosure, there is provided a method of forming an electrochromic device comprising:

(i) applying a mixture of ionic liquid A, ionic liquid B, crosslinking agent, a photoinitiator, and optionally a metal borate complex between two electrodes; and

(ii) curing the mixture with light irradiation,

wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B); and

wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI), the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).

Advantageously, the disclosed method to form an electrochromic device is a rapid in-situ polymerization method, which is perform under ambient conditions. The disclosed method utilizes curing with light irradiation, which is, simple, convenient, easy to perform and apply and require less energy demand. Furthermore, it enables easy upscaling.

Also advantageously, the composite materials may be of low viscosity. This advantageously results in a composite material which can be applied in an easy and controlled manner, leading to improved handling and uniform coatings of the electrolytes.

Furthermore, this ensures better interface quality and reduces the likelihood of defects of the electrolytes in the electrochromic devices. In addition, it may be easy to apply and handle a low viscosity electrolyte and thus the electrolyte is able to be applied directly on the electrode for in-situ polymerization of electrolyte in the electrochromic device. The in-situ method may be an effective approach to improve the processability and enhance electrolyte contact, while maintaining the dimension of the composite materials in the electrochromic devices, which in turn give excellent electrochromic performance.

Further advantageously, the polymer matrix may be formed by reaction of alkene with reactive groups which allows the polymer matrix to be formed via in-situ polymerization. This greatly enhances its processability and facilitates its translation into industrial settings, offering controllability over the manufacturing process.

Claims

1. A composite material comprising:

   an ionic liquid A, wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI); and

   a polymer matrix comprising a network of crosslinked poly(ionic liquid B), wherein the polymer matrix is formed by reaction of an ionic liquid B with a crosslinking agent, wherein the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).

2. The composite material of claim 1, wherein the polymer matrix is formed by reaction of an alkene of ionic liquid B with an acrylate of the crosslinking agent.

3. The composite material of claim 1 or 2, further comprising a metal borate complex.

4. The composite material of claim 3, wherein

   the metal borate complex is lithium methacrylate trifluoroborate complex in propylene carbonate.

5. The composite material of any one of claims 1 to 4, wherein the composite material is an ionogel.

6. The composite material of any one of claims 1 to 5, wherein the composite material has a transmittance of about 90% to about 98% at 1 mm thickness.

7. The composite material of any one of claims 1 to 6, where the composite material has a crosslink density of about 0.02 mol/g to about 0.05 mol/g, or 0.035 mol/cm^3 to about 0.06 mol/cm^3.

8. A method of preparing a composite material of any one of claims 1 to 7, comprising the steps of:

   (i) preparing a mixture of ionic liquid A, ionic liquid B, crosslinking agent, and a photoinitiator; and

   (ii) curing the mixture with light irradiation,

   wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B); and

   wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI), the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).

9. The method of claim 8, wherein step (i) further comprises adding a metal borate complex.

10. The method of claim 8 or 9, wherein step (ii) is performed for a duration of about 30 seconds to about 90 seconds.

11. The method of any one of claims 8 to 10 , wherein the photoinitiator is selected from the group consisting of diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO), benzophenone, phenyl bis (2,4,6-trimethylbenzoyl)phosphine oxide, 2-hydroxy-2-methyl-1-phenyl-propan-1-one, 2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone, 2,2'-azobis[2-methyl-n-(2-hydroxyethyl)propionamide], 2,2-dimethoxy-2-phenylacetophenone, lithium phenyl(2,4,6-trimethylbenzoyl)phosphinate), and ethyl (2,4,6-trimethylbenzoyl) phenylphosphinate.

12. An electrochromic device comprising an electrolyte sandwiched between two electrodes, wherein the electrolyte comprises the composite material of any one of claims 1 to 7.

13. A method of forming an electrochromic device comprising:

(i) applying a mixture of ionic liquid A, ionic liquid B, crosslinking agent, a photoinitiator, and optionally a metal borate complex between two electrodes; and

(ii) curing the mixture with light irradiation,

wherein the crosslinking agent reacts with ionic liquid B to form a polymer matrix comprising a network of crosslinked poly(ionic liquid B); and

wherein the ionic liquid A is 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (EMIMTFSI), the ionic liquid B is 1-butyl-3-vinylimidazolium bis(trifluoromethanesulfonyl) imide (BVIMTFSI), and the crosslinking agent is poly(ethylene glycol) diacrylate (PEGDA).