

ELECTRICALLY CONDUCTIVE POLYMERS



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Field of the invention

The present invention relates to a method of preparing electrically conductive polymeric material by treatment with a viologen salt and to electrically conductive polymeric articles formed thereby.

Description of related art

In recent years electrically conductive polymers have been widely studied because of their potential important commercial applications. Such polymers include polypyrrole and its derivatives and polyaniline and its derivatives.

The aniline family of polymers is an example of one of the most widely studied electroactive polymers because of the ease of synthesis and the unusual nature of its electrical conductivity which can be varied over a wide range. Polyaniline (PANi) in its insulating base form is readily soluble in N-methylpyrrolidinone and can be cast into films or coated on different substrates. The insulating form can be converted to the conductive form by the following methods:

(1) Treatment with protonic acids

PANi in the emeraldine (50% oxidated) base state when treated with protonic acids shows an increase in electrical conductivity. The resulting conductivity is a strong function of the pH of the equilibrating solution. For example, when aqueous HCl is used at pH greater than 4, the PANi remains as the essentially insulating non-protonated form whereas at pH~0 (i.e. with 1 M HCl), the conductivity increases by 10 orders of magnitude (J. C. Chiang and A. G. MacDiarmid, *Synth. Met.* 13, 193 (1986)). In the latter case, the imine units of the PANi are protonated to give a N⁺/N ratio of about 0.5. In this form of doping, there is no change in the number of electrons in the PANi chains.

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The electrical conductivity of the PANi treated with protonic acids depends not only on the pH of the equilibrating solution but also on the oxidation states of the PANi. For example, PANi in the leucoemeraldine (100% reduced) state shows only a small increase in conductivity when treated with protonic acids (J. C. Chiang and A. G. MacDiarmid, *Synth. Met.* 13, 193 (1986)).

(2) Charge transfer interaction with organic electron acceptors

PANi in the emeraldine base state can undergo charge transfer interaction with organic electron acceptors such as tetrachloro-o-benzoquinone and 2,3-dichloro-5,6-dicyano-p-benzoquinone in acetonitrile (S. H. Khor, K. G. Neoh and E. T. Kang, *J. Appl. Polym. Sci.* 40, 2015 (1990)). An increase in electrical conductivity is achieved and the magnitude of the conductivity is dependent on the type of organic acceptors and acceptor concentration. The charge transfer interaction of emeraldine base with the organic electron acceptor is analogous to that of protonation by HCl, with the hydrogen atoms in the latter replaced by the partially dehalogenated halobenquinone rings. The maximum conductivity achieved is at least an order of magnitude lower than that achievable in protonic acid doping of emeraldine base.

PANi in the leucoemeraldine state undergoes oxidative doping by organic electron acceptors in acetonitrile solution which involves first the oxidation of the amine nitrogen and also the formation of the imine structure through hydrogen transfer from the amine nitrogen to the acceptor. The so-produced imine nitrogen is then in turn doped by the acceptor, as described above for PANi in the emeraldine state (E. T. Kang, K. G. Neoh, T. C. Tan, S. H. Khor, and K. L. Tan, *Macromolecules.* 23, 2918 (1990)). The maximum electrical conductivity obtained is also about an order of magnitude lower than that obtained from protonic acid doping of emeraldine.

It would be a significant advance in the art if a method of preparing an electrically conductive polyaniline material could be provided which would function irrespective of the oxidation state of the polyaniline. The polyaniline base material may be a substituted or unsubstituted polyaniline. It would be a further significant

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advance in the art if a method could be provided which did not involve the use of acid or organic solvents such as acetonitrile.

It is accordingly an object of the present invention to overcome, or at least alleviate, one or more of the difficulties and deficiencies related to the prior art.

5 Summary of the invention

Accordingly, in a first aspect of the present invention there is provided an electrically conductive polymeric article including a polymeric material capable of exhibiting electrical conductivity;

10 the polymeric material being rendered electrically conductive by treatment with a viologen salt.

It has surprisingly been found that the electrically conductive polymeric article according to this aspect of the present invention exhibits a high level of electrical conductivity. For example, electrically conductive polyaniline may be prepared with resistances (R_s) decreasing from approximately 10^{10} to
15 approximately $10^6 \Omega/\text{sq}$ or below, irrespective of the oxidation state of the polyaniline material. Polyaniline material may be in the leucoemeraldine (0% oxidation state) or emeraldine (50% oxidation state) states or in any oxidation state between these two states.

20 Examples of polymeric materials capable of being rendered electrically conductive by treatment with a viologen include polymers derived from aromatic bases such as aniline and its derivatives and from heterocyclic bases such as pyrrole and its derivatives.

Prepared polymeric materials for inclusion in the polymeric articles of the invention include polyaniline and its derivatives and polypyrrole and its derivatives.
25 Polyaniline and polypyrrole are particularly preferred polymeric materials.

The electrically conductive polymeric material may be formed in any suitable manner and may take any suitable shape. The polymeric may be in the

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form of a film, e.g. a free standing film, a film coating, e.g. a thin film coating, or a powder.

5 In a preferred aspect the polymeric material may be deposited or supported on a suitable substrate. The substrate may be a fabric, polymeric matrix film or other construct. A polyethylene substrate, e.g. a low density polyethylene (LDPE) substrate may be used.

The viologen salt utilised to dope the polymeric material may be of any suitable type. Viologen salts such as a dihalide salt of a viologen (1,1'-disubstituted 4,4'-bipyridinium dihalide) have been found to be particularly suitable.

10 The substituents on the bipyridinium molecule may be selected from alkyl or aryl groups. The alkyl groups may be substituted or unsubstituted C1 to C4 alkyl groups. The alkyl groups may be straight or branched chains. Substituents for the alkyl groups may be selected from a wide range of substituents including halogen, phenyl and substituted phenyl. Examples of preferred alkyl groups include methyl, ethyl, propyl, butyl and phenylmethyl (benzyl). The aryl groups may be substituted or unsubstituted aryl or heteroaryl.

Viologen salts may be provided as free compounds, shown below as I, or in the form of polymers, shown below as II, where:

20 R and R¹ are independently chosen from alkyl or aryl groups as indicated above;

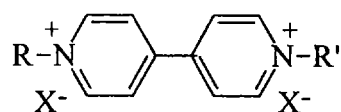
R² is an alkylene group, preferably a C₂ to C₄ alkylene group;

X⁻ is an anion, preferably a halide ion; and

n is an integer greater than or equal to 2.

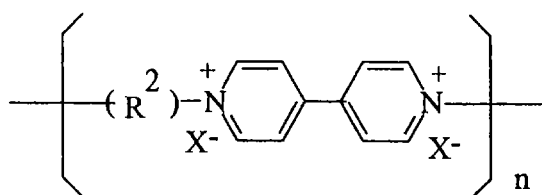
25 Particularly preferred viologens include ethyl viologen dichloride, benzyl viologen dichloride and poly(butyl viologen dibromide).

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(I)

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(II)

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In a preferred aspect of the present invention the polymeric material may be directly treated with a viologen to render it electrically conductive.

Accordingly, in a preferred aspect of the present invention there is provided a method of preparing an electrically conductive polymeric article, which method includes providing

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a polymeric material capable of exhibiting electrical conductivity; and
a viologen;

contacting a surface of the polymeric material with the viologen for a time sufficient to permit the polymeric material to be rendered electrically conductive.

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Although not wishing to be bound by theory it is believed that when the polymeric material is treated with a viologen salt that the polymeric material undergoes oxidative doping and the halide anions are incorporated into the polymer. Surprisingly the method may be conducted at or above room temperature in the presence of air and preferably utilising an aqueous solution of the viologen salt. Thus the use of protonic acids or organic solvents may be avoided.

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The rate of the reaction is dependent on the ease of the reduction of the viologen, e.g. a viologen dication, and the transfer of the anions to the polymeric

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material to form a doped and conductive form of the polymeric material.

Pursuant to the present invention, the reactions may be carried out by contacting the surface of the polymeric material with an aqueous solution of viologen salt. The reactions may continue for a time sufficient to permit a
5 substantial degree of oxidative doping of the polymeric material to be achieved.

The viologen salt may be selected from any suitable materials as discussed above. A viologen dihalide is preferred.

The method of contacting the surfaces of the polymeric material with the viologen may vary widely, depending on the state of the polymeric material and
10 the method selected for the reactions. One simple and preferred method involves immersing the polymeric material in an aqueous solution of the viologen salt, preferably a viologen dihalide, more preferably in excess, with proper agitation. The preferred concentration of the solution is between 0.01 M and 0.5 M.

The method may be conducted at any suitable temperature, e.g. at a
15 temperature between 0° and approximately 100°C. The method may be conducted in the presence of air and under ordinary room lighting.

The method may be carried out for a period of time which is dependent on the form of the polymeric material (coating, thick film or powder), type of viologen salt and concentration. For example, for a thin PANi coating and a monomeric
20 viologen dichloride at a concentration of 0.1 M, the reaction is rapid and the film turns conductive within 5 mins. For thick PANi films, and using a similar viologen type and concentration, the period of the experiment is extended to 1 day to ensure completion.

After completion of the reaction, the polymeric material may, for example,
25 be blotted dry between filter paper to remove the unreacted viologen salt. The change of the PANi from the insulating base state (brown and blue for emeraldine freestanding film and coating, respectively) to the conductive state (blue and green for freestanding film and coating, respectively) is visually apparent, and may be

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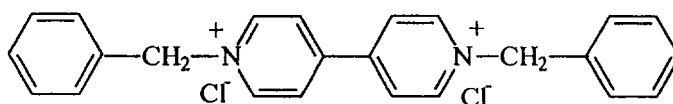
confirmed by sheet resistance (R_s) measurement, X-ray photoelectron spectroscopy or UV-visible absorption spectroscopy. Figure 1 shows the sheet resistance (R_s in $\Omega/\text{sq.}$) of emeraldine base free standing film treated in 0.24 M benzylviologen dichloride. Figure 2 shows the UV-visible absorption spectra of PANi coating on LDPE film treated in 0.024 M polybutylviologen dibromide.

EXAMPLES

The following specific examples are provided to illustrate this invention and the manner in which it may be carried out. It will be understood, however, that the specific details given in each example have been selected for the purpose of illustration, and are not to be construed as being limitations on the scope of the invention.

EXAMPLE 1

Polyaniline (in the emeraldine or 50% oxidation state) was synthesized via the oxidative polymerization of aniline using ammonium persulfate in 0.5 M H_2SO_4 (A.G. MacDiarmid et al. *Synth. Met.* 18, 285 (1987)). The polyaniline powder was undoped using excess 0.5 M NaOH and the polyaniline (emeraldine) base powder was dissolved in N-methyl pyrrolidinone (NMP). Freestanding film of 10-20 μm was cast from the polyaniline base (8% wt) in NMP solution. This film was immersed in a 0.24 M solution of benzyl viologen dichloride



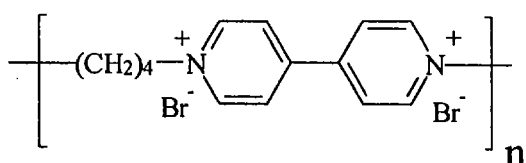
in water. The pH of the solution was between 5 and 6 and the experiment was carried out at 25 °C in an open test tube. A sharp decrease in R_s was observed within the first hour. The change in R_s with time of treatment is shown in Figure 1.

The doping level as given by the N^+/N ratio obtained is 0.4 after 24 h.

EXAMPLE 2

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A coating of polyaniline (in the emeraldine state) on low density polyethylene (LDPE) substrate was prepared by immersing a O₂ plasma pretreated LDPE film into a reaction mixture containing 0.10 M aniline and 0.025 M ammonium persulfate in 0.5 M H₂SO₄ for 2 h. The green polyaniline coated LDPE film was undoped in 0.5 M NaOH for 2 h and then washed with deionized water and pumped dry under reduced pressure. The base film was immersed in a 0.024 M poly(butylviologen dibromide)



solution in water under ordinary room lighting. The change in the UV-visible absorption spectrum from that of emeraldine base to a conductive salt is illustrated in Figure 2.

EXAMPLE 3

Polyaniline freestanding (emeraldine) base film was synthesized as described in Example 1. Leucoemeraldine was prepared by treating the emeraldine base film with 10% hydrazine for 48 h. After treatment of the leucoemeraldine film (pale brown) with 0.12 M benzyl viologen dichloride at 25 °C and under ordinary room lighting for 24 h, the film has turned blue and R_s decreased from 10¹⁰ to 6×10⁵ Ω/sq.

EXAMPLE 4

Polyaniline freestanding (emeraldine) base film was synthesized as described in Example 1. Treatment of the film with 0.12 M benzyl viologen dichloride at 5 °C was carried out for 24 h under ordinary room lighting. The R_s obtained was 3×10⁵ Ω/sq.

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EXAMPLE 5

Polyaniline freestanding (emeraldine) base film was synthesized as described in Example 1. Treatment of the film with 0.12 M benzyl viologen dichloride at 25 °C was carried out for 24 h in the absence of light. The Rs
5 obtained was $4 \times 10^5 \Omega/\text{sq}$.

EXAMPLE 6

Polypyrrole (PPY) freestanding film was electrochemically synthesized in a one-compartment cell with 0.1 M pyrrole, 0.1 M p-toluenesulfonic acid in acetonitrile containing 1% v/v water. The film was grown with a charge density of
10 10 Coulomb cm^{-2} at 0~5° C (X. Zhang, E. T. Kang, K. G. Neoh, K. L. Tan, D. Y. Kim and C. Y. Kim, *J. Appl. Polym. Sci.* 60, 1996, 625). The PPY film was then undoped by treatment in 0.5M NaOH for 24h. This dried PPY film was immersed in 0.24 M aqueous solution of benzyl viologen dichloride for 24h at 25°C under ordinary room lighting. The film turned dark blue and Rs decreased from 10^7 to 10^4
15 Ω/sq .

Finally, it is to be understood that various alterations, modifications and/or additions may be made without departing from the spirit of the present invention as outlined herein.

CLAIMS

1. An electrically conductive polymeric article comprising a polymeric material comprising aromatic bases and/or heterocyclic bases,
said material being rendered electrically conductive by treatment with a viologen salt.

2. The electrically conductive polymeric article according to claim 1 wherein the polymeric material comprises polyaniline and/or a derivative of polyaniline.

3. The electrically conductive polymeric article according to claim 1 wherein the polymeric material comprises polypyrrole and/or a derivative of polypyrrole.

4. The electrically conductive polymeric article according to claim 2 wherein the polymeric material is polyaniline.

5. The electrically conductive polymeric article according to claim 3 wherein the polymeric material is polypyrrole.

6. The electrically conductive polymeric article according to Claim 4, wherein the polyaniline has an oxidation state between 0% and 50% oxidized.

7. The electrically conductive polymeric article according to Claim 1, wherein the polymeric material is in the form of a film, film coating, or powder.

8. The electrically conductive polymeric article according to Claim 7, wherein the polymeric material is deposited on a suitable substrate.

9. The electrically conductive polymeric article according to Claim 1, wherein the viologen salt is a viologen dihalide.

10. The electrically conductive polymeric article according to claim 9

wherein in the viologen dihalide the substituents on the bipyridinium are selected from the group consisting of substituted alkyl groups, unsubstituted alkyl groups, substituted aryl groups and unsubstituted aryl groups.

11. The electrically conductive polymeric article according to claim 10 wherein the substituted and unsubstituted alkyl groups are C1 to C4 alkyl groups optionally substituted with at least one halogen, aryl or substituted aryl group.

12. The electrically conductive polymeric article according to claim 11 wherein the substituted and unsubstituted alkyl groups are chosen from C1 to C4 alkyl and benzyl.

13. The electrically conductive polymeric article according to claim 9 wherein the halide ions of the viologen dihalide are selected from the group consisting of chloride, bromide and iodide ions.

14. The electrically conductive polymeric article according to Claim 1, wherein the viologen salt is present in a monomeric form.

15. The electrically conductive polymeric article according to Claim 1, wherein the viologen salt is present in a polymeric form.

16. The electrically conductive polymeric article according to Claim 9, wherein the viologen dihalide is benzyl viologen dichloride, poly(butylviologen dibromide) or a mixture thereof.

17. The electrically conductive polymeric article according to Claim 4, wherein the resistance of the polymeric material, R_s , is $10^6 \Omega/\text{sq}$ or less.

18. A method of preparing an electrically conductive polymeric article, which method comprises:

i) providing a polymeric material comprising aromatic bases and/or heterocyclic bases and capable of exhibiting electrical conductivity and a viologen salt; and

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ii) contacting a surface of the polymeric material with the viologen salt for a time sufficient to permit the polymeric material to be rendered electrically conductive.

19. The method according to Claim 18, wherein the polymeric material is a polyaniline which has an oxidation state between 0% and 50% oxidized.

20. The method according to claim 18 wherein the polymeric material is a polypyrrole.

21. The method according to Claim 18, wherein the viologen salt is a viologen dihalide.

22. The method according to Claim 21, wherein the viologen salt is selected from viologen benzyl dichloride, poly(butylviologen dibromide) or a mixture thereof.

23. The method according to Claim 21, wherein the viologen salt is present in the form of an aqueous solution.

24. The method according to Claim 23, wherein the method is conducted at a temperature of approximately 0°C to approximately 100°C in the presence of air.

25. An electrically conductive polymeric article prepared according to the method according to Claim 18.