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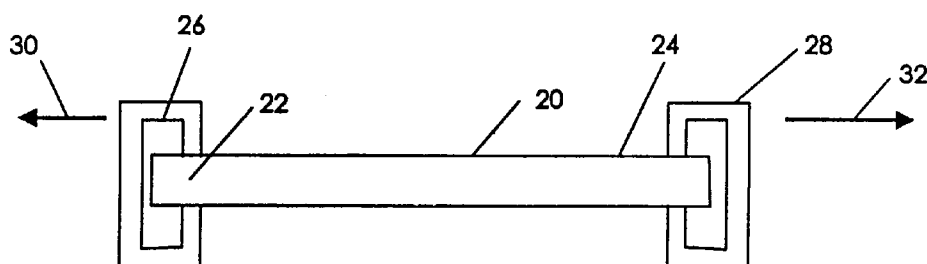
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(54) Deaggregated electrically conductive polymers and precursors thereof

(57) Deaggregated substituted and unsubstituted polyparaphenylenes, polyparaphenylevinylenes, polyanilines, polyazines, polythiophenes, poly-p-phenylene sulfides, polyfuranes, polypyrroles, polyselenophene, polyacetylenes formed from soluble precursors and combinations thereof and copolymers thereof and methods of fabrication are described. The deaggregated pol-

ymers when subsequently doped show higher electrical conductivity. Agents such as lithium chloride, m-cresol and nonylphenol are used to deaggregate the polymer molecules. The deaggregating agents can be added prior to or during doping the molecules.

FIG. 21



Description

CROSS REFERENCE TO RELATED APPLICATION

5 The teaching of U.S. Application Serial No. 08/370,128 entitled "Methods of Fabrication of Deaggregated Electrically Conductive Polymers and Precursors Thereof" to M. Angelopoulos and B. Furman, filed on the same day herewith is incorporated herein by reference.

FIELD OF THE INVENTION

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The present invention is directed to methods of fabrication of electrically conducting polymers having enhanced electrical conductivity. In particular, the present invention is directed to methods to deaggregate electrically conductive polymers and precursors thereof.

15 BACKGROUND OF THE INVENTION

Electrically conductive organic polymers have been of scientific and technological interest since the late 1970's. These relatively new materials exhibit the electronic and magnetic properties characteristic of metals while retaining the physical and mechanical properties associated with conventional organic polymers. Herein we describe electrically con-
 20 ducting polyparaphenylene vinylenes, polyparaphenylenes, polyanilines, polythiophenes, polyazines, polyfuranes, polypyrroles, polyselenophenes, poly-p-phenylene sulfides, polyacetylenes formed from soluble precursors, combinations thereof and blends thereof with other polymers and copolymers of the monomers thereof. In order for these materials to be used in place of metals in more applications, it is desirable to increase the conductivity of these materials. The article "The Concept of Secondary Doping as Applied to Polyaniline", A.G. MacDiarmid, A.J. Epstein, Synthetic Metals,
 25 65 (1994), 103-116, describes increasing the electrical conductivity of a polyaniline by exposing a doped polyaniline to a secondary dopant, such as metacresol. MacDiarmid et al. teaches that the secondary dopant results in an intra-molecular conformational change in the polyaniline molecule. Prior to being exposed to the secondary dopant, the doped polyaniline molecule is in a compact coil intra-molecular conformation. Intra-molecular conformation refers to the conformation of a single molecule or a single polymer chain in which the molecular chain is coiled around itself. In contra-
 30 distinction inter-molecular structure refers to the structural arrangement of more than one molecule or polymer chain in which the molecules or chains are bonded together or coiled around each other forming aggregates. These aggregates are then comprised of many polymer chains intertwined or entangled. MacDiarmid et al. teaches that the secondary dopant causes a intra-molecular conformational change, i.e., the molecule or the chain unravels and assumes an expanded coil conformation. A film of this expanded coil polyaniline has enhanced electrical conductivity because of an increase in the crystallinity of the material formed from the aggregated straightened molecules. In the article "Transport
 35 studies of protonated emeraldine powder: A granular polymeric metal system", F. Zuo et al., Phys. Rev. B 36, 3475 (1987) it has been reported that the polyaniline which has been doped has electrically conductive regions or islands which are of the order of 20-30 nm (200-300Å). The spaces between these regions are significantly less electrically conductive. When an electrical current flows along the polyaniline molecules, current flows through the electrically con-
 40 ductive regions and hops over the less electrically conductive region to an adjacent electrically conductive region.

It is an object of the present invention to increase the electrical conductivity of electrically conductive polymers.

It is another object of the present invention to enhance the electrical conductivity of an electrically conductive polymer by deaggregating aggregated molecules which are precursors of the electrically conducting polymers so that the mol-
 ecules can be more uniformly doped.

45 It is another object of the present invention to deaggregate polymer molecules prior to being doped to the electrically conducting state.

It is another object of the present invention to lower the glass transition temperature of the precursor to an electrically conductive polymer and of an electrically conductive polymer by the addition of deaggregating agents.

50 It is another object of the present invention to increase the electrical conductivity of electrically conductive polymers by extending the electrically conductive regions or islands of the electrically conductive polymer.

It is another object of the present invention to further increase the electrical conductivity of a deaggregated electrically conductive polymer by stretch orientation.

It is another object of the present invention to increase the shelf-life of a precursor to an electrically conductive polymer and of an electrically conductive polymer by the addition of deaggregating agents.

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SUMMARY OF THE INVENTION

A broad aspect of the present invention is an electrically conductive polymer having electrically conductive regions having a dimension greater than about 300Å.

Another broad aspect of the present invention is a precursor to an electrically conductive polymer containing a deaggregating agent, such as a complexing agent. In a more particular aspect of the present invention, the dimension of the electrically conductive regions are enhanced by a deaggregating agent.

Another broad aspect of the present invention is a body of material containing precursor molecules to electrically conductive molecules wherein the body of material has regions of aggregated precursor molecules of less than about 100 nm.

Another broad aspect of the present invention is a method for fabricating electrically conducting polymers, the electrical conductivity of which is enhanced by deaggregating the polymer either prior to being doped to the electrically conducting state or after being doped to the electrically conducting state.

A more specific aspect of a method of the present invention is deaggregating the precursor polymer or electrically conducting polymer either in solution or in the solid state, such as by using complexing agents.

Another more specific aspect of a method of the present invention includes steps of providing a first admixture of an additive in a solvent; forming a second admixture by dissolving in the first admixture precursor polymers to electrically conducting polymers wherein the additive deaggregates the precursor molecules and either adding a dopant to the second admixture to dope the precursor to the electrically conductive polymer or forming a film of the second admixture and then doping the film in the solid state.

Another more specific aspect of a method of the present invention includes providing aniline molecules which are oxidatively polymerized in an acid solution in the presence of a deaggregating agent to result in a deaggregated polyaniline. Another more specific aspect of a method of the present invention includes the steps of providing aniline molecules which are oxidatively polymerized in an acid solution to form an electrically conducting polyaniline salt which is then neutralized to the base non-doped form and deaggregated upon exposure to a deaggregating agent.

Another more specific aspect of a method according to the present invention includes neutralizing a polyaniline salt to the base form in the presence of a deaggregating agent.

Another broad aspect of the present invention is a method of causing a doped electrically conductive polymer in a compact coil conformation to undergo a conformational change from a compact coil to an expanded coil conformation by exposing the doped polymer to salts and surfactants.

BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features, and advantages of the present invention will become apparent from a consideration of the following detailed description of the invention when read in conjunction with the drawing FIGs., in which:

Fig. 1 is a gel permeation chromatograph (GPC) plot of polyaniline base in NMP which shows a bimodal distribution: a very high molecular weight component which is aggregated polyaniline molecules and a lower molecular weight peak.

Fig. 2 shows a GPC plot of polyaniline base in NMP and 0.5 wt % lithium chloride which shows that the high molecular weight peak of Fig. 1 has been eliminated and the molecular weight of the other peak is actually higher.

Fig. 3 is a general formula for a polyaniline.

Fig. 4.1 is a general formula for a doped polyaniline.

Fig. 4.2 is a general formula for the polysemiquinone radical cation form of doped polyaniline.

Fig. 5 is a Dynamic Mechanical Thermal Analysis (DMTA) plot of polyaniline base film cast from 100% NMP. (First Run; ~ 21% NMP remaining in film; under N_2 ; $2^\circ C/min$)

Fig. 6 is the DMTA plot (2nd run) of the same polyaniline film as shown in Fig. 5. This film has 0% NMP remaining in the film. The T_g is $251^\circ C$.

Fig. 7 is a DMTA plot (2nd run) of polyaniline base which has been cast from 100% NMP doped with 1N HCl and undoped with 0.1 M NH_4OH showing a T_g of $256^\circ C$. This film has ~ 2.8% NMP remaining in the film.

Fig. 8 is a DMTA plot (2nd run) of polyaniline cast from NMP/.5 wt % LiCl showing a T_g of $180^\circ C$.

Fig. 9 shows inter-molecular hydrogen bonding between undoped polyaniline molecules.

Fig. 10 shows disruption of the intermolecular hydrogen bonding by a LiCl salt.

Fig. 11 shows a schematic view of polyaniline molecules aggregated through inter-molecular hydrogen bonding.

Fig. 12 shows a UV/VIS/near IR spectrum of polyaniline doped with an organic sulfonic acid in NMP showing a localized polaron peak.

Fig. 13 shows the same plot as Fig. 12 but with 0.5 wt% LiCl added to the initial NMP solution from which the doped polyaniline was cast and shows a delocalization of the polaron peak.

Fig. 14 shows the same plot as in Fig. 12, but with 1 wt% LiCl added to the initial NMP solution from which the doped polyaniline was cast and shows a significantly delocalized polaron peak.

Fig. 15 is an atomic force micrograph of a polyaniline film cast from 100% NMP showing clusters or bundles of polyaniline molecules of about 100 nm in size which are interpreted as aggregated regions.

Fig. 16 is an atomic force micrograph of polyaniline film cast from NMP and subsequently exposed to m-cresol.

Fig. 17 is an atomic force micrograph of the same material shown in Fig. 16 with the m-cresol pumped out.

Fig. 18 is an atomic force micrograph of a polyaniline film cast from NMP and treated with 0.5 wt% nonylphenol showing deaggregation.

Fig. 19 is an atomic force micrograph of a polyaniline film cast from NMP and treated with 0.5 wt% triton showing deaggregation.

Fig. 20 is an atomic force micrograph of a polyaniline film cast from NMP and treated with 1.0 wt% nonylphenol showing more deaggregation than shown in Fig. 19.

Fig. 21 schematically shows stretch orientation of a film to enhance electrical conductivity.

DETAILED DESCRIPTION

The present invention is directed to enhancing the electrical conductivity of polymer materials, which when doped, are electrically conducting. Examples of polymers which can be used to practice the present invention are of substituted and unsubstituted polyparaphenylenes, polyparaphenylenevinyls, polyanilines, polyazines, polythiophenes, poly-p-phenylene sulfides, polyfurans, polypyrroles, polyselenophenes, polyacetylenes formed from soluble precursors and combinations thereof and copolymers of monomers thereof.

The general formula for these polymers can be found in U.S. Patent 5,198,153 to Angelopoulos et al. The present invention will be described with reference to one type of polymer which is a substituted or unsubstituted polyaniline or copolymers of polyaniline having general formula shown in Fig. 3 wherein each R can be H or any organic or inorganic radical; each R can be the same or different; wherein each R¹ can be H or any organic or inorganic radical, each R¹ can be the same or different; $x \geq 1$; preferably $x \geq 2$ and y has a value from 0 to 1. Examples of organic radicals are alkyl or aryl radicals. Examples of inorganic radicals are Si and Ge. This list is exemplary only and not limiting. The most preferred embodiment is emeraldine base form of the polyaniline wherein y has a value of approximately 0.5.

In Fig. 4.1 polyaniline is shown doped with a dopant. If the polyaniline base is exposed to cationic species QA, the nitrogen atoms of the imine part of the polymer becomes substituted with the Q⁺ cation to form an emeraldine salt as shown in Fig. 4.1. Q⁺ can be selected from H⁺ and organic or inorganic cations, for example, an alkyl group or a metal. QA can be a protic acid where Q is hydrogen. When a protic acid HA is used to dope the polyaniline, the nitrogen atoms of the imine part of the polyaniline are protonated. The emeraldine base form is greatly stabilized by resonance effects. The charges distribute through the nitrogen atoms and aromatic rings making the imine and amine nitrogens indistinguishable. The actual structure of the doped form is a delocalized polysemiquinone radical cation as shown in Fig. 4.2.

The emeraldine base form of polyaniline is soluble in various organic solvents and in various aqueous acid solutions. Examples of organic solvents are dimethylsulfoxide (DMSO), dimethylformamide (DMF) and N-methylpyrrolidinone (NMP). This list is exemplary only and not limiting. Examples of aqueous acid solutions is 80% acetic acid and 60-88% formic acid. This list is exemplary only and not limiting.

Although the present invention is described in terms of polyaniline, it is not limited thereto. Fig. 1 shows a GPC (gel permeation chromatograph) of polyaniline in the base form dissolved in 100% solvent N-methylpyrrolidinone (NMP). The vertical axis is the ultraviolet visible (UV VIS) detector response and the horizontal axis is the peak retention time in minutes. Two peaks are evident in Fig. 1, peak 2 which corresponds to a weight average molecular weight of approximately 371,700 and peak 4 which corresponds to a weight average molecular weight of approximately 29,500.

Fig. 2 shows the GPC of polyaniline in the base form in NMP/.5 wt % lithium chloride (LiCl) which shows a single peak 6 corresponding to a weight average molecular weight of approximately 45,500. It is evident in comparing Fig. 1 to Fig. 2 that the high molecular weight peak 2 of Fig. 1 has disappeared and that the molecular weight of the major peak is higher than that in NMP, corresponding to a higher hydrodynamic volume. Fig. 5 is a plot of a first run of a dynamic mechanical thermal analysis (DMTA) plot of an undoped polyaniline base film cast from 100% NMP. The as-cast film contains approximately 21% NMP which is determined from thermo gravimetric analysis. The dashed line in Fig. 5 which is the plot of $\tan(\delta)$ shows several transitions of which some are related to the residual solvent.

Fig. 6 shows a plot of a DMTA (second run) of the same material as for Fig. 5. The solvent is substantially driven off in the first run. The single peak of the dashed curve which corresponds to the $\tan(\delta)$ measurement shows that the polyaniline base has a glass transition temperature (T_g) of 251°C.

Fig. 7 shows a plot of a DMTA (second run) for polyaniline base, cast from 100 wt% NMP, which has been doped in 1N HCl and subsequently undoped with .1M NH_4OH . Most of the NMP was removed in the process. It has been determined from thermogravimetric analysis (TGA) that there is only 2.8% NMP remaining in the film. The glass transition temperature of this sample is 256°C, relatively the same as that measured for the sample of Fig. 6.

Fig. 8 shows a plot of a DMTA (second run) of polyaniline base cast from 99.5 wt% NMP/.5 wt% lithium chloride. The peak in the $\tan(\delta)$ curve gives a T_g of 180°C. Table I summarizes the results of Figs. 5-8 and also gives additional results for films cast from combinations of NMP and m-cresol and a surfactant nonylphenol.

TABLE I

Material	History	Tg from DMTA (°C)
Polyaniline Base Cast from 100%NMP	Thermally annealed* (0% residual NMP in film)	251
Polyaniline Base cast from 100% NMP	Doped with HCL undoped in ammonia (2.8% residual NMP in film)	256
Polyaniline Base cast from 90 wt % NMP/10 wt % m-cresol	Thermally annealed*	186
Polyaniline Base cast from 75 wt % NMP/25 wt % m-cresol	Thermally annealed*	175
Polyaniline Base cast from 99.5 wt % NMP/0.5 wt % LiCL	Thermally annealed*	180°C
Polyaniline Base cast from 99 wt % NMP/1 wt % nonylphenol	Thermally annealed*	222°C

*Thermally annealed - scanned to 350°C under N_2 at 2°C/min

The drop in glass transition temperature of the polyaniline base upon exposure to an additive such as m-cresol, LiCl and nonylphenol indicates that there is a drop in the crosslink density of the polyaniline base material as a result of deaggregation of the polyaniline base molecules. While applicant's do not want to be limited to a particular theory, this cross-link is believed to be in the form of inter-chain or intermolecular hydrogen bonding.

Fig. 9 shows two polyaniline base molecules wherein a hydrogen atom from an amine site on one molecule is hydrogen bonded as represented by the dashed line to an imine nitrogen on an adjacent molecule. Fig. 10 shows the effect of adding lithium chloride to the arrangement shown in Fig. 9.

The lithium chloride can complex with the imine nitrogen lone pairs as shown in the Fig. 10 thereby disrupting the interchain hydrogen bonding between polyaniline chains.

Fig. 11 is a schematic diagram showing three polyaniline molecules 20, 22 and 24 wherein there are a plurality of hydrogen bonds 26 interlocking each of the three polyaniline molecules shown.

It is evident from Fig. 11 that where there is a high density of hydrogen bonding between adjacent polyaniline molecules, there is effective crosslinking between the molecules which will affect the glass transition temperature of a polyaniline material. (Generally the glass transition temperature increases as the cross-linking density increases.) The high degree of crosslink density will result in a significant degree of aggregation of polyaniline molecules. The atomic force micrograph (AFM)(Fig. 15) of the polyaniline film processed from 100% NMP shows "clusters" or "bundles" on the order of 100 nm. This structure agrees well with previous results on evaporated films (no solvent) by T.L. Porter et al., Surface Science, 293, 81 (1993). When the hydrogen bonded and unravelled molecules of Fig. 11 are exposed to a deaggregating agent such as LiCl, an inter-molecular structural change occurs wherein the molecules are no longer hydrogen bonded and the molecules are unravelled and deaggregated.

The present results together with the previous results by Porter indicate that polyaniline in the solid-state is highly aggregated. (Examples of solid state forms of polymers are powders and films.) When the polyaniline is then dissolved in NMP, the NMP does not appreciably solvate the polyaniline to disrupt the interchain interactions of the polyaniline and the material remains aggregated. When the polyaniline molecules are exposed to a dopant, this high degree of aggregation will prevent the dopant from being able to dope all regions of the polyaniline molecules uniformly and may be responsible for the formation of the metallic islands characteristic of conducting polyaniline (described above) which are approximately 20-30 nm (200-300 Å).

This will result in less than an optimal conductivity for a doped polyaniline material. If the aggregated polyaniline molecules are deaggregated by the methods according to the present invention, the polyaniline molecules will be more effectively doped when contacted with a dopant. In this fashion the size of the metallic islands may in turn be increased above 20-30 nm (200-300 Å) thereby enhancing the mobility of the carriers, and in turn the electrical conductivity. It may be possible to ultimately eliminate the formation of islands by more uniform doping; in this fashion the material would be more homogeneous and hopping through less conducting regions to go from metallic island to metallic island would thereby be eliminated. An exemplary list of solvents useful to practice the present invention is:

List of Solvents:

N-methyl pyrrolidinone (NMP)
 dimethyl sulfoxide (DMSO)
 dimethyl formamide (DMF)
 pyridine
 toluene
 xylene
 m-cresol
 phenol
 dimethylacetamide
 tetramethylurea
 n-cyclohexylpyrrolidinone
 aqueous acetic acid
 aqueous formic acid
 pyrrolidinone
 N,N'-dimethyl propylene urea (DMPU)
 benzyl alcohol
 water

An exemplary list of salts which can be used as a deaggregation agent or additive is:

Salts:

lithium chloride
 lithium bromide
 lithium iodide
 lithium fluoride
 lithium tetrafluoroborate
 lithium hexafluorophosphate
 lithium perchlorate
 lithium phenoxide
 lithium triflate
 lithium niobate
 magnesium bromide
 magnesium chloride
 magnesium ethoxide
 magnesium fluoride
 magnesium sulfate
 magnesium perchlorate
 magnesium nitrate
 sodium bromide
 sodium chloride
 sodium chlorate
 sodium hexafluorophosphate

potassium bromide
 potassium chlorate
 potassium chloride
 potassium fluoride
 5 potassium hexafluorophosphate
 rubidium chloride
 rubidium fluoride
 rubidium nitrate
 cesium bromide
 10 cesium chloride
 cesium fluoride
 cesium iodide
 calcium bromide
 calcium chloride
 15 calcium iodide
 calcium nitrate
 barium chloride
 barium fluoride
 barium iodide
 20 barium sulfate
 barium perchlorate
 tetrabutylammonium chloride
 tetrabutylammonium fluoride
 tetrabutylammonium hexafluorophosphate
 25 tetrabutylammonium iodide
 tetrabutylammonium nitrate
 tetraethylammonium iodide, etc.
 tetramethylammonium bromide, etc.
 tetrapentylammonium bromide, etc.

30 An exemplary list of surfactants which can be used as a deaggregation agent or additive is:

Surfactants:

Reference: Encyclopedia of Chemical Technology, 3rd Edition, K. Othmer, Wiley-Interscience, Pub., vol. 22, p. 332

35 Cationic, anionic, nonionic, and amphoteric surfactants included.

Examples of each are given below:

(1) anionic surfactants - Examples

40 i) Carboxylates $RCOOM$ R is hydrocarbon chain
 M is a metal or ammonium ion
 e.g., 3M Fluorad series, polyalkoxycarboxylates
 ii) sulfonates RSO_3M R is alkyl, aryl, or e.g., alkylbenzene sulfonates such as dodecylbenzene
 45 iii) sulfates $R-OSO_3M$
 alkyl sulfates such as octylsulfate sodium
 alcohol sulfates ethoxylated alcohol sulfates,
 50 iv) phosphates
 e.g., phosphate esters such as potassium butylphosphate,
 potassium hexylphosphate, phenol ethoxylated and phosphated, nonylphenol ethoxylated and phosphated, dodecylphenol ethoxylated and phosphated, etc.

55 (2) nonionic surfactants - Examples

i) polyoxyethylene surfactants (ethoxylates)
 - alcohol ethoxylates $R[OCH_2CH_2]_nOH$

- alkylphenol ethoxylates $RC_6H_4(OC_2H_5)_nOH$

e.g., Triton N-57
Triton N-111
Triton X-45
Triton X-102
Triton X-305
Triton X-705

ii) alkylphenols, e.g. nonylphenol, docecylphenol

iii) glycerol esters of fatty acids

iv) polyoxyethylene esters

v) carboxylic amides

vi) polyoxyethylene fatty acid amides

vii) polyalkylene oxide block copolymers

viii) poly(oxyethylene - co- oxypropylene)
e.g., pluronic series

(3) cationic surfactants

- aliphatic mono, di, and polyamines derived from fatty and rosin acids

- alkylamine ethoxylates

- amine oxides

- alkoxyates of ethylenediamine

- 2-alkyl-1-(2-hydroxyethyl)-2-imidazolines

- quaternary ammonium salts

e.g. dialkyldimethylammonium salts
alkylbenzyltrimethylammonium chlorides
alkylpyridinium halides

(4) amphoteric surfactants

Examples: imidazolinium derivatives
alkylbetaines
amidopropylbetaines, etc.

An exemplary list of acidic additives which can be used as a deaggregation agent or additive is:

Acidic Additives

(1) Preferred acidic additives

naphthol
thiocresol
2-hydroxydibenzofuran
1-[2-(2-hydroxyethoxy) ethyl] piperazine
2-hydroxy-9-fluorenone
5-hydroxyisoquinoline

2-hydroxy-1,4 naphthoquinone
 1-hydroxypyrene
 9-hydroxyxanthene
 indophenol
 5 dihydroxynaphthalene
 4-propyl resorcinol
 2-isopropylhydroquinone
 2,6 - bis(hydroxymethyl)-p-cresol
 resorcinol
 10 catechol
 hydroquinone
 pyrogallol
 benzylalcohol
 hydroxybenzylalcohol
 15 trihydroxytoluene
 iminodiphenol
 (2) Acidic additives also include:
 m-cresol
 phenol
 20 4-propoxyphenol

An exemplary list of dopants which can be used to dope the polymer to the conducting state are: hydrochloric acid, acetic acid, formic acid, oxalic acid, toluenesulfonic acid, dodecylbenzene sulfonic acid, benzenesulfonic acid, naphthalene sulfonic acid, methyl iodide and camphor sulfonic acid.

25 When deaggregation is done in solution the deaggregating agent is present in an amount less than about 25 wt%. When deaggregation is done in solution using a salt as the deaggregation agent, the salt is preferably present in an amount from about 0.0001 wt% to about 5 wt%, more preferably from about 0.0001 wt% to about 2.5 wt%; most preferably from about 0.001 wt% to about 1 wt%. When the deaggregation is done in solution using a surfactant as the deaggregation agent, the surfactant is preferably present in an amount from about 0.0001 wt% to about 10 wt%; more preferably from about 0.001 wt% to about 5 wt%; most preferably from about 0.01 wt% to about 2.5 wt%. When the deaggregation is done in solution using an acidic additive as the deaggregation agent, the acidic additive is preferably present in an amount from about 0.0001 wt% to about 25 wt%; preferably from about 0.001 wt% to about 15 wt%; most preferably from about 0.01 wt% to about 10 wt%.

30 Fig. 15, 16, 17, 18, 19 and 20 are atomic force micrographs each having a dimension of 1000 nm X 1000 nm. Fig. 15 is for polyaniline base cast from 100% NMP; Fig. 16 is for polyaniline cast from 100% NMP and subsequently exposed to m-cresol; and Fig. 17 of the same sample as in Fig. 16 with the m-cresol pumped out and shows no tendency to reaggregate. Fig. 15 shows aggregated regions of the order of 100 nm. Fig. 16 shows the substantial elimination of the aggregated regions caused by exposure to the deaggregating agent, m-cresol, which remains when the m-cresol is removed. Therefore, the deaggregated structure is locked or remains without the deaggregating agent.

40 Fig. 15 shows bundles of aggregated regions which are not present in Fig. 16 and 17. Figs. 18, 19 and 20 show similar results for treatment with nonylphenol and triton surfactant. The level of deaggregation is not as complete as in Fig. 16 but shows the onset of deaggregation.

Basic Synthesis of Polyaniline

Unsubstituted Polyaniline

45 The unsubstituted polyaniline is synthesized by the chemical oxidative polymerization of aniline in 1N HCL using ammonium peroxydisulfate as an oxidizer. Polyaniline can also be oxidatively polymerized electrochemically as taught by W.Huang, B. Humphrey, and A.G. Macdiarmid, J. Chem. Soc., Faraday Trans. 1, 82, 2385, 1986. In the chemical synthesis, the conducting polyaniline:hydrochloride salt precipitates from solution. The polymerization is allowed to proceed for several hours after which the powder is filtered, washed with excess 1N hydrochloric acid. The polyaniline:hydrochloride is then converted to the non-conducting or non-doped polyaniline base by reaction with 0.1M ammonium hydroxide. The polyaniline base is then filtered, washed with ammonium hydroxide, then washed with methanol and dried. The polymer in this stage is in the undoped base form as a powder.

50 The polymer is generally processed by taking the polyaniline base powder and dissolving it in organic solvents, most commonly N-methylpyrrolidinone. This solution can be used to spin-coat thin films of the base polymer or can be used to solution cast thick films or can be used to fabricate structural parts of the polyaniline base. The substituted polyaniline derivatives are made by the oxidative polymerization of the appropriate substituted aniline monomer. Copol-

ymers can also be made by the oxidative polymerization of one or more monomers. In addition different acids other than hydrochloric acid can be used in the synthesis.

Doping generally involves reaction with most commonly protonic acids. Other electrophiles can also be used as dopants, for example alkylating agents, etc. The doping can be done in solution or it can be done heterogeneously in the solid state. For example, the NMP solution of the polyaniline base can be used to spin-coat films of the polyaniline base. These films can be doped or made conducting by dipping into a solution of the appropriate acid such as 1N HCL, or aqueous toluene sulfonic acid or the vapor of the acid. The polyaniline base powder can also be doped by stirring in an aqueous solution of the dopant. The doping can also be carried out in solution which is generally preferred as it allows the conducting form to be processable. To the NMP solution of the polyaniline base is added the appropriate dopant, for example camphorsulfonic acid. The acid reacts with the polyaniline base to form the conducting polyaniline salt. Any other acid or electrophile can be used in the same manner. The conducting salt will either precipitate or remain in solution depending on the particular dopant used. If it stays in solution, the conducting solution can then be used to fabricate films of the conducting polyaniline by spin-coating, dip coating, spray-coating, etc. or fabricated into some structural components.

Typical experimental for the additives: The present invention uses additives in the starting solvent, eg. NMP. For example, 0.00001 wt % to 5 wt %, preferably 0.0001 to 2.5 %, and most preferably .001 to 1% ratio) LiCl is added to the NMP. The salt is allowed to dissolve in the NMP. To this solvent is added the polyaniline base powder and allowed to stir. Once the polyaniline base is dissolved, it is filtered through a 0.2 micron millipore filter and then to the filtered solution is added the dopant. Dopants used in this study include toluenesulfonic acid, camphor sulfonic acid, acrylamidopropanesulfonic acid, hydrochloric acid.

The conductivity of the polyaniline salt is found to depend on the processing conditions. Generally polyaniline doped heterogeneously with aqueous 1N HCL gives conductivity on the order of approx. 1 S/cm. Doping in NMP generally gives much lower conductivity (approx. .1 S/cm). A great deal of variation in conductivity has been observed depending on the solvent system used for doping. When a polyaniline base is doped in NMP with an organic sulfonic acid a localized polaron peak is observed on the ultraviolet-visible near IR spectrum. When this film is exposed to m-cresol a highly delocalized polaron peak is observed extending out to 2500 nm with the conductivity increasing to hundreds of S/cm. Conductivity of .2 S/cm is attained when an NMP solution of the polyaniline base is reacted with camphorsulfonic acid or acrylamidopropanesulfonic acid. The uv/visible/near IR spectrum for the polyaniline doped with acrylamidopropane sulfonic acid is shown in Fig. 12.

As can be seen a localized polaron peak is attained. When .5 wt.% LiCl is added to the NMP, a delocalized polaron peak (Fig. 13) is attained and with 1 wt. % LiCl a highly delocalized polaron peak is attained (Fig. 14). This delocalized polaron is indicative of higher conductivity as a result of more highly delocalized carriers.

Also, an NMP/additive (e.g. LiCl) solvent system was used to spin-coat the polyaniline base films. The UV of the base also shows a red shift to longer wavelengths with the incorporation of additives as compared to films cast from 100% NMP. This red shift is indicative of an extension of the conjugation length. When these films are doped with hydrochloric acid vapor, the films which include the lithium chloride show a more highly delocalized polaron peak as compared to the NMP film alone.

The additives can also be surfactants such as nonylphenol or the tritons. The triton for example is dissolved in the NMP prior to the addition of the pani base as described above. This solution was used to cast thick films of the pani base. Upon doping of the thick films with hydrochloric acid, the conductivity of the film was 11 S/cm for the triton containing film; 40 S/cm for the nonylphenol containing film; and only 1 S/cm for the NMP only film.

Films processed according to the present invention can give rise to enhanced stretch orientation and a corresponding increase in electrical conductivity.

Fig. 21 schematically shows an undoped deaggregated film 20 held at end 22 and end 24 by clamps 26 and 28 respectively. Ends 22 and 24 are pulled apart as indicated by arrows 30 and 32, respectively. The molecules in the deaggregated film are unravelled and therefore when film 20 is stretched there is increased propensity for alignment of the molecules in the stretch direction and thereby enhanced electrical conductivity in the stretch direction.

Solutions processed according to the present invention exhibit enhanced shelf life stability. Polyaniline solutions in general tend to gel over time. The time for gelling to occur is dependent on solvent and concentration of solids in solution. For example, a solution of polyaniline base in NMP made to 5% solids by weight tends to gel within days. Solutions higher in solids content gel within minutes. Gellation limits the full use of the polyaniline solutions for many applications. Gellation occurs because of interactions between chains, most probably hydrogen bonding. As the hydrogen bonding between chains increase, chain entanglements increase. As this entangled or highly aggregated structure is less soluble than the non-aggregated structure, the solutions of the aggregated structure in turn gel. The addition of salts such as lithium chloride, for example, breaks the interchain hydrogen bonds and in turn prevents the solution from gelling thereby enhancing the long term shelf life stability of the polyaniline solutions. Also, the use of these additives allows higher solids polyaniline solutions to be made (higher than can normally be made without the additives) with good shelf life stability.

Claims

1. A composition of matter comprising:
an electrically conductive polymer having electrically conductive regions, said have a dimension greater than about
5 30 nm (about 300Å).
2. A composition of matter according to claim 1
wherein said electrically conductive polymer is selected from the group consisting of electrically conductive substituted and unsubstituted polyparaphenylenes, polyparaphenylenevinylenes, polyanilines, polyazines, polythiophenes, poly-p-phenylene ì sulfides, polyfuranes, polypyrroles, polyselenophenes, polyacetylenes formed from
10 soluble precursors and combinations thereof and blends thereof with other polymers and copolymers of the monomers thereof.
3. A composition of matter
15 according to claim 1 or 2 wherein said electrically conductive polymer includes a dopant.
4. A composition of matter
according to claim 3 wherein said dopant is selected from the group consisting of hydrochloric acid, acetic acid, formic acid, oxalic acid, toluenesulfonic acid, dodecylbenzene sulfonic acid, benzenesulfonic acid, naphthalene sulfonic acid, methyl iodide, and camphor sulfonic acid.
20
5. A composition of matter
according to claim 2, additionally comprising a surfactant or a salt or an acidic additive as a deaggregating agent.
- 25 6. A composition of matter
according to claim 5, wherein said surfactant is selected from the group consisting of carboxylates, sulfonates, sulfates, phosphates, ethoxylates, alkylphenols, glycerol esters, polyoxyethylene esters, carboxylic amides, polyoxyethylenes, polyalkylene oxides, poly(oxyethylene-co-oxypropylenes), aliphatic amines, alkylamine ethoxylates, amine oxides, alkoxyates of ethylenediamine, imidazolines, quaternary ammonium salts, imidazolinium derivatives, alkylbetaines and amidopropylbetaines.
30
7. A composition of matter
according to claim 5, wherein said salt is selected from the group consisting of lithium salts, magnesium salts, sodium salts, potassium salts, rubidium salts, cesium salts, calcium salts, barium salts, tetrabutylammonium salts, tetraethyl ammonium salts, tetramethyl ammonium salts and tetrapentyl ammonium salts.
35
8. A composition of matter
according to claim 5 wherein said acidic additive is selected from the group consisting of
phenol
40 naphthol
thiocresol
2-hydroxydibenzofuran
1-[2-(2-hydroxyethoxy) ethyl] piperazine
2-hydroxy-9-fluorenone
45 5-hydroxyisoquinoline
2-hydroxy-1,4 naphthoquinone
1-hydroxypyrene
9-hydroxyxanthene
indophenol
50 dihydroxynaphthalene
4-propoxyphenol
4-propyl resorcinol
2-isopropylhydroquinone
2,6 - bis(hydroxymethyl)-p-cresol
55 resorcinol
catechol
hydroquinone
pyrogallol
benzylalcohol

hydroxybenzylalcohol
trihydroxytoluene
iminodiphenol

- 5 9. A composition of matter according to any one of claims 5 to 8 wherein there are aggregated regions having a dimension smaller therein if said deaggregating agent was not present.
- 10 10. A composition of matter according to claim 1, further including a deaggregating agent.
- 15 11. A composition of matter according to claim 10, wherein said deaggregating agent is selected from the group consisting of salts, surfactants, acidic additives, crown ethers, metal chelates and ionic complexing agents.
12. A composition of matter according to any one of claims 5 to 9, wherein said polymer molecules are nonelectrically conductive.
- 20 13. A composition of matter according to any one of claims 5 to 9, wherein said polymer molecules are doped and electrically conductive.
- 25 14. A body of material comprising: precursor molecules to an electrically conductive polymer molecules, said body has regions of aggregation of said precursor molecules, said regions having a size of less than about 100 nm.
- 30 15. A body of material according to claim 14, wherein said precursor molecules are selected from the group consisting of substituted and unsubstituted polyparaphenylenes, polyparaphenylenevinylenes, polyanilines, polyazines, polythiophenes, poly-p-phenylene sulfides, polyfuranes, polypyrroles, polyselenophenes, polyacetylenes formed from soluble precursors and combinations thereof, and blends thereof with other polymers and copolymers of the monomers thereof.
- 35 16. A body of material according to claim 14 or 15 further including a dopant which dopes said polymer molecules to be electrically conductive.
- 40 17. A method according to claim 16 wherein said dopants are selected from the group consisting of hydrochloric acid, acetic acid, formic acid, oxalic acid, toluenesulfonic acid, dodecylbenzene sulfonic acid, benzenesulfonic acid, naphthalene sulfonic acid, methyl-iodide, camphor sulfonic acid.
18. A composition of matter according to claim 1, wherein there are a plurality of said polymers, said plurality being deaggregated.
- 45 19. A composition of matter according to any one of claims 5 to 8 wherein said polymer molecules have a glass transition temperature less than the glass transition temperature of said polymer molecules without said deaggregating agent.
20. A composition of matter according to any one of claims 5 to 8 wherein said polymer molecules have a deaggregated structure.
- 50 21. A composition of matter according to any one of claims 5 to 8 wherein each of said polymer molecules has an expanded coil conformation.
- 55 22. A method to form a composition of matter according to any one of the preceding claims comprising the steps of: providing a first admixture of an additive and a solvent; forming a second admixture by dissolving in said first admixture precursor polymers according to claim 2 to electrically conducting polymers, said additive deaggregates said precursor molecules; thereafter adding a dopant to said second admixture to dope said precursor to be an electrically conductive polymer.

23. A method according to claim 22

wherein said solvent is selected from the group consisting of N-methyl pyrrolidinone, dimethyl sulfoxide, dimethyl formamide, pyridine, toluene, xylene, m-cresol, phenol, dimethylacetamide, tetramethylurea, n-cyclohexylpyrrolidinone, aqueous acetic acid, aqueous formic acid, pyrrolidinone, N, N' dimethylpropylene, urea, benzyl alcohol and water.

24. A method according to claim 22 or 23

wherein said additive is selected from the group consisting of salts, selected from the group consisting of lithium salts, magnesium salts, sodium salts, potassium salts, rubidium salts, cesium salts, calcium salts, barium salts and tetrabutylammonium salts, surfactants, selected from the group consisting of cationic, anionic, nonionic and amphoteric surfactants, acidic additive, selected from the group of:

m-cresol, phenol naphthol, thiocresol, 2-hydroxydibenzofuran, 1-[2-(2-hydroxyethoxy) ethyl] piperazine, 2-hydroxy-9-fluorenone, 5-hydroxyisoquinoline, 2-hydroxy-1,4 naphthoquinone, 1-hydroxypyrene, 9-hydroxyxanthene, indophenol, dihydroxynaphthalene, 4-propoxypnol, 4-propyl resorcinol, 2-isopropylhydroquinone, 2,6 - bis(hydroxymethyl)-p-cresol, resorcinol, catechol, hydroquinone, pyrogallol, benzylalcohol, hydroxybenzylalcohol, trihydroxytoluene, iminodiphenol, crown ethers, metal chelates and ionic complexing agents.

25. A method according to claim 24,

wherein said surfactant is selected from the group consisting of carboxylates, sulfonates, sulfates, phosphates, ethoxylates, alkylphenols, glycerol esters, polyoxyethylene esters, carboxylic amides, polyoxyethylenes, polyalkene oxides, poly(oxyethylene-co-oxypropylenes), aliphatic amines, alkylamine ethoxylates, amine oxides, alkoxylates of ethylenediamine, imidazolines, quaternary ammonium salts, imidazolinium derivatives, alkylbetaines and amido-propylbetaines.

26. A method comprising the steps of:

providing substituted or unsubstituted aniline molecules, preferably in solution;
oxidatively polymerizing said aniline molecules in an acid solution in the presence of a deaggregating agent according to claim 11 to result in a deaggregated polyaniline molecules.

27. A method according to claim 26

wherein said oxidatively polymerized aniline precipitates out as a conductive polyaniline.

28. A method according to claim 26 or 27

further including the steps of:
neutralizing said polyaniline to a polyaniline salt.

29. A method according to claim 28

wherein said step of neutralizing is done using a material selected from the group consisting of ammonium hydroxide, sodium hydroxide and potassium hydroxide.

30. A method according to claim 27

wherein said conductive polyaniline is dried to form a powder, said powder comprising deaggregated polyaniline base molecules.

31. A method according to claim 26

wherein said acid is selected from the group consisting of HCl, toluenesulfonic acid, benzenesulfonic acid, sulfuric acid, acetic acid, formic acid, naphthalene sulfonic acid, camphor sulfonic acid, dodecylbenzene sulfonic acid and oxalic acid.

32. A method according to claim 22

wherein said electrically conductive polyaniline base has electrically conductive regions.

33. A method according to claim 32

wherein said electrically conductive polymer has less electrically conductive regions between said electrically conductive regions, said electrically conductive regions have an electrical conductivity greater than about 10^6 times the electrical conductivity of the less-electrically conductive regions.

34. A method according to claim 22

further including the step of removing said additive.

35. A method according to claim 28
wherein said step of neutralizing said polyaniline base and said step of deaggregating said polyaniline base are
done substantially at the same time.

5 36. A method comprising the steps of:
providing a group of precursor polymers to electrically conductive polymers;
exposing said group to a deaggregating agent to deaggregate said group of precursor polymers.

10 37. A method according to claim 36,
wherein said group is in a solid state, or in solution.

38. A method according to claim 37,
wherein a film is formed from said group in a solid state and said film is stretch oriented.

15 39. A method according to claim 37,
wherein said solution contains a solvent, further including forming a film by removing said solvent.

20 40. A method according to claim 39,
wherein said step of forming a film comprises disposing said solution on a substrate and removing said solvent.

41. A method according to claim 36,
wherein said step of exposing said group to said deaggregating agent deaggregates said group by intermolecular
structural changes.

25 42. A method according to claim 41
wherein said deaggregating agent causes intramolecular conformational changes in the precursor polymers of said
group.

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FIG. 1

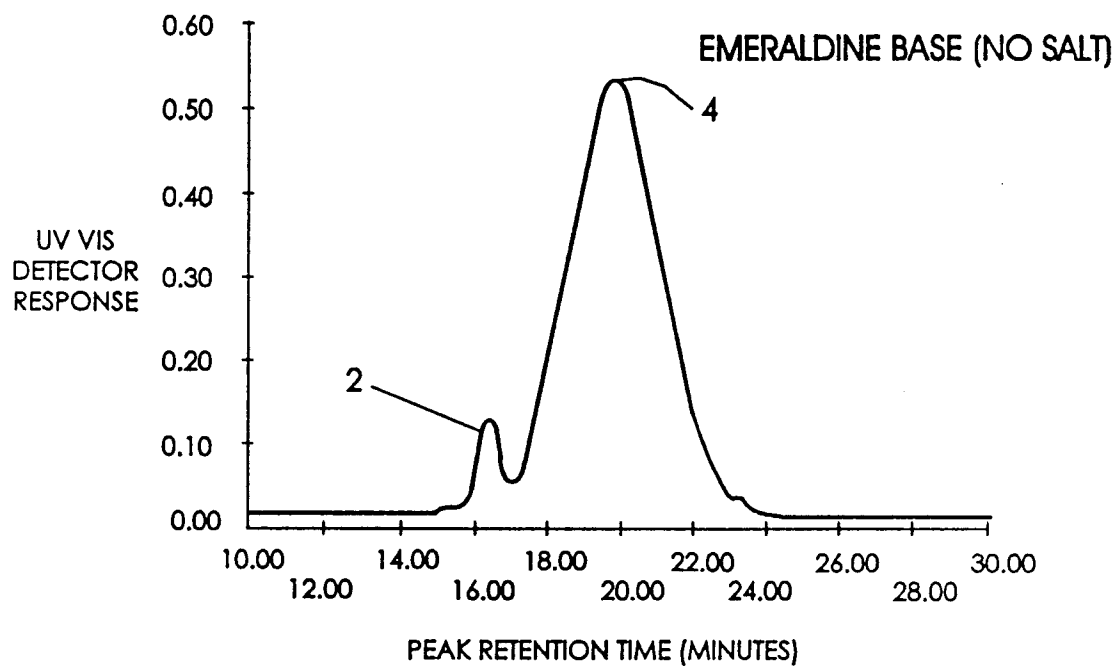


FIG. 2

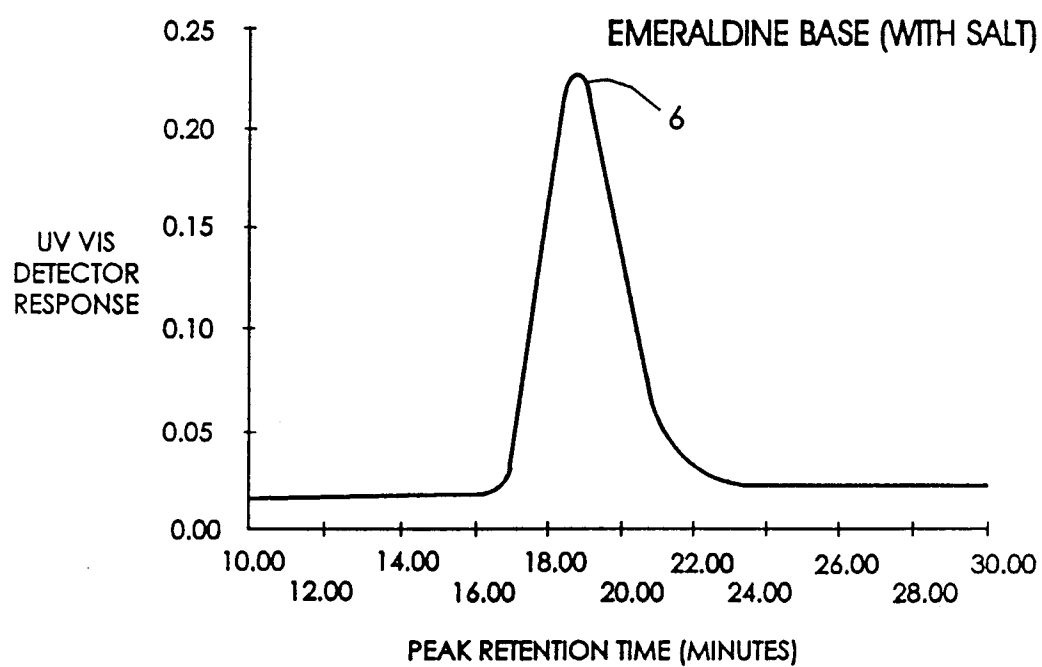


FIG. 3

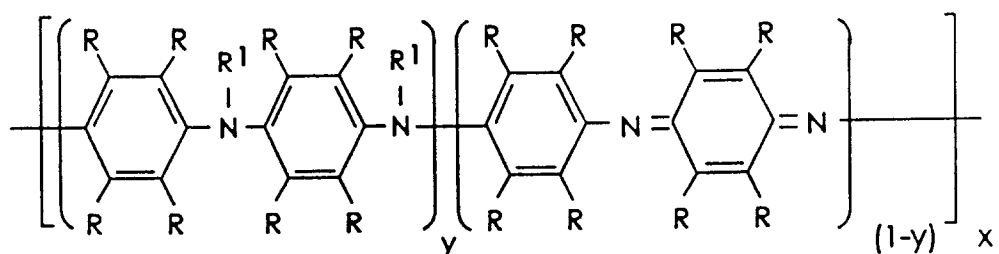


FIG. 4.1

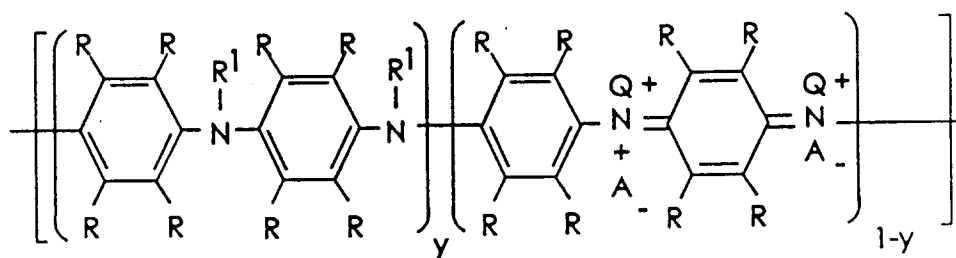


FIG. 4.2

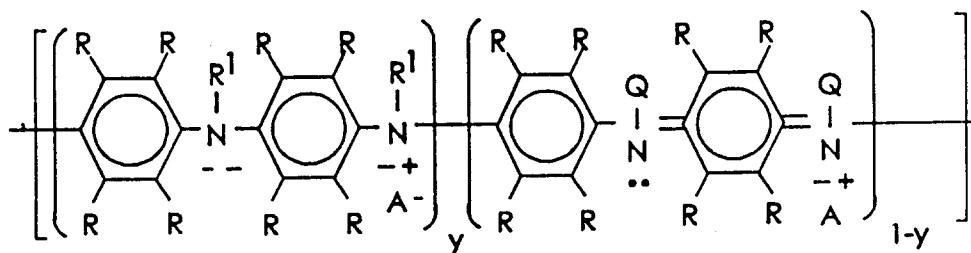


FIG. 5

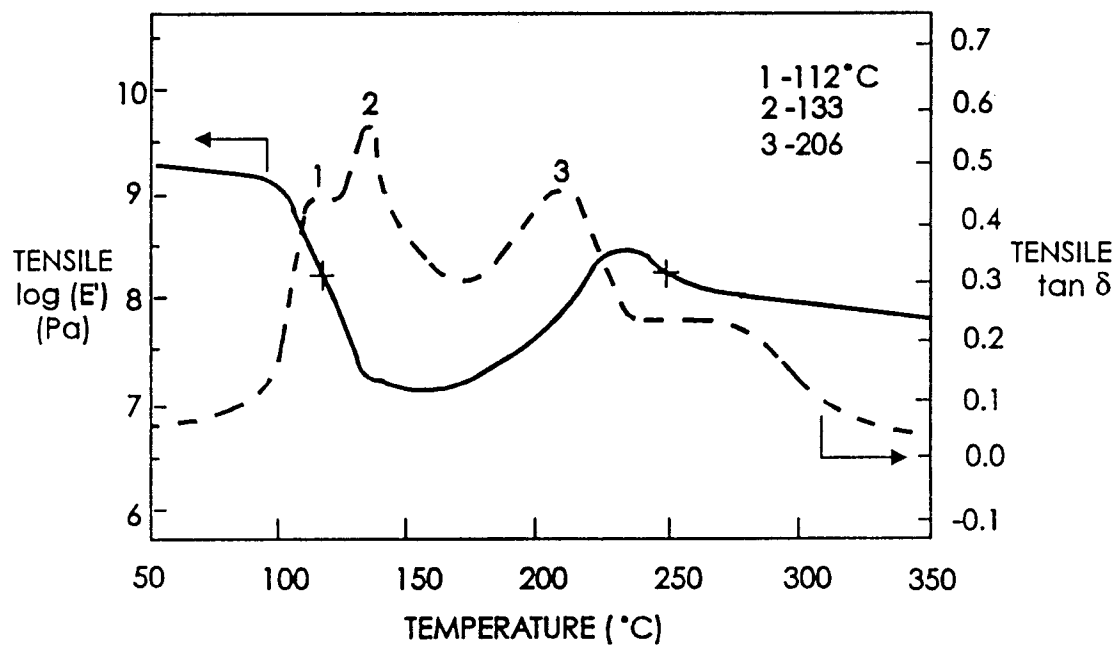


FIG. 6

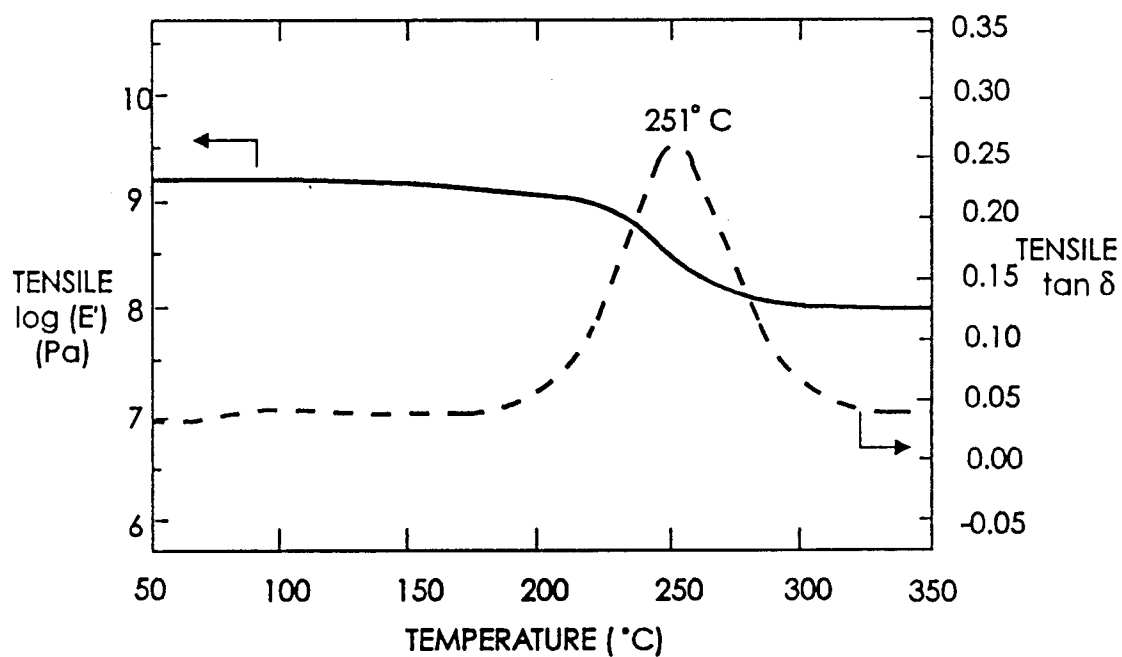


FIG. 7

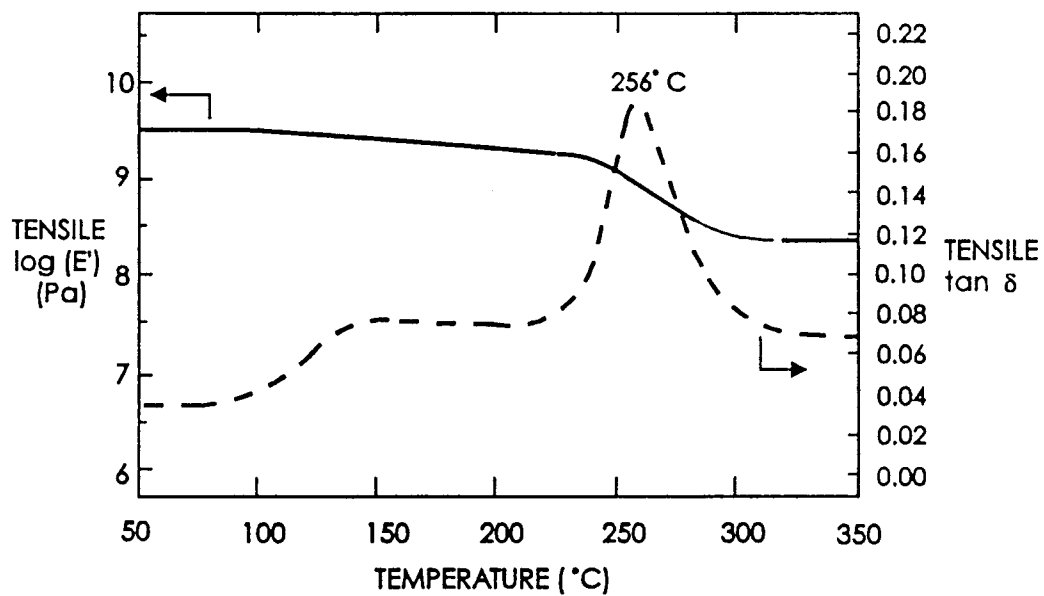


FIG. 8

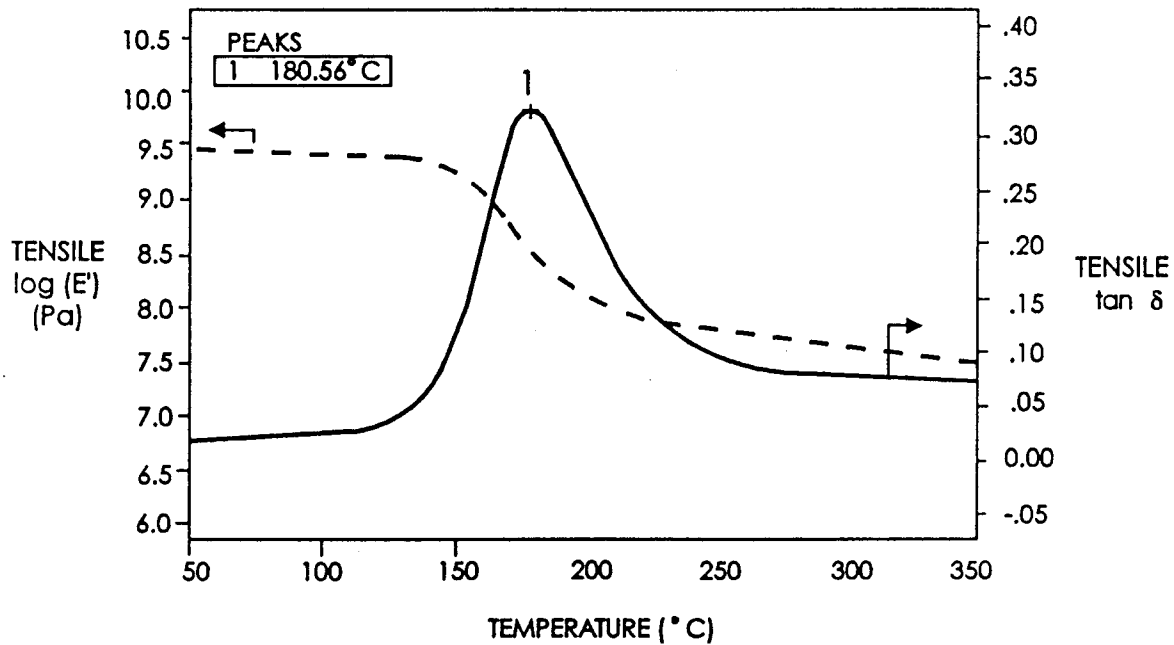


FIG. 9

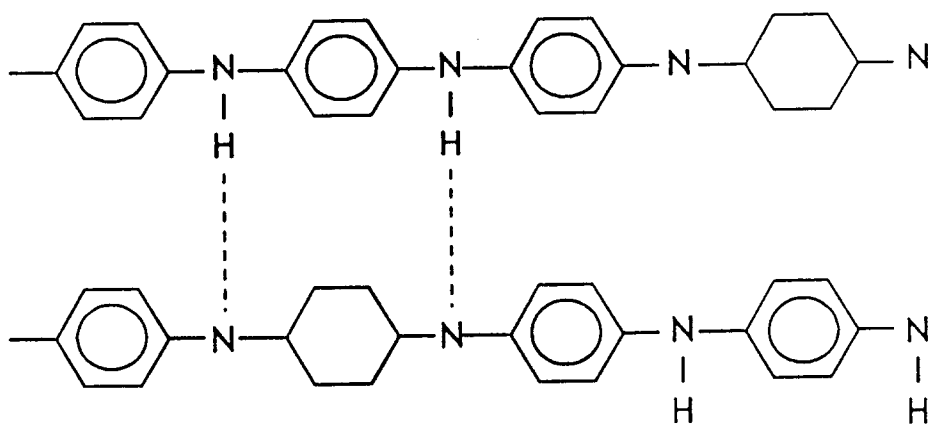


FIG. 10

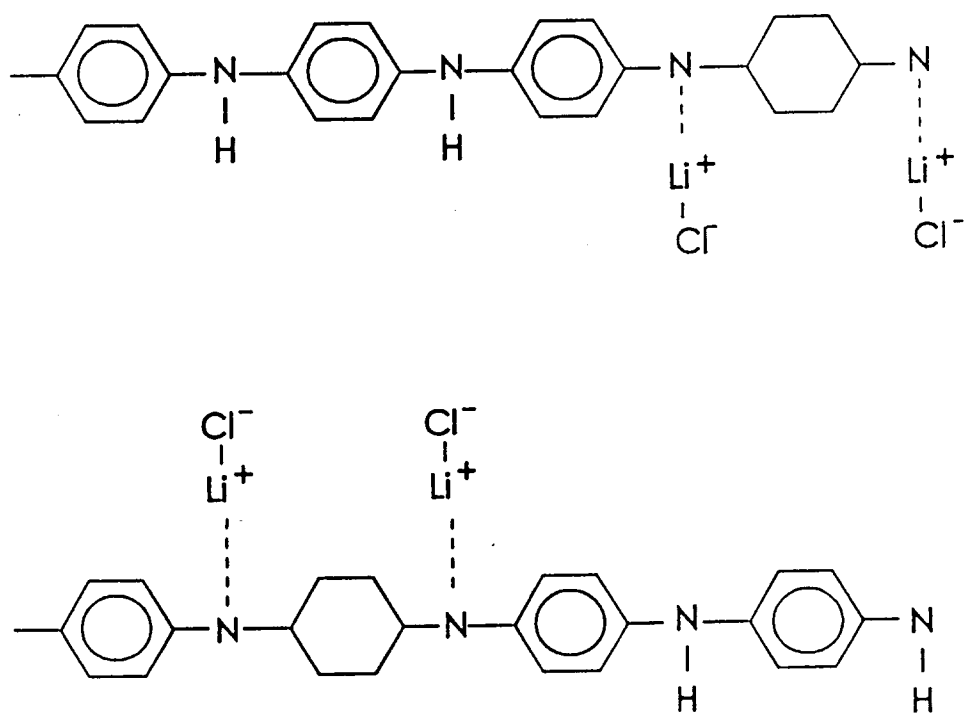


FIG. 11

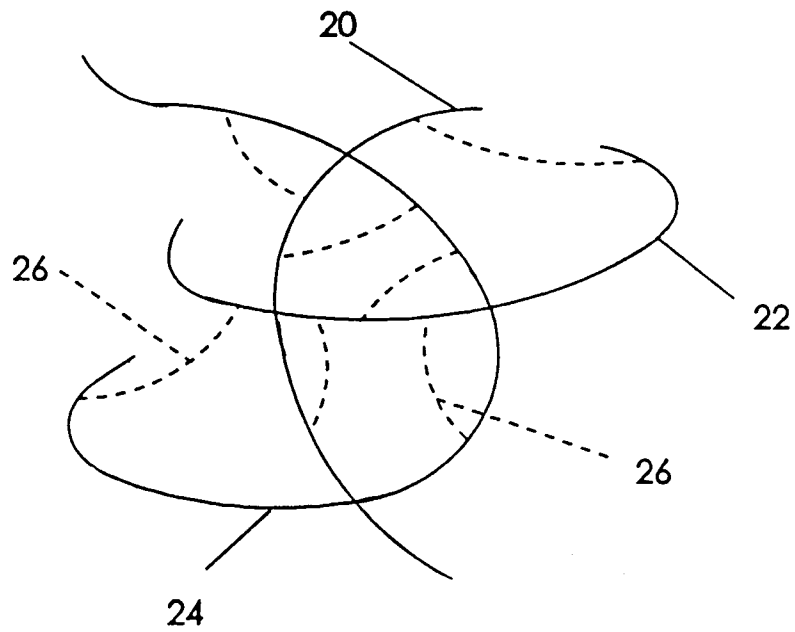


FIG. 21

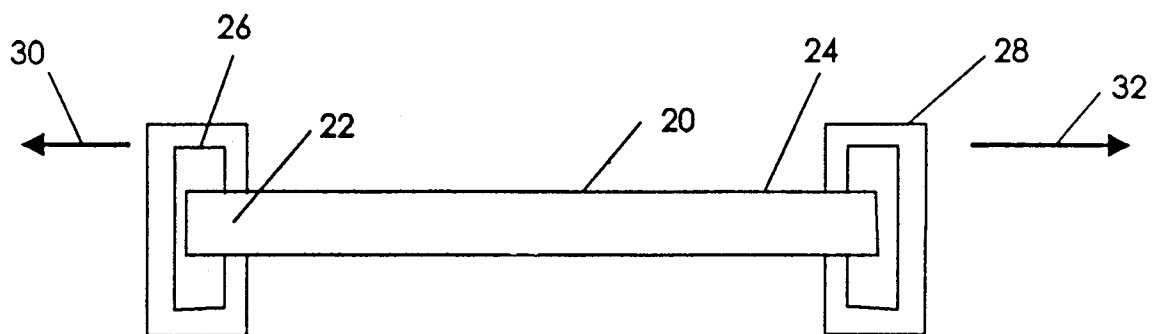


FIG. 12

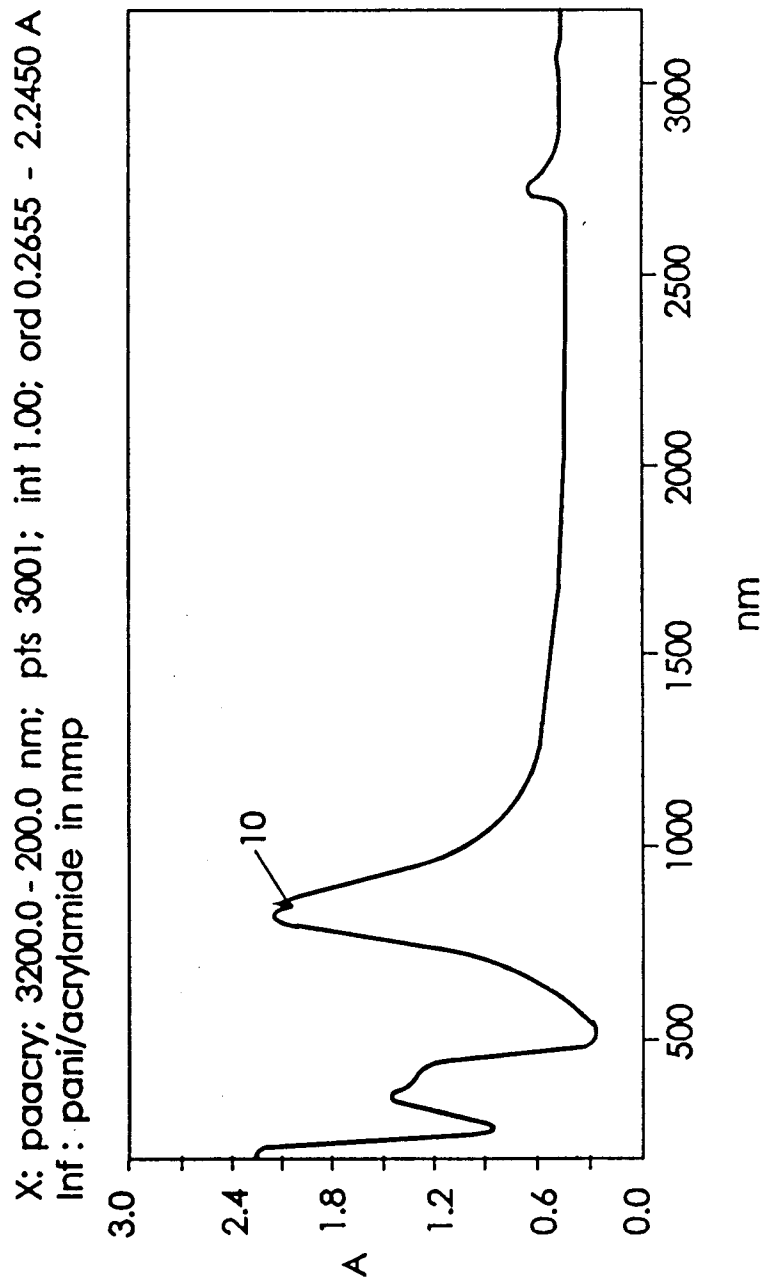


FIG. 13

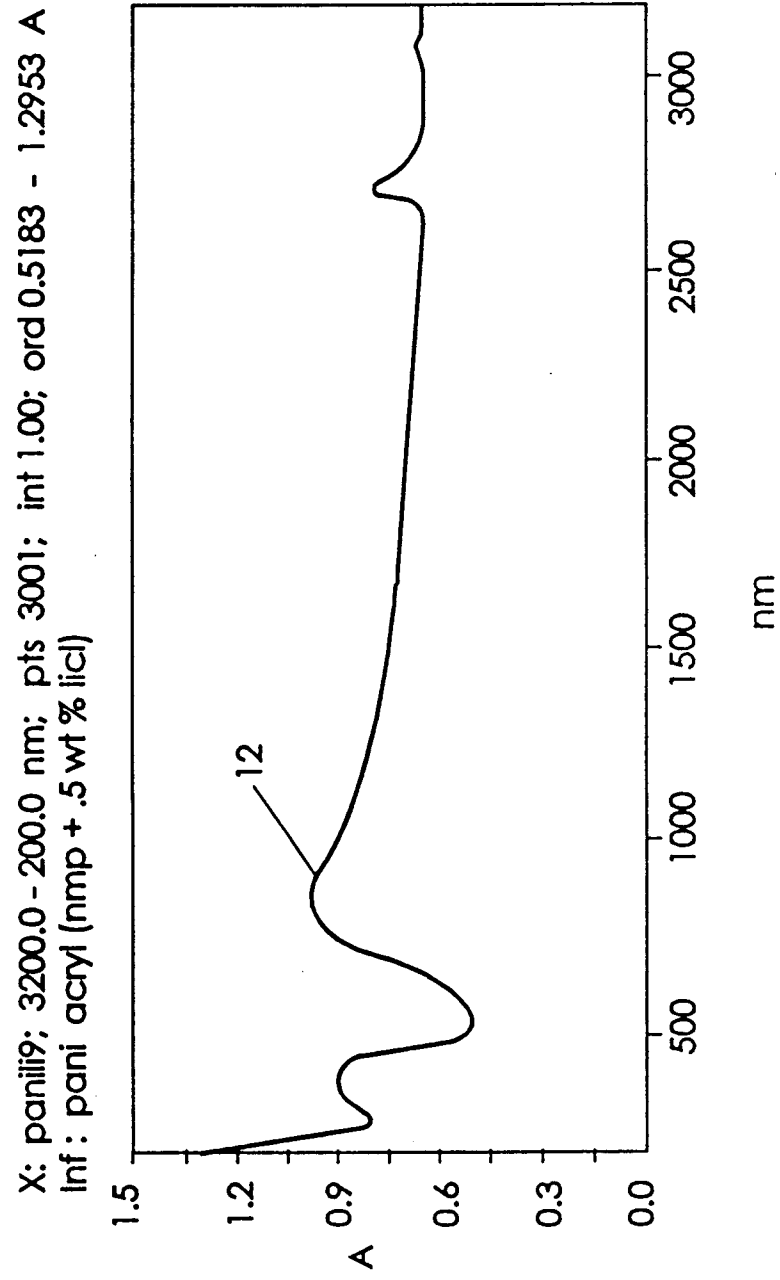


FIG. 14

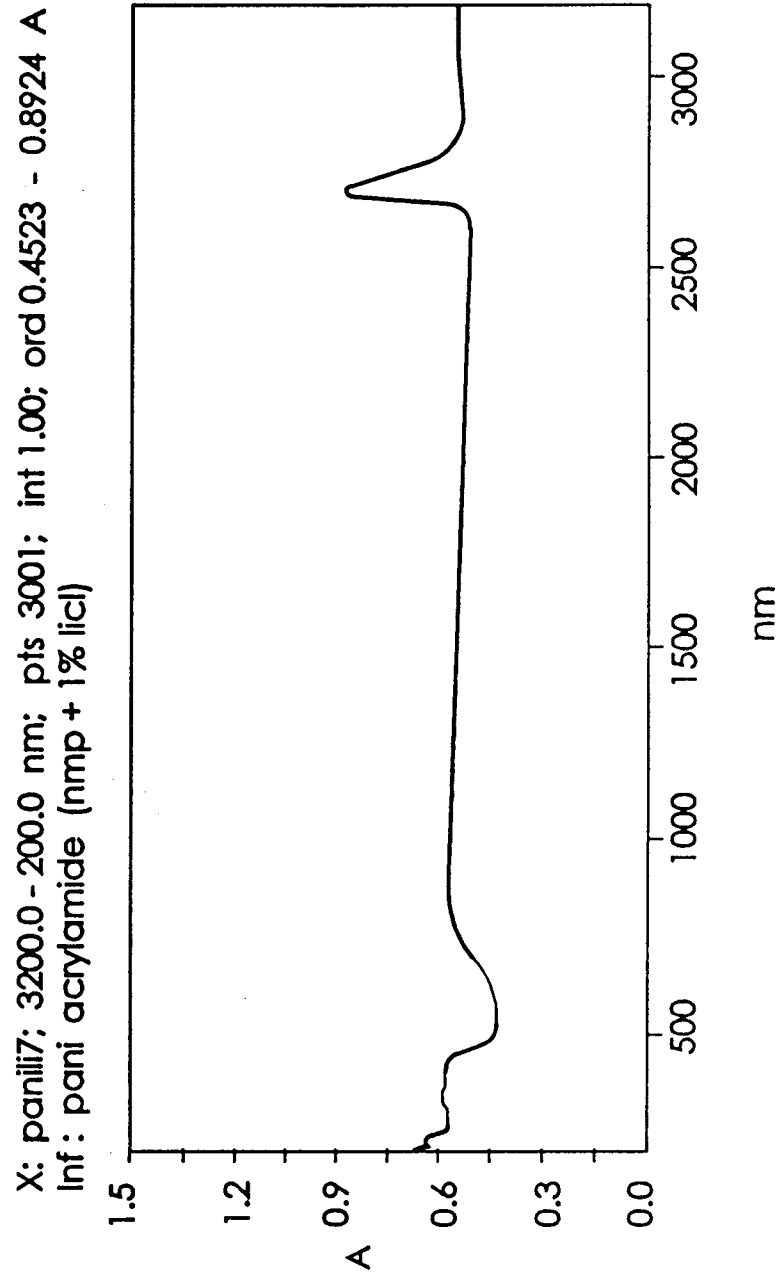




FIG. 15

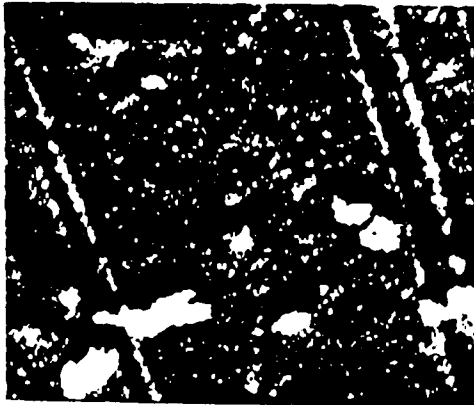


FIG. 16



FIG. 17

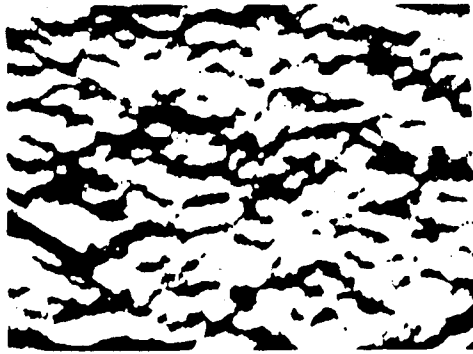
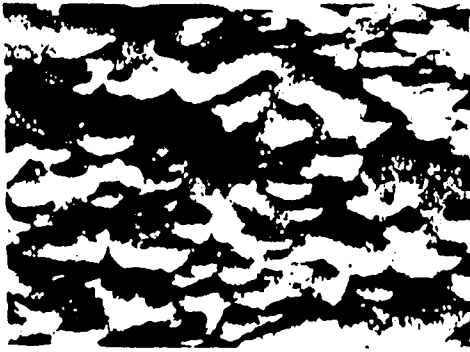


FIG. 19

FIG. 18



FIG. 20