

TRICYCLIC ARYLAMINE MONOMER AND POLYMERS AND DEVICES THEREOF

This invention relates to a tricyclic arylamine monomer and polymers and compositions made therefrom and electronic devices that include films of such polymers and compositions.

Fluorene based conjugated polymers are known to have optoelectronic properties. Several reports have demonstrated blue light emission from fluorene homopolymers for example, A.W. Grice; D.D.C. Bradley, M.T. Bernius; M. Inbasekaran, W. Wu, E.P. Woo; Appl. Prep. Lett. 1998, 73, Y. Young and Q. Pei; J. Appl. Prep. 81, 3294 (1997).

Attempts have been made to modify fluorene containing polymers to increase device efficiency. Attempts have also been made to control an undesired red shift in emission of polyfluorene based devices.

WO 01/81294 A1 teaches a fluorene polymer that is end-capped with a charge transporting tricyclic arylamine. That reference states that end-capping with at least one charge transporting moiety provides advantages. The purported advantages include higher efficiency and color stability without alteration of the electronic properties of the polyfluorene polymer main chain. The reference also states that approaches that include chemical moieties incorporated into the polyfluorene main chain or the copolymerization with other monomers inevitably modify essential properties of the main chain.

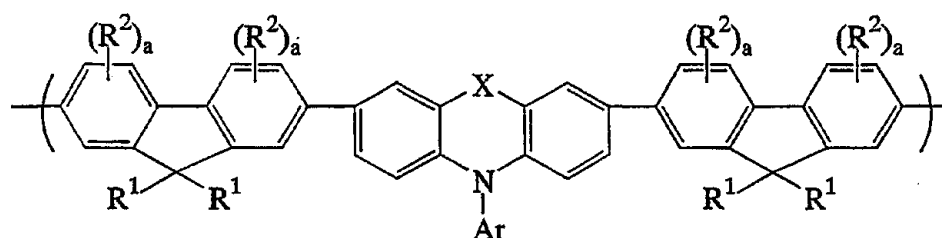
U.S. Patent No. 5,874,179 (Kreuder et al) teaches optoelectronic polymers based on polyphenylenevinylene with nitrogen containing comonomers. Additionally, Kreuder further teaches that fluorene could be part of a fused nitrogen containing ring structure in a polyphenylenevinylene based polymer.

U.S. Patent No. 5,879,821 (Hsieh) teaches polymers containing repeat units of two tricyclic arylamines which are either bonded together or are arranged in a bis structure on either side of a divalent atom or moiety "G". G can be O, S, N-Phenyl, vinylene, acetylene, p-phenylene, m-phenylene, o-phenylene, or $-\text{CH}=\text{CH}-\text{Phenyl}-\text{CH}=\text{CH}-$.

A need remains for optoelectronic materials and devices that exhibit good conductivity, improved efficiency, emit a variety of colored light and have high brightness at low drive voltages.

Surprisingly, the present inventors have discovered that the inclusion of a tricyclic arylamine in the main chain of a fluorene based optoelectronic polymer provides improved conductivity at low voltages as well as higher device efficiency compared to polyfluorenes having other charge transporting groups such as acyclic triarylamines.

Thus, in a first embodiment, the invention is a polymer comprising repeat units of Formula I.



Formula I

wherein R^1 is independently, in each occurrence H, C_{1-40} hydrocarbyl or C_{3-40} hydrocarbyl containing one or more S, N, O, P or Si atoms, or both of R^1 together with the 9-carbon on the fluorene forms a C_{5-20} ring structure containing one or more S, N, or O atoms;

R^2 is independently in each occurrence C_{1-20} hydrocarbyl, C_{1-20} hydrocarbyloxy, thioether, C_{1-20} hydrocarbyloxycarbonyl, C_{1-20} hydrocarbylcarbonyloxy, or cyano;

a is independently, in each occurrence 0 or 1;

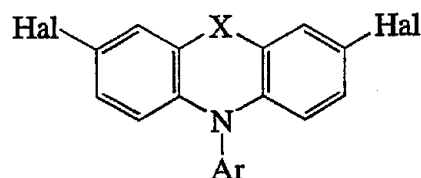
X is O, S, SO_2 , $C(R^3)_2$, $N-R^3$, $Si(R^3)_2$ wherein R^3 is a substituted or unsubstituted C_6 to C_{40} aryl, C_6 to C_{24} aralkyl, or a C_1 to C_{24} alkyl. Preferably R^3 is a C_6 to C_{24} aryl group, more preferably R^3 is a C_6 to C_{24} aralkyl group.

Ar is a substituted or unsubstituted C_6 to C_{40} aryl or heteroaryl group, preferably C_6 - C_{24} , and most preferably C_6 - C_{14} .

In another aspect, the invention is an electroluminescent device comprising a film of the polymer of the present invention, disposed between an anode and a cathode such that under an applied voltage, the film emits visible light which is transmitted through a transparent exterior portion of the device.

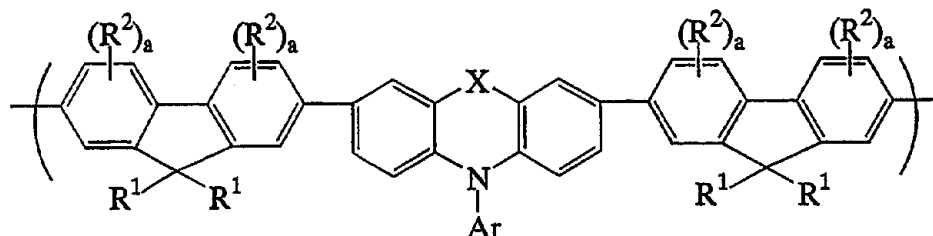
In another aspect, the invention is a device comprising the polymer of the present invention disposed as a semiconductor layer for a field effect transistor.

In another aspect, the invention is a composition of the formula:



wherein X is O, S, SO_2 , $C(R^3)_2$, $N-R^3$, or $Si(R^3)_2$ wherein R^3 is substituted or unsubstituted C_6 to C_{40} aryl, C_6 to C_{24} -aralkyl, or C_1 to C_{24} -alkyl; and Ar is substituted or unsubstituted C_6 to C_{40} aryl or heteroaryl; and Hal is Br, Cl, or I. Preferably, Hal is Cl, or Br, more preferably, Br.

In a preferred embodiment, the invention is a polymer comprising a repeat unit of Formula I:



Formula I

R^1 is independently in each occurrence H, C_{1-40} hydrocarbyl or C_{3-40} hydrocarbyl containing one or more heteroatoms of S, N, O, P or Si. Alternatively, both of R^1 together with the 9-carbon on the fluorene may form a C_{5-20} aliphatic or aromatic ring structure or a

C_{4-20} aliphatic or aromatic ring structure which may contain one or more heteroatoms of S, N, or O. Preferably R^1 is C_{1-12} alkyl, C_{6-10} aryl, C_{6-40} hydrocarbyloxyaryl or alkyl-substituted aryl, C_{4-16} hydrocarbyl carboxylate or C_{9-16} aryl trialkylsiloxy moiety. More preferably, R^1 is *n*-hexyl, *n*-octyl, *n*-hexyloxyphenyl, 4-ethoxyethoxyphenyl, phenyl, or biphenyl; most preferably, R^1 is *n*-hexyl, *n*-octyl, *n*-hexyloxyphenyl, or 4-ethoxyethoxyphenyl.

In the embodiment where the two R^1 form a ring structure with the 9-carbon atom of the fluorene ring, the ring structure formed is preferably a C_{5-20} straight- or branched-ring structure or a C_{4-20} straight- or branched-chain ring structure containing one or more heteroatoms of S, N or O; even more preferably a C_{5-10} aliphatic or aromatic ring or a C_{4-10} aliphatic or aromatic ring containing one or more of S or O; and most preferably a C_{5-10} cycloalkyl or C_{4-10} cycloalkyl containing oxygen.

R^2 is independently in each occurrence C_{1-20} hydrocarbyl, C_{1-20} hydrocarboxyloxy, C_{1-20} thioether, C_{1-20} hydrocarbyloxycarbonyl, C_{1-20} hydrocarbylcarbonyloxy or cyano. R^2 is preferably C_{1-12} alkyl, C_{6-10} aryl or alkyl-substituted aryl, C_{6-10} aryloxy or alkyl-substituted aryloxy, C_{1-12} alkoxycarbonyl, C_{6-10} arloxycarbonyl or alkyl-substituted arloxycarbonyl, C_{1-12} alkoxy, C_{1-12} alkylcarbonyloxy, C_{6-10} arylcarbonyloxy or alkyl-substituted arylcarbonyloxy, cyano or C_{1-20} alkylthio.

"a" is independently in each occurrence from 0 to 1. Preferably, a is 0.

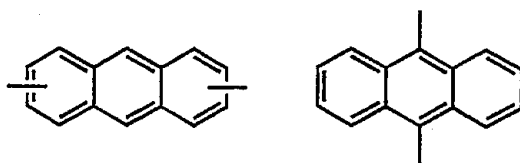
The term "hydrocarbyl" is used herein to refer to a monovalent aromatic, aliphatic, or cycloaliphatic group or any combination thereof.

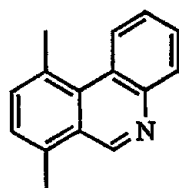
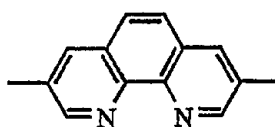
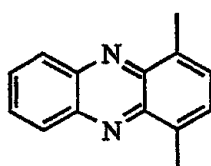
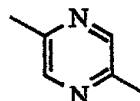
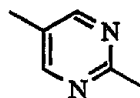
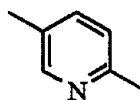
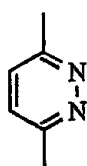
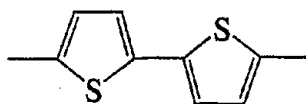
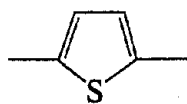
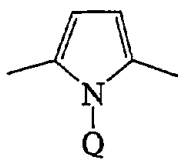
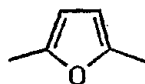
X is preferably O, S, SO_2 , $C(R^3)_2$, $N-R^3$, $Si(R^3)_2$.

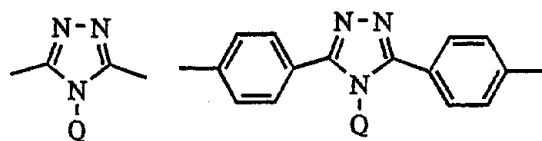
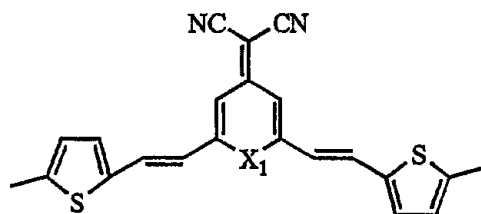
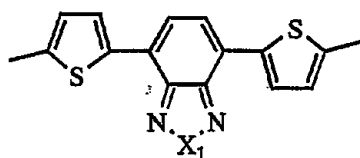
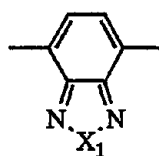
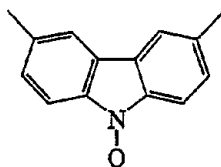
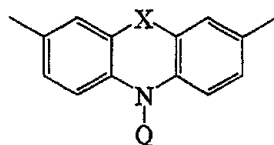
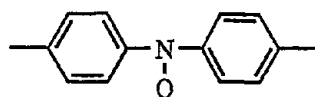
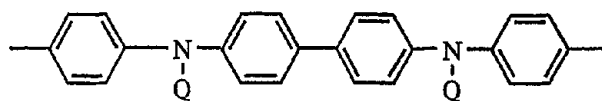
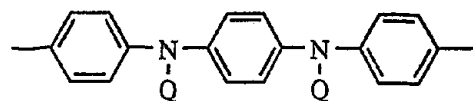
R^3 is a substituted or unsubstituted C_6 to C_{40} aryl, C_6 to C_{24} aralkyl, or a C_1 to C_{24} alkyl. Preferably R^3 is a C_6 to C_{24} aryl group, more preferably R^3 is a C_6 to C_{24} aralkyl group.

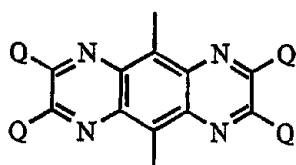
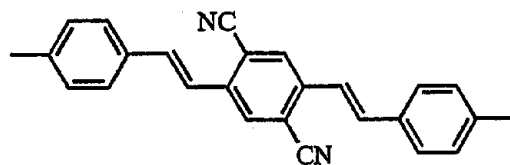
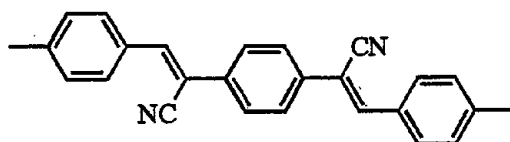
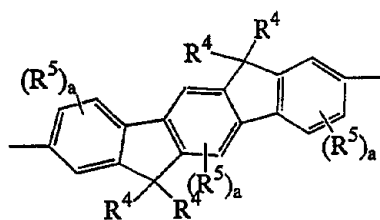
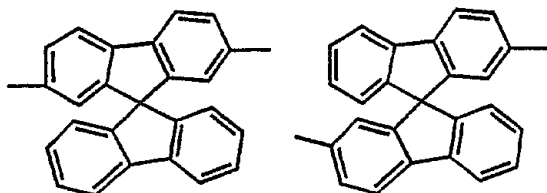
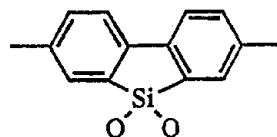
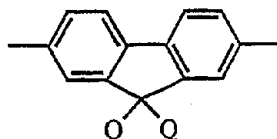
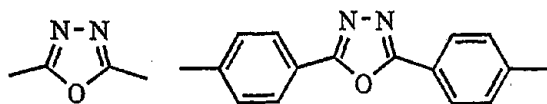
Ar is a substituted or unsubstituted C_6 to C_{40} aryl or heteroaryl group. Examples of suitable Ar groups include phenyl, alkylated phenyl, 9,9-dialkyl-2-fluorenyl, anthryl, phenanthryl, pyrenyl, pyridinyl, isoquinolinyl, quinolinyl, triazinyl, triazolyl, benzotriazolyl, or phenanthridinyl.

In a preferred embodiment, additional conjugated units including hole transporting moieties, electron transporting moieties, and/or light emitting moieties are present. The additional units are used to optimize one or more of the following: charge injection, charge transport, electroluminescent device efficiency and lifetime. Additional units include:









wherein the conjugated unit may bear substituents, such substituents being independently in each occurrence C_{1-20} hydrocarbyl, C_{1-20} hydrocarboxyloxy, C_{1-20} thioether, C_{1-20} hydrocarboxycarboxyly, C_{1-20} hydrocarbylcarbonyloxy, cyano or fluoro group.

X_1 is O or S;

Q is R or Ar;

R is C_1 to C_{20} ;

R^4 is independently in each occurrence H, C_{1-40} hydrocarbyl or C_{3-40} hydrocarbyl containing one or more S, N, O, P, or Si atoms or both R^4 together with carbon to which both R^4 are bonded may form a C_{5-20} ring structure which may contain one or more S, N, or O atoms. R^5 is independently C_{1-20} hydrocarbyl, C_{1-20} hydrocarblyoxy, C_{1-20} thioether, C_{1-20} hydrocarblyoxycarbonyl, C_{1-20} hydrocarbylcarbonyloxy or cyano.

The polymers of the invention preferably have a weight average molecular weight of 10,000 Daltons or greater, more preferably 20,000 Daltons or greater, even more preferably 50,000 Daltons or greater; preferably 1,000,000 Daltons or less, more preferably 500,000 Daltons or less, and most preferably 400,000 Daltons. Molecular weights are determined using gel permeation chromatography using polystyrene as an internal standard.

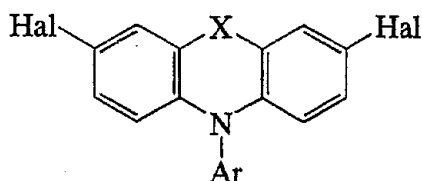
Preferably, the polymers demonstrate a polydispersity (M_w/M_n) of 10 or less, more preferably 5 or less, even more preferably 4 or less and most preferably 3 or less.

The polymers and copolymer blends of the invention demonstrate strong photoluminescence in dilute solutions or in the solid state. When such materials are exposed to a light of a wavelength of 360-500 nanometers (nm), the materials emit light of wavelengths in the region of 400-700 nm. More preferably, such materials absorb light of wavelengths of from 380-450 nm and emit light of wavelengths 420-680 nm.

The polymers of this invention may be assembled by any known coupling reaction for making aromatic compounds. Preferably, the Suzuki coupling reaction is used. The Suzuki reaction couples aromatic compounds using a diboronated aromatic moiety and a dihalogenated aromatic moiety. The reaction allows for the creation of long chain, high

molecular weight polymers. Additionally, by controlling the sequence of addition, either random or block copolymers may be produced.

Preferably, the Suzuki reaction starts with a diboronated fluorene monomer or diboronated substituted fluorene monomer and a dihalogenated conjugated monomer having the formula:



Where X is O, S, SO₂, C(R³)₂, N-R³, Si(R³)₂, preferably O or S; Ar is as previously defined and is preferably 4-alkylphenyl, 4-alkoxyphenyl, 4-aminophenyl. More preferred Ar is 4-*n*-butylphenyl, (9,9-dibutyl)-2-fluorenyl, methoxyphenyl, ethoxyphenyl, or 4-ditolylaminophenyl.

Optionally, additional dihalogenated conjugated monomers may be used. The polymer structure will have the structure fluorene-conjugated monomer, fluorene-conjugated monomer, etc.

Optionally, a conjugated dihalogenated moiety such as dihalogenated versions of phenylenediamine, substituted phenylenediamine, benzidine, substituted benzidine, triarylamine, substituted triarylamine, benzothiadiazole, thiophene, bis-thiophene-benzothiadiazole, dicyanovinylenepyrans or thiopyrans may also be used.

The Suzuki process is taught in U.S. Patent No. 5,777,070, which is expressly incorporated herein by reference.

Toluene or xylenes are the preferred solvents for the Suzuki reaction to prepare the polymers of the instant invention. Sodium carbonate in water is the preferred base, tetrakis(triphenylphosphine)palladium is the preferred catalyst, and a phase transfer catalyst preferably a quaternary ammonium salt is used to speed up the reaction for achieving high molecular weight in a short period of time.

Tricyclic amines unsubstituted on the nitrogen atom are commercially available from many commercial vendors including Aldrich Chemical Company. Aryl substituted tricyclic amines are produced through the reaction of a N-unsubstituted precursor with a brominated or iodinated aryl or substituted aryl compound. The ratio of diarylamine to bromoaryl or iodoaryl or substituted bromo or iodo aryl is 1 to 1.2-2. The materials are reacted in the presence of a catalyst. Preferably, the catalyst is palladium acetate and tri-*o*-tolylphosphine. Preferably, sodium tert-butoxide may be used as the base. The materials are heated and refluxed for 15 hours at 80-110 °C in toluene. The solution is cooled. Tricyclic amine is isolated and further brominated with bromination techniques known to those skilled in the art. The most preferred brominating agent is N-bromosuccinimide in a solvent such as DMF, methylene chloride, etc.

Another aspect of this invention is related to polymer blends. The blends comprise a polymer containing repeat units of Formula I or Formula I and Formula II blended with at least one other conjugated polymer. As used herein, the term "conjugated polymer" means a polymer with a backbone of overlapping pi orbitals. Conjugated polymers that may be used in the blends include polyfluorenes, poly(arylenevinylene), polyphenylenes, polyindenofluorenes and polythiophenes, including homopolymers, co-polymers or substituted homopolymers and/or copolymers of any of these conjugated polymers.

Preferably the polymer blend is composed of at least 10 percent of a polymer containing units of Formula I or Formula I and Formula II and 90 percent of another conjugated polymer. Preferably the band gap of the conjugated polymer is narrower than the band gap of polymer containing units of Formula I or Formula I and Formula II. The most preferred polymer blends have high photoluminescent and electroluminescent efficiency. Other additives such as viscosity modifiers, antioxidants and coating improvers may optionally be added. Additionally, blends of two or more low polydispersity polymers of similar compositions but different molecular weight can also be formulated.

Another aspect of this invention is the films formed from the polymers of the invention. Such films can be used in polymeric light emitting diodes, photovoltaic cells and field effect transistors. Preferably such films are used as emitting layers or charge carrier

transport layers. The films may also be used as protective coatings for electronic devices and as fluorescent coatings. The thickness of the film or coating is dependent upon the use.

Generally, such thickness can be from 0.005 to 200 micron. When the coating is used as a fluorescent coating, the coating or film thickness is from 50 to 200 microns. When the coatings are used as electronic protective layers, the thickness of the coating can be from 5 to 20 microns. When the coatings are used in a polymeric light-emitting diode, the thickness of the layer formed is 0.005 to 0.2 microns. The polymers of the invention form good pinhole and defect-free films.

The films are readily formed by coating the polymer composition from another embodiment of this invention in which the composition comprises the polymer and at least one organic solvent. Preferred solvents are aliphatic hydrocarbons, chlorinated hydrocarbons, aromatic hydrocarbons, ketones, ethers and mixtures thereof. Additional solvents which can be used include 1,2,4-trimethylbenzene, 1,2,3,4-tetramethyl benzene, pentylbenzene, mesitylene, cumene, cymene, cyclohexylbenzene, diethylbenzene, tetralin, decalin, 2,6-lutidine, 2-fluoro-m-xylene, 3-fluoro-o-xylene, 2-chlorobenzotrifluoride, dimethylformamide, 2-chloro-6-fluorotoluene, 2-fluoroanisole, anisole, 2,3-dimethylpyrazine, 4-fluoroanisole, 3-fluoroanisole, 3-trifluoro-methylanisole, 2-methylanisole, phenetol, 4-methylansiole, 3-methylanisole, 4-fluoro-3-methylanisole, 2-fluorobenzonitrile, 4-fluoroveratrol, 2,6-dimethylanisole, 3-fluorobenzonitrile, 2,5-dimethylanisole, 2,4-dimethylanisole, benzonitrile, 3,5-dimethylanisole, N,N-dimethylaniline, ethyl benzoate, 1-fluoro-3,5-dimethoxybenzene, 1-methylnaphthalene, N-methylpyrrolidinone, 3-fluorobenzotrifluoride, benzotrifluoride, benzotrifluoride, diosane, trifluoromethoxybenzene, 4-fluorobenzotrifluoride, 3-fluoropyridine, toluene, 2-fluorotoluene, 2-fluorobenzotrifluoride, 3-fluorotoluene, 4-isopropylbiphenyl, phenyl ether, pyridine, 4-fluorotoluene, 2,5-difluorotoluene, 1-chloro-2,4-difluorobenzene, 2-fluoropyridine, 3-chlorofluorobenzene, 3-chlorofluorobenzene, 1-chloro-2,5-difluorobenzene, 4-chlorofluorobenzene, chlorobenzene, o-dichlorobenzene, 2-chlorofluorobenzene, p-xylene, m-xylene, o-xylene or mixture of o-, m-, and p- isomers. It is preferable that such solvents have relatively low polarity. High boilers and solvent mixtures are better for ink jetting, but xylenes and toluene are best for spin coating.

Preferably the solution contains from 1 to 5 percent of a polymer comprising a repeat unit of Formula I and/or a repeat unit of Formula I and a repeat unit of Formula II.

Films can be prepared by means well known in the art including spin-coating, spray-coating, dip-coating, roll-coating, offset printing, ink jet printing, screen printing, stamp-coating or doctorblading.

In a preferred embodiment, the invention is a composition comprising a polymer or polymer blend of the invention in a solvent. Solvents which can be used include toluene, xylene, a mixture of *o*, *m* and *p*-isomers of xylene, mesitylene, diethylbenzene, ethylbenzene or benzene derivatives or higher substitute level. Preferably, the solution contains from 0.1 to 10 weight percent of the composition. For thin coatings, it is preferred that the composition contains from 0.5 to 5.0 percent by weight of the composition. The composition is applied to the appropriate substrate by the desired method and the solvent is allowed to evaporate. Residual solvent may be removed by vacuum, heat and/or by sweeping with an inert gas such as nitrogen.

The polymers of this invention demonstrate strong electroluminescence in addition to photoluminescence. Thus, another aspect of the invention relates to organic electroluminescent (EL) devices having a film comprising the polymers of this invention. EL devices based on the polymers of this invention demonstrate improved efficiency over devices in which the electroluminescent polymer film does not contain a repeat unit comprising a tricyclic amine. Preferably, the EL devices of this invention emit light when subjected to an applied voltage of preferably 20 volts or less, preferably 10 volts or less and most preferably 6 volts or less.

An organic EL device typically consists of an organic film sandwiched between an anode and a cathode. When a positive bias is applied to the device, holes are injected into the organic film from the anode, and electrons are injected into the organic film from the cathode. The combination of a hole and an electron may give rise to an exciton that may undergo radiative decay to the ground state by liberating a photon.

In practice, the anode is commonly a mixed oxide of tin and indium for its conductivity and transparency. The mixed oxide (ITO) is deposited on a transparent

substrate such as glass or plastic so that the light emitted by the organic film may be observed. The organic film may be the composite of several individual layers each designed for a distinct function. Because holes are injected from the anode, the layer next to the anode should have the functionality of transporting holes. Similarly, the layer next to the cathode should have the functionality of transporting electrons. In many instances, the electron or hole transporting layer may also act as the emitting layer. In some instances, a single layer may perform the combined functions of hole and electron transport and light emission.

The metallic cathode may be deposited either by thermal evaporation or by sputtering. The thickness of the cathode may be from 1 nm to 10,00 nm. The preferred metals are calcium, magnesium, indium, aluminum and barium. A thin layer (1-10 nm) of an alkali or alkaline metal halide, for example, LiF, NaF, CsF or RbF may be used as a buffering layer between the light emitting polymer and the cathode, calcium, barium, or magnesium. Alloys of these metals may also be used. Alloys of aluminum containing 1 to 5 percent of lithium and alloys of magnesium containing at least 80 percent of magnesium are preferred.

In a preferred embodiment, the electroluminescent device comprises at least one hole injecting polymer film (PEDOT film, for example) and a light-emitting polymer film comprised of the composition of the invention, arranged between an anode material and a cathode material such that under an applied voltage, holes are injected from the anode material into the light emitting polymer via the hole-injecting polymer film and electrons are injected from the cathode material into the light-emitting polymer film when the device is forward biased, resulting in light emission from the light-emitting layer. In another preferred embodiment, layers of hole-transporting polymers are arranged so that the layer closest to the anode has the lowest oxidation potential, with the adjacent layers having progressively higher oxidation potentials. By these methods, electroluminescent devices having relatively high light output per unit voltage may be prepared.

Another embodiment of the invention relates to photocells comprising one or more of the polymers of the invention wherein the polymers are present as single-layer films or as multiple-layer films, whose combined thickness is in the range of 10 nm to 1000 nm,

preferably in the range of 25 nm to 500 nm, most preferably in the range of 50 nm to 300 nm. When two or more polymers are used, they may be deposited separately as distinct layers or deposited as one layer from a solution containing a blend of the desired polymers.

"Photocells" means a class of optoelectronic devices that can convert incident light energy into electrical energy. Examples of photocells are photovoltaic devices, solar cells, photodiodes, and photodetectors. A photocell generally comprises a transparent or semi-transparent first electrode deposited on a transparent substrate. A polymer film is then formed onto the first electrode that is, in turn, coated by a second electrode. Incident light transmitted through the substrate and the first electrode is converted by the polymer film into excitons that can dissociate into electrons and holes under the appropriate circumstances, thus generating an electric current.

Another embodiment of the invention relates to metal-insulator-semiconductor field effect transistors comprising one or more of the polymers of the invention which serve as a semiconducting polymer. A field effect transistor comprises five elements. The first element is an insulator layer. The insulator layer is an electrical insulator, having a first side and a second side. The second element is a gate. The gate is an electrical conductor. The gate is positioned adjacent the first side of the insulator layer.

The third element is a semiconductor layer. The semiconductor layer comprises a polymer comprising a repeat unit of fluorene or substituted fluorene bonded to a tricyclic arylamine which is then bonded to a fluorene or substituted fluorene which is then bonded to a conjugated moiety. The semiconductor layer has a first side, a second side, a first end and a second end, the second side of the semiconductor layer being adjacent to the second side of the insulator layer. The polymer is deposited onto an insulator wherein the polymers are present as single-layer films or as multiple-layer films whose combined thickness is in the range of 10 nm to 1000 nm, preferably in the range of 25 nm to 500 nm, most preferably in the range of 50 nm to 300 nm.

The fourth element of a field effect transistor is a source. The source is an electrical conductor. The source is in electrical contact with the first end of the semiconductor layer. The fifth element is a drain. The drain is an electrical conductor. The drain is in electrical

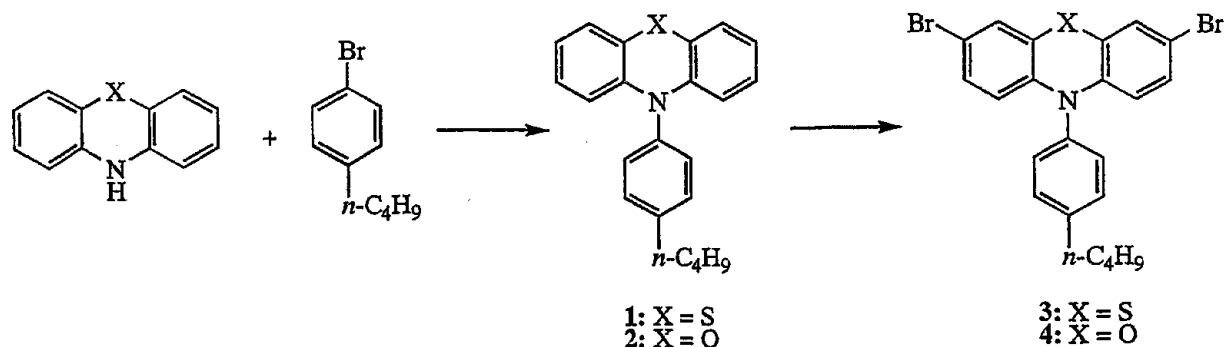
contact with the second end of the semiconductor layer. A negative voltage bias applied to the gate causes the formation of a hole conduction channel in the semiconductor layer connecting the source to the drain. A positive bias applied to the gate causes the formation of an electron-conducting channel in the semiconductor layer.

As with electroluminescent devices, the polymer films comprising the semiconductor layer may be formed by solvent-based processing techniques such as spin-coating, roller-coating, dip-coating, spray-coating and doctor-blading and ink jet printing. When two or more polymers are used, they may be deposited separately as distinct layers or deposited as one layer from a solution containing a blend of the desired polymers.

Two electrodes (source and drain) are attached to the semiconducting polymer and a third electrode (gate) onto the opposite surface of the insulator. If the semiconducting polymer is hole transporting (i.e, the majority carriers are positive holes), then applying a negative DC voltage to the gate electrode induces an accumulation of holes near the polymer-insulator interface, creating a conduction channel through which electric current can flow between the source and the drain. The transistor is in the "on" state. Reversing the gate voltage causes a depletion of holes in the accumulation zone and cessation of current. The transistor is in the "off" state.

Examples

The following examples are included for illustrative purposes only and do not limit the scope of the claims.

Example 1**Synthesis of Dibromotricyclic Arylamines****Scheme 1.** Synthesis of N-(4-butylphenyl)phenothiazine and phenoxazine compounds

a) $\text{Pd}(\text{OCOCH}_3)_2$, tri-*o*-tolylphosphine, *t*-BuO Na^+ , toluene, reflux
b) N-bromosuccinimide, CH_2Cl_2 , 0°C -r.t.

N-(4-*n*-Butylphenyl)phenothiazine (1: X=S)

A 2 L 3 neck round bottom flask equipped with overhead stirrer, reflux condensor and a nitrogen line was charged with 0.948 g (4.216 mmol) palladium acetate and 2.647 g (8.746 mmol) tri-*o*-tolylphosphine and 50 ml toluene. The mixture was stirred at ambient temperature for 20 minutes until an orange-red solution was formed. At that time, phenothiazine (19.93 g, 100 mmol), 1-bromo-4-butyl benzene (23.6 g, 110 mmol) and sodium *t*-butoxide (10.71 g, 100 mmol) along with 1000 mL toluene were added. The reaction was placed in an oil bath and heated to reflux for 15 hours. A sample was taken for HPLC showing that all starting material were gone. A major peak with the retention time of 8.6 minutes was seen. The solution was cooled. 15 mL concentrated HCl were added. The solution was stirred for an additional hour. Then the solution was passed through a neutral alumina column (750 g). The column was rinsed with toluene. The solvent was removed using a rotary evaporator to yield a yellow solid. The solid was recrystallized from toluene/MeOH. 19.6 g of white solid was obtained with 99 percent purity. The yield was 60.6 percent. MS: 331. ^1H NMR (DMSO) δ 0.92 (t, 3H), 1.36 (m, 2H), 1.62 (m, 2H), 2.73 (t, 2H), 6.13 (d, 2H), 6.87 (m, 4H), 7.05 (d, 2H), 7.30 (d, 2H), 7.47 (d, 2H).

N-(4-*n*-Butylphenyl)phenoxazine (2: X=O)

This compound was prepared essentially according to the above procedure for preparation of **1**. The crude product was recrystallized from toluene/MeOH and 8.1 g shiny white solid was obtained with ~100 percent purity. The yield was 51.24 percent.

3,7-Dibromo-N-(4-*n*-butylphenyl)phenothiazine (3: X=S)

A 500 mL 3 neck round bottom flask equipped with overhead stirrer, reflux condensor and a nitrogen line was charged with **1** (9.1 g, 27.5 mmol) and 140 mL methylene chloride. The solution was kept in an ice bath. To the stirring mixture, a solution of N-bromosuccinimide (10.26 g, 57.0 mmol) in 20 mL dimethyl foramide ("DMF") was added in drops through a syringe over a 10 minute period. The reaction mixture was brought to room temperature and allowed to stir for 2 hours. A sample was taken for HPLC showing all starting material (8.6 minute) were gone and a major peak with the retention time of 10.3 minutes was shown. The reaction mixture was washed three times with 2N HCl 200 mL, then washed with 200 mL water twice until the water layer turned to neutral. The organic portion was dried with Na₂SO₄. Na₂SO₄ was filtered out, and then the solution was passed through a neutral alumina column. The column was rinsed with toluene. The solvent was removed using a rotary evaporator to yield a light yellow solid with a purity of 96.7 percent. After three recrystallizations from hexanes, 5.6 g (41.2 percent) of a final product was obtained with a purity of 99.5 percent. MS: 487. ¹H NMR (DMSO): δ 0.95 (t, 3H), 1.36 (m, 2H), 1.62 (m, 2H), 2.75 (t, 2H), 5.97 (d, 2H), 7.08 (dd, 2H), 7.26 (m 4H), 7.48 (d, 2H).

This compound was prepared essentially according to the procedure for preparation of **3**. The crude product was recrystallized from toluene/methanol, and 5.1 g of white shiny solid with a purity of 99.8 percent was obtained. The yield was 85 percent.

Scheme 2. Synthesis of phenothiazine and phenoxazine compounds with a fluorene unit as a pendant group



A mixture of palladium acetate (180 mg, 0.81 mmol), tri-*o*-tolylphosphine (530 mg, 1.74 mmol) and toluene (12 mL) was stirred at ambient temperature for 30 minutes until a homogenous yellow solution was formed. The reaction mixture was covered under nitrogen. Phenothiazine (3.99 g, 20 mmol), 2-bromo-9,9-dibutylfluorene (7.85 g, 22 mmol), sodium *tert*-butoxide (2.88 g, 30 mmol) and more toluene (175 mL) were added to this mixture. The reaction vessel was placed into an oil-bath and heated to reflux overnight. HPLC showed that the reaction was incomplete. An additional 800 mg of 2-bromo-9,9-dibutylfluorene was added to the reaction flask. The mixture was refluxed for an additional 6 hours. The mixture was then cooled to ambient temperature, treated with hydrochloric acid (10 mL), passed through a column of neutral Alumina (Brockman Activity I) and eluted with toluene. The solvent was removed on a rotary evaporator under reduced pressure. The crude product was recrystallized from toluene/ethanol. Finally, 4.75 g (50 percent) of product was obtained. HPLC analysis indicated the product was in 98 percent

purity. ^1H NMR was consistent with the structure. ^1H NMR (THF) δ 8.02 (d, 1H), 7.82 (m, 1H), 7.5-7.3 (m, 5H), 6.98 (m, 2H), 6.79 (m, 4H), 6.25 (m, 2H), 2.07 (m, 4H), 1.12 (m, 4H), 0.69 (m, 10H).

***N*-(9,9-Di-*n*-butylfluorene)phenoxazine (6: X=O)**

The compound was prepared essentially according to the procedure for synthesis of 5. Phenoxazine was used in place of phenothiazine. 14.9 g (64 percent) of product 6 was obtained. HPLC analysis indicated the product was in 98 percent purity. NMR was consistent with the structure. ^1H NMR (THF) δ 8.00 (d, 1H), 7.82 (m, 1H), 7.5-7.3 (m, 5H), 6.62 (m, 6H), 6.00 (m, 2H), 2.07 (m, 4H), 1.10 (m, 4H), 0.69 (m, 10H).

3,7-Dibromo-*N*-(9,9-di-*n*-butylfluorene)phenothiazine (7: X=S)

4.28 g (9 mmol) of 5, 40 mL of DMF and 40 mL of tetrahydrofuran ("THF") were charged to a 500 mL flask equipped with a stirring bar. The mixture was covered with nitrogen. To this mixture, 3.20 g (18 mmol) of NBS in 10 mL of DMF was slowly added at 0 °C. The mixture was allowed to warm up to room temperature and stirred for 6 hours. 200 mL $\text{H}_2\text{O}/\text{EtOH}$ (1:1) was added to reaction mixture. White solid was precipitated. The resulting mixture was filtered. The solid was washed with hot *iso*-propanol and CH_3CN . The crude product was recrystallized twice from $\text{CH}_2\text{Cl}_2/\text{CH}_3\text{CN}$. 2 g (35 percent) of product was obtained as light yellow solid. HPLC analysis indicated the product was in 99 percent purity. ^1H NMR and mass spec were consistent with the structure. ^1H NMR (THF) δ 8.02 (d, 1H), 7.84 (m, 1H), 7.5-7.3 (m, 6H), 7.18 (m, 2H), 6.74 (m, 2H), 6.10 (m, 2H), 2.07 (m, 4H), 1.12 (m, 4H), 0.69 (m, 10H).

3,7-Dibromo-*N*-(9,9-di-*n*-butylfluorene)phenoxazine (8: X=O)

This compound was prepared essentially according to the procedure described for 7. Phenoxazine was used in place of phenothiazine. 12.2 g (66 percent) of product was obtained. HPLC analysis indicated the product was in 99 percent purity. NMR and mass spec were consistent with the structure. ^1H NMR (THF) δ 8.02 (d, 1H), 7.83 (m, 1H), 7.5-7.3 (m, 6H), 6.88 (m, 1H), 6.75 (m, 2H), 5.90 (d, 2H), 2.06 (m, 4H), 1.12 (m, 4H), 0.69 (m, 10H).

Example 3

Preparation of Blue Light Emitting Polymer 1

2,7-Bis(1,3,2-dioxaborolan-2-yl)-9,9-dihexylfluorene (3.554 g, 7.4857 mmol), 2,7-dibromo-9,9-dihexylfluorene (3.074 g, 6.2381 mmol), 3,7-dibromo-N-(4-*n*-butylphenyl)phenothiazine (0.193 g, 0.3669 mmol), 2,7-dibromo-9,9-dibiphenylfluorene (0.231 g, 0.3669 mmol) and N,N'-bis(4-bromophenyl)-N,N'-bis(4-*n*-butylphenyl)phenylenediamine (0.253 g, 0.3669 mmol), Aliquat 336® phase transfer reagent (1.21 g), tetrakis(triphenylphosphine)palladium (10.9 mg), and 50 mL toluene were added to a 250 mL three necked round bottom flask equipped with a stir shaft, glass stopper and reflux condensor. The solid was allowed to dissolve in toluene then 15.5 mL of a 2M Na₂CO₃ solution was added. The total volume of the mixture was 65.5 mL. The entire system was connected to a nitrogen line through the reflux condenser so that a dynamic blanket of nitrogen was over the solution throughout the duration of the reaction. All solids went into the solution in 4 hours and 5 minutes. Polymerization took 5 hours and 25 minutes at 100°C. The reaction was capped after polymerization by adding 0.202 g phenylboronic acid followed by 20 mL toluene. After overnight stirring at 100 °C, the reaction vessel was cooled to 84 °C and 3 g of diethyldithiocarbamic acid sodium salt trihydrate was added directly to the polymer solution followed by 30 mL of water. The reaction was allowed to stir for 5 hours and then was taken out of the oil bath and cooled. The polymer solution was transferred to a 2 L separatory funnel and allowed to sit for 15 minutes. After the water layer was separated from the polymer solution, the polymer solution was washed twice with 2 percent of acetic acid (100 mL) and twice with water (100 mL). The polymer solution was then passed through a column of celite, silica gel, basic alumina, and celite. The column was then eluted with warm toluene (2X volume of polymer solution). The isolated polymer was placed in a vacuum oven at 55°C to dry overnight. The crude polymer was re-dissolved in toluene (3 percent wt/vol solution) and re-precipitated from excess methanol. The polymer was collected by filtration and dried in a vacuum oven at 55°C overnight. Total polymer collected was: 3.95 g; $\eta_{inh} = 2.07$ dL/g (THF, 25°C, 0.5 g/dL); Mw: 234,723; PDI (poly-dispersity indx): 3.182.

Preparation of Blue Light Emitting Polymer 2

9,9-Dihexylfluorene-2,7-boronic acid ethylene glycol ester (~99.9 percent, 3.518 g, 7.408 mmol), 2,7-dibromo-9,9-dihexylfluorene (~99.9 percent, 3.043 g, 6.174 mmol), *N,N'*-bis(4-*n*-butylbenzene)-*N,N'*-bis(4-bromophenyl)-1,4-phenylenediamine (~98.8 percent, 0.251 g, 0.363 mmol), 3,7-dibromo-*N*-(9,9-di-*n*-butylfluorene)phenothiazine (~99 percent, 0.233 g, 0.363 mmol), 2,7-dibromo-9,9-dibiphenylfluorene (~100 percent, 0.228 g, 0.363 mmol), toluene (50 mL), Aliquat 336 phase transfer agent, (1.07 g, 2.600 mmol), tetrakis(triphenylphosphine)palladium (0) (7.6 mg, 0.007 mmol), and 2M aqueous sodium carbonate solution (15 mL) were placed in a 250 mL three-neck flask equipped with an overhead stirrer and condensor. The system was purged with nitrogen. The mixture was gently refluxed overnight. A viscous mixture was observed at the end of the polymerization. To terminate the polymerization, 0.2 g of benzene boronic acid (dissolved in 2 mL THF) and 50 mL of toluene were added, and the reaction was allowed to continue for 8 more hours. After cooling, the mixture was diluted with toluene and transferred to a separatory funnel. The aqueous phase was removed and the organic phase was washed with water. The toluene layer was then transferred to a 500 mL three-necked flask, and an aqueous solution of sodium diethyldithiocarbamate trihydrate (DDC, 3g in 30 water) was added. The mixture was stirred at ~88°C overnight. The aqueous layer was removed. The organic phase was washed with 2 percent AcOH and water, then passed through a column of celite, silica gel and basic alumina, and eluted with toluene. The eluates were concentrated with a rotary evaporator. The polymer was first precipitated from methanol/water and dried under vacuum at 45°C. The crude polymer was re-dissolved in toluene with heating and then precipitated from methanol. The polymer was filtered and washed with methanol. After drying under vacuum at 45°C overnight, 3.8 g (76 percent) of polymer was obtained: $\eta_{inh} = 2.93 \text{ dL/g}$ (THF, 25°C, 0.5 g/dL).

Preparation of Blue Light Emitting Polymer 3

9,9-Dioctylfluorene-2,7-boronic acid ethylene glycol ester (3.089 g, 5.8186 mmol), 3,7-dibromo-*N*-(4-*n*-butylphenyl)phenoxazine (0.545 g, 4.6088 mmol), 2,7-dibromo-9,9-

di(4-hexyloxyphenyl)fluorene (3.134 g, 4.6088 mmol) and Aliquot 336 (1.14 g, 2.0619 mmol), and 35 mL toluene were added to a 250 mL three necked round bottom flask quipped with a stirring shaft, glass stopper and reflux condensor. The solid was allowed to dissolve in toluene and 14 mL of a 2M Na_2CO_3 solution was added. Then tetrakis(triphenylphosphine)palladium (6.9 mg, 0.0056 mmol) was added and rinsed with 15 mL of toluene. Next, the whole system was connected to a nitrogen line through the reflux condenser so that a dynamic blanket of nitrogen was over the solution throughout the duration of the reaction. The reaction was started by stirring. Due to the bending rod, stirring was not smooth and solid was splashed all over the flask. The stirring rod was replaced. Some of the solid was pushed down and stirred at 640 RPM at 110°C. After four hours and fifty minutes, some solid was refluxed down to the solution. A spatula was used to push some more solid down. 35 mg of 9,9-dioctylfluorene-2,7-boronic acid ethylene glycol ester and 2 mg of tetrakis(triphenylphosphine)palladium and 10 mL of toluene were then added. The mixture was stirred at 700 RPM, 110°C. After thirty minutes, the reaction appeared to gel. The polymerization was capped by adding 0.52 g bromobenzene followed by 25 mL toluene and 40 mL THF. The color turned from brown to blue. The reaction was then stirred at 340 RPM, 110°C then overnight. The next morning, the reaction was sampled by GPC. The M_w was 560,000. The reaction was capped with 0.58 g of phenyl boronic acid followed by 20 mL of tetrahydrofuran. The reaction was then stirred at 300 RPM. After 14 hrs of stirring at 105°C, the reaction vessel was cooled to 84°C and 5 g of diethyldithiocarbamic acid sodium salt trihydrate was added directly to the polymer. 40 mL of water was then added. The reaction was allowed to stir overnight. After 100 mL of toluene was added, the reaction was taken out of the oil bath and cooled (the whole organic volume is 200 mL). The polymer solution was then transferred to a 2 L separatory funnel and allowed to sit for 15 minutes. After a water layer was separated from the polymer solution, the polymer solution was washed with 2 percent acetic acid (4 X 250 mL), water (4 x 250 mL) and then precipitated into 2.5 L of methanol. A fiber-like polymer was filtered out and dried overnight. The polymer was dissolved in 150 mL toluene then passed through basic aluminum oxide (3 inch)-silica gel (3 inch) column (The column was rinsed with 1 L toluene before using.). The column was rinsed with 1.5 L toluene. The polymer precipitate was collected and dried on a rotor evaporator at 60°C for an hour. It was then redissolved into 150 mL toluene and precipitated a third time into 2.5 L of methanol. The fiber-like

polymer was dried in an oven overnight at 55°C. The total polymer collected was: 4.3 g; $\eta_{inh} = 2.52$ dL/g (THF, 25°C, 0.5 g/dL); Mw: 669,000 ; PDI (poly-dispersity index): 3.40

Preparation of Blue Light Emitting Polymer 4

A 500 mL, three-necked, round bottom flask, equipped with an overhead stirrer and a reflux condenser which is connected to a nitrogen line, was charged with 2,7-bis(1,3,2-dioxaborolan-2-yl)-9,9-dihexylfluorene (6.037 g, 12.73 mmol, 2 mol percent excess), 2,7-dibromo-9,9-dihexylfluorene (4.914 g, 9.98 mmol), POZ, (0.591 g, 1.25 mmol), 1,4-dibromo-2,5-difluorobenzene (0.339 g, 1.25 mmol), Aliquat 336 phase-transferring reagent (1.5 g) and toluene (125 mL). The mixture was stirred until a homogenous solution was observed. To the solution aqueous sodium carbonate (2 M, 30 mL) was added and the system was stirred and purged with nitrogen for 10 min. Tetrakis(triphenylphosphine) palladium (14.7 mg, 0.1 mol percent) was added and the reaction was stirred and heated in an oil-bath at 95°C for 6 hours resulting in a very viscous yellow mixture. The mixture was diluted with 100 mL of toluene, and 1.0 g of phenyl boronic acid dissolved in 15 mL of THF was added and the mixture was stirred overnight. The mixture was diluted with 250 mL of toluene, transferred to a 1 L flask, and stirred with an aqueous solution of diethyldithiocarbamic acid sodium salt trihydrate (15 g/ 300 mL) at 80°C for 24 hours. The aqueous layer was separated and the toluene layer was washed with hot dilute acetic acid (2 percent, 3 x 300 mL) and warm water (1 x 300 mL). The polymer was precipitated from methanol (3.0 L), collected by filtration, and washed with methanol. The product was transferred to a 2 L round bottom flask, and the remaining methanol was removed by vacuum on a rotary evaporator. The solid was dissolved in 800 mL of toluene and passed through a column tightly packed with silica gel (4 x 8 cm), basic alumina (1 x 8 cm) and topped with filter paper. The polymer containing fractions were collected and the volume was reduced to ~ 400 mL. The polymer was precipitated from methanol and washed with methanol. The dissolving, precipitation process was performed one more time and the polymer was dried in a vacuum oven overnight to yield 6.3 g (79 percent) of a light yellow fibrous material. $\eta_{inh} = 2.15$ dL/g (THF, 25°C, 0.5 g/dL), Mw 250,900, Mn 92,800, PDI (polydispersity index): 2.7; Tg = 117.64°C.

Preparation of a Yellow Light Emitting Polymer 5

A 250 mL, three-necked, round bottom flask equipped with an overhead stirrer and a reflux condenser connected to a nitrogen line was charged with 2,7-bis (1,3,2-dioxaborolan-2-yl)-9,9-dioctylfluorene (99.7 percent, 7.26 mmol, 3.864 g), 4,7-dibromo-2, 1, 3-benzothiadiazole (99.8 percent, 5.69 mmol, 1.678 g), 3, 7-dibromo-N- (4-*n*-butyl phenyl)phenothiazine (99.0 percent, 1.42 mmol, 0.704 g), aqueous sodium carbonate (2M, 15mL), Aliquat 336 phase-transferring reagent (1 g, Aldrich), tetrakis(triphenylphosphine)palladium catalyst (7.7 mg, 0.10 mol percent, Strem) and toluene (40 mL, Fisher HPLC Grade). The reaction was stirred and heated to reflux in an oil bath at 105 °C for 15 hours. Ten mL toluene was added and the reaction heated for an additional hour. An orange viscous solution was observed. At this time, phenylboronic acid (0.6 g, Aldrich), toluene (10 mL) and THF (10 mL) were added and the stirring was continued for an additional 8 hours at 93°C. After cooling to 60°C, the organic layer was separated and washed with water (2 x 100 mL). The solution was then stirred with an aqueous solution of diethyldithiocarbamic acid sodium salt trihydrate (5 percent, 60mL) at 82°C for 18 hours. After cooling, the aqueous phase was separated and the organic solution was washed with 2 percent of acetic acid (3 x 200 mL) and water (2 x 200 mL). The organic layer was passed through a tightly packed column of celite (1'')-alumina, basic (1'') -silica gel (3'')-celite (1'') eluted with toluene. (The column had been eluted with 1 L toluene before using.) The polymer containing fractions were collected and the volume of solution was concentrated by rotary evaporation to ~100 mL. The polymer was precipitated from methanol/water (2 L/100 mL), collected by filtration and dried for 4 hours in a vacuum oven at 55°C. The polymer was redissolved in toluene (150 mL) and precipitated from methanol (2 L). The product was collected, washed with methanol and dried overnight in a vacuum oven at 55°C to yield an orange-yellow fibrous material. 3.2 g (80 percent) of polymer was obtained: $\eta_{inh} = 1.31$ dL/g (THF, 25°C, 0.5g/dL); Mw: 143,000; PDI (poly-dispersity index): 2; DSC measurements revealed a Tg of 129°C.

Preparation of Red Light Emitting Polymer 6

A 250 mL, three-necked, round bottom flask equipped with an overhead stirrer and a reflux condenser connected to a nitrogen line was charged with 2,7-bis(1,3,2-dioxaborolan-2-yl)-9,9-dioctylfluorene (99.7 percent, 6.59 mmol, 3.506 g), 4,7-dibromo-2,1,3-benzothiadiazole (99.8 percent, 3.83 mmol, 1.128 g), 3,7-dibromo-N-(4-n-butylphenyl)phenothiazine (99.0 percent, 0.479 mmol, 0.236 g), 2,7-dibromo-9,9-dioctylfluorene (100 percent, 1.915 mmol, 1.049 g), 4,7-bis(2-bromo-5-thiophenyl)benzothiadiazole (99.4 percent, 0.2394 mmol, 0.111 g), aqueous sodium carbonate (2 M, 14 mL), Aliquat 336® phase-transferring reagent (a trademark of Henkel, 0.95 g, Aldrich), tetrakis(triphenyl-phosphine)palladium catalyst (7.4 mg, 0.10 molpercent, Strem) and toluene (40 mL, Fisher HPLC Grade). The reaction was stirred and heated to reflux in an oil bath at 102°C for 15 hours. Twenty mL toluene was added and the reaction heated for an additional hour and forty five minutes. A red-orange viscous solution was observed. At this time, phenylboronic acid (0.68 g, Aldrich) and THF (20 mL) were added and the stirring was continued for an additional 8 hours at 93°C. After cooling to 60 °C, the organic layer was separated and washed with water (2 x 100 mL). The solution was then stirred with an aqueous solution of diethyldithiocarbamic acid sodium salt trihydrate (5 percent, 60 mL) at 81°C for 18 hours. After cooling, the aqueous phase was separated and the organic solution was washed with 2 percent of acetic acid (3 x 200 mL) and water (2 x 200 mL). The organic layer was passed through a tightly packed column of celite (1'')-alumina, basic (1'')-silica gel (3'')-celite (1'') eluted with toluene. (The column had been eluted with 1 L toluene before using.) The polymer containing fractions were collected and the volume of solution was concentrated by rotary evaporation to approximately 150 mL. The polymer was precipitated from methanol/water (2 L / 100 mL), collected by filtration and dried for 4 hours in a vacuum oven at 55°C. The polymer was redissolved in toluene (150 mL) and precipitated from methanol (2 L). The product was collected, washed with methanol and dried overnight in a vacuum oven at 55°C to yield an orange-red fibrous material. 3.31 g (83 percent) of polymer was obtained; η_{inh} = 2.35 dL/g (THF, 25 °C, 0.5g/dL); Mw: 333,000; PDI (poly-dispersity index): 2.58; DSC measurements revealed a Tg of 106°C.

Preparation of Green Light Emitting Polymer 7

A 500 mL, three-necked, round bottom flask, equipped with an overhead stirrer and a reflux condenser connected to a nitrogen line was charged with 2,7-bis(1,3,2-dioxaborolan-2-yl)-9,9-dioctylfluorene (1.84 g, 3.44 mmol), 4,7-dibromo-2,1,3-benzothiadiazole (1.01 g, 3.44 mmol), aqueous sodium carbonate (2 M, 5.0 mL), DI water (3.0 mL), Aliquat 336® phase-transferring reagent (0.3 g), tetrakis(triphenyl-phosphine)palladium (3.0 mg), and toluene (40 mL). The reaction was stirred and heated in an oil-bath at 95 °C for 16 hours. A red-orange solution was observed. The reaction was charged with 2,7-bis(1,3,2-dioxaborolan-2-yl)-9,9-dihexylfluorene (7.43 g, 15.7 mmol), 2,7-dibromo-9,9-dihexylfluorene (5.78 g, 11.73 mmol), and N-(4-butylphenyl)-3,7-dibromophenothiazine (1.78 g, 3.63 mmol), aqueous sodium carbonate (2 M, 31 mL), Aliquat 336 phase-transferring reagent (2.5 g), and tetrakis(triphenyl-phosphine)palladium (14 mg) and toluene (100 mL). The reaction was allowed to run for 8 hours and a very viscous material was observed. Bromobenzene (0.32 g) and toluene (50 mL) were added. Stirring was continued for 4 hours. Phenylboronic acid (1.22 g) was then added and the stirring was continued for another 14 hours. After cooling, the mixture was diluted with toluene (200 mL) and transferred into a 2 L three-neck round bottom flask. The aqueous layer was separated and the organic layer was transferred to a 3-necked round bottom flask. The solution was then stirred with an aqueous solution of diethyldithiocarbamic acid sodium salt trihydrate (5 percent, 250 mL) at 80°C for 8 hr. After cooling, the aqueous phase was separated, and the organic solution was washed with water (3 x 300 mL), then with 1percent of AcOH (3 x 300 mL). The water residue was azeotroped by rotary evaporation. The volume of the solution was adjusted to 350 mL and the polymer was precipitated from methanol (3 L) and collected by filtration. The crude polymer was dissolved in toluene (500 mL) with gentle heating. The solution was then passed through a silicon gel column eluted with toluene. The polymer containing fractions were collected, the volume of the solution was concentrated to 350 mL. The polymer was precipitated from methanol (3 L) and collected by filtration. The polymer was redissolved in toluene (300 mL) and precipitated again from methanol (3 L). The product was washed with methanol and dried in a vacuum oven at 60°C overnight to give a yellow fibrous material, 11.88 g (99 percent). Inherent viscosity $\eta_{inh} = 3.52$ dL/g (THF, 25°C, 0.5 g/dL), $T_g = 120.30^\circ\text{C}$.

Preparation of White Light Emitting Polymer 8

To a 1-liter, 3-neck round bottom flask equipped with reflux condenser and an overhead stirrer, the following monomers were added: 9,9-dioctylfluorene-2,7-boronicacid ethylene glycol ester (13.627 g, 25.692 mmol), 2,7-dibromo-9,9-dioctylfluorene (12.403 g, 22.615 mmol), 3,7-dibromo-N-(4-*n*-butylphenyl)-phenoxazine (0.595 g, 1.256 mmol), 4,7-dibromo-2,1,3-benzothiadiazole (8.2 mg, 0.028 mmol), 4,7-bis(5-bromo-2-thienyl)-2,1,3-benzothiadiazole (1.2 mg, 0.003 mmol) *N,N'*-di(4-bromophenyl)-*N,N'*-bis-(9,9-dibutyl)fluorene-1,4-phenylenediamine (1.220 g, 1.256 mmol) and bis(4-bromophenyl)-4-methylphenylamine (1.1 mg, 0.003 mmol). A 0.74M solution of Aliquat 336 phase transfer reagent ® in toluene (10.8 mL) was added, followed by 190 mL of toluene. After addition of the Pd(PPh₃)₄ catalyst, the mixture was stirred for fifteen minutes in an oil bath (105°C) until all of the monomer was dissolved. An aqueous solution of sodium carbonate (2.0 M, 48 mL) was added and the reaction was stirred in an oil bath (105°C) for 16.5 hours. Phenyl boronic acid (1.0 g) was then added and the reaction stirred for 7 hours. The aqueous layer was removed and the organic layer was washed with water (100 mL). The organic layer was placed back in the reaction flask, and 5.0 g of sodium diethyldithio-carbamate and 50 mL water were added. The reaction was stirred in an oil bath (85°C) for 16 hours. The aqueous layer was removed, the organic layer was washed with water (3 X 100 mL), then passed through a column of silica gel and basic alumina. The toluene/polymer solution was then precipitated into methanol (twice), and the polymer dried under vacuum at 60°C. Yield = 10.37 g (56.1 percent) $M_w = 167,000$; $M_w/M_n = 2.4$

Preparation of White Light Emitting Polymer 9

To a 1-liter, 3-neck round bottom flask equipped with reflux condenser and an overhead stirrer, the following monomers were added: 9,9-dioctylfluorene-2,7-boronicacid ethylene glycol ester (3.541 g, 6.677 mmol), 2,7-dibromo-9,9-dioctylfluorene (2.7786 g, 5.066 mmol), 3,7-dibromo-N-(4-*n*-butylphenyl)-phenothiazine (0.6969 g, 1.473 mmol), 4,7-bis(5-bromo-2-thienyl)-2,1,3-benzothiadiazole (3.0 mg, 0.007 mmol). A 0.74M solution of Aliquat 336® phase transfer reagent in toluene (2.9 mL) was added, followed by 100 mL of toluene. After addition of the Pd(PPh₃)₄ catalyst (7.6 mg), the mixture was stirred for fifteen

minutes in an oil bath (105°C) until all of the monomer was dissolved. An aqueous solution of sodium carbonate (2.0 M, 13 mL) was added and the reaction was stirred in an oil bath (105°C) for 22 hours. Phenyl boronic acid (0.5 g) was then added and the reaction stirred for 7 hours. The aqueous layer was removed and the organic layer was washed with water (100 mL). The organic layer was placed back in the reaction flask, and 2.0 g of sodium diethyldithiocarbamate and 50 mL water were added. The reaction was stirred in an oil bath (85°C) for 15 hours. The aqueous layer was removed, the organic layer was washed with water (3 X 100 ml), then passed through a column of silica gel and basic alumina. The toluene/polymer solution was then precipitated into methanol (twice), and the polymer dried under vacuum at 60°C. Yield = 3.01 g (60.2 percent) $M_w = 80,445$; $M_w/M_n = 2.4$

Preparation of Blue Light Emitting Polymer 10

Into a 250 mL three-necked flask equipped with an overhead stirrer and a condenser, was placed 9,9-dioctylfluorene-2,7-boronic acid ethylene glycol ester (99.9 percent, 3.105 g, 5.850 mmol), 2,7-dibromo-9,9-di(4'-ethoxyethoxyphenyl)fluorene (99.6 percent, 3.415 g, 5.213 mmol), 3,7-dibromo-N-(4-*n*-butylphenyl)phenoxazine (99.9 percent, 0.274 g, 0.5792 mmol), toluene (50 mL), Aliquat 336 phase transfer reagent, (0.86 g), trans-dichlorobis-(triphenylphosphine)-palladium(II) (3.8 mg), and 2M aqueous sodium carbonate solution (12 mL). The system was purged with nitrogen. The mixture was gently refluxed (105°C) for ~2.5 hours until a viscous mixture was observed. To terminate the polymerization, 0.2 g phenyl boronic acid in THF and 10 mL toluene were added. The mixture was refluxed for 16 hours. An aqueous solution of sodium diethyldithiocarbamate trihydrate (DDC, 3.5 g in 35 mL of water) was added. The mixture was stirred under nitrogen at ~84°C for 5 hours. The mixture was transferred to a separatory funnel and the aqueous layer was removed. The organic phase was washed twice with 2 percent acetic acid (aq) and three times with warm distilled water, passed through a column of Celite (~1"), silica gel (~3") and basic alumina (~1"), and eluted with toluene. The diluted polymer solution was concentrated on a rotary evaporator to a ~2 percent by weight solution. The polymer was precipitated from methanol/water and dried under vacuum at 55°C. The crude polymer was re-dissolved in toluene (CMOS grade) with heating and precipitated a second time from methanol (CMOS grade). The polymer was filtered, washed with methanol (CMOS grade) and dried in a

vacuum oven at 55°C overnight. 3.5 g (70 percent) of polymer was obtained: Mw = 281,000; PDI (polydispersity index) = 2.2.

Electroluminescent device fabrication and performance

Electroluminescent devices were prepared by the following procedures: ITO (indium tin oxide)-coated glass substrates were cleaned, coated with polyethylene dioxythiophene (PEDOT) and appropriate xylene solutions of emitting polymers. After drying, the cathode metal (calcium) was vapor deposited over the luminescent polymer film.

Device operational parameters at a brightness of 1000 Cd/m² are tabulated in Table 1, together with a measure of light efficiency, Cd/A, obtained according to the formula $L/(10J)$ where L is 1000 Cd/m². Bias voltage (V) is the voltage at which a brightness of 1000 Cd/m² is attained; similarly current density (J) is the current per unit area of the device at 1000 Cd/m², and is given in mA/cm². The maximum brightness in Cd/m², efficiency and CIE (1931) color coordinates are presented in Table 2.

Tables 3, 4, 5 and 6 compare the current density of devices containing polymers of the invention with devices containing similar polymers with repeat units of triaryl amines rather than the tricyclic amines. The data presented in Tables 3, 4, 5 and 6 demonstrate that the polymers comprising tricyclic aryl amines in a repeat unit are more conductive and improved device efficiency compared to polymers which include triaryl amines but do not contain tricyclic aryl amines.

As a convention, the polymers depicted in Tables 3, 4, 5 and 6 show a fluorene unit bonded to another conjugated moiety. This convention should be taken to mean that a fluorene based moiety is present on both sides of any conjugated moiety shown as part of a repeat unit.

Table 1: EL performance data (ITO/PEDOT/luminescent polymer/Ca/Al) @ brightness of 1000 Cd/m²

Polymer examples	Voltage (V)	Current Density J (mA/cm ²)	Light Efficiency (Cd/A)
Polymer 1 (Blue)	9.67	33.80	2.98
Polymer 2 (Blue)	9.50	32.65	3.01
Polymer 3 (Blue)	7.07	67.04	1.53
Polymer 4 (Blue)	8.22	93.50	1.09
Polymer 5 (Yellow)	7.97	218.1	0.46
Polymer 6 (Red)	8.75	199.9	0.50
Polymer 7 (Green)	4.51	38.61	2.59
Polymer 8 (White)	8.15	23.78	4.21
Polymer 9 (White)	9.8	176	0.56
Polymer 10* (Blue)	7.27	20.72	4.83

*Device data using Ba/Al as cathode

Table 2

Polymers	Max Brightness (Cd/m ²)	Efficiency (Cd/A @ 200 Cd/m ²)	Color Coordinates CIE (1931) (X, Y)
Polymer 1	9,179	3.11	0.18, 0.34
<u>Polymer 2</u>	9,952	3.00	0.17, 0.31
Polymer 3	8,909	0.96	0.15, 0.21
Polymer 4	5,916	0.68	0.15, 0.18
Polymer 5	1,445	0.47	0.54, 0.46
Polymer 6	1,580	0.68	0.67, 0.33
Polymer 7	12,957	2.19	0.42, 0.56
Polymer 8	15,600	3.9	0.26, 0.36
Polymer 9	2,400	0.38	0.31, 0.38
Polymer 10*	4,143 @ 102 mA/cm ²	5.28	0.15, 0.24

*Device data using Ba/Al as cathode

Table 3:

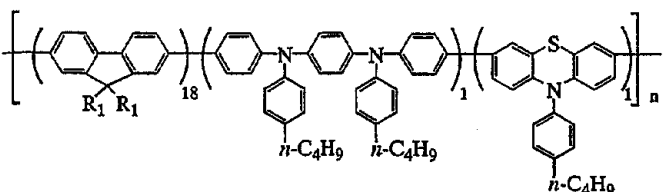
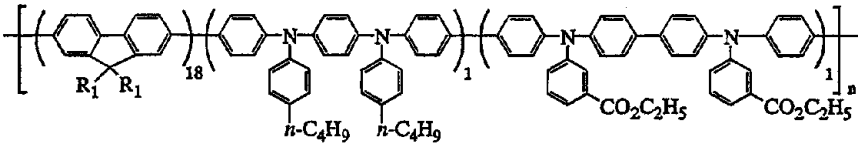
Polymers	Current Density ma/cm2 @ 8V	Current Density ma/cm2 @ 10V
 R1 = Hexyl or Biphenyl	29.8	104.1
 R1 = Hexyl or Biphenyl	8.0	44.3

Table 4:

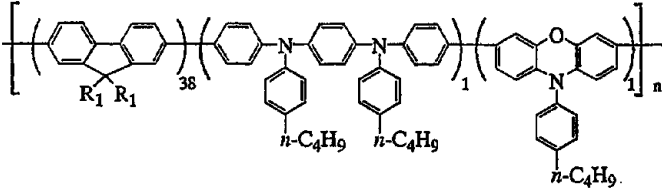
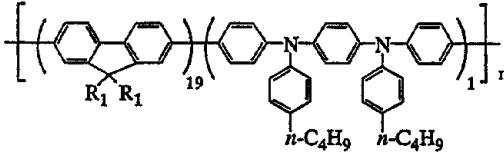
Polymers	Current Density ma/cm2 @ 8V	Current Density ma/cm2 @ 10V
 R1 = Octyl	27.6	91.0
 R1 = Octyl	2.3	11.8

Table 5:

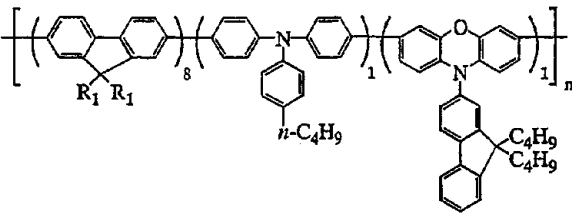
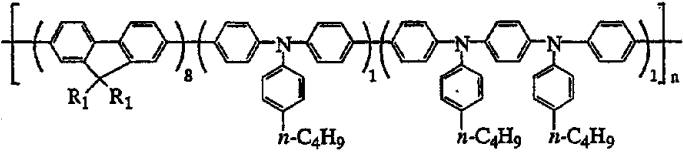
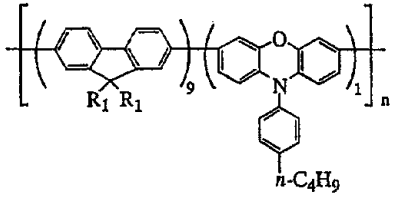
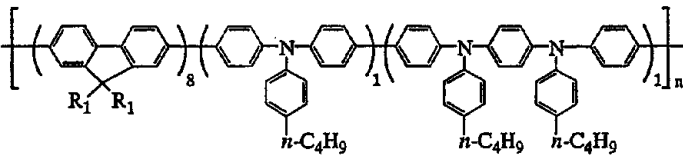
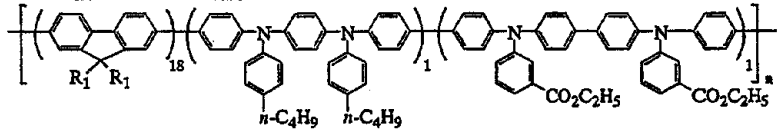
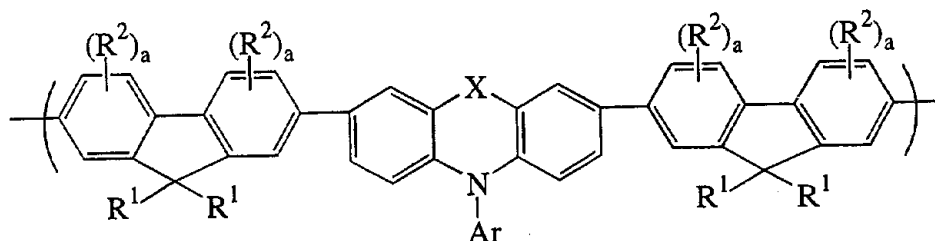
Polymers	Current Density ma/cm2 @ 8V	Current Density ma/cm2 @ 10V
 R1 = Octyl or Phenyl	68.7	194.9
 R1 = Octyl or Phenyl	47.0	126.0

Table 6:

Polymers	Current Density ma/cm2 @ 8V	Current Density ma/cm2 @ 10V
 R1 = Octyl	194.9	332.0
 R1 = Octyl or Phenyl	46.0	131.7
 R1 = Hexyl or Biphenyl	8.0	44.3

WHAT IS CLAIMED IS:

1. A polymer comprising a backbone with repeat units of Formula I:

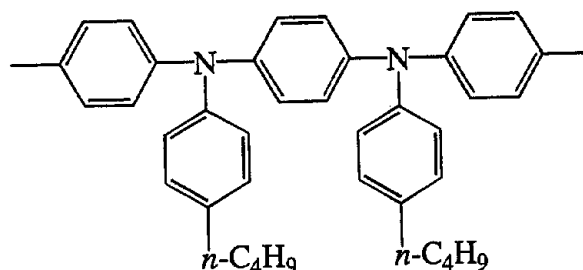


wherein R^1 is independently, in each occurrence H, C_{1-40} hydrocarbyl or C_{3-40} hydrocarbyl containing one or more S, N, O, P or Si atoms, or both of R^1 together with the 9-carbon on the fluorene forms a C_{5-20} ring structure containing one or more S, N, or O atoms;

R^2 is independently in each occurrence C_{1-20} hydrocarbyl, C_{1-20} hydrocarbyloxy, thioether, C_{1-20} hydrocarbyloxycarbonyl, C_{1-20} hydrocarbylcarbonyloxy, or cyano; a is independently, in each occurrence 0 or 1;

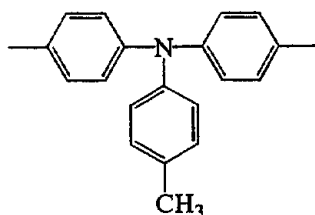
X is O, S, SO_2 , $C(R^3)_2$, $N-R^3$, $Si(R^3)_2$ wherein R^3 is a substituted or unsubstituted C_6 to C_{40} aryl, a C_6 to C_{24} aralkyl, or a C_1 to C_{24} alkyl; and Ar is a substituted or unsubstituted C_6 to C_{40} aryl or heteroaryl group.

2. The polymer of Claim 1 wherein a is 0; R^1 is independently in each occurrence n -hexyl, n -octyl, n -hexyloxyphenyl, 4-ethoxyethoxyphenyl, phenyl, or biphenyl, X is S or O, and Ar is 4-alkylphenyl, 4-alkoxyphenyl, or 4-aminophenyl.
3. The polymer of either of Claims 1 or 2 which further includes repeat units of the following formula:

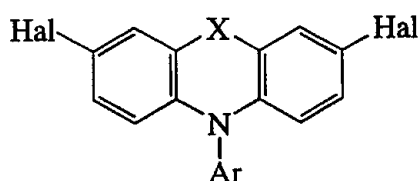


4. The polymer of any of Claims 1 to 3 which further includes repeat units of benzothiadiazole, dithiophenebenzothiadiazole, or both.

5. The polymer of any of Claims 1 to 4 which further includes repeat units of a triarylamine of the following structure:



6. The polymer of any of Claims 1 to 5 wherein Ar is 4-*n*-butylphenyl, (9,9-dibutyl)-2-fluorenyl, methoxyphenyl, ethoxyphenyl, or 4-ditolylaminophenyl.
7. A composition comprising the polymer of any of Claims 1 to 7, a solvent for the polymer, and optionally at least one other conjugated polymer.
8. An electroluminescent device comprising a film of the polymer of any of Claims 1 to 8 disposed between an anode and a cathode such that under an applied voltage, the film emits visible light which is transmitted through a transparent exterior portion of the device.
9. A device comprising the polymer of any of Claims 1 to 7 as a semiconductor layer for a field effect transistor.
10. A compound of the formula:



wherein X is O, S, SO₂, C(R³)₂, N-R³, or Si(R³)₂ wherein R³ is substituted or unsubstituted C₆ to C₄₀ aryl, C₆ to C₂₄ aralkyl, or C₁ to C₂₄ alkyl; and Ar is substituted or unsubstituted C₆ to C₄₀, substituted or unsubstituted heteroaryl, or 4-*n*-butylphenyl, or alkoxyphenyl or aminophenyl; and Hal is Br, Cl, or I.