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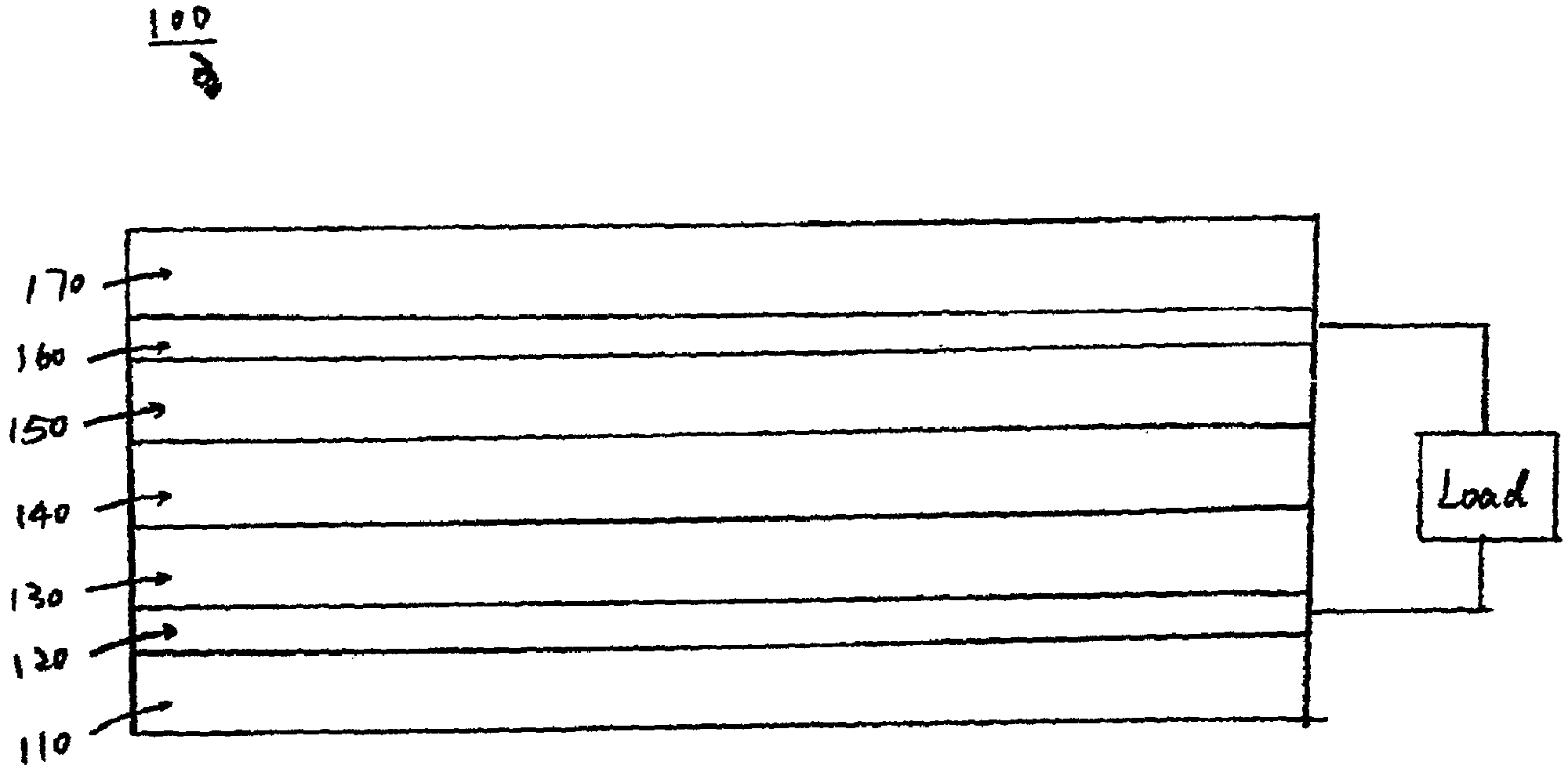
(54) Titre : POLYMERES A FAIBLE BANDE INTERDITE ET A MOBILITE DE CHARGE ELEVEE
(54) Title: POLYMERS WITH LOW BAND GAPS AND HIGH CHARGE MOBILITY



(57) Abrégé/Abstract:

Polymers with low band gaps and high charge mobility, as well as related systems, methods, and components are disclosed.

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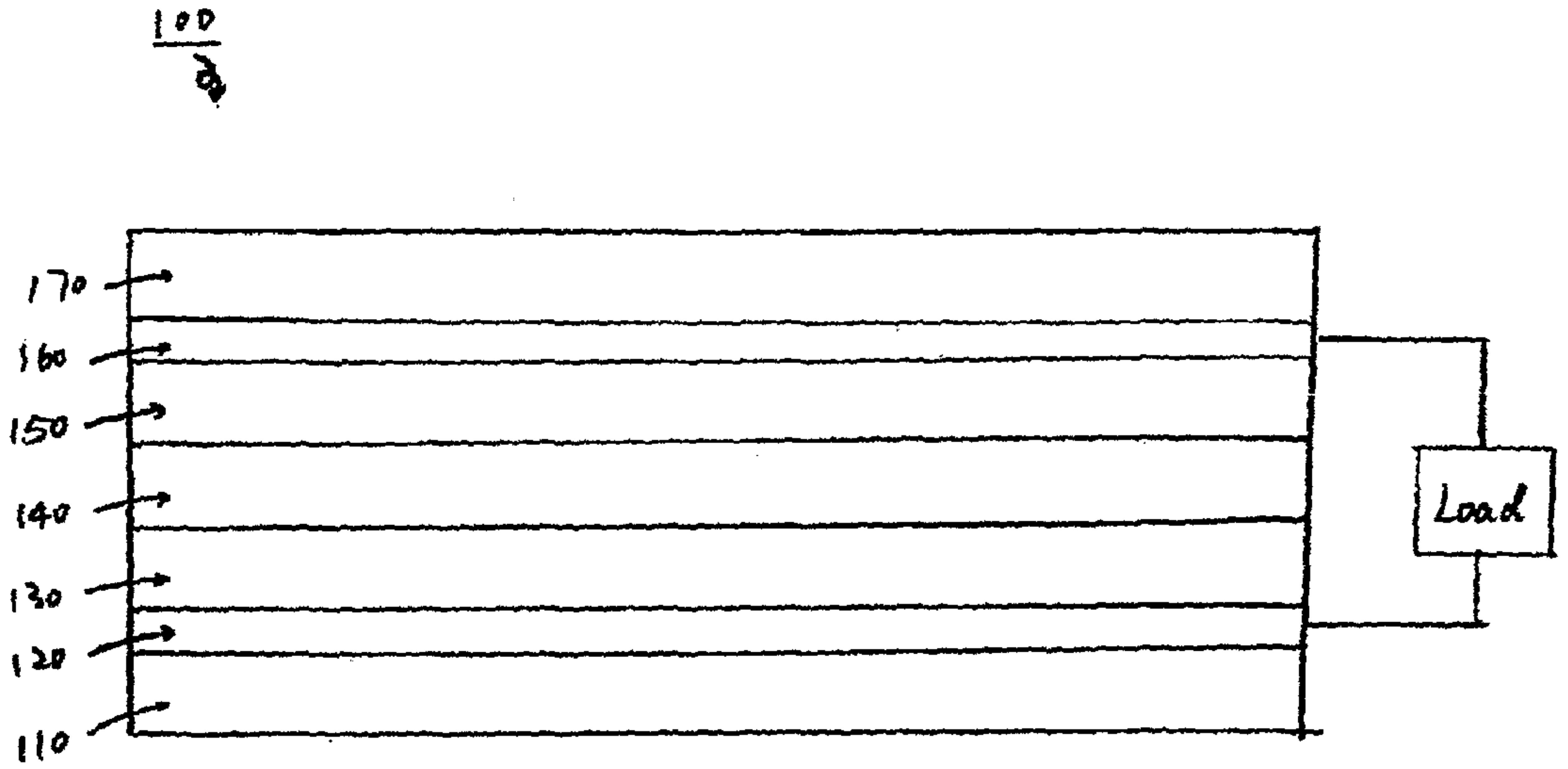
(54) Title: POLYMERS WITH LOW BAND GAPS AND HIGH CHARGE MOBILITY



(57) Abstract: Polymers with low band gaps and high charge mobility, as well as related systems, methods, and components are disclosed.

WO 2007/011739 A2

POLYMERS WITH LOW BAND GAPS AND HIGH CHARGE MOBILITY

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Utility Application Serial No.: 11/450,521, filed June 9, 2006, which in turn is a continuation-in-part of U.S. Utility Application Serial No.: 11/375,643, filed March 14, 2006, which claims priority to U.S. Provisional Application Serial No. 60/699,123, filed July 14, 2005, the contents of which are hereby incorporated by reference.

TECHNICAL FIELD

This disclosure generally relates to the field of electron donor materials, as well as related photovoltaic cells.

BACKGROUND OF THE INVENTION

Photovoltaic cells are commonly used to transfer energy in the form of light into energy in the form of electricity. A typical photovoltaic cell includes a photoactive material disposed between two electrodes. Generally, light passes through one or both of the electrodes to interact with the photoactive material. As a result, the ability of one or both of the electrodes to transmit light (e.g., light at one or more wavelengths absorbed by a photoactive material) can limit the overall efficiency of a photovoltaic cell. In many photovoltaic cells, a film of semiconductive material (e.g., indium tin oxide) is used to form the electrode(s) through which light passes because, although the semiconductive material can have a lower electrical conductivity than electrically conductive materials, the semiconductive material can transmit more light than many electrically conductive materials.

SUMMARY

An aspect of the invention relates to a new combination of monomers that produce polymers, wherein the polymers have properties suitable for use as charge carriers in the active layer of a photovoltaic cell.

In one aspect, the invention features a class of co-polymers including at least two co-monomers, at least one of which is a cyclopentadithiophene.

In another aspect, this invention features a photovoltaic cell including a first electrode, a second electrode, and a photoactive material disposed between the first and second electrodes. The photoactive material includes a polymer having a first comonomer repeat unit and a second comonomer repeat unit. The first comonomer repeat unit includes a cyclopentadithiophene moiety. The second comonomer repeat unit includes a silole moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, or a tetrahydroisoindole moiety.

In another aspect, this invention features a photovoltaic cell including a first electrode, a second electrode, and a photoactive material disposed between the first and second electrodes. The photoactive material includes a polymer having a first comonomer repeat unit and a second comonomer repeat unit different from the first comonomer repeat unit. The first comonomer repeat unit includes a cyclopentadithiophene moiety.

In another aspect, this invention features a polymer that includes a first comonomer repeat unit containing a cyclopentadithiophene moiety, and a second comonomer repeat unit containing a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a fluorene moiety, a thiophene moiety, a silole moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, or a moiety containing at least three thiophene moieties.

In another aspect, this invention features a polymer that includes a first comonomer repeat unit and a second comonomer repeat unit different from the first comonomer repeat unit. The first comonomer repeat unit contains a cyclopentadithiophene moiety substituted with at least one substituent selected from the group consisting of hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, and C_3-C_{20} heterocycloalkyl.

In another aspect, this invention features a device (e.g., a photovoltaic cell) that includes a first electrode, a second electrode, and a photoactive material disposed between the first and second electrodes. The photoactive material includes a polymer having a first monomer repeat unit, which includes a benzothiadiazole moiety, a thiophene oxide moiety, a cyclopentadithiophene oxide moiety, a thiadiazoloquinoxaline moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, a silole moiety, or a fluorene moiety.

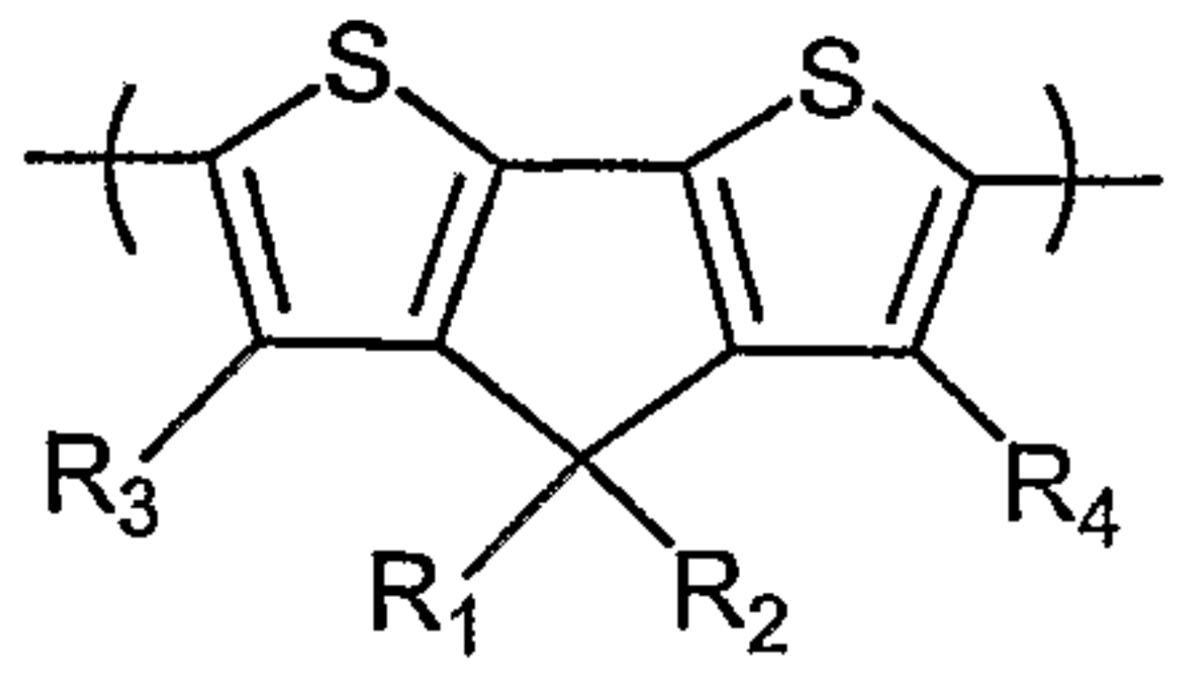
In another aspect, this invention features a device (e.g., a photovoltaic cell) that includes a first electrode, a second electrode, and a photoactive material disposed between the first and second electrodes. The photoactive material includes a polymer having a first monomer repeat unit, which includes a cyclopentadithiophene moiety substituted with at least one substituent selected from the group consisting of hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

Embodiments can include one or more of the following features.

In some embodiments, the cyclopentadithiophene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. Examples of C_1-C_{20} alkyl can be hexyl, 2-ethylhexyl, or 3,7-dimethyloctyl.

In some embodiments, the cyclopentadithiophene moiety can be substituted at 4-position.

In some embodiments, the first monomer or comonomer repeat unit can include a cyclopentadithiophene moiety of formula (I):

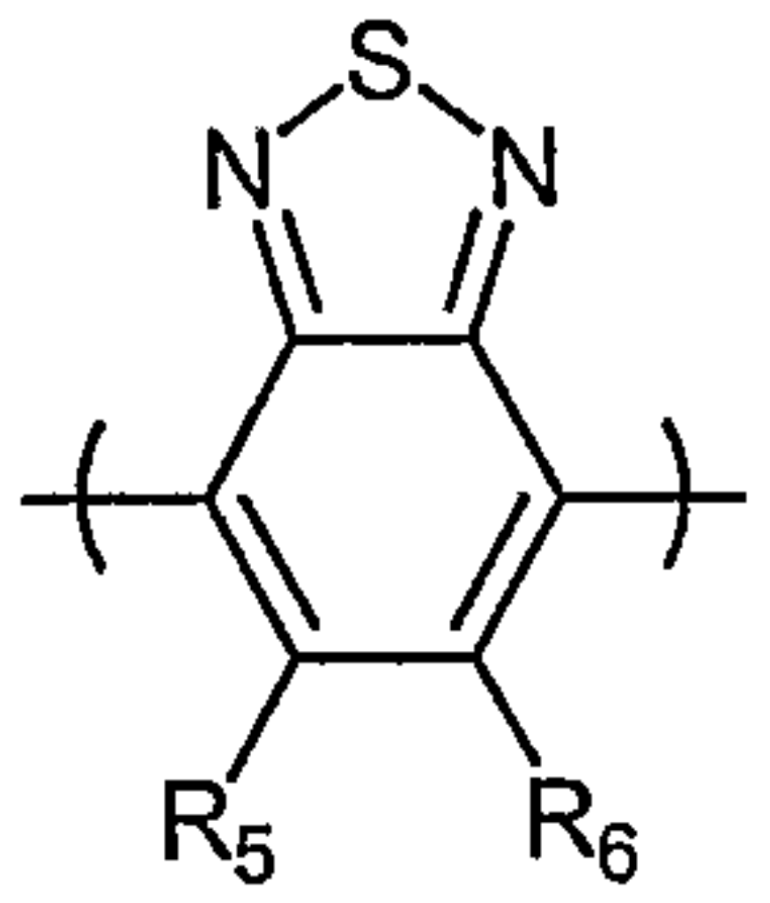


(I).

In formula (I), each of R_1, R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, at least one of R_1 and R_2, independently, is hexyl, 2-ethylhexyl, or 3,7-dimethyloctyl. In certain embodiments, each of R_1 and R_2, independently, is hexyl, 2-ethylhexyl, or 3,7-dimethyloctyl. In some embodiments, one of R_1 and R_2 is hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl, the other of R_1 and R_2 is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, at least one of R_1 and R_2, independently, is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$). In certain embodiments, each of R_1 and R_2, independently, is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

In some embodiments, the second comonomer repeat unit can include a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety, each of which is optionally substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, the second comonomer repeat unit can include a 3,4-benzo-1,2,5-thiadiazole moiety.

In some embodiments, the second comonomer repeat unit can include a benzothiadiazole moiety of formula (II), a thiadiazoloquinoxaline moiety of formula (III), a cyclopentadithiophene dioxide moiety of formula (IV), a cyclopentadithiophene monoxide moiety of formula (V), a benzoisothiazole moiety of formula (VI), a benzothiazole moiety of formula (VII), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene dioxide moiety of formula (IX), or a cyclopentadithiophene tetraoxide moiety of formula (X):



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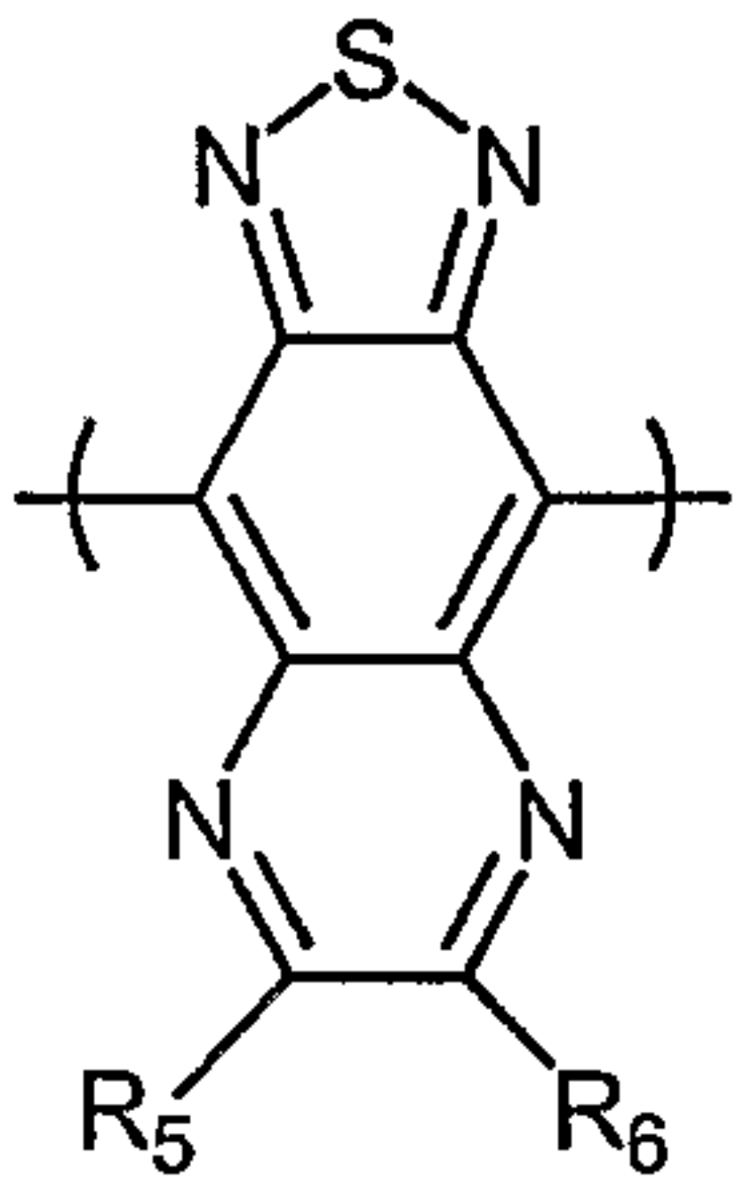

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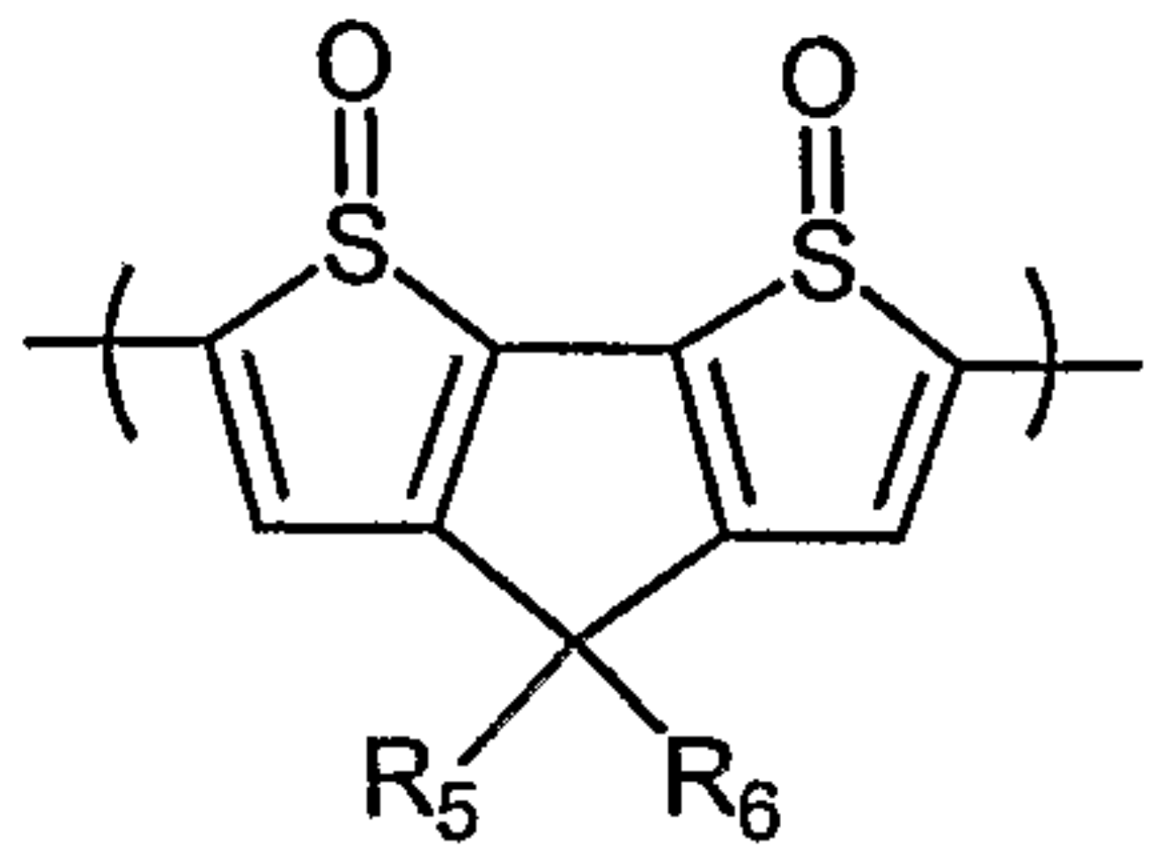

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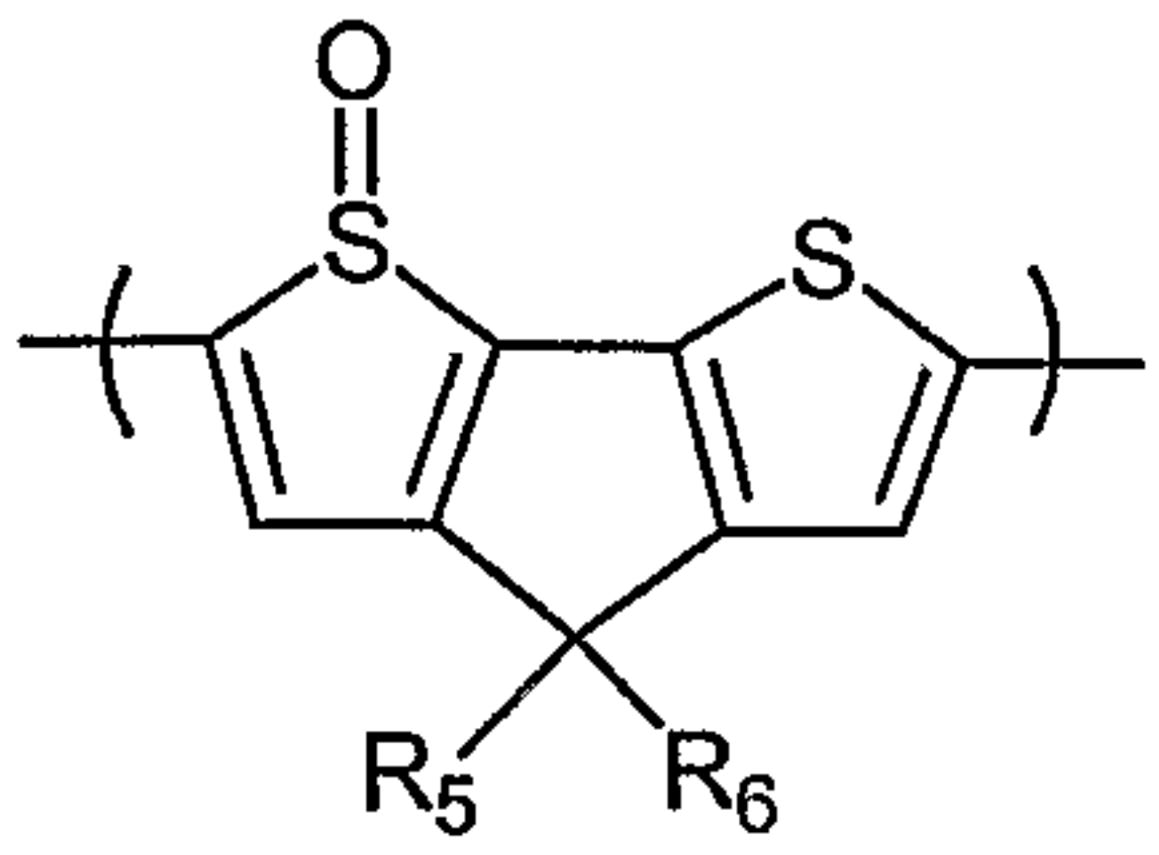

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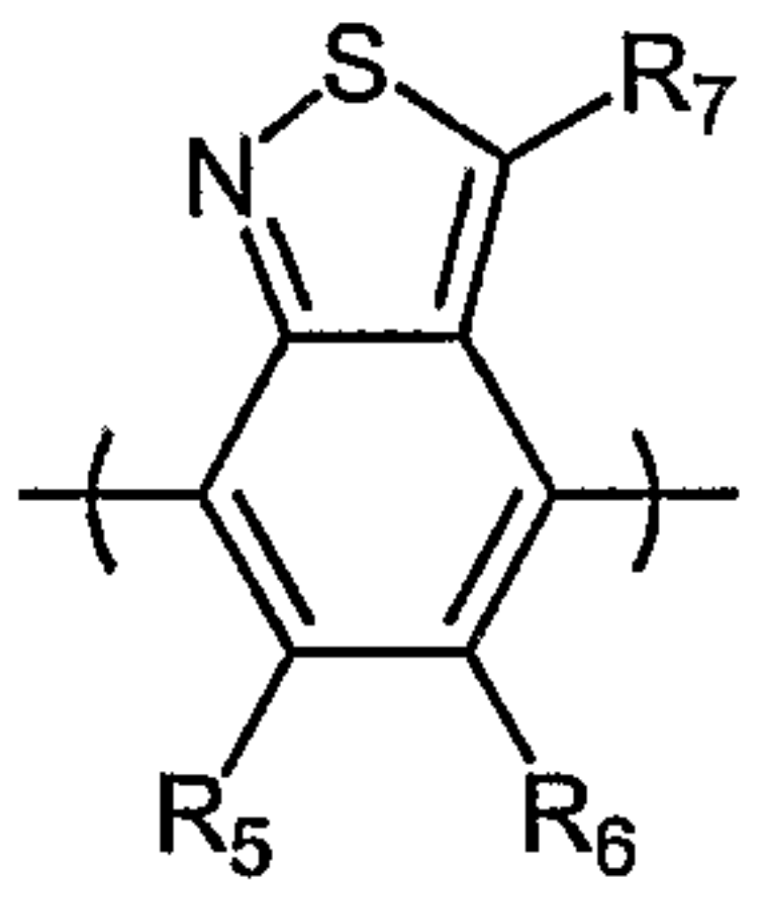

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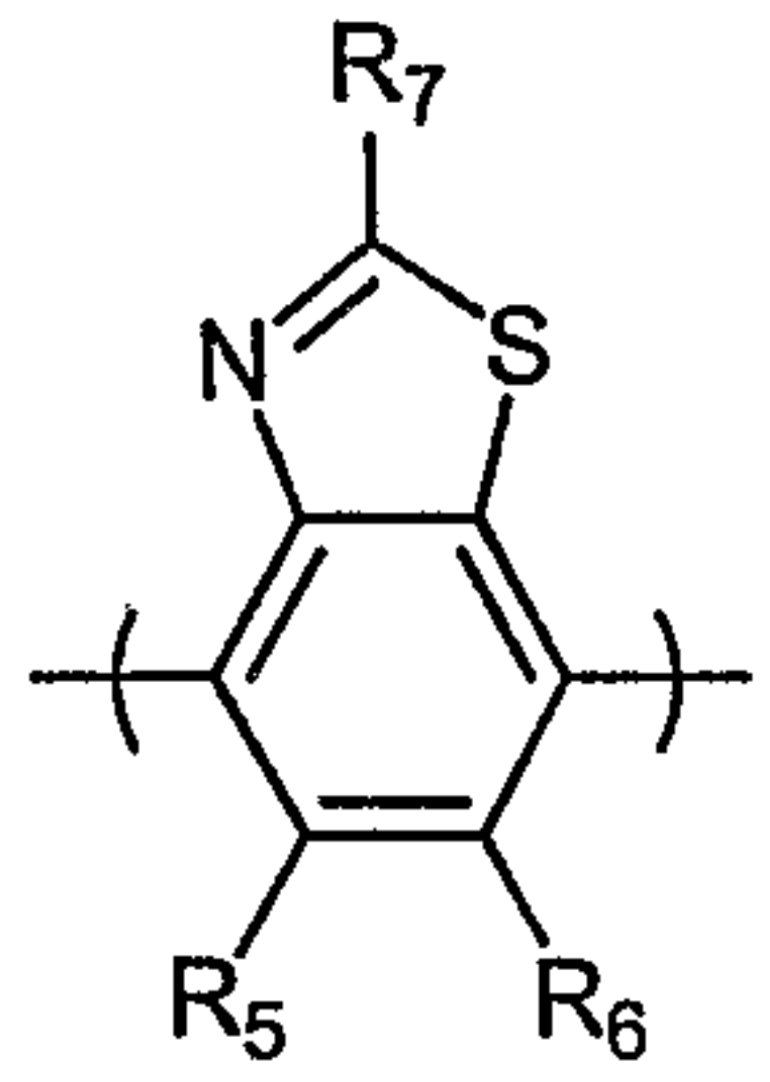

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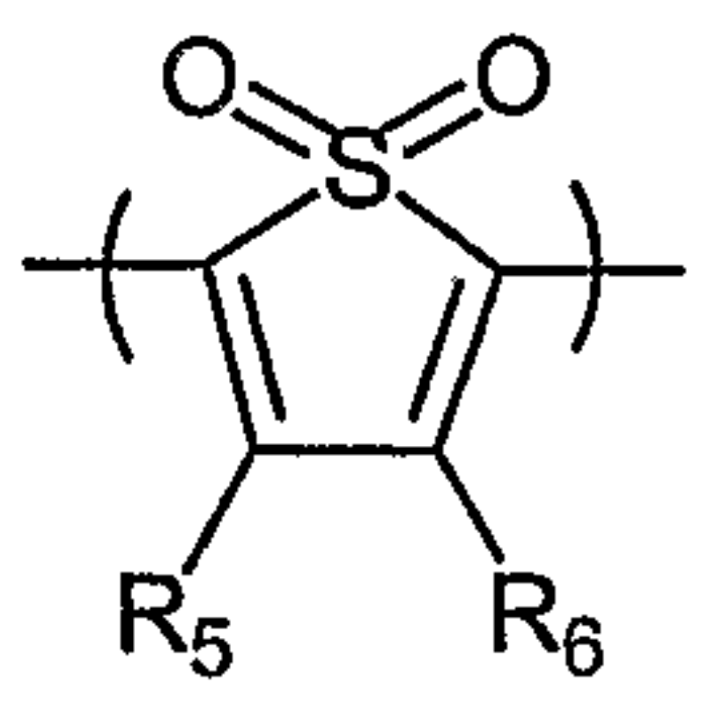

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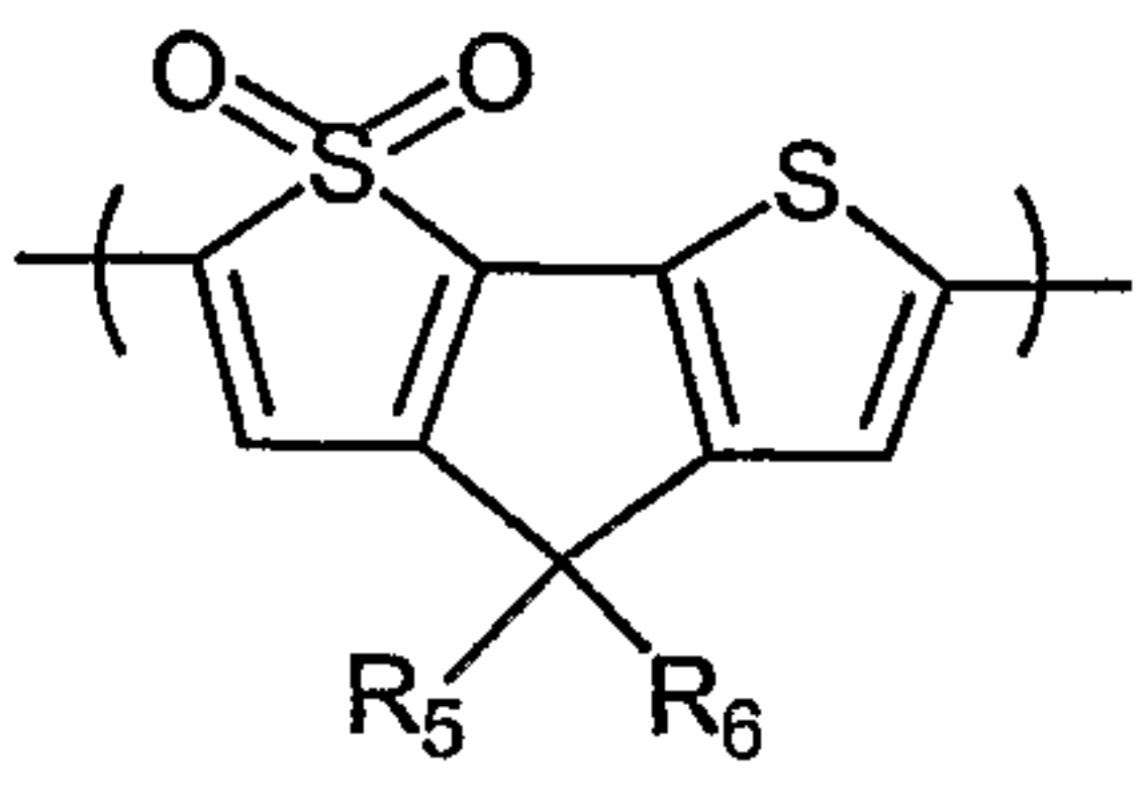

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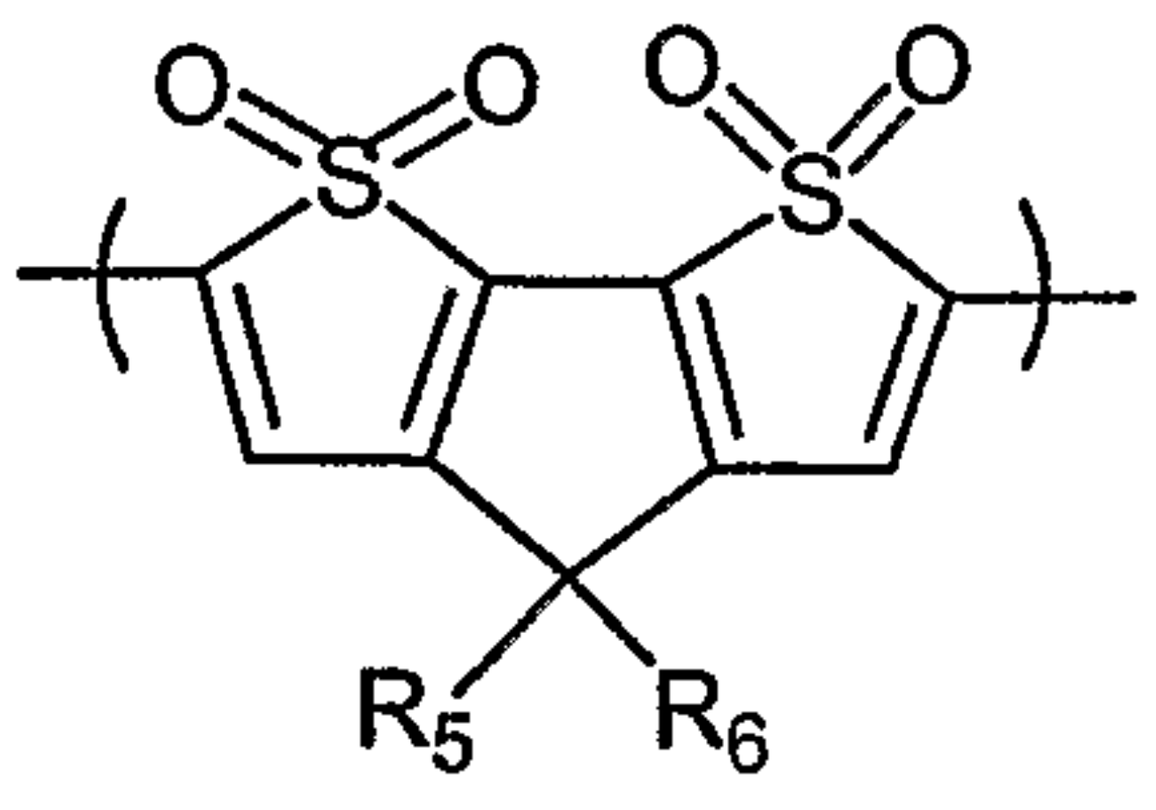
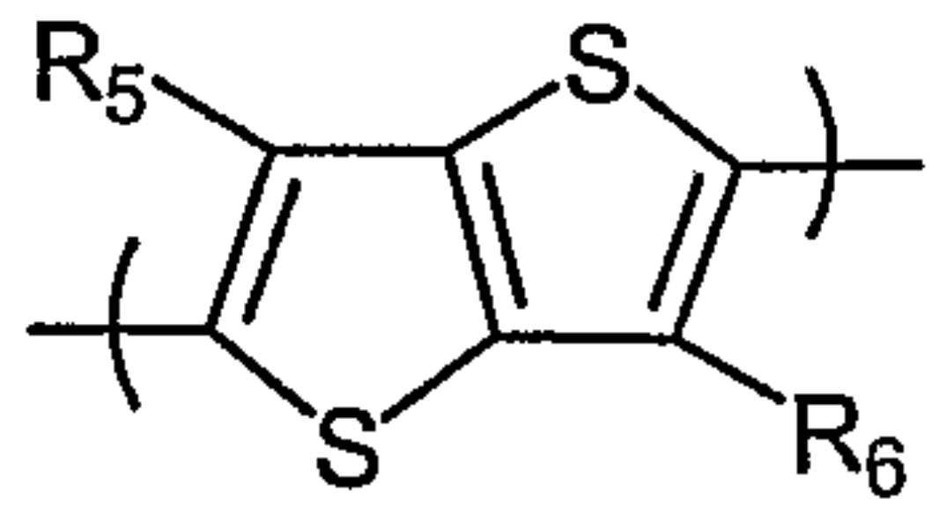


(X),

in which each of R_5, R_6, and R_7, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, the second comonomer repeat unit can include a benzothiadiazole moiety of formula (II). In certain embodiments, R_5 and R_6 is H.

In some embodiments, the second comonomer repeat unit can include at least three thiophene moieties. In some embodiments, at least one of the thiophene moieties is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In certain embodiments, the second comonomer repeat unit includes five thiophene moieties.

In some embodiments, the second comonomer repeat unit can include a thienothiophene moiety of formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), or a dithienothiophene dioxide moiety of formula (XVIII):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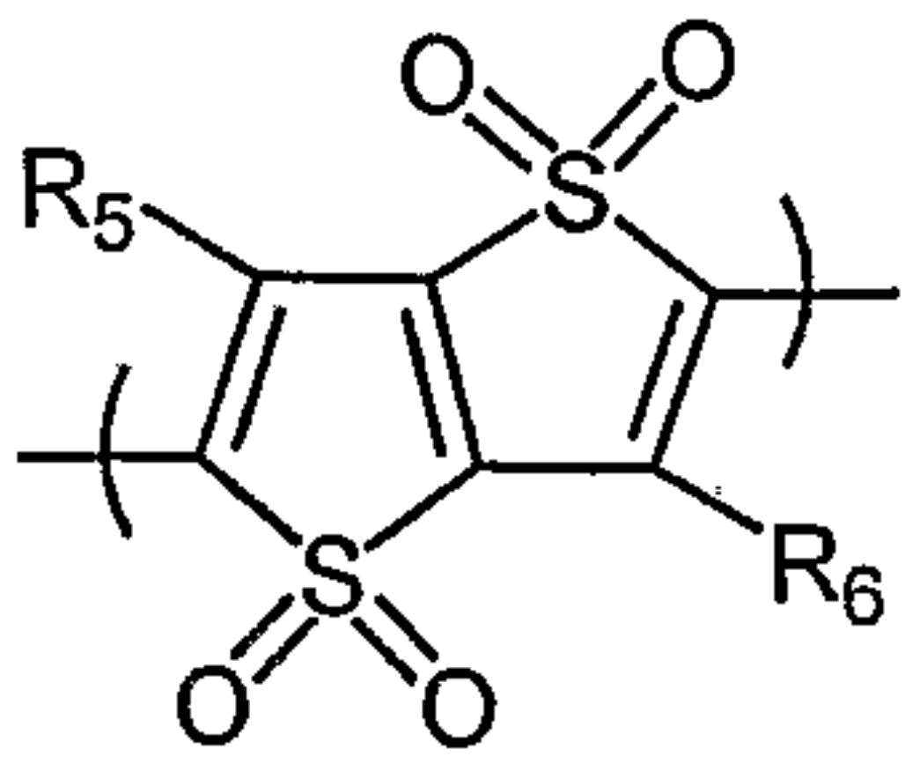
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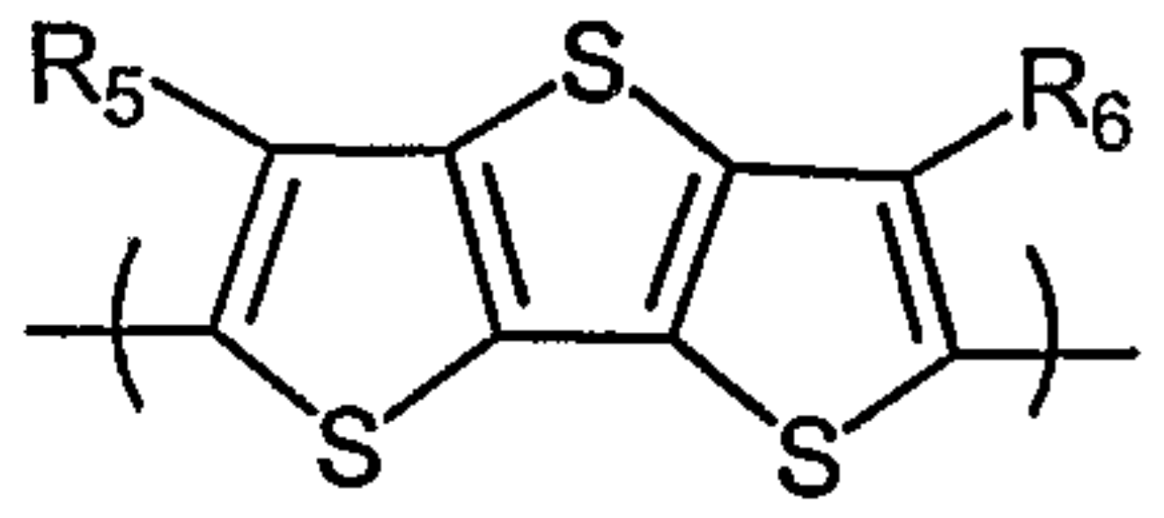
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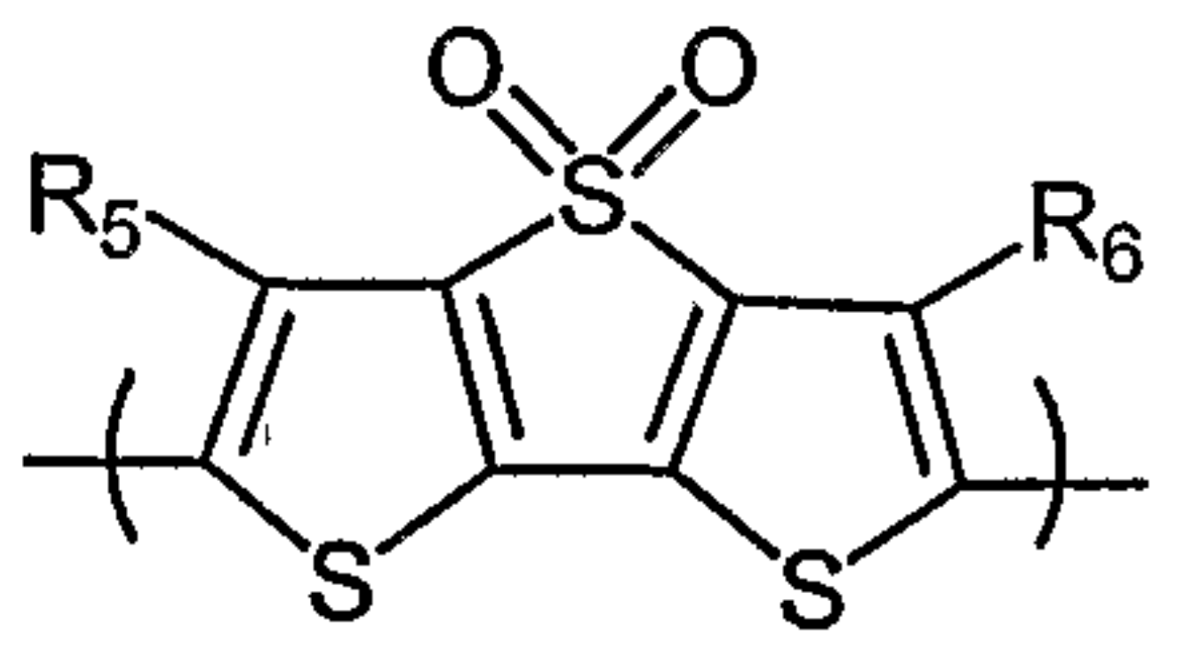
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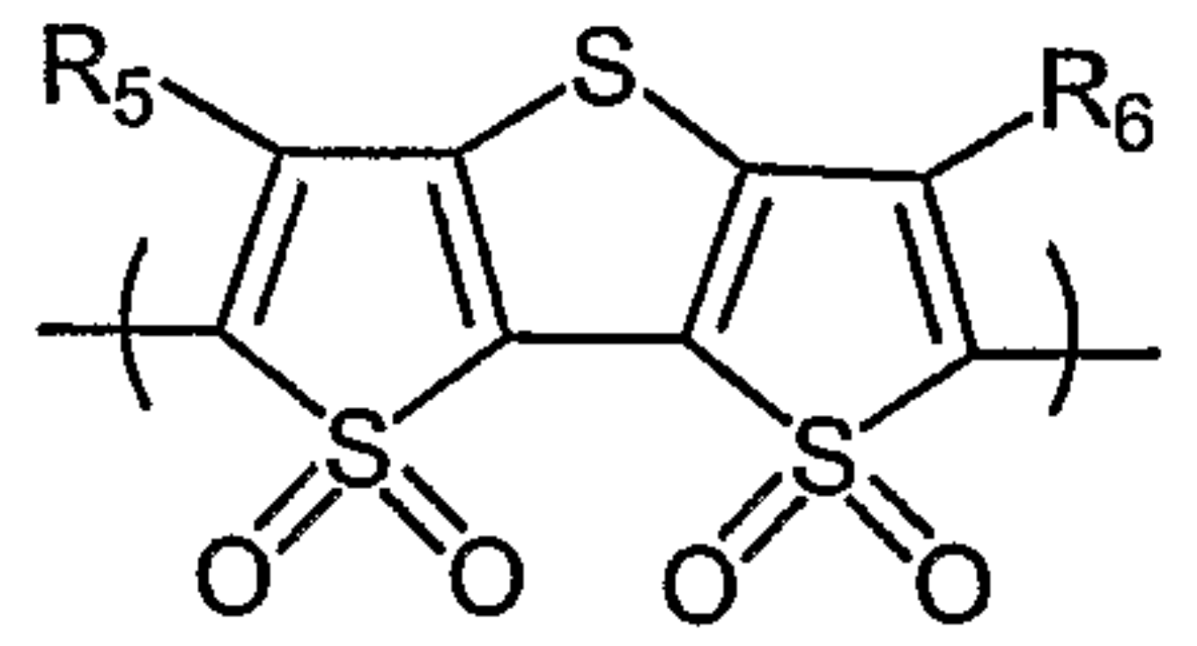
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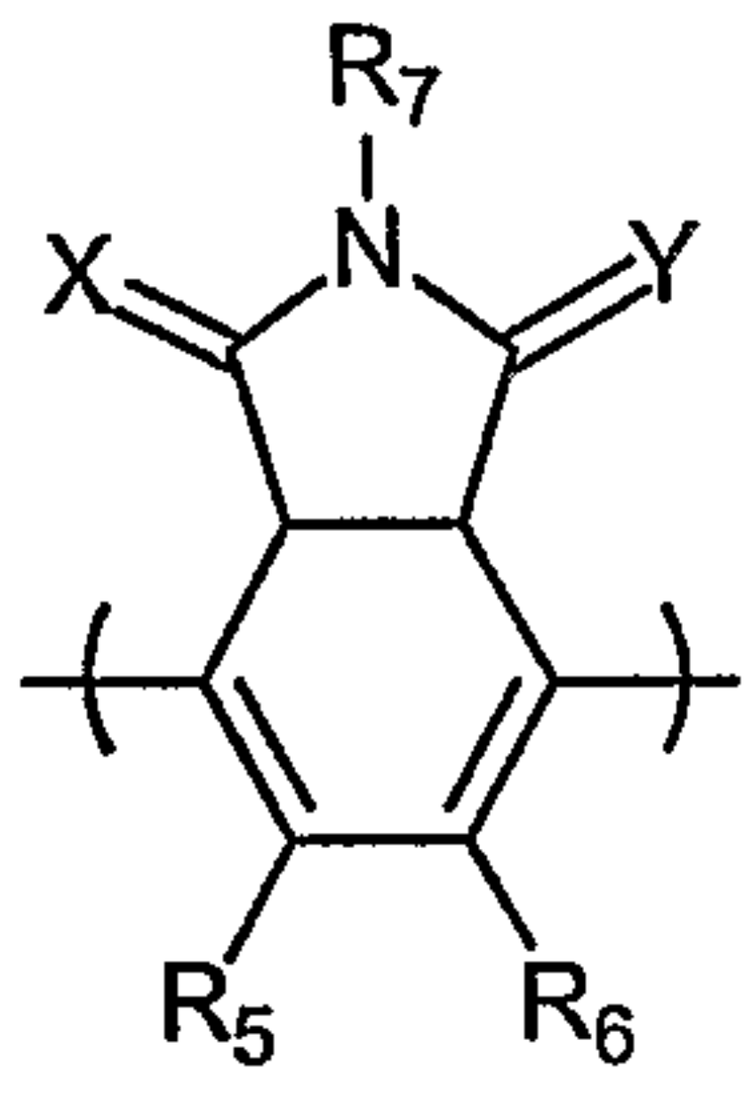
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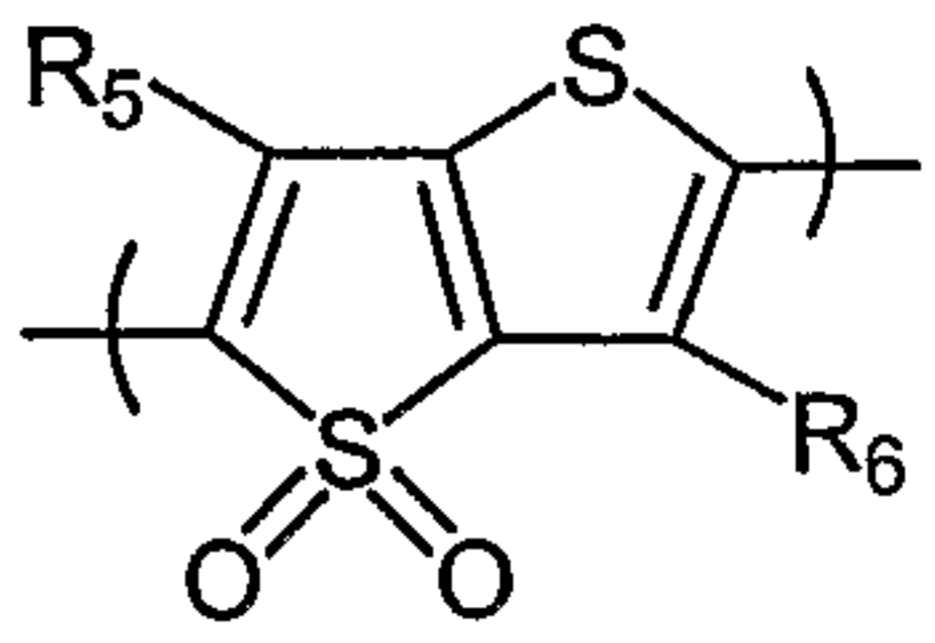
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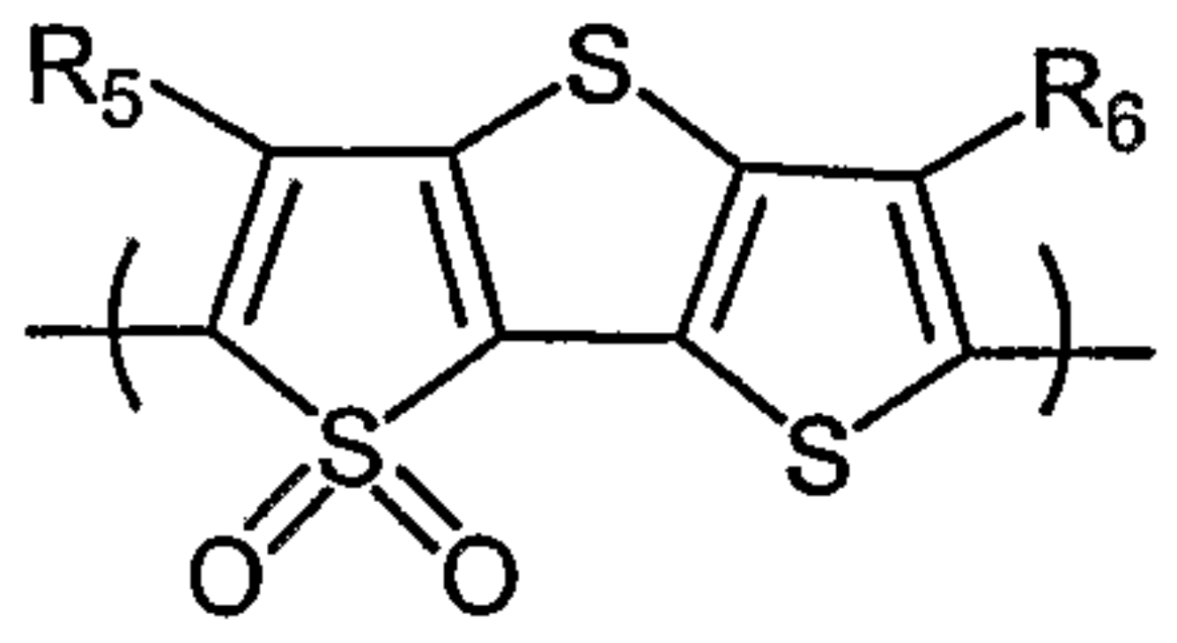
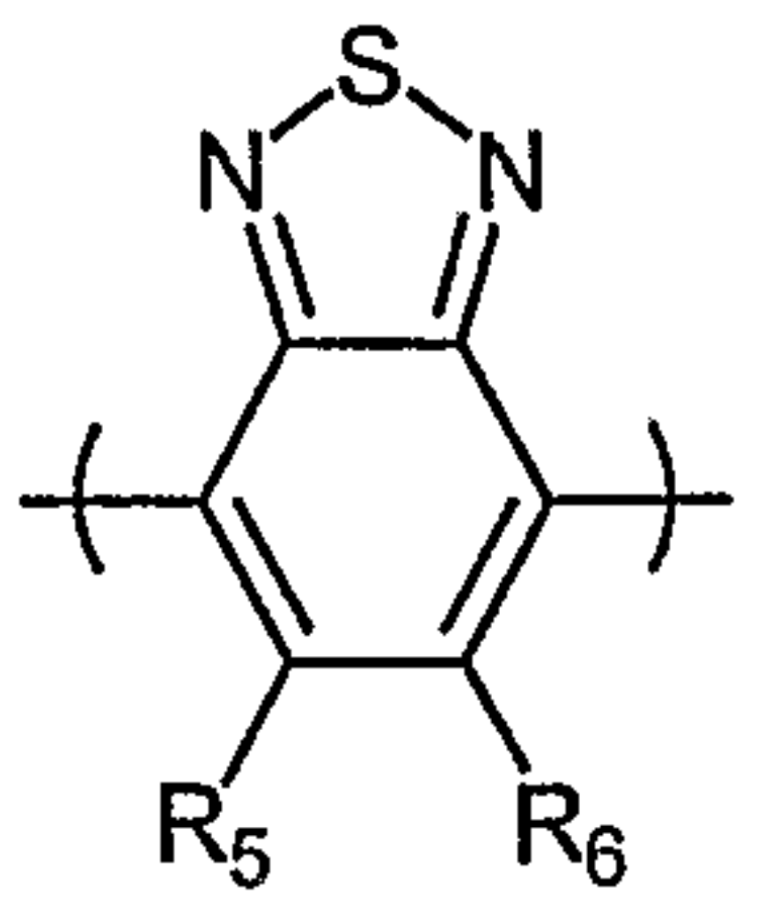

(XVIII),

in which each of X and Y, independently, is CH_2, O, or S; each of R_5 and R_6, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl; and R_7 is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

In some embodiments, the polymer can further include a third comonomer repeat unit that contains a thiophene moiety or a fluorene moiety. In some embodiments, the thiophene or fluorene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, and C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

In some embodiments, the first monomer or comonomer repeat unit can include a benzothiadiazole moiety of formula (II), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene tetraoxide moiety of formula (X), or a fluorene moiety of formula (XIX):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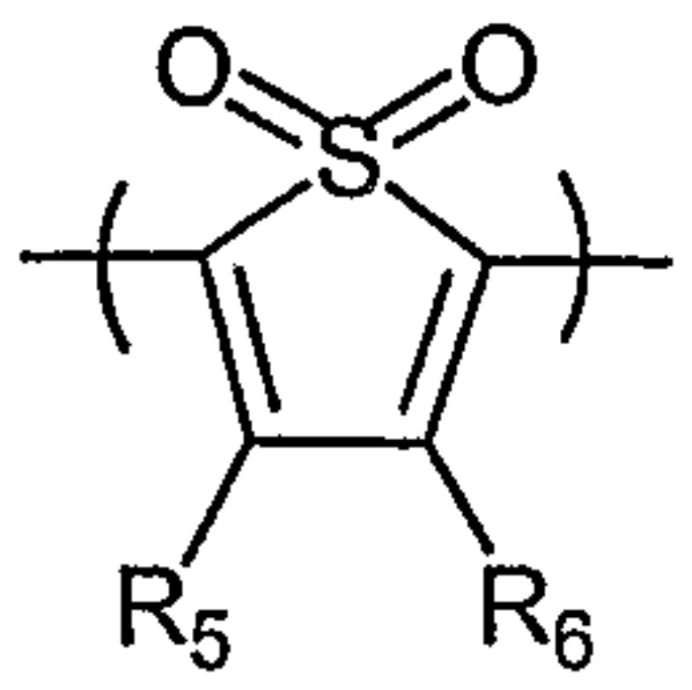
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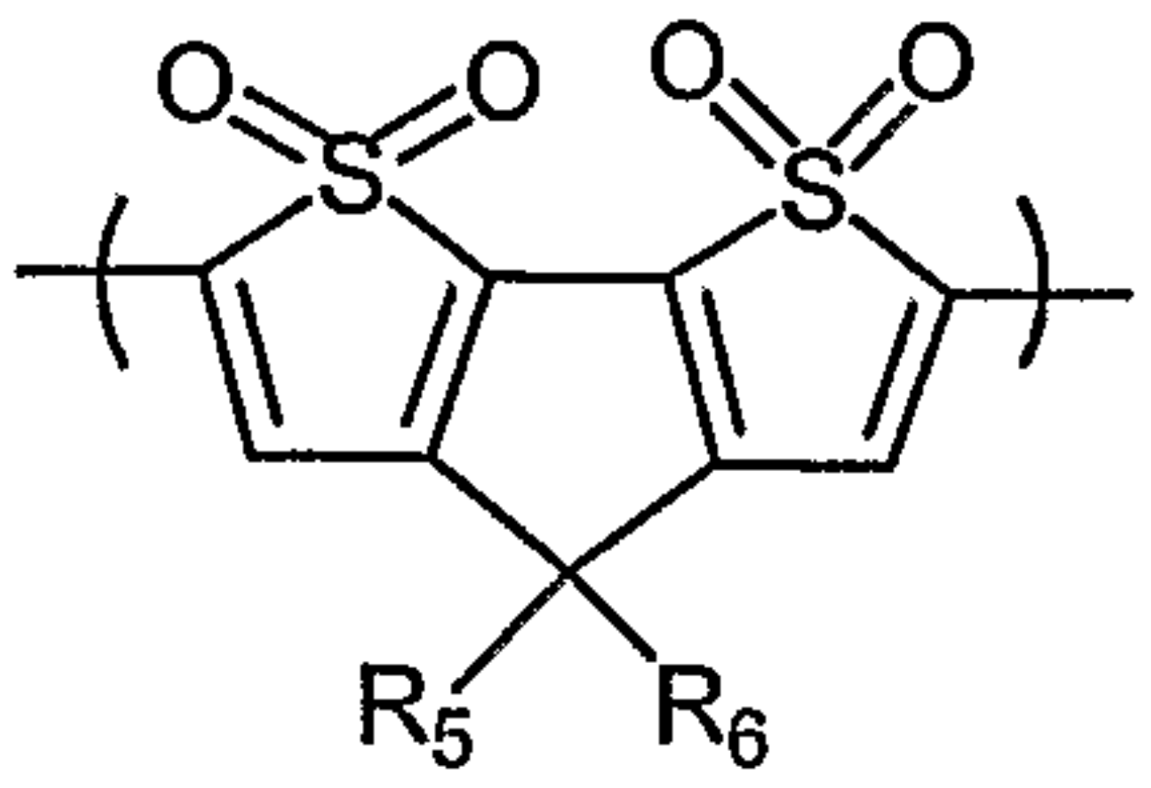
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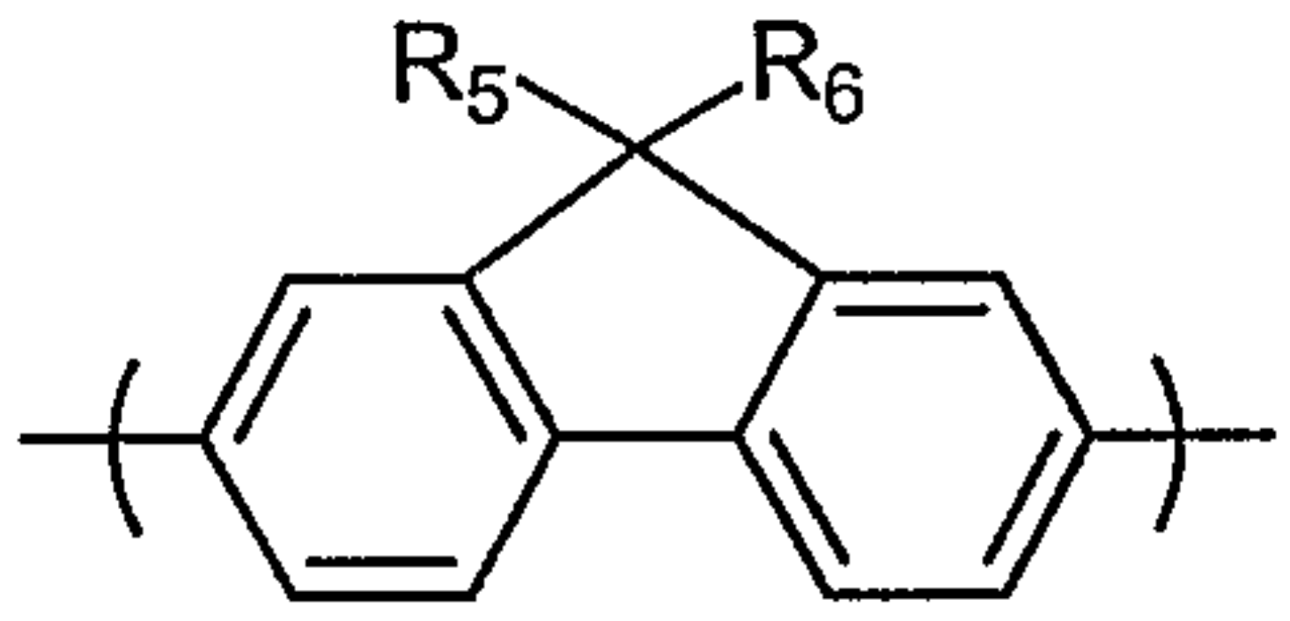
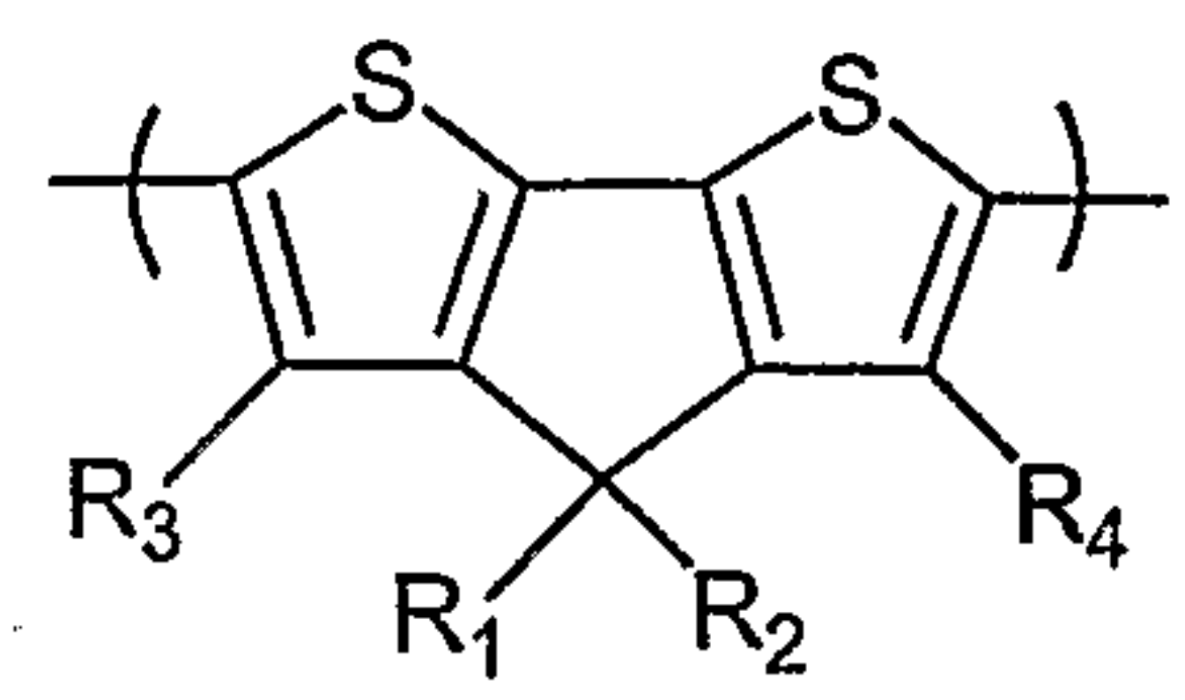

(XIX),

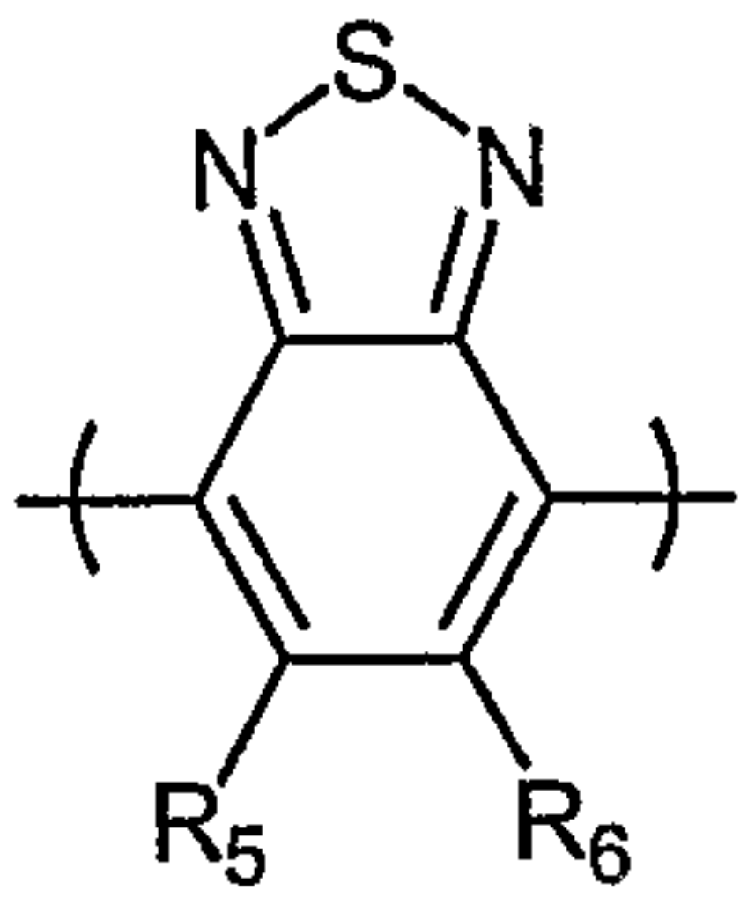
in which each of R_5 and R_6, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R. R can be C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, at least one of R_5 and R_6 can be C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$).

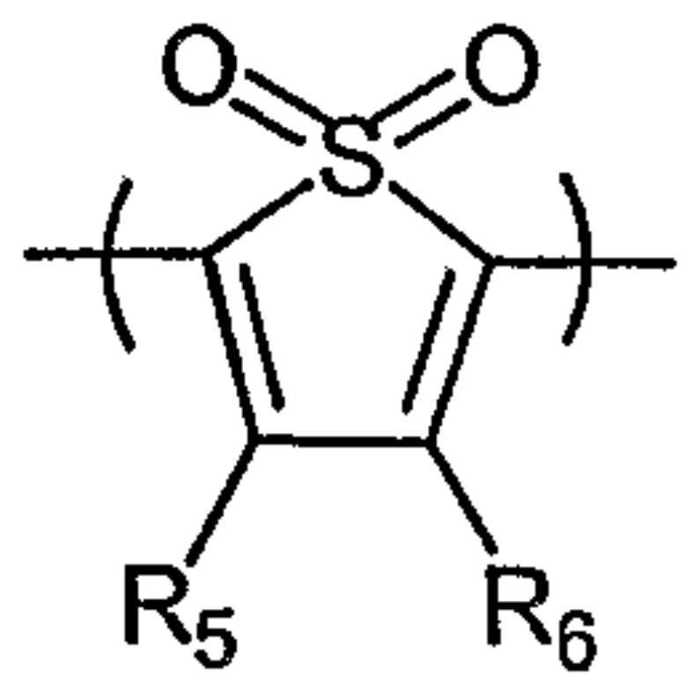
In some embodiments, the polymer can include a second monomer repeat unit different from the first monomer repeat unit. The second monomer repeat unit can include a cyclopentadithiophene moiety, a benzothiadiazole moiety, a thiophene oxide moiety, a cyclopentadithiophene oxide moiety, a fluorene moiety, or a thiophene moiety.

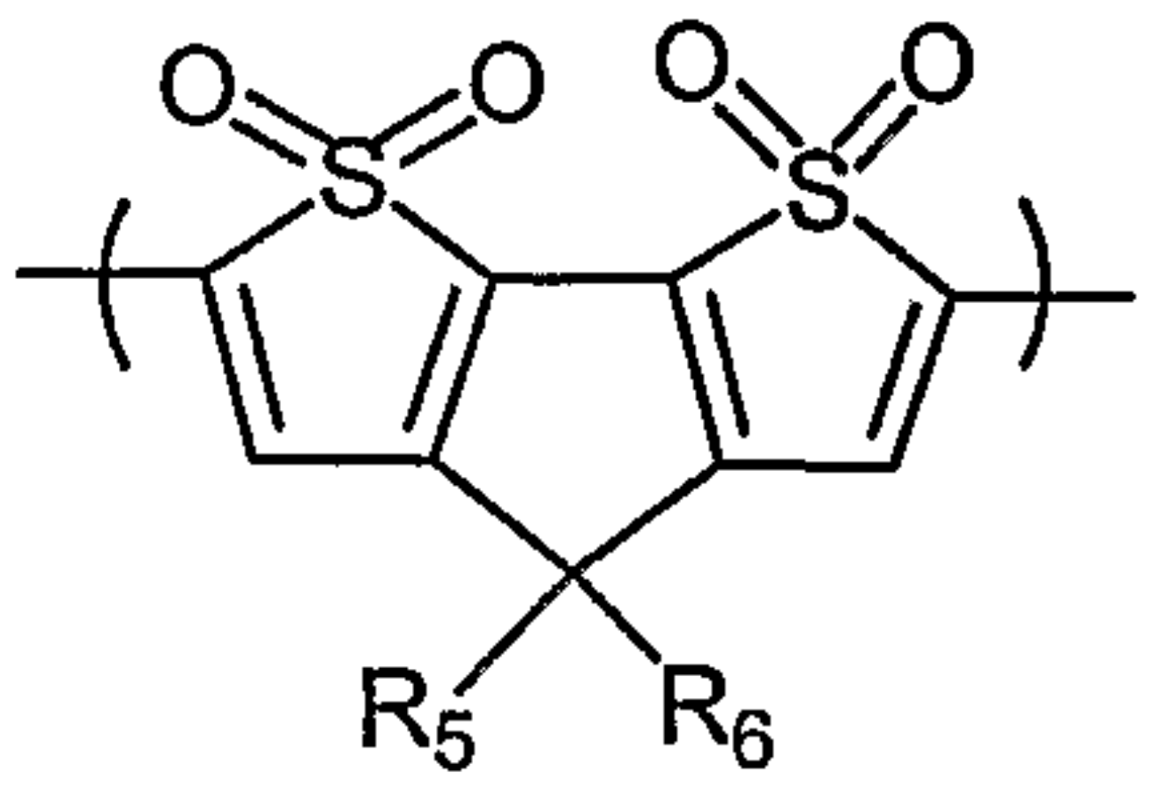
In some embodiments, the first or second monomer repeat unit can include at least one substituent on a ring selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. The substituent can be hexyl, ethylhexyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$).

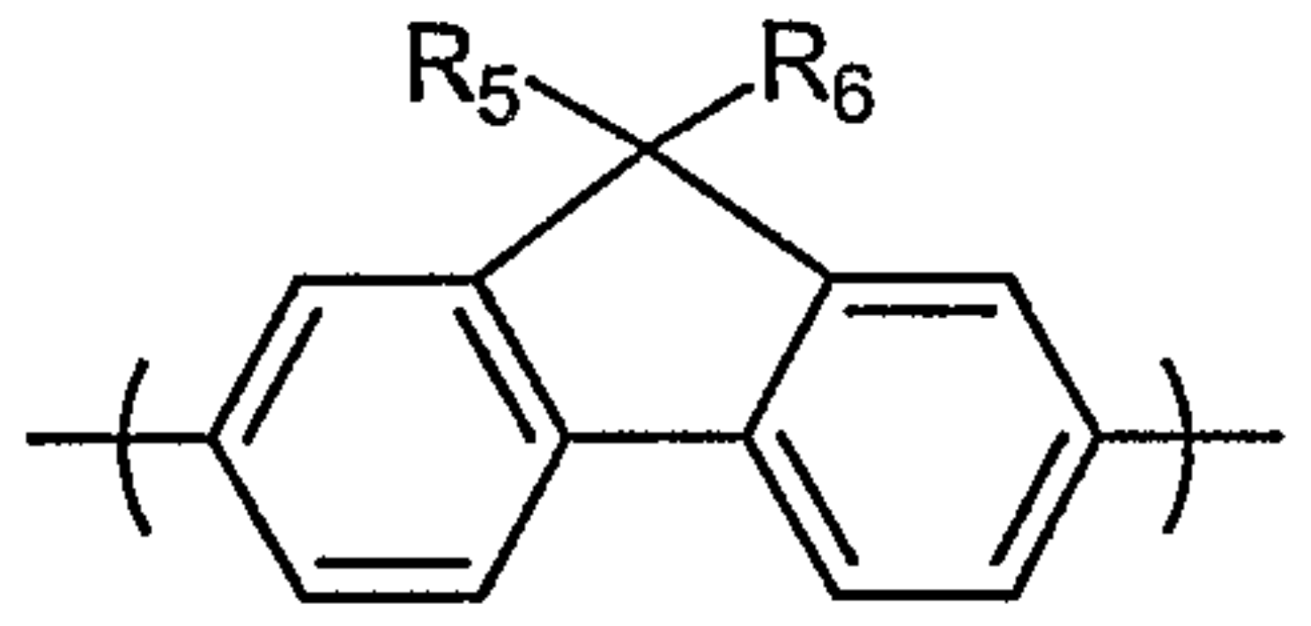
In some embodiments, the second monomer repeat unit can include a cyclopentadithiophene moiety of formula (I), a benzothiadiazole moiety of formula (II), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene tetraoxide moiety of formula (X), a fluorene moiety of formula (XIX), a thiophene moiety of formula (XX), or a silole moiety of formula (XXI):

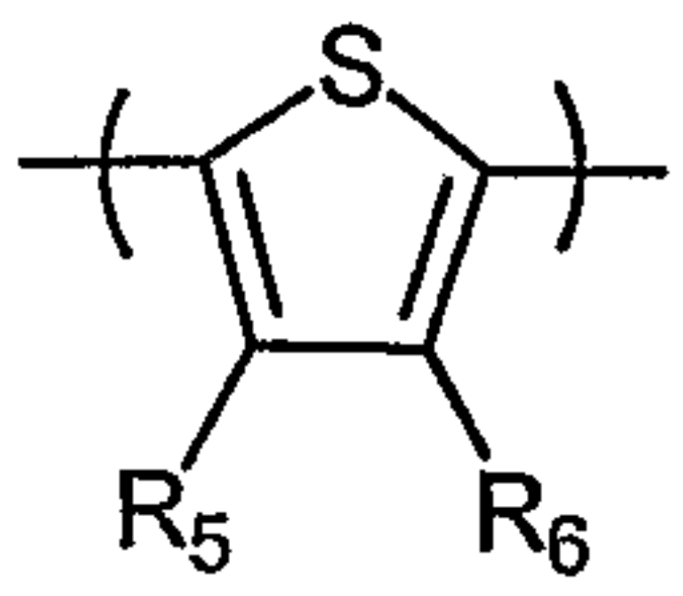

(I),

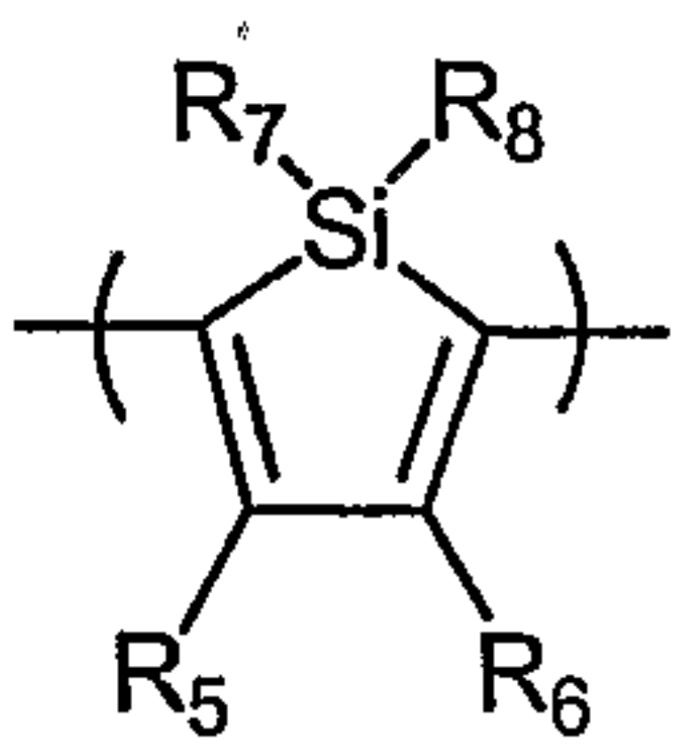

(II),


(VIII),

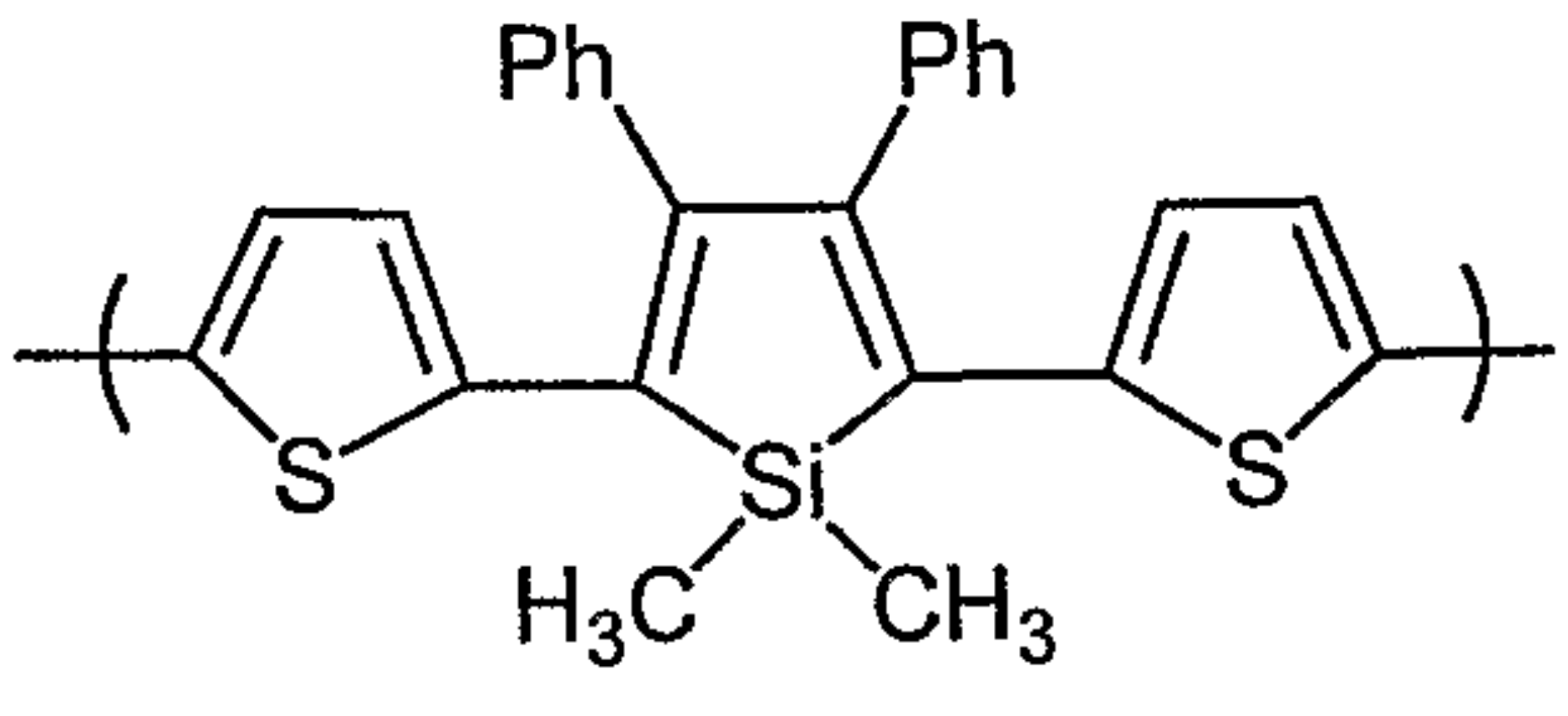

(X),


(XIX),


(XX), or

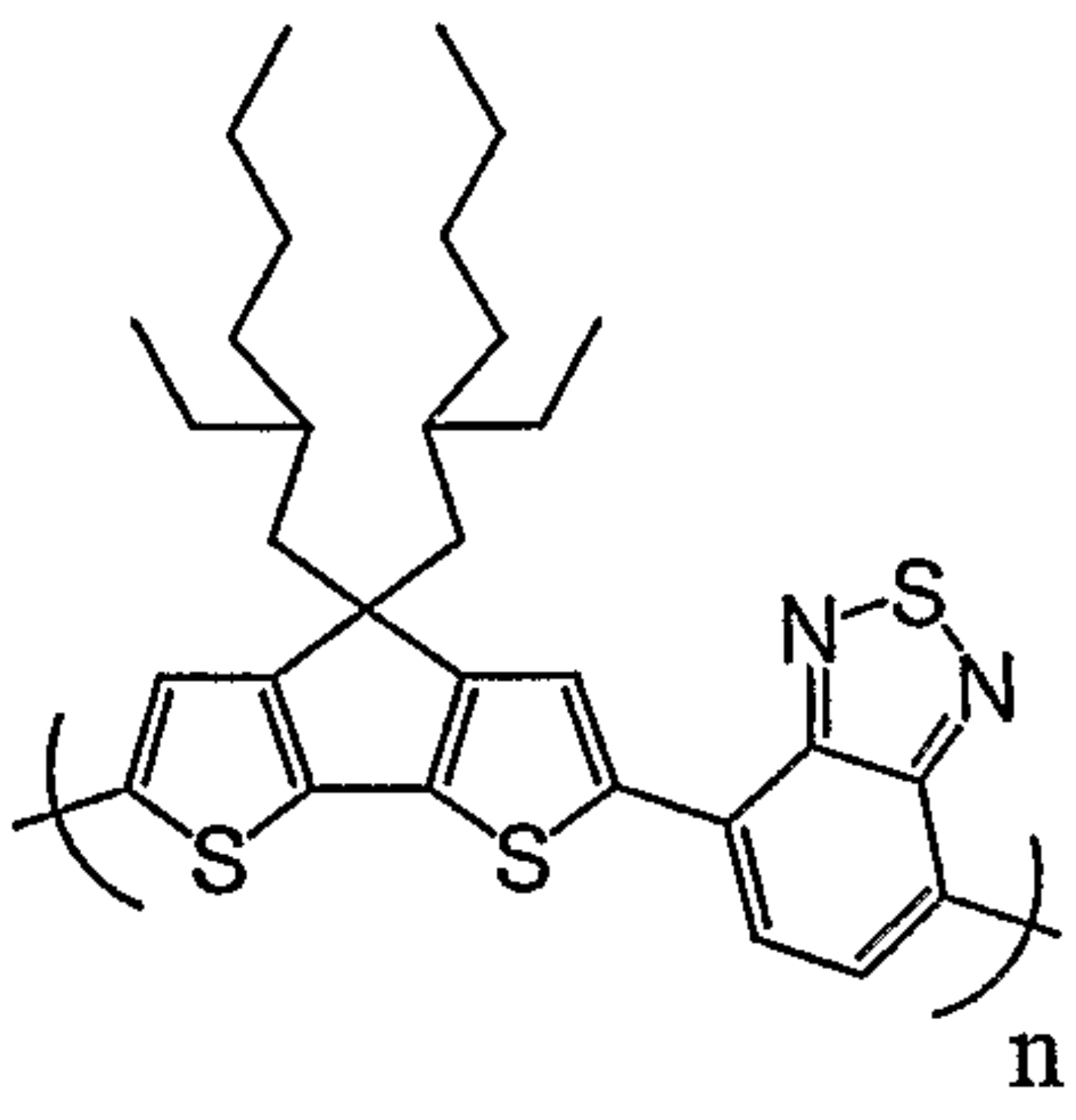

(XXI)

in which each of R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R. R can be C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. In some embodiments, at least one of R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8, can be C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$).

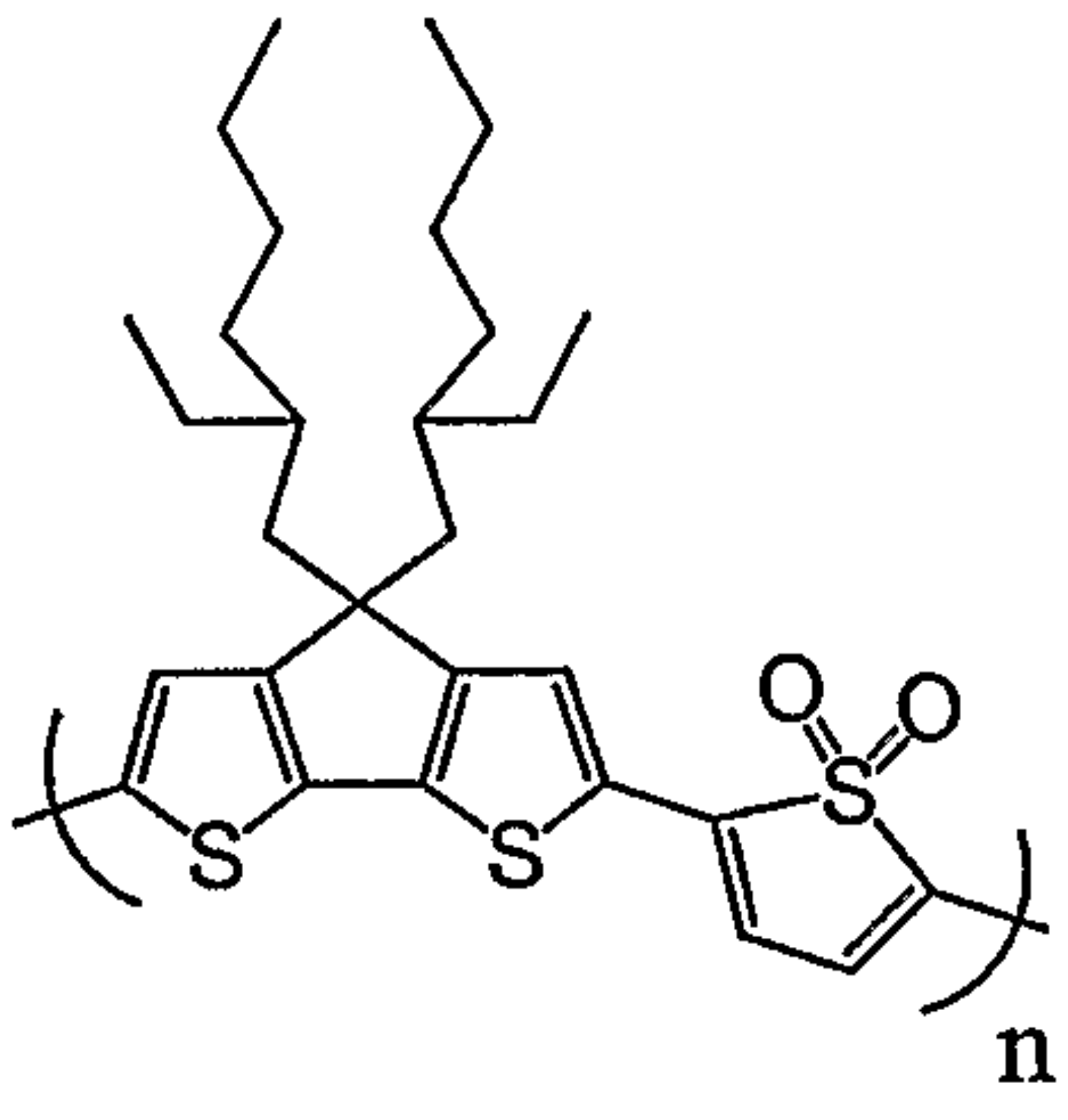
In some embodiments, when the second comonomer contains a silole moiety of formula (XXI), at least one of R_5, R_6, R_7 and R_8 can be C_1-C_{20} alkyl optionally substituted with halo, or aryl optionally substituted with C_1-C_{20} alkyl. In certain embodiments, each of R_5 and R_6, independently can be aryl optionally substituted with C1-C20 alkyl, and each of R_7 and R_8, independently, can be C_1-C_{20} alkyl optionally substituted with halo. An example of a silole moiety is  .

In some embodiments, the polymer can be an electron donor material or an electron acceptor material.

In some embodiments, the polymer can be



or



, in which n can be an integer greater than 1.

In some embodiments, the photovoltaic cell can be a tandem photovoltaic cell.

In some embodiments, the photoactive material can include an electron acceptor material. In some embodiments, the electron acceptor material can be a fullerene (e.g., C61-phenyl-butyric acid methyl ester, PCBM).

In some embodiments, the polymer and the electron acceptor material each can have a LUMO energy level. The LUMO energy level of the polymer can be at least about 0.2 eV (e.g., at least about 0.3 eV) less negative than the LUMO energy level of the electron acceptor material.

In some embodiments, the device can be an organic semiconductive device. In certain embodiments, the device can be a member selected from the group consisting of field effect transistors, photodetectors, photovoltaic detectors, imaging devices, light emitting diodes, lasing devices, conversion layers, amplifiers and emitters, storage elements, and electrochromic devices.

Embodiments can provide one or more of the following advantages.

In some embodiments, using a polymer containing a cyclopentadithiophene moiety can be advantageous because the cyclopentadithiophene moiety can contribute to a shift in the maximum absorption wavelength toward the red or near IR region of the electromagnetic spectrum. When such a polymer is incorporated into a photovoltaic cell, the current and efficiency of the cell can increase.

In some embodiments, substituted fullerenes or polymers containing substituted monomer repeat units (e.g., substituted with long-chain alkoxy groups such as oligomeric ethylene oxides or fluorinated alkoxy groups) can have improved solubility in organic solvents and can form an photoactive layer with improved morphology.

In some embodiments, a polymer containing a silole moiety can absorb light at a relatively long wavelength and have improved solubility in organic solvents. In some embodiments, a polymer containing a silole moiety can be used to prepare an electron donor material with improved semiconductive properties.

In some embodiments, a polymer fullerene cell containing a polymer described above can have a band gap that is relatively ideal for its intended purposes.

In some embodiments, a photovoltaic cell having high cell voltage can be created, whereby the HOMO level of the polymer is at least about 0.2 electron volts more negative relative to the LUMO or conduction band of an electron acceptor material.

In some embodiments, a photovoltaic cell containing a polymer described above can have relatively fast and efficient transfer of an electron to an electron acceptor material, whereby the LUMO of the donor is at least about 0.2 electron volt (e.g., at least about 0.3 electron volt) less negative than the conduction band of the electron acceptor material.

In some embodiments, a photovoltaic cell containing a polymer described above can have relatively fast charge separation, whereby the charge mobility of the positive charge, or hole, is relatively high and falls within the range of 10^{-4} to 10^{-1} cm^2/Vs.

In some embodiments, the polymer is soluble in an organic solvent and/or film forming.

In some embodiments, the polymer is optically non-scattering.

In some embodiments, the polymer can be used in organic field effect transistors and OLEDs.

Other features and advantages of the invention will be apparent from the description, drawings, and claims.

DESCRIPTION OF DRAWING

FIG. 1 is a cross-sectional view of an embodiment of a photovoltaic cell.

FIG. 2 is a schematic of a system containing one electrode between two photoactive layers.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

FIG. 1 shows a cross-sectional view of a photovoltaic cell 100 that includes a substrate 110, a cathode 120, a hole carrier layer 130, an active layer 140 (containing an electron acceptor material and an electron donor material), a hole blocking layer 150, an anode 160, and a substrate 170.

In general, during use, light impinges on the surface of substrate 110, and passes through substrate 110, cathode 120, and hole carrier layer 130. The light then interacts with active layer 140, causing electrons to be transferred from the electron donor material (e.g., a polymer described above) to the electron acceptor material (e.g., PCBM). The electron acceptor material then transmits the electrons through hole blocking layer 150 to anode 160, and the electron donor material transfers holes through hole carrier layer 130 to cathode 120. Anode 160 and cathode 120 are in electrical connection via an external load so that electrons pass from anode 160, through the load, and to cathode 120.

Electron acceptor materials of active layer 140 can include fullerenes. In some embodiments, active layer 140 can include one or more unsubstituted fullerenes and/or one or more substituted fullerenes. Examples of unsubstituted fullerenes include C_{60}, C_{70}, C_{76}, C_{78}, C_{82}, C_{84}, and C_{92}. Examples of substituted fullerenes include PCBM or fullerenes substituted with C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$). Without wishing to be bound by theory, it is believed that fullerenes substituted with long-chain alkoxy groups (e.g., oligomeric ethylene oxides) or fluorinated alkoxy groups have improved solubility in organic solvents and can form an photoactive layer with improved morphology.

In some embodiments, the electron acceptor materials can include polymers (e.g., homopolymers or copolymers). A polymers mentioned herein include at least two identical or different monomer repeat units (e.g., at least 5 monomer repeat units, at least 10 monomer repeat units, at least 50 monomer repeat units, at least 100 monomer repeat units, or at least 500 monomer repeat units). A copolymer mentioned herein refers to a polymer that includes at least two co-monomers of differing structures. In some embodiments, the polymers used as an electron acceptor material can include one or more monomer repeat units listed in Tables 1 and 2 below. Specifically, Table 1 lists examples of the monomers that can be used as an electron donating monomer and can serve as a conjugative link. Table 2 lists examples of the monomers that can be used as an electron withdrawing monomer. Note that depending on the substituents, monomers listed in Table 1 can also be used as electron withdrawing monomers and monomers listed in Table 2 can also be used as electron donating monomers. Preferably, the polymers used as an electron acceptor material include a high molar percentage (e.g., at least about 50%, at least about 60%, at least about 70%, at least about 80%, at least about 90%) of an electron withdrawing monomer.

Electron donor materials of active layer 140 can include polymers (e.g., homopolymers or copolymers). In some embodiments, the polymers used as an electron donor material can include one or more monomer repeat units listed Tables 1 and 2. Preferably, the polymers used as an electron donor material include a high molar percentage (e.g., at least about 50%, at least about 60%, at least about 70%, at least about 80%, at least about 90%) of an electron donating monomer. In some embodiments, the polymers include a monomer containing C_1-C_{20} alkoxy on a ring, which is optionally further substituted with C_1-C_{20} alkoxy or halo (e.g., $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$). Without wishing to be bound by theory, it is believed that polymers containing monomers substituted with long-chain alkoxy groups (e.g., oligomeric ethylene oxides) or fluorinated alkoxy groups have improved solubility in organic solvents and can form an photoactive layer with improved morphology.

TABLE 1

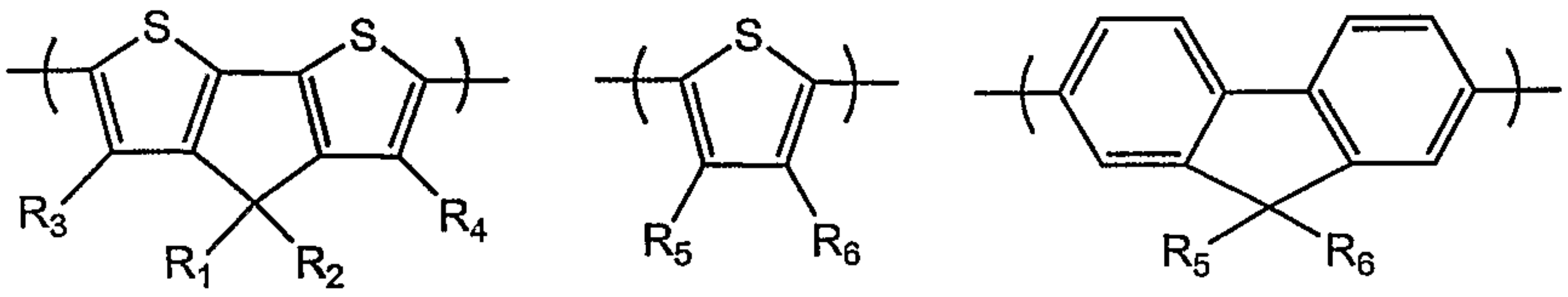
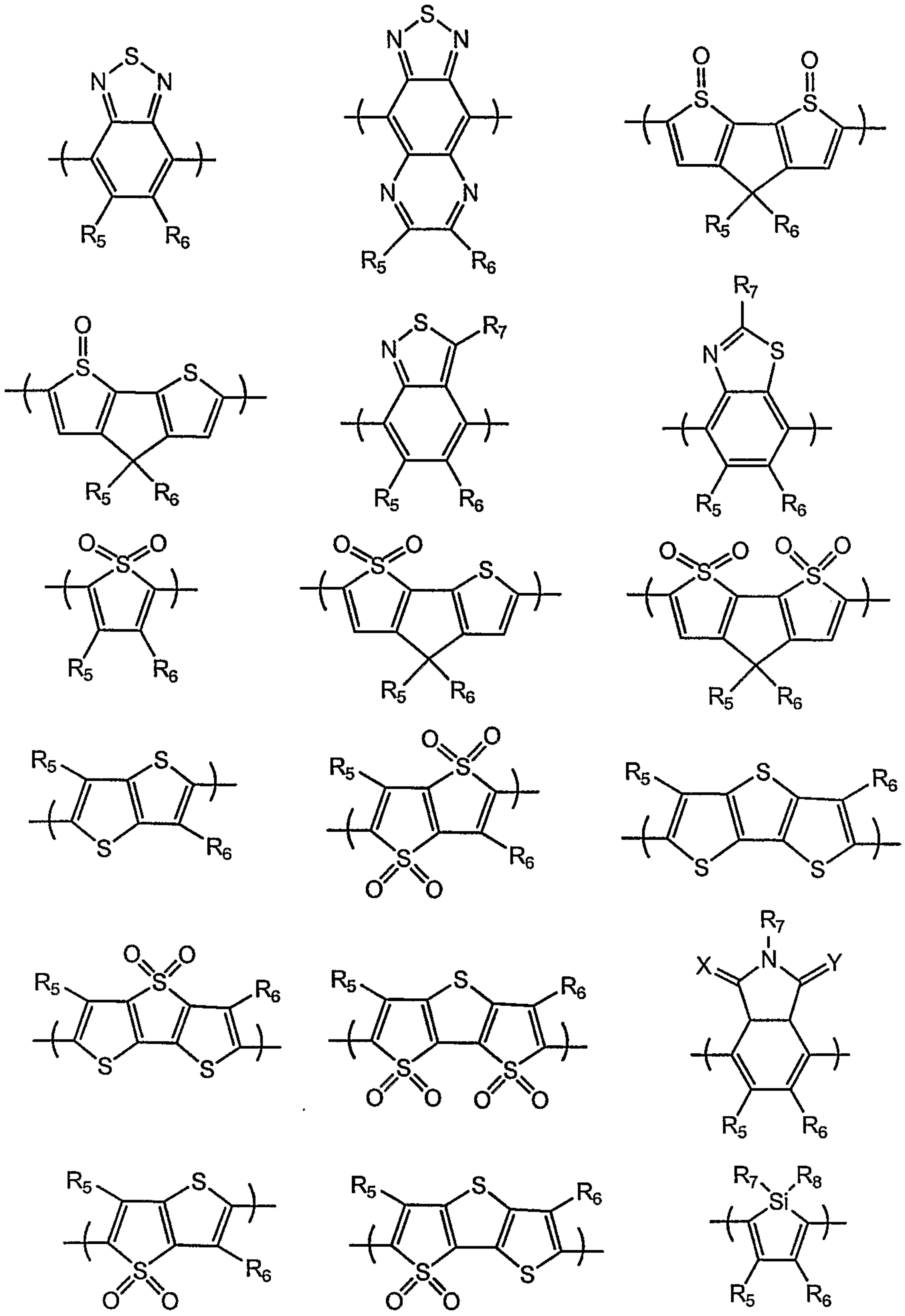


TABLE 2



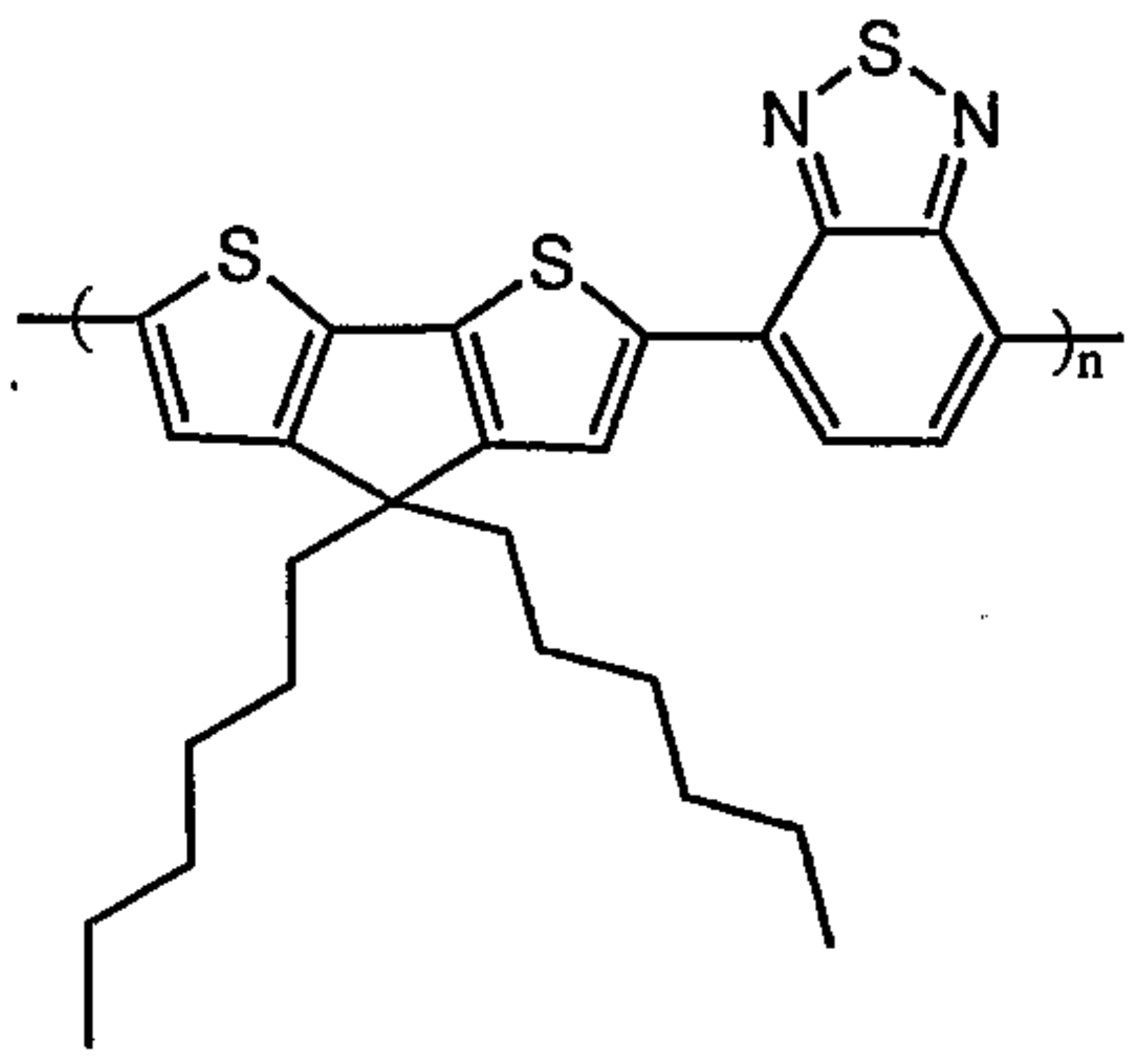
Referring to formulas listed in Tables 1 and 2 above, each of X and Y, independently, can be CH_2, O, or S; each of R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8, independently, can be H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl (e.g., phenyl or substituted phenyl), heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R; and R_7 can be H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl (e.g., phenyl or substituted phenyl), heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl; in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl. An alkyl can be saturated or unsaturated and branch or straight chained. A C_1-C_{20} alkyl contains 1 to 20 carbon atoms (e.g., one, two , three, four, five, six, seven, eight, nine, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20 carbon atoms). Examples of alkyl moieties include $-CH_3$, $-CH_2-$, $-CH_2=CH_2-$, $-CH_2-CH=CH_2$, and branched $-C_3H_7$. An alkoxy can be branch or straight chained and saturated or unsaturated. An C_1-C_{20} alkoxy contains an oxygen radical and 1 to 20 carbon atoms (e.g., one, two , three, four, five, six, seven, eight, nine, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20 carbon atoms). Examples of alkoxy moieties include $-OCH_3$ and $-OCH=C_2H_4$. A cycloalkyl can be either saturated or unsaturated. A C_3-C_{20} cycloalkyl contains 3 to 20 carbon atoms (e.g., three, four, five, six, seven, eight, nine, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20 carbon atoms). Examples of cycloalkyl moieities include cyclohexyl and cyclohexen-3-yl. A heterocycloalkyl can also be either saturated or unsaturated. A C_3-C_{20} heterocycloalkyl contains at least one ring heteroatom (e.g., O, N, and S) and 3 to 20 carbon atoms (e.g., three, four, five, six, seven, eight, nine, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, and 20 carbon atoms). Examples of heterocycloalkyl moieties include 4-tetrahydropyranyl and 4-pyranyl. An aryl can contain one or more aromatic rings. Examples of aryl moieties include phenyl, phenylene, naphthyl, naphthylene, pyrenyl, anthryl, and phenanthryl. A heteroaryl can contain one or more aromatic rings, at least one of which contains at least one ring heteroatom (e.g., O, N, and S). Examples of heteroaryl moieties include furyl, furylene, fluorenyl, pyrrolyl, thienyl, oxazolyl, imidazolyl, thiazolyl, pyridyl, pyrimidinyl, quinazolinyl, quinolyl, isoquinolyl, and indolyl.

Alkyl, alkoxy, cycloalkyl, heterocycloalkyl, aryl, and heteroaryl mentioned herein include both substituted and unsubstituted moieties, unless specified otherwise. Examples of substituents on cycloalkyl, heterocycloalkyl, aryl, and heteroaryl include C_1-C_{20} alkyl, C_3-C_{20} cycloalkyl, C_1-C_{20} alkoxy, aryl, aryloxy, heteroaryl, heteroaryloxy, amino, C_1-C_{10} alkylamino, C_1-C_{20} dialkylamino, arylamino, diarylamino, hydroxyl, halogen, thio, C_1-C_{10} alkylthio, arylthio, C_1-C_{10} alkylsulfonyl, arylsulfonyl, cyano, nitro, acyl, acyloxy, carboxyl, and carboxylic ester. Examples of substituents on alkyl include all of the above-recited substituents except C_1-C_{20} alkyl. Cycloalkyl, heterocycloalkyl, aryl, and heteroaryl also include fused groups.

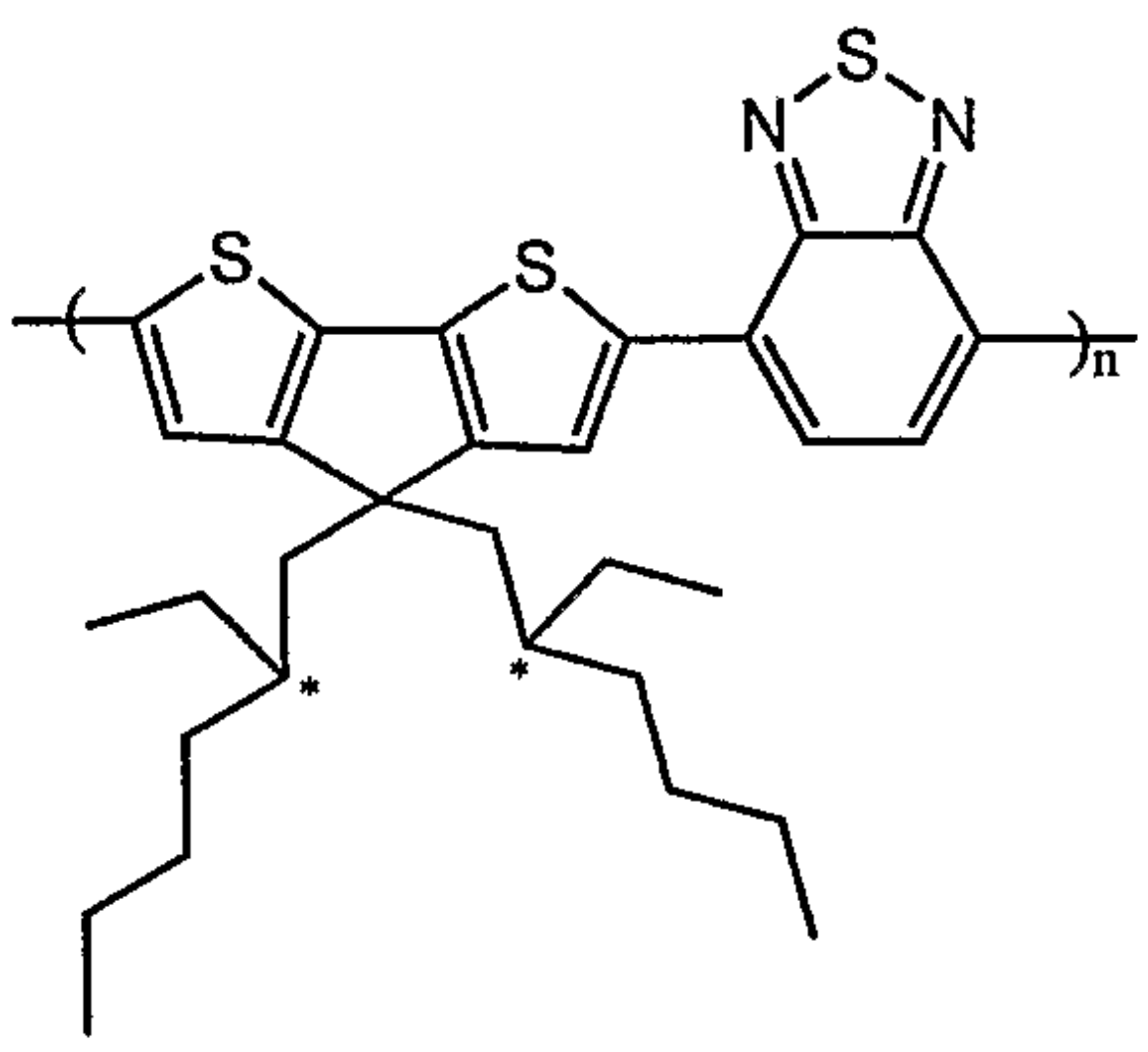
The copolymers described above can be prepared by methods known in the art. For example, a copolymer can be prepared by a cross-coupling reaction between one or more comonomers containing two alkylstannyl groups and one or more comonomers containing two halo groups in the presence of a transition metal catalyst. As another example, a copolymer can be prepared by a cross-coupling reaction between one or more comonomers containing two borate groups and one or more comonomers containing two halo groups in the presence of a transition metal catalyst. The comonomers can be prepared by the methods described herein or by the methods know in the art, such as those described in Coppo et al., *Macromolecules* 2003, 36, 2705-2711 and Kurt et al., *J. Heterocycl. Chem.* 1970, 6, 629, the contents of which are hereby incorporated by reference.

Table 3 below lists three exemplary polymers (i.e., polymers 1-3) described in the Summary section above. These polymers can have unique properties, which make them particularly suitable as charge carriers in the active layer of a photovoltaic cell. Polymers 1 and 2 can be obtained by the methods described in Examples 4 and 7 below.

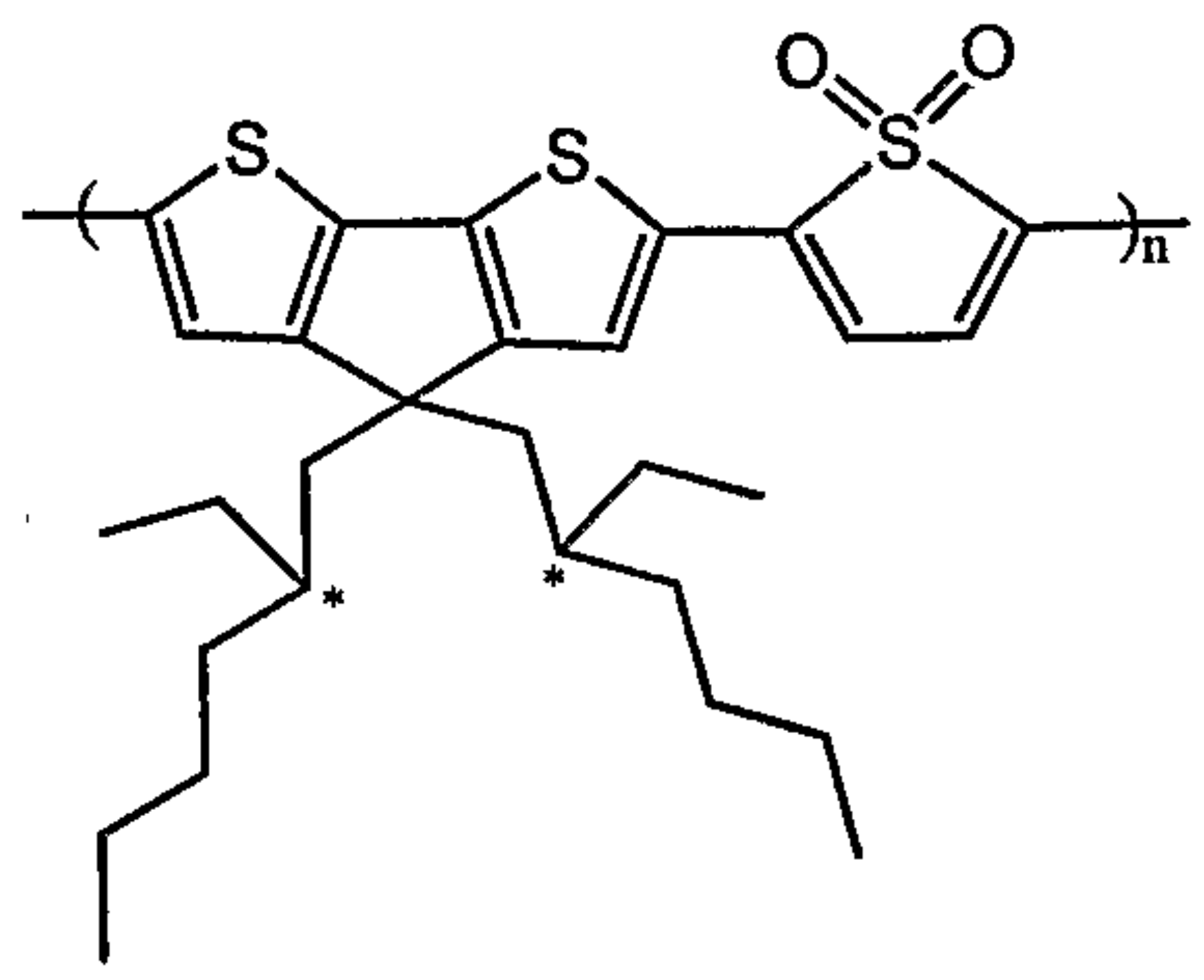
TABLE 3



Polymer 1



Polymer 2



Polymer 3

Generally, one co-monomer in the polymers described in the Summary section above is a cyclopentadithiophene. An advantage of a co-polymer containing a cyclopentadithiophene moiety is that its absorption wavelength can shift toward the red and near IR portion (e.g., 650 – 800 nm) of the electromagnetic spectrum, which is not accessible by most other polymers. When such a co-polymer is incorporated into a photovoltaic cell, it enables the cell to absorb the light in this region of the spectrum, thereby increasing the current and efficiency of the cell.

The polymers described above can be useful in solar power technology because the band gap is close to ideal for a photovoltaic cell (e.g., a polymer-fullerene cell). The HOMO level of the polymers can be positioned correctly relative to the LUMO of an electron acceptor (e.g., PCBM) in a photovoltaic cell (e.g., a polymer-fullerene cell), allowing for high cell voltage. The LUMO of the polymers can be positioned correctly relative to the conduction band of the electron acceptor in a photovoltaic cell, thereby creating efficient transfer of an electron to the electron acceptor. For example, using a polymer having a band gap of about 1.4 – 1.6 eV can significantly enhance cell voltage. Cell performance, specifically efficiency, cam benefit from both an increase in photocurrent and an increase in cell voltage, and can approach and even exceed 15 % efficiency. The positive charge mobility of the polymers can be relatively high and approximately in the range of 10^{-4} to 10^{-1} cm^2/Vs. In general, the relatively high positive charge mobility allows for relatively fast charge separation. The polymers can also be soluble in an organic solvent and/or film forming. Further, the polymers can be optically non-scattering.

Components in photovoltaic cell other than the electro acceptor materials and he electron donor materials are known in the art, such as those described in U.S. Patent Application Serial No. 10/723,554, the contents of which are incorporated herein by references.

In some embodiments, the polymer described above can be used as an electron donor material or an electro acceptor material in a system in which two photovoltaic cells share a common electrode. Such a system is also known as tandem photovoltaic cell. Examples of tandem photovoltaic cells are discussed in U.S. Patent Application Serial No. 10/558,878, filed November 29, 2005, the contents of which are hereby incorporated by reference.

As an example, Fig. 2 is a schematic of a tandem photovoltaic cell 200 having a substrate 210, three electrodes 220, 240, and 260, and two photoactive layers 230 and 250. Electrode 240 is shared between photoactive layers 230 and 250, and is electrically connected with electrodes 220 and 260. In general, electrodes 220, 240, and 260 can be formed of an electrically conductive material, such as those described in U.S. Patent Application Serial No. 10/723,554. In some embodiments, one or more (i.e., one, two, or three) electrodes 220, 240, and 260 is a mesh electrode. In some embodiments, one or more electrodes 220, 240, and 260 is formed of a semiconductive material. Examples of semiconductive materials include titanium oxides, indium tin oxides, fluorinated tin oxides, tin oxides, and zinc oxides. In certain embodiments, one or more (i.e., one, two, or three) electrodes 220, 240, and 260 are formed of titanium dioxide. Titanium dioxide used to prepare an electrode can be in any suitable forms. For example, titanium dioxide can be in the form of interconnected nanoparticles. Examples of interconnected titanium dioxide nanoparticles are described, for example, in U.S. Patent 7,022,910, the contents of which are incorporated herein by reference. In some embodiments, at least one (e.g., one, two, or three) of electrodes 220, 240, and 260 is a transparent electrode. As referred to herein, a transparent electrode is formed of a material which, at the thickness used in a photovoltaic cell, transmits at least about 60% (e.g., at least about 70%, at least about 75%, at least about 80%, at least about 85%, at least about 90%, at least about 95%) of incident light at a wavelength or a range of wavelengths used during operation of the photovoltaic cell. In certain embodiments, both electrodes 220 and 260 are transparent electrodes.

Each of photoactive layers 230 and 250 can contain at least one semiconductive material. In some embodiments, the semiconductive material in photoactive layer 230 has the same band gap as the semiconductive material in photoactive layer 250. In certain embodiments, the semiconductive material in photoactive layer 230 has a band gap different from that of the semiconductive material in photoactive layer 250. Without wishing to be bound by theory, it is believed that incident light not absorbed by one photoactive layer can be absorbed by the other photoactive layer, thereby maximizing the absorption of the incident light.

In some embodiments, at least one of photoactive layers 230 and 250 can contain an electron acceptor material (e.g., PCBM or a polymer described above) and an electron donor material (e.g., a polymer described above). In general, suitable electron acceptor materials and electron donor materials can be those described above. In certain embodiments, each of photoactive layers 230 and 250 contains an electron acceptor material and an electron donor material.

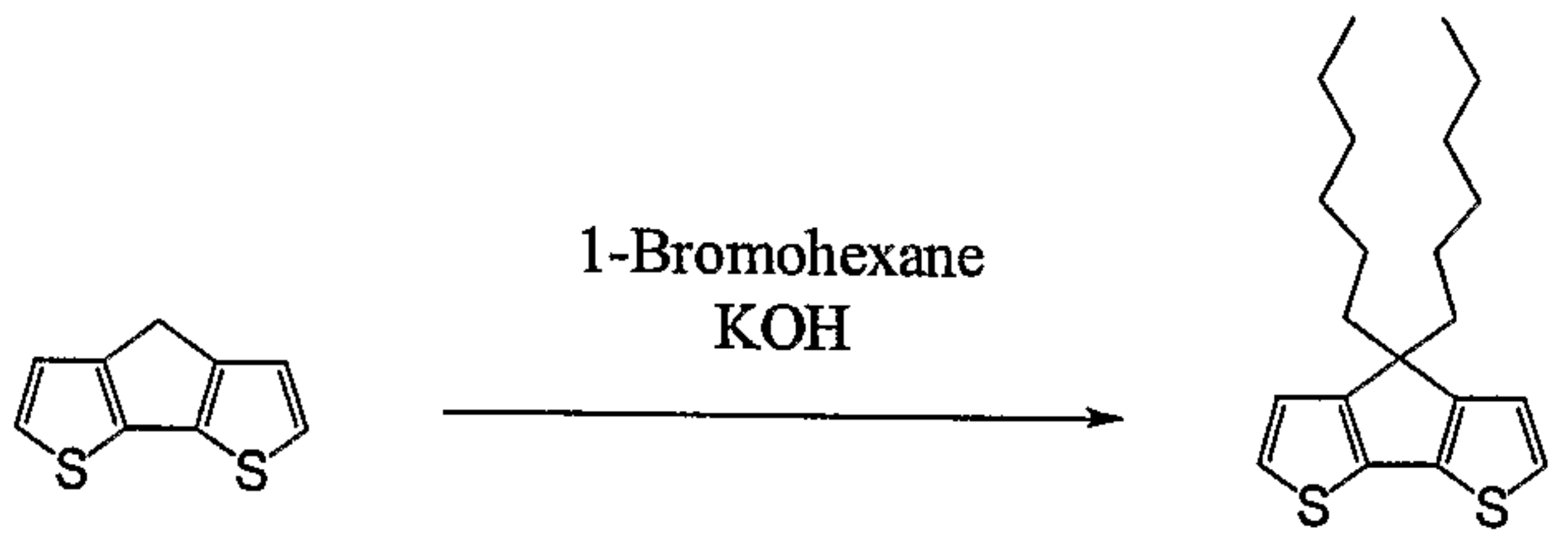
Substrate 210 can be formed of one or more suitable polymers, such as those described in U.S. Patent Application Serial No. 10/723,554. In some embodiments, an additional substrate (not shown in Fig. 2) can be disposed on electrode 260.

Photovoltaic cell 200 can further contain a hole carrier layer (not shown in Fig. 2) and a hole blocking layer (not shown in Fig. 2), such as those described in U.S. Patent Application Serial No. 10/723,554.

While photovoltaic cells have been described above, in some embodiments, the polymers described herein can be used in other devices and systems. For example, the polymers can be used in suitable organic semiconductive devices, such as field effect transistors, photodetectors (e.g., IR detectors), photovoltaic detectors, imaging devices (e.g., RGB imaging devices for cameras or medical imaging systems), light emitting diodes (LEDs) (e.g., organic LEDs or IR or near IR LEDs), lasing devices, conversion layers (e.g., layers that convert visible emission into IR emission), amplifiers and emitters for telecommunication (e.g., dopants for fibers), storage elements (e.g., holographic storage elements), and electrochromic devices (e.g., electrochromic displays).

The following examples are illustrative and not intended to be limiting.

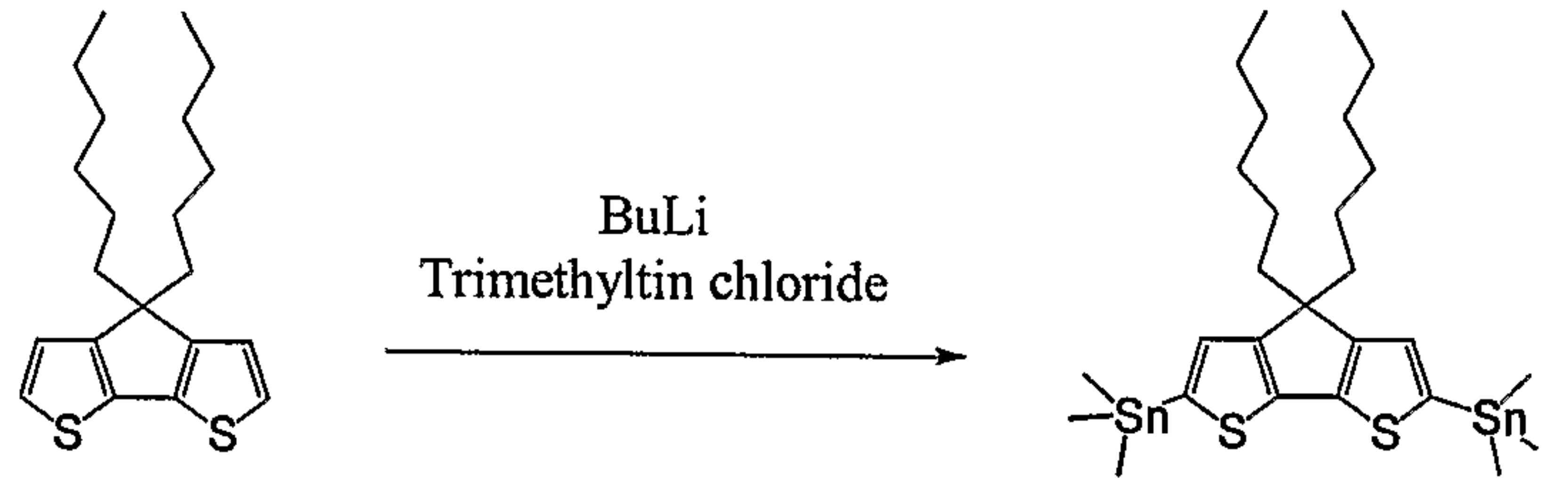
Example 1: Synthesis of 4,4-Dihexyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene



4H-Cyclopenta[2,1-b;3,4-b']dithiophene was synthesized according to literature procedure illustrated in Coppo et al., *Macromolecules* 2003, *36,* 2705-2711. All other starting materials were purchased from Sigma-Aldrich and used as received.

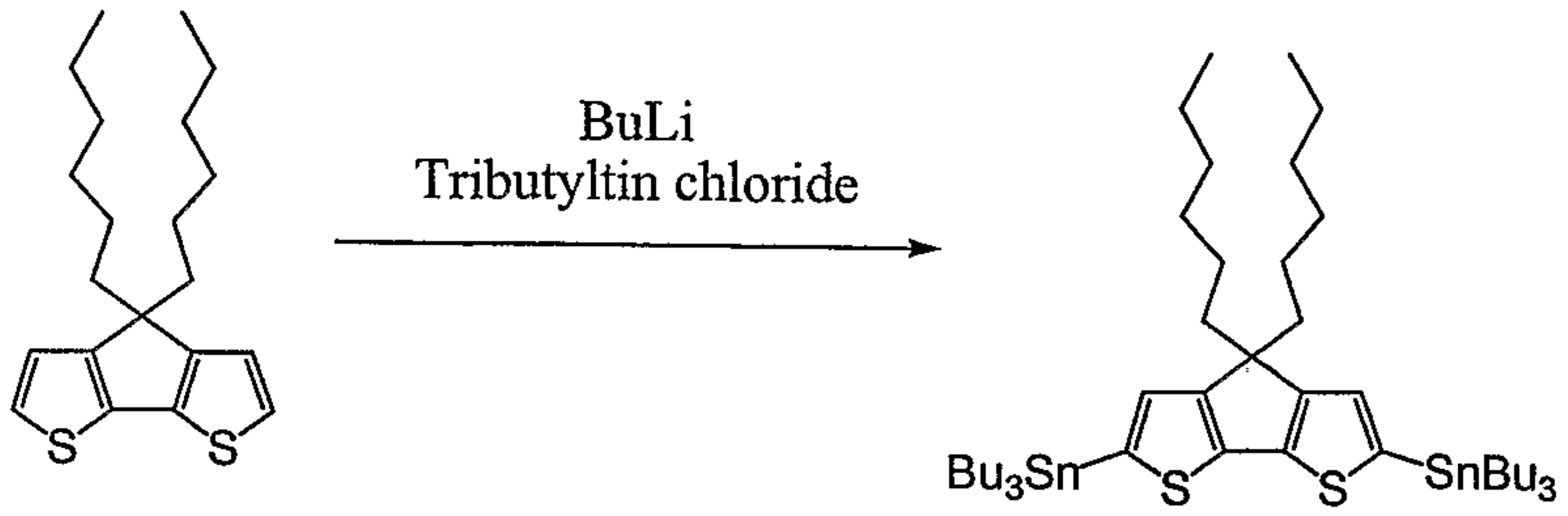
4H-Cyclopenta[2,1-b;3,4-b']dithiophene (1.5 g, 0.00843 mol) was dissolved in DMSO (50 mL). The solution was purged with nitrogen, and grounded KOH (1.89 g, 0.0337 mol) and sodium iodide (50 mg) were added, followed by hexyl bromide (3.02 g, 0.0169 mol). The reaction was stirred for 17 h under nitrogen at room temperature. Water was added and the reaction was extracted with t-butyl-methyl ether. The organic layer was separated and dried over magnesium sulfate. Solvent was removed under vacuum and the residue was purified by chromatography using hexanes as eluent. Fractions containing pure 4,4-dixeyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene product were combined and the solvents evaporated. The product was obtained as a colorless oil. Yield: 2.36 g (81%).

Example 2: The Synthesis of 4,4-Dihexyl-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene



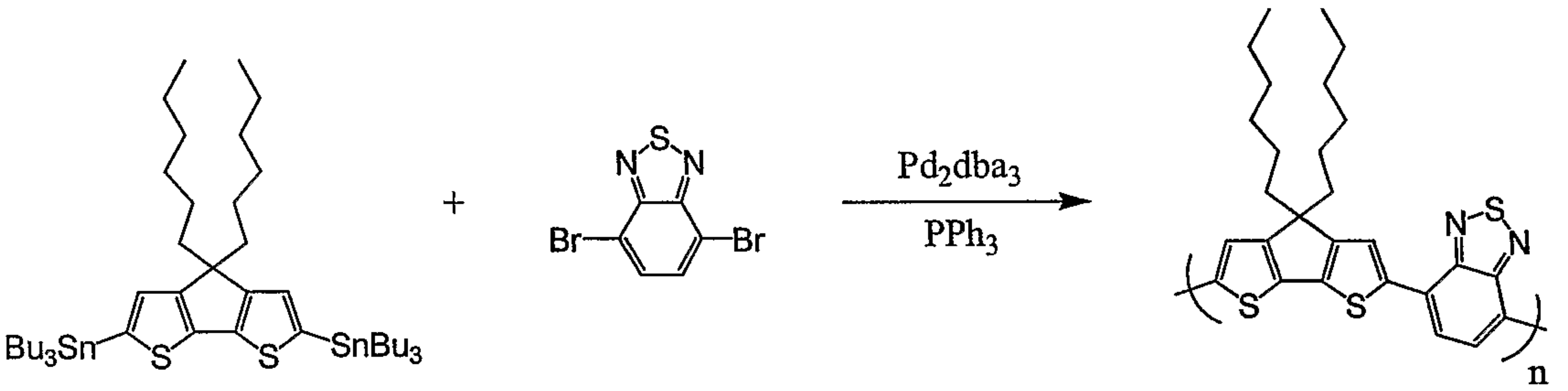
Starting material 4,4-dihexyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene (1.5 g, 0.00433 mol) was dissolved in dry THF (30 mL). The solution was cooled to -78 °C and butyl lithium (6.1 mL, 0.0130 mol) was added drop wise. The reaction was stirred at this temperature for 2 h and warmed to room temperature, stirred for 3 h. Again reaction was cooled to -78 °C and trimethyltin chloride (1 M in hexanes, 16.0 mL, 16.0 mmol) was added dropwise. The reaction was allowed to warm to rt and stirred for 17 h. Water was added and the reaction was extracted with toluene. The organic layer was washed with water and dried over sodium sulfate. Solvent was removed under vacuum and the residue was dissolved in toluene, and quickly passed through a plug of silica gel pretreated with triethyl amine. Solvent was removed and the residue dried under vacuum to afford 2.65 g of the bis(trimethyltin) monomer. ^{1}H NMR ($CDCl_3$, 200 MHz): 6.97 (m, 2H), 1.84 (m, 4H), 1.20 (m, 16H), 0.88 (m, 6H), 0.42 (m, 18H).

Example 3: The Synthesis of bis-(tributylstannyl)-4,4-dihexyl-cyclopenta[2,1-b:3,4-b']dithiophene



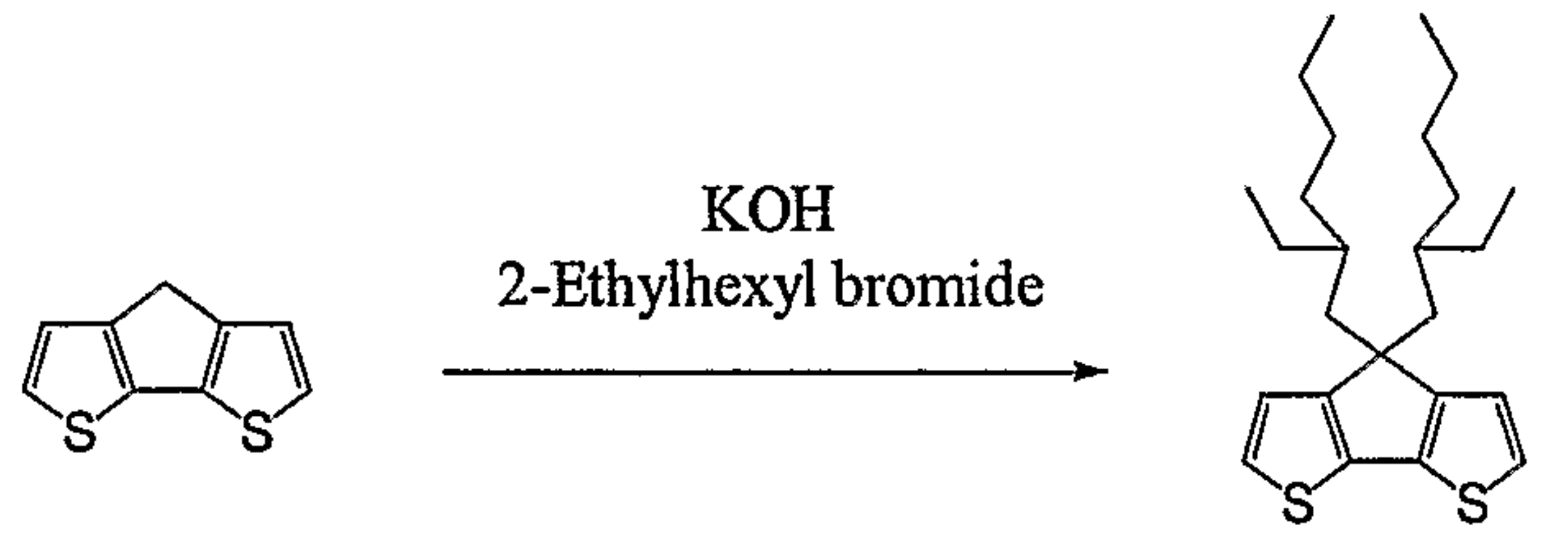
4,4-Dihexyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene (2.2 g, 0.0065 mol) was dissolved in dry THF (20 mL). The solution was cooled to -78°C. BuLi (7.62, 2.5 M in hexanes, 0.019 mol) was then added to the solution. The reaction mixture was allowed to warm to room temperature and was stirred for 5 hours. The mixture was then cooled again to -78°C and Bu_3SnCl (7.44g, 0.0229 mol) was added. The reaction mixture was allowed to warm to room temperature and was stirred for another 48 hours. Water was then added and the mixture was extracted with dihicholomethane. Organic layer was collected, dried over anhydrous Na_2SO_4, and concentrated. The residue thus obtained was dissolved in hexane and quickly passed through a plug of silica gel pretreated with triethylamine. The solvent was removed and the residue was dried under vacuum to afford bis-(tributylstannyl)-4,4-dihexyl-cyclopenta[2,1-b:3,4-b']dithiophene (5.7 g).

Example 4: Polymerization of bis-(tributylstannyl)-4,4-dihexyl-cyclopenta[2,1-b:3,4-b']dithiophene and 4,7-dibromo-2,1,3-benzothiadiazole



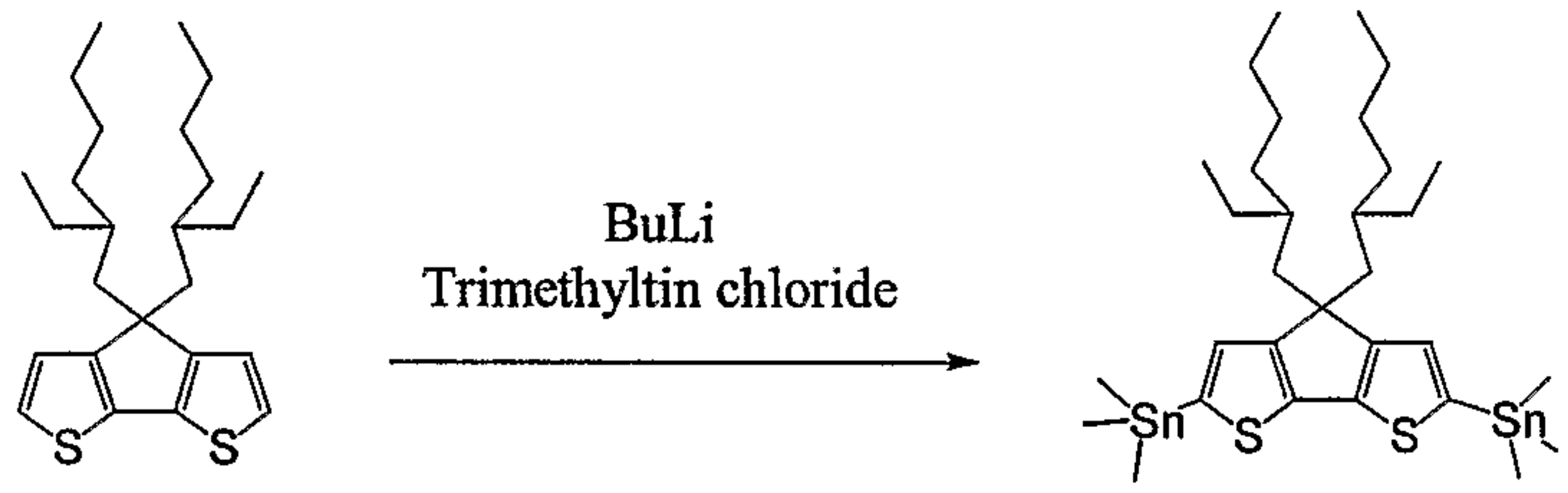
Bis-(tributylstannyl)-4,4-dihexyl-cyclopenta[2,1-b:3,4-b']dithiophene (0.775 g, 0.000816 mol) and 4,7-dibromo-2,1,3-benzothiadiazole (0.24 g, 0.000816 mol) were first dissolved in toluene. After the reaction was purged with nitrogen, palladium tretakistriphenylphosphine (15 mg, 0.0065 mmol) was added. The reaction mixture was heated at 100°C for 24 hour. After the solvent was removed, the residue was washed with acetone and extracted in a Soxlet extractor for 8 hours to afford the product as an insoluble blue solid.

Example 5: Synthesis of 4,4-Bis-(2-ethyl-hexyl)-4H-cyclopenta[2,1-b;3,4-b']dithiophene



4H-Cyclopenta[2,1-b;3,4-b']dithiophene (1.5 g, 0.00843 mol) was dissolved in DMSO (50 mL). After the solution was purged with nitrogen, and grounded KOH (1.89 g, 0.0337 mol), sodium iodide (50 mg), and 2-ethylhexyl bromide (3.25 g, 0.0169 mol) were sequentially added. The reaction mixture was stirred overnight under nitrogen (c.a. 16 hours). Water was added and the reaction was extracted with t-butylmethyl ether. The organic layer was collected, dried over magnesium sulfate, and concentrated. The residue was purified by chromatography using hexanes as eluent. Fractions containing pure 4,4-Bis-(2-ethyl-hexyl)-4H-cyclopenta[2,1-b;3,4-b']dithiophene product were combined and concentrated. The product was obtained as a colorless oil after drying under vacuum. Yield: 2.68 g (79%). ^{1}H NMR ($CDCl_3$, 250 MHz): 7.13 (m, 2H), 6.94 (m, 2H), 1.88 (m, 4H), 0.94 (m, 16H), 0.78 (t, 6.4 Hz, 6H), 0.61 (t, 7.3 Hz, 6H).

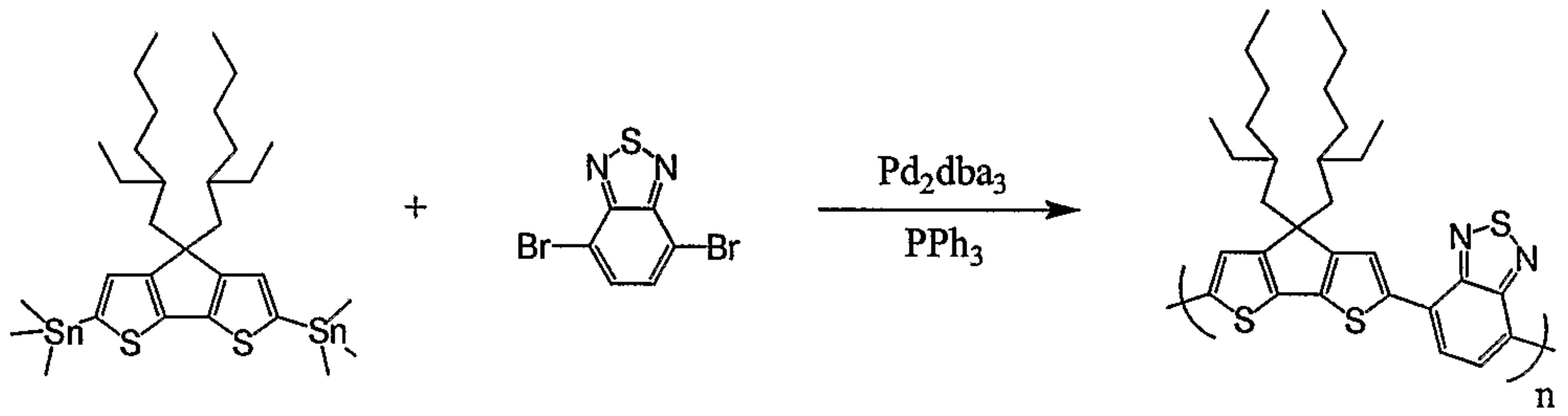
Example 6: Synthesis of 4,4-Bis-(2-ethyl-hexyl)-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene



Starting material 4,4-Bis-(2-ethyl-hexyl)-4H-cyclopenta[2,1-b;3,4-b']dithiophene (1.5 g, 0.00372 mol) was dissolved in dry THF (20 mL). After the solution was cooled to -78°C, butyl lithium (5.21 mL, 0.0130 mol) was added dropwise. The reaction mixture was stirred at this temperature for 1 hour. It was then warmed to room temperature and stirred for another 3 hours. The mixture was again cooled to -78°C and trimethyltin chloride (1 M in hexane, 15.6 mL, 15.6 mmol) was added dropwise. The reaction mixture was allowed to warm to room temperature and stirred overnight (c.a. 16 hours).

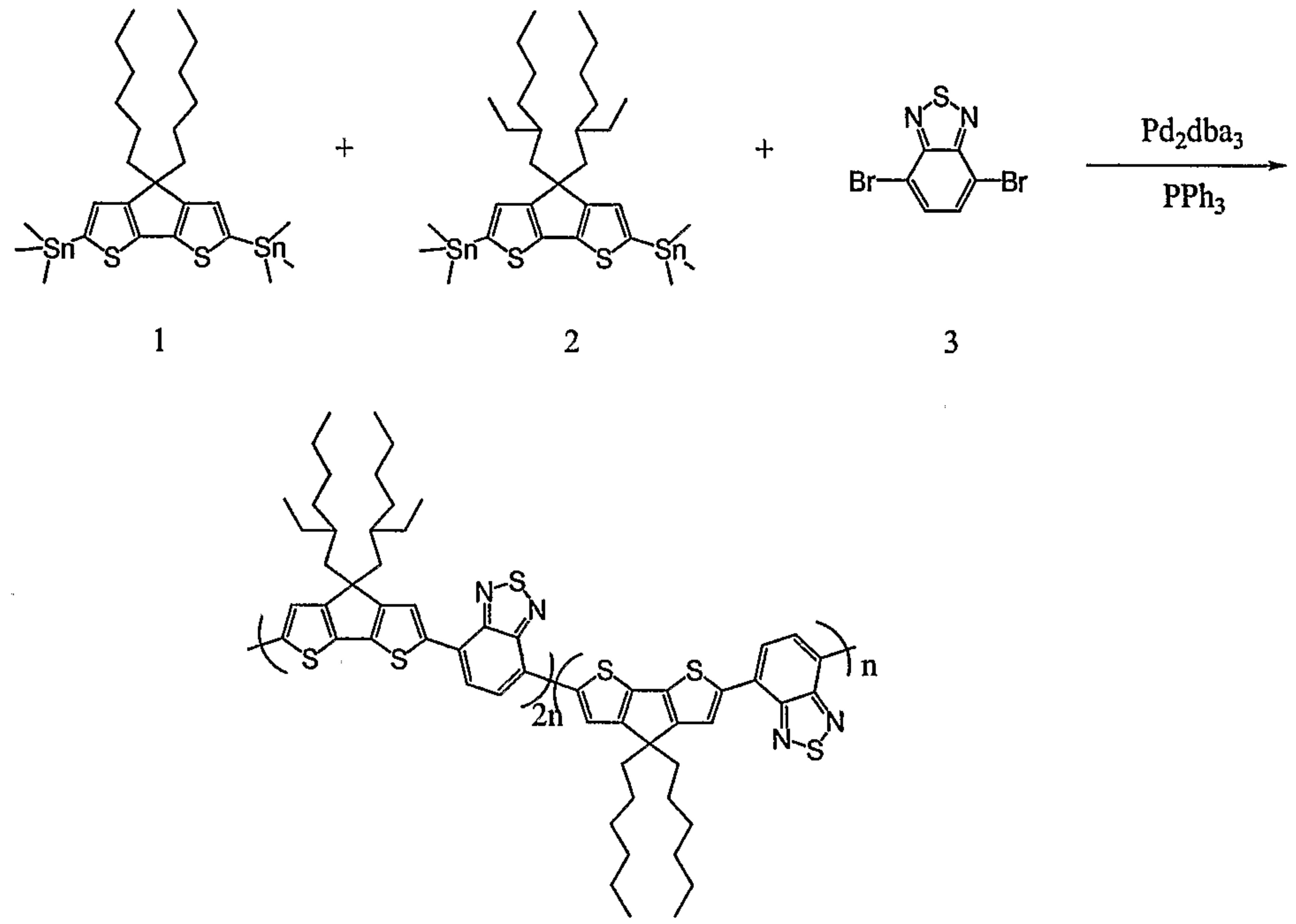
Water was added and the reaction was extracted with toluene. The organic layer was washed with water, dried over sodium sulfate, and concentrated. The residue was dissolved in toluene, and quickly passed through a small plug of silica gel pretreated with triethylamine. The solvent was removed and the residue was dried under vacuum. 1.25 g of the product was obtained. ^{1}H NMR ($CDCl_3$, 250 MHz): 6.96 (m, 2H), 1.85 (m, 4H), 1.29 (m, 2H), 0.92 (m, 16H), 0.78 (t, 6.8 Hz, 6H), 0.61 (t, 7.3 Hz, 6H), 0.38 (m, 18H).

Example 7: Polymerization of Bis-(trimethylstannyl)-4,4-Di(2-ethylhexyl)-cyclopenta[2,1-b:3,4-b']dithiophen and 4,7-dibromo-2,1,3-benzothiadiazole



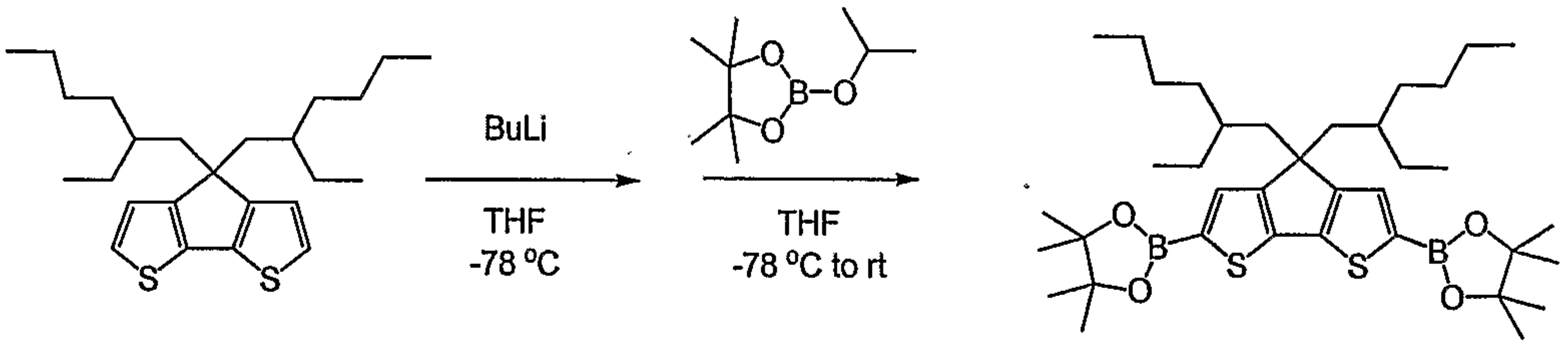
Bis-(trimethylstannyl)-4,4-di(2-ethylhexyl)-cyclopenta[2,1-b:3,4-b']dithiophene (0.686 g, 0.000943 mol) and 4,7-dibromo-2,1,3-benzothiadiazole (0.269 g, 0.000915 mol) were dissolved in toluene (20 mL). After the reaction was purged with nitrogen, tris(dibenzylideneacetone)dipalladium(0) (25.1 mg, 0.0275 mmol) and triphenylphosphine (57.6 mg, 0.220 mmol) were added. The reaction was further purged with nitrogen for 10 minutes and heated to 120°C under nitrogen for 24 hours. The solvent was removed under vacuum and the residue was dissolved in chloroform. After the mixture was poured into methanol (500 mL), the blue precipitate thus obtained was collected by filtration, washed with methanol, and dried. The precipitate was dissolved in chloroform (30 mL) under heating, and filtered through a 0.45 μm membrane. The solution was loaded on to recycling HPLC (2H + 2.5H column on a Dychrome recycling HPLC, 5 cycles for each injection), in 3 mL portions for purification. Higher-molecular-weight fractions were combined to give 120 mg pure polymer (Mn = 35 kDa).

Example 8: Copolymerization of 4,4-Dihexyl-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene, 4,4-Bis-(2-ethyl-hexyl)-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene, and 4,7-Dibromo-benzo[1,2,5]thiadiazole



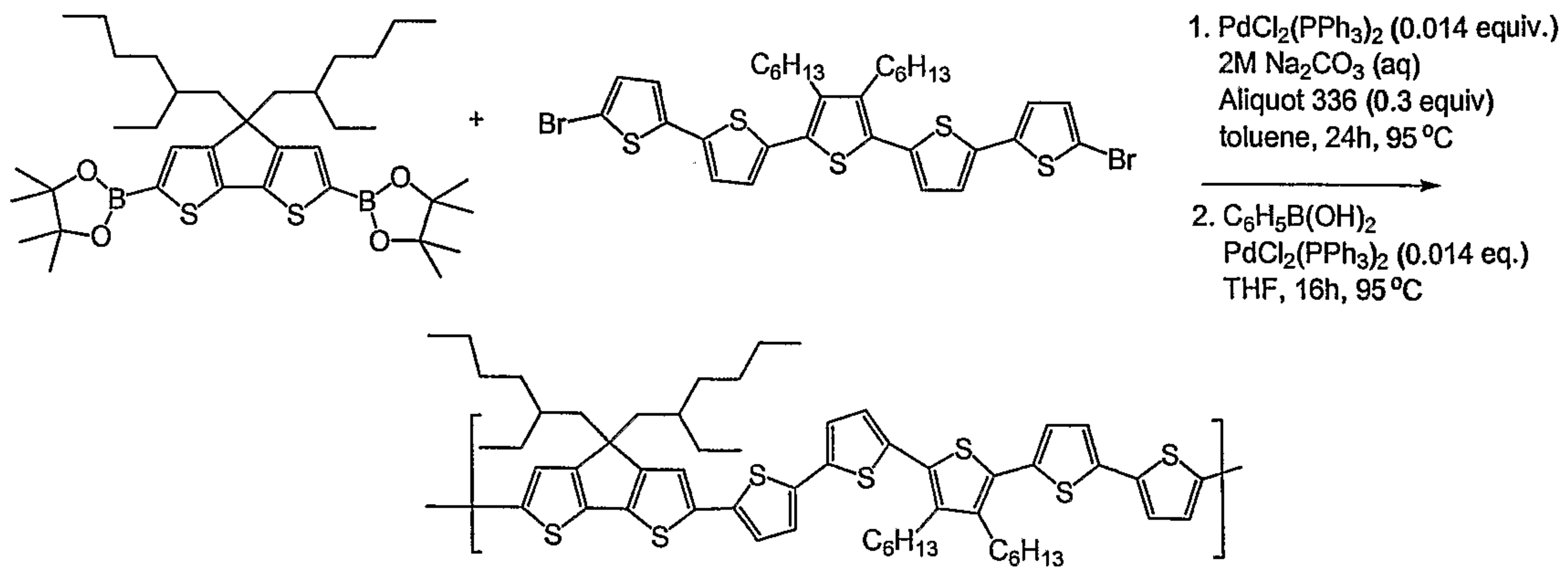
4,4-Dihexyl-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene (0.0863 g, 0.000128 mol),4,4-bis-(2-ethyl-hexyl)-2,6-bis-trimethylstannanyl-4H-cyclopenta[2,1-b;3,4-b']dithiophene (0.187 g, 0.000257 mol), and 4,7-Dibromo-benzo[1,2,5]thiadiazole (0.111 g, 0.000378 g) were dissolved in toluene (15 mL) and the solution was degassed and purged with N_2. Tris(dibenzylideneacetone)dipalladium(0) (6.78 mg, 0.0074 mmol) and triphenylphosphine (15.5 mg, 0.0 593 mmol) were then added. The reaction was purged again with nitrogen for 30 minutes and heated at 120°C under nitrogen. The solvent was then removed under vacuum. The residue was dissolved in chloroform and the solution was added into methanol. The precipitates were collected and extracted with hexane for 24 hours and then extracted with chloroform for 8 hours. The resultant blue solution was concentrated and added to methanol. The precipitates were collected to afford a first fraction of the polymer (70 mg). The remaining materials on the thimble was further extracted with chloroform for 20 hours. 20 mg additional polymer was collected.

Example 9: Preparation of 4H-4,4-bis(2′-ethylhexyl)cyclopenta[2,1-b:3,4-b′]thiophene-2,6-bis(pinacolborate) ester



100 mL oven dried Schlenk flask was charged with 1.097 g (2.72 mmol) of 4*H*-4,4-bis(2′-ethylhexyl)cyclopenta[2,1-*b*:3,4-*b*′]dithiophene. The flask was evacuated and purged with argon three times. To this flask was then added 20 mL of dry, distilled THF. The resulting solution was cooled to -78°C and 4.35 mL (10.88 mmol, 4 equv.) of 2.5M BuLi was added dropwise. The reaction was stirred for 1 hout at -78 °C and then warmed to room temperature and stirred for an additional 3 hours. The solution was cooled again to -78 °C and 2.77 mL (13.6 mmol, 5 equiv.) of 2-isopropoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane was added in one portion via syringe. The reaction was stirred at -78 °C for 1 hour and then allowed to warm to room temperature overnight. The solution was poured into water and extracted with 4 × 150 mL of methyl tert-butyl ether. The organic layers were combined and washed with 2 × 150 mL of brine, dried with anhydrous $MgSO_4$, and filtered. The solvent was removed under vacuum to yield and orange oil, which was purified by column chromatography (5% EtOAc in hexanes) to yield a colorless, viscous oil, 1.34g (75% yield).

Example 10: Preparation of a Pentathienyl-cyclopentadithiophene Copolymer



A 50 mL Schlenk flask was charged with 0.309 g (0.472 mmol) of 4*H*-4,4-bis(2′-ethylhexyl)cyclopenta[2,1-*b*:3,4-*b*′]dithiophene-2,6-bis(pinacolborate) ester prepared in Example 9, 0.367 g (0.510 mmol) of 5,5'-dibromo-3'',4''-dihexyl-a-pentathiophene (its synthesis was described in WO 2005/092947, which is incorporated herein by reference) 0.0013 g (0.00185 mmol) of $PdCl_2(PPh_3)_2$, and 0.057 g (0.142 mmol) of trioctylmethylammonium chloride (Aliquot 336, Aldrich, St. Louis, MO). The flask was fitted with a reflux condenser and the flask was evacuated and refilled with nitrogen three times. The solids were dissolved in 6 mL of toluene and then 0.88 mL of 2M Na_2CO_3 were added via syringe. The reaction was then heated to 95°C with stirring for 5 hours. Phenylboronic acid (0.031 g, 0.250 mmol) and 0.0016 g (0.00228 mmol) of $PdCl_2(PPh_3)_2$ were dissolved in 1 mL of THF and added to the reaction mixture, and stirring was continued for 16 h at 95°C. The reaction mixture was diluted with toluene (50 mL) and the organic layer was separated and washed with warm water (3 × 50 mL). The solution was then treated with an aqueous solution of diethyldithiocarbamic acid sodium salt trihydrate (7.5 %, DDC, 5 mL) and heated at 80°C overnight. The aqueous layer was separated and discarded and the organic layer was washed with warm water (3 × 50 mL) and the polymer precipitated into methanol (500 mL). The polymer was collected by filtration, washed with methanol (50 mL) and redissolved in hot toluene (200 mL). The hot polymer solution was passed through a tightly packed column of celite (1 × 8 cm), silica get (3 × 8 cm), and basic alumina (3 × 8 cm) (previously rinsed with 200 mL of hot toluene). The polymer solution was collected and the volume concentrated to approximately 50 mL. The polymer was precipitated into methanol (500 mL), washed with methanol (100 mL), acetone (100 mL) and again with methanol (100 mL). The polymer was then dried *in vacuo* overnight to yield a brick red material. Yield: 0.327 g.

Example 11: Fabrication of solar cell

The polymer solar cells were fabricated by doctor-blading a blend of the polymer prepared in Example 7 (PCPDTBT) and $PC_{61}BM$ or $PC_{71}BM$ (purchased from Nano-C, Westwood, MA) in a 1:3 *w/w* ratio sandwiched between a transparent anode and an evaporated metal cathode. The transparent anode was an indium tin oxide (ITO)-covered glass substrate (Merck, Whitehouse Station, NJ) which was coated with a ~60 nm thick

PEDOT:PSS layer (Baytron PH from H.C. Starck) applied by doctorblading. The ITO-glass-substrate was cleaned by ultrasonification subsequently in acetone, isopropyl alcohol and deionized water. The cathode, a bilayer of a thin (1 nm) LiF layer covered with 80 nm Al, was prepared by thermal evaporation. PCPDTBT and $PC_{61}BM$ or $PC_{71}BM$ were dissolved together in *o*-dichlorobenzene (ODCB) to give an overall 40 mg/ml solution and was stirred overnight at 60-70°C inside a glovebox. The active layer thickness, as determined by AFM, was between 150 - 250 nm. Device characterization was done under AM 1.5G irradiation (100 mW/cm^2) on an Oriel Xenon solar simulator with a well calibrated spectral mismatch of 0.98 jV-characteristics were recorded with a Keithley 2400. Active areas were in the range of 15 to 20 mm^2. EQE was detected with a lock-in amplifier under monochromatic illumination. Calibration of the incident light was done with a monocrystalline silicon diode. Mobility measurements were done using an Agilent 4155C parameter analyzer. Absorption measurements were done inside the glovebox with an Avantes fiberoptic spectrometer or outside with a HP spectrometer.

The interaction with PCBM and the photoinduced charge transfer was investigated by PL quenching. The PL of pristine PCPDTBT versus PCPDTBT / PCBM composites was measured at liquid N_2 temperatures in a cryostat, excitation was provided by an Ar laser at 488 nm.

Electrochemical experiments were carried out on dropcast polymer films at room temperature in a glovebox. The supporting electrolyte was tetrabutylammonium-hexafluorophosphate ($TBAPF_6$, electrochemical grade, Aldrich) ~0.1 M in acetonitrile anhydrous (Aldrich). The working electrode (WE), as well as the counter electrode (CE), was a platinum foil. A silver wire coated with AgCl was used as a reference electrode (RE). After each measurement, the RE was calibrated with ferrocene (E^0 = 400 mV vs. NHE) and the potential axis was corrected to NHE (using -4.75 eV for NHE[24,25]) according to the difference of E^0 (ferrocene) and the measured $E^{1/2}$ (ferrocene). λ_{max} ($CHCl_3$) = 710 nm, $\lambda_{band\ edge}$ ($CHCl_3$) = 780 nm, band gap ($CHCl_3$) = 1.59 eV, λ_{max} (film) = 700 – 760 nm, $\lambda_{band\ edge}$ (film) = 855 nm, band gap (film) = 1.45eV, HOMO = -5.3eV, -5.7eV (electrochem), LUMO = -3.85eV, -4.25eV, $\mu_+ = 2x10^{-2}$ cm_2/Vs (TOF), $1x10^{-3}$ cm^2/Vs (FET).

Other embodiments are in the claims.

WHAT IS CLAIMED IS:

1. A photovoltaic cell, comprising:

a first electrode,

a second electrode, and

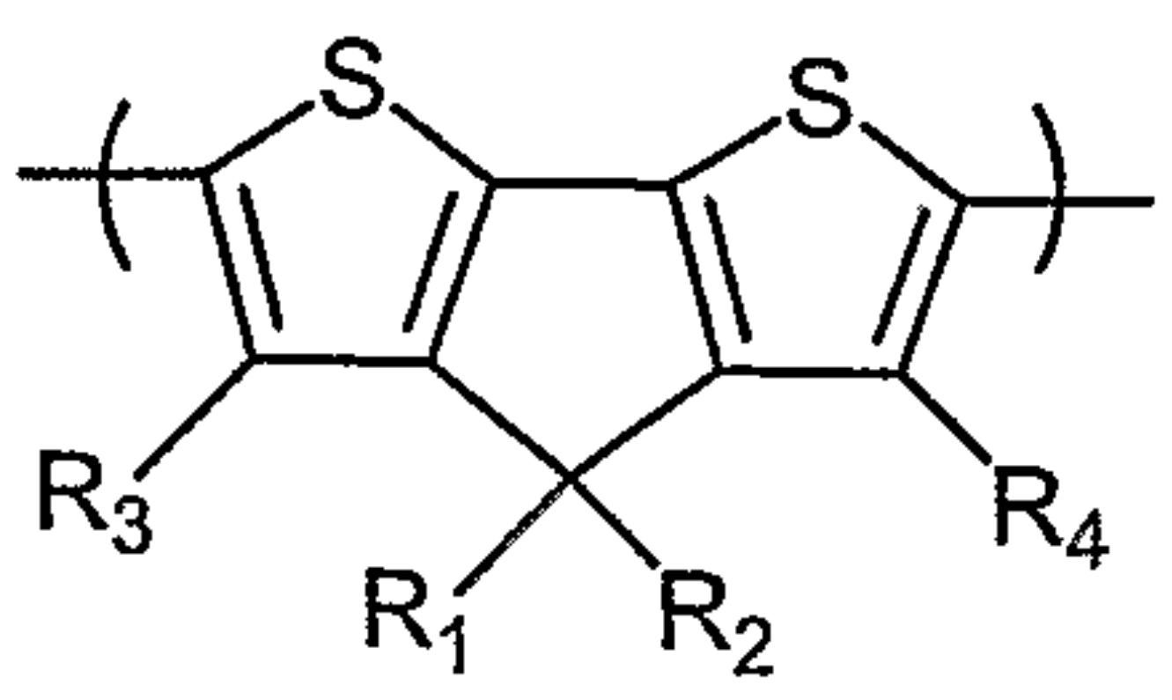
a photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first comonomer repeat unit and a second comonomer repeat unit, wherein the first comonomer repeat unit comprises a cyclopentadithiophene moiety, and the second comonomer repeat unit comprises a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, or a silole moiety.

2. The photovoltaic cell of claim 1, wherein the cyclopentadithiophene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

3. The photovoltaic cell of claim 2, wherein the cyclopentadithiophene moiety is substituted with hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

4. The photovoltaic cell of claim 2, wherein the cyclopentadithiophene moiety is substituted at 4-position.

5. The photovoltaic cell of claim 1, wherein the first comonomer repeat unit comprises a cyclopentadithiophene moiety of formula (I):



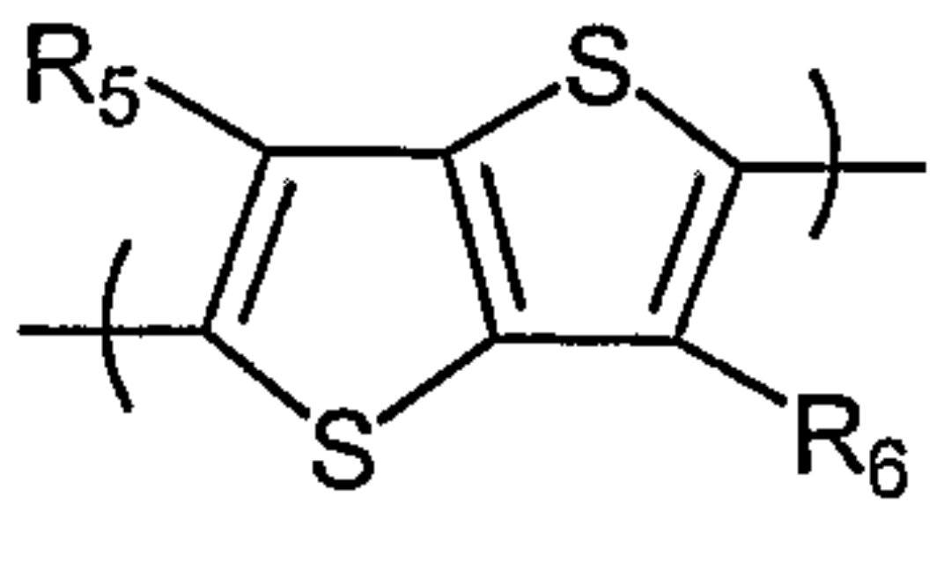
(I),

wherein each of R_1, R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

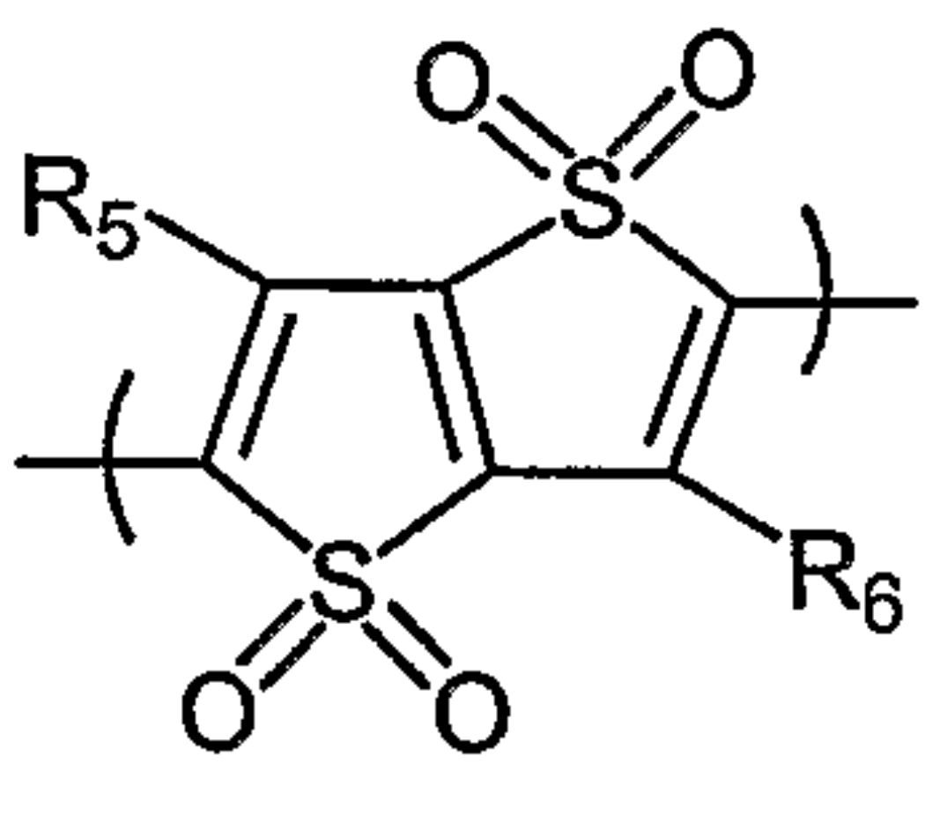
6. The photovoltaic cell of claim 5, wherein each of R_1 and R_2, independently, is hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

7. The photovoltaic cell of claim 1, wherein the second comonomer repeat unit is substituted on a ring with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

8. The photovoltaic cell of claim 1, wherein the second comonomer repeat unit comprises a thienothiophene moiety of formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), a dithienothiophene dioxide moiety of formula (XVIII), or a silole moiety of formula (XXI):



(XI),



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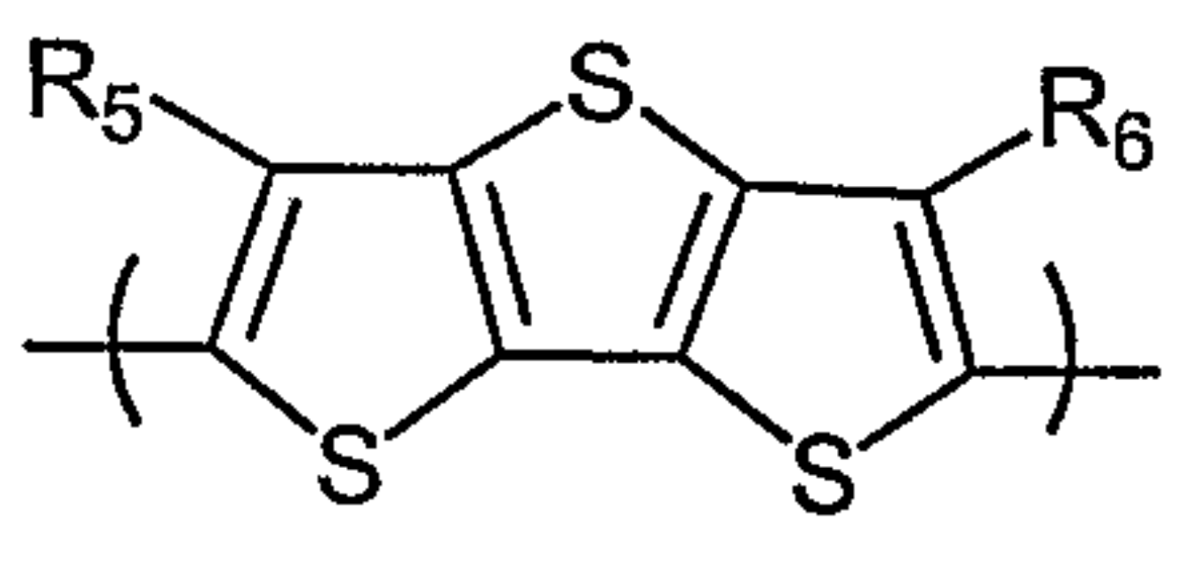

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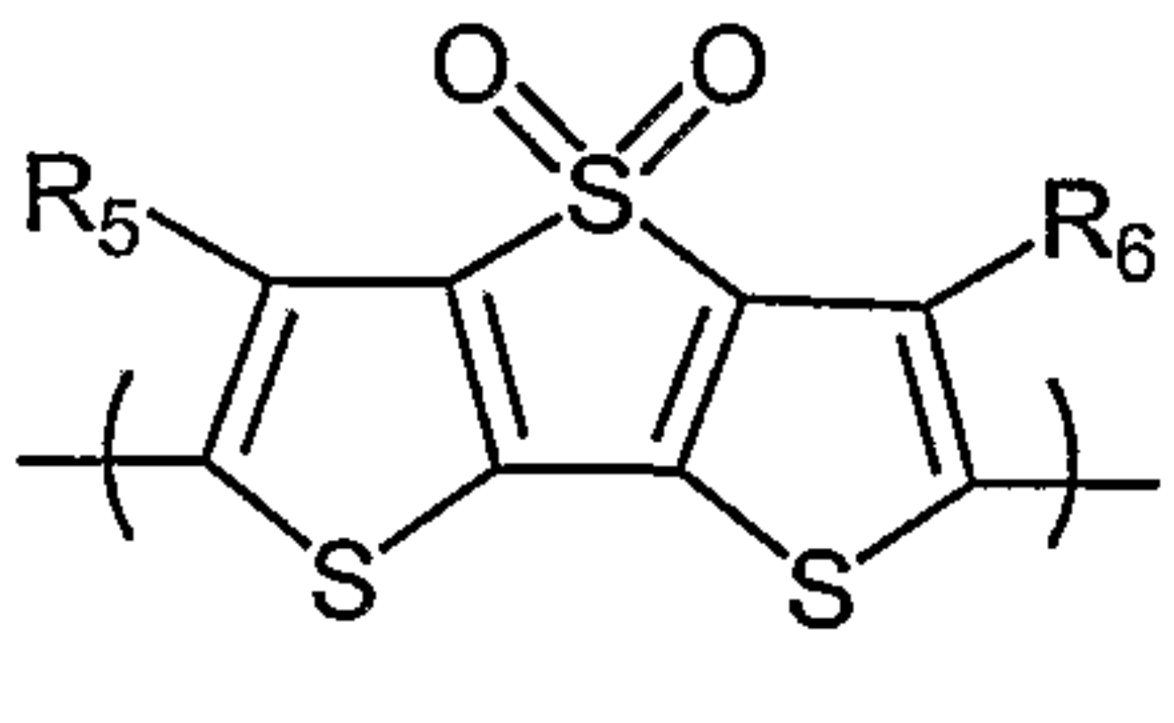

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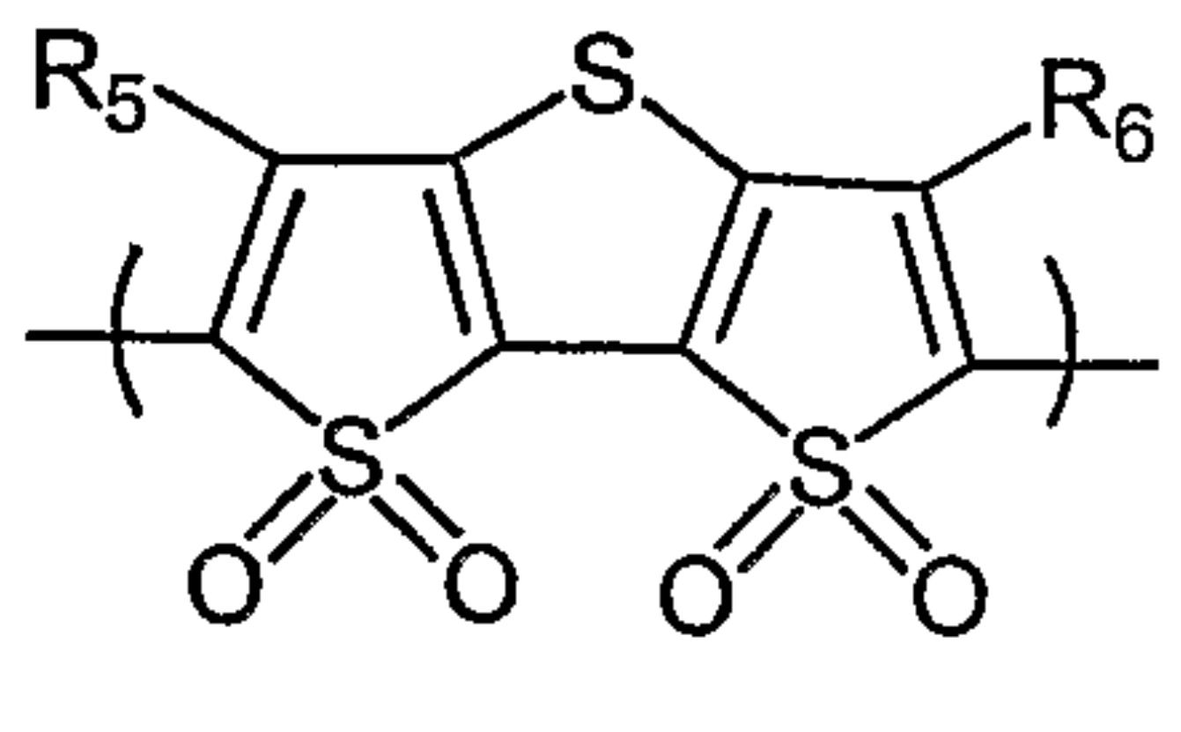
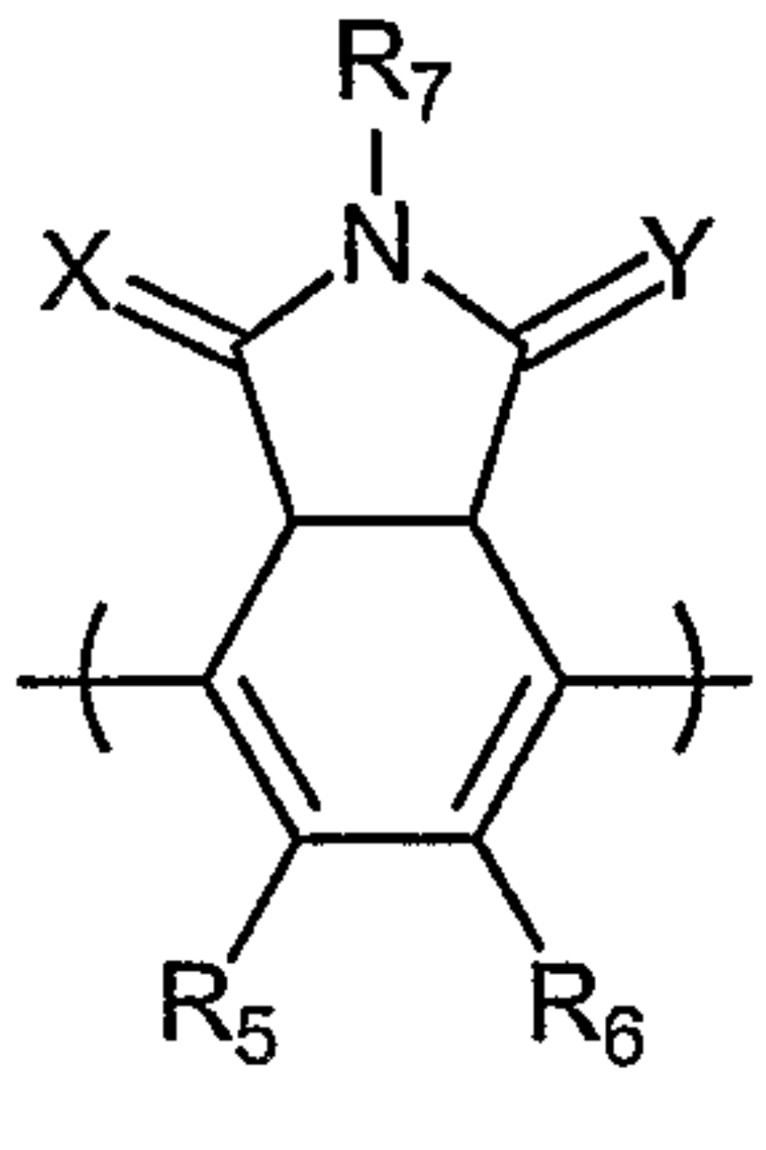
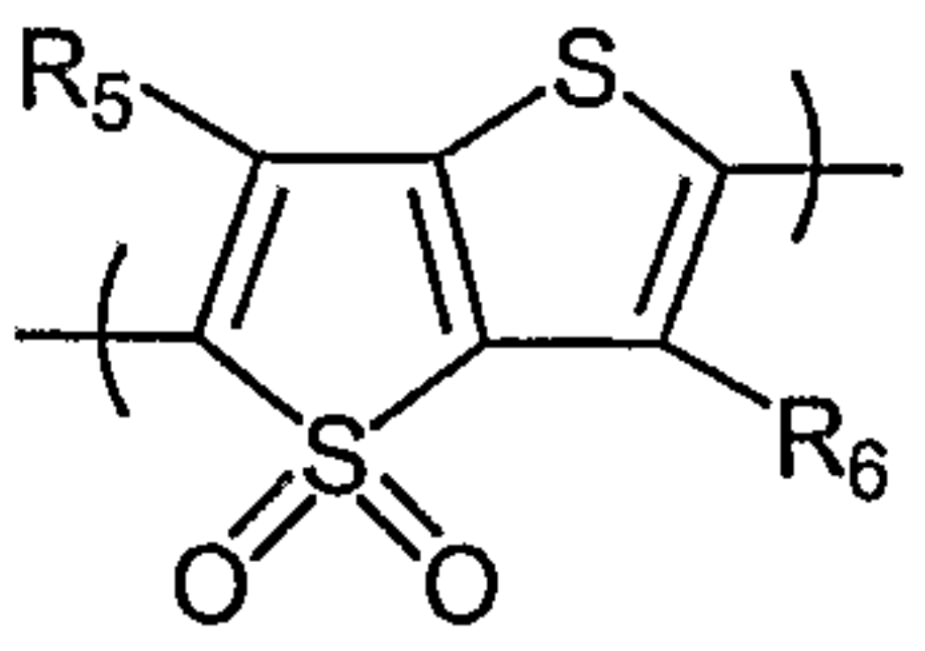


(XV),



(XVI),



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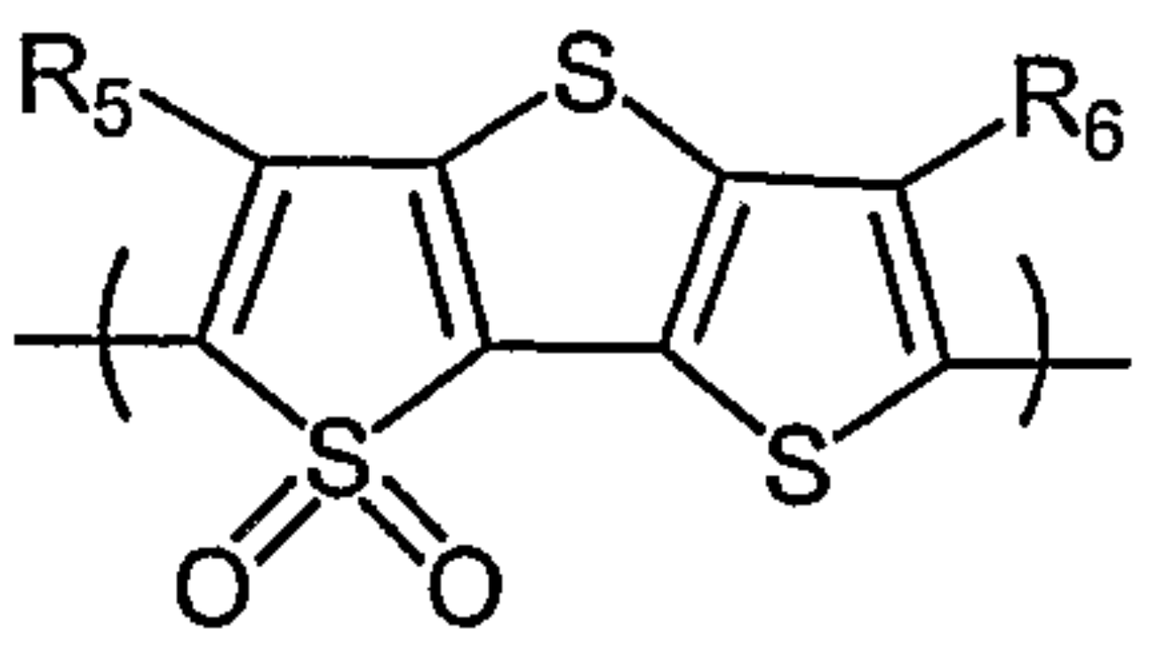
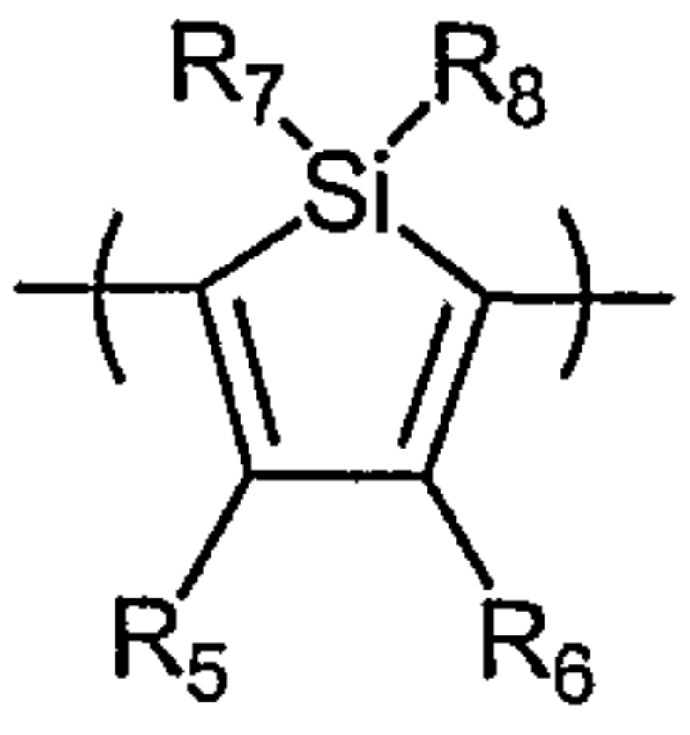


(XVIII), or



(XXI),

wherein

each of X and Y, independently, is CH_2, O, or S;

each of R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl; and

9. The photovoltaic cell of claim 1, wherein the photovoltaic cell is a tandem photovoltaic cell.

10. A photovoltaic cell, comprising:

a first electrode,

a second electrode, and

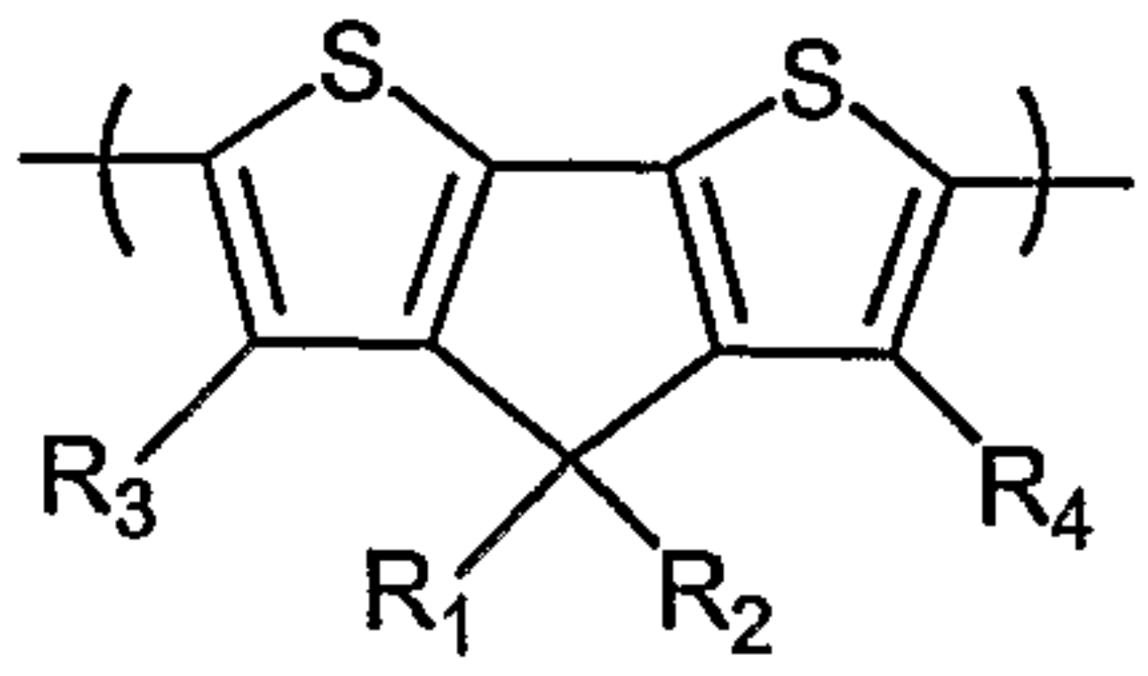
an photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first comonomer repeat unit and a second comonomer repeat unit different from the first comonomer repeat unit, the first comonomer repeat unit comprising a cyclopentadithiophene moiety.

11. The photovoltaic cell of claim 10, wherein the cyclopentadithiophene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

12. The photovoltaic cell of claim 11, wherein the cyclopentadithiophene moiety is substituted with hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

13. The photovoltaic cell of claim 11, wherein the cyclopentadithiophene moiety is substituted at 4-position.

14. The photovoltaic cell of claim 10, wherein the first comonomer repeat unit comprises a cyclopentadithiophene moiety of formula (I):



(I),

wherein each of R_1, R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

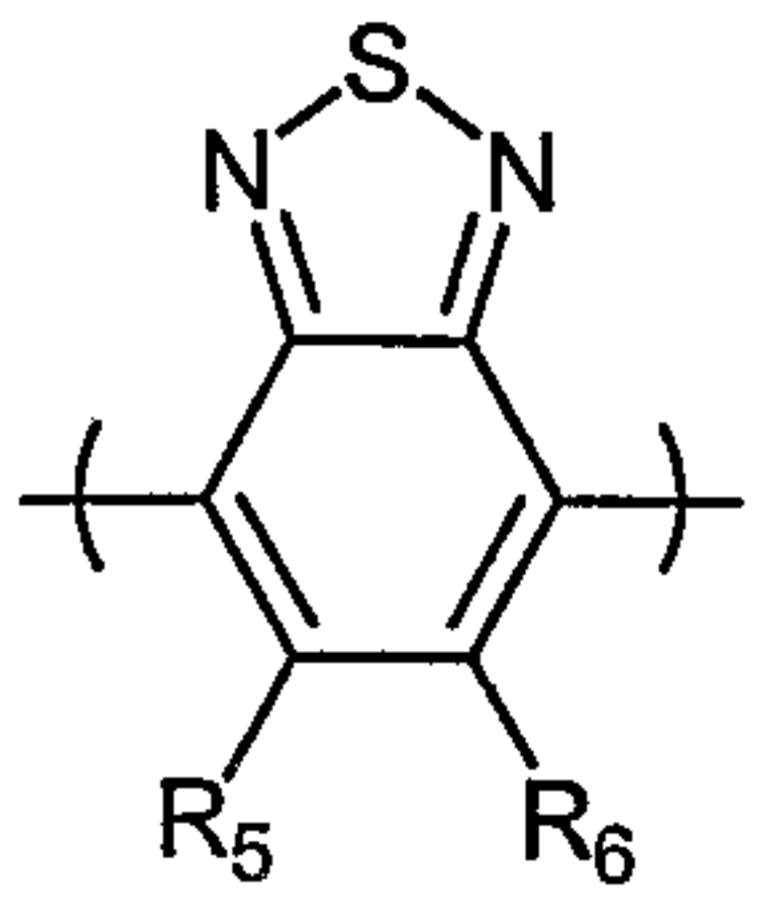
15. The photovoltaic cell of claim 14, wherein each of R_1 and R_2, independently, is hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

16. The photovoltaic cell of claim 10, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety.

17. The photovoltaic cell of claim 16, wherein the second comonomer repeat unit comprises a 3,4-benzo-1,2,5-thiadiazole moiety.

18. The photovoltaic cell of claim 16, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II), a thiadiazoloquinoxaline moiety of formula (III), a cyclopentadithiophene dioxide moiety of formula (IV), a cyclopentadithiophene monoxide moiety of formula (V), a benzoisothiazole moiety of

formula (VI), a benzothiazole moiety of formula (VII), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene dioxide moiety of formula (IX), or a cyclopentadithiophene tetraoxide moiety of formula (X), a thienothiophene moiety of formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), or a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), a dithienothiophene dioxide moiety of formula (XVIII), a fluorene moiety of formula (XIX), a thiophene moiety of formula (XX), or a silole moiety of formula (XXI):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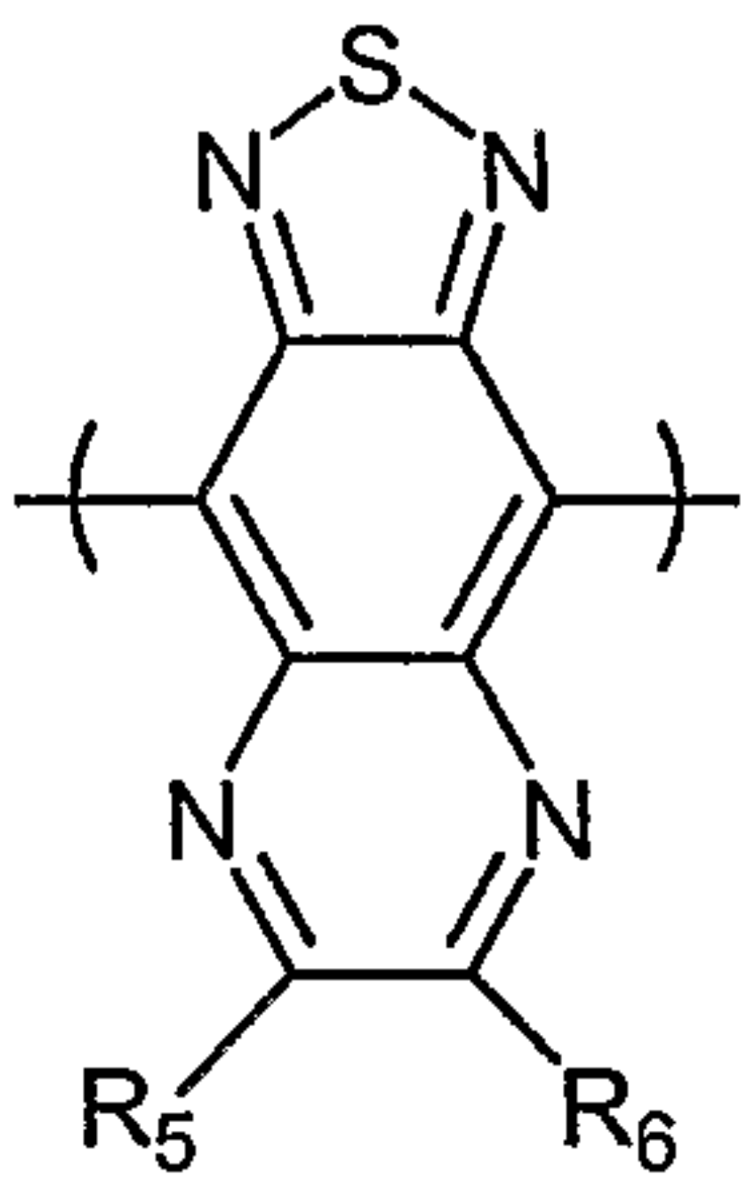
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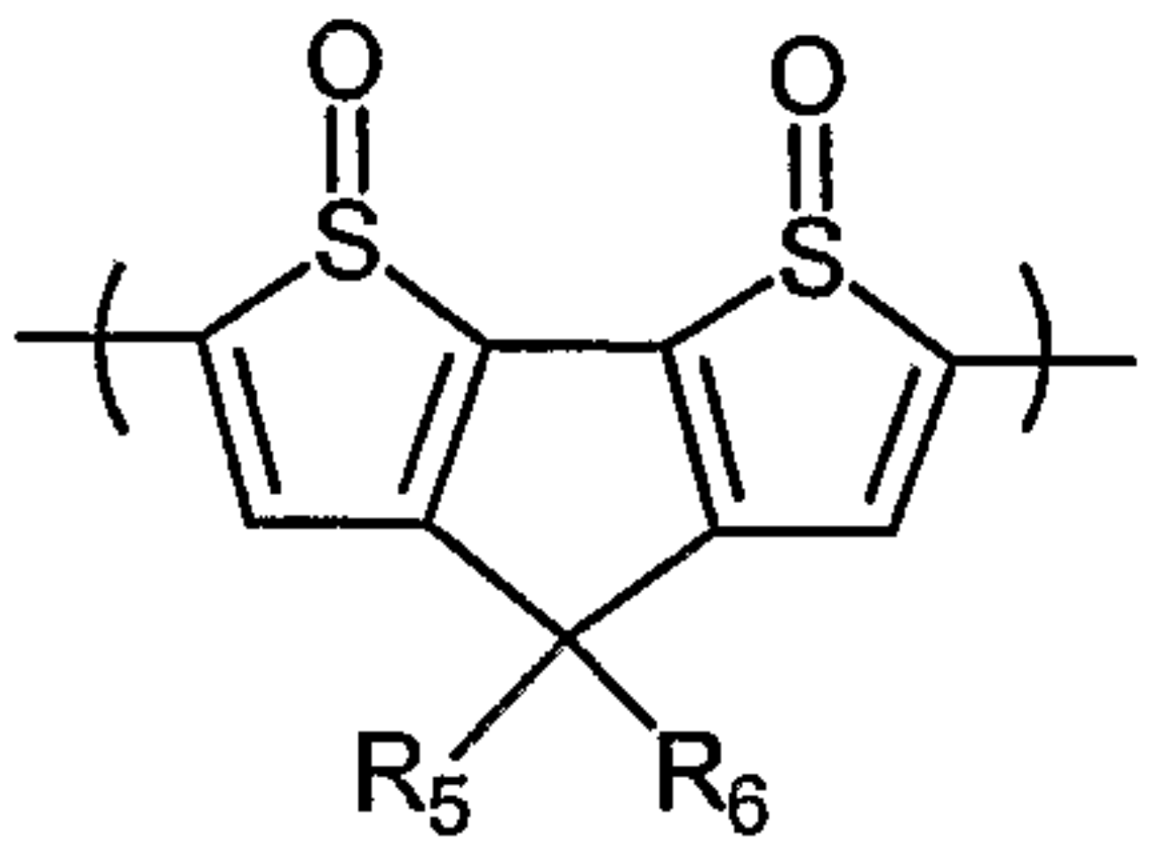
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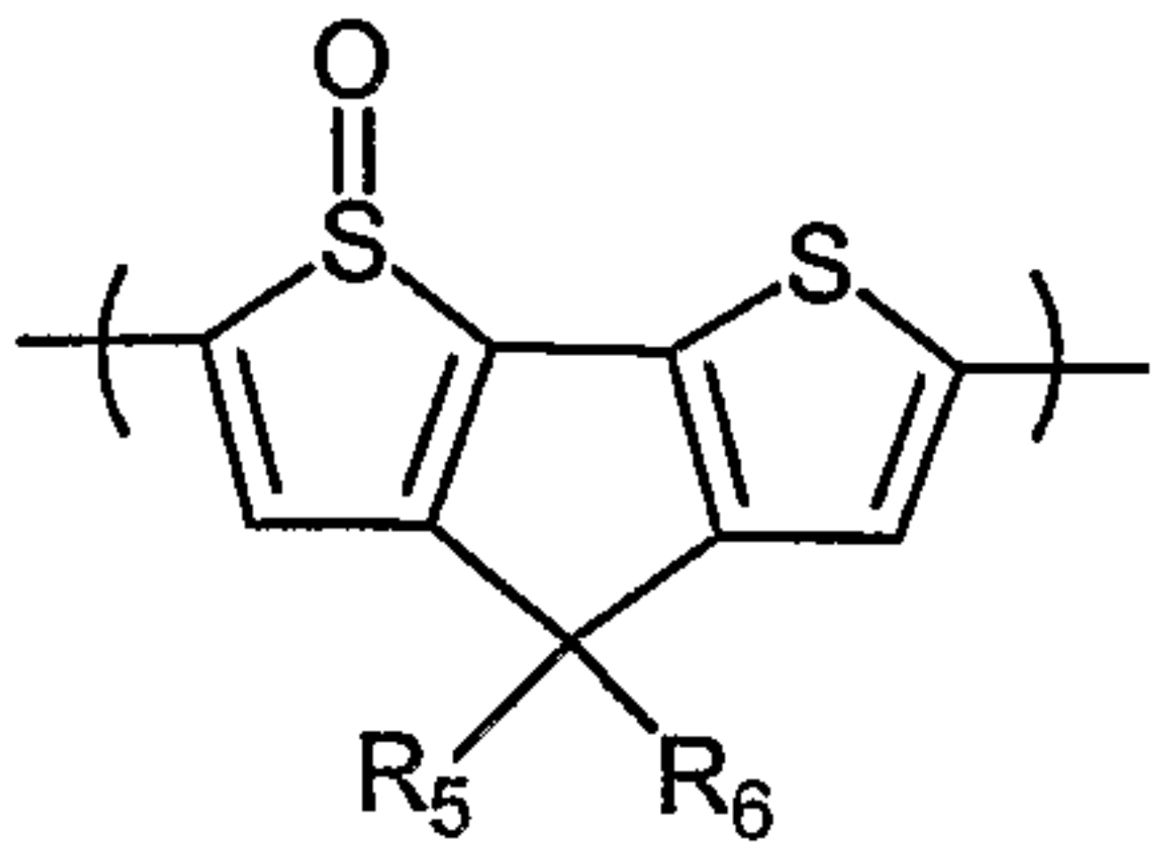
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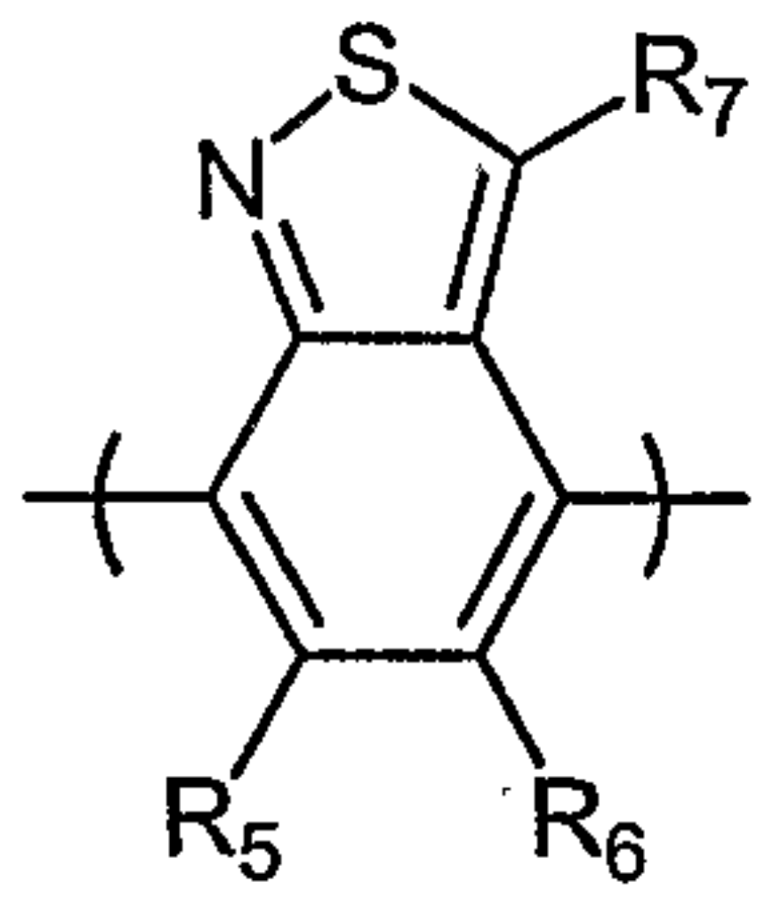
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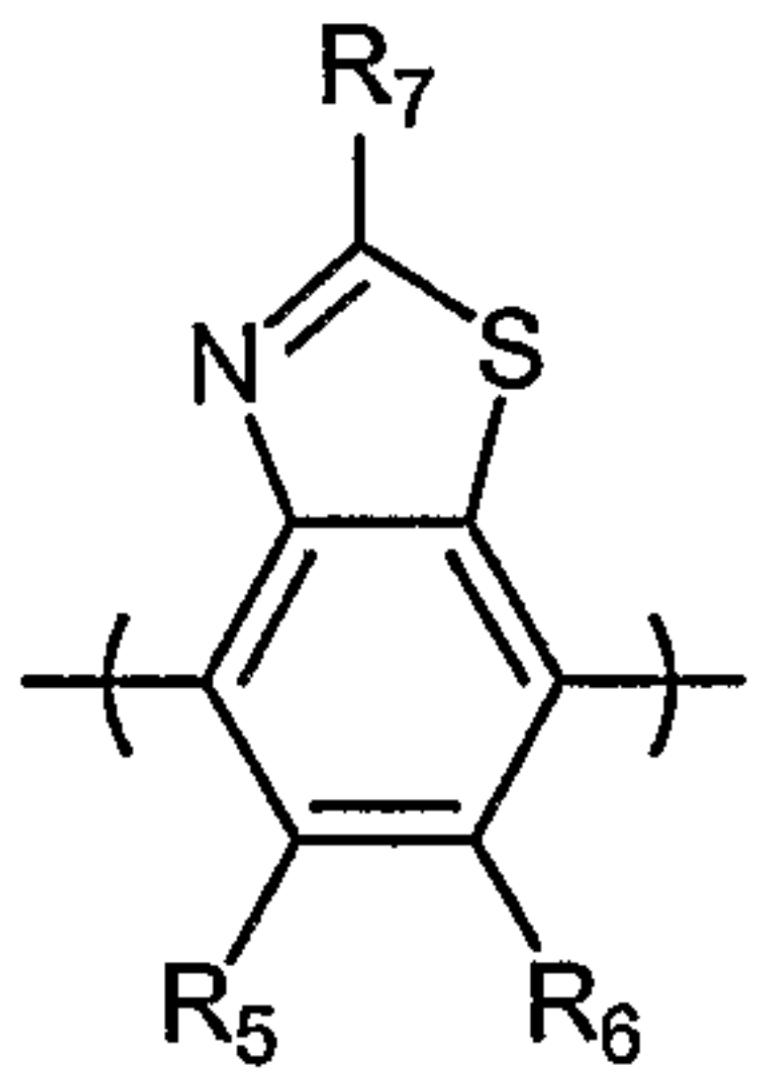
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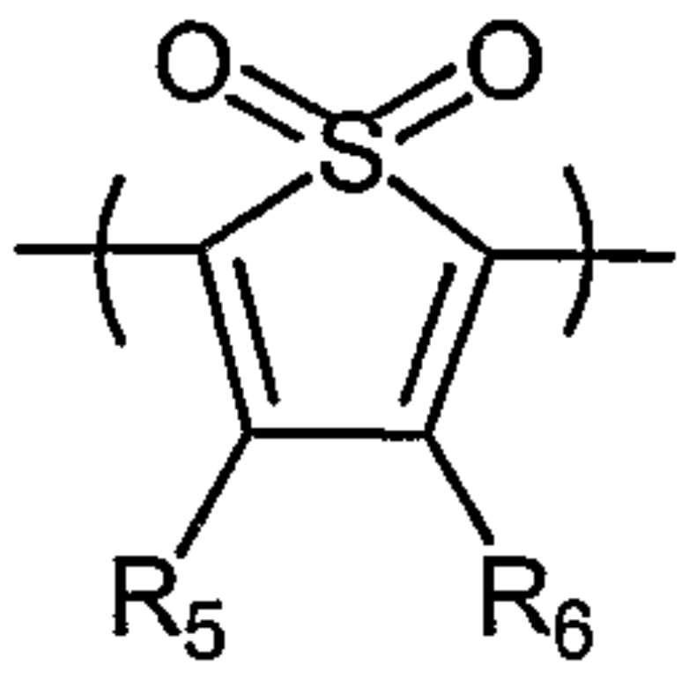
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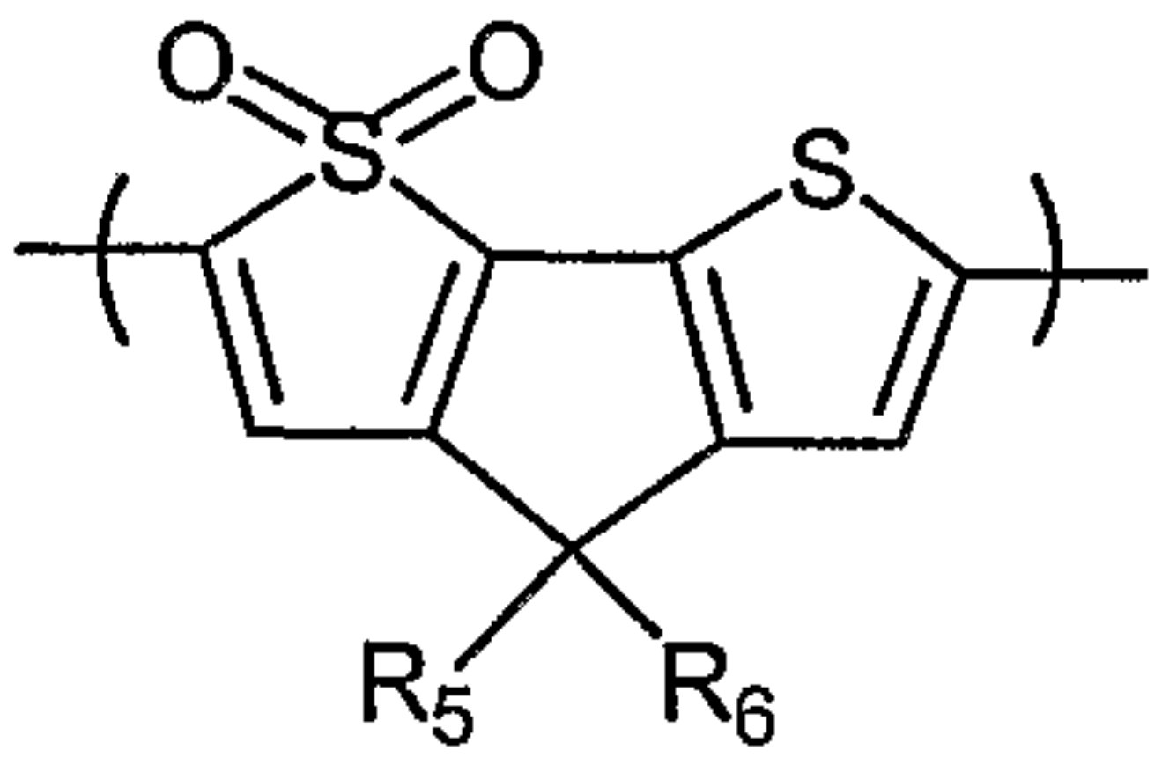
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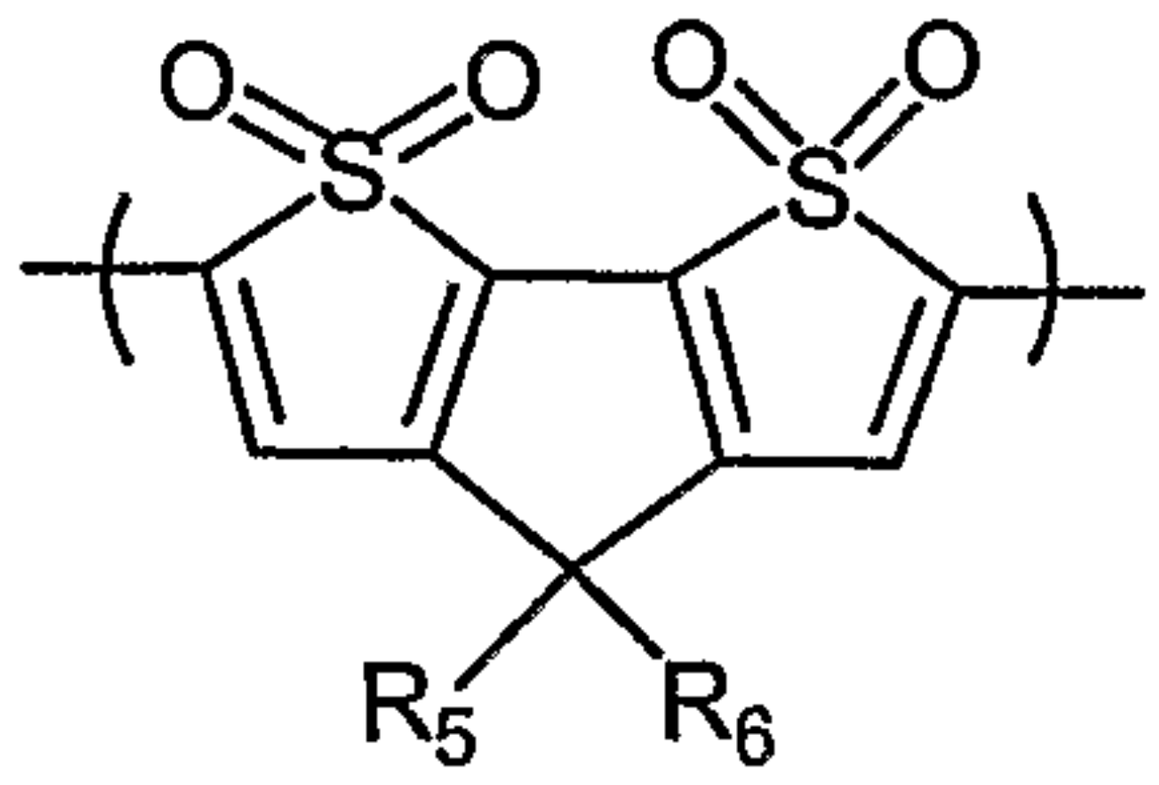
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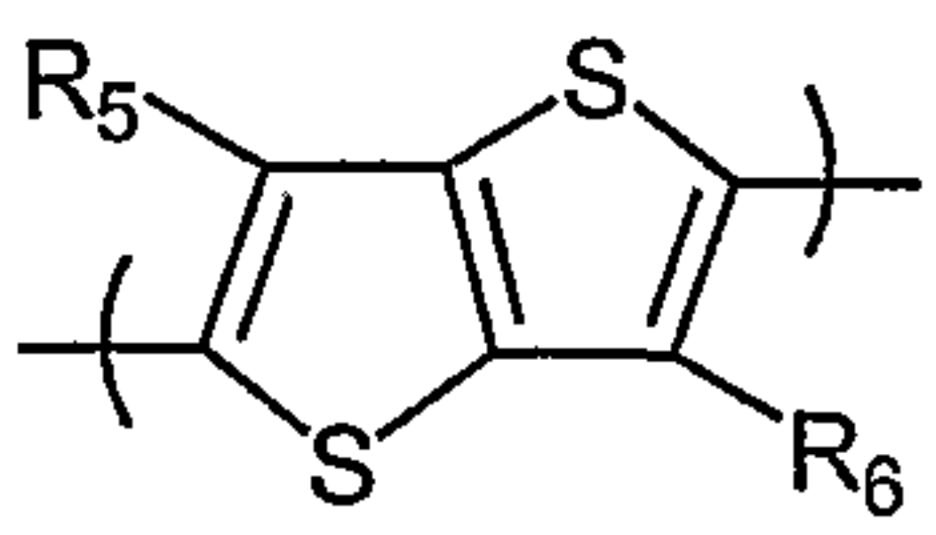
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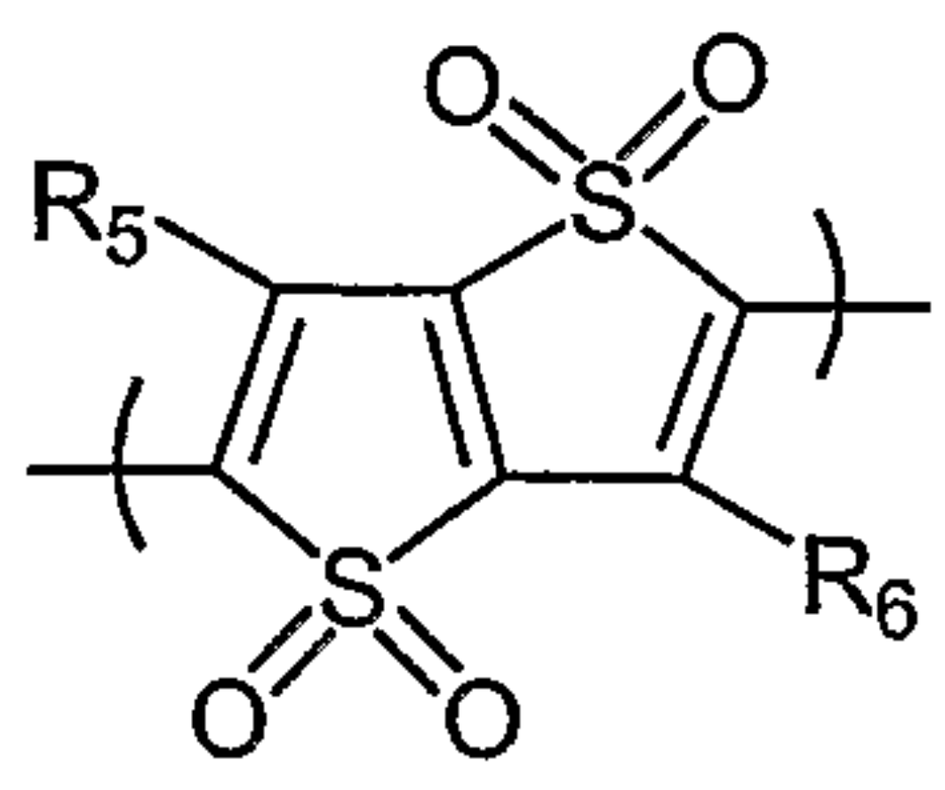
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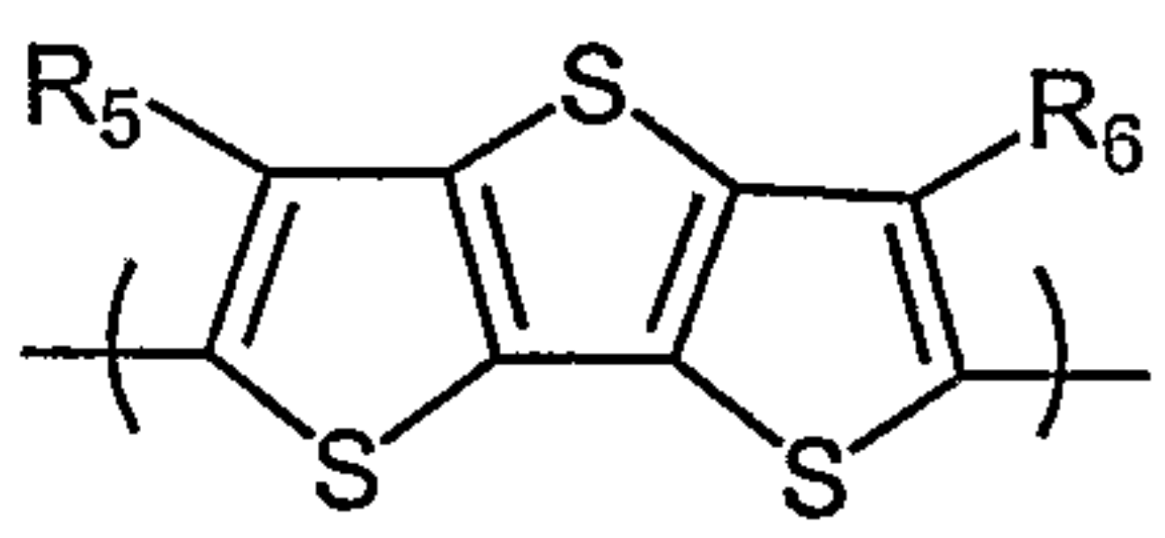
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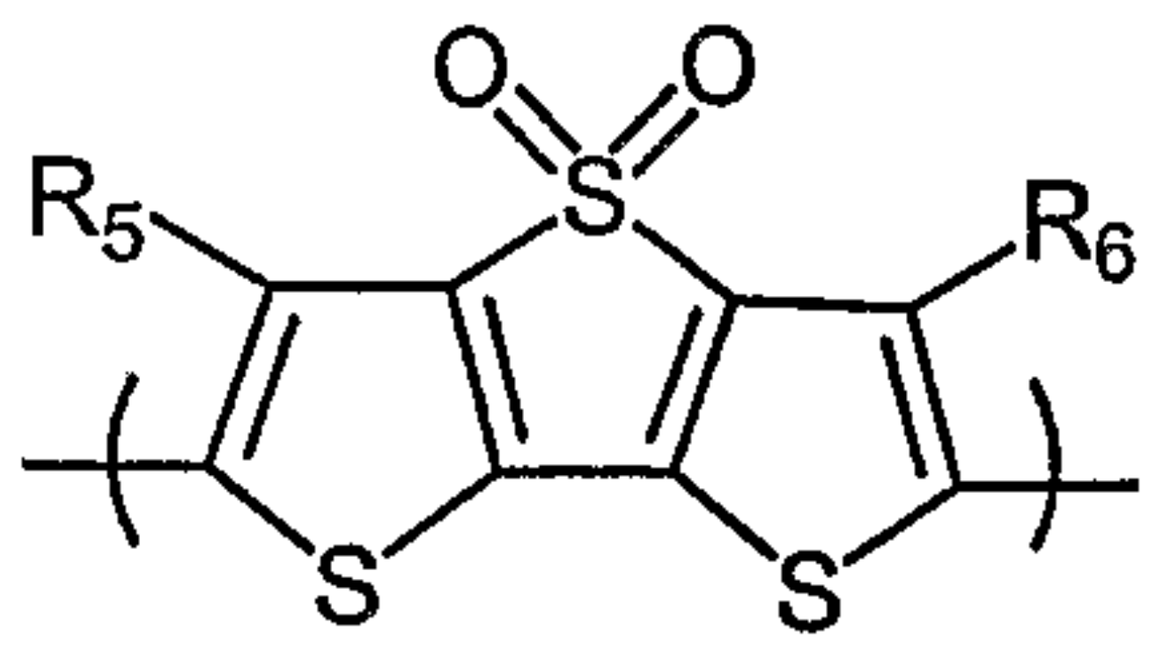

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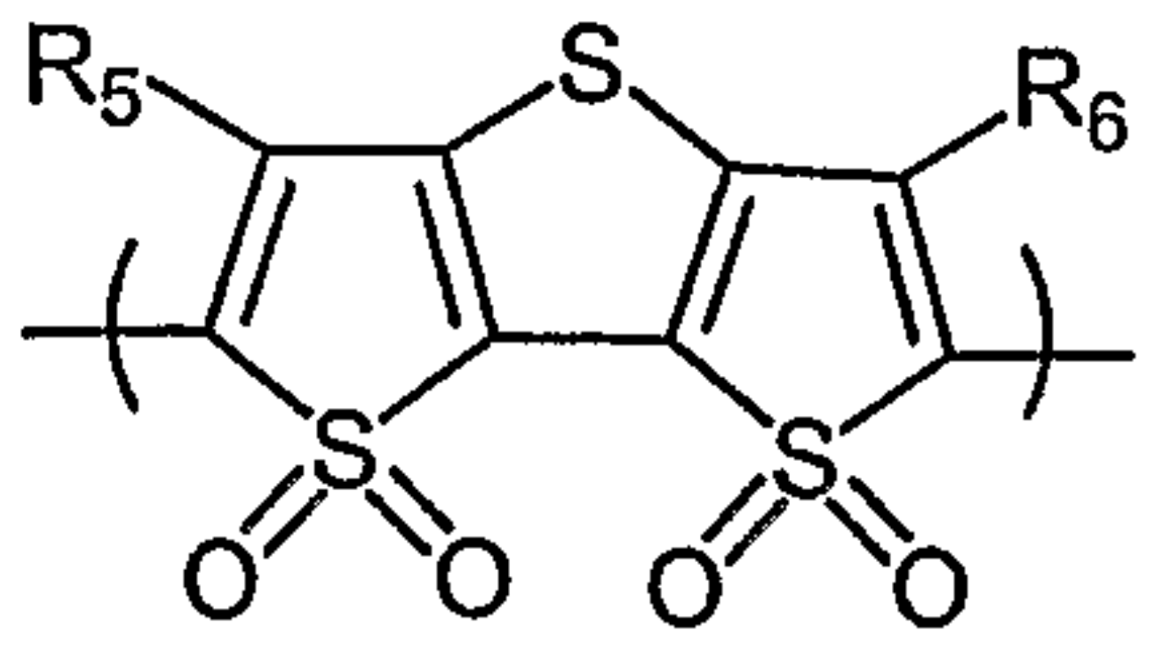

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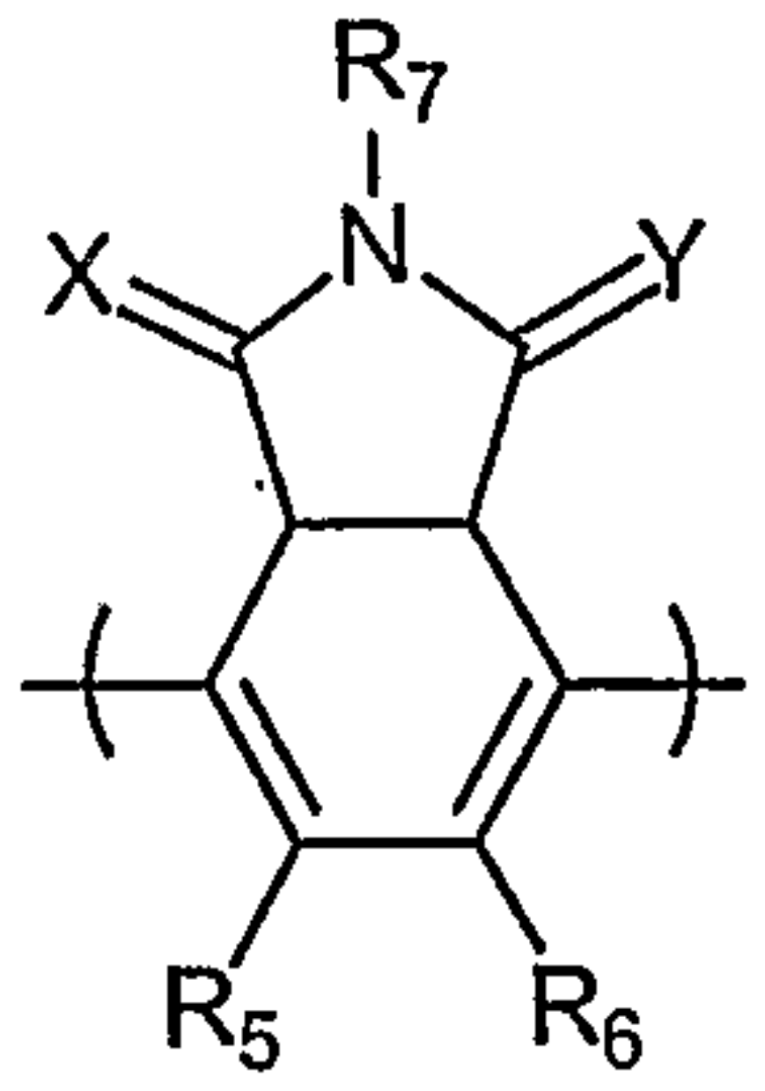

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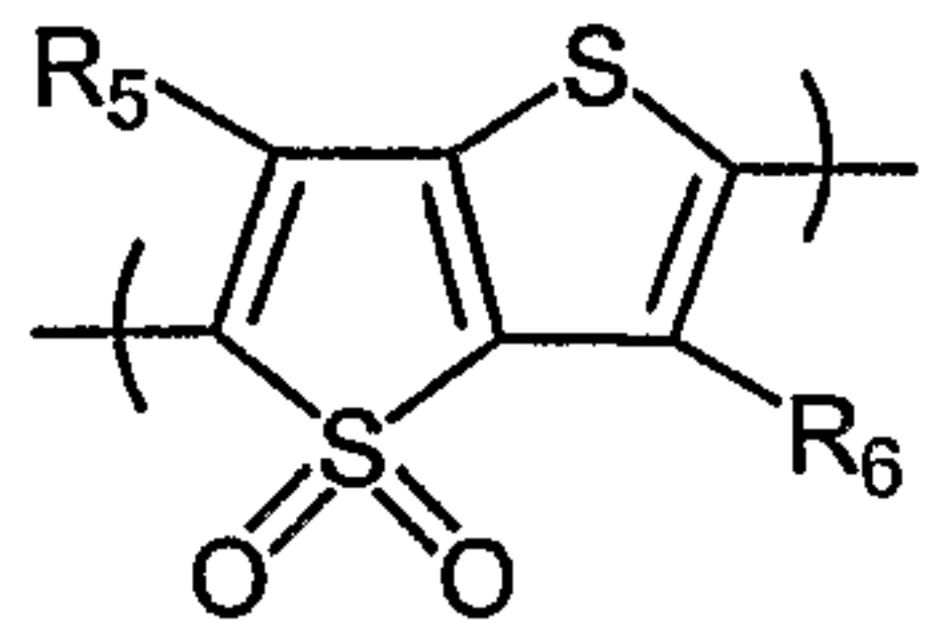

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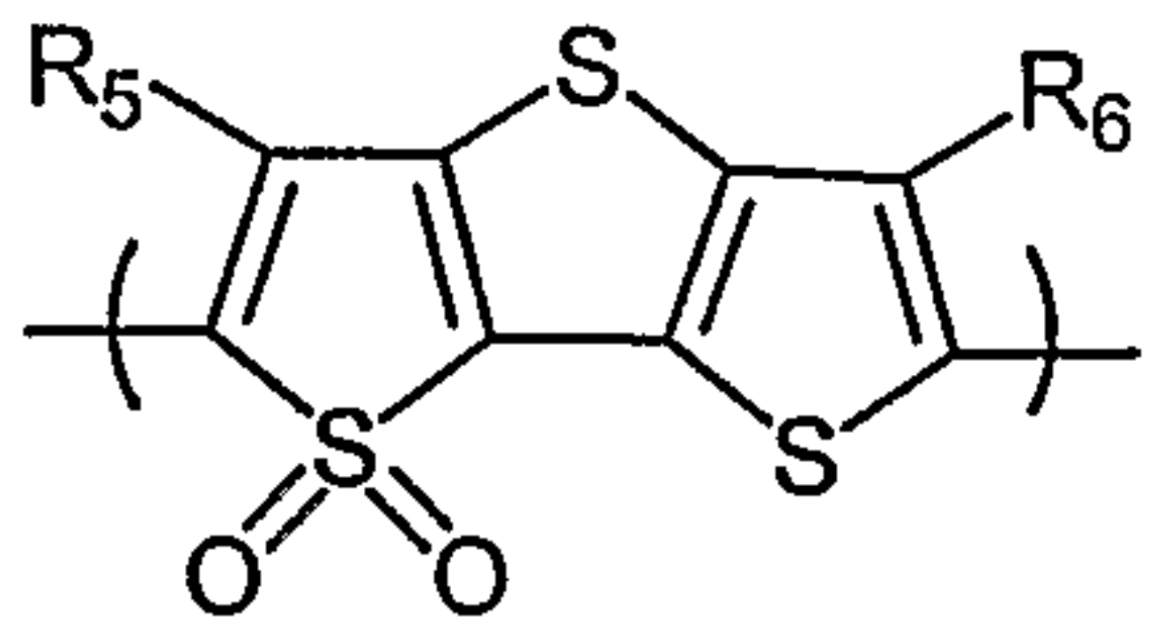

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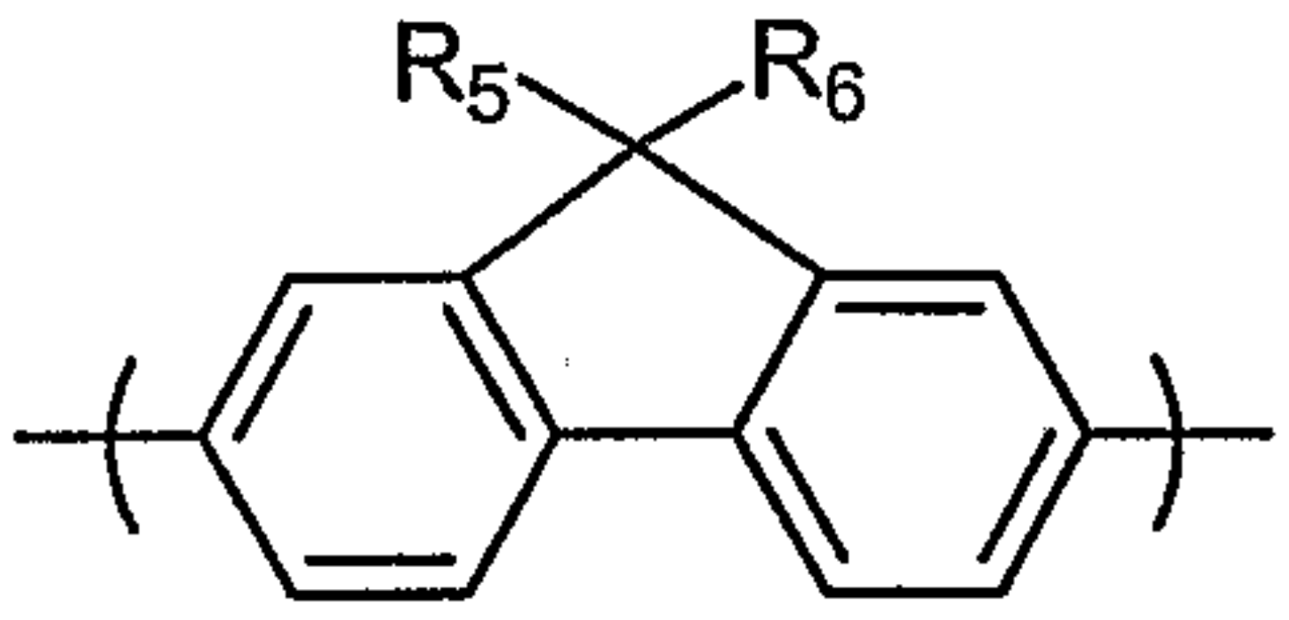

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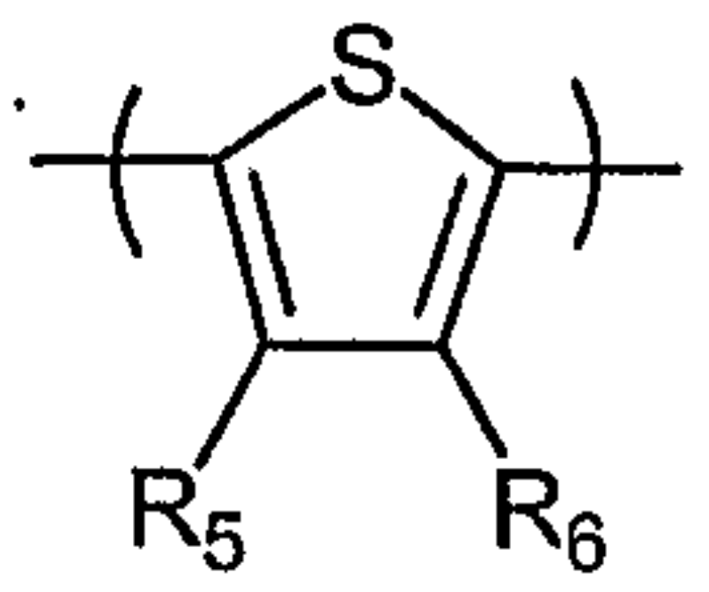

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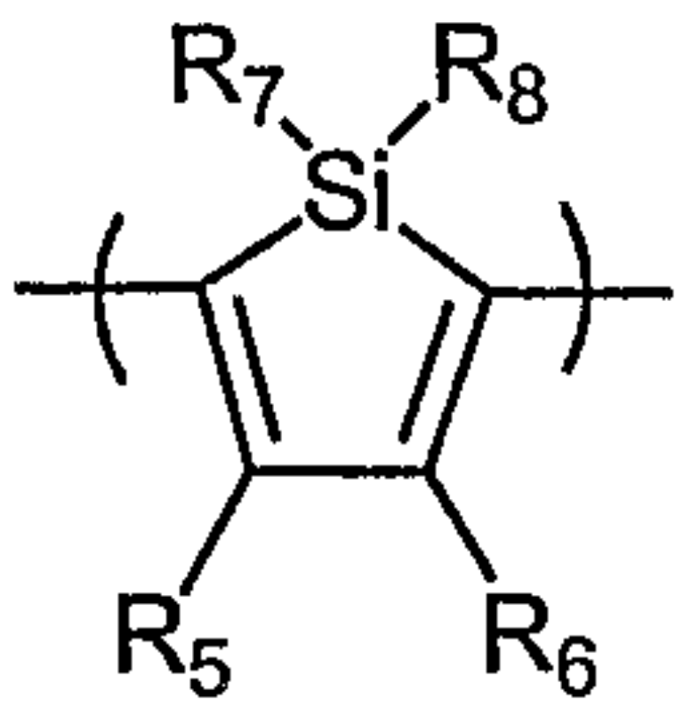


(XXI),

wherein each of R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

19. The photovoltaic cell of claim 18, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II).

20. The photovoltaic cell of claim 19, wherein each of R_5 and R_6 is H.

21. The photovoltaic cell of claim 10, wherein the second comonomer repeat unit comprises at least three thiophene moieties.

22. The photovoltaic cell of claim 21, wherein at least one of the thiophene moieties is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

23. The photovoltaic cell of claim 21, wherein the second comonomer repeat unit comprises five thiophene moieties.

24. The photovoltaic cell of claim 10, wherein the polymer further comprises a third comonomer repeat unit, the third comonomer repeat unit comprising a thiophene moiety or a fluorene moiety.

25. The photovoltaic cell of claim 24, wherein the thiophene or fluorene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

26. The photovoltaic cell of claim 10, wherein the photoactive material further comprises an electron acceptor material.

27. The photovoltaic cell of claim 26, wherein the electron acceptor material comprises a fullerene.

28. The photovoltaic cell of claim 27, wherein the electron acceptor material comprises PCBM.

29. The photovoltaic cell of claim 26, wherein the polymer and the electron acceptor material each has a LUMO energy level, the LUMO energy level of the polymer is at least about 0.2 eV less negative than the LUMO energy level of the electron acceptor material.

30. A polymer, comprising:

a first comonomer repeat unit comprising a cyclopentadithiophene moiety, and

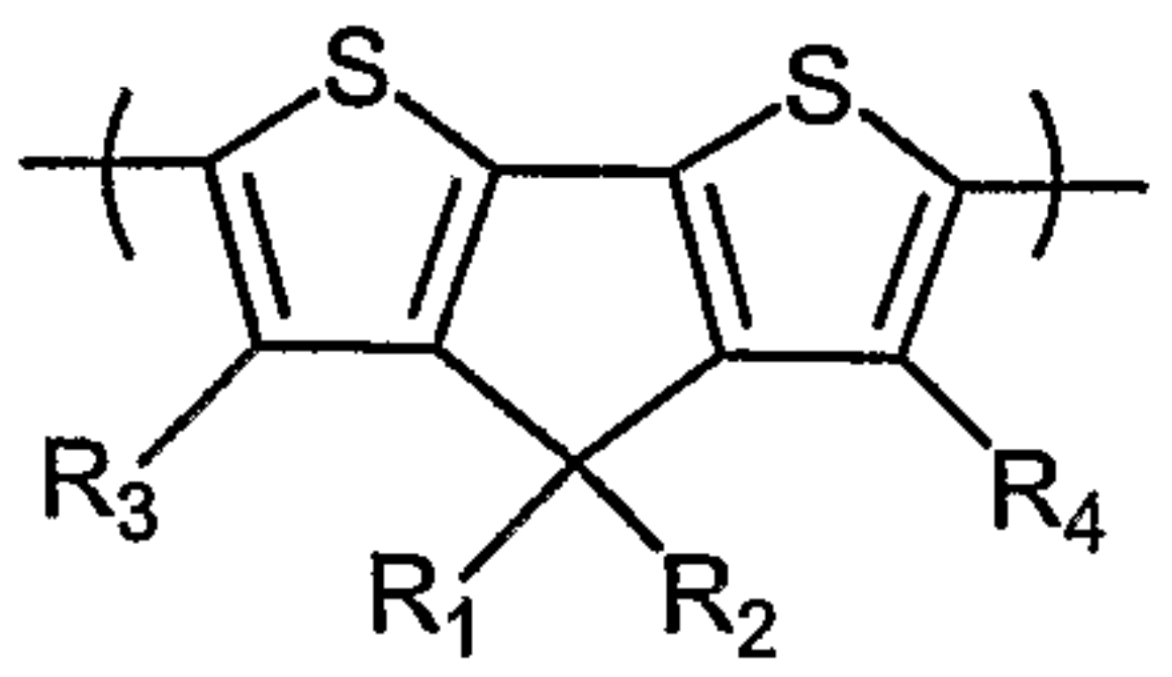
a second comonomer repeat unit comprising a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, a silole moiety, or a moiety containing at least three thiophene moieties.

31. The polymer of claim 30, wherein the cyclopentadithiophene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

32. The polymer of claim 31, wherein the cyclopentadithiophene moiety is substituted with hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

33. The polymer of claim 31, wherein the cyclopentadithiophene moiety is substituted at 4-position.

34. The polymer of claim 30, wherein the first comonomer repeat unit comprises a cyclopentadithiophene moiety of formula (I):



(I),

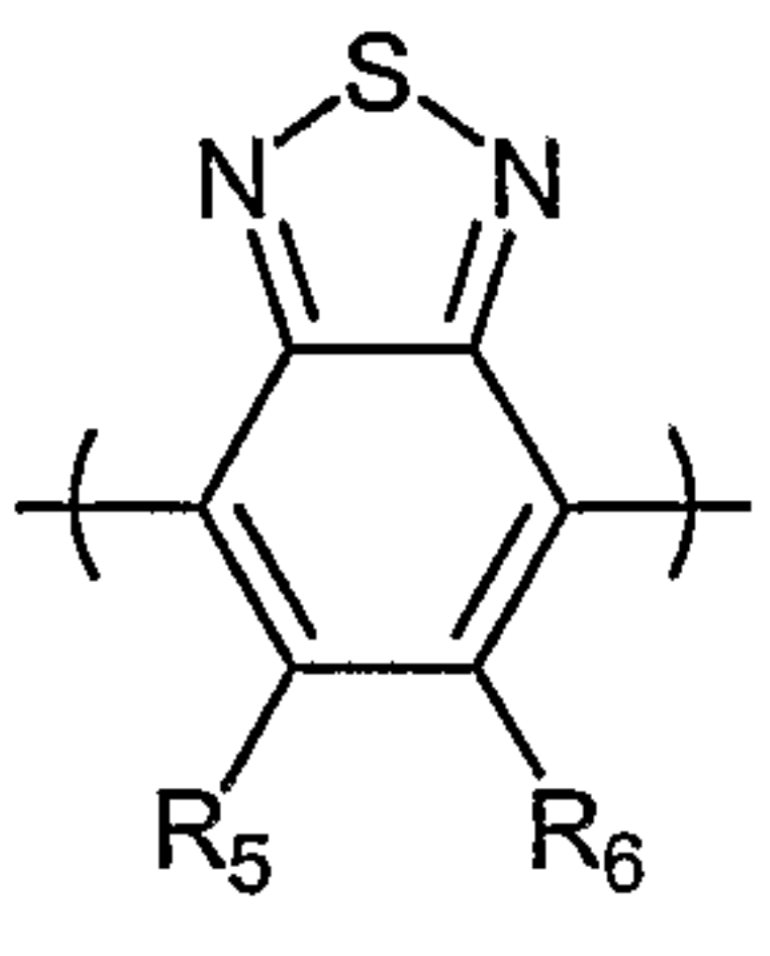
wherein each of R_1, R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

35. The polymer of claim 34, wherein each of R_1 and R_2, independently, is hexyl, 2-ethylhexyl, 3,7-dimethyloctyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

36. The polymer of claim 30, wherein the second comonomer repeat unit comprises a 3,4-benzo-1,2,5-thiadiazole moiety.

37. The polymer of claim 30, wherein the second comonomer is substituted on a ring with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

38. The polymer of claim 30, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II), a thiadiazoloquinoxaline moiety of formula (III), a cyclopentadithiophene dioxide moiety of formula (IV), a cyclopentadithiophene monoxide moiety of formula (V), a benzoisothiazole moiety of formula (VI), a benzothiazole moiety of formula (VII), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene dioxide moiety of formula (IX), a cyclopentadithiophene tetraoxide moiety of formula (X), a thienothiophene moiety of formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), or a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), a dithienothiophene dioxide moiety of formula (XVIII), a fluorene moiety of formula (XIX), a thiophene moiety of formula (XX), or a silole moiety of formula (XXI):



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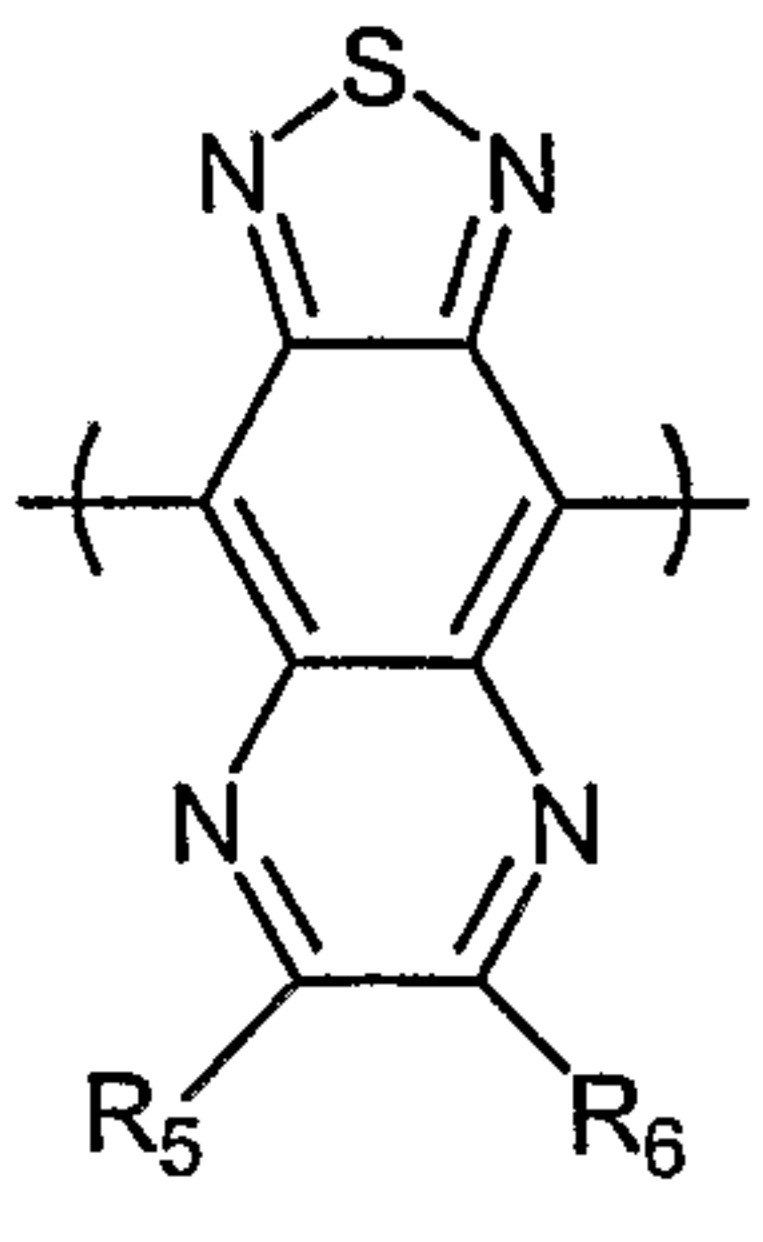

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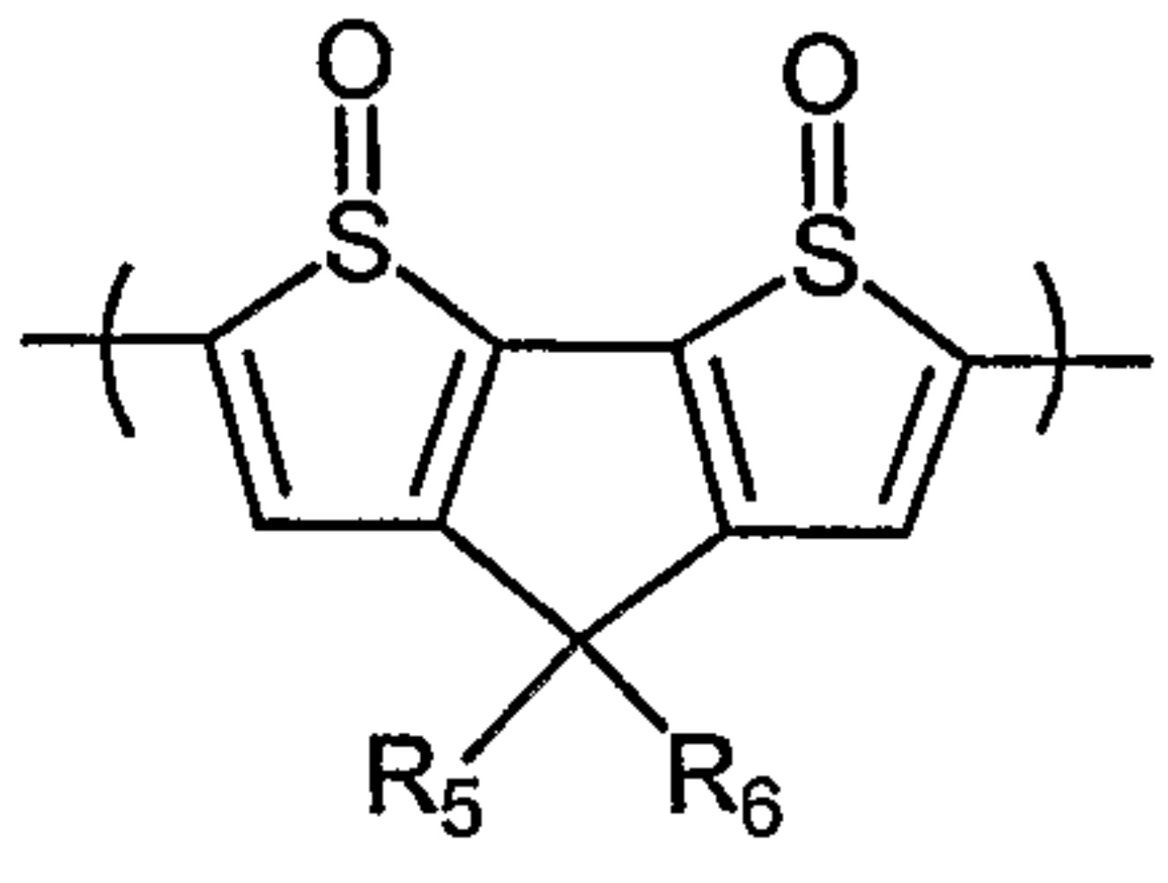

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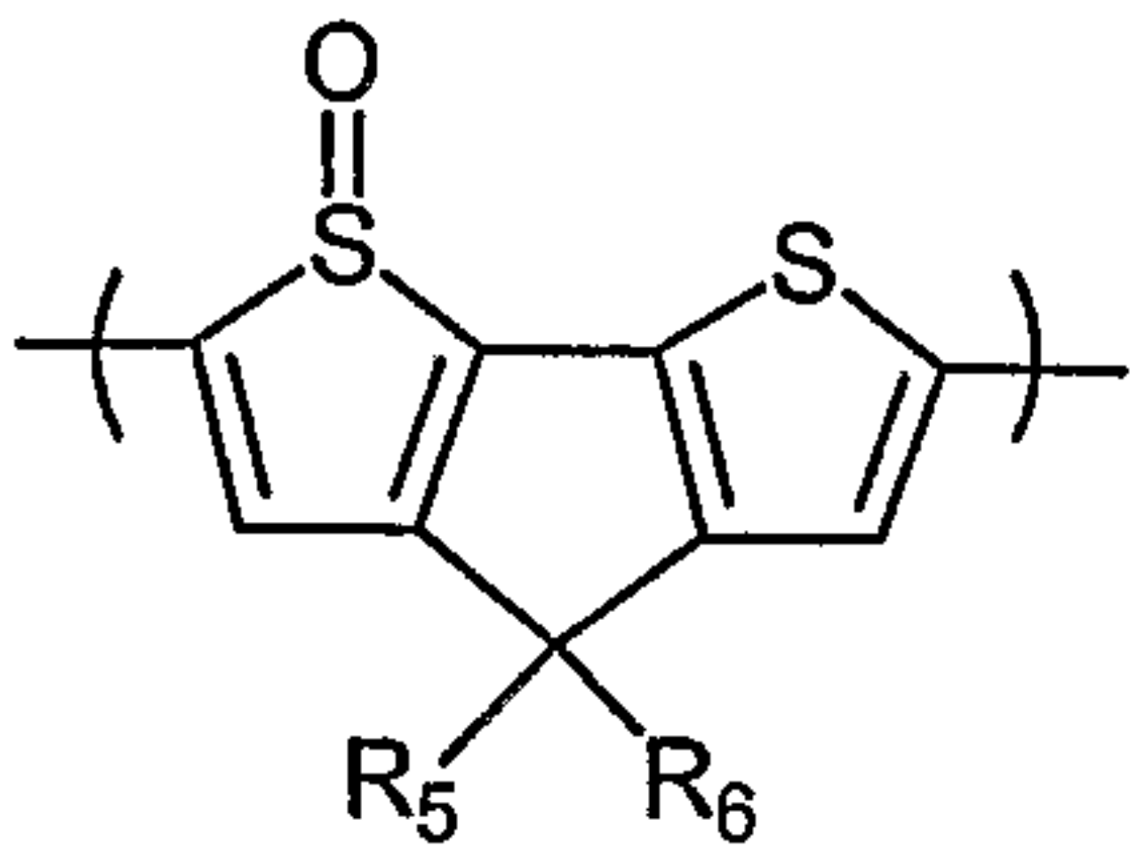
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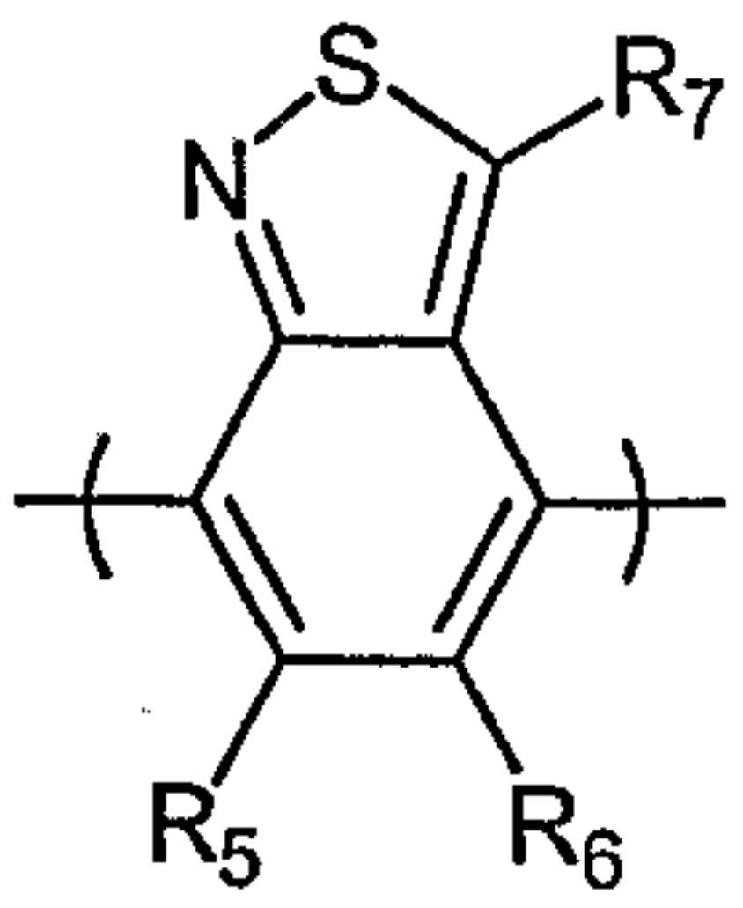
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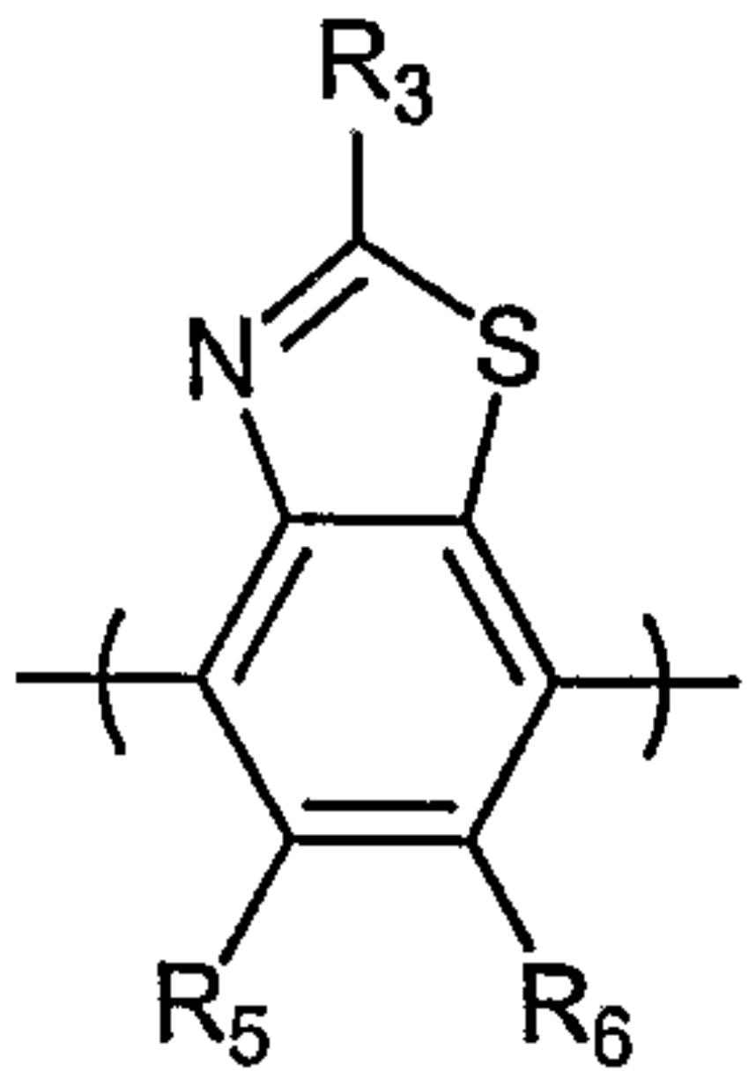
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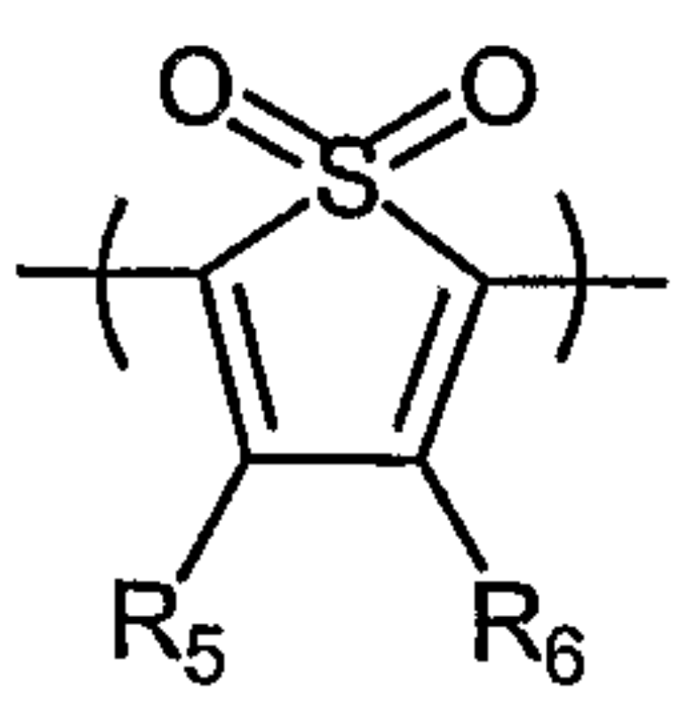
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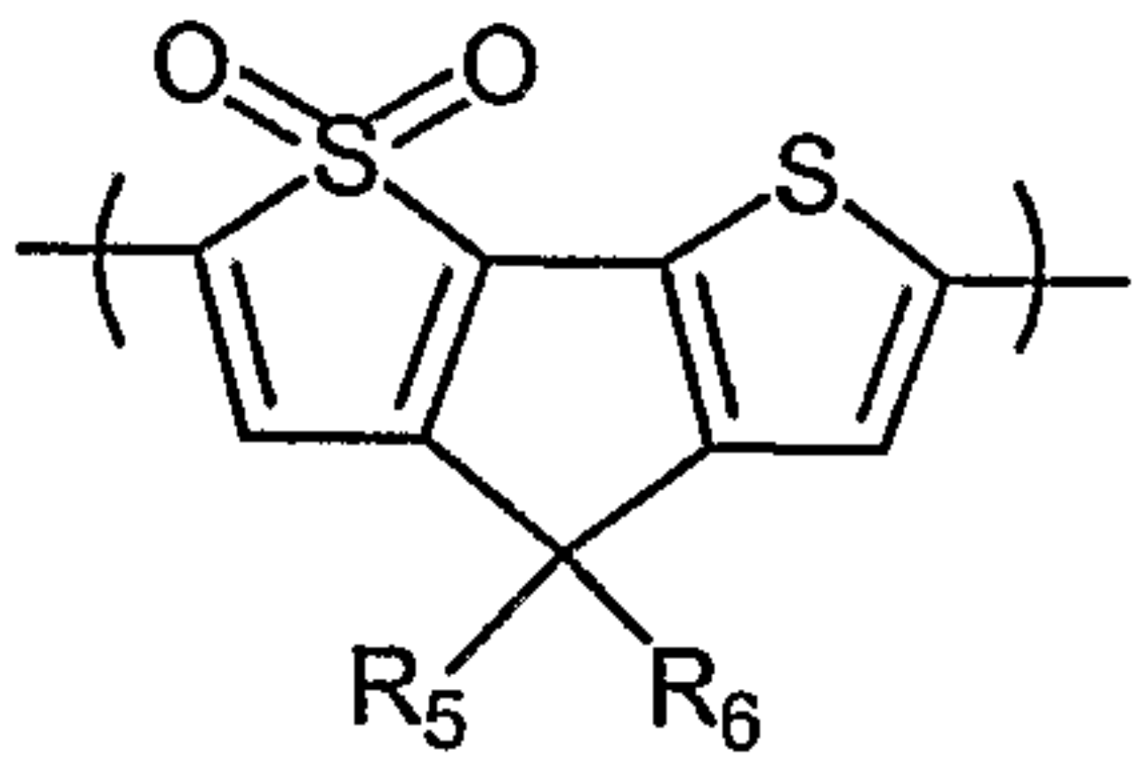
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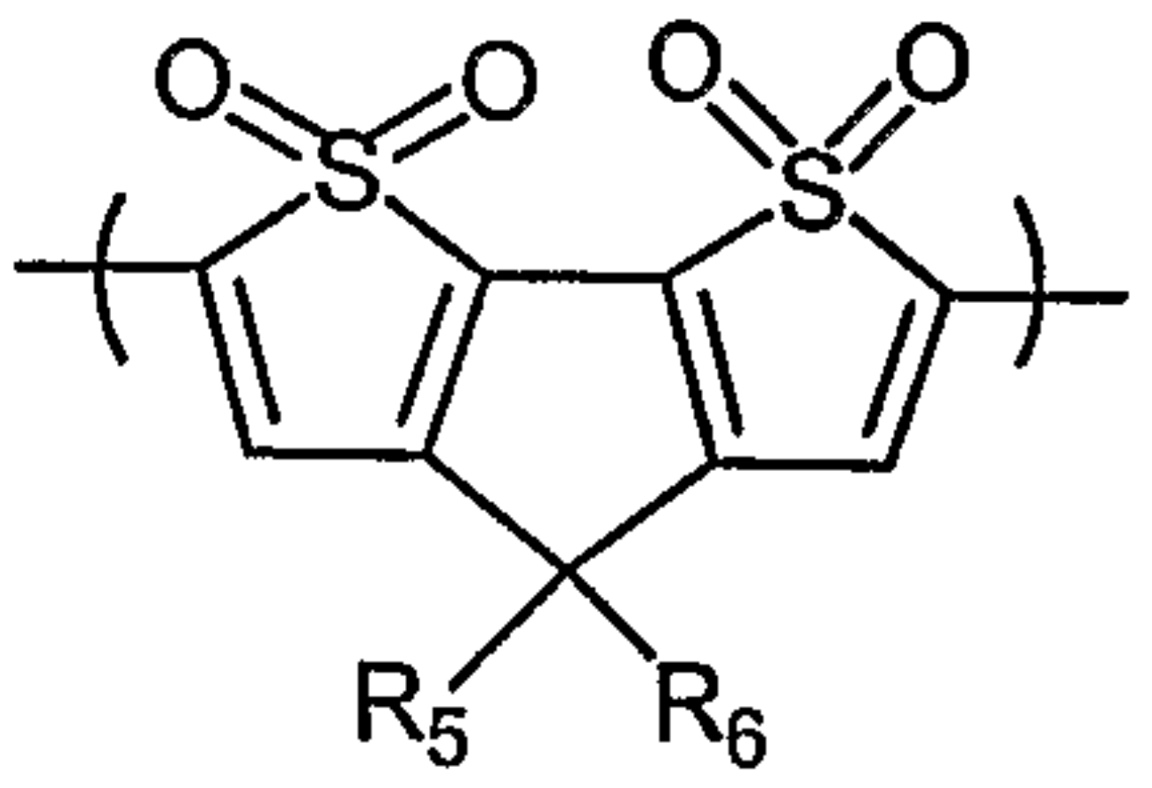
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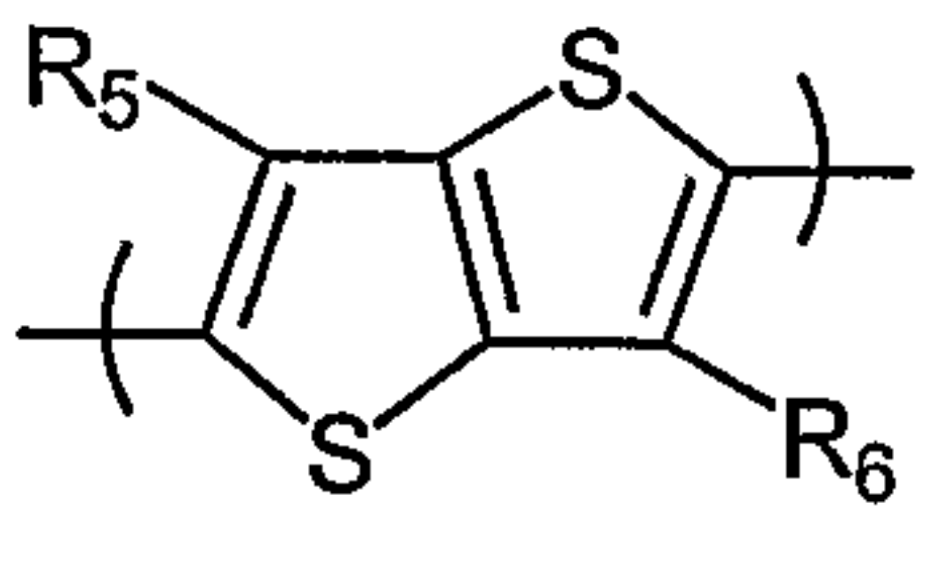
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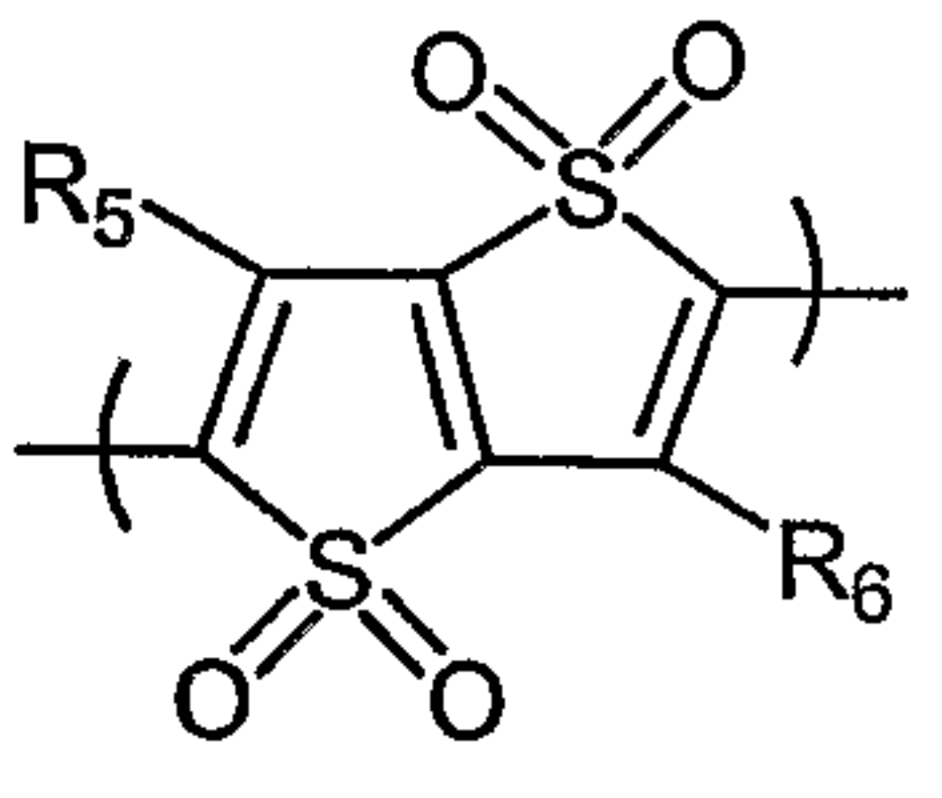
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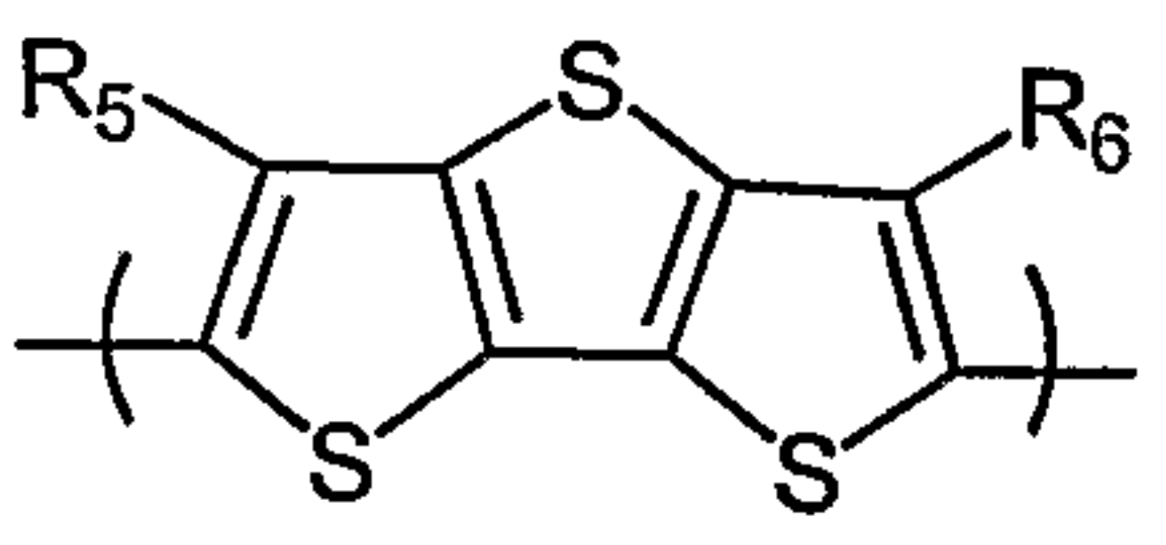
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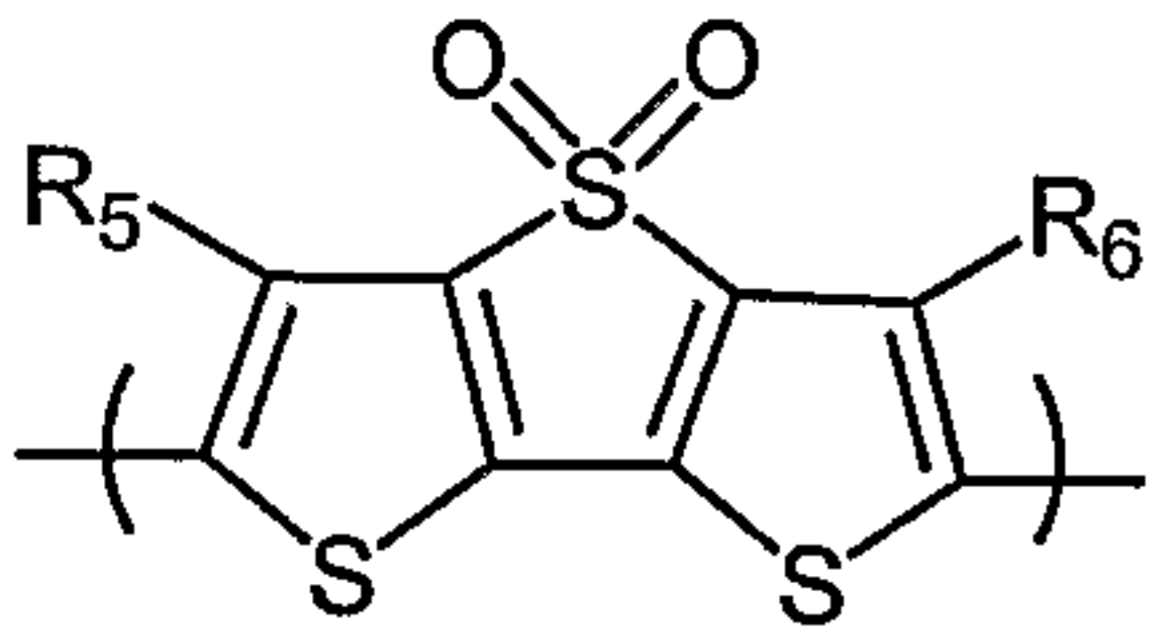
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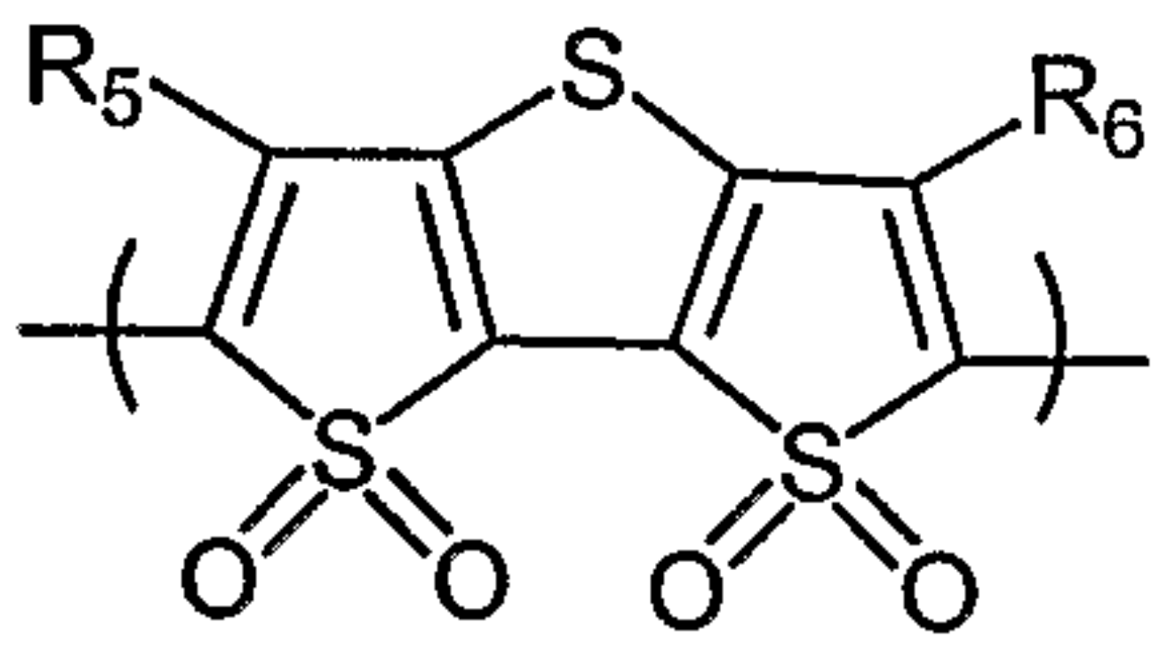
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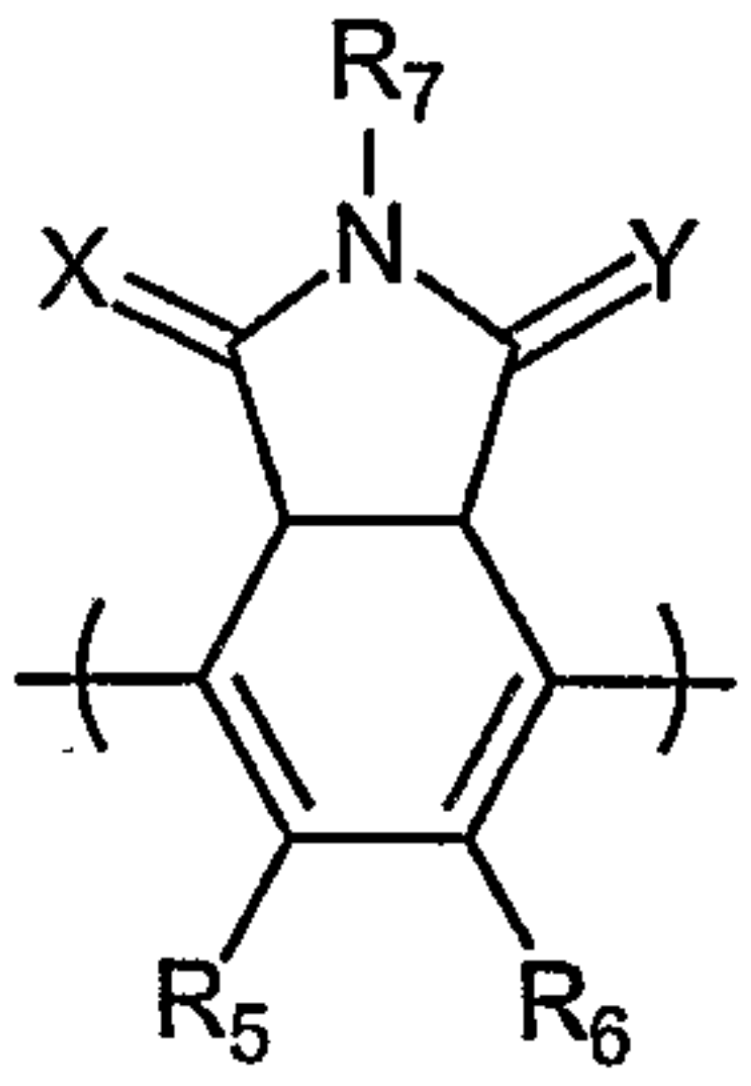
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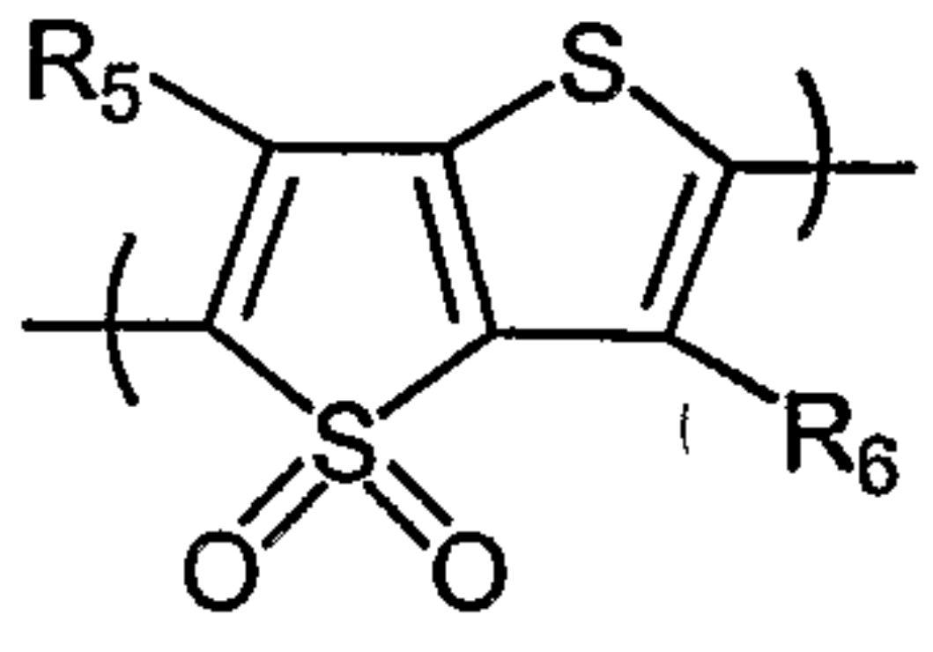
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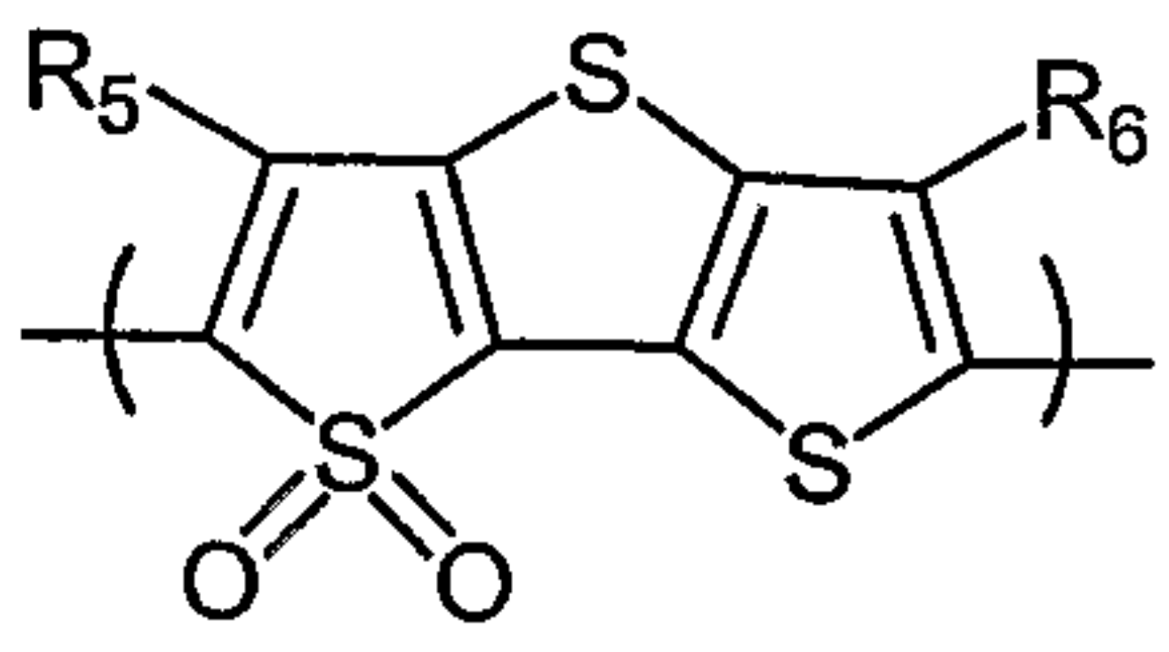
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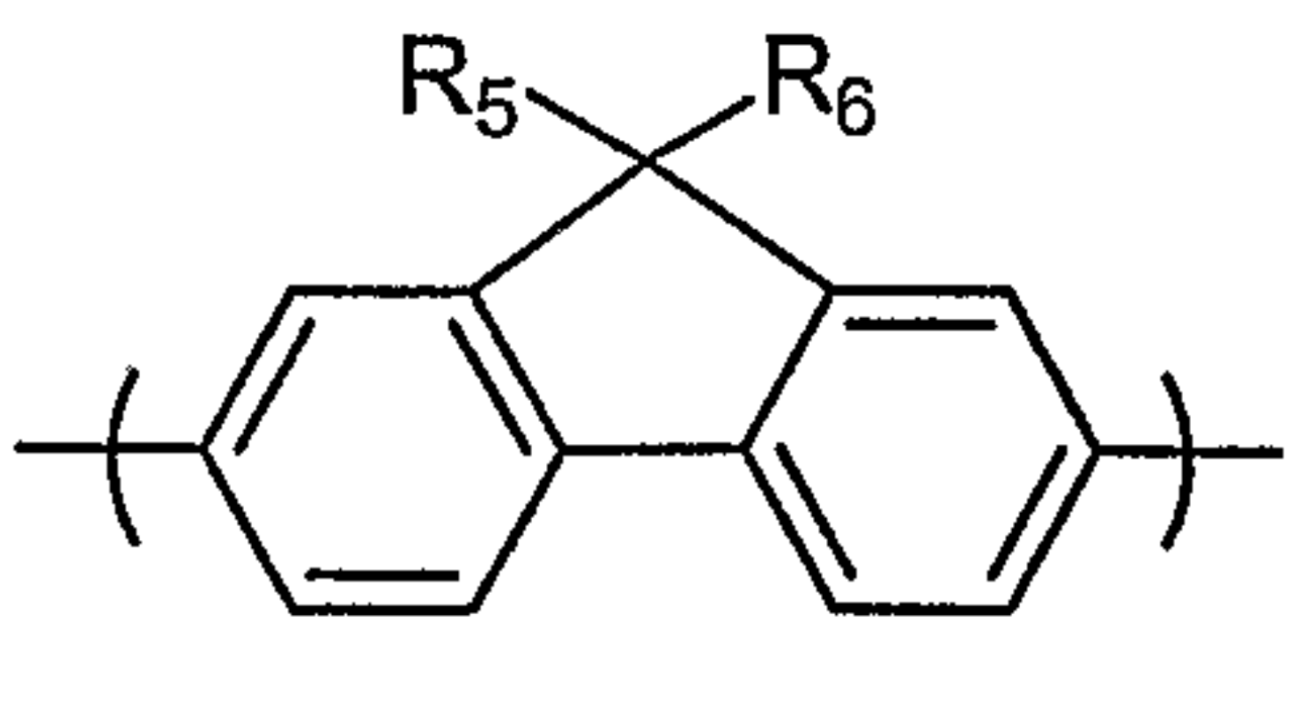
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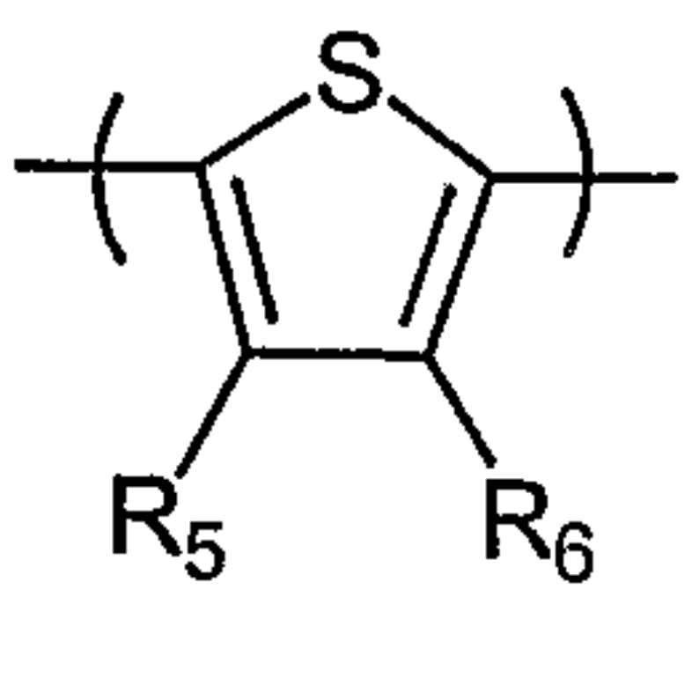
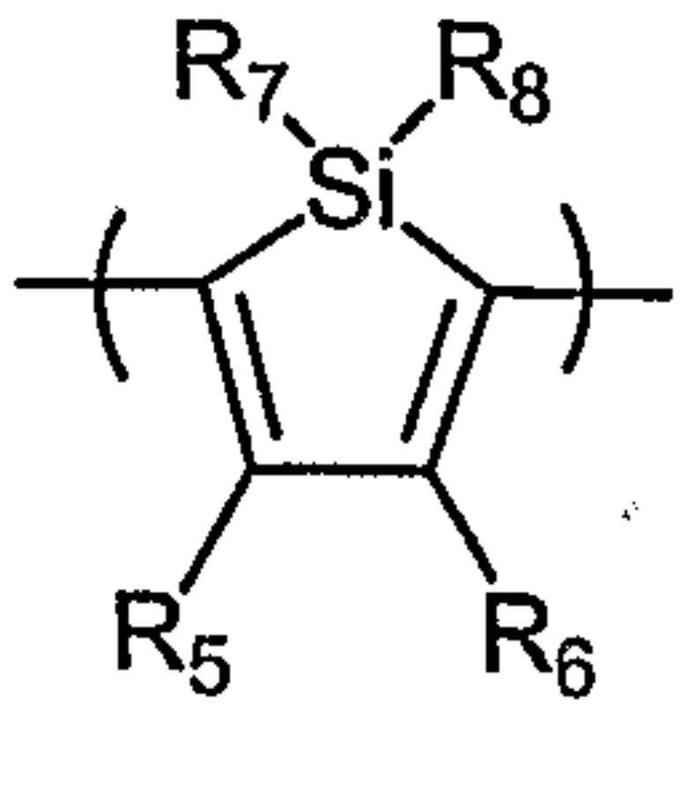

(XX), or


(XXI),

wherein each of R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

39. The polymer of claim 38, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II).

40. The polymer of claim 39, wherein each of R_5 and R_6 is H.

41. The polymer of claim 30, wherein the second comonomer repeat unit comprises a moiety containing at least three thiophene moieties, at least one of the thiophene moieties being substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

42. The polymer of claim 30, wherein the second comonomer repeat unit comprises a moiety containing five thiophene moieties.

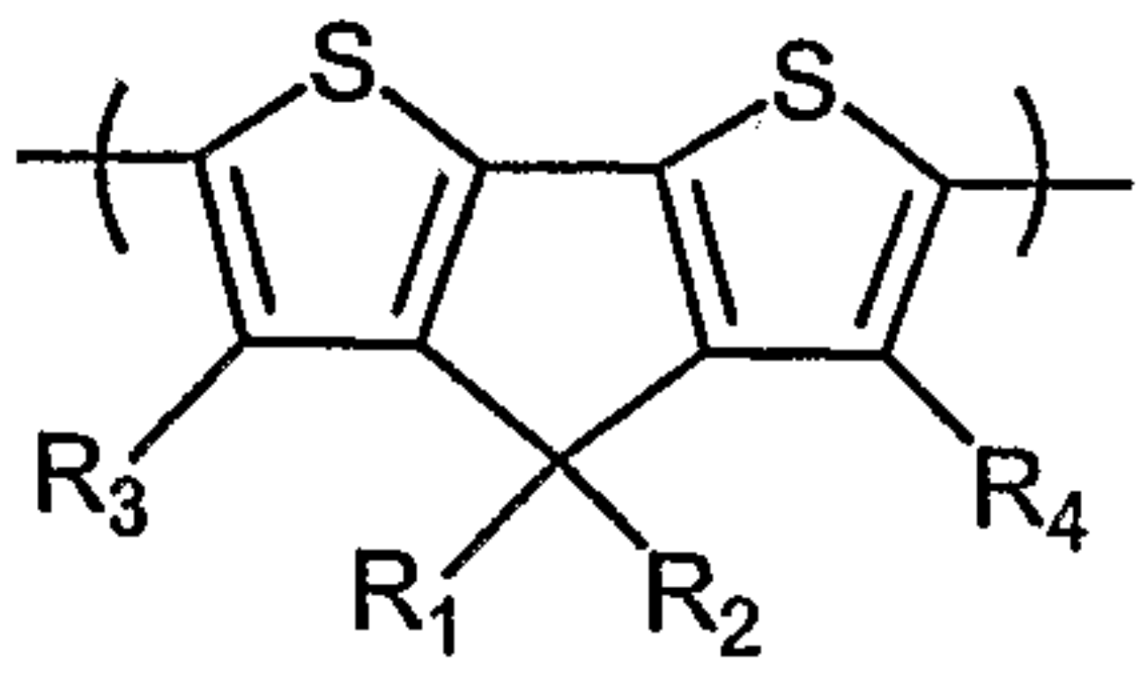
43. The polymer of claim 30, further comprising a third comonomer repeat unit, the third comonomer repeat unit comprising a thiophene moiety or a fluorene moiety.

44. The polymer of claim 43, wherein the thiophene or fluorene moiety in the third comonomer repeat unit is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

45. A polymer, comprising a first comonomer repeat unit and a second comonomer repeat unit different from the first comonomer repeat unit, the first comonomer repeat unit comprising a cyclopentadithiophene moiety substituted with at least one substituent selected from the group consisting of hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20}

heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

46. The polymer of claim 45, wherein the first comonomer repeat unit comprises a cyclopentadithiophene moiety of formula (I):



(I),

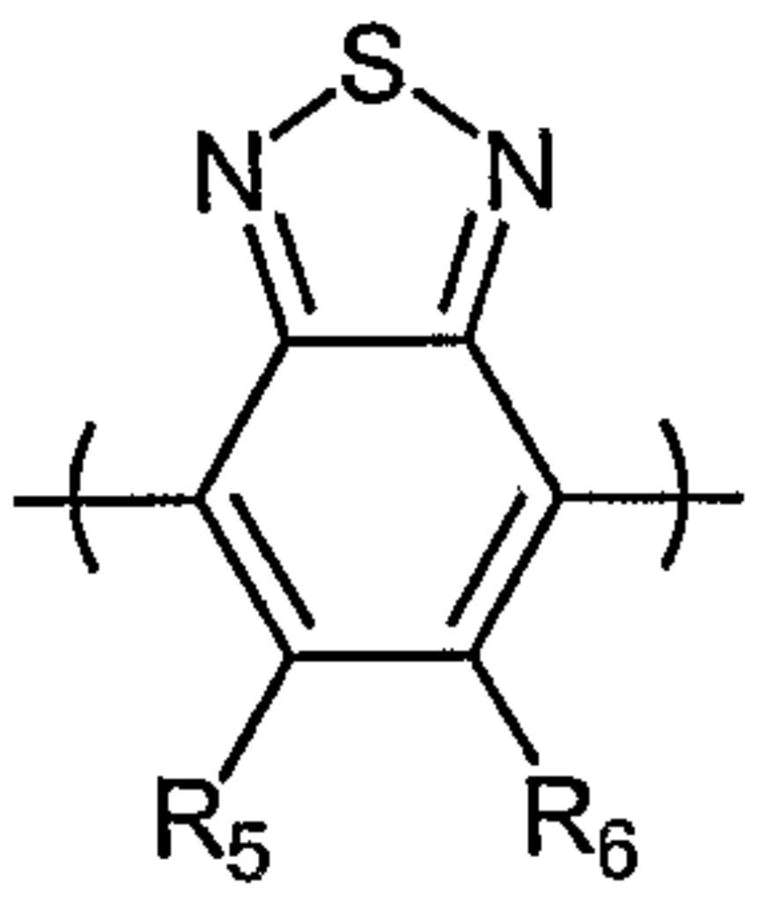
wherein one of R_1, R_2, R_3, and R_4 is hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl, the other of R_1, R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl .

47. The polymer of claim 45, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety.

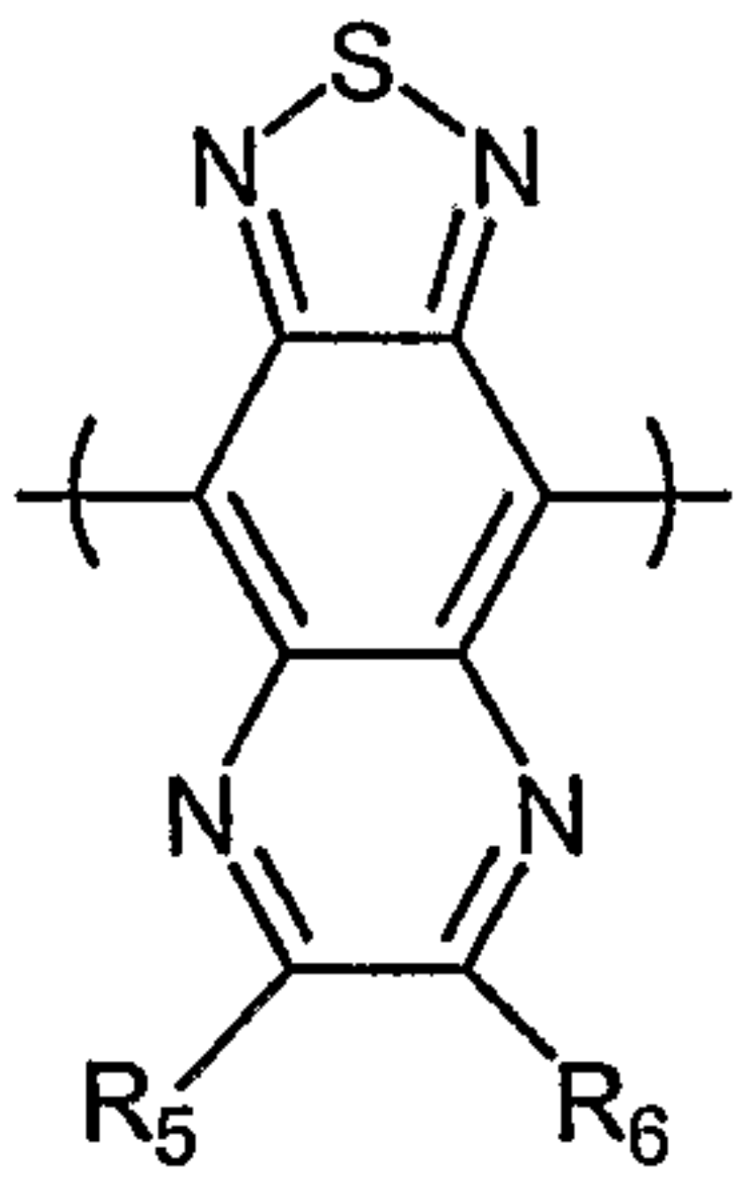
48. The polymer of claim 47, wherein the second comonomer repeat unit comprises a 3,4-benzo-1,2,5-thiadiazole moiety.

49. The polymer of claim 45, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II), a thiadiazoloquinoxaline moiety of formula (III), a cyclopentadithiophene dioxide moiety of formula (IV), a cyclopentadithiophene monoxide moiety of formula (V), a benzoisothiazole moiety of formula (VI), a benzothiazole moiety of formula (VII), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene dioxide moiety of formula (IX), or a cyclopentadithiophene tetraoxide moiety of formula (X), a thienothiophene moiety of

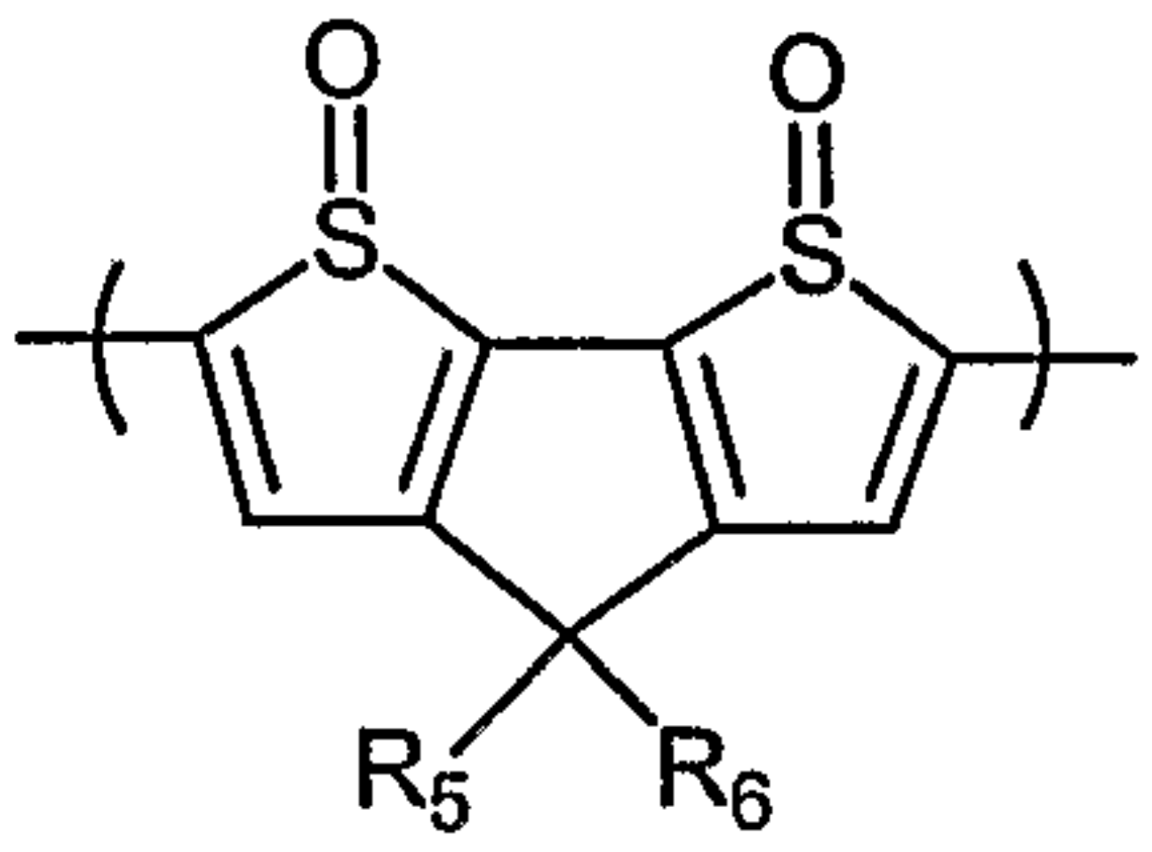
formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), or a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), a dithienothiophene dioxide moiety of formula (XVIII), a fluorene moiety of formula (XIX), a thiophene moiety of formula (XX), or a silole moiety of formula (XXI):



(II),



(III),



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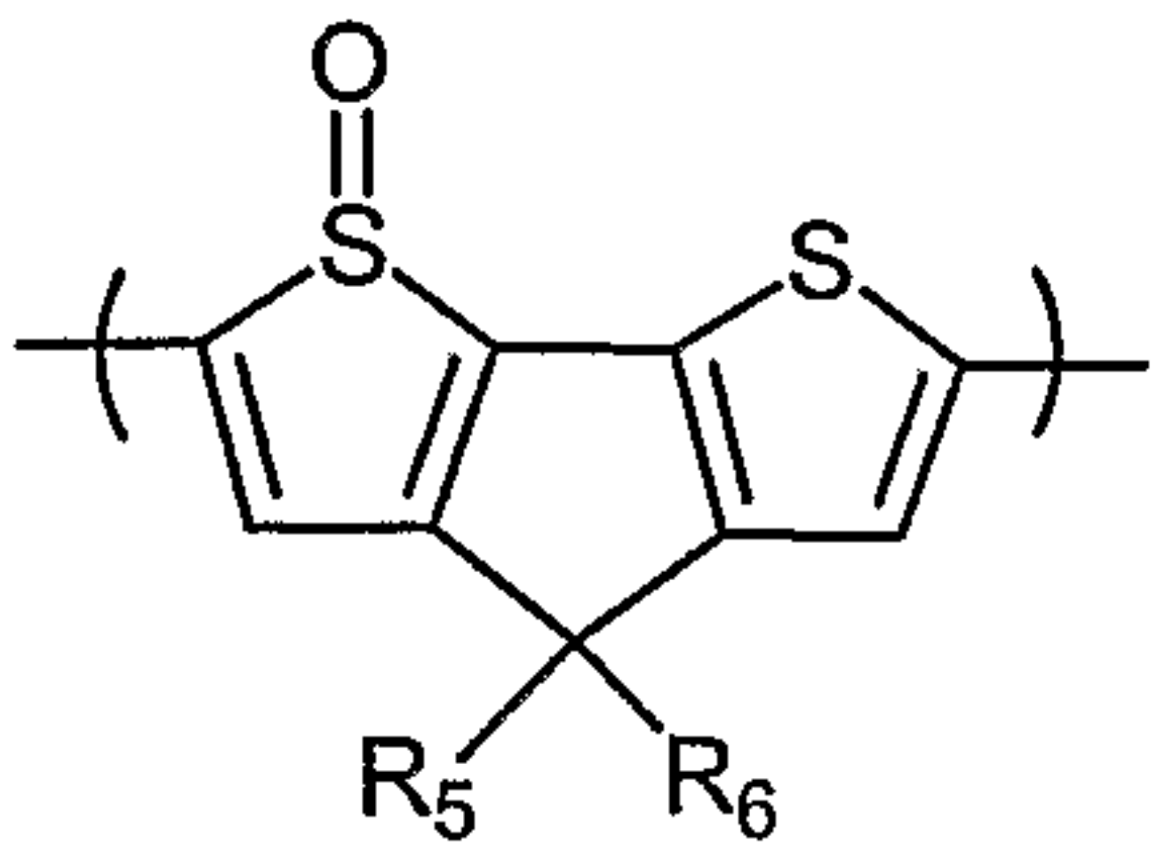

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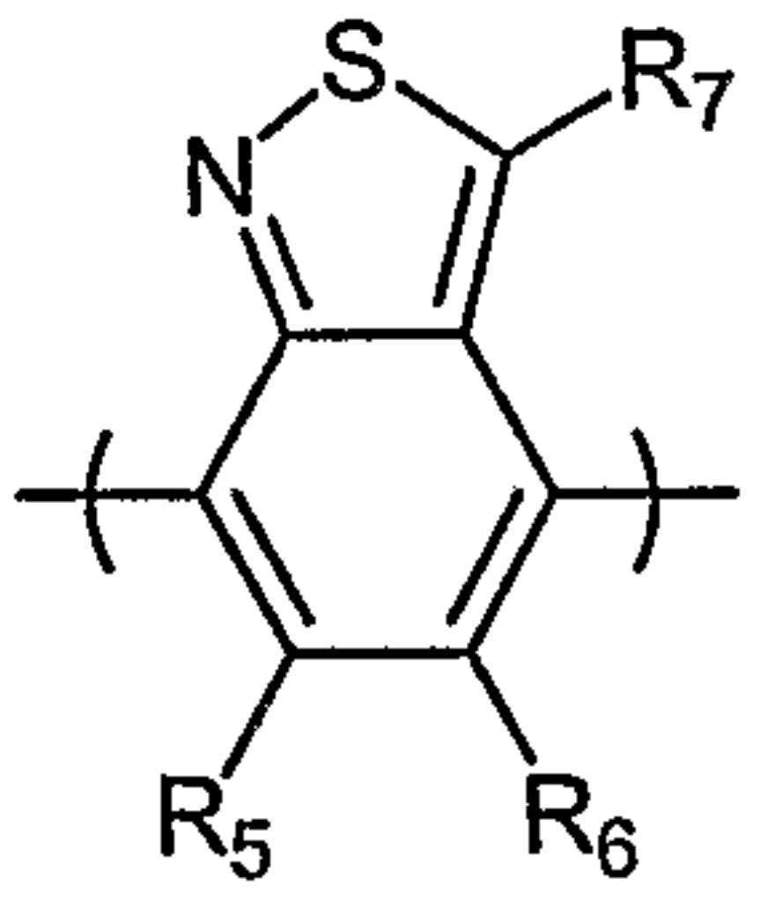

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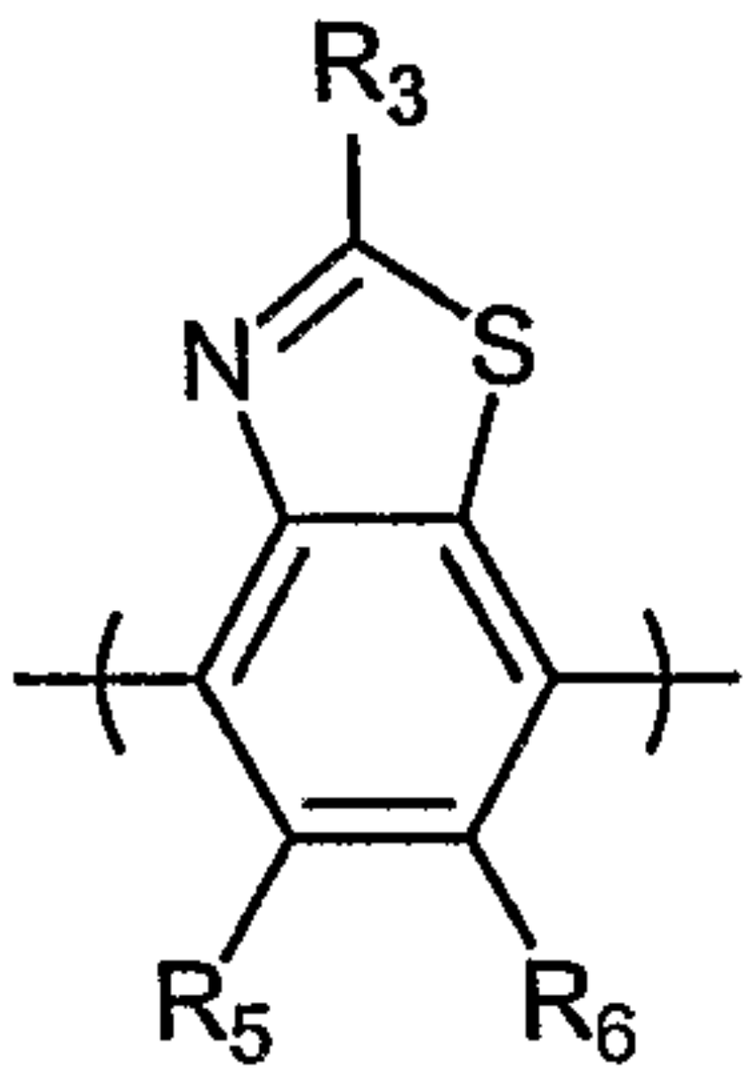

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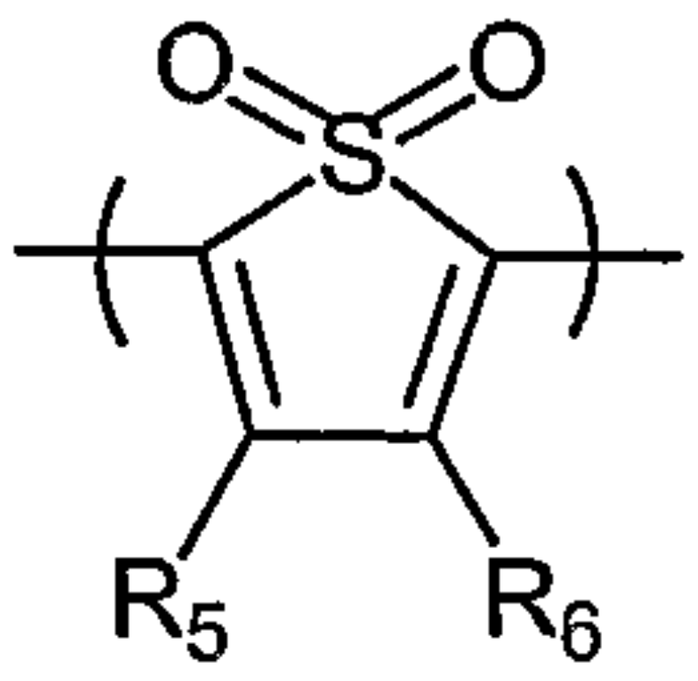
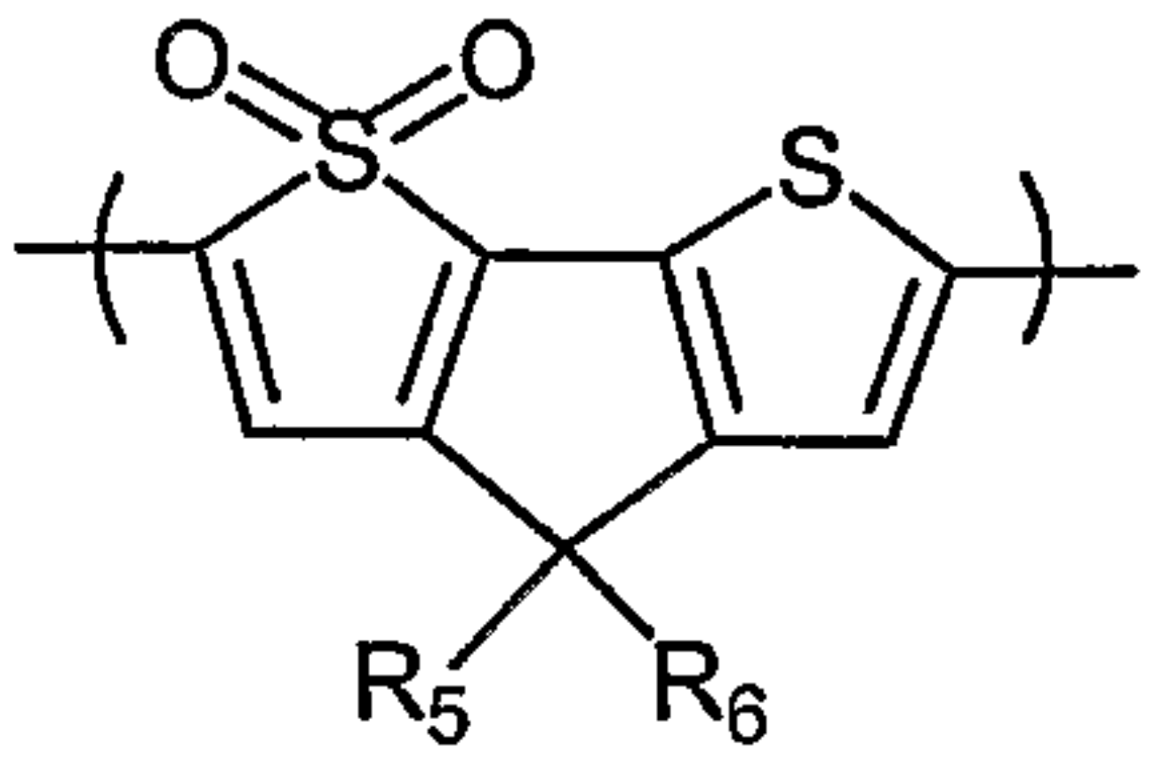
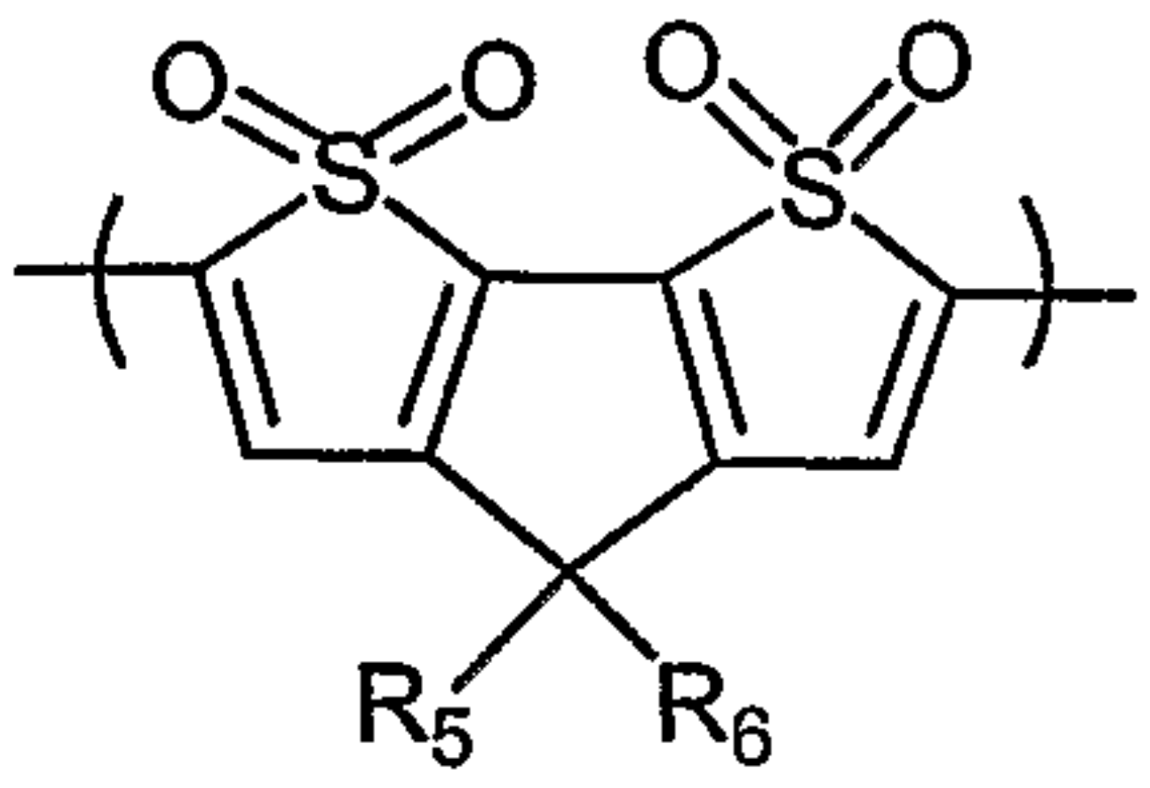


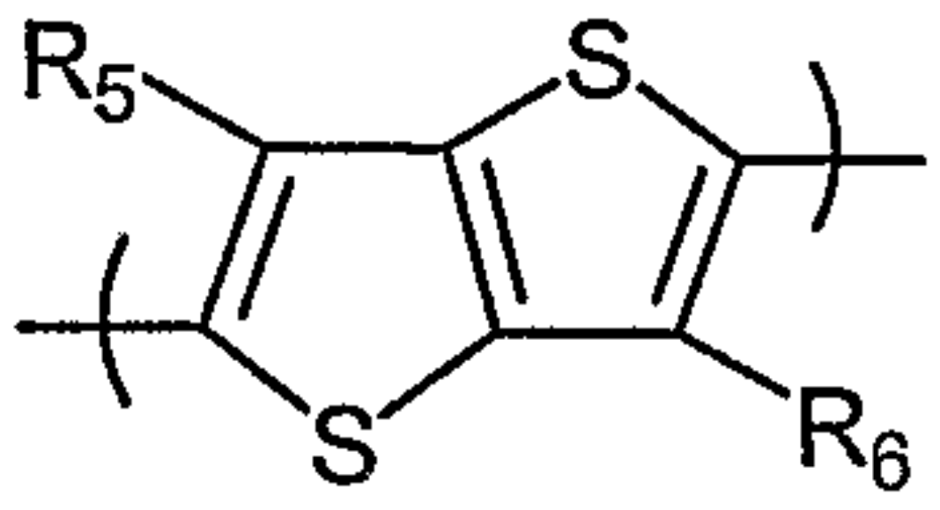
(VIII),



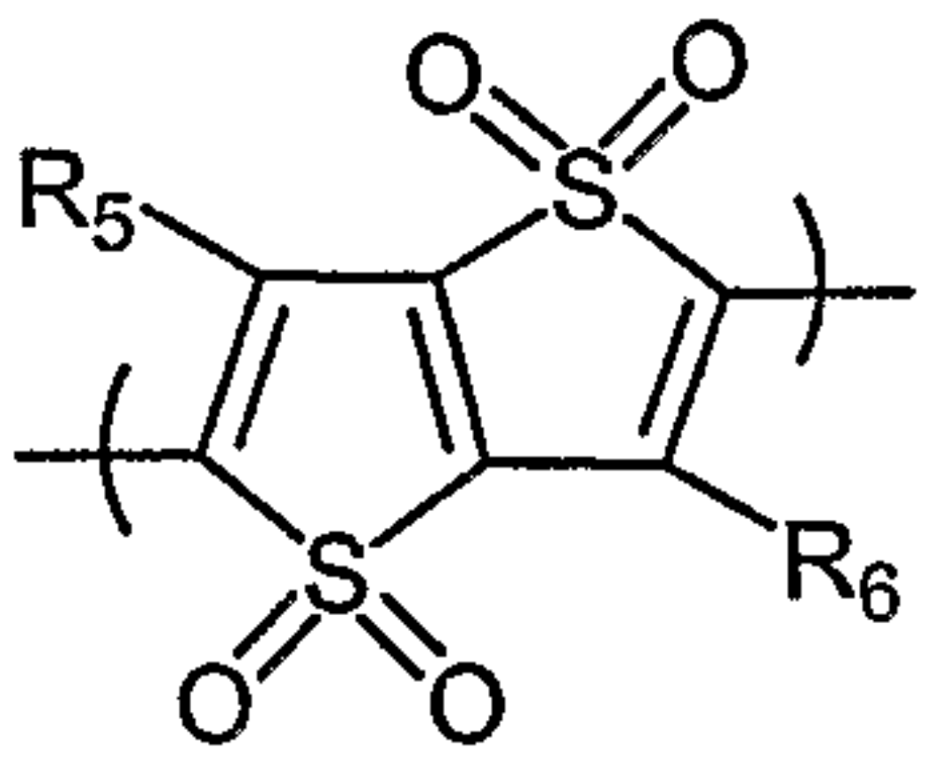
(IX), or



(X),



(XI),



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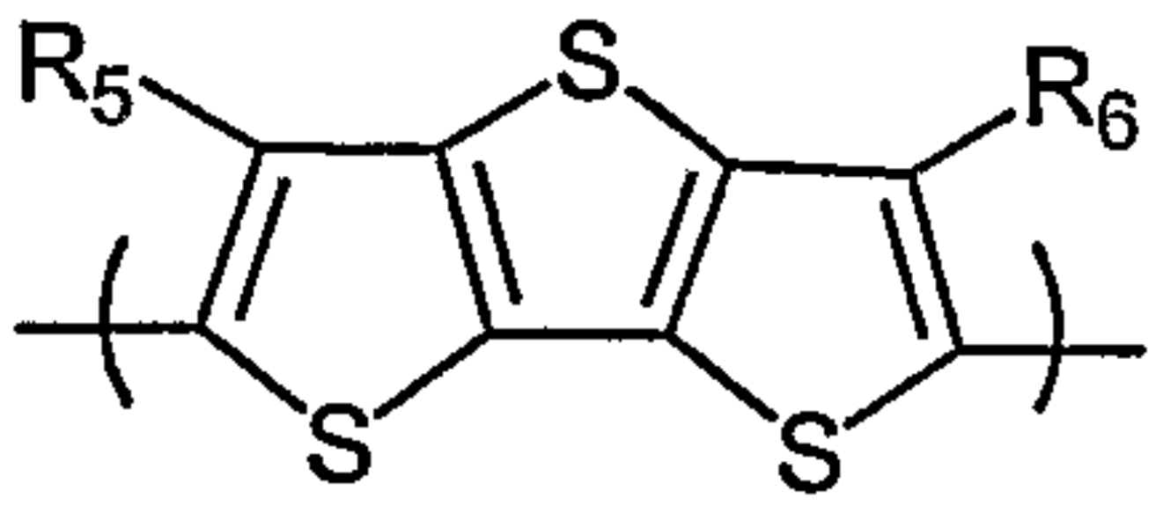
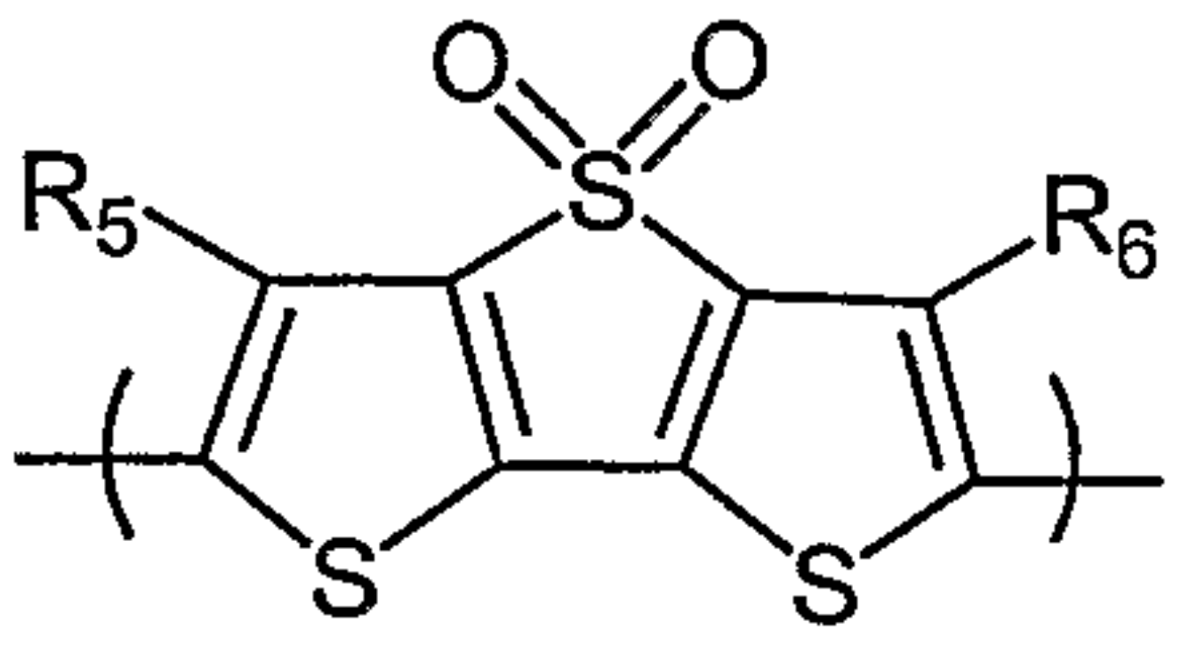
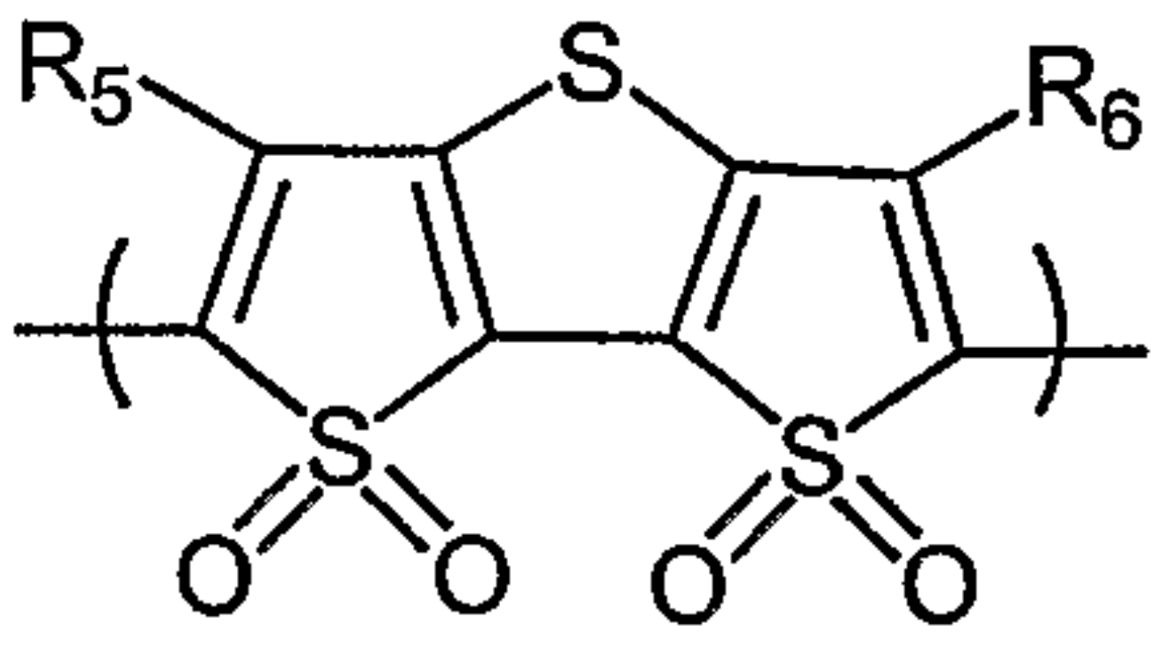


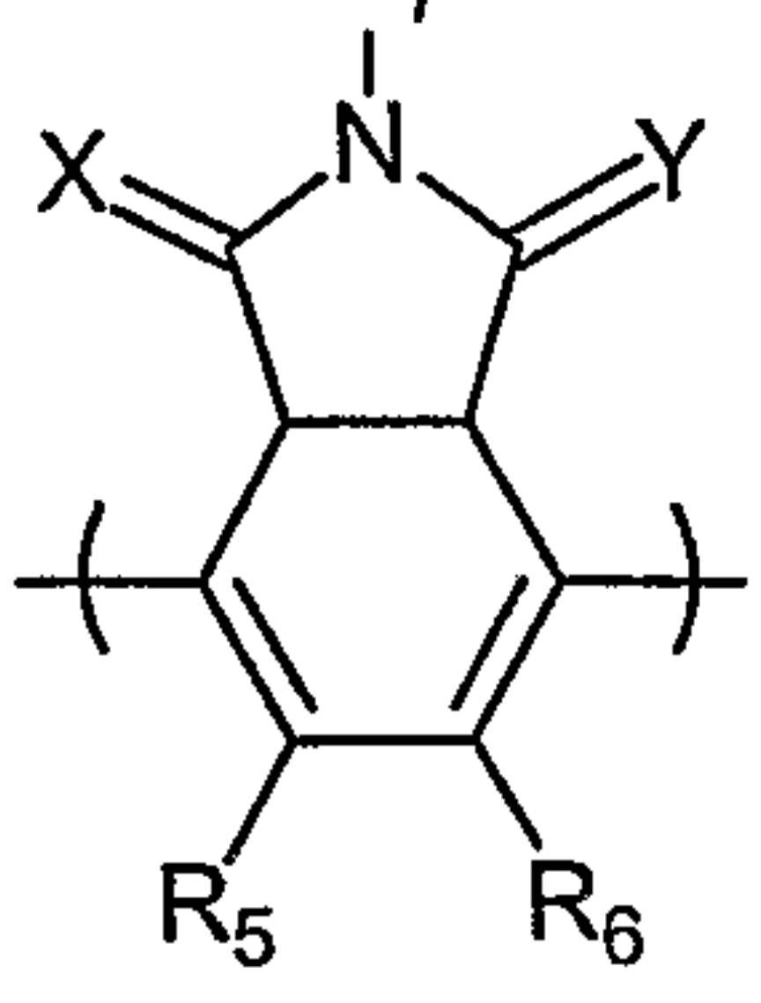
(XIII),



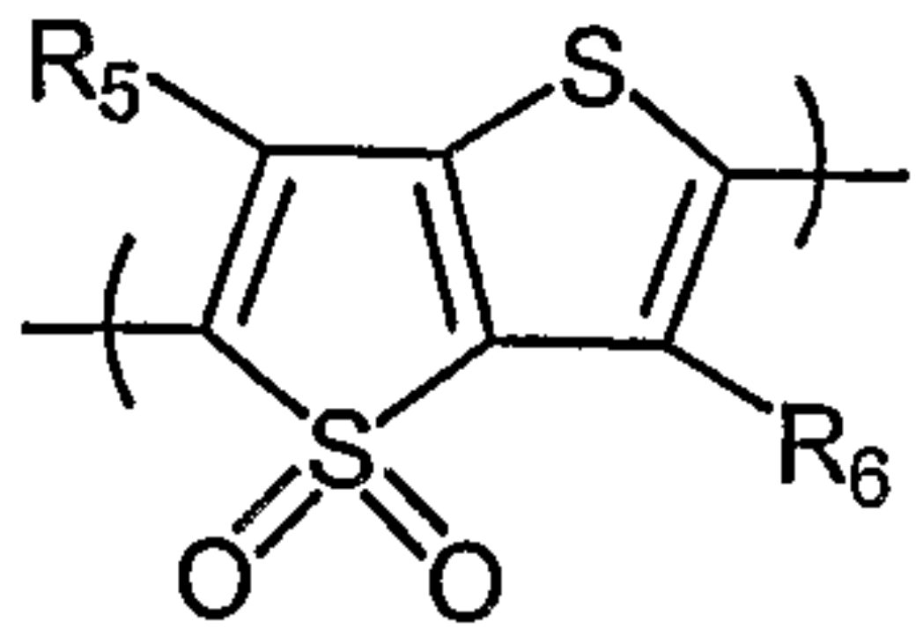
(XIV),



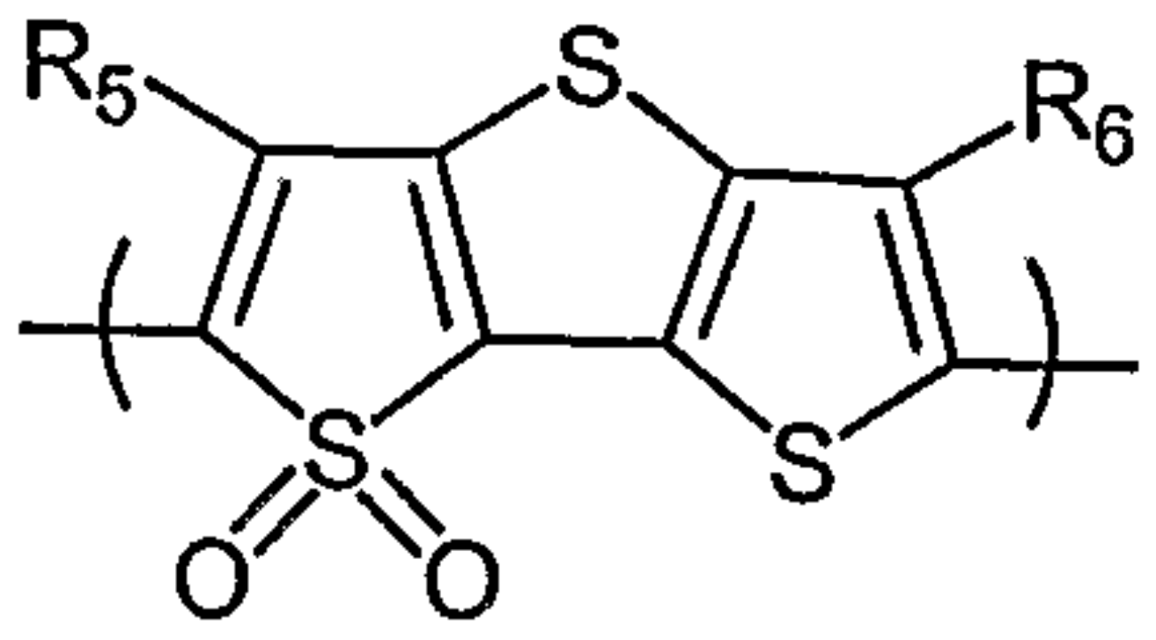
(XV),



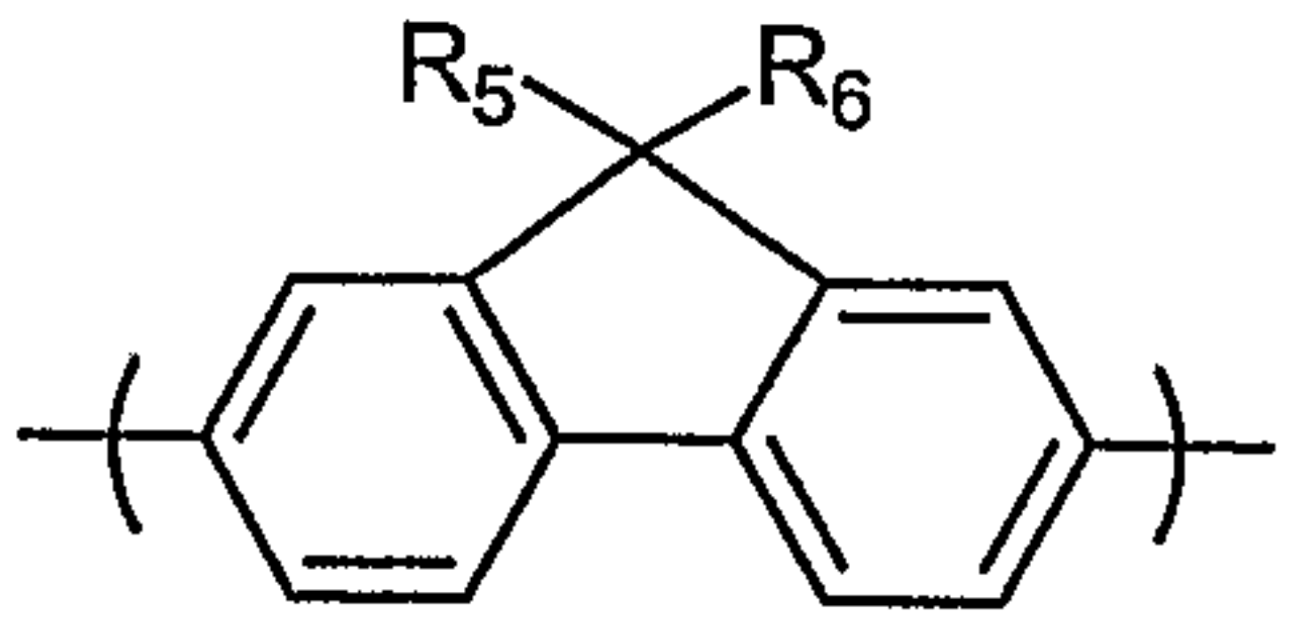
(XVI),



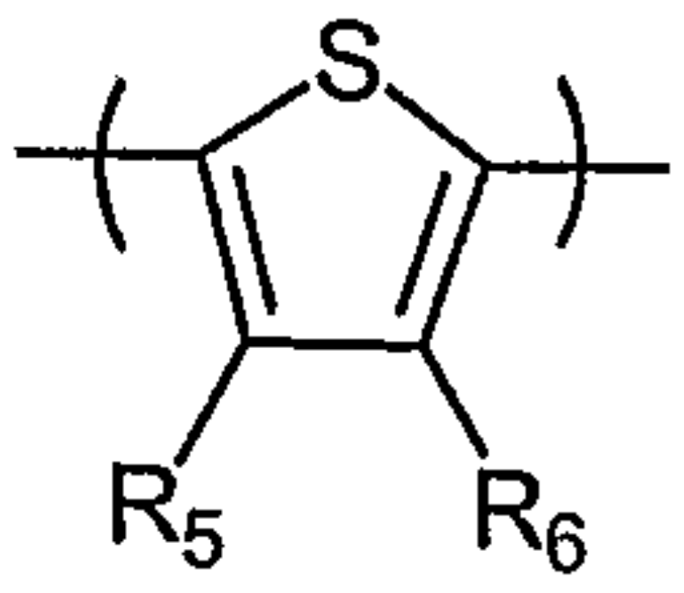
(XVII),



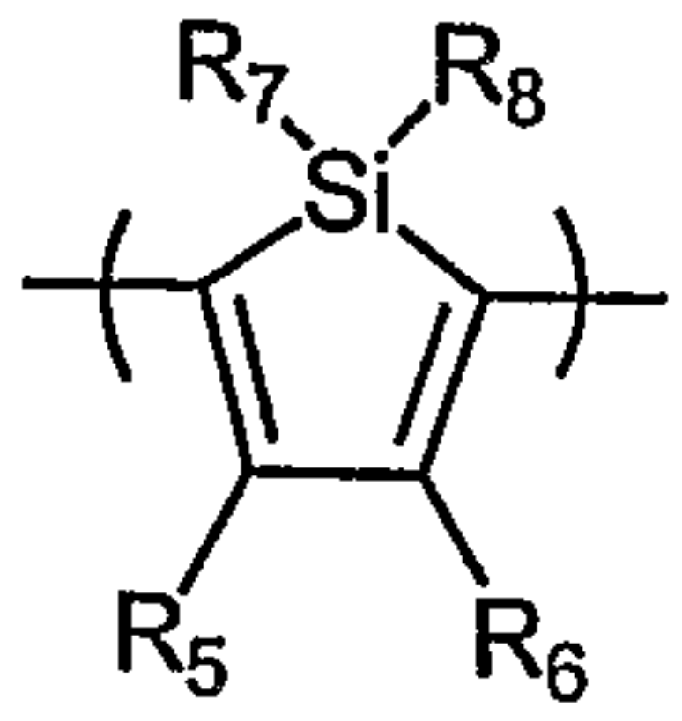
(XVIII),



(XIX),



(XX), or



(XXI),

wherein each of R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

50. The polymer of claim 49, wherein the second comonomer repeat unit comprises a benzothiadiazole moiety of formula (II).

51. The polymer of claim 50, wherein each of R_5 and R_6 is H.

52. The polymer of claim 45, wherein the second comonomer repeat unit comprises three thiophene moieties, at least one of the thiophene moieties being substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

53. The polymer of claim 52, wherein the second comonomer repeat unit comprises five thiophene moieties.

54. The polymer of claim 45, further comprising a third comonomer repeat unit, the third comonomer repeat unit comprising a thiophene moiety or a fluorene moiety.

55. The polymer of claim 54, wherein the thiophene or fluorene moiety is substituted with at least one substituent selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

56. A photovoltaic cell, comprising:

a first electrode,

a second electrode, and

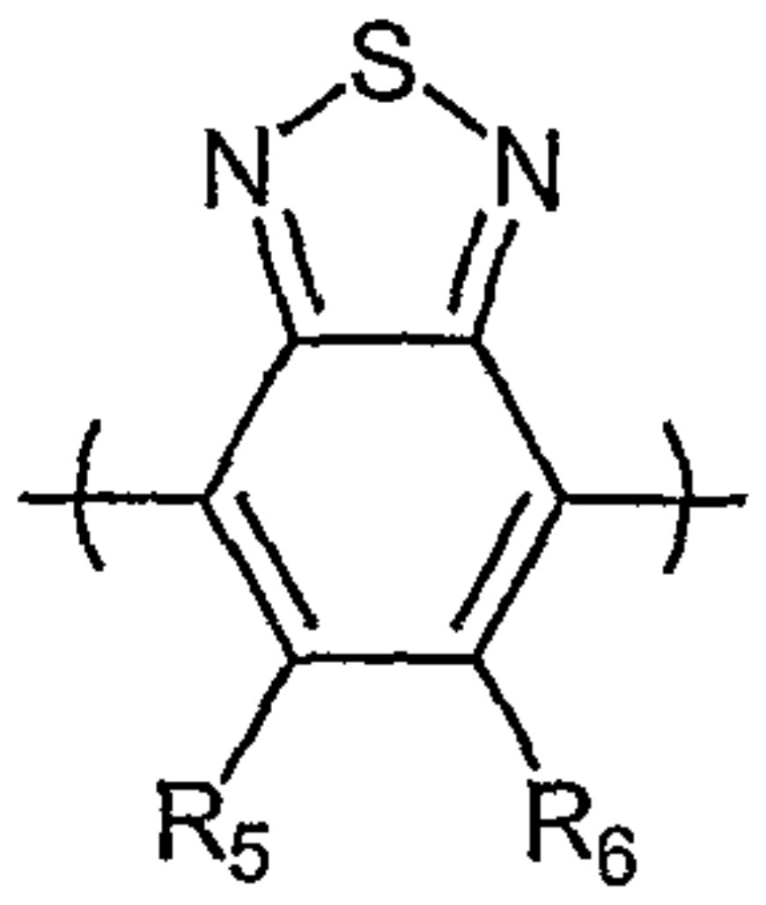
a photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first monomer repeat unit, wherein the first monomer repeat unit comprises a benzothiadiazole moiety, a thiophene oxide moiety, or a cyclopentadithiophene oxide moiety.

57. The photovoltaic cell of claim 56, wherein the first monomer repeat unit includes at least one substituent on a ring selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

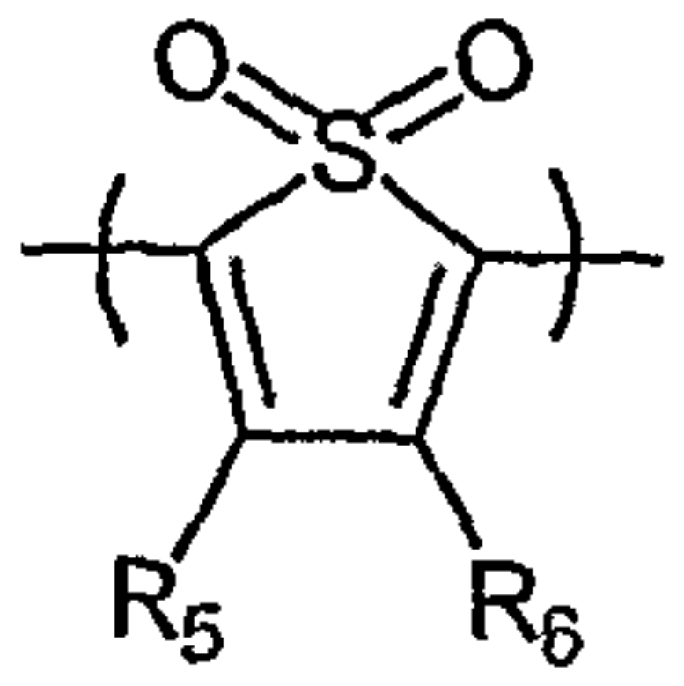
58. The photovoltaic cell of claim 57, wherein the substituent is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

59. The photovoltaic cell of claim 57, wherein the substitutent is $(OCH_2CH_2)_2OCH_3$, or $OCH_2CF_2OCF_2CF_2OCF_3$.

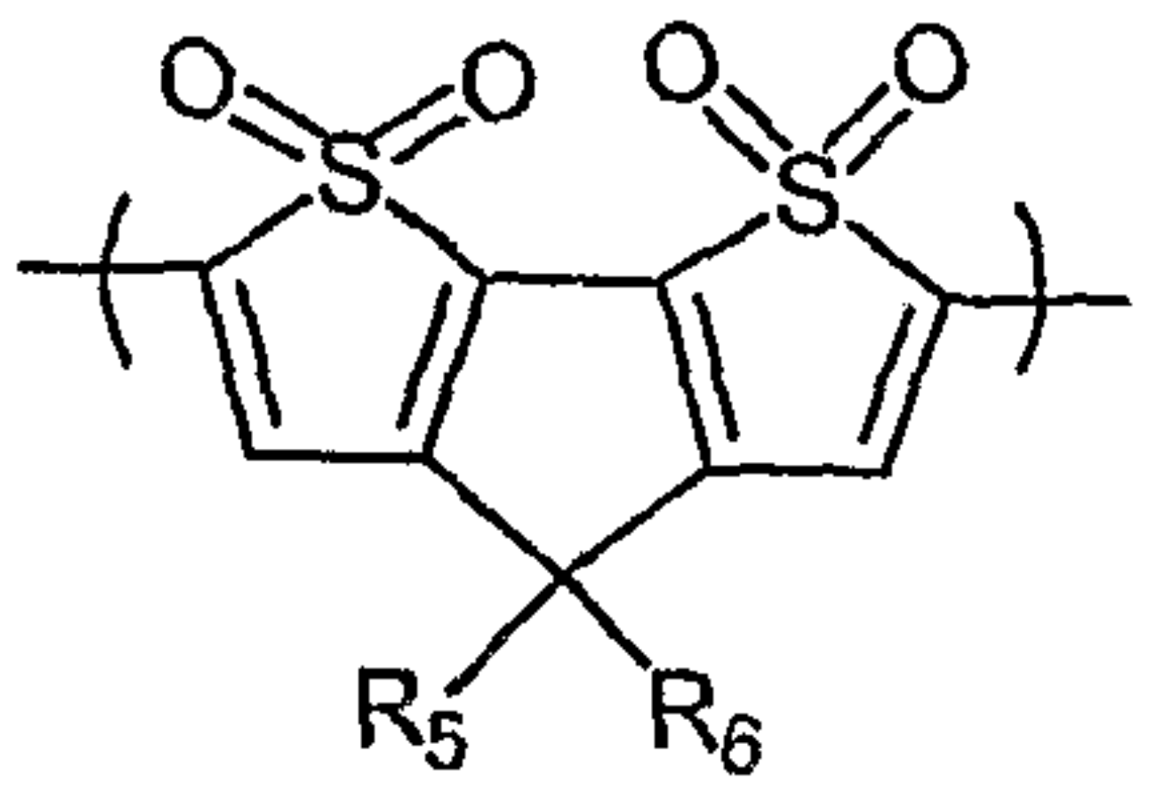
60. The photovoltaic cell of claim 56, wherein the first monomer repeat unit comprises a benzothiadiazole moiety of formula (II), a thiophene dioxide moiety of formula (VIII), or a cyclopentadithiophene tetraoxide moiety of formula (X):



(II),



(VIII), or



(X),

wherein each of R_5 and R_6, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

61. The photovoltaic cell of claim 60, wherein at least one of R_5 and R_6 is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

62. The photovoltaic cell of claim 60, wherein at least one of R_5 and R_6 is $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$.

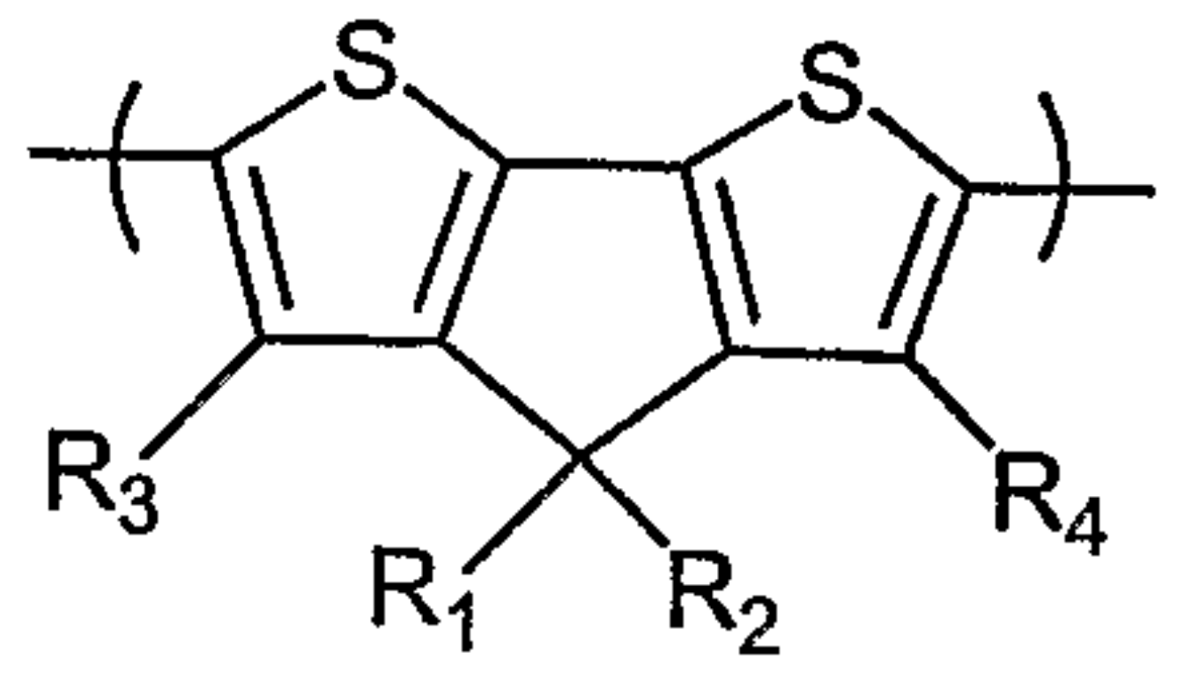
63. The photovoltaic cell of claim 56, further comprising a second monomer repeat unit different from the first monomer repeat unit, the second monomer repeat unit comprising a cyclopentadithiophene moiety, a benzothiadiazole moiety, a thiophene oxide moiety, a cyclopentadithiophene oxide moiety, a fluorene moiety, or a thiophene moiety.

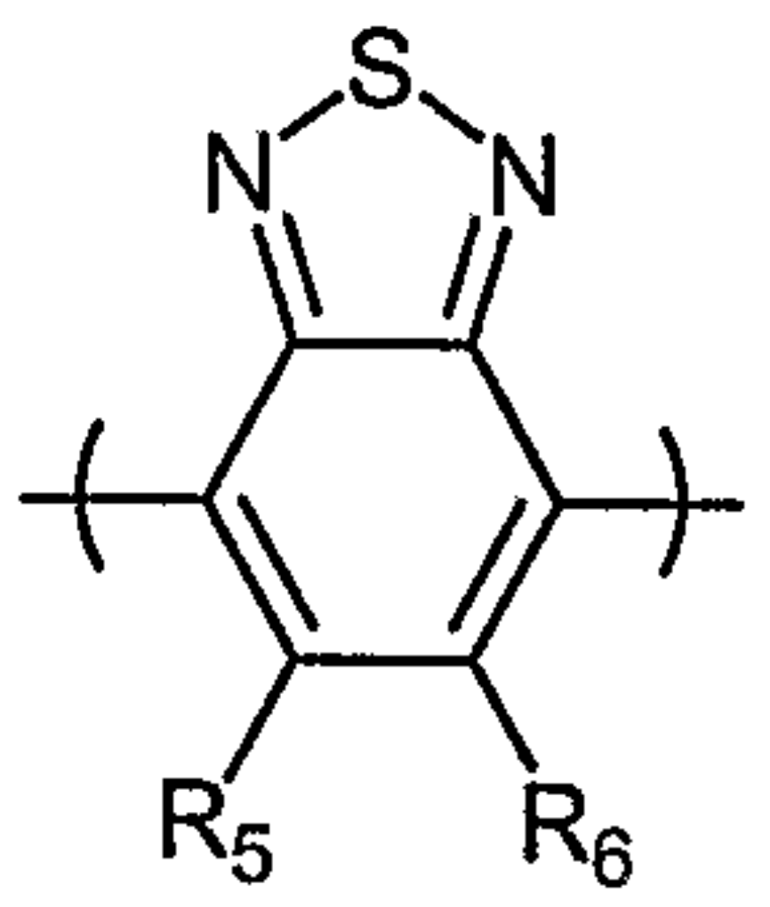
64. The photovoltaic cell of claim 63, wherein the second monomer repeat unit includes at least one substituent on a ring selected from the group consisting of C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

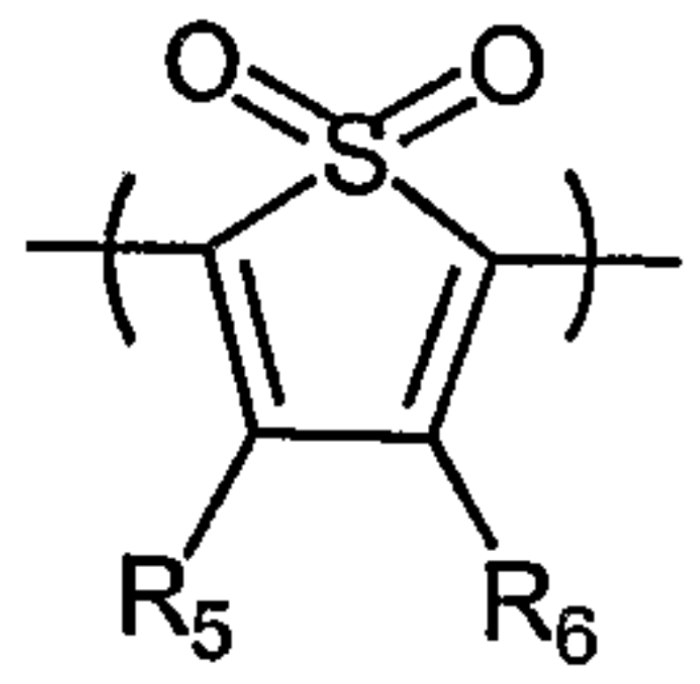
65. The photovoltaic cell of claim 64, wherein the substituent is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

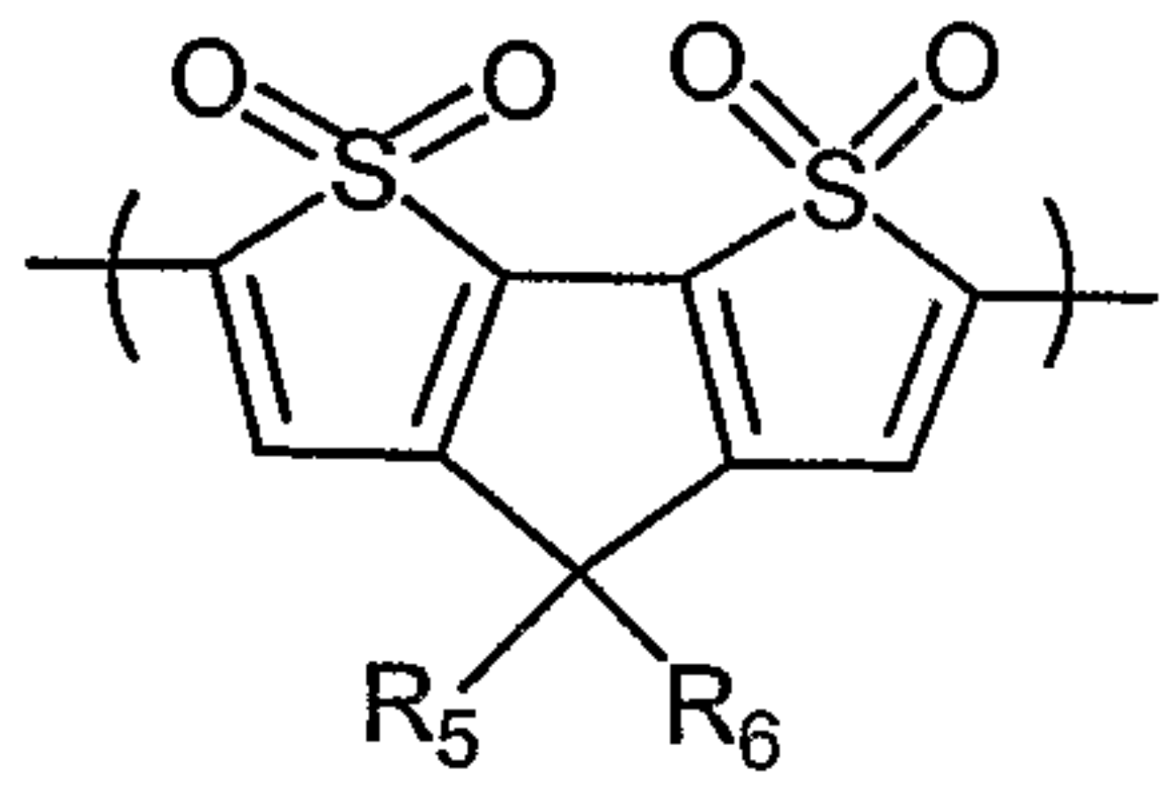
66. The photovoltaic cell of claim 64, wherein the substituent is $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$.

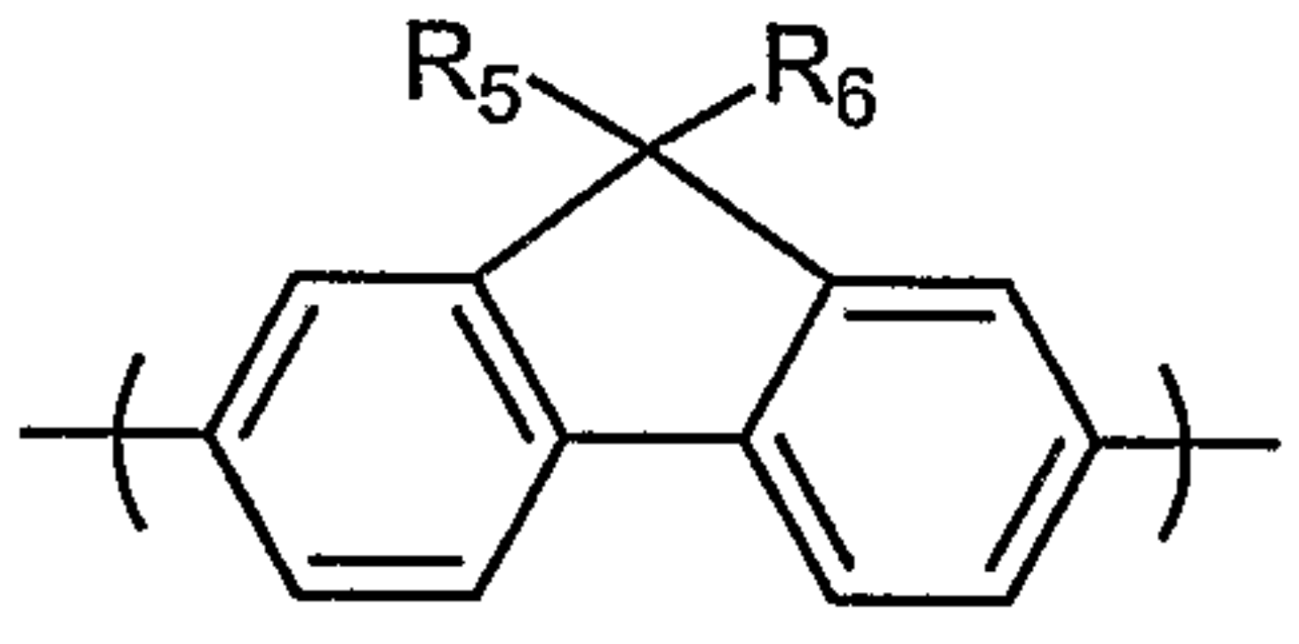
67. The photovoltaic cell of claim 63, wherein the second monomer repeat unit comprises a cyclopentadithiophene moiety of formula (I), a benzothiadiazole moiety of formula (II), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene tetraoxide moiety of formula (X), a fluorene moiety of formula (XIX), or a thiophene moiety of formula (XX):

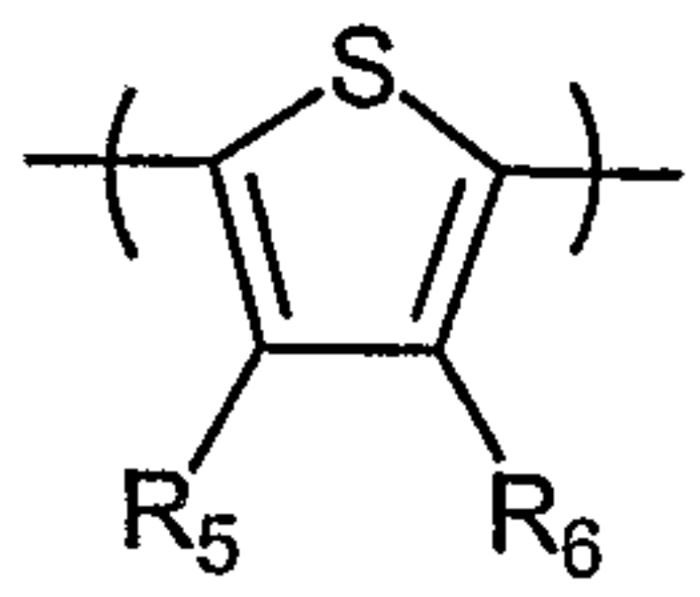

(I),


(II),


(VIII),


(X),


(XIX), or

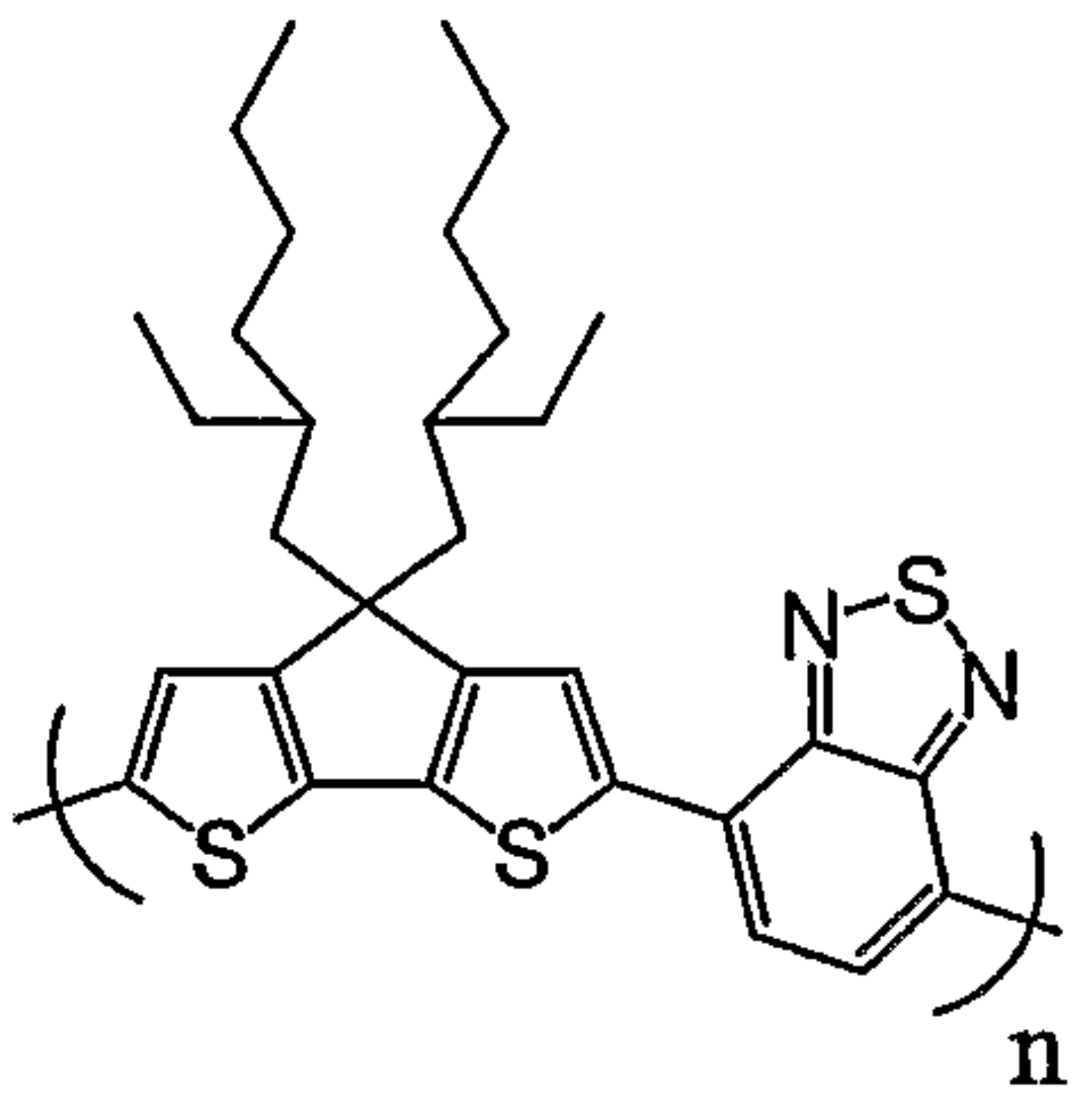

(XX),

wherein each of R_1, R_2, R_3, R_4, R_5 and R_6, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

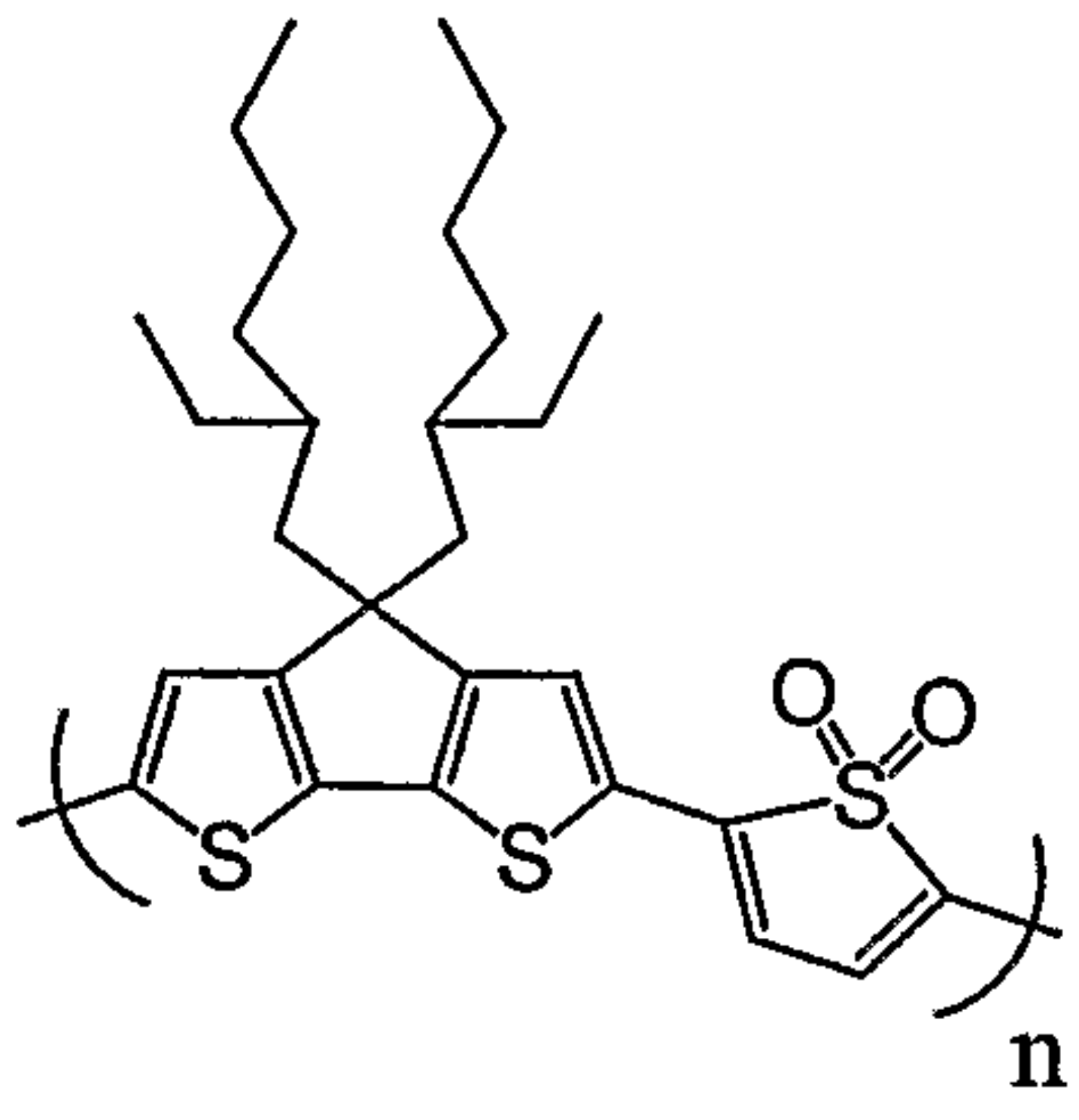
68. The photovoltaic cell of claim 67, wherein at least one of R_1, R_2, R_3, R_4, R_5, and R_6 is C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

69. The photovoltaic cell of claim 67, wherein at least one of R_1, R_2, R_3, R_4, R_5, and R_6 is $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$.

70. The photovoltaic cell of claim 56, wherein the polymer is



or



, n being an integer greater than 1.

71. The photovoltaic cell of claim 56, wherein the polymer is an electron donor material.

72. The photovoltaic cell of claim 56, wherein the polymer is an electron acceptor material.

73. A photovoltaic cell, comprising:

a first electrode,

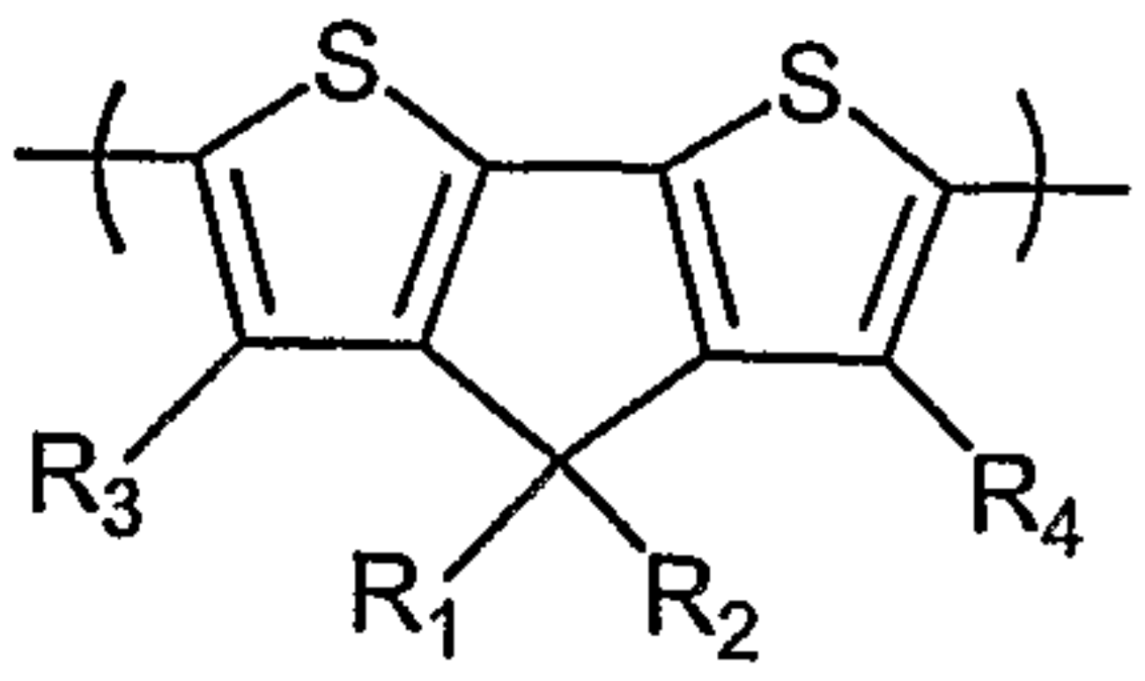
a second electrode, and

a photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first monomer repeat unit, wherein the first monomer repeat unit comprises a cyclopentadithiophene moiety substituted with at least one substituent selected from the group consisting of hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R, in which R is C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

74. The photovoltaic cell of claim 73, wherein the substituent is hexyl, ethylhexyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

75. The photovoltaic cell of claim 73, wherein the substitutent is hexyl, ethylhexyl, $(OCH_2CH_2)_2OCH_3$ or $OCH_2CF_2OCF_2CF_2OCF_3$.

76. The photovoltaic cell of claim 73, wherein the polymer comprises a cyclopentadithiophene moiety of formula (I):



(I),

wherein

R_1 is hexyl, ethylhexyl, dimethyloctyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R; and

each of R_2, R_3, and R_4, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, or SO_2R;
in which each R, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

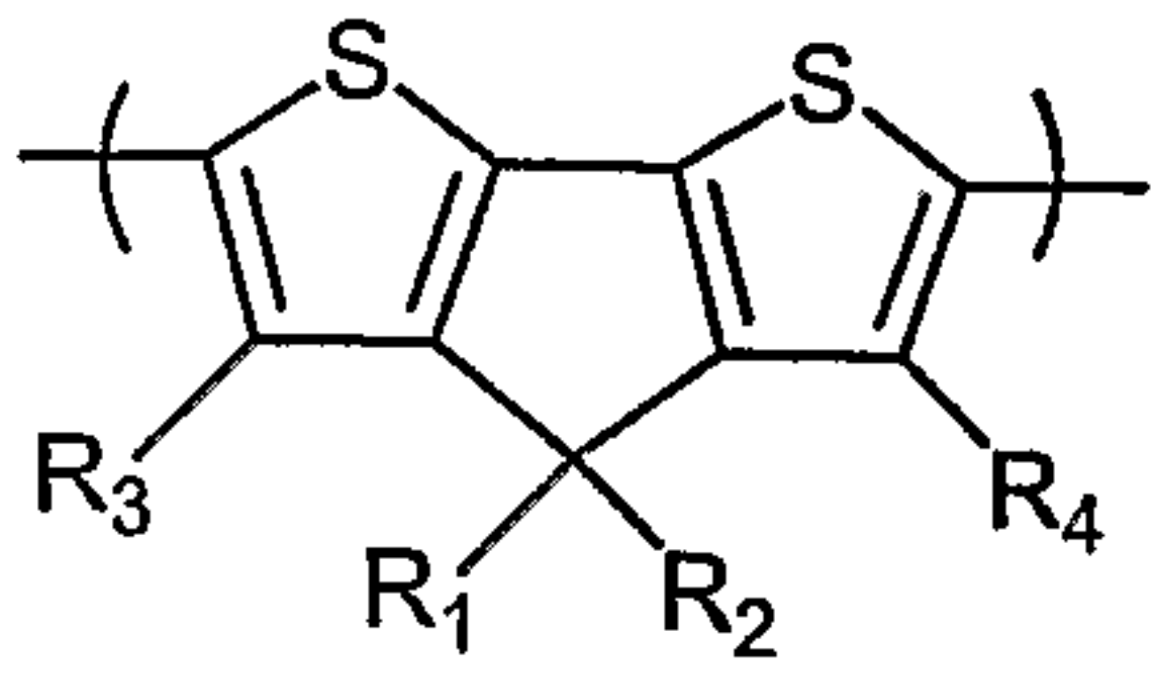
77. The photovoltaic cell of claim 76, wherein R_1 is hexyl, ethylhexyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

78. The photovoltaic cell of claim 76, wherein R_1 is hexyl, ethylhexyl, $(OCH_2CH_2)_2OCH_3$, or $OCH_2CF_2OCF_2CF_2OCF_3$.

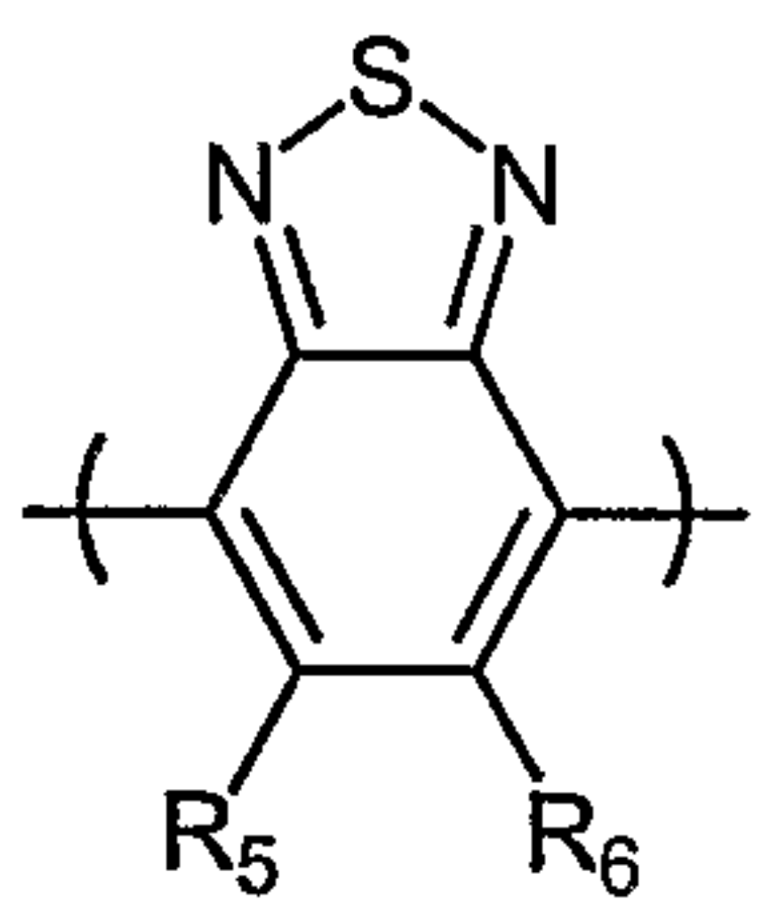
79. The photovoltaic cell of claim 76, wherein R_2 is hexyl, ethylhexyl, or C_1-C_{20} alkoxy optionally further substituted with C_1-C_{20} alkoxy or halo.

80. The photovoltaic cell of claim 73, further comprising a second monomer repeat unit different from the first monomer repeat unit, the second monomer repeat unit comprising a cyclopentadithiophene moiety, a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety.

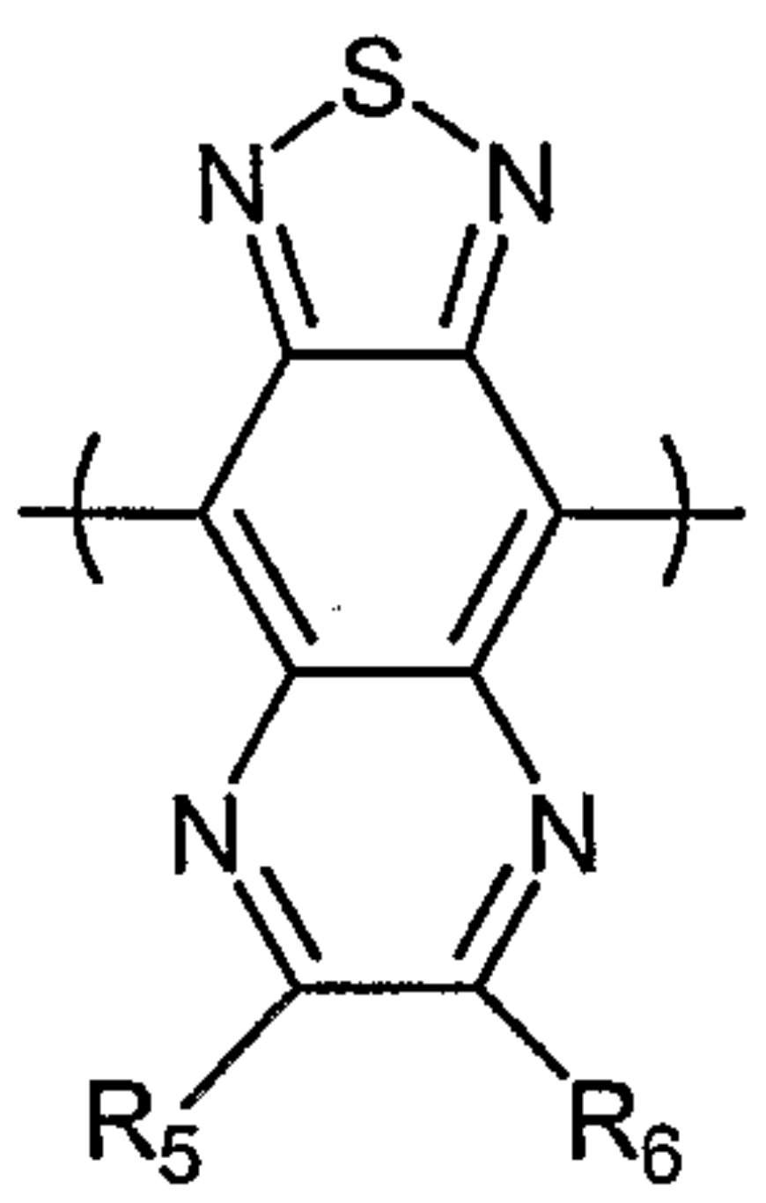
81. The photovoltaic cell of claim 80, wherein the second monomer repeat unit comprises a cyclopentadithiophene moiety of formula (I), a benzothiadiazole moiety of formula (II), a thiadiazoloquinoxaline moiety of formula (III), a cyclopentadithiophene dioxide moiety of formula (IV), a cyclopentadithiophene monoxide moiety of formula (V), a benzoisothiazole moiety of formula (VI), a benzothiazole moiety of formula (VII), a thiophene dioxide moiety of formula (VIII), a cyclopentadithiophene dioxide moiety of formula (IX), a cyclopentadithiophene tetraoxide moiety of formula (X), a thienothiophene moiety of formula (XI), a thienothiophene tetraoxide moiety of formula (XII), a dithienothiophene moiety of formula (XIII), a dithienothiophene dioxide moiety of formula (XIV), a dithienothiophene tetraoxide moiety of formula (XV), or a tetrahydroisoindole moiety of formula (XVI), a thienothiophene dioxide moiety of formula (XVII), a dithienothiophene dioxide moiety of formula (XVIII), a fluorene moiety of formula (XIX), a thiophene moiety of formula (XX), or a silole moiety of formula (XXI):



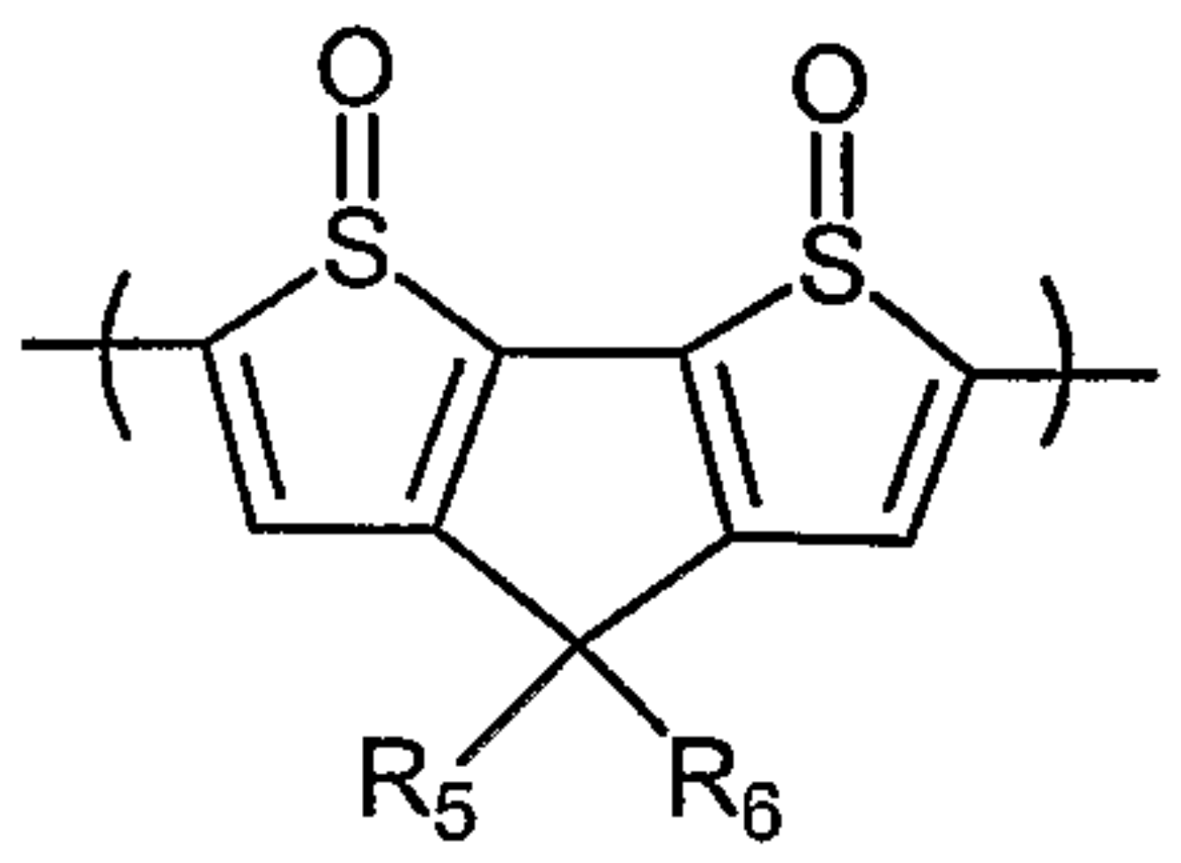
(I),



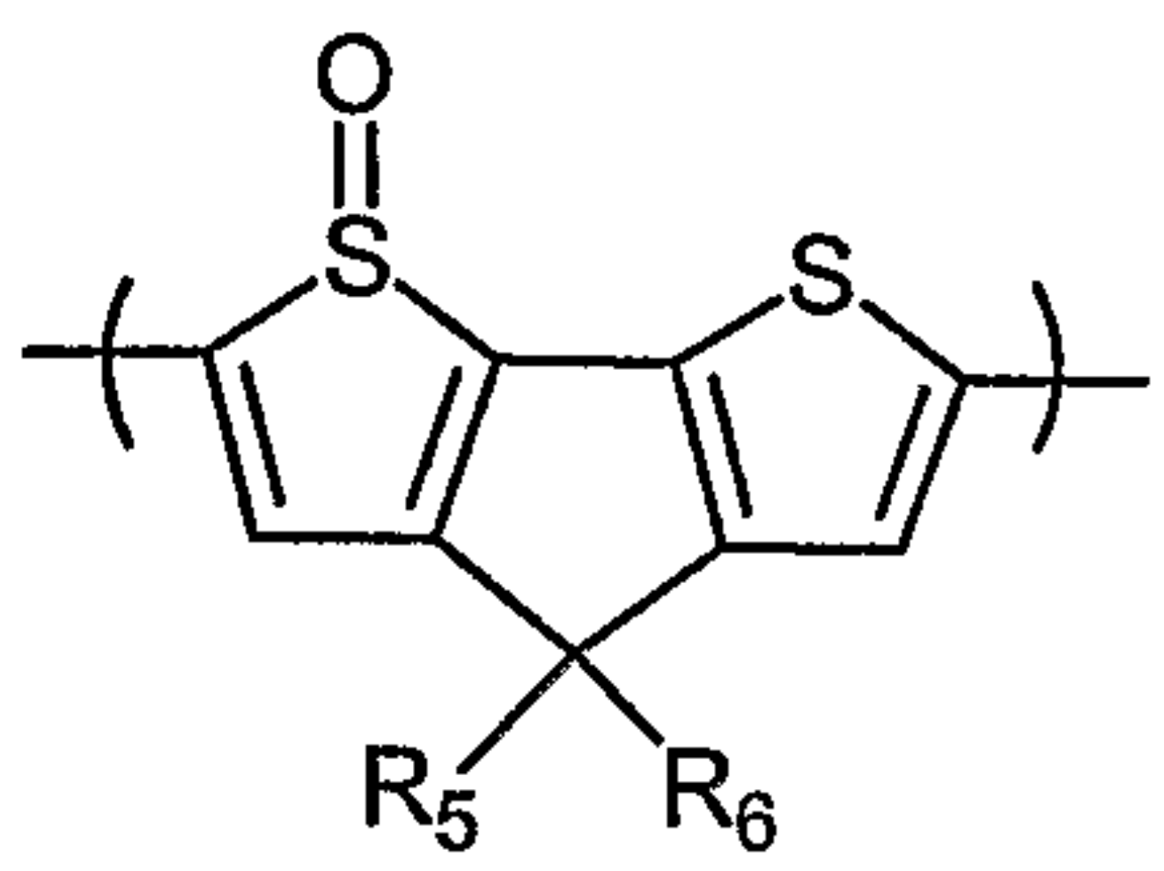
(II),



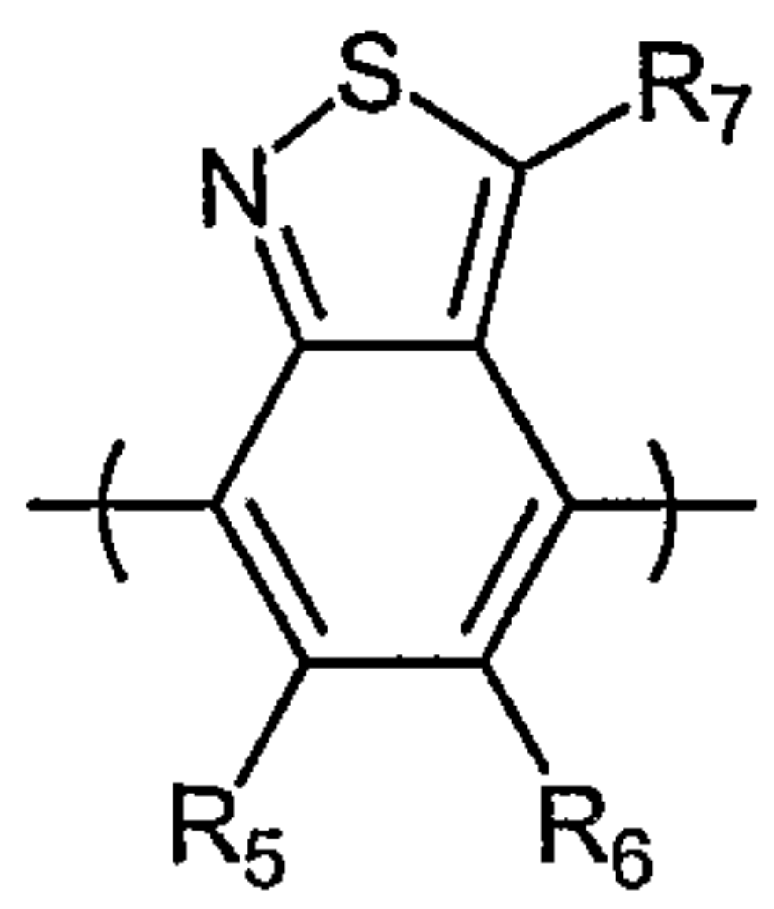
(III),



(IV),



(V),



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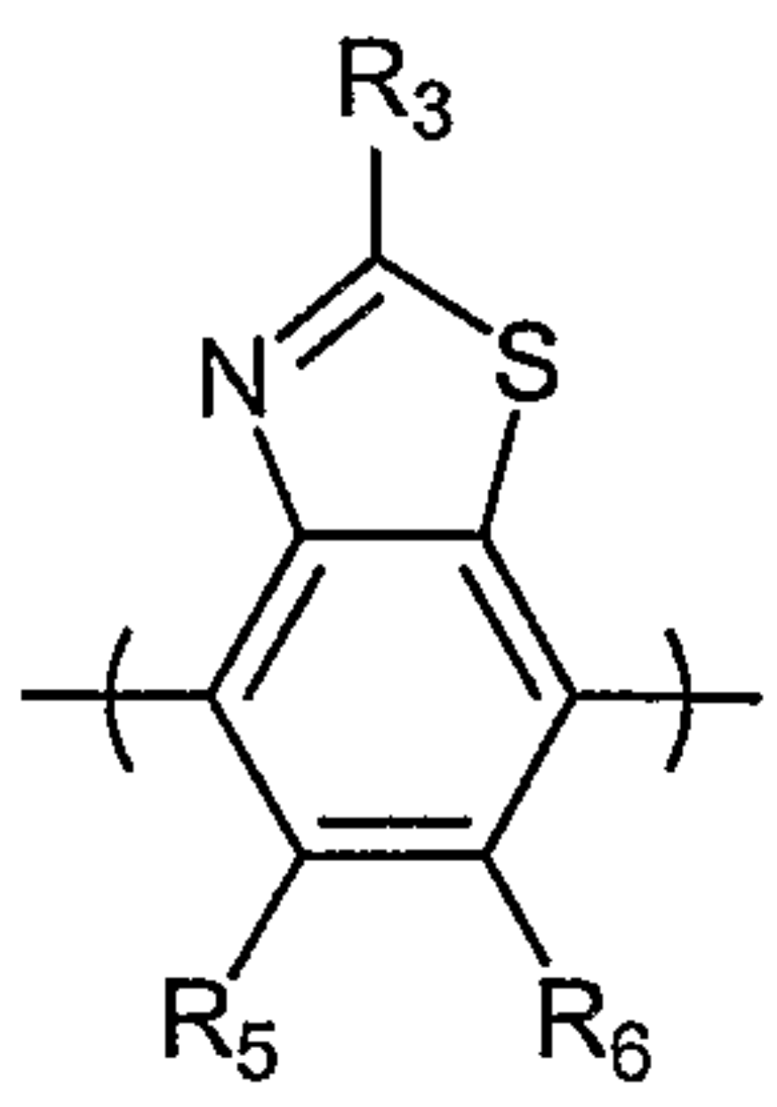

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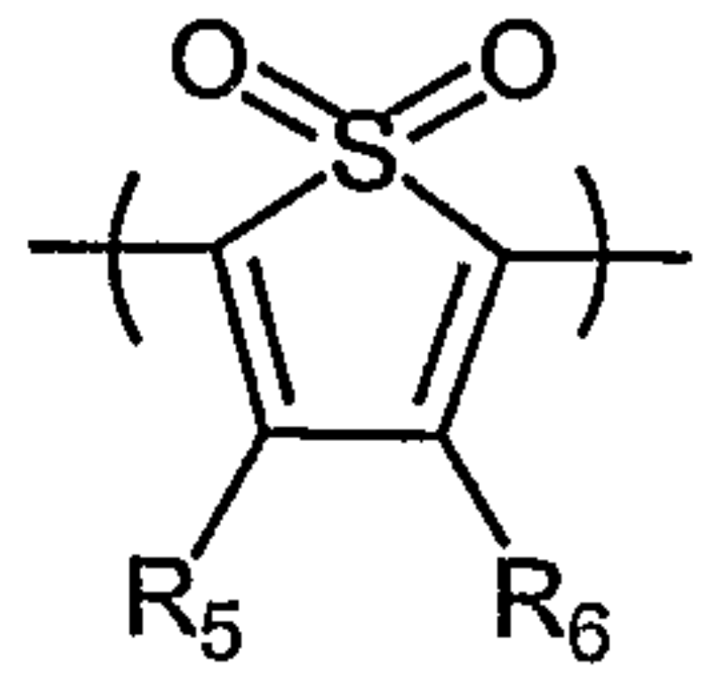

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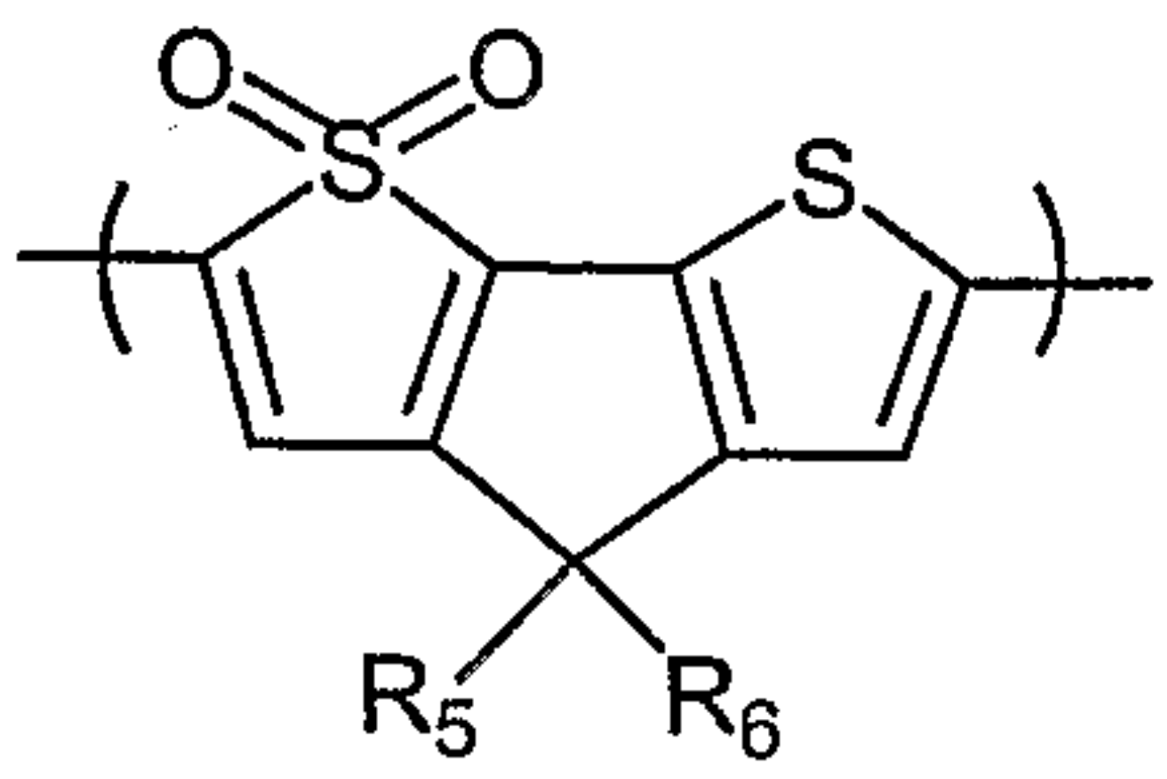

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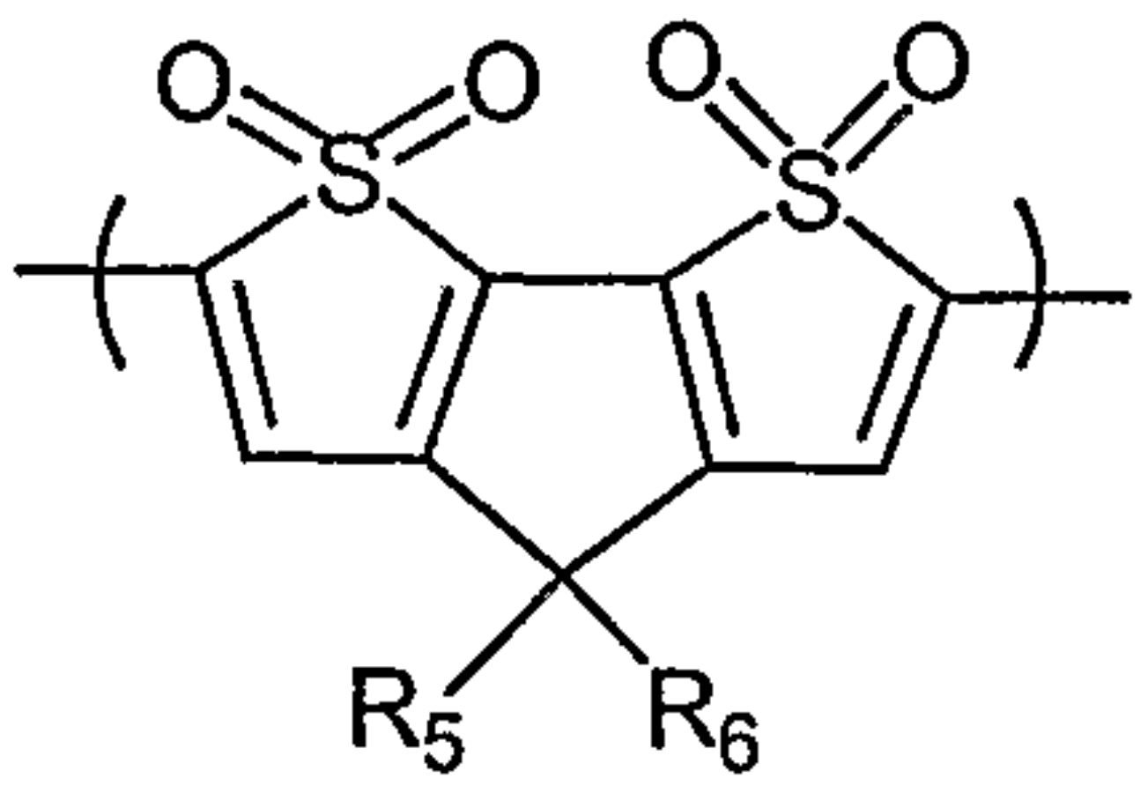
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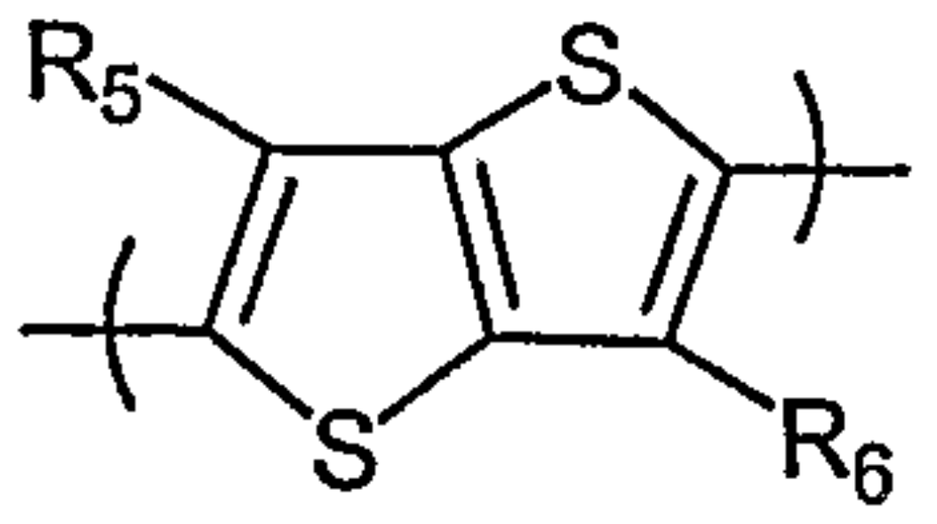
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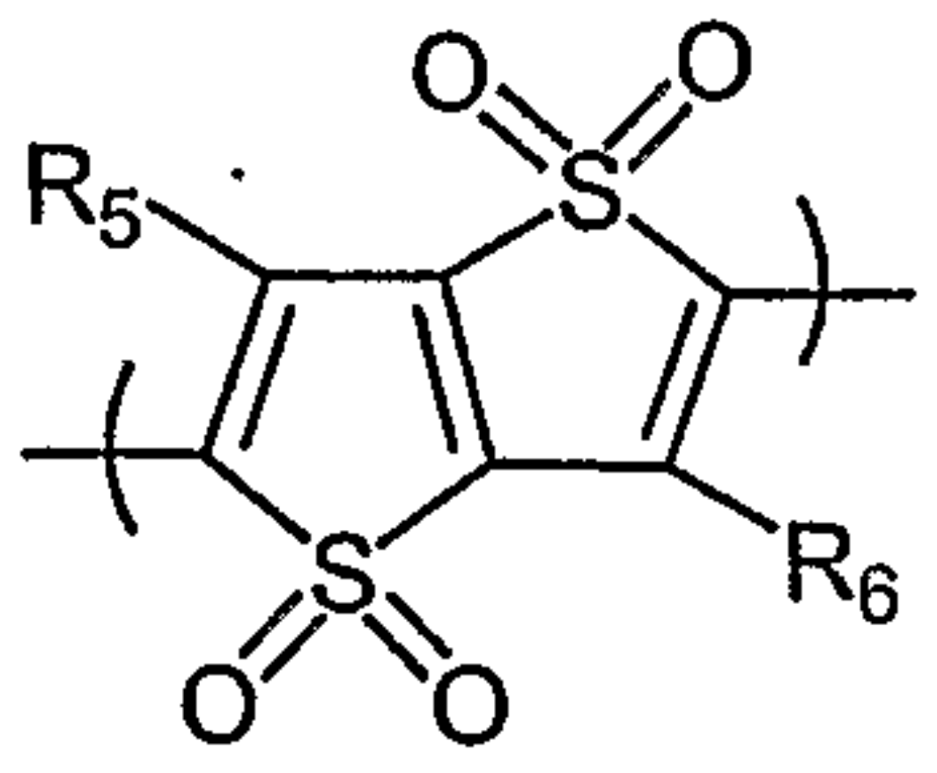
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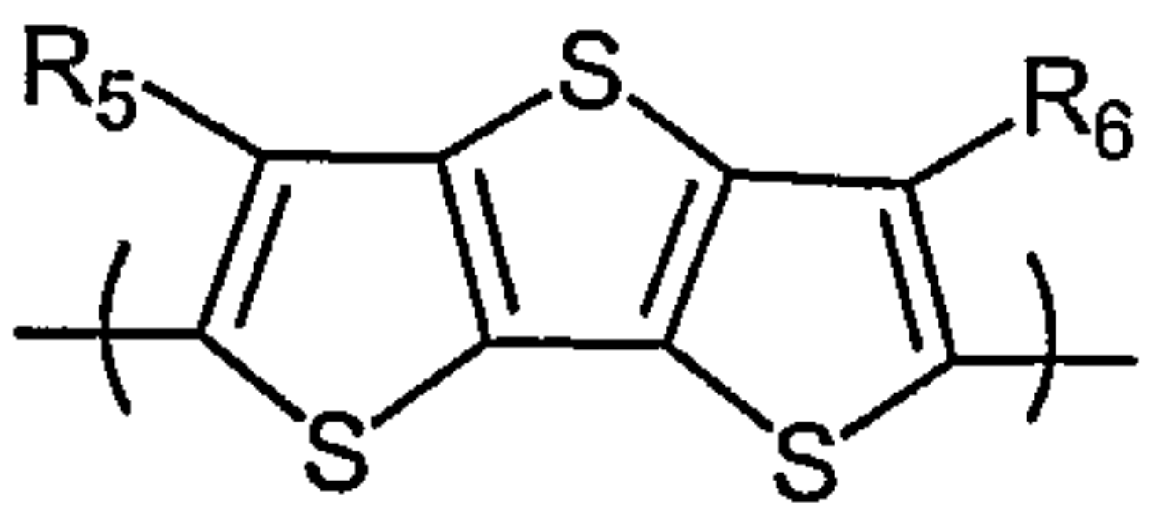
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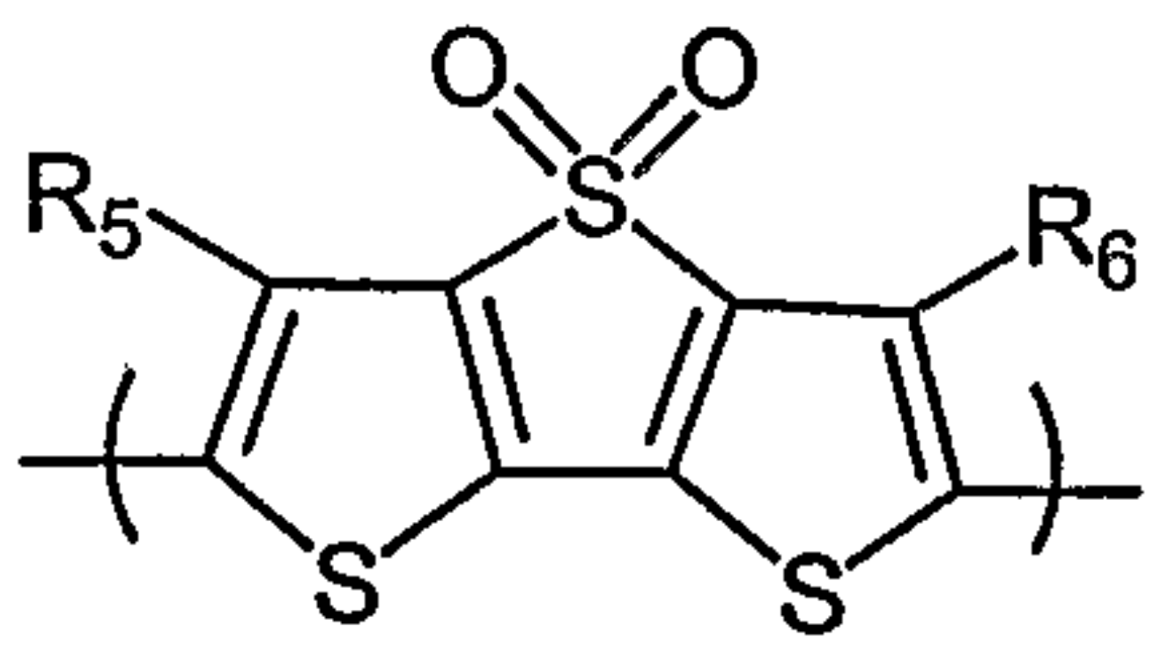
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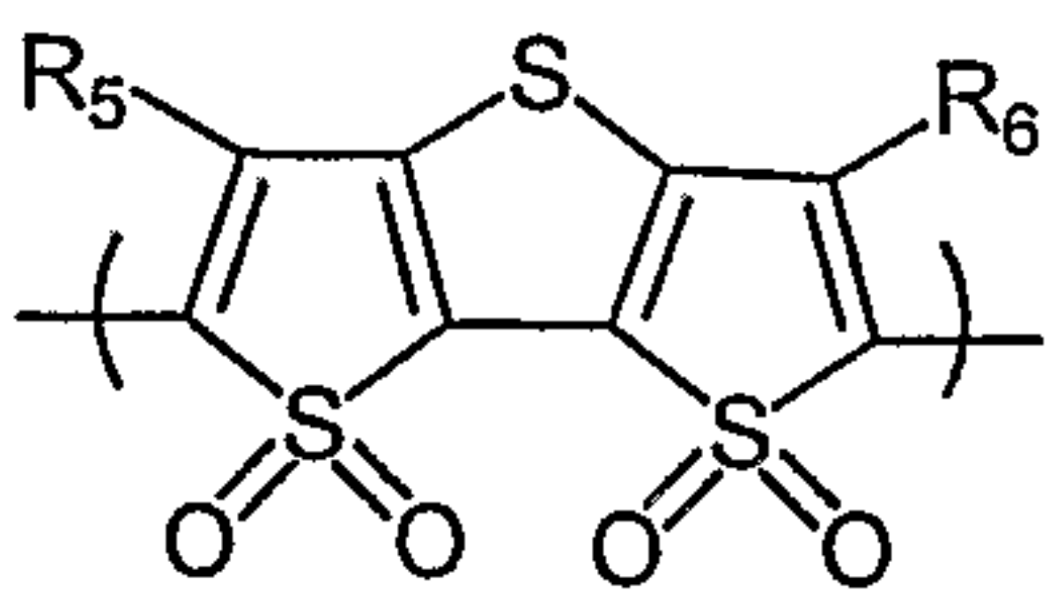
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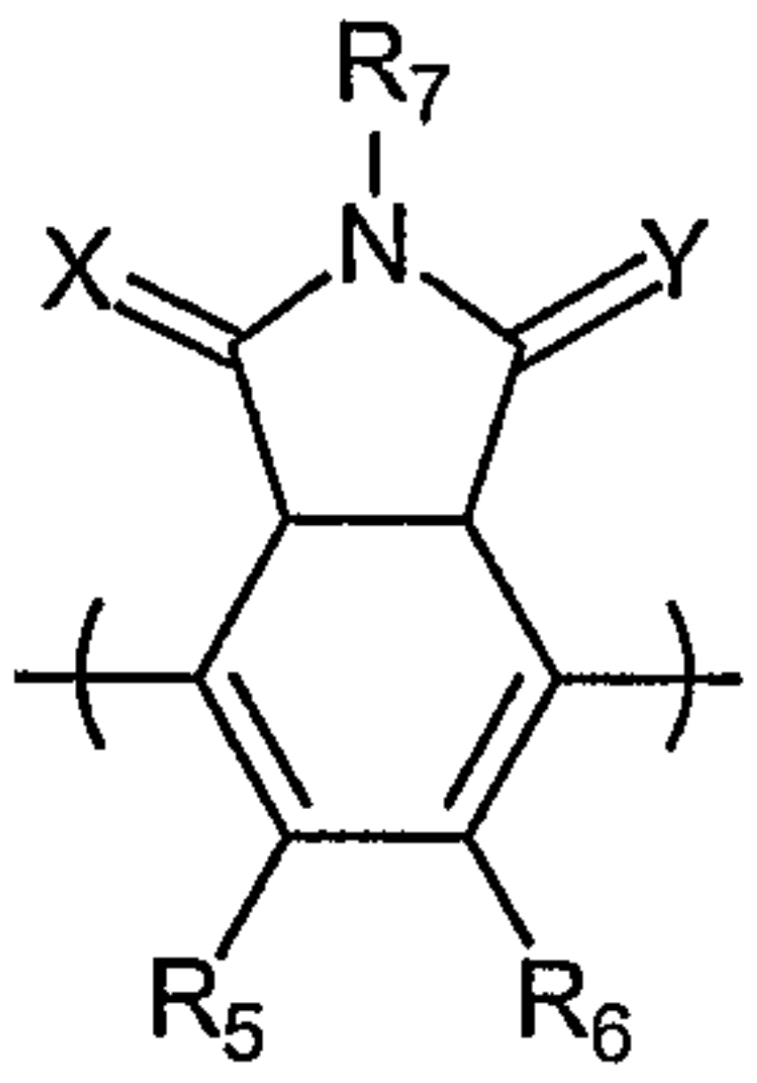
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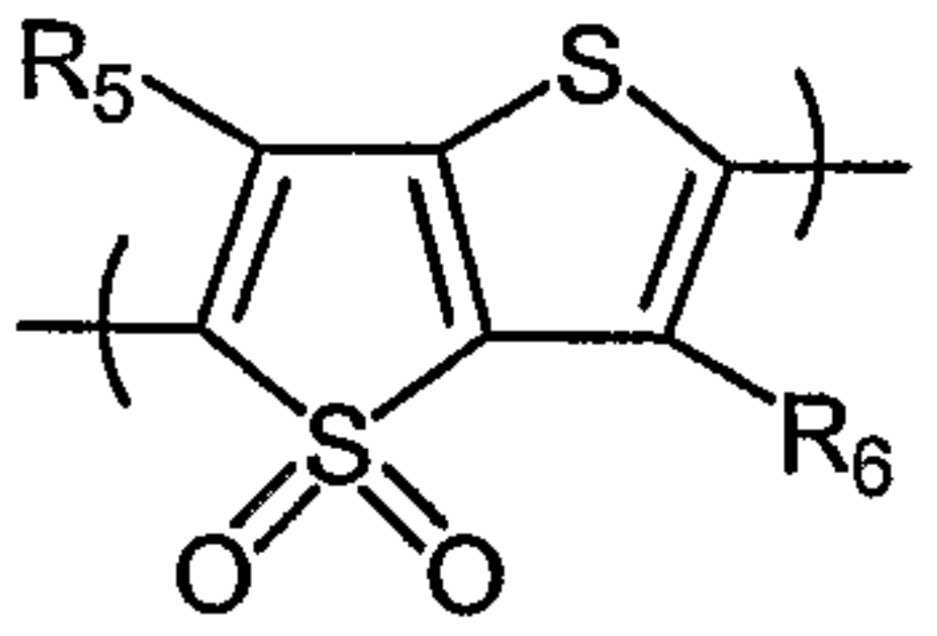
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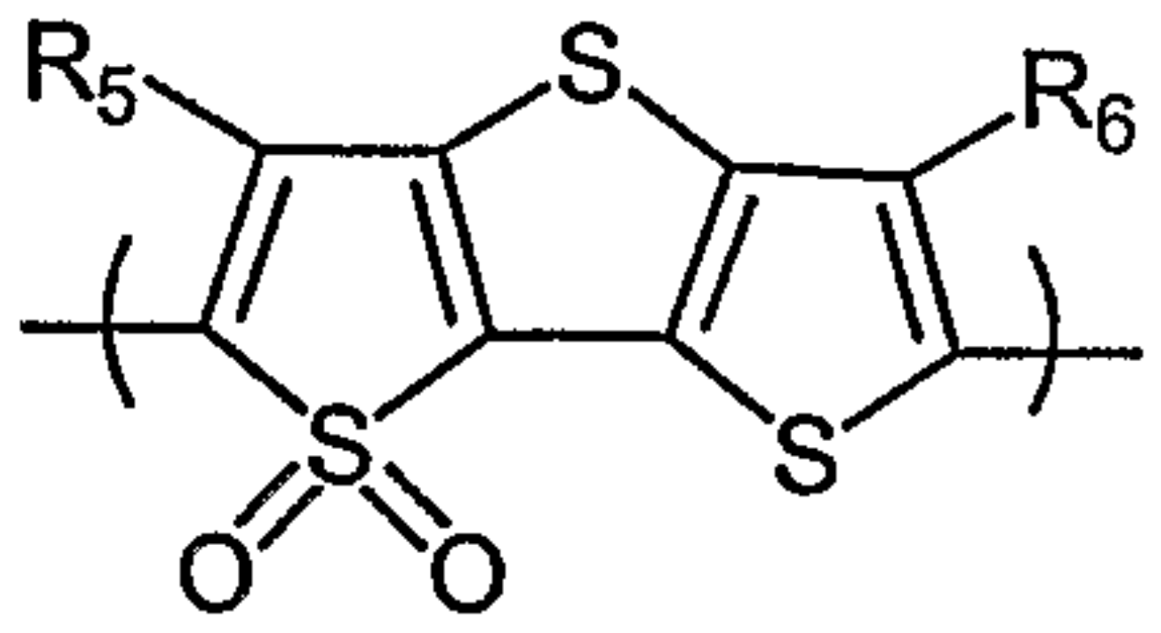
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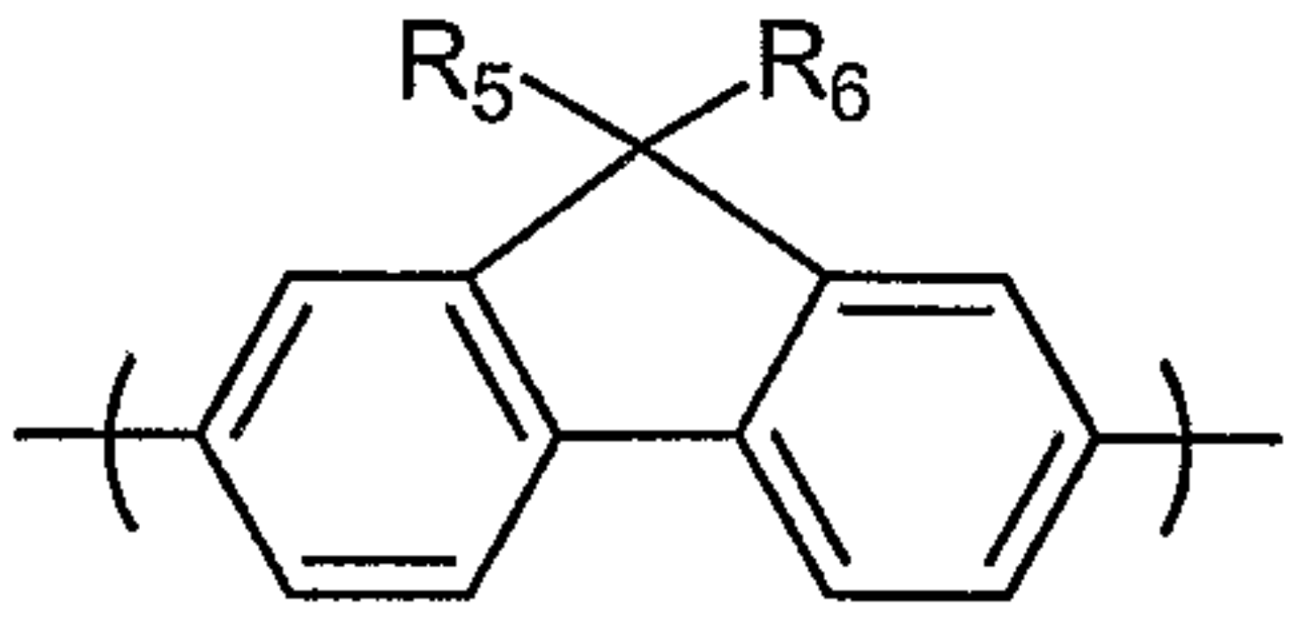
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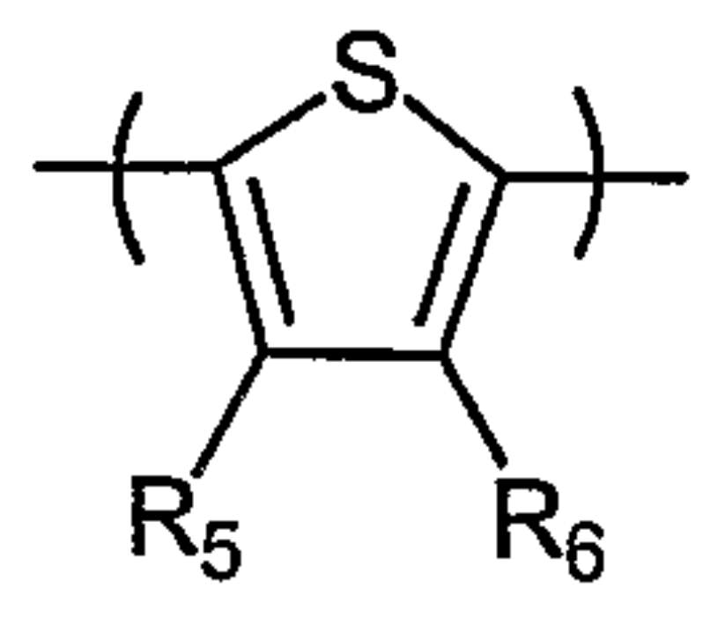
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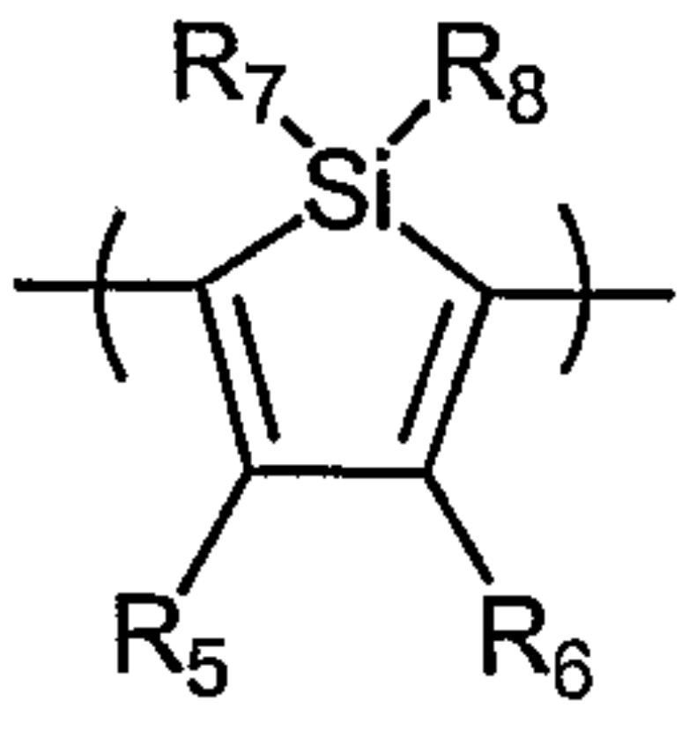

(XXI),

wherein each of R_1, R_2, R_3, R_4, R_5, R_6, R_7, and R_8, independently, is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, C_3-C_{20} heterocycloalkyl, halo, CN, NO_2, and SO_2R, in which R is H, C_1-C_{20} alkyl, C_1-C_{20} alkoxy, aryl, heteroaryl, C_3-C_{20} cycloalkyl, or C_3-C_{20} heterocycloalkyl.

82. A device, comprising:

a first electrode,

a second electrode, and

a photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first monomer repeat unit, wherein the first monomer repeat unit comprises a benzothiadiazole moiety, a thiophene oxide moiety, a cyclopentadithiophene oxide moiety, a thiadiazoloquinoxaline moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, or a tetrahydroisoindole moiety.

83. The device of claim 82, wherein the device is an organic semiconductive device.

84. The device of claim 82, wherein the device is a member selected from the group consisting of photovoltaic cells, field effect transistors, photodetectors, photovoltaic detectors, imaging devices, light emitting diodes, lasing devices, conversion layers, amplifiers, emitters, storage elements, and electrochromic devices.

85. The device of claim 82, wherein the polymer further comprising a second monomer repeat unit different from the first monomer repeat unit.

86. The device of claim 85, wherein the second monomer repeat unit a cyclopentadithiophene moiety, a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety.

87. A device, comprising:

a first electrode,

a second electrode, and

a photoactive material disposed between the first and second electrodes, the photoactive material comprising a polymer including a first monomer repeat unit, wherein the first monomer repeat unit comprises a cyclopentadithiophene moiety.

88. The device of claim 87, wherein the device is an organic semiconductive device.

89. The device of claim 87, wherein the device is a member selected from the group consisting of photovoltaic cells, field effect transistors, photodetectors,

photovoltaic detectors, imaging devices, light emitting diodes, lasing devices, conversion layers, amplifiers, emitters, storage elements, and electrochromic devices.

90. The device of claim 87, wherein the polymer further comprising a second monomer repeat unit different from the first monomer repeat unit.

91. The device of claim 90, wherein the second monomer repeat unit a cyclopentadithiophene moiety, a benzothiadiazole moiety, a thiadiazoloquinoxaline moiety, a cyclopentadithiophene oxide moiety, a benzoisothiazole moiety, a benzothiazole moiety, a thiophene oxide moiety, a thienothiophene moiety, a thienothiophene oxide moiety, a dithienothiophene moiety, a dithienothiophene oxide moiety, a tetrahydroisoindole moiety, a fluorene moiety, a thiophene moiety, or a silole moiety.

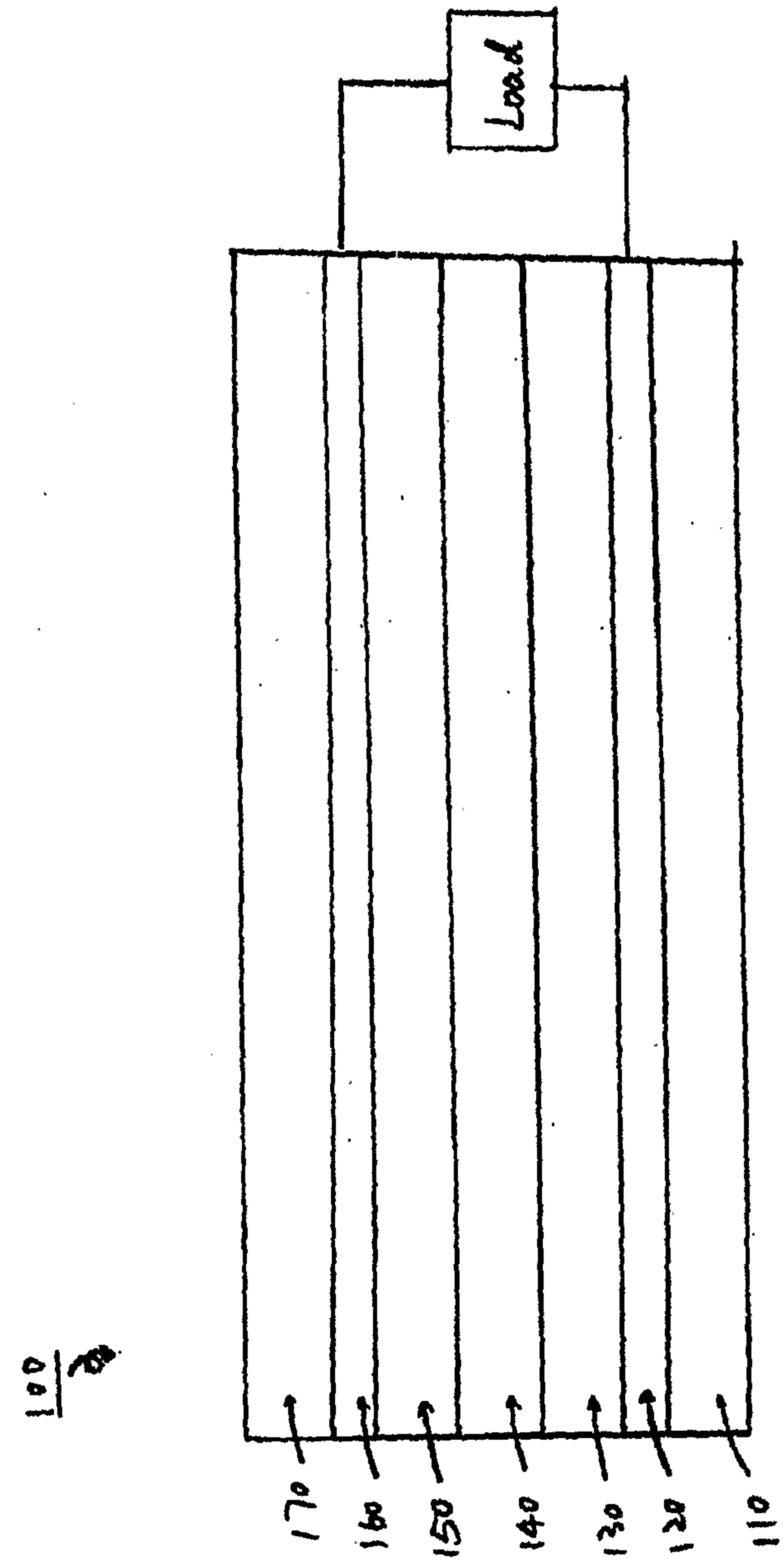
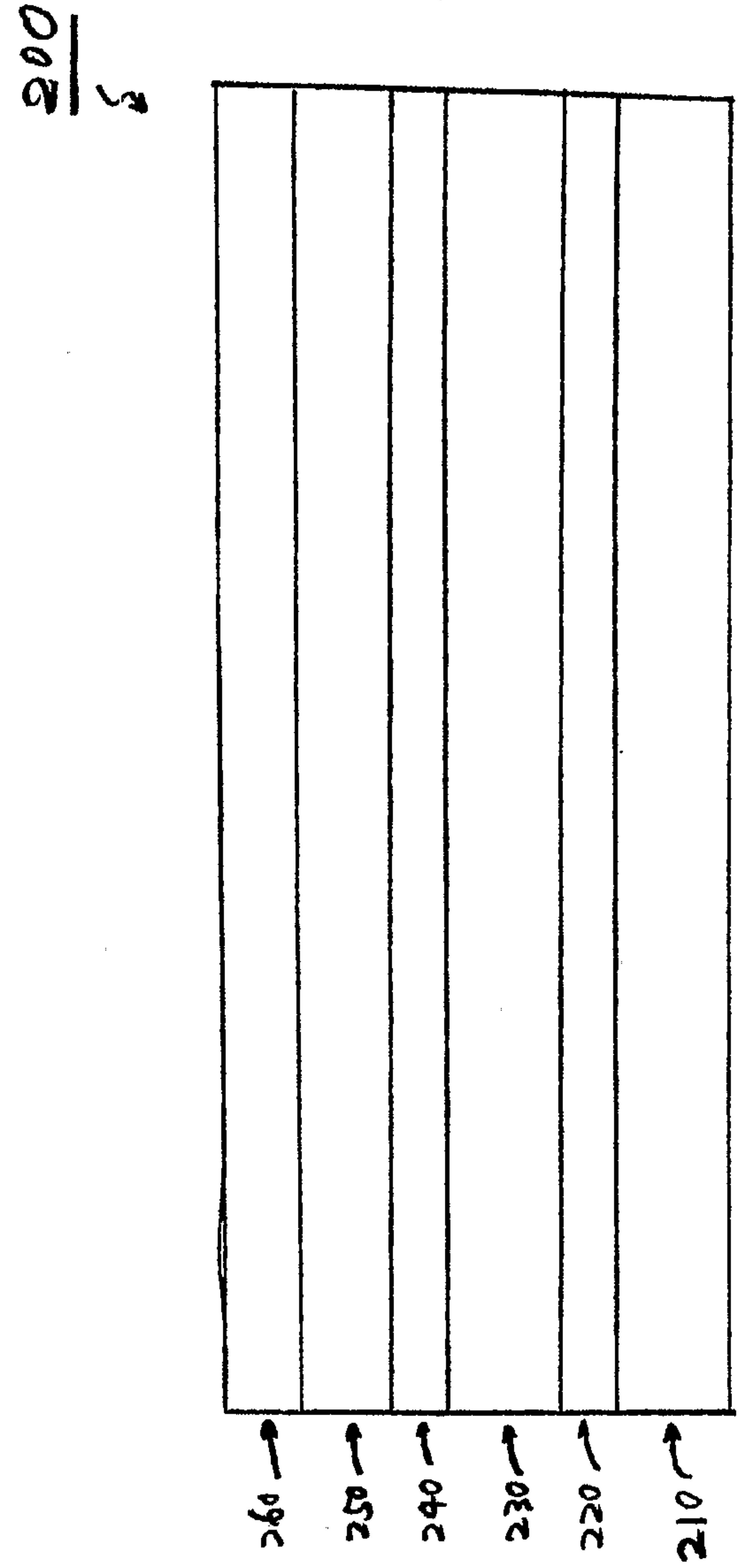


FIG. 1

Fig. 2

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