6-10-2008

Silylethynylated Heteroacenes and Electronic Devices Made Therewith

John E. Anthony
University of Kentucky, john.anthony@uky.edu

Marcia M. Payne
University of Kentucky, marcia.payne@uky.edu

Susan A. Odom
University of Kentucky, susan.odom@uky.edu

Sean Parkin
University of Kentucky, spark2@uky.edu

US007385221B1

(12) United States Patent
Anthony et al.

(10) Patent No.: US 7,385,221 B1
(45) Date of Patent: Jun. 10, 2008

(54) SILYLETHYNYLATED HETEROACENES AND ELECTRONIC DEVICES MADE THEREWITH

(75) Inventors: **John E. Anthony**, Lexington, KY (US); **Marcia M. Payne**, Lexington, KY (US); **Susan A. Odom**, Atlanta, GA (US); **Sean Richard Parkin**, Lexington, KY (US)

(73) Assignee: **University of Kentucky Research Foundation**, Lexington, KY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 195 days.

(21) Appl. No.: **11/075,144**

(22) Filed: **Mar. 8, 2005**

(51) **Int. Cl.**
C07D 327/00 (2006.01)
C07D 305/00 (2006.01)
C07F 7/02 (2006.01)

(52) **U.S. Cl.** **257/40**; 548/406; 549/4; 549/214; 257/E51.05; 257/E51.046

(58) **Field of Classification Search** 548/406; 549/4, 214; 257/40, E51.046, E51.047, E51.049, 257/E51.05; 438/99
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,936,259 A 8/1999 Katz et al.
6,184,540 B1 2/2001 Chmii et al.
6,509,110 B1 1/2003 Salbeck et al.
6,608,323 B2 8/2003 Marks et al.
6,626,566 B2 9/2003 Holmes et al.
6,690,029 B1 2/2004 Anthony et al.
6,806,374 B2 10/2004 Heeney et al.
6,818,260 B2 11/2004 Farrand et al.
2005/0277776 A1* 12/2005 Liu et al. 549/59
2006/0046092 A1* 3/2006 Towns et al. 428/690

FOREIGN PATENT DOCUMENTS

WO WO 2005055248 A2 * 6/2005

OTHER PUBLICATIONS

Sakamoto, Y., Suzuki, T., Kobayashi, M., Gao, Y., Fukau, Y., Inoue, Y., Sato, F. and Tokito, S. "Perfluoropentacene: High-Performance p-n Junctions and Complementary Circuits with Pentacene." J. AM. CHEM. SOC. vol. 126 (2004); pp. 8138-8140.*
Payne, Marcia M. et al., Organic field-effect transistors from solution-deposited functionalized acenes with mobilities as high as 1 cm2 / Vs; J. Am. Chem. Soc.; vol. 127 (2005) pp. 4986-4987.
Marcia M. Payne et al., Stable, Crystalline Acenedithiophenes with up to Seven Linearly-Fused Rings Organic Letters, vol. 6 (2004), pp. 3325-3328.
Laquindanum, Joyce G. et al., Synthesis, Morphology, and Field-Effect Mobility of Anthradithiophenes, J. Am. Chem. Soc. 1998, 120, pp. 664-672.
Kwon, O. et al., Characterization of the molecular parameters determining charge transport in anthradithiophene J. Chem. Phys., vol. 120, No. 17, May 1, 2004, 8186-8194.

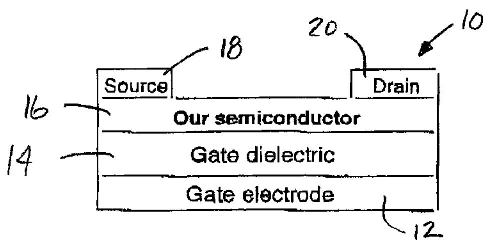
* cited by examiner

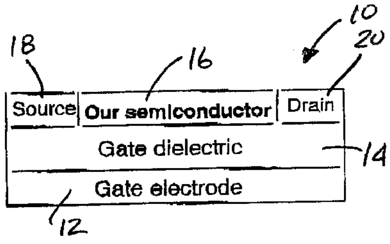
Primary Examiner—Bradley W. Baumeister
Assistant Examiner—Matthew W Such
(74) *Attorney, Agent, or Firm*—King & Schickli, PLLC

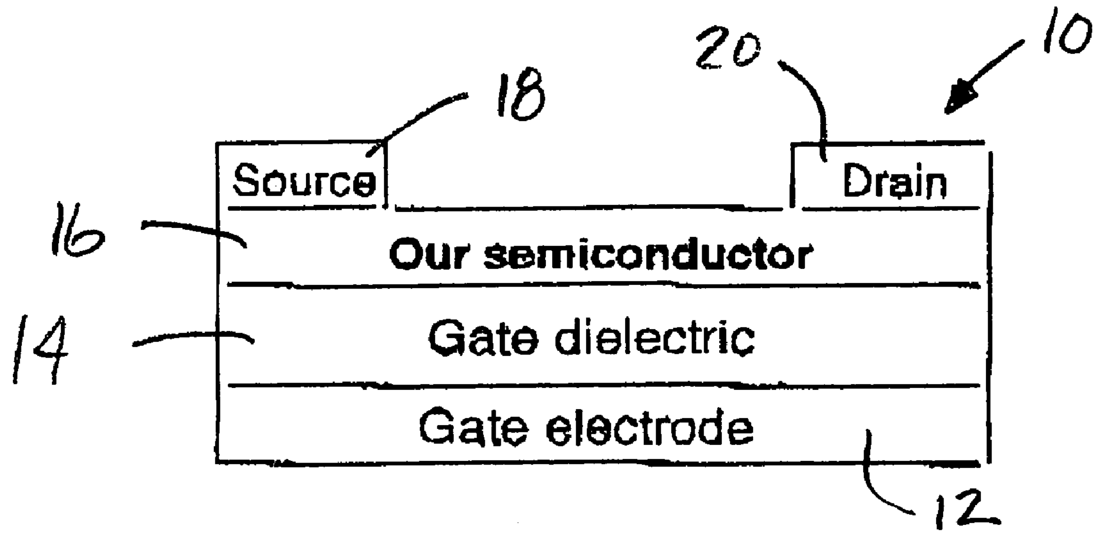
(57) **ABSTRACT**

Novel silylethynylated heteroacenes and electronic devices made with those compounds are disclosed.

14 Claims, 2 Drawing Sheets

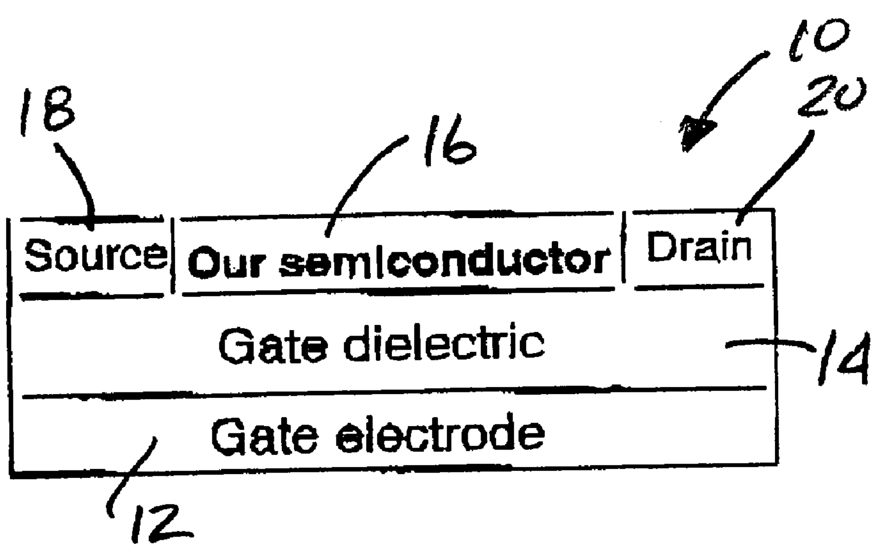






10
20
18
Source
Drain
16
Our semiconductor
14
Gate dielectric
Gate electrode
12

Fig. 1a



10
20
18
16
Source
Our semiconductor
Drain
Gate dielectric
14
Gate electrode
12

Fig. 1b

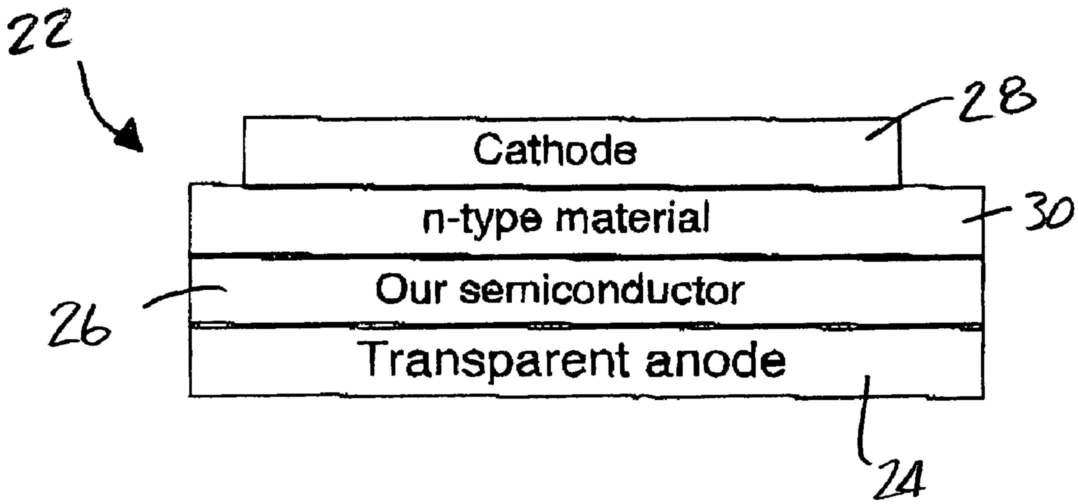

22
Cathode
28
n-type material
30
Our semiconductor
26
Transparent anode
24

Fig. 2a

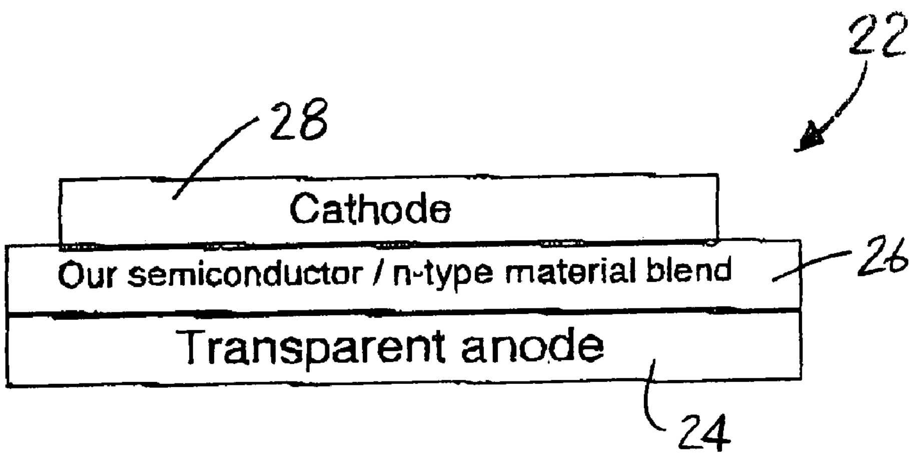

22
28
Cathode
Our semiconductor / n-type material blend
26
Transparent anode
24

Fig. 2b

SILYLETHYNYLATED HETEROACENES AND ELECTRONIC DEVICES MADE THEREWITH

This invention was made with support from the Office of Naval Research and by the Defense Advanced Research Projects Agency under Grant No. N00014-02-1-0033. The government may have certain rights in this invention.

TECHNICAL FIELD

The present invention relates generally to the field of organic semiconductors and, more particularly, to silylethynylated heteroacenes as well as to electronic devices made with these compounds.

BACKGROUND OF THE INVENTION

Display technology is expected to become a dominant sector of high-tech industry in the future. It is also expected that the flat panel display technology will be revolutionized by the use of organic semiconductors that will allow manufacture of cheap, flexible, lightweight, fully portable flat panel displays with no apparent limits to their size. It is predicted that due to the lower manufacturing cost, organic semiconductor based displays will eventually gain dominance over amorphous silicon based counterparts and the respective market share will grow to $1.6 billion by 2007. To realize these goals, however, significant breakthroughs will have to take place in the area of organic semiconductor material and device processing.

Interest in organic thin film transistors (OTFTs) for possible use in displays, sensors and other large area electronic applications has been increasing rapidly. Best reported organic thin film transistor (OTFT) device performance rivals or exceeds that of hydrogenated amorphous silicon devices, and low OTFT process temperatures allow fabrication on a range of surfaces including cloth, paper or lower temperature polymeric substrates.

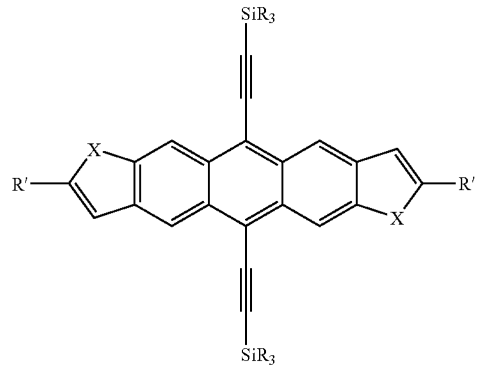
Organic semiconductors for use in OTFTs can be broadly divided into two groups as high and low mobility materials. High mobility materials have mobility >0.1 cm^2/V-s, usefully large carrier energy bandwidth (>0.1 eV) and weak or sometimes absent temperature activation of mobility. To date, most high mobility organic semiconductors have been small molecule materials (with pentacene the most notable example) and most have been deposited by vacuum sublimation or from a solution precursor with a high-temperature (>150° C.) conversion step. Low mobility materials have mobility from about 10^{-5}-10^{-1} cm^2/V-s, typically transport carriers by hopping, and have strong temperature activation of mobility. Most polymeric organic semiconductors fall into this group and many have the potential advantage that they can be deposited from solution.

To date, there have been few reports of low-temperature solution processed organic semiconductors with high mobility. In addition, even for low mobility materials, current solution deposition techniques have not demonstrated material structure, thickness and property control comparable to vacuum deposition techniques. The present invention relates to new organic semiconductor compounds with relatively low OTFT process temperatures and relatively high mobility.

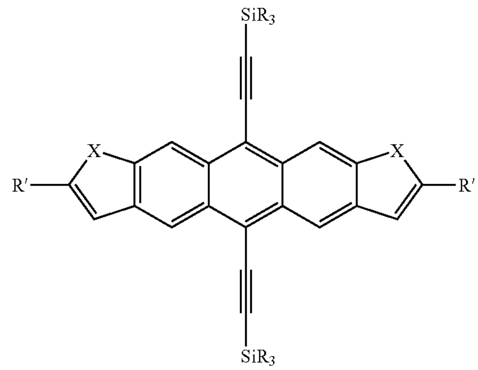
SUMMARY OF THE INVENTION

The present invention relates to novel silylethynylated heteroacenes (anthra(diheterocycles), tetra(diheterocycles) and penta(diheterocycles) compounds) as well as to transistors and photovoltaic apparatus made from those compounds. The novel compounds comprise the following formula:

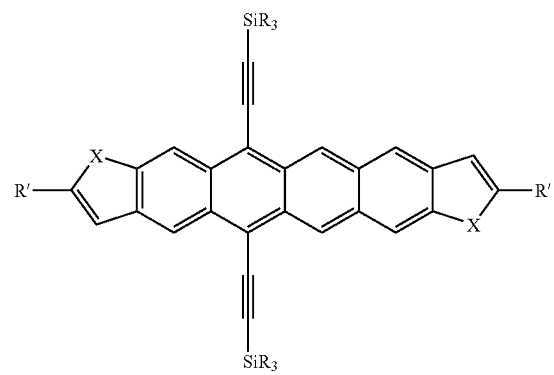
(A1)



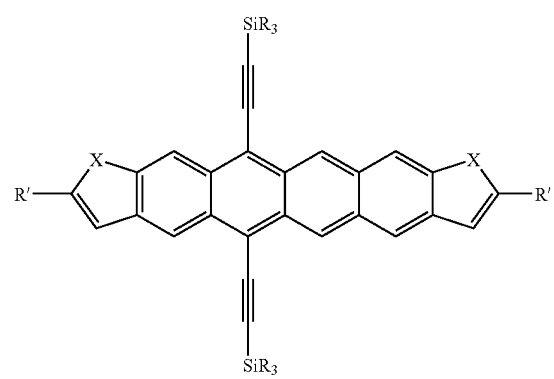
(A2)



(B1)

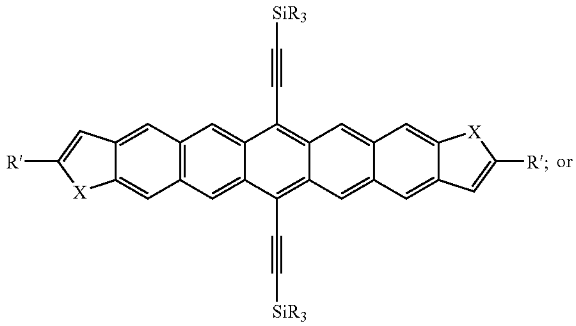


(B2)

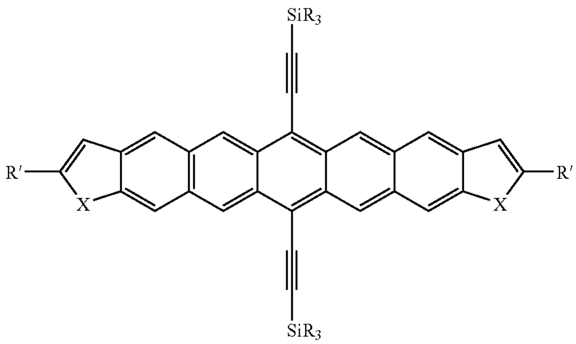


-continued

(C1)



(C2)



wherein R=an alkyl having C_1-C_8, perfluoroalkyl having C_1-C_8, aryl, alkoxy or trialkylsilyl, R^1=hydrogen, alkyl having C_1-C_8, aryl, perfluoroalkyl having C_1-C_8, alkoxy, halogen and x=—O, —S, —Se or —NH.

In accordance with yet another aspect of the present invention a transistor is constructed from the novel compounds of the present invention. The transistor comprises a gate electrode, a semiconductor constructed from the novel compound of the present invention, an insulator between the gate electrode and the semiconductor, a source electrode and a drain electrode.

In accordance with yet another aspect of the present invention, a photovoltaic apparatus is provided. That photovoltaic apparatus comprises a transparent anode, a semiconductor constructed from a novel compound of the present invention, an n-type material and a cathode.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The accompanying drawing incorporated in and forming a part of the specification, illustrates several aspects of the present invention and together with the description serves to explain certain principles of the invention. In the drawing:

FIGS. **1***a* and **1***b* are schematical illustrations of two possible embodiments for the field-effect transistor of the present invention; and

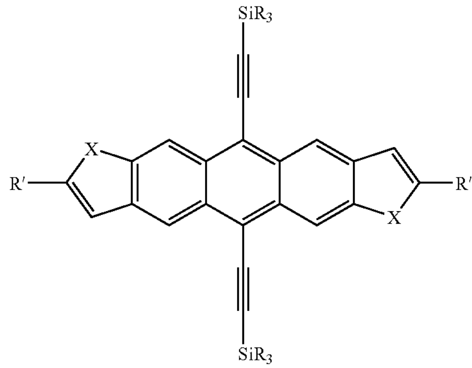
FIGS. **2***a* and **2***b* are schematical representations illustrating two possible embodiments of the photovoltaic apparatus of the present invention.

Reference will now be made in detail to the present preferred embodiments of the invention as illustrated in the accompanying drawing figures.

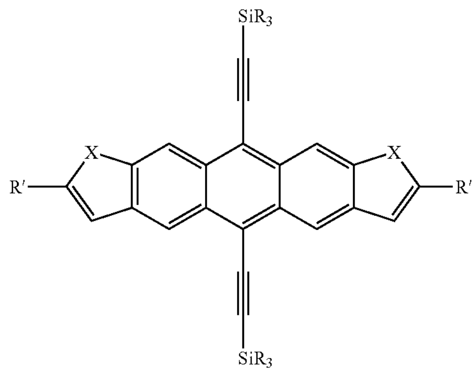
DETAILED DESCRIPTION OF THE INVENTION

The novel compounds of the present invention may be broadly described as silylethynylated heteroacenes. The compounds have the following structural formulae:

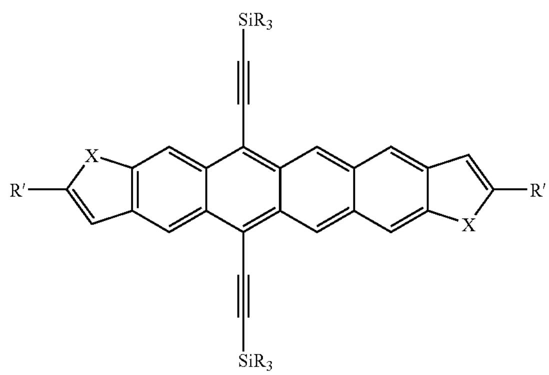
(A1)



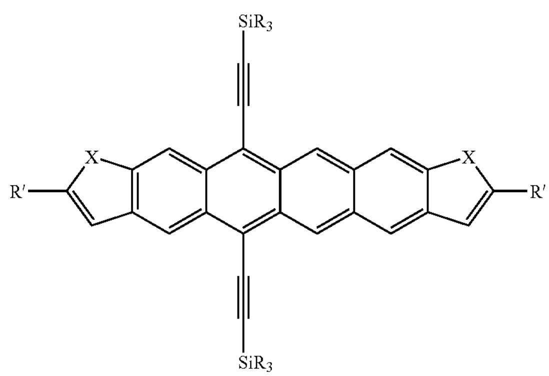
(A2)



(B1)

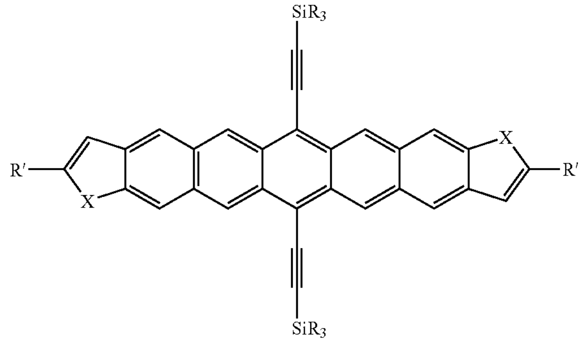


(B2)

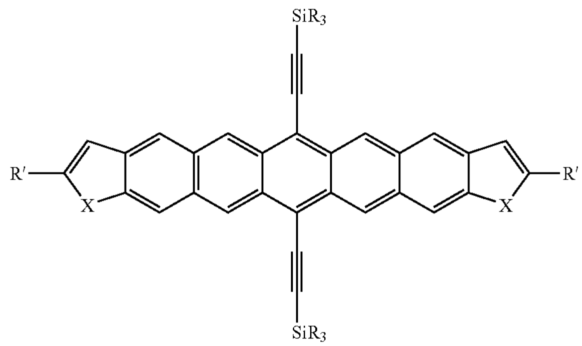


-continued

(C$_1$)



(C$_2$)

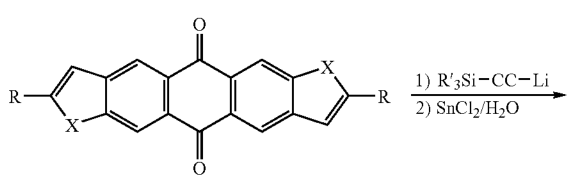


The silylethynylated heteroacenes are prepared as a mixture of isomers.

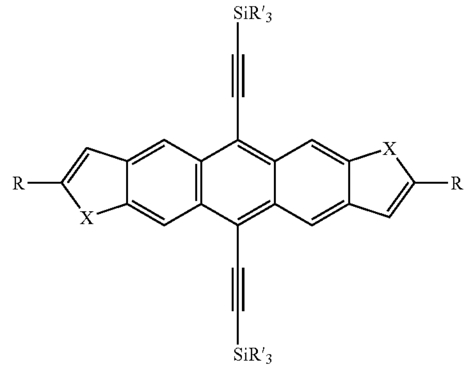
Formulae A_1 and A_2 represent the two isomers of anthra (diheterocylces). Formulae B_1 and B_2 represent the two isomers of tetra (diheterocyles). Formulae C_1 and C_2 represent the two isomers of penta (diheterocyles). The novel compounds of the present invention include both the mixture of the isomers of Formulae A_1, A_2; B_1, B_2; or C_1, C_2 and the pure isomers A_1, A_2, B_1, B_2, C_1, or C_2.

The isomers A_1, A_2, B_1, B_2, C_1, or C_2 may be purified from the mixture of isomers of Formulae A_1, A_2; B_1, B_2; or C_1, C_2 by methods known to those skilled in the art including but not limited to high-performance liquid chromatography (HPLC).

The novel compounds of the present invention are prepared by a relatively simple and straightforward method. Specifically, the silylethynylated heteroacenes are easily made by the addition of an alkynyllithium to the corresponding acenequinone, followed by reductive workup with either HI or tin (II) chloride:



-continued



This type of reaction is well-described in:

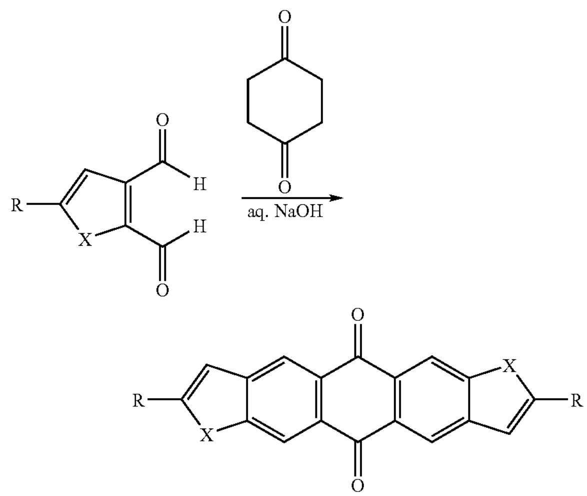
Miller, G. P.; Mack, J.; Briggs, J. *Org. Lett.* 2000, 2, 3983.

Anthony, J. E.; Eaton, D. L.; Parkin, S. R. *Org. Lett.* 2002, 4, 15.

Anthony, J. E.; Brooks, J. S.; Eaton, D. L.; Parkin, S. *J. Am. Chem. Soc.* 2001, 123, 9482.

Payne, M. M.; Odom, S. A.; Parkin, S. R.; Anthony, J. E. *Org. Lett.* 2004 6, 3325.

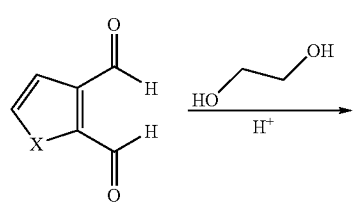
The acenequinone is very easily prepared by a 4-fold aldol condensation between a dialdehyde and commercially-available 1,4-cyclohexanedione:



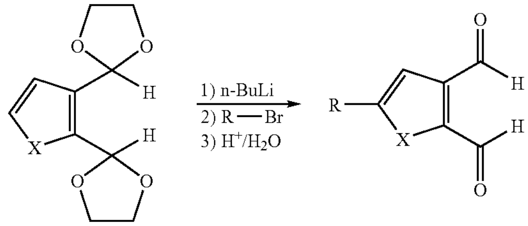
This condensation is well-described in:

De la Cruz, P.; Martin, N.; Miguel, F.; Seoane, C.; Albert, A.; Cano, H.; Gonzalez, A.; Pingarron, J. M. *J. Org. Chem.* 1992, 57, 6192.

The "R" group of these dialdehydes is typically installed by the following sequence:



-continued



This procedure is described for thiophene dialdehyde in detail in:

Laquindanum, J. G.; Katz, H. E.; Lovinger, A. J. *J. Am. Chem. Soc.* 1998, 120, 664.

Thus the “base unit” for all of these materials is the heterocyclic dialdehyde. Many of these are known in the literature, and some are even commercially available:

Thiophene 2,3-dialdehyde: Commercially available from Aldrich and Acros chemical

Furan 2,3-dialdehyde: Prepared as in Zaluski, M. C.; Robba, M.; Bonhomme, M. *Bull. Chim. Soc. Fr.* 1970, 4, 1445.

Selenophene 2,3-dialdehyde: Prepared as in Paulmier, C.; Morel, J.; Pastour, P.; Semard, D. *Bull. Chim. Soc. Fr.* 1969, 7, 2511.

Thiazole dialdehyde: Prepared as in Robba, M.; Le Guen, Y. *Bull Chim. Soc. Fr.* 1969, 11, 4026.

Imidazole dialdehyde: Prepared as in Kolks, G.; Frihart, C. R.; Coughlin, P. K.; Lippard, S. J. *Inorg. Chem.* 1981, 20, 2933

Other heterocyclic dialdehydes can be prepared by the same methods outlined for the synthesis of the furan and selenophene compounds.

The following synthesis and examples are prepared to further illustrate the invention, but it is not to be considered as limited thereto.

EXAMPLE 1

5,11-Bis(triethylsilylethynyl)anthra [2,3-b:6,7-b'] dithiophene and 5,11-Bis(triethylsilylethynyl)anthra [2,3-b:7,6-b'] dithiophene. To an oven-dried 250-mL round-bottom flask equipped with a stir bar and cooled under N_2 was added hexanes (20 mL) and 0.38 mL of triethylsilyl acetylene (2.0 mmol), followed by the dropwise addition of 0.73 mL of n-BuLi (1.8 mmol, 2.46 M solution in hexanes). This mixture was stirred for 1 h, then hexanes (80 mL) and anthradithiophenequinone (prepared by method described in De la Cruz, P. et al. *J. Org. Chem.* 1992, 57, 6192.) (0.16 g, 0.34 mmol) were added. The mixture was heated at 60° C. overnight, then quenched with 0.5 mL of water. $SnCl_2.2H_2O$ (0.50 g, 2.2 mmol) in 10% aq. HCl (1 mL) was added and the mixture was stirred for 2 h at 60° C. The solution was dried over $MgSO_4$, then loaded onto a thick pad of silica. The silica was rinsed with hexanes (500 mL), then the product was eluted using hexanes:DCM (5:1). Removal of solvent yielded 0.18 g (0.31 mmol, 91%) of a reddish powder. Recrystallization from hexanes yielded thick dark-red plates. Recrystallized **3**× from hexanes. Yield: 91%. MP: 151° C. ^{1}H-NMR (400 MHz, $CDCl_3$) δ=9.18 (s, 2H), 9.13 (s, 2H), 7.57 (d, J=5.6 Hz, 2H, syn isomer), 7.57 (d, J=5.2 Hz, 2H, anti isomer), 7.47 (d, J=5.6 Hz, 2H), 1.27 (tt, J=8.0 Hz, 1.6 Hz, 18H), 0.94 (q, J=8.0 Hz, 12H). ^{13}C-NMR (400 MHz, $CDCl_3$) δ=140.27, 140.18, 139.82, 139.68, 133.70, 130.11 (2C), 130.01 (2C), 129.92 (2C), 129.81, 129.17, 123.95, 121.50, 121.44, 120.20, 118.05, 117.69, 8.04 (2C), 7.82, 4.93 (2C), 4.50. Anal. calcd % C: 72.02, % H: 6.75. Found % C: 71.68, % H: 6.75.

For preparation of systems with alternative “R” groups, a different acetylene would be substituted for triethylsilyl acetylene in the above preparation. For preparation of systems where “R'” is different from “H” the requisite precursor quinones can be prepared as in (Laquindanum, J. G. et al., *J. Am. Chem. Soc.* 1998, 120, 664.)

EXAMPLE 2

Tetra[2,3-b:8,9-b'] dithiophene-5,13-dione and Tetra[2,3-b:9,8-b']dithiophene-5,13-dione. A 1:2 mixture of 2,3-thiophenedicarboxaldehyde (0.85 g, 6.07 mmol) and benzo [1,2-b]thiophene-4,5-dicarboxaldehyde (1.66 g, 8.70 mmol) was dissolved in THF (200 mL) in a 500-mL round-bottom flask with a stir bar, then 1,4-cyclohexanedione (0.83 g, 7.40 mmol) was added and the solution was stirred until uniform. After the addition of 15% KOH (2 mL), precipitate began to form immediately, and vigorous stirring was continued overnight. The solution was filtered to yield 3.87 g of a light brown powder made up of insoluble quinones which were used directly in the next step: MS (70 eV, EI) m/z 370 (100%, M+).

5,13-Bis(tris(trimethylsilyl)silylethynyl)tetra [2,3-b:8,9-b'] dithiophene and 5,13-Bis(tris(trimethylsilyl)silylethynyl) tetra[2,3-b:9,8-b']dithiophene. To an oven-dried 500-mL round-bottom flask cooled under N_2 and equipped with a stir bar was added hexanes (150 mL) and tris((trimethylsilyl) silyl acetylene (14 g, 51.1 mmol). n-BuLi.(19.5 mL, 47,9 mmol, 2.6 M in hexanes) was added dropwise and the mixture was stirred for 2 hr. The above quinone mixture (3.87 g) was added and stirring was continued overnight, followed by the addition of anhydrous THF (20 mL) and additional stirring for 2 d. Water (2 mL) and a solution of $SnCl_2.H_2O$ (10.0 g, 44 mmol) in 10% HCl (20 mL) was added and the solution was stirred for 2 hr. DCM (100 mL) was then added and the organic layer was separated, dried over $MgSO_4$, and rinsed through a thin pad of silica (DCM). Solvent was concentrated to a volume of 10 mL, then diluted with hexanes (200 mL), and rinsed onto a thick pad of silica. The silica was rinsed with hexanes (600 mL), then hexanes: DCM (1:1) to elute the product mixture, and solvent was removed from this second fraction. Using column chromatography (hexanes:ethyl acetate (9:1)), 0.82 g of the desired tetradithiophene were isolated. The tetradithiophene was recrystallized from acetone to yield dark-blue needles. ^{1}H-NMR (400 MHz, $CDCl_3$) δ=9.53 (s, 1H), 9.45 (s, 1H), 9.16 (s, 1H), 9.13 (s, 1H), 8.53 (s, 1H), 8.49 (s, 1H), 7.54 (d, J=5.6 Hz, 1H), 7.50 (d, J=6.2 Hz, 1H), 7.41 (s, 1H), 7.40 (s, 1H), 1.08 (s, 54H). ^{13}C-NMR (400 MHz, $CDCl^3$) δ=140.49, 140.46, 140.20, 140.19, 139.92, 139.86, 138.98, 138.90, 130.27, 129.74, 129.61, 126.84, 125.35, 124.02, 123.72, 122.34, 122.29, 121.64, 121.04, 120.99, 120.29, 107.05, 106.72, 105.64, 104.85, 104.76, 11.5. UV-VIS (DCM): λ_{abs} (ε): 244 (18700), 300 (32400), 328 (61800), 372 (6940), 392 (5610), 465 (2110),528 (766), 555 (1340), 599 (2810), 653 (4960). IR (KBr) υ_{max} (cm^{-1}): 2956 (m), 2945 (m), 2860 (s), 2129 (m), 1460 (m), 1400 (m), 1366 (s), 1061 (m), 997 (w), 882 (s), 752 (s), 720 (vs), 661 (s), 586 (m).

EXAMPLE 3

Penta[2,3-b:9,10-b']dithiophene-6,14-dione and Penta[2,3-b:10,9-b']dithiophene-6,14-dione. In a 500-mL round-bottom flask equipped with a stir bar, benzo[1,2-b]thiophene-4,5-dicarboxaldehyde (2.35 g, 12.4 mmol) was dissolved in THF (200 mL). 1,4-Cyclohexanedione (0.70 g, 6.2 mmol) was added and stirred until the solution was uniform, then 15% KOH (2 mL) was added. Vigorous stirring was continued overnight, then the solution was filtered and rinsed with ether (20 mL) and DCM (20 mL). The brown solid was heated to reflux in DMF (400 mL) for 2 hr, then cooled and filtered to yield 1.6 g (3.8 mmol) of the desired quinone as a light brown insoluble powder. MS (70 eV, EI) m/z 420 (42%, M^+).

6,14-Bis(tri(t-butyl)silylethynyl)-penta [2,3-b:9,10-b'] dithiophene and 6,14-Bis(tri(t-butyl)silylethynyl)-penta [2,3-b:10,9-b']dithiophene (*6b*). To an oven-dried 250-mL round-bottom flask equipped with a stir bar and cooled under N_2 was added anhydrous THF (40 mL) and tri(t-butyl) silyl acetylene (3.59 g, 16.0 mmol). n-BuLi (5.7 mL, 14 mmol, 2.6 M in hexanes) was added dropwise and the solution was stirred for 1 hr, then the abovementioned quinone (1.6 g, 3.8 mmol) was added. After stirring for 24 hr, additional anhydrous THF (40 mL) was added and stirring was continued for 3 days. Water (2 mL) and a solution of $SnCl_2.H_2O$ (1.0 g, 4.4 mmol) in 10% HCl (2 mL) was added and the solution was stirred for 2 hr. DCM (200 mL) was added and the organic layer was separated, dried over $MgSO_4$, and rinsed through a thin pad of silica (DCM). Solvent was concentrated to a volume of 10 mL then diluted with hexanes (200 mL). This solution was poured onto a thick pad of silica and rinsed with hexanes (500 mL), then hexanes:DCM (1:1) to elute the product. Removal of solvent yielded 0.44 g (0.53 mmol, 14%) of product as a sparingly-soluble green powder. Recrystallization from toluene, then from CS_2 yielded 6b as slender dark green needles. ^1H-NMR (400 MHz, $CDCl_3$) δ=9.49 (s, 2H), 9.41 (s, 2H), 8.41 (s, 2H), 8.38 (s, 2H), 7.46 (d, J=5.6 Hz, 2H), 7.36 (s, J=5.6 Hz, 2H), 1.50 (s, 54H). ^{13}C-NMR (400 MHz, CS^2/C_6D_6) δ=140.52, 138.91, 130.98, 130.86, 130.67, 130.55, 129.57, 128.92, 128.88, 128.78, 128.75, 128.26, 127.96, 127.94, 127.59, 126.11, 124.08, 122.94, 121.61, 109.10, 106.70, 97.94, 31.12, 30.81, 28.89, 22.73. UV-VIS (DCM): λ_{abs} (ε): 277 (42500), 342 (69500), 373 (6350), 398 (2770), 416 (2740), 441 (2220), 475 (1730), 577 (145), 623 (474), 690 (1170), 762 (2600). IR (KBr) υ_{max} (cm^{-1}): (cmol): 3400 (w), 2972 (m), 2935 (m), 2859 (5), 2133 (5), 1648 (w), 1385 (s), 1115 (m), 1032 (w), 890 (s), 820 (s), 748 (s), 619 (s). Anal calcd for $C_{54}H_{66}S_2Si_2.H_2O$ % C: 75.99, % H: 8.03. Found % C: 75.61, % H: 7.93. MS (70 eV, EI) m/z 834 (100%, M^+), 777 (63%, M^+-C_4H_9). MP: 268° C. (dec.).

The compounds of the present invention demonstrate remarkable physical and electronic properties. The silyl acetylene unit substituted on the inner aromatic ring serves two important purposes. First it lends solubility to the molecule, allowing processing by simple, solution-based methods. Secondly and perhaps more importantly, this functional group causes the molecules to self-assemble into π-stacked arrays that are critical to improved device performance. More specifically, this molecular arrangement leads to improved conductivity, reduced band gap and field effect transistors (FETs) devices with a hole mobility of 0.001 to 1.0 cm^2/Vs.

A number of useful electronic devices may be constructed from the novel compounds of the present invention. As illustrated in FIG. **1***a* a field effect transistor (FET) **10** is comprised of a gate electrode **12** of a type known in the art, an insulator or gate dielectric **14** also of a type known in the art and a semiconductor **16** in the form of a thin layer or film of the compounds of the present invention. In addition, the FET **10** includes a conductive source electrode **18** and a drain electrode **20** both operatively connected to the semiconductor **16**.

The insulator **14** may, for example, be a dielectric or metal oxide or even an insulating polymer like poly(methylmethacrylate). The conducting source and drain electrodes **18**, **20** may be metals known in the art to be useful as electrodes, heavily doped semiconductors such as silicon or even a conducting polymer.

The FET illustrated in FIG. **1***a* is known as a top-contact configuration. An alternative embodiment of the FET **10** of the present invention is illustrated in FIG. **1***b*. This configuration is known as a bottom-contact configuration. The gate electrode **12**, source electrode **18** and drain electrode **20** may again be any sort of conductor: gold, silver, aluminum, platinum, heavily-doped silicon or an organic conducting polymer. The insulator or gate dielectric **14** can be an oxide such as aluminum oxide or silicone oxide or an insulating polymer such as poly(methylmethacrylate). In either configuration the compound of the present invention may be applied either by solution or vapor methods to form the semiconductor **16**.

EXAMPLE 4

The substrate for the field-effect transistors consisted of a heavily-doped Si wafer with thermally grown oxide layer (370 nm), serving as gate electrode and dielectric. Gold source and drain contacts were evaporated to yield devices with channel length of 22 μm and channel width of 340 μm. The gold electrodes were then treated with pentafluorobenzenethiol to improve the electrode interface. A 1-2 wt % solution of the triethylsilyl anthradithiophene derivative of Example 1 in toluene was spread across the device surface using a plastic blade, and the solvent allowed to evaporate. The devices were then heated in air at 90° C. for two minutes to drive off residual solvent.

The triethylsilyl anthradithiophene derivative of Example 1 formed a uniform film of excellent quality yielding hole mobility of 1.0 cm^2/Vs with excellent on/off current ratio (10^7). The performance of this material is likely due to the close π-stacked interactions in the crystal. The triethylsilyl anthradithiophene derivative adopts a 2-D π-stacking arrangement with a π-face separation of approximately 3.25 Å. The triethylsilyl anthradithiophene derivative was also characterized by a π-overlap of 1.57 $Å^2$ and a lateral slip of 2.75, 1.76 Å. All measurements were performed in air at room temperature and the mobility was calculated from the saturation currents.

A photovoltaic apparatus **22** is illustrated in FIG. **2***a*. The photovoltaic apparatus **22** comprises a transparent conductive electrode or anode **24**, a semiconductor **26** in the form of a thin layer or film of the compound of the present invention and a bottom electrode or cathode **28**.

In the photovoltaic apparatus embodiment illustrated in FIG. **2***a*, a layer **30** of n-type material is provided between the semiconductor **26** and the cathode **28**. In the photovoltaic apparatus **22** illustrated in FIG. **2***b* the semiconductor **26** comprises the compound of the present invention blended with an n-type material.

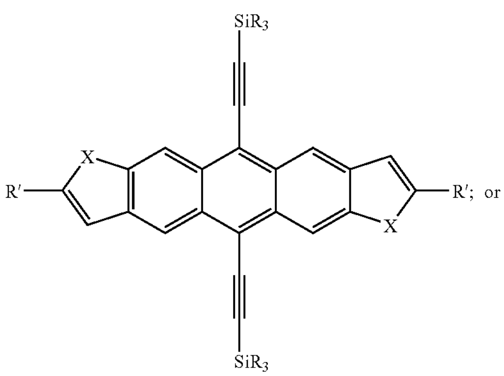
In the case of organic solar cells, the compounds of the present invention are typically used as the hole transporter (the "p-type" material). This material must be used in conjunction with an n-type material, defined as any electron-accepting compound (examples: C60 or solubilized derivatives PTCBI, other perylene diimides).

The photovoltaic apparatus **22** can typically be constructed in the two ways illustrated in FIGS. **2***a* and **2***b*. As illustrated in FIG. **2***a*, the p-type compound and the n-type compound are both deposited from vapor or solution in sequential steps, leading to a single heterojunction interface. Alternatively, as illustrated in FIG. **2***b*, the p-type material and the n-type material may be mixed and deposited from solution on the anode prior to deposition of the cathode material. In this embodiment the p-type and n-type materials phase segregate, leading to multiple heterojunctions in the bulk. In both cases the anode material typically has a high work function and is transparent (ITO or 10 oxide on glass or plastic). In contrast, the cathode **28** is a low work function conductor, and is typically reflective to improve efficiency (aluminum, silver or an indium-gallium eutectic). In either case the anode layer can be pre-coated with a commercial conducting polymer PEDOT in order to improve charge injection efficiency.

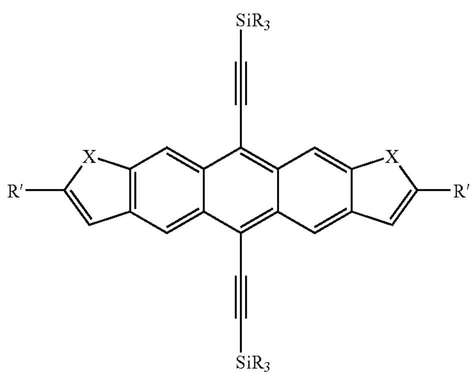
What is claimed is:

1. A compound of the formula:

(A_1)



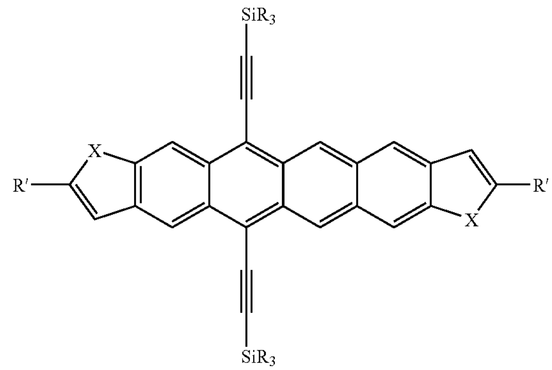
(A_2)



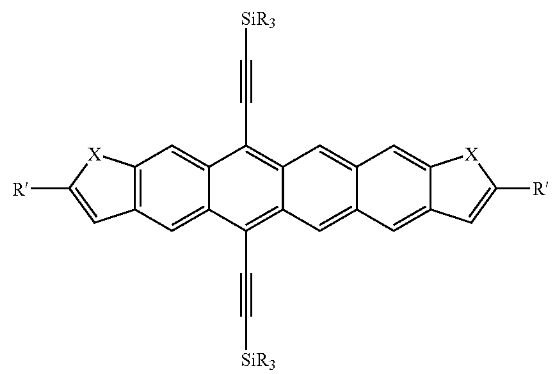
wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=halogen and X=—O, —S, —Se, or —NH.

2. A compound of the formula:

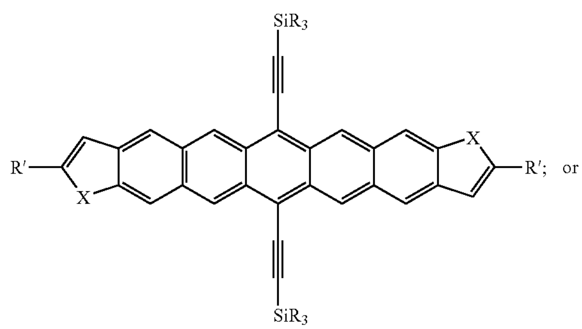
(B_1)



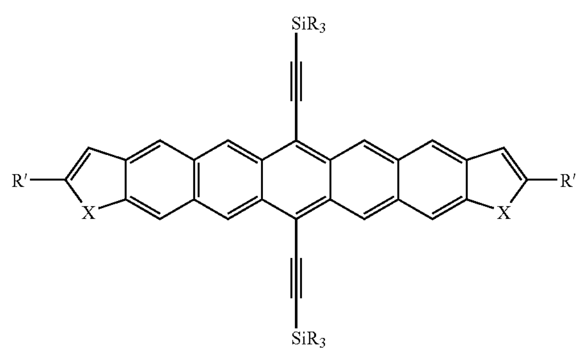
(B_2)



(C_1)



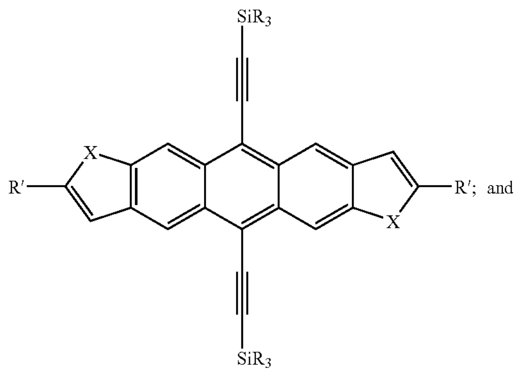
(C_2)



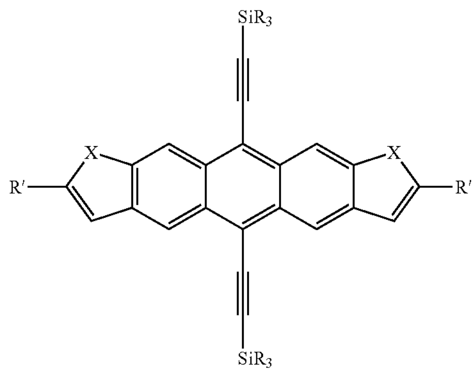
wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH.

3. A compound, comprising: a mixture of stereoisomers of the following formulae:

(A_1)



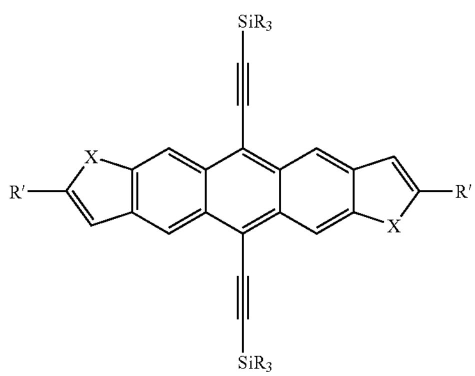
(A_2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=halogen and X=—O, —S, —Se, or —NH.

4. A compound of the formula:

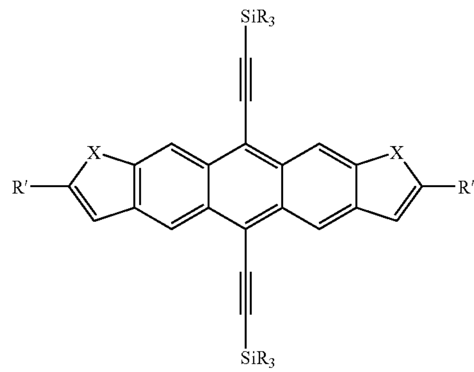
(A_1)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy or trialkylsilyl, R^1=halogen and X=—O, —S, —Se or —NH.

5. A compound of the formula:

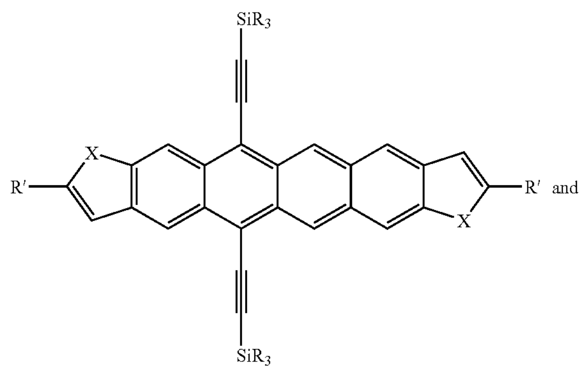
(A_2)



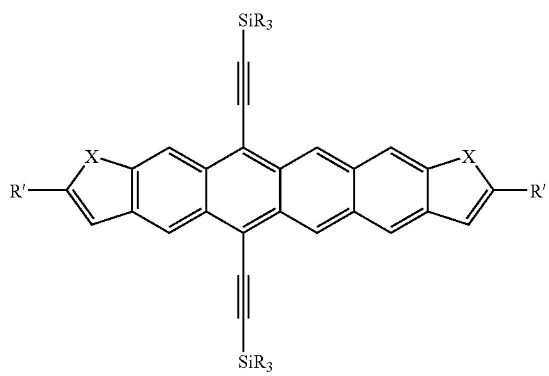
wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy or trialkylsilyl, R^1=halogen and X=—O, —S, —Se or —NH.

6. A compound, comprising: a mixture of stereoisomers of the following formulae:

(B_1)



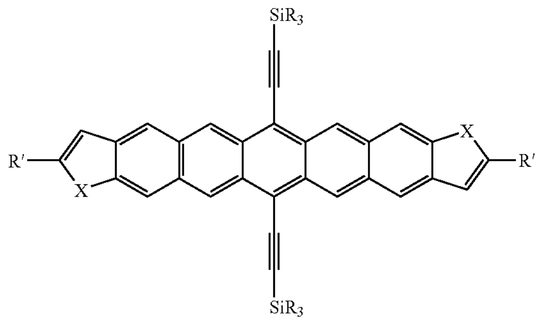
(B_2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl alkoxy, halogen and X=—O, —S, —Se, or —NH.

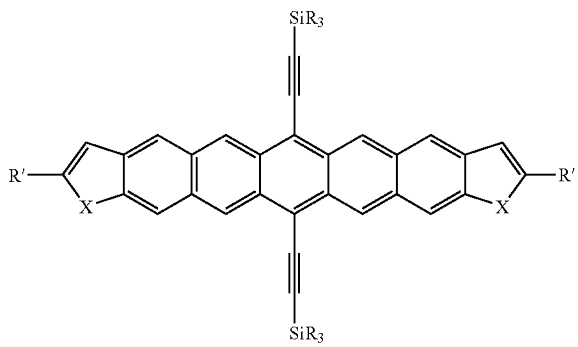
7. A compound, comprising: a mixture of stereoisomers of the following formulae:

(C1)



and

(C2)



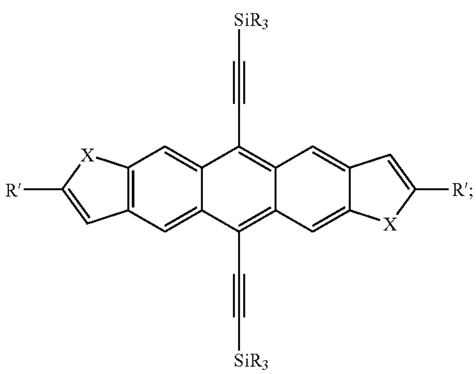
wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH.

8. A transistor, comprising:

a gate electrode;

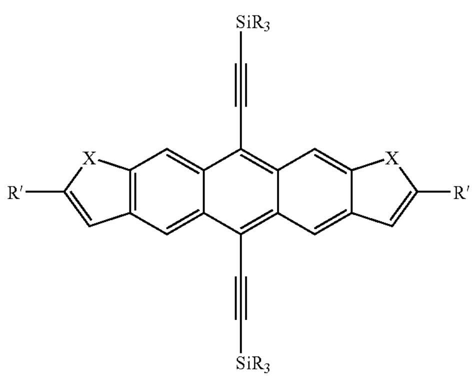
a semiconductor constructed from at least one material selected from a group consisting of

(A1)



; or

(A2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=halogen and X=—O, —S, —Se, or —NH;

an insulator between said gate electrode and said semiconductor;

a source electrode; and

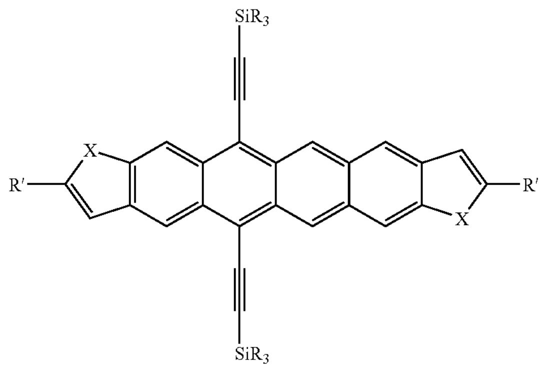
a drain electrode.

9. A transistor, comprising:

a gate electrode;

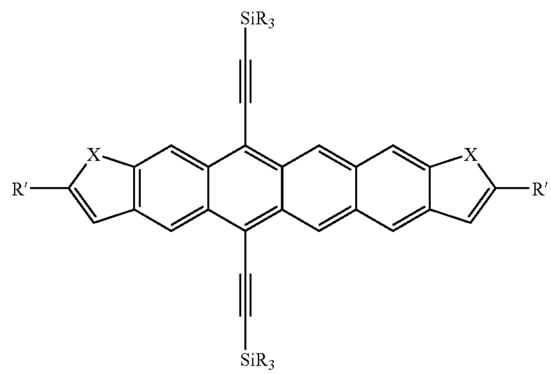
a semiconductor constructed from at least one material selected from a group consisting of

(B1)



; and

(B2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH;

an insulator between said gate electrode and said semiconductor;

a source electrode; and

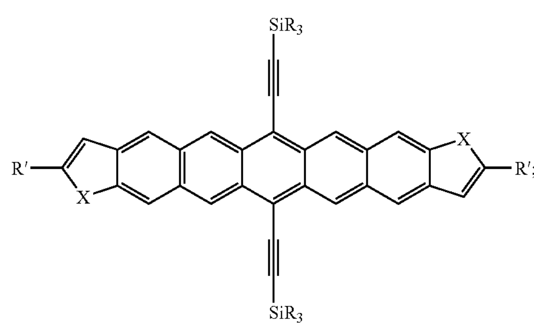
a drain electrode.

10. A transistor, comprising:

a gate electrode;

a semiconductor constructed from at least one material selected from a group consisting of

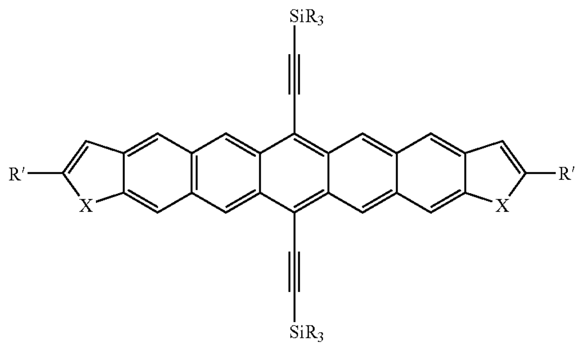
(C1)



; and

-continued

(C2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH;

an insulator between said gate electrode and said semiconductor;

a source electrode; and

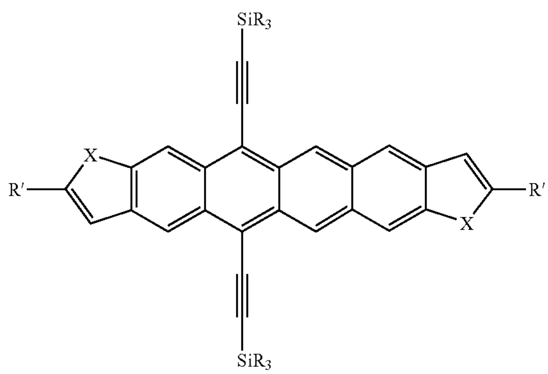
a drain electrode.

11. A photovoltaic apparatus, comprising:

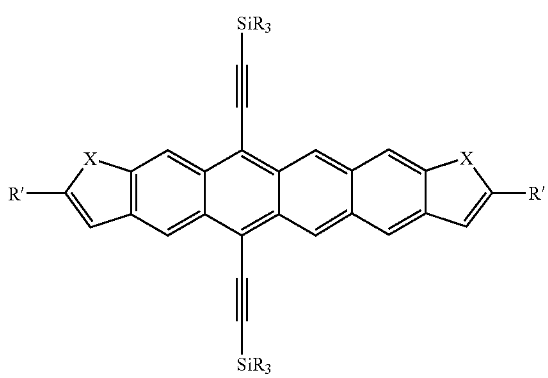
a transparent anode;

a semiconductor constructed from at least one material selected from a group consisting of

(B1)

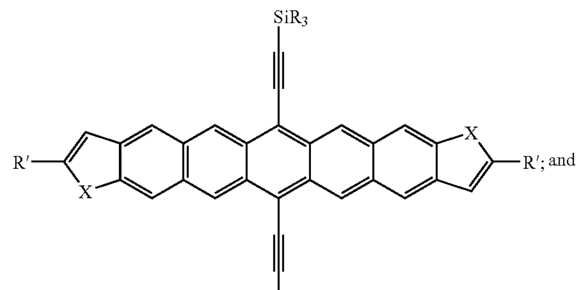


(B2)

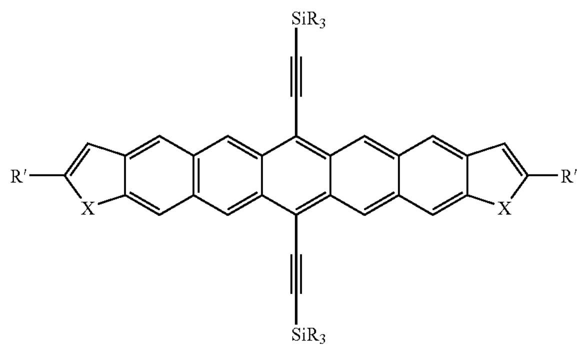


-continued

(C1)



(C2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH;

an n-type material; and

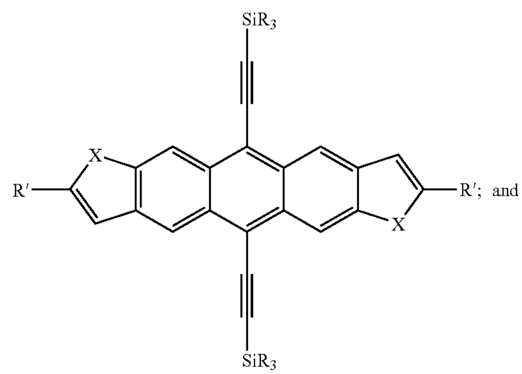
a cathode.

12. A photovoltaic apparatus, comprising:

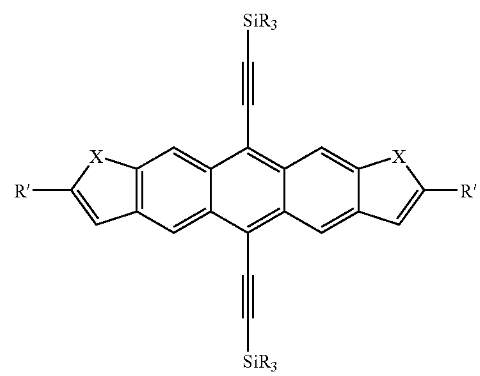
a transparent anode;

a semiconductor constructed from at least one material selected from a group consisting of

(A1)



(A2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=halogen and X=—O, —S, —Se, or —NH;

an n-type material; and

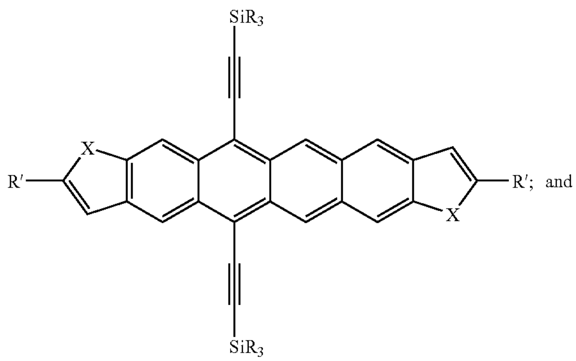
a cathode.

13. A photovoltaic apparatus, comprising:

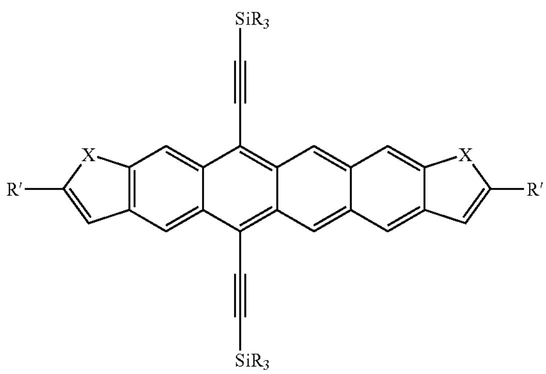
a transparent anode;

a semiconductor constructed from at least one material selected from a group consisting of

(B_1)



(B_2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH;

an n-type material; and

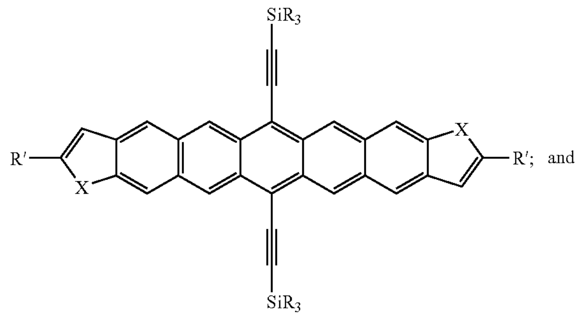
a cathode.

14. A photovoltaic apparatus, comprising:

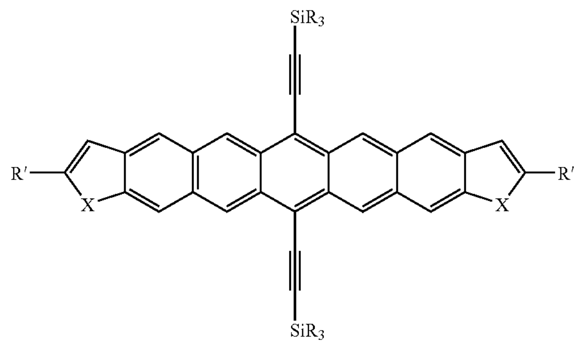
a transparent anode;

a semiconductor constructed from at least one material selected from a group consisting of

(C_1)



(C_2)



wherein R=an alkyl, perfluoroalkyl, aryl, alkoxy, or triakylsilyl, R'=hydrogen, alkyl, aryl, perfluoroalkyl, alkoxy, halogen and X=—O, —S, —Se, or —NH;

an n-type material; and

a cathode.

* * * * *