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(54) Title: ORGANIC ELECTROLUMINESCENT TRANSISTOR

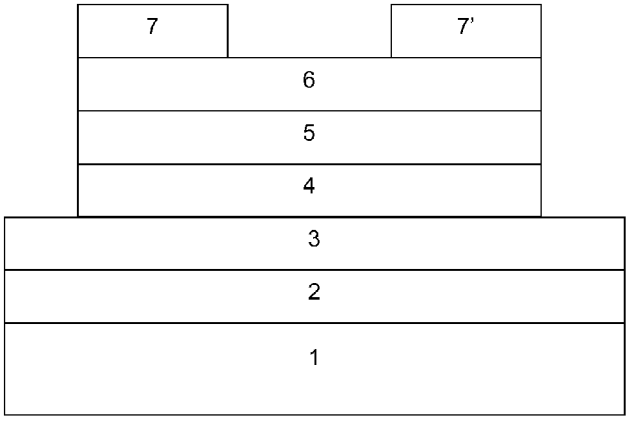

Fig. 1

(57) Abstract: The present teachings relate to an organic electroluminescent transistor with improved light-emission characteristics. More specifically, the present organic electroluminescent transistor has an emissive ambipolar channel including at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material, and at least one layer of an emissive material arranged between the layers of the p-type and n-type semiconductor materials, where the multilayer emissive ambipolar channel includes, among various layers, a layer of a p-type semiconductor material comprising a benzothieno-benzothiophene compound, and/or a layer of an emissive material comprising a blend material that includes an organic carbazole derivative as the host matrix compound and an iridium complex as the guest emitter.

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ORGANIC ELECTROLUMINESCENT TRANSISTOR

FIELD

[0001] The present teachings relate to organic electroluminescent transistors with improved light emission characteristics. More specifically, the present electroluminescent transistors include a multilayer emissive ambipolar channel and by incorporating specific material(s) as one or more of the functional layers, the present electroluminescent transistors can achieve maximum brightness and efficiency simultaneously.

BACKGROUND

[0002] Organic electroluminescent field effect transistors, also known as OLETs (Organic Light Emitting Transistors) are a relatively recent type of devices, that have characteristics and applications that make them particularly interesting. For example, compared to OLEDs (Organic Light Emitting Diodes), ambipolar OLETs have enhanced efficiency and luminosity, and also can afford the possibility of using low-cost production processes once they have been optimized.

[0003] Further details about the structure of an ambipolar OLET device may be found in European Patent No. EP 1609195. More specifically, EP 1609195 discloses a three-layer organic light emitting transistor having an emissive ambipolar channel that includes at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material and at least one layer of an emissive material arranged between said layers of p-type and n-type semiconductor materials. Further details about the applications and the functional characteristics of these devices may be found in R. Capelli et al., "Organic light-emitting transistors with an efficiency that outperforms the equivalent light-emitting diodes," Nature Materials, vol. 9, pp. 496–503 (2010). The three-layer organic light-emitting transistor disclosed in Capelli et al. has a layer of an n-type semiconductor material composed of 5,5'-bis((5-perfluorohexyl)thiophen-2-yl)-2,2'-bithiophene (DFH4T), a layer of a p-type semiconductor material composed of 5,5′-bis(3-hexyl-2-thienyl)-2,2′-bithiophene (DH4T), and a layer of an emissive material composed of tris(8-hydroxyquinolinato)aluminium:4-(dicyanomethylene)-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran (Alq_3:DCM).

[0004] Among different p-type semiconductor materials that have been reported in the literature, diacene-fused thienothiophenes, specifically, [1]benzo-thieno[3,2-b][1]benzothiophenes (BTBTs) and dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes

(DNTTs) have been shown to exhibit high mobility, air stability, and good reproducibility. See e.g., M.J. Kang et al., "Two Isomeric Didecyl-dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes: Impact of Alkylation Positions on Packing Structures and Organic Field Effect Transistor Characteristics," Jpn. J. Appl. Phys., vol. 51, pp. 11PD04 (2012); and H. Ebata et al., "Highly Soluble [1]Benzothieno[3,2-b]benzothiophene (BTBT) Derivatives for High-Performance, Solution-Processed Organic Field-Effect Transistors," J. Am. Chem. Soc., vol. 129, pp. 15732-15733 (2007). In Ebata et al., a series of 2,7-dialkylderivatives of BTBT (C_n-BTBT) were synthesized and used to fabricate organic field-effect transistors (OFETs). The OFETs were evaluated under ambient conditions and thin films of C_n-BTBT derivatives were shown to provide mobilities higher than 10^{-1} cm^2 V^{-1} s^{-1}. In Kang et al., two isomeric dodecyl-dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes (2,9- and 3,10-C_{10} DNTTs) were shown to afford high-performance OFETs with an average mobility of 6.8 cm^2 V^{-1} s^{-1} for 2,9-C_{10}-DNTT, and an average mobility of 4 cm^2 V^{-1} s^{-1} for 3,10-C_{10}-DNTT.

[0005] European Patent Application Publication No. EP 2402348 describes dialkyl-substituted DNTTs and related selenium analogs. OTFTs fabricated with the described compounds showed mobilities close to 4 cm^2 V^{-1} s^{-1}. No BTBT compounds are described.

[0006] International Publication Number WO 2013/039842 describes various acene-fused thienothiophenes and related chalcogen analogs that are mono- or bis-substituted with branched alkyl. OTFTs fabricated with the described compounds showed mobilities close to 2.3 cm^2 V^{-1} s^{-1}. No BTBT compounds are described.

[0007] Each of the above-identified documents is silent as to the possibility of using BTBT compounds in an OLET device having a trilayer emissive ambipolar channel and how the performance of such OLET device may compare to a similar OLET device using DNTT compounds.

[0008] So far, all studies and characterizations have shown that ambipolar OLET devices have an enhanced luminosity, though obtained at bias conditions where the efficiency of charge current conversion into light emission is very low (in the order of 1x 10^{-1} %). Conversely, the device efficiency can be usually maximized by modifying its bias conditions but with detrimental effects on the luminosity. These emission characteristics limit the possible application fields when high brightness and high efficiency are simultaneously needed such as, for example, in the fields of light emitting

displays, Point of Care biomedical applications, and photon sources integrated on photonic chips. Further improvements in electroluminescence intensity (from the order of nanoWatt (nW) to microWatt (μW) with constant device geometry) also is desirable.

SUMMARY

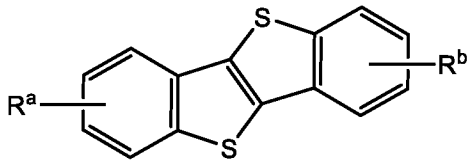
[0009] An objective of the present teachings is to provide an organic electroluminescent transistor that can overcome the above mentioned drawbacks known in the art, in particular, to provide an organic electroluminescent transistor that can achieve maximum light emission efficiency and brightness simultaneously.

[0010] In one aspect, an organic electroluminescent transistor according to the present teachings comprises at least one dielectric layer, at least one control electrode, an assembly comprising an emissive ambipolar channel, at least one source electrode and at least one drain electrode, wherein:

the dielectric layer is arranged between the control electrode and the assembly;

the ambipolar channel comprises at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material and at least one layer of an emissive material arranged between the layers of p-type and n-type semiconductor materials; and

the p-type semiconductor material is suitable to transport holes across the ambipolar channel of the transistor and comprises a benzothieno-benzothiophene (BTBT) compound having general formula (P-I)



(P-I),

wherein R^a and R^b are independently selected from the group consisting of H, a C_{1-18} alkyl group, and a C_{6-14} aryl group.

[0011] In certain embodiments, the n-type semiconductor material is a bis(p-fluoroalkyl)phenyl-substituted thieno[3,2-b]thiophene, non-limiting examples of which include 2,5-bis(4-(perfluorooctyl)phenyl)thieno[3,2-b]thiophene (NF2-6) and 2,5-bis(4-(trifluoromethyl)phenyl)thieno[3,2-b]thiophene (NF2-6-CF3).

[0012] In certain embodiments, the emissive layer is selected from the group consisting of 4,4',4"-tris(carbazole-9-yl)triphenylamine:tris(1-phenylisoquinoline) iridium(III) (TCTA:$Ir(piq)_3$), 4,4'-bis(3,6-dineopentyl-9H-carbazole-9-yl)-1,'-biphenyl:

tris(1-phenylisoquinoline)iridium(III) (NP4-CBP:Ir(piq)$_3$), 4,4'-bis(3,6-dineopentyl-9H-carbazole-9-yl)-1,'-biphenyl:tris(2-phenylpyridine)iridium(III) (NP4-CBP:Ir(ppy)), 4,4'-bis(3,6-dineopentyl-9H-carbazole-9-yl)-1,'-biphenyl:bis(4,6-difluorophenyl-pyridine)(picolinate)iridium(III) (NP4-CBP:FIrpic).

[0013] In another aspect, an organic electroluminescent transistor according to the present teachings comprises at least one dielectric layer, at least one control electrode, an assembly comprising an emissive ambipolar channel, at least one source electrode and at least one drain electrode, wherein:

the dielectric layer is arranged between the control electrode and the assembly;

the ambipolar channel comprises at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material and at least one emissive layer of an emissive material arranged between the layers of the p-type and n-type semiconductor materials; and

wherein the emissive layer comprises a blend material comprising a carbazole derivative as a host matrix compound and an iridium complex as a guest emitter.

[0014] In various embodiments, the organic electroluminescent transistor can include one or more additional layers selected from the group consisting of a hole-injection sublayer, an electron-injection sublayer, and a passivation layer. In one embodiment, as example, the source electrode is in contact with the layer of p-type semiconductor material and the drain electrode is in contact with the layer of n-type semiconductor material. In another embodiment, an injection sublayer can be interposed between the source electrode and the layer of p-type or n-type semiconductor material and/or an injection sublayer is interposed between the drain electrode and the layer of p-type or n-type semiconductor material.

[0015] The foregoing as well as other features and advantages of the present teachings will be more clearly understood from the following figures, description, examples, and claims. The claims as filed are an integral part of this specification and are herein incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Fig. 1 is a cross-sectional view of an organic light emitting transistor (OLET) according to an embodiment of the present teachings, which includes a substrate (1), a control electrode (2), a dielectric layer (3), an assembly comprising an emissive ambipolar channel that includes a layer of a first-type of semiconductor material (4), a

layer of an emissive material (5), a layer of a second-type of semiconductor material (6), and an electron electrode and a hole electrode (7 and 7').

[0017] Fig. 2 plots drain-source current I_{DS} (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, as obtained from a first exemplary OLET having the architecture shown in Fig. 1 and incorporating a BTBT compound represented by formula (P-I) as the p-type semiconductor material.

[0018] Fig. 3 plots drain-source current I_{DS} (left scale – black curve) and electroluminescence optical output power EL (right scale – gray curve) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the first exemplary OLET.

[0019] Fig. 4 plots external quantum efficiency EQE (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the first exemplary OLET.

[0020] Fig. 5 plots drain-source current I_{DS} (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, as obtained from a second exemplary OLET having the architecture shown in Fig. 1 and incorporating a different BTBT compound represented by formula (P-I) as the p-type semiconductor material.

[0021] Fig. 6 plots drain-source current I_{DS} (left scale – black curve) and electroluminescence optical output power EL (right scale – gray curve) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the second exemplary OLET.

[0022] Fig. 7 plots external quantum efficiency EQE (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias

voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the second exemplary OLET.

[0023] Fig. 8 plots drain-source current I_{DS} (left scale – black curves) and electroluminescence output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, as obtained from a first comparative OLET having the architecture shown in Fig. 1 and incorporating a comparative hole-transporting compound (DNTT) that is structurally similar to a BTBT compound but not within formula (P-I) as the p-type semiconductor material.

[0024] Fig. 9 plots drain-source current I_{DS} (left scale – black curve) and electroluminescence optical output power EL (right scale – gray curve) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the first comparative OLET.

[0025] Fig. 10 plots external quantum efficiency EQE (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the first comparative OLET.

[0026] Fig. 11 plots drain-source current I_{DS} (left scale – black curves) and electroluminescence output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, as obtained from a second comparative OLET having the architecture shown in Fig. 1 and incorporating a comparative hole-transporting compound previously reported in the literature that is not within formula (P-I) as the p-type semiconductor material.

[0027] Fig. 12 plots drain-source current I_{DS} (left scale – black curve) and electroluminescence optical output power EL (right scale – gray curve) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the second comparative OLET.

[0028] Fig. 13 plots external quantum efficiency EQE (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of

the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the second comparative OLET.

[0029] Fig. 14 plots drain-source current I_{DS} (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, as obtained from a third exemplary OLET having the architecture shown in Fig. 1 and incorporating a blend material including an organic carbazole-based host matrix compound and an iridium complex guest emitter as the emissive layer.

[0030] Fig. 15 plots drain-source current I_{DS} (left scale – black curve) and electroluminescence optical output power EL (right scale – gray curve) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the third exemplary OLET.

[0031] Fig. 16 plots external quantum efficiency EQE (left scale – black curves) and electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), as obtained from the third exemplary OLET.

[0032] Fig. 17 depicts graphs of the drain-source current I_{DS} (left scale – black curves) and of the electro-luminescence optical output power EL (right scale – gray curves) as a function of the drain-source voltage V_{DS} at different values of the gate-source voltage V_{GS}, for a third comparative electroluminescent transistor not according to the present teachings. Specifically, the emissive layer is composed of a blend material including a metal complex host matrix compound and a platinum-based guest emitter.

[0033] Fig. 18 depicts graphs of the drain-source current I_{DS} (left scale – black curve) and of the electro-luminescence optical output power EL (right scale – gray curves) in function of the gate-source voltage V_{GS} whilst the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), for the third comparative electroluminescent transistor.

[0034] Fig. 19 depicts graphs of the external quantum efficiency (left scale – black

curve) and of the electro-luminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} whilst the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V), for the third comparative electroluminescent transistor.

DETAILED DESCRIPTION

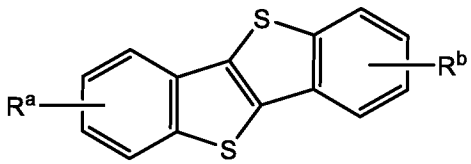
[0035] Fig. 1 shows the structure of an organic electroluminescent transistor (OLET) according to an embodiment of the present teachings. In this particular embodiment, the OLET includes a substrate 1 that acts as a supporting layer, over which there is an electrode 2 that acts as the control (or gate) electrode and that may be a transparent electrode, and a layer of dielectric material 3, over which there is a light-emitting assembly. The light-emitting assembly generally includes a charge carrier transport layer of a first type 4, a layer 5 of emissive material, and a charge carrier transport layer of a second type 6. The charge carrier transport layer of the first type 4, for example, can be a hole transport layer made of a p-type semiconductor material and the charge carrier transport layer of the second type 6 can be an electron transport layer made of an n-type semiconductor material, although an inverted assembly (with layer 4 being an electron transport layer made of an n-type semiconductor material and layer 6 being a hole transport layer made of a p-type semiconductor material) also can be used. Hole and electron electrodes 7 and 7' are realized so as to inject charge carriers into the light-emitting assembly. In the shown embodiment, the hole and electron electrodes are directly in contact with the charge carrier transport layer of the second type 6. According to certain embodiments (not shown), an injection sublayer (i.e., a hole-injection sublayer) can be interposed between the hole electrode and the layer 6 in embodiments where the layer 6 is a layer of p-type semiconductor material. In embodiments where the layer 6 is a layer of n-type semiconductor material, an injection sublayer (i.e., an electron-injection sublayer) can be interposed between the electron electrode and the layer 6.

[0036] As understood by those skilled in the art, the hole electrode and the electron electrode can function, respectively, as the source electrode and the drain electrode (or vice versa) depending on the polarity of the gate voltage. Briefly, because the source electrode is typically grounded (0 V), if the gate voltage is -100V and the drain voltage is -80V, then the source electrode is the hole electrode (negatively biased) and the drain electrode is the electron electrode (positively biased). On the other hand, if the gate voltage is +100V, the source electrode is the electron electrode and the drain electrode

is the hole electrode. An OLET typically is operated by applying a first appropriate bias voltage to the gate electrode, and injecting electrons from the electron electrode and holes from the hole electrode, while maintaining a second bias voltage between the latter two electrodes. In some embodiments, the first and second bias voltages can be continuous voltages. In other embodiments, the first and second bias voltages can be pulsed voltages.

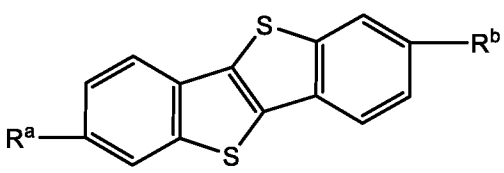
[0037] Instead of the bottom-gate architecture depicted in Fig. 1, an OLET can have a top-gate architecture. Further, the hole and electron electrodes and/or the control electrode can have alternative arrangements as described in International Publication No. WO 2014/035841. Specifically, the hole and electron electrodes can be in contact with different layers of the light-emitting assembly. For example, the hole electrode can be in contact with the layer of p-type semiconductor material, while the electron electrode can be in contact with the layer of n-type semiconductor material. Furthermore, as described in International Publication Nos. WO 2013/018002, WO 2013/017999, WO 2014/035842, and WO 2013/018000, additional control electrode(s) and/or additional layer(s) of dielectric material, emissive material, and/or charge carrier transport materials can be incorporated into the OLET. Optionally, a passivation layer can be present covering the top surface of the emissive ambipolar channel.

[0038] The inventors have found that the foregoing organic electroluminescent transistors such as, but not limited to, those configured according to the embodiment shown in Fig. 1, can have enhanced light emission if the p-type semiconductor material includes a benzothieno-benzothiophene (BTBT) compound of the formula (P-I):

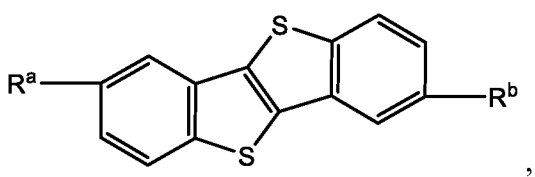


(P-I),

where R^a and R^b are independently selected from the group consisting of H, a C_{1-18} alkyl group, and a C_{6-14} aryl group. In preferred embodiments, the benzothieno-benzothiophene compound can have the formula:



or



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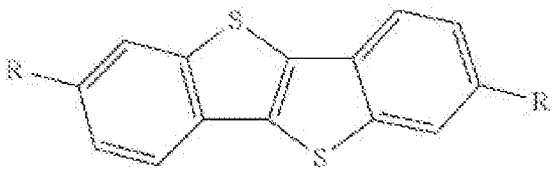
wherein R^a and R^b are identical C_{1-18} alkyl groups, preferably identical C_{3-12} alkyl

groups, and most preferably identical linear C_{3-12} alkyl groups. Specific non-limiting examples include 2,7-dioctyl[1]benzo-thieno[3,2-b][1] benzothiophene (C8-BTBT) and 2,7-dipentyl[1]benzo-thieno[3,2-b][1] benzothiophene (C5-BTBT).

[0039] In an alternative embodiment, the benzothieno-benzothiophene compound can have the formula:



wherein each R can be a phenyl group.

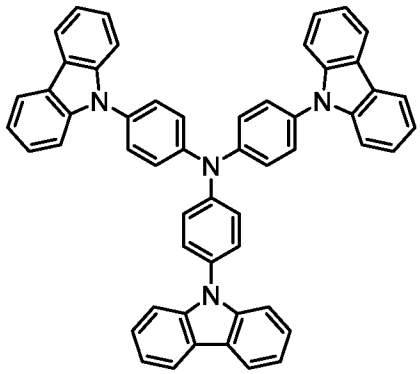
[0040] The inventors surprisingly have found that although various p-type organic semiconducting compounds are known in the art (such as 5,5′-bis(3-hexyl-2-thienyl)-2,2′-bithiophene (DH4T) reported in R. Capelli et al., "Organic light-emitting transistors with an efficiency that outperforms the equivalent light-emitting diodes," Nature Materials, vol. 9, pp. 496–503 (2010)), the use of BTBT compounds as the p-type semiconductor material in an OLET device having a trilayer emissive ambipolar channel can lead to the simultaneous achievement of high electroluminescence and efficiency. Meanwhile, in previously reported devices, the use of other p-type semiconductor material such as DH4T inevitably could only either optimize electroluminescence at the expense of low efficiency or optimize efficiency at the expense of low electroluminescence but could not optimize both electroluminescence and efficiency under the same operating conditions as shown in the Examples below.

[0041] The inventors also unexpectedly found that, although dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes (DNTTs) are often considered very similar to BTBT compounds given their structural similarities and comparable hole mobilities as having been reported in the literature, OLET devices incorporating a DNTT compound as the p-type semiconductor material in the trilayer emissive ambipolar channel have significantly lower electroluminescence compared to OLET devices according to the present teachings.

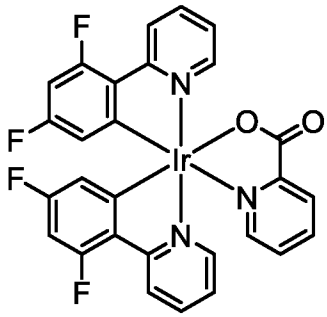
[0042] Further enhanced emissive properties also may be obtained if the emissive material comprises a blend of an organic carbazole-based host matrix compound and an iridium complex guest emitter. More specifically, the organic carbazole-based host matrix compound can be represented by either formula (H-1) (TCTA), formula (H-2) (NP4-CBP), or formula (H-3) (CBP or 4,4′-bis(N-carbazolyl)-1,1′-biphenyl) and a guest

emitter represented by formula (G-1) (FIrpic), formula (G-2) (Ir(ppy)), or formula (G-3) ($Ir(piq)_3$) as provided below. In various embodiments, the layer of emissive material can include between 5% and 22% of its total weight of the guest emitter.

[0043] For example, in embodiments where the emissive material is blue-emitting, the emissive material can include a blend of the arylamine matrix compound of (H-1) and the blue emitter of formula (G-1):

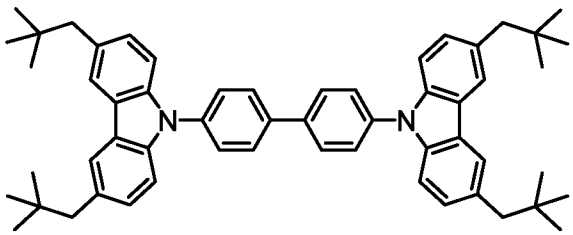


(H-1)

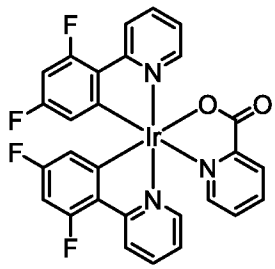


(G-1)

or a blend of the arylamine matrix compound of formula (H-2) and the blue emitter of formula (G-1):

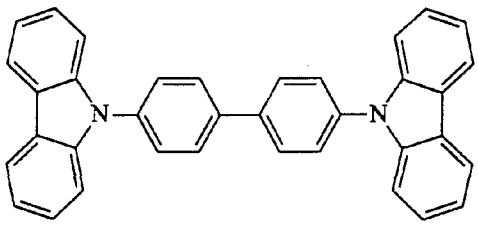


(H-2)

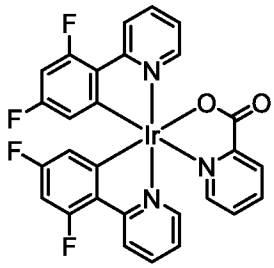


(G-1)

or a blend of the arylamine matrix compound of formula (H-3) and the blue emitter of formula (G-1):

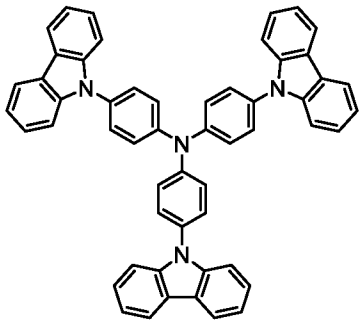


(H-3)

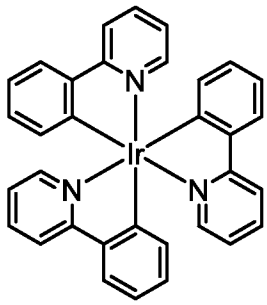


(G-1).

[0044] In embodiments where the emissive material is green-emitting, the emissive material can include a blend of the arylamine matrix compound of formula (H-1) and the green emitter of formula (G-2):

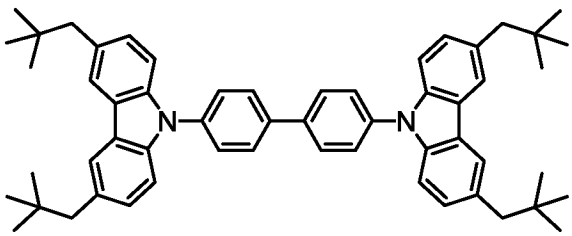


(H-1)

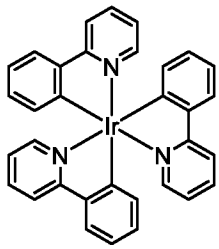


(G-2)

or a blend of the arylamine matrix compound of formula (H-2) and the green emitter of formula (G-2):

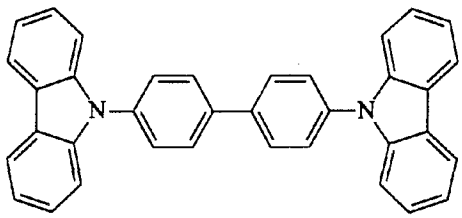


(H-2)

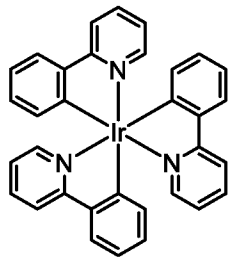


(G-2)

or a blend of the arylamine matrix compound of formula (H-3) and the green emitter of formula (G-2):

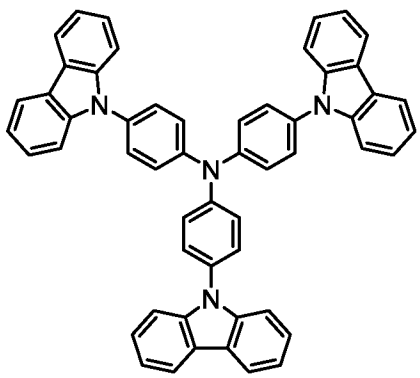


(H-3)

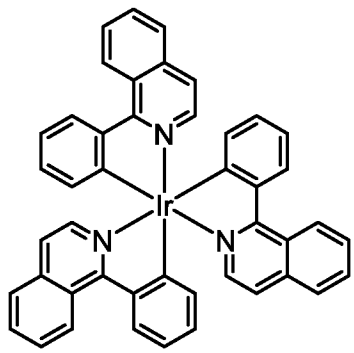


(G-2).

[0045] In embodiments where the emissive material is red-emitting, the emissive material can include a blend of the arylamine matrix compound of formula (H-1) and the red emitter of formula (G-3):

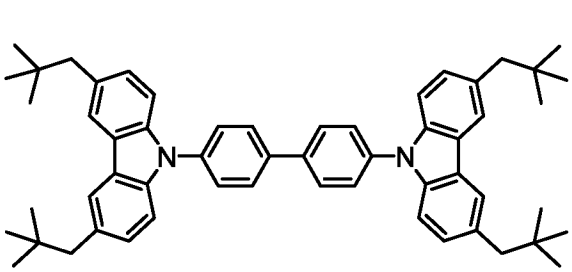


(H-1)

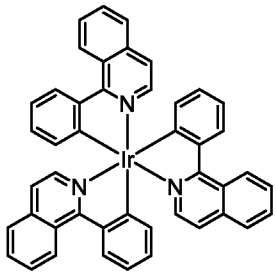


(G-3)

or a blend of the arylamine matrix compound of formula (H-2) and the red emitter of formula (G-3):

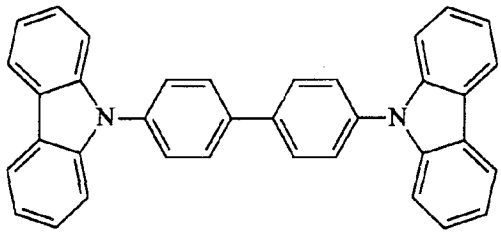


(H-2)

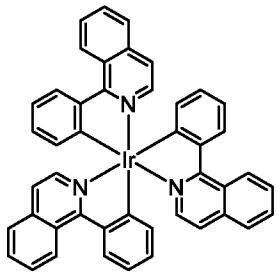


(G-3)

or a blend of the arylamine matrix compound of formula (H-3) and the red emitter of formula (G-3):



(H-3)



(G-3).

[0046] However, the emissive material can be selected from various single-component host-emitting materials and blend materials including a host matrix compound and a guest fluorescent or phosphorescent emitter known in the art. Suitable organic electroluminescent light-emitting materials include those having been used in OLED applications. For example, an alternative emissive material can be a blend of tris(8-hydroxyquinolinato)aluminium (Alq_3) as the host matrix compound and 4-(dicyanomethylene)-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran (DCM) as the guest emitter.

[0047] Various examples of host materials, guest emitters, and single-component host-emitting materials are described in Chaskar et al., "Bipolar Host Materials: A Chemical Approach for Highly Efficient Electrophosphorescent Devices," *Adv. Mater.*, 23(34): 3876-3895 (2011); Tao et al., "Organic host materials for phosphorescent organic light-emitting diodes," *Chem. Soc. Rev.*, 40(5): 2943-2970 (2011); Sasabe et al., "Multifunctional Materials in High-Performance OLEDs: Challenges for Solid-State Lighting," *Chem. Mater.*, 23(3): 621-630 (2011); Tsuboi, "Recent advances in white organic light emitting diodes with a single emissive dopant," *J. Non-Cryst. Solids*, 356(37-40): 1919-1927 (201); Singh et al., "Bio-organic optoelectronic devices using DNA," *Adv. Polym. Sci.*, 223 (Organic Electronics): 189-212 (2010); Kappaun et al.,

"Phosphorescent organic light-emitting devices: working principle and iridium based emitter materials," *Int. J. Mol. Sci.*, 9(8): 1527-1547 (2008); Tokito et al., "Phosphorescent organic light-emitting devices: triplet energy management," *Electrochemistry*, 76(1): 24-31 (2008); Chen, "Evolution of Red Organic Light-Emitting Diodes: Materials and Devices," *Chem. Mater.,* 16(23): 4389-4400 (2004); Liu et al., "Polyfluorenes with on-chain metal centers," *Adv. Poly. Sci.*, 212 (Polyfluorenes): 125-144 (2008); Danev et al., "Vacuum deposited polyimide – a perfect matrix for nanocomposite materials," *J. Optoelectron. Adv. Mater.*, 7(3): 1179-1190 (2005); U.S. Patent No. 5,747,183; U.S. Patent No. 5,683,823; U.S. Patent No. 6,626,722; U.S. Patent No. 7,074,502; U.S. Patent No. 7,671,241; and U.S. Patent No. 7,772,762.

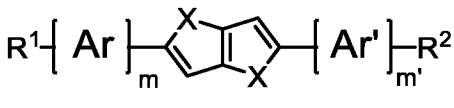
To illustrate, some exemplary host-emitting materials include phosphorescent host-emitting compounds based on carbazole derivatives, fluorene derivatives, or 9-naphthylanthracene derivatives, and fluorescent host-emitting compounds based on organometallic chelates such as tris(8-quinolinol) aluminum complexes. Some exemplary host materials include polymers such as poly(*p*-phenylene vinylene), poly(alkyphenylphenylvinylene), poly(alkyphenylphenylvinylene-co-alkoxyphenylenevinylene), polyfluorene, poly(n-vinylcarbazole), and copolymers thereof. Various carbazole compounds, triphenylamine compounds, including hybrids with oxadiazole or benzimidazole also have been used as host materials.

[0048] Some exemplary guest emitters (light-emitting dyes or dopants) include fluorescent dyes such as various perylene derivatives, anthracene derivatives, rubrene derivatives, carbazole derivatives, fluorene derivatives, and quinacridone derivatives, and phosphorescent emitters such as various transition metal complexes including Ir, Os, or Pt. Tests carried out by the applicant showed that light emission figures are further enhanced when the emissive layer is selected among TCTA:$Ir(piq)_3$, NP4-CBP:$Ir(piq)_3$, NP4-CBP:Ir(ppy), NP4-CBP:FIrpic. According to one embodiment, the layer of emissive material contains a concentration of a doping material (e.g. one of the above described transition metal complexes) that is comprised between 5 and 22% of the total weight of the emissive layer.

[0049] In certain embodiments, the n-type semiconductor material can include a bis(p-fluoroalkyl)phenyl-substituted oligomeric thiophene compound, where the oligomeric thiophene compound can have 2, 3, 4, 5 or 6 thiophene moieties, optionally where two or more of the thiophene moieties can be fused. For example, the bis(p-fluoroalkyl)phenyl-substituted oligomeric thiophene compound can be selected from the

group consisting of a dithiophene, a quaterthiophene, and a thienothiophene,

[0050] The inventors have found that the foregoing organic electroluminescent transistors can have enhanced emissive properties if the n-type semiconductor material includes an electron-transporting compound represented by formula (N-1):



(N-1),

wherein:

X is selected from the group consisting of S, O, and Se;

Ar and Ar', at each occurrence, independently are identical or different monocyclic aryl or heteroaryl groups;

R^1 and R^2 independently are identical or different electron-withdrawing groups selected from the group consisting of –CN, R^3, $–C(O)R^4$, and $–C(O)OR^4$; wherein R^3 is an alkyl, alkenyl, or alkynyl group substituted with one or more F or CN groups, and R^4 is an alkyl, alkenyl, or alkynyl group optionally substituted with one or more F or CN groups; and

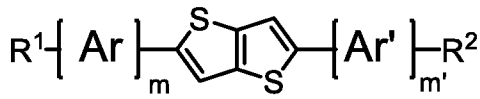
m and m' independently are 1 or 2.

[0051] For example, R^1 and R^2 can be R^3 which is selected from the group consisting of (i) a C_{1-20} alkyl group substituted with one or more F or CN groups having the general formula $C_xF_yH_{2x+1-y}$ or $C_xCN_yH_{2x+1-y}$, provided that x is an integer ranging between 1 and 20, y is an integer ranging between 1 and 41, and $y \leq 2x+1$; (ii) a C_{2-20} alkenyl group substituted with one or more F or CN groups having the general formula $C_xF_yH_{2x-1-y}$ or $C_xCN_yH_{2x-1-y}$, provided that x is an integer ranging between 2 and 20, y is an integer ranging between 1 and 39, and $y \leq 2x-1$; (iii) a C_{2-20} alkynyl group substituted with one or more F or CN groups having the general formula $C_xF_yH_{2x-3-y}$ or $C_xCN_yH_{2x-3-y}$, provided that x is an integer ranging between 2 and 20, y is an integer ranging between 1 and 37, and $y \leq 2x-3$. In certain embodiments, R^1 and R^2 can be a C_{1-20} alkyl group substituted with one or more F groups having the general formula $C_xF_yH_{2x+1-y}$, provided that x is an integer ranging between 1 and 20, y is an integer ranging between 1 and 41, and $y \leq 2x+1$. In particular embodiments, R^1 and R^2 can be a C_{1-18} perfluoroalkyl group having the general formula C_nF_{2n+1}, provided that n is an integer ranging between 1 and 20.

[0052] In other embodiments, R^1 and R^2 can be $–C(O)R^4$ or $–C(O)OR^4$, where R^4 is selected from the group consisting of (i) H, (ii) a C_{1-18} alkyl group optionally substituted

with one or more F or CN groups having the general formula $C_xF_yH_{2x+1-y}$ or $C_xCN_yH_{2x+1-y}$, provided that x is an integer ranging between 1 and 20, y is an integer ranging between 0 and 41, and $y \leq 2x+1$ (ii) a C_{2-18} alkenyl group optionally substituted with one or more F or CN groups having the general formula $C_xF_yH_{2x-1-y}$ or $C_xCN_yH_{2x-1-y}$, provided that x is an integer ranging between 2 and 20, y is an integer ranging between 0 and 39, and $y \leq 2x-1$; and (iii) a C_{2-18} alkynyl group substituted with one or more F or CN groups having the general formula $C_xF_yH_{2x-3-y}$ or $C_xCN_yH_{2x-3-y}$, provided that x is an integer ranging between 2 and 20, y is an integer ranging between 0 and 37, and $y \leq 2x-3$.

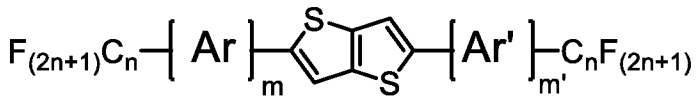
[0053] In preferred embodiments, the electron-transporting compound can be represented by formula (N-2):



(N-2),

wherein Ar, Ar', R^1, R^2, m and m' are as defined herein.

In more preferred embodiments, the electron-transporting compound can be represented by formula (N-3):

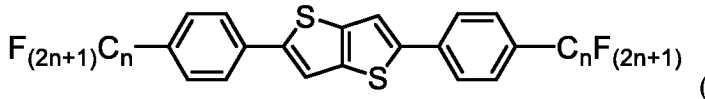


(N-3),

wherein n is an integer ranging from 1 to 12 (inclusive), preferably, from 4 to 12 (inclusive), and wherein Ar, Ar', m and m' are as defined herein.

[0054] In any of the foregoing embodiments, Ar and Ar', at each occurrence, independently can be selected from the group consisting of a phenyl group, a thienyl group, a thiazolyl group, an isothiazolyl group, a thiadiazolyl group, a furyl group, an oxazolyl group, an isoxazolyl group, an oxadiazolyl group, a pyrrolyl group, a triazolyl group, a tetrazolyl group, a pyrazolyl group, an imidazolyl group, a pyridyl group, a pyrimidyl group, a pyridazinyl group, and a pyrazinyl group.

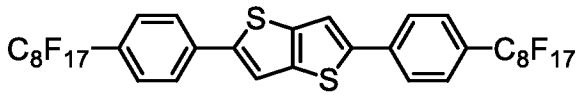
[0055] In particular embodiments, the electron-transporting compound can be represented by formula (N-4):



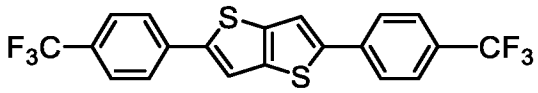
(N-4),

wherein n is an integer ranging from 1 to 12 (inclusive), and preferably, from 4 to 12 (inclusive).

[0056] In one specific embodiment, the electron-transporting compound can be 2,5-bis(4-(perfluorooctyl)phenyl)thieno[3,2-b]thiophene (**N-F2-6**):



[0057] In another specific embodiment, the electron-transporting compound can be 2,5-bis(4-(trifluoromethyl)phenyl)thieno[3,2-b]thiophene (**NF2-6-CF3**):



[0058] The dielectric layer can be an electrically insulating material selected from the group consisting of an inorganic oxide or nitride, a molecular dielectric, a polymeric dielectric, and combination thereof. In embodiments where the dielectric layer is a metal oxide or nitride, such dielectric material can be selected from the group consisting of SiO_2, Si_3N_4, Al_2O_3, ZrO_x, Al-doped ZrO_x, and HfO_x. In embodiments where the dielectric layer is a molecular dielectric, such dielectric can be a self-assembled nanodielectric. In embodiments where the dielectric layer is a polymeric dielectric, such dielectric material can be selected from the group consisting of polyolefins, polyacrylates, polyimides, polyesters, and fluoropolymers. Hybrid organic/inorganic materials also may be used. In preferred embodiments, the dielectric layer comprises an organic dielectric, particularly, a polymeric dielectric.

[0059] Another aspect of the present teachings is directed to organic electroluminescent transistors including at least one dielectric layer, at least one control electrode, an assembly comprising an emissive ambipolar channel, at least one source electrode and at least one drain electrode, wherein:

the dielectric layer is arranged between the control electrode and the assembly;

the ambipolar channel comprises at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material and at least one emissive layer of an emissive material arranged between the layers of the p-type and n-type semiconductor materials; and

wherein the emissive layer is composed of a blend material that includes an organic carbazole derivative as the host matrix compound and an iridium complex as the guest emitter.

[0060] For example, as described above, the organic carbazole-based host matrix compound can be represented by either formula (H-1) (TCTA), formula (H-2) (NP4-

CBP), or formula (H-3) (CBP or 4,4′-bis(N-carbazolyl)-1,1′-biphenyl) and the guest emitter can be represented by formula (G-1) (FIrpic), formula (G-2) (Ir(ppy)), or formula (G-3) ($Ir(piq)_3$).

[0061] The inventors surprisingly have found that although various host-guest emitter systems are known in the art, the use of a blend material that includes an organic carbazole-based host matrix compound and an iridium complex guest emitter as the emissive material in an OLET device having a trilayer emissive ambipolar channel can lead to the simultaneous achievement of high electroluminescence and efficiency. Meanwhile, in previously reported devices, the use of a metal complex host matrix compound (such as Alq_3) in combination with a metal complex guest emitter that is not iridium-based inevitably could only either optimize electroluminescence at the expense of low efficiency or optimize efficiency at the expense of low electroluminescence but not both electroluminescence and efficiency under the same operating conditions as shown in the Examples below.

[0062] OLETs according to the present teachings can be fabricated using processes known in the art. For example, organic layers (e.g., the layer of emissive material, the layers of p-type and n-type semiconductor materials, and the organic dielectric layer of certain embodiments) can be formed by vapor-phase processes such as chemical vapor deposition or physical vapor deposition, as well as solution-phase processes such as printing (e.g., flexo printing, litho printing, gravure printing, ink-jetting, pad printing, and so forth), drop casting, slot coating, dip coating, doctor blading, roll coating, or spin-coating.

[0063] The hole/electron and gate electrodes can be formed using conventional processing techniques. For example, any of the electrical contacts can be deposited through a mask, or can be deposited then etched or lifted off (photolithography). Suitable deposition techniques include electrodeposition, vaporization, sputtering, electroplating, coating, laser ablation and offset printing, from the same or different metals or metal alloys such as copper, aluminum, gold, silver, molybdenum, platinum, palladium, copper, titanium, chromium, and/or nickel, a transparent conducting oxide such as tin-doped indium oxide (ITO), or an electrically conductive polymer such as polyethylenethioxythiophene (PEDOT). Charge carrier injection can be facilitated by the use of a material for the injection electrode (hole electrode or electron electrode) that has a low barrier against injection of a charge carrier type into the hole transport

sublayer and the electron transport sublayer, respectively. For example, the electron electrode can comprise one or more elements selected from the group consisting of Au, Ca, Mg, Al, In, and a perovskite manganites ($RE_{1-x}A_xMnO_3$, RE = rare earth element such as La, Nd, Pr etc., A = alkaline metal). The hole electrode can comprise at least one material selected from the group consisting of Au, indium tin oxide, Cr, Cu, Fe, Ag, poly(3,4-ethylenedioxthiophene) combined with poly(styrenesulfonate) (PEDOT:PSS), and a perovskite manganite ($Re_{1-x}A_xMnO_3$). In certain embodiments, the hole electrode and the electron electrode can be made of conductors with different work functions to favor both hole and electron injection.

[0064] If present, the hole and electron injection sublayers can be prepared by self-assembly of thiolates, phosphonates, or aliphatic or aromatic carboxylates; by thermal evaporation of various charge transfer complexes and other heteroaromatic or organometallic complexes; or by thermal evaporation or sputtering of various metal oxides, fluorides, or carbonates. The hole injection sublayer and the electron injection sublayer can be made of materials that provide a staircase of electronic levels between the energy level of the hole electrode and the electron electrode, and the energy level required for injection into the hole transport sublayer and the electron transport sublayer, respectively. *See e.g.*, Li et al., "Low operating-voltage and high power-efficiency OLED employing MoO_3-doped CuPc as hole injection layer," *Displays*, 33(1): 17-20 (2012); Wen et al., "Self-assembled of conducting polymeric nanoparticles and its application for OLED hole injection layer," *Energy Procedia,* 12: 609-614 (2011); Zhang et al., "Role of Fe_3O_4 as a p-dopant in improving the hole injection and transport of organic light-emitting devices," *IEEE Journal of Quantum Electronics*, 47(5): 591-596 (2011); Choo et al., "Luminance and charge transport mechanisms for phosphorescent organic light-emitting devices fabricated utilizing a tris(2-phenylpyridine)iridium-doped N,N'-dicarbazolyl-3,5-benzene emitting layer," *Thin Solid Films*, 519(15): 5253-5256 (2011); Tao et al., "Odd-even modulation of electrode work function with self-assembled layer: Interplay of energy barrier and tunneling distance on charge injection in organic light-emitting diodes," *Organic Electronics*, 12(4): 602-608 (2011); Sung et al., "AC Field-Induced Polymer Electroluminescence with Single Wall Carbon Nanotubes," *Nano Letters*, 11(3): 966-972 (2011); Qiao et al., "Controlling charge balance and exciton recombination by bipolar host in single-layer organic light-emitting diodes," *Journal of Applied Physics*, 108(3): 034508/1-034508/8 (2011); Khizar-ul-Haq et al., "Blue organic light-emitting diodes with low driving

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[0065] OLETs according to the present teachings can be fabricated on various substrates including plastic, flexible substrates that have a low temperature resistance. Examples of such flexible substrates include polyesters such as polyethylene terephthalate, polyethylene naphthalate, polycarbonate; polyolefins such as polypropylene, polyvinyl chloride, and polystyrene; polyphenylene sulfides such as polyphenylene sulfide; polyamides; aromatic polyamides; polyether ketones; polyimides; acrylic resins; polymethylmethacrylate, and blends and/or copolymers thereof. In some embodiments, the substrate can be a rigid transparent substrate such as glass, quartz and VYCOR®. Substrate-gate materials commonly used in thin-film transistors also can be used. Examples include doped silicon wafer, tin-doped indium oxide (ITO) on glass, tin-doped indium oxide on polyimide or mylar film, aluminum or other metals alone or coated on a polymer such as polyethylene terephthalate, a doped polythiophene, and the like.

[0066] The thicknesses of the various layers may be adapted in order to optimize performances and scaling down of the electroluminescent transistor of this disclosure. In this regard it is preferable to have the thickness of the layer of p-type semiconductor material comprised between 5 and 50 nm, preferably between 15 and 45 nm, the thickness of the layer of n-type semiconductor material may be comprised between 30 nm and 60 nm and the thickness of the layer of emissive material may be comprised

between 30 nm and 60 nm.

[0067] A plurality of OLETs can be arranged in a matrix to provide a display device. The display device can include optional driving and switching elements, compensating transistor elements, capacitors, and/or light-emitting diodes. Particularly, such optional driving and switching elements and compensating transistor elements can be organic field-effect transistors.

[0068] The following examples are provided to illustrate further and to facilitate understanding of the present disclosure and are not in any way intended to limit the invention.

[0069] Acronyms are used in the examples to represent certain chemical compounds. Table 1 below provides the IUPAC names and the acronyms of such compounds.

Table 1

C8-BTBT	2,7-dioctyl[1]benzo-thieno[3,2-b][1]benzothiophene
C5-BTBT	2,7-dipentyl[1]benzo-thieno[3,2-b][1]benzothiophene
DNTT	dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene
DH4T	5,5′-bis(3-hexyl-2-thienyl)-2,2′-bithiophene
N-F2-6	2,5-bis(4-(perfluorooctyl)phenyl)thieno[3,2-b]thiophene
N-F2-6-CF3	2,5-bis(4-(trifluoromethyl)phenyl)thieno[3,2-b]thiophene
N-F4-1	2,6-bis(4-heptadecafluorooctylphenyl)-dithieno[3,2-b:2',3'-d] thiophene
DFH4T	5,5'-bis((5-perfluorohexyl)thiophen-2-yl)-2,2'-bithiophene
TCTA	4,4',4"-tris(carbazole-9-yl)triphenylamine
NP4-CBP	4,4'-bis(3,6-dineopentyl-9H-carbazole-9-yl)-1,'-biphenyl
$Ir(piq)_3$	tris(1-phenylisoquinoline)iridium(III)
$Ir(ppy)_3$	tris(2-phenylpyridine)iridium(III)
FIrpic	bis(4,6-difluorophenyl-pyridine)(picolinate)iridium(III)
PtOEP	2,3,7,8,12,13,17,18-octaethylporphyrin-22,24-diide; platinum(2+)
Alq_3	tris(8-hydroxyquinolinato)aluminium
DCM	4-(dicyanomethylene)-2-methyl-6-(4-dimethylaminostyryl)-4H-pyran

[0070] Example 1

[0071] With reference to Fig. 1, an organic ambipolar light-emitting transistor (OLET) according to the present teachings was fabricated on a glass substrate (first layer 1), onto which a transparent control electrode 2 made of ITO (indium tin oxide) was provided. A 450 nm-thick dielectric layer 3 composed of poly(methyl methacrylate) (PMMA) was fabricated on the ITO electrode by spin-coating and cured in vacuum at 90°C. An organic emissive ambipolar channel was formed on the dielectric layer by sublimation in vacuum (10^{-7} mbar) and includes the following layers:

- a hole transport layer 4 composed of a p-type semiconductor material deposited over the dielectric layer 3, specifically, a 15 nm-thick film made of C8-BTBT sublimated at a rate of 0.1 Å/s, while the substrate was maintained at room temperature;

- an emissive layer 5 in contact with the hole transport layer 4, specifically, a 60 nm-thick recombination layer composed of a host-guest system (with a guest emitter concentration of 20%). TCTA was used as the host matrix and it was sublimated at a rate of 1 Å/s, while the substrate was maintained at room temperature. $Ir(piq)_3$ was used as the guest emitter and it was sublimated at a rate of 0.25 Å/s, while the substrate was maintained at room temperature; and

- an electron transport layer 6 in contact with the emissive layer 5, specifically, a 45 nm-thick film of N-F2-6 sublimated at a rate of 0.1 Å/s, while the substrate was maintained at room temperature.

[0072] The metal source and drain electrodes 7 and 7', made of silver (Ag), were deposited in vacuum (10^{-6} mbar) and each has a thickness of 70 nm.

[0073] The device channel length (L) and channel width (W) are 70 μm and 12 mm, respectively.

[0074] The OLET described above was found to have the following characteristic parameters:

p-type threshold voltage = -40.1 V;
p-type mobility = 5.2×10^{-1} cm^2/Vs;
n-type threshold voltage = 38.4 V;
n-type mobility= 3.6×10^{-3} cm^2/Vs.

[0075] Current-voltage graphs of the tested OLET are shown in Fig. 2 and Fig. 3. Fig. 2 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a

function of the drain-source voltage (V_{DS}) at different gate-source voltages (V_{GS}), while the source contact was grounded. Fig. 3 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0076] Fig. 4 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0077] As shown in Fig, 4, the tested OLET which has an organic emissive ambipolar channel that includes a hole transport layer composed of a BTBT compound (in this case, C8-BTBT) unexpectedly achieved maximum brightness (EL ~ 45 μW) and efficiency (EQE ~ 2.25%) simultaneously.

[0078] Example 2

[0079] A second OLET was fabricated in the same manner and using the same materials as the OLET described in Example 1, except that a different BTBT compound was used in the hole transport layer 4. Specifically, the hole transport layer 4 was composed of a 15 nm-thick film made of C5-BTBT instead of C8-BTBT.

[0080] The resulting OLET showed the following characteristic parameters:

p-type threshold voltage = -54.5 V;
p-type-mobility = 1.2×10^{-1} cm^2/Vs;
n-type threshold voltage = 25.9 V;
n-type mobility= 4.2×10^{-3} cm^2/Vs.

[0081] Current-voltage graphs of the tested OLET are shown in Fig. 5 and Fig. 6. Fig. 5 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a function of the drain-source voltage (V_{DS}) at different gate-source voltage (V_{GS}), while the source contact was grounded. Fig. 6 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain

contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0082] Fig. 7 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0083] As shown in Fig. 7, the tested OLET which has an organic emissive ambipolar channel that includes a hole transport layer composed of a BTBT compound (in this case, C5-BTBT) unexpectedly achieved maximum brightness (EL > 50 μW) and efficiency (EQE > 2.5%) simultaneously.

[0084] Example 3 (Comparative)

[0085] The comparative device tested in this example incorporated a DNTT compound as the p-type semiconductor material in the hole transport layer 4. Previous reports have suggested that DNTT compounds (which have naphthalene, i.e., 2 benzene rings, fused to each side of the thienothiophene center) can achieve higher mobilities than BTBT compounds (which have only 1 benzene ring fused to each side of the thienothiophene center) despite their structural similarity. See e.g., M.J. Kang et al., "Two Isomeric Didecyl-dinaphtho[2,3-b:2′,3′-f]thieno[3,2-b]thiophenes: Impact of Alkylation Positions on Packing Structures and Organic Field Effect Transistor Characteristics," Jpn. J. Appl. Phys., vol. 51, pp. 11PD04 (2012); and H. Ebata et al., "Highly Soluble [1]Benzothieno[3,2-b]benzothiophene (BTBT) Derivatives for High-Performance, Solution-Processed Organic Field-Effect Transistors," J. Am. Chem. Soc., vol. 129, pp. 15732-15733 (2007).

[0086] Specifically, the comparative OLET was fabricated in the same manner and using the same materials as the OLET described in Example 1, except that the hole transport layer 4 was composed of a 15 nm-thick film made of DNTT instead of C8-BTBT.

[0087] The resulting transistor showed the following characteristic parameters:

p-type threshold voltage = -40 V;

p-type-mobility = 5×10^{-5} cm^2/Vs;

n-type threshold voltage = 34 V;

n-type mobility= 0.5 cm^2/Vs.

[0088] Current-voltage graphs of the tested OLET are shown in Fig. 8 and Fig. 9. Fig. 8 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a function of the drain-source voltage (V_{DS}) at different gate-source voltage (V_{GS}), while the source contact was grounded. Fig. 9 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0089] Fig. 10 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0090] As shown in Fig. 10, although the tested DNTT-based OLET was able to achieve maximum brightness (EL ~ 20 μW) and efficiency (EQE ~ 2.5%) simultaneously like the BTBT-based OLETs, the electroluminescence achieved by the DNTT-based OLET was less than 50% of the electroluminescence achieved by the BTBT-based OLETs (which was EL ~ 45 μW, and EL > 50 μW, respectively).

[0091] The significantly higher EL values observed with the BTBT-based OLETs are surprising given that DNTT compounds have been shown to exhibit comparable, if not higher, mobilities, compared to BTBT compounds in the literature.

[0092] Example 4 (Comparative)

[0093] The comparative OLET device tested in this example incorporated the p-type semiconductor material (DH4T), the n-type semiconductor material (DFH4T, a bis(fluoroalkyl-substituted) oligothiophene), and the emissive material (Alq_3:DCM) used in the organic light-emitting transistor reported in R. Capelli et al., "Organic light-emitting transistors with an efficiency that outperforms the equivalent light-emitting diodes," Nature Materials, vol. 9, pp. 496–503 (2010).

[0094] Specifically, and with reference again to Fig. 1, a comparative OLET was fabricated on a glass substrate (first layer 1), onto which a transparent control electrode

2 made of ITO (indium tin oxide) was provided. A 450 nm-thick dielectric layer 3 composed of poly(methyl methacrylate) (PMMA) was fabricated on the ITO electrode by spin-coating and cured in vacuum at 90°C. An organic emissive ambipolar channel was formed on the dielectric layer by sublimation in vacuum (10^{-7} mbar) and includes the following layers:

- an electron transport layer 4 of an n-type semiconductor material deposited over the dielectric layer 3, specifically, a layer of 15 nm-thick film made of DFH4T sublimated at a rate of 0.1 Å/s, while the substrate was maintained at room temperature;

- an emissive layer 5 in contact with the hole transport layer 4, specifically, a 60 nm-thick recombination layer composed of a host-guest system (with a guest emitter concentration of 20%). Alq_3 was used as the host matrix and it was sublimated at a rate of 1 Å/s, while the substrate was maintained at room temperature. DCM was used as the guest emitter and it was sublimated at a rate of 0.25 Å/s, while the substrate was maintained at room temperature; and

- a hole transport layer 6 in contact with the emissive layer 5, in this case, a 45 nm-thick film of DH4T sublimated at a rate of 0.1Å/s, while the substrate was maintained at room temperature.

[0095] The metal source and drain electrodes 7 and 7', made of silver (Ag), were deposited in vacuum (10^{-6} mbar) and each has a thickness of 70 nm.

[0096] The device channel length (L) and channel width (W) are 70 μm and 12 mm, respectively.

[0097] The resulting OLET was found to have the following characteristic parameters:

p-type threshold voltage = -60 V;
p-type mobility = 5.3×10^{-1} cm^2/Vs;
n-type threshold voltage = 23.7 V;
n-type mobility= 3.6×10^{-3} cm^2/Vs.

[0098] Current-voltage graphs of the tested OLET are shown in Fig. 11 and Fig. 12. Fig. 11 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a function of the drain-source voltage (V_{DS}) at different gate-source voltage (V_{GS}), while the source contact was grounded. Fig. 12 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output

power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain contact was maintained at a constant bias voltage of 90V and the source contact was grounded (V_{DS} = 90V).

[0099] Fig. 13 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of 90V and the source contact was grounded (V_{DS} = 90V).

[0100] As shown in Fig. 13, the comparative OLET tested in this example, which incorporated a combination of materials previously reported in the art, showed significantly lower brightness (EL < 0.25 μW) and efficiency (EQE < 0.8%) compared to the devices of Examples 1 and 2. Further, the maximum brightness was obtained under conditions when the efficiency was very low, and vice versa (as indicated by the inverse relationship of the EQE and EL curves, especially between V_{GS} = 20 V and V_{GS} = 60 V).

[0101] Example 5

[0102] Another aspect of the present teachings is directed to the use of an emissive material in a trilayer OLET device, where the emissive material is a blend including an organic arylamine matrix compound (H-1) or (H-2) and an iridium-based emitter selected from (G-1), (G-2), and (G-3).

[0103] Referring to Fig 1, an organic ambipolar light-emitting transistor (OLET) according to the present teachings was fabricated on a glass substrate (first layer 1), onto which a transparent control electrode 2 made of ITO (indium tin oxide) was provided. A 450 nm-thick dielectric layer 3 composed of poly(methyl methacrylate) (PMMA) was fabricated on the ITO electrode by spin-coating and cured in vacuum at 90°C. An organic emissive ambipolar channel was formed on the dielectric layer by sublimation in vacuum (10^{-7} mbar) and includes the following layers:

- a hole transport layer 4 composed of a p-type semiconductor material deposited over the dielectric layer 3, specifically, a 45 nm-thick film made of DH4T sublimated at a rate of 0.1 Å/s, while the substrate was maintained at room temperature;

- an emissive layer 5 in contact with the hole transport layer 4, specifically, a 60 nm-thick recombination layer composed of a host-guest system (with a guest emitter concentration of 20%). TCTA was used as the host matrix and it was sublimated at a

rate of 1 Å/s, while the substrate was maintained at room temperature. $Ir(piq)_3$ was used as the guest emitter and it was sublimated at a rate of 0.25 Å/s, while the substrate was maintained at room temperature; and

- an electron transport layer 6 in contact with the emissive layer 5, specifically, a 45 nm-thick film of N-F4-1 sublimated at a rate of 0.1 Å/s, while the substrate was maintained at room temperature.

[0104] The metal source and drain electrodes 7 and 7', made of silver (Ag), were deposited in vacuum (10^{-6} mbar) and each has a thickness of 70 nm.

[0105] The device channel length (L) and channel width (W) are 70 μm and 12 mm, respectively.

[0106] The OLET described above was found to have the following characteristic parameters:

p-type threshold voltage = -49 V;
p-type mobility = 1.3×10^{-1} cm^2/Vs;
n-type threshold voltage = null;
n-type mobility= null.

[0107] Current-voltage graphs of the tested OLET are shown in Fig. 14 and Fig. 15. Fig. 14 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a function of the drain-source voltage (V_{DS}) at different gate-source voltages (V_{GS}), while the source contact was grounded. Fig. 15 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0108] Fig. 16 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0109] As shown in Fig, 16, the tested OLET which has an emissive layer within the trilayer channel that includes a blend material composed of TCTA:$Ir(piq)_3$, i.e., the

carbazole derivative TCTA as the host matrix compound and the iridium complex $Ir(piq)_3$ as the guest emitter, unexpectedly achieved maximum brightness (EL ~ 2 μW) and efficiency (EQE > 0.4%) simultaneously.

[0110] Example 6 (Comparative)

[0111] In this example, a comparative OLET device was fabricated in the same manner and using the same materials as the OLET described in Example 5, except that a different blend material was used in the emissive layer 5. Specifically, the emissive layer 5 was a blend material composed of Alq_3:PtOEP, that is, both the host matrix and the guest emitter are metal complexes, and the guest emitter is a platinum-based complex instead of an iridium-based complex.

[0112] The resulting OLET showed the following characteristic parameters:

p-type threshold voltage = -55.2 V;

p-type-mobility = 3.8×10^{-2} cm^2/Vs;

n-type threshold voltage = null;

n-type mobility= null.

[0113] Current-voltage graphs of the tested OLET are shown in Fig. 17 and Fig. 18. Fig. 17 illustrates variations of the drain-source current (I_{DS}) (left scale – black curves) and the electroluminescence optical output power (EL) (right scale – gray curves) as a function of the drain-source voltage (V_{DS}) at different gate-source voltage (V_{GS}), while the source contact was grounded. Fig. 18 illustrates variations of the drain-source current (I_{DS}) (left scale – black curve) and of the electroluminescence optical output power (EL) (right scale – gray curve) as a function of the gate-source voltage (V_{GS}) while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0114] Fig. 19 shows graphs of the external quantum efficiency (EQE, left scale – black curve) and of the electroluminescence optical output power EL (right scale – gray curves) as a function of the gate-source voltage V_{GS} while the drain contact was maintained at a constant bias voltage of -100V and the source contact was grounded (V_{DS} = -100V).

[0115] As shown in Fig. 19, the comparative device tested in this example showed much lower brightness (EL ~ 0.30 μW) compared to the device of Example 5 (EL ~ 2 μW). Further, the maximum brightness was obtained under conditions when the efficiency was not optimized, and vice versa (as indicated by the inverse relationships

between the EQE and EL curves). Specifically, when EL was optimized to ~ 0.30 μW under the condition that V_{GS} = -100V, EQE was only ~ 0.15%. Conversely, when EQE was optimized to ~ 0.9% under the condition that V_{GS} = -20V, EL was only ~0.05 μW.

[0116] Table 2 below summarizes the materials used in each layer within the trilayer ambipolar channel of the OLET devices described in Examples 1-6, together with their respective maximum EL and EQE values.

Table 2

	Trilayer ambipolar channel composition			Device Performance	
Example	4	5	6	EL_{max} (μW)	EQE_{max} (%)
1	C8-BTBT	TCTA/$Ir(piq)_3$	N-F2-6	~45	~2.5*
2	C5-BTBT	TCTA/$Ir(piq)_3$	N-F2-6	>50	>2.5
3 (comparative)	DNTT	TCTA/$Ir(piq)_3$	N-F2-6	~20	~2.5
4 (comparative)	DFH4T (n-type)	Alq_3/DCM	DH4T (p-type)	<0.25	~0.8**
5	DH4T	TCTA/$Ir(piq)_3$	N-F4-1	2	> 0.4
6 (comparative)	DH4T	Alq_3/PtOEP	N-F4-1	0.3	<0.9***

*The maximum EL of ~45 μW was achieved when EQE was at a slightly reduced 2.25%.

**The maximum EL of <0.25 μW was achieved when EQE was < 0.05% (when V_{GS} = 60V), while the maximum EQE of ~0.8% was achieved when EL was only ~ 0.025 (when V_{GS} = 20V).

***The maximum EL of 0.3 μW was achieved when EQE was ~ 0.5% (when V_{GS} = -100V), while the maximum EQE of ~0.9% was achieved when EL was < 0.025 (when V_{GS} = -20V).

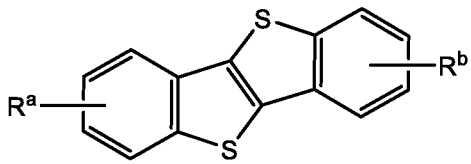
CLAIMS

1. An organic electroluminescent transistor comprising: at least one dielectric layer; at least one control electrode; at least one hole electrode; at least one electron electrode; and an assembly comprising an emissive ambipolar channel, wherein:

said dielectric layer is arranged between said control electrode and said assembly;

said emissive ambipolar channel comprises at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material, and at least one layer of an emissive material arranged between said layers of p-type and n-type semiconductor materials;

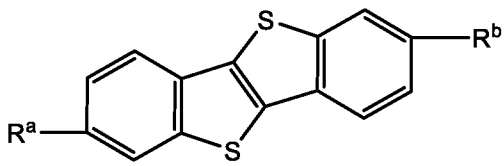
said p-type semiconductor material comprises a benzothieno-benzothiophene compound having general formula (P-I)



(P-I)

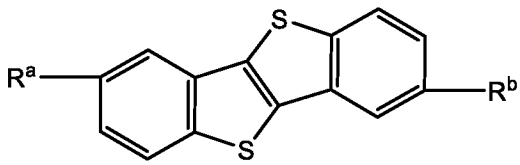
wherein R^a and R^b are independently selected from the group consisting of H, a C_{1-18} alkyl group, and a C_{6-14} aryl group.

2. An organic electroluminescent transistor according to claim 1, wherein said p-type semiconductor material comprises a benzothieno-benzothiophene compound having general formula



.

3. An organic electroluminescent transistor according to claim 1 where said p-type semiconductor material comprises a benzothieno-benzothiophene compound having general formula



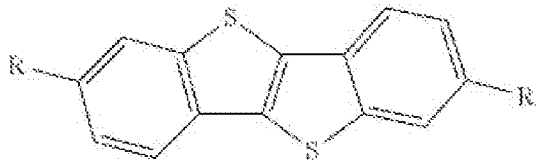
.

4. An organic electroluminescent transistor according to any one of claims 1-3, wherein R^a and R^b are identical C_{1-18} alkyl group.

5. An organic electroluminescent transistor according to any one of claims 1-3, wherein R^a and R^b are identical C_{3-12} alkyl groups.

6. An organic electroluminescent transistor according to claim 5, wherein R^a and R^b are identical linear C_{3-12} alkyl groups.

7. An organic electroluminescent transistor according to claim 1, wherein said p-type semiconductor material comprises a compound having the formula



wherein each R is a phenyl group.

8. An organic electroluminescent transistor according to any one of claims 1-7, wherein said n-type semiconductor material comprises a bis(p-fluoroalkyl)phenyl-substituted oligomeric thiophene compound, wherein the oligomeric thiophene compound has 2, 3, 4, 5 or 6 thiophene moieties, optionally wherein two or more of the thiophene moieties are fused.

9. An organic electroluminescent transistor according to claim 8, wherein the bis(p-fluoroalkyl)phenyl-substituted oligomeric thiophene compound is selected from the group consisting of a dithiophene, a quaterthiophene, and a thienothiophene.

10. An organic electroluminescent transistor according to claim 1, wherein the thickness of said layer of p-type semiconductor material is between 5 and 50 nm.

11. An organic electroluminescent transistor according to claim 10, wherein the thickness of said layer of p-type semiconductor material is between 15 and 45 nm.

12. An organic electroluminescent transistor according to claim 1, characterized in that the thickness of said layer of n-type semiconductor material is between 30 nm and 60 nm.

13. An organic electroluminescent transistor according to claim 1, characterized in that said layer of emissive material has a thickness between 30 nm and 60 nm.

14. An organic electroluminescent transistor according to any one of claims 1-13, wherein the emissive material comprises a blend material comprising an organic carbazole derivative as the host matrix compound and an iridium complex as the guest emitter.

15. An organic electroluminescent transistor according to claim 1 wherein said source electrode is in contact with said layer of p-type semiconductor material and said drain electrode is in contact with said layer of n-type semiconductor material.

16. An organic electroluminescent transistor according to claim 1 wherein said source electrode and said drain electrode are composed of at least one different material.

17. An organic electroluminescent transistor according to claim 1 wherein an injection sublayer is interposed between said source electrode and the layer of p-type or n-type semiconductor material and/or an injection sublayer is interposed between said drain electrode and the layer of the p-type or n-type semiconductor material.

18. An organic electroluminescent transistor according to claim 1, wherein each of the control electrode, drain electrode, and source electrode independently comprises a metal or a transparent conducting oxide selected from the group consisting of gold, silver, molybdenum, copper, titanium, chromium, tin-doped indium oxide and combination thereof.

19. An organic electroluminescent transistor according to claim 1, wherein the dielectric layer comprises an electrically insulating material selected from the group consisting of an inorganic oxide or nitride, a molecular dielectric, a polymeric dielectric, and combination thereof.

20. An organic electroluminescent transistor according to claim 1, wherein the inorganic oxide or nitride is selected from the group consisting of SiO_2, Si_3N_4, Al_2O_3, ZrO_x, Al-doped ZrO_x, and HfO_x.

21. An organic electroluminescent transistor according to claim 1, further comprising a passivation layer covering a top surface of the emissive ambipolar channel.

22. An optoelectronic device for producing an image, the optoelectronic device comprising a plurality of identical or different organic electroluminescent transistors according to any one of previous claims, interconnected to each other and deposited on a substrate.

23. An organic electroluminescent transistor comprising: at least one dielectric layer; at least one control electrode; at least one hole electrode; at least one electron electrode; and an assembly comprising an emissive ambipolar channel, wherein:

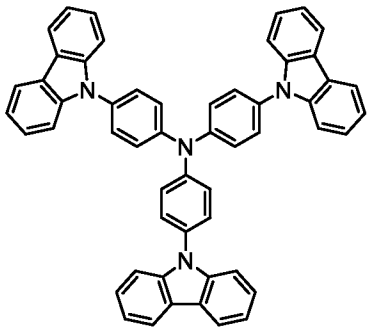
said dielectric layer is arranged between said control electrode and said assembly;

said emissive ambipolar channel comprises at least one layer of an n-type semiconductor material, at least one layer of a p-type semiconductor material, and at least one layer of an emissive material arranged between said layers of p-type and n-type semiconductor materials;

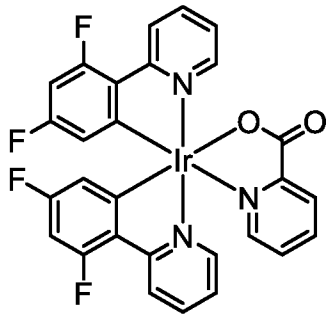
said emissive material comprising a blend material comprising an organic carbazole derivative as the host matrix compound and an iridium complex as the guest emitter.

24. An organic electroluminescent transistor according to claim 23, wherein the emissive material is blue-emitting.

25. An organic electroluminescent transistor according to claim 24, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-1) and a blue emitter of the formula (G-1):

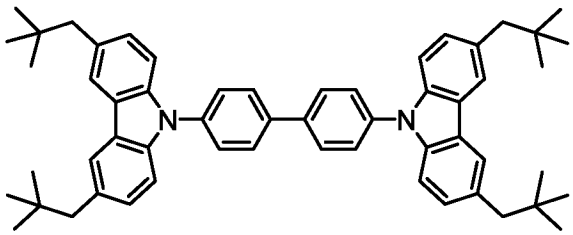


(H-1)

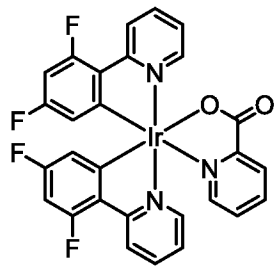


(G-1).

26. An organic electroluminescent transistor according to claim 24, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-2) and a blue emitter of the formula (G-1):

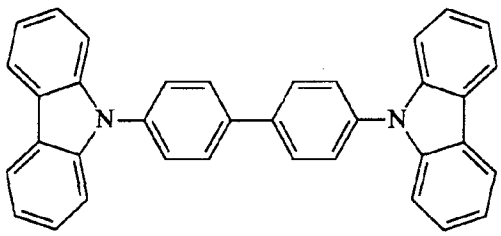


(H-2)

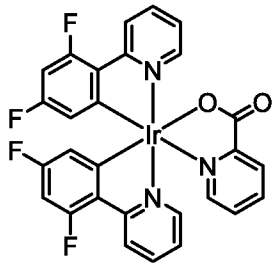


(G-1).

27. An organic electroluminescent transistor according to claim 24, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-3) and a blue emitter of the formula (G-1):



(H-3)

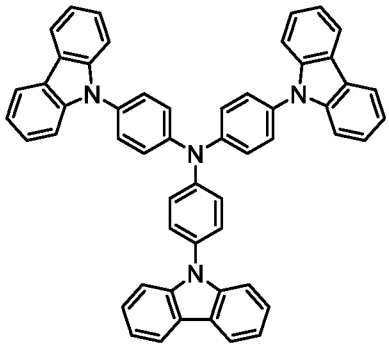


(G-1).

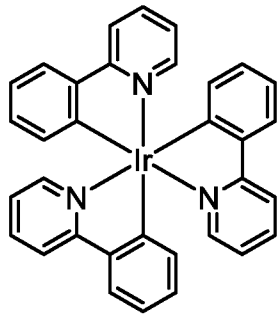
28. An organic electroluminescent transistor according to claim 23, wherein the emissive material is green-emitting.

29. An organic electroluminescent transistor according to claim 28, wherein the emissive material comprises a blend material comprising a host matrix compound of the

formula (H-1) and a green emitter of the formula (G-2):

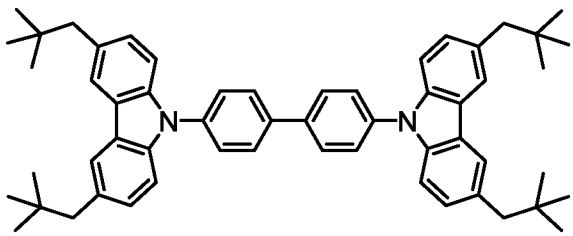


(H-1)

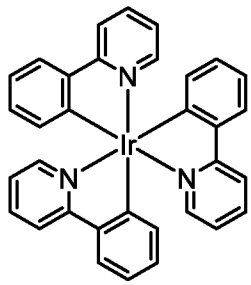


(G-2).

30. An organic electroluminescent transistor according to claim 28, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-2) and a green emitter of the formula (G-2):

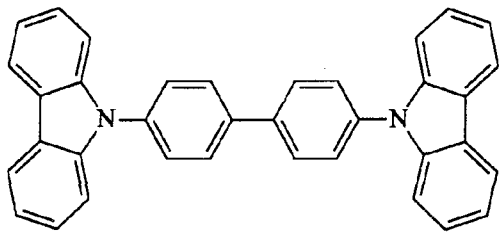


(H-2)

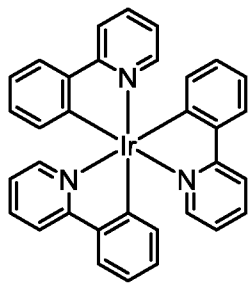


(G-2)

31. An organic electroluminescent transistor according to claim 28, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-3) and a green emitter of the formula (G-2):



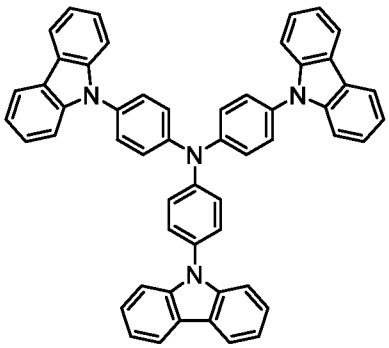
(H-3)



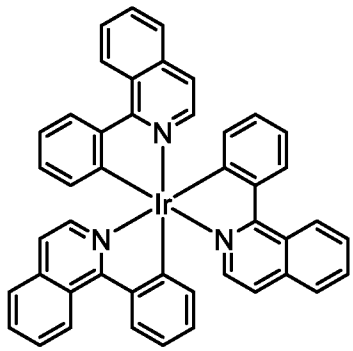
(G-2).

32. An organic electroluminescent transistor according to claim 23, wherein the emissive material is red-emitting.

33. An organic electroluminescent transistor according to claim 32, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-1) and a red emitter of the formula (G-3):

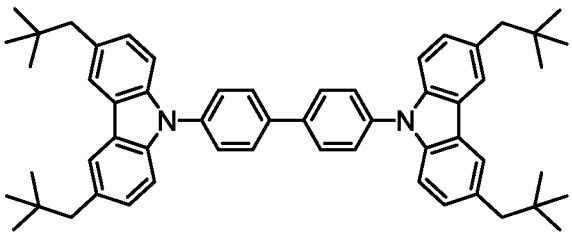


(H-1)

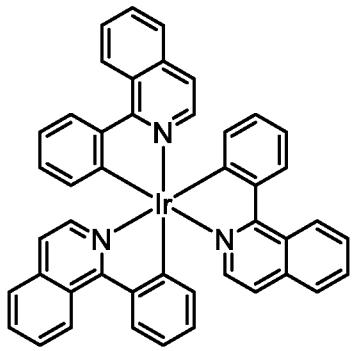


(G-3).

34. An organic electroluminescent transistor according to claim 32, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-2) and a red emitter of the formula (G-3):

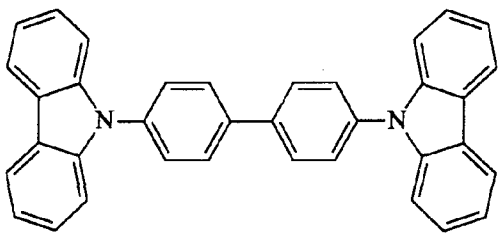


(H-2)

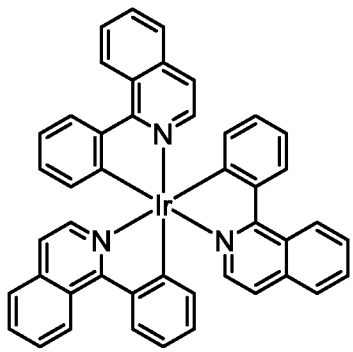


(G-3)

35. An organic electroluminescent transistor according to claim 28, wherein the emissive material comprises a blend material comprising a host matrix compound of the formula (H-3) and a red emitter of the formula (G-3):



(H-3)



(G-3).

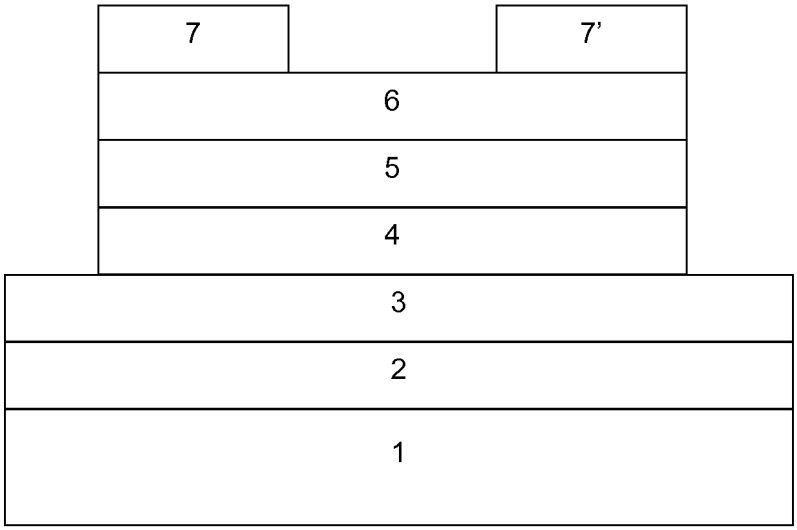


Fig. 1

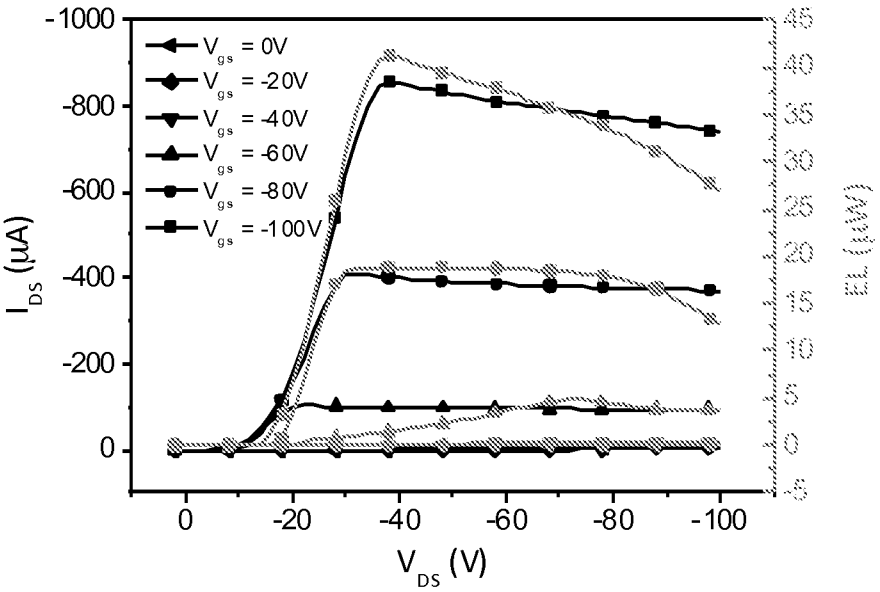

-1000
-800
-600
-400
-200
0
I_{DS} (μA)
V_{gs} = 0V
V_{gs} = -20V
V_{gs} = -40V
V_{gs} = -60V
V_{gs} = -80V
V_{gs} = -100V
0
-20
-40
-60
-80
-100
V_{DS} (V)
45
40
35
30
25
20
15
10
5
0
-5
EL (μW)

Fig. 2

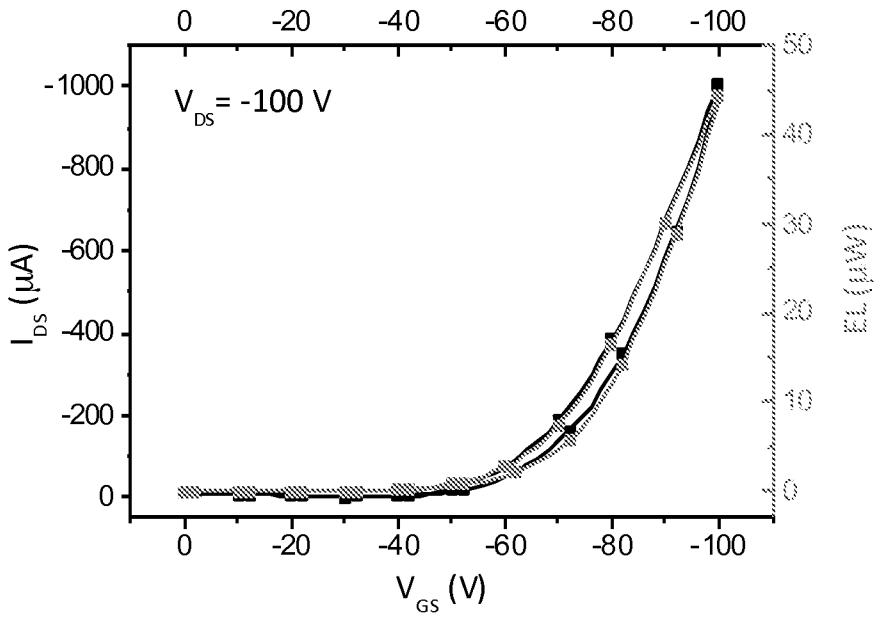

0
-20
-40
-60
-80
-100
-1000
-800
-600
-400
-200
0
I_{DS} (μA)
V_{DS} = -100 V
V_{GS} (V)
50
40
30
20
10
0
EL (μW)

Fig. 3

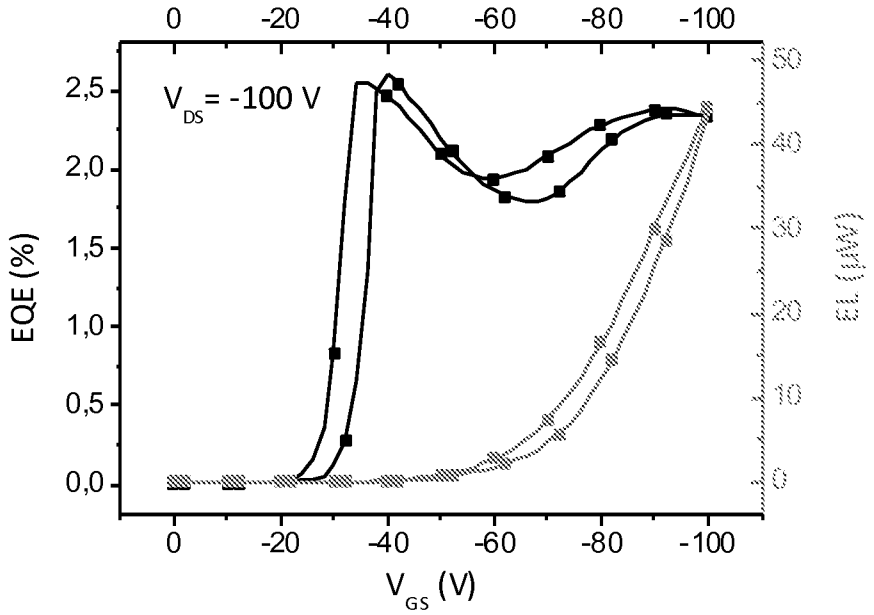

0 -20 -40 -60 -80 -100
2,5
2,0
1,5
1,0
0,5
0,0
EQE (%)
V_DS = -100 V
50
40
30
20
10
0
(mW) EL
0 -20 -40 -60 -80 -100
V_GS (V)

Fig. 4

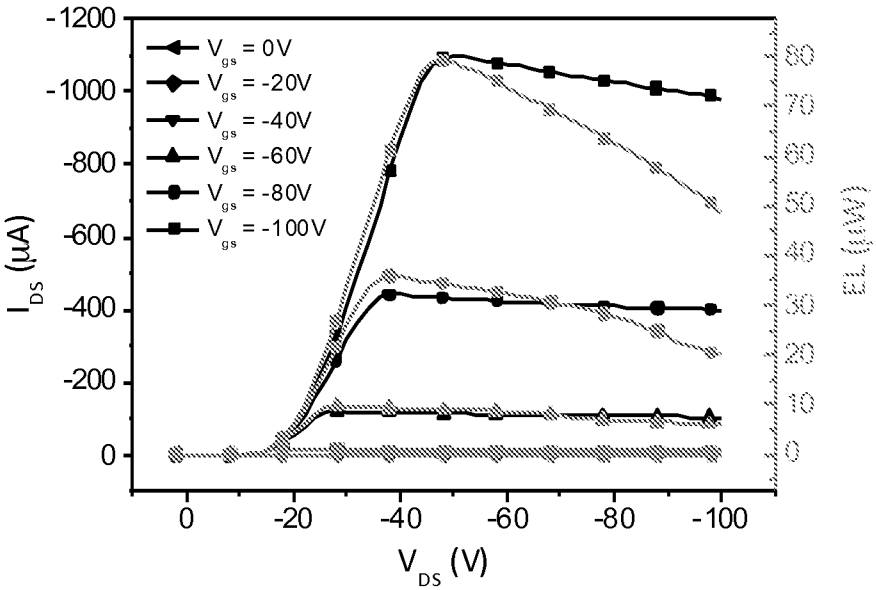

-1200
-1000
-800
-600
-400
-200
0
I_DS (μA)
V_gs = 0V
V_gs = -20V
V_gs = -40V
V_gs = -60V
V_gs = -80V
V_gs = -100V
80
70
60
50
40
30
20
10
0
(mW) EL
0 -20 -40 -60 -80 -100
V_DS (V)

Fig. 5

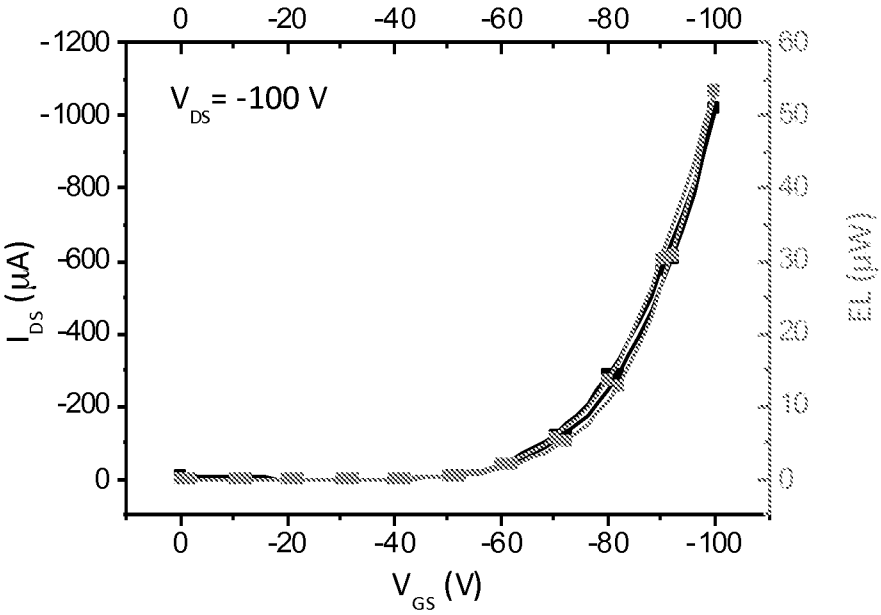

0 -20 -40 -60 -80 -100
-1200
-1000
-800
-600
-400
-200
0
V_{DS}= -100 V
I_{DS} (μA)
EL (μW)
60
50
40
30
20
10
0
0 -20 -40 -60 -80 -100
V_{GS} (V)

Fig. 6

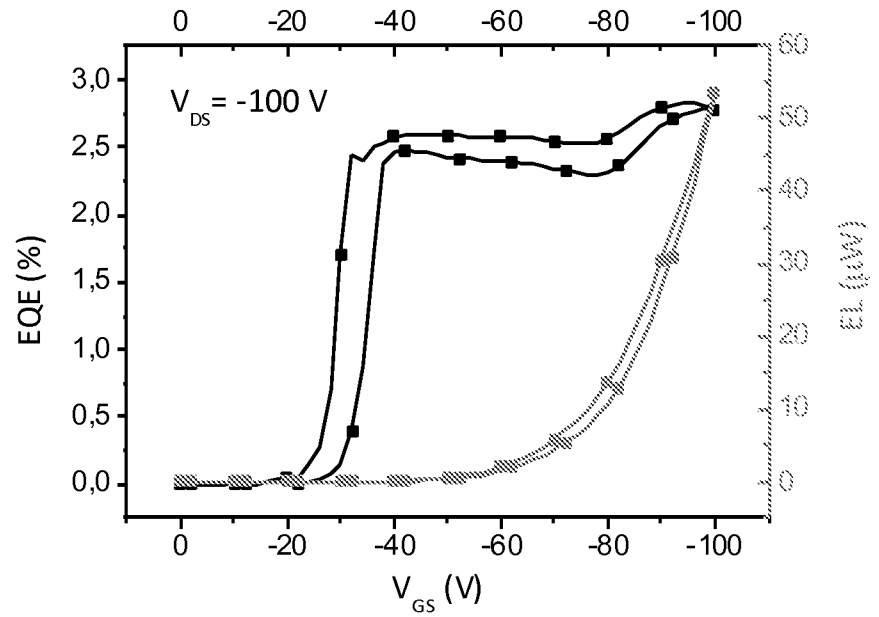

0 -20 -40 -60 -80 -100
3,0
2,5
2,0
1,5
1,0
0,5
0,0
V_{DS}= -100 V
EQE (%)
EL (μW)
60
50
40
30
20
10
0
0 -20 -40 -60 -80 -100
V_{GS} (V)

Fig. 7

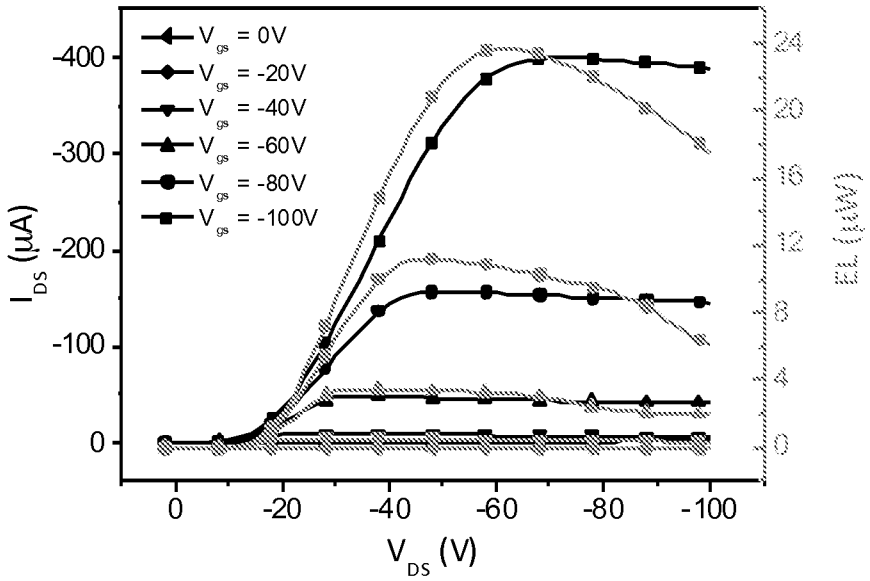

V_gs = 0V
V_gs = -20V
V_gs = -40V
V_gs = -60V
V_gs = -80V
V_gs = -100V
I_DS (μA)
V_DS (V)
EL (μW)

Fig. 8

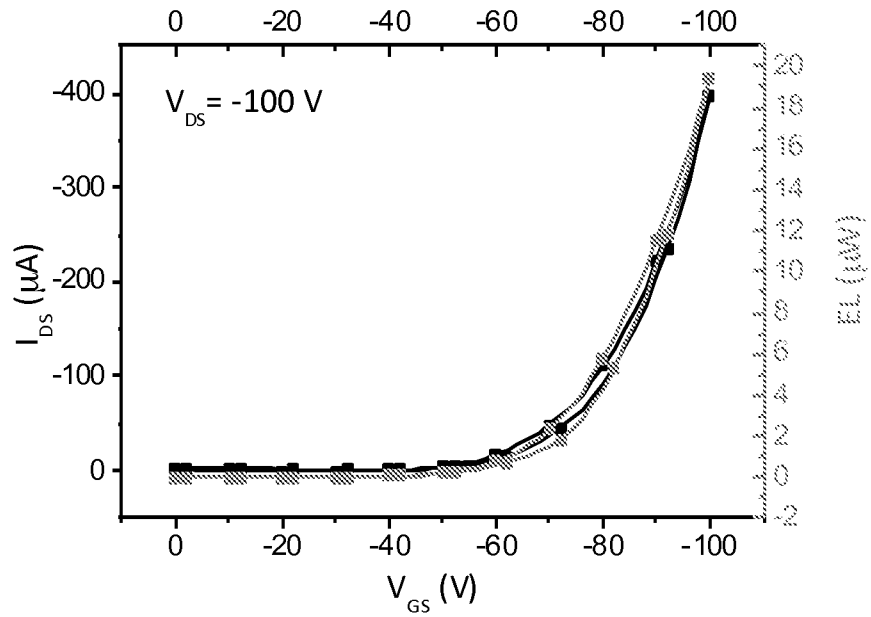

V_DS = -100 V
I_DS (μA)
V_GS (V)
EL (μW)

Fig. 9

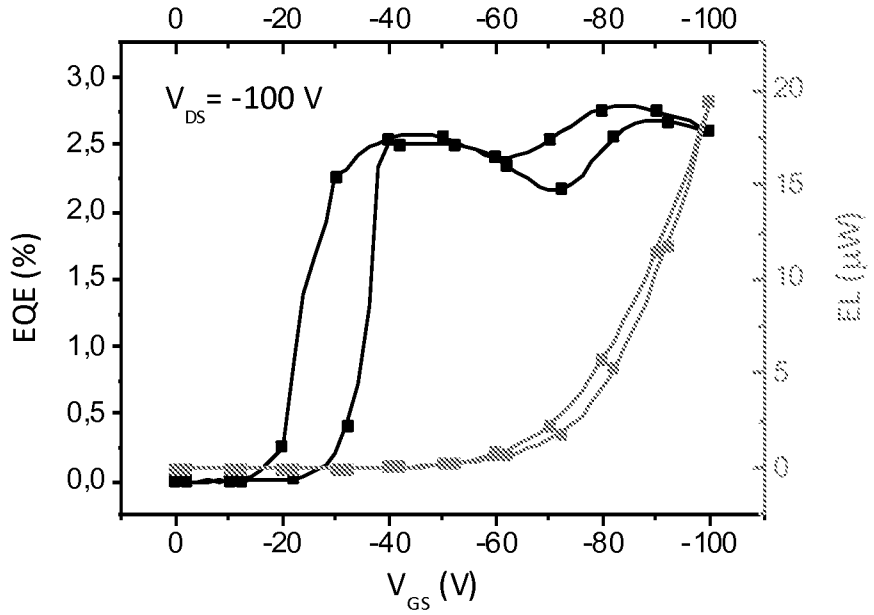

0 -20 -40 -60 -80 -100
3,0
2,5
2,0
1,5
1,0
0,5
0,0
EQE (%)
V_DS = -100 V
20
15
10
5
0
EL (μW)
0 -20 -40 -60 -80 -100
V_GS (V)

Fig. 10

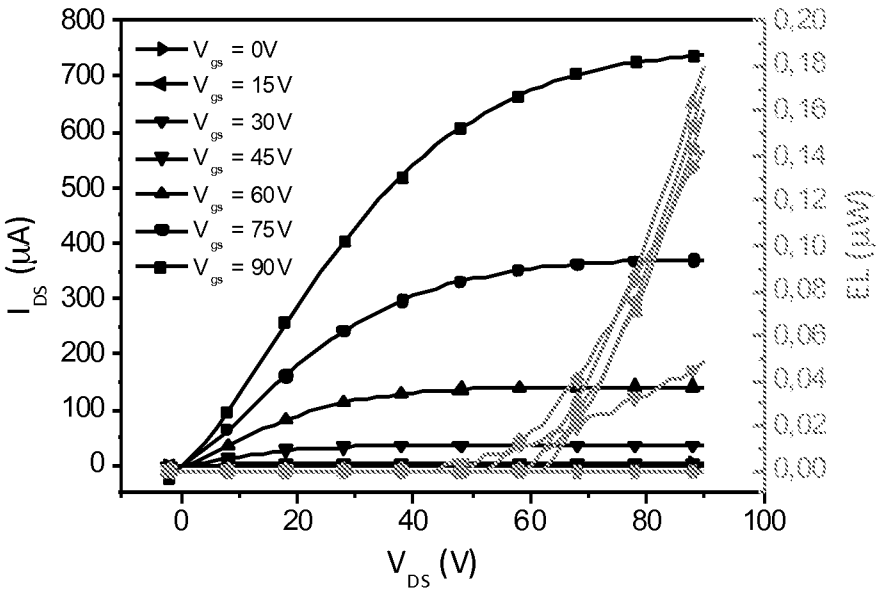

800
700
600
500
400
300
200
100
0
I_DS (μA)
V_gs = 0V
V_gs = 15V
V_gs = 30V
V_gs = 45V
V_gs = 60V
V_gs = 75V
V_gs = 90V
0,20
0,18
0,16
0,14
0,12
0,10
0,08
0,06
0,04
0,02
0,00
EL (μW)
0 20 40 60 80 100
V_DS (V)

Fig. 11

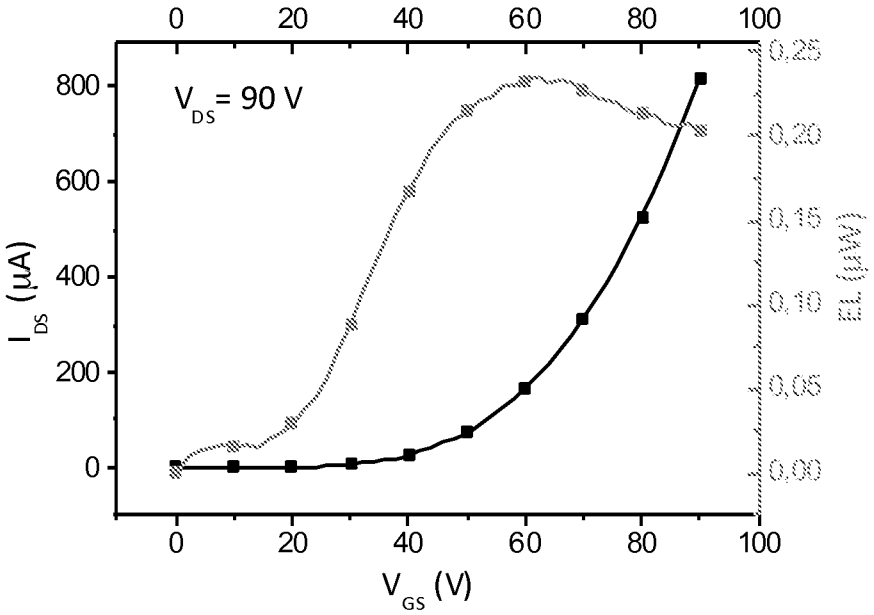

0
20
40
60
80
100
800
600
400
200
0
V_{DS}= 90 V
I_{DS} (μA)
0,25
0,20
0,15
0,10
0,05
0,00
EL (μW)
V_{GS} (V)

Fig. 12

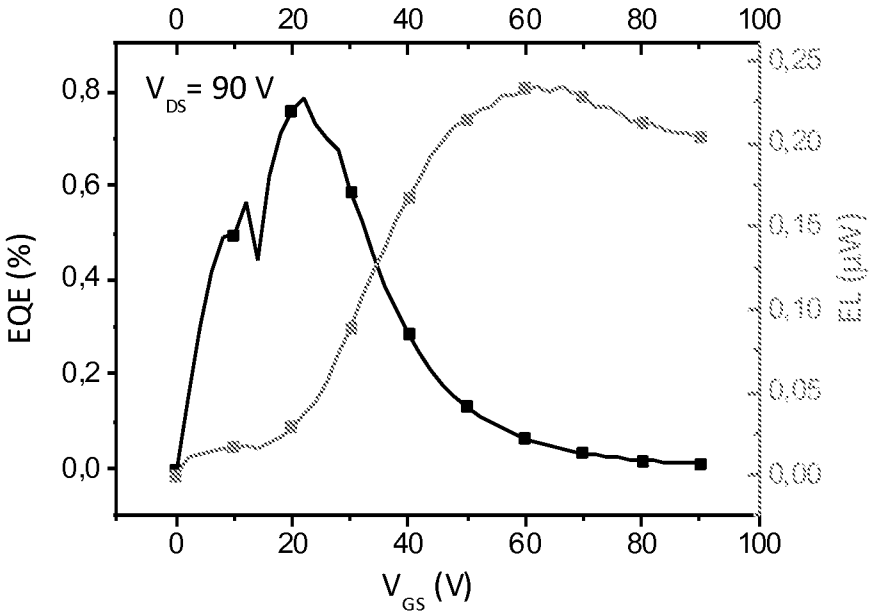

0
20
40
60
80
100
0,8
0,6
0,4
0,2
0,0
V_{DS}= 90 V
EQE (%)
0,25
0,20
0,15
0,10
0,05
0,00
EL (μW)
V_{GS} (V)

Fig. 13

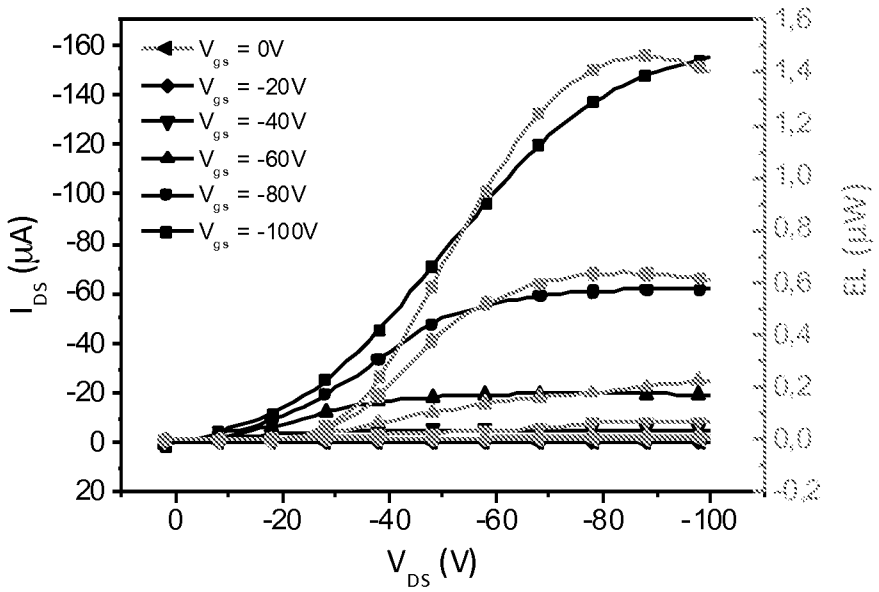

V_gs = 0V
V_gs = -20V
V_gs = -40V
V_gs = -60V
V_gs = -80V
V_gs = -100V
I_DS (μA)
EL (μW)
V_DS (V)

Fig. 14

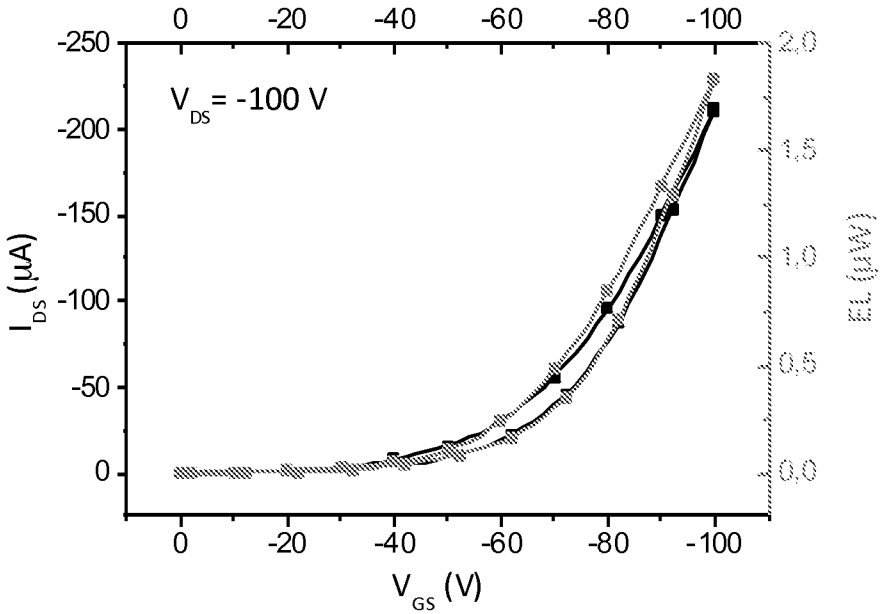

V_DS = -100 V
I_DS (μA)
EL (μW)
V_GS (V)

Fig. 15

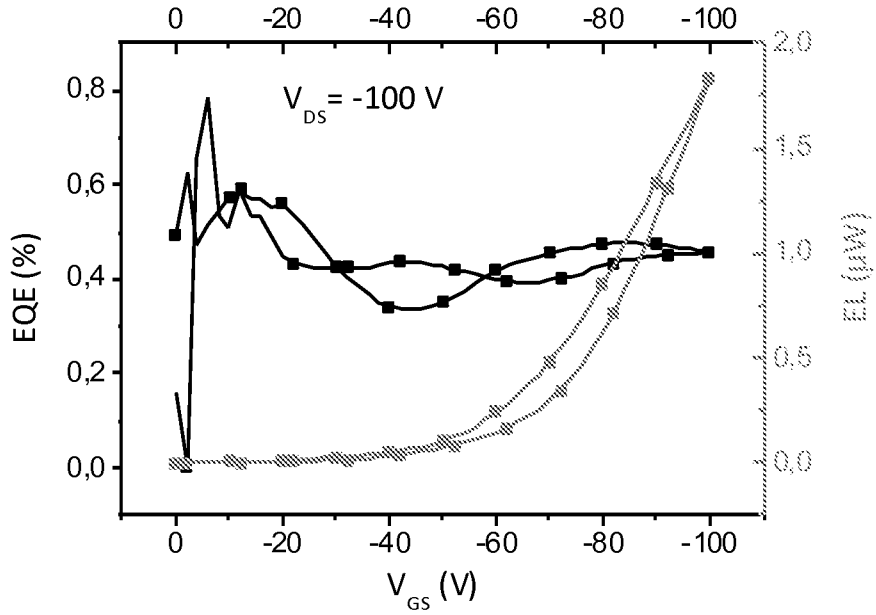

0
-20
-40
-60
-80
-100
V_{DS}= -100 V
EQE (%)
0,8
0,6
0,4
0,2
0,0
2,0
1,5
1,0
0,5
0,0
EL (μW)
V_{GS} (V)

Fig. 16

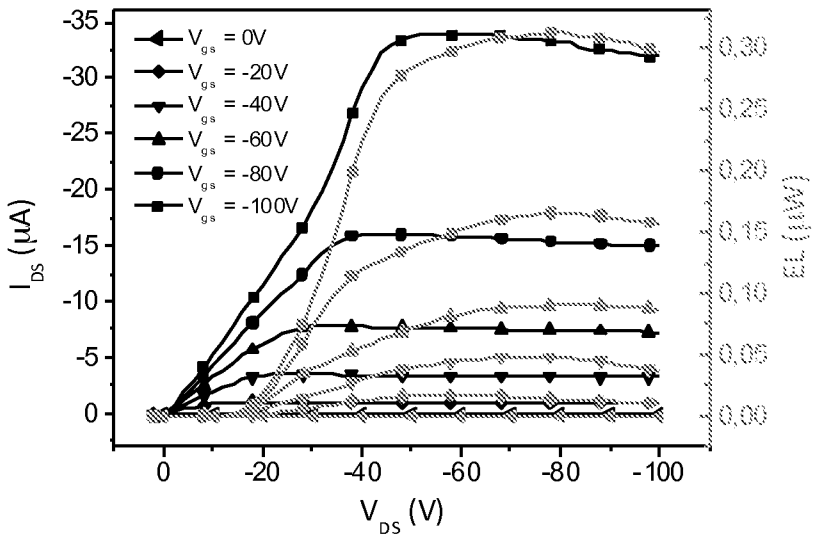

V_{gs} = 0V
V_{gs} = -20V
V_{gs} = -40V
V_{gs} = -60V
V_{gs} = -80V
V_{gs} = -100V
I_{DS} (μA)
-35
-30
-25
-20
-15
-10
-5
0
0,30
0,25
0,20
0,15
0,10
0,05
0,00
EL (μW)
V_{DS} (V)

Fig. 17

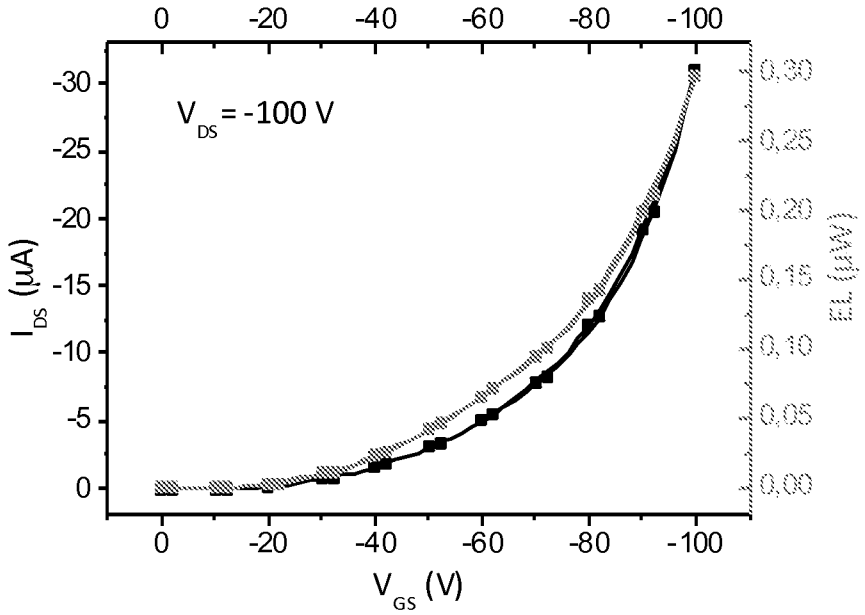

0
-20
-40
-60
-80
-100
-30
-25
-20
-15
-10
-5
0
V_{DS} = -100 V
I_{DS} (μA)
0,30
0,25
0,20
0,15
0,10
0,05
0,00
EL (μW)
V_{GS} (V)

Fig. 18

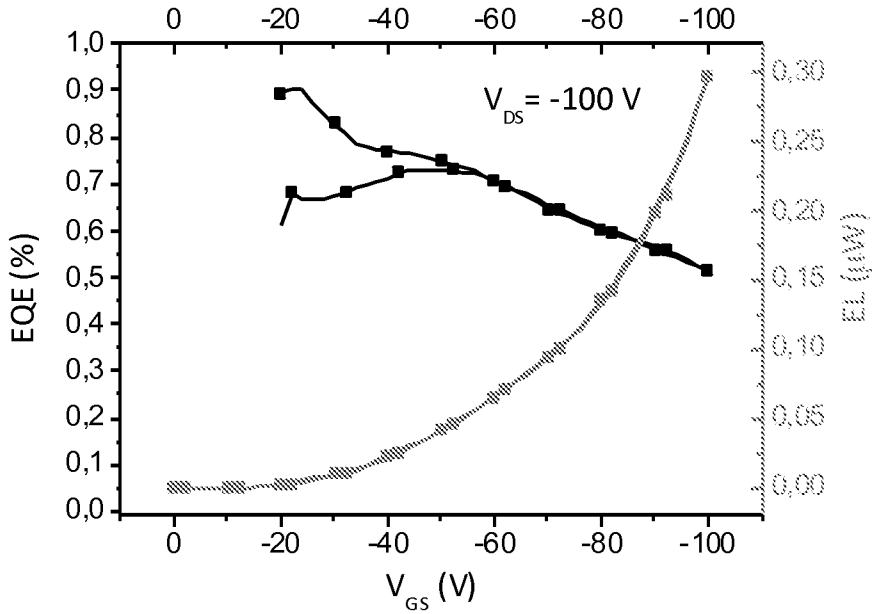

0
-20
-40
-60
-80
-100
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
V_{DS} = -100 V
EQE (%)
0,30
0,25
0,20
0,15
0,10
0,05
0,00
EL (μW)
V_{GS} (V)

Fig. 19

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/042063

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L51/52 H01L51/54 H01L51/00 C07D495/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L C07D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2014/035842 A1 (POLYERA CORP [US]) 6 March 2014 (2014-03-06) cited in the application	1-6, 14-22
Y	paragraphs [0008] - [0014], [0056] - [0057], [0060] - [0063], [0071] - [0074], [0079] - [0081]	7-13

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 October 2015	13/01/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Welter, Steve

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Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	MYEONG JIN KANG ET AL: "Two Isomeric Didecyl-dinaphtho[2,3- b :2$'$,3$'$- f]thieno[3,2- b]thiophenes: Impact of Alkylation Positions on Packing Structures and Organic Field Effect Transistor Characteristics", JAPANESE JOURNAL OF APPLIED PHYSICS, vol. 51, 20 November 2012 (2012-11-20), page 11PD04, XP055165373, ISSN: 0021-4922, DOI: 10.1143/JJAP.51.11PD04 abstract; figure 1	7
Y	YU-CHANG CHANG ET AL: "Crystal Engineering for [pi]-[pi] Stacking via Interaction between Electron-Rich and Electron-Deficient Heteroaromatics", THE JOURNAL OF ORGANIC CHEMISTRY, vol. 73, no. 12, 22 May 2008 (2008-05-22), pages 4608-4614, XP055155782, ISSN: 0022-3263, DOI: 10.1021/jo800546j the whole document	8,9
Y	EP 2 737 559 A1 (E T C SRL [IT]) 4 June 2014 (2014-06-04) paragraphs [0010] - [0013], [0028] - [0029]	10-13
A	HIDEAKI EBATA ET AL: "Highly Soluble (1)Benzothieno(3,2-b)benzothiophene (BTBT) Derivatives for High-Performance, SOlution-Processed Organic Field-Effect Transistors", JOURNAL OF THE AMERICAN CHEMICAL SOCIETY, AMERICAN CHEMICAL SOCIETY, vol. 129, no. 51, 29 November 2007 (2007-11-29), pages 15732-15733, XP009147953, ISSN: 0002-7863, DOI: 10.1021/JA074841I the whole document	2-6
A	WO 2013/039842 A1 (POLYERA CORP [US]; USTA HAKAN [US]; BOUDINET DAMIEN [US]; QUINN JORDAN) 21 March 2013 (2013-03-21) paragraphs [0004] - [0005], [0046], [0053]	1-22
A	EP 2 402 348 A1 (UNIV HIROSHIMA [JP]; NIPPON KAYAKU KK [JP]) 4 January 2012 (2012-01-04) paragraphs [0001], [0009], [0010], [0022]	1-22

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/042063

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-22

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-22

An organic electroluminescent transistor with an emissive ambipolar channel comprising an n-type semiconductor material layer, a p-type semiconductor material layer, and an emissive material layer arranged between said layers of p-type and n-type semiconductor materials; said p-type semiconductor material layer comprising a benzothieno-benzothiophene compound having general formula (P-I).

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2. claims: 23-35

An organic electroluminescent transistor with an emissive ambipolar channel comprising an n-type semiconductor material layer, a p-type semiconductor material layer, and an emissive material layer arranged between said layers of p-type and n-type semiconductor materials; said emissive material comprising a blend material comprising an organic carbazole derivative as the host matrix compound and an iridium complex as the guest emitter.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2015/042063

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2014035842 A1	06-03-2014	CN 104718638 A	17-06-2015
		EP 2888768 A1	01-07-2015
		JP 2015532768 A	12-11-2015
		KR 20150046126 A	29-04-2015
		US 2014054566 A1	27-02-2014
		US 2014054613 A1	27-02-2014
		WO 2014035841 A1	06-03-2014
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EP 2737559 A1	04-06-2014	CN 103782408 A	07-05-2014
		EP 2737559 A1	04-06-2014
		JP 2014522113 A	28-08-2014
		KR 20140056303 A	09-05-2014
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		EP 2755978 A1	23-07-2014
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		WO 2013039842 A1	21-03-2013
EP 2402348 A1	04-01-2012	CN 102333780 A	25-01-2012
		EP 2402348 A1	04-01-2012
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		KR 20110133025 A	09-12-2011
		US 2011303910 A1	15-12-2011
		WO 2010098372 A1	02-09-2010